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GEOLOGICAL SURVEY OF CANADA COMMISSION GÉOLOGIQUE DU CANADA

DESCRIPTIVE NOTES

INTRODUCTION

The Manitouwadge greenstone belt comprises a highly deformed remnant of upper amphibolite-facies supracrustal rocks adjacent to the boundary between the Wawa and Quetico subprovinces of the Archean Superior Province (Fig. 2). These 1:10 000 (Fig. 1) and 1:25 000 (Map 1917A) maps of the Manitouwadge greenstone belt are the result of new mapping with supporting structural studies, petrology, geochemistry, and geochronology, funded by the Canada–Ontario Northern Ontario Development Agreement (NODA) from 1991–1996.

The Manitouwadge greenstone belt is host to major volcanogenic Cu-Zn-Ag deposits which produced 63.9 Mt of ore collectively. Production came to an end with the closure of the Geco mine (Noranda Mineral Inc., Geco Division) in 1995. The known economic deposits were discovered in the 1950s on the basis of surface exposures and conventional geophysical methods that detected orebodies under thin overburden. The belt is still highly prospective terrain, but further exploration will benefit from an improved understanding of the primary depositional setting and its subsequent modification. The 1:10 000 map, focused on the area of known economic mineralization, is based on detailed new mapping supplemented by compilation of existing published and unpublished maps and, in some cases, subsurface information from drill holes and underground workings. The 1:25 000 map shows the regional setting and structure of the greenstone belt, and its relationship to the Wawa–Quetico subprovince boundary.

The Manitouwadge greenstone belt lies in the volcano-plutonic Wawa Subprovince, immediately south of the boundary with the migmatitic metasedimentary Quetico Subprovince (Fig. 2). The Superior Province was initially subdivided into subprovinces on the basis of structural trends and style, for example, contrasting the linear east-west trends of the Quetico Subprovince with the curvilinear trends of the Wawa and Wabigoon subprovinces, as defined by remnants of greenstone belts lying between batholithic domes (Stockwell, 1964). Lithological, metamorphic, and geophysical characteristics were subsequently used as distinguishing features (Stockwell, 1970; Card and Ciesielski, 1986). The tectonic significance of the subprovinces and their belt-like configuration has stimulated much debate. Langford and Morin (1976) proposed assembly of the Superior Province by successive accretion of island arcs and inter-arc sedimentary basins, based on comparison with the belt structure of the Canadian Cordillera. More recent refinements of arc-accretionary models have been proposed for the Wabigoon, Quetico, and Wawa subprovinces by Percival (1989), Percival and Williams (1989), and Williams (1990), among others. Arc-accretionary models commonly describe the Quetico Subprovince as an accretionary complex that accumulated southward from the margin of the Wabigoon arc above a northerly dipping subduction zone, with collision of the Wawa arc from the south amalgamating the three subprovinces.

The Manitouwadge project illustrates the importance of detailed study in constraining regional tectonic models. The geological evolution of the Manitouwadge greenstone belt is related to its proximity to the Wawa–Quetico subprovince boundary, and the end result is a complex geometry from which the structural evolution and primary stratigraphic relationships need to be unravelled.

REGIONAL SETTING

Together with the Faries Lake and Moshkinabi belts to the east (Williams and Breaks, 1990a, 1996), the Manitouwadge belt is part of a semicontinuous supracrustal suite (Manitouwadge–Hornpayne assemblage, Williams et al., 1991) along the northern margin of the Wawa Subprovince. The greenstone belts are deformed by east-northeasterly trending folds, including the Jim Lake synform, Blackman Lake antiform, and Manitouwadge synform (Map 1917A). Gradients in deformation state and metamorphic grade are in part related to the subprovince boundary. The folds tighten toward the north, and their axial traces curve, becoming transitional to the steeply dipping east-west trends of the Quetico Subprovince. The regional metamorphic grade increases from upper amphibolite facies in the Manitouwadge belt toward a zone of orthopyroxene-bearing granulite rocks in the Quetico Subprovince (Williams and Breaks, 1990a, b; Pan et al., 1994). All supracrustal rocks in the map area have been regionally metamorphosed and are generally characterized by upper amphibolite- to granulite-facies assemblages.

The Manitouwadge greenstone belt is bounded to the west and south by foliated multiphase plutonic rocks of the Black Pic batholith which extend south to the Schreiber–Hemlo greenstone belt (Williams et al., 1991). Between the Manitouwadge and Hemlo–Schreiber belts, foliations in the batholith define a structural dome (Williams and Breaks, 1990a, b).

The regional map pattern is dominated by F_3 folds, including the Manitouwadge synform which plunges to the east at about 25°. The supracrustal rocks are thickest in the hinge region of the Manitouwadge synform and along its southern limb, the area shown in detail on Figure 1. Away from the hinge region, supracrustal rocks are increasingly attenuated and invaded by intrusions.

PREVIOUS MAPPING

The first systematic mapping of the Manitouwadge greenstone belt was undertaken by Pye (1957) for the Ontario Department of Mines. He outlined the general shape of the belt and recognized mafic metavolcanic rocks along the inner and outer margins of the folded supracrustal sequence. At the time of Pye's mapping, most of the presently known orebodies had already been discovered and, in many cases, his detailed maps of mine properties are the only published record of geological relationships since obliterated by mining. Pye regarded the mineralization as Algoman replacement that postdated all intrusive activity, with the possible exception of diabase dykes. He interpreted most supracrustal rocks as metasedimentary. Milne (1974) remapped the area of major economic interest and reinterpreted the felsic rocks to be of volcanic, volcaniclastic, and sedimentary origin. Regional mapping by Williams and Breaks (1990a, 1996) provided a regional context and structural interpretation for the Manitouwadge belt and the Wawa–Quetico boundary region. The trace of the orthopyroxene-in isograd, and the locations of several iron-formation layers in the Quetico Subprovince (Map 1917A) are partly compiled from their work.

In addition to published maps, detailed geological mapping and geophysical surveys of claim groups have been undertaken by private-sector companies and prospectors. Unpublished claim maps were made available by Noranda Mining and Exploration Inc., Minnova Inc., and Granges Inc., and these were used as a starting point for mapping. The area near Gaug and Agam lakes (Fig. 1) was in part compiled from detailed mapping by Keast (1991) and Bates (1993) for Granges Inc.

TECTONOSTRATIGRAPHY AND GEOCHRONOLOGY

Manitouwadge greenstone belt

The stratigraphy of the Manitouwadge greenstone belt was defined in the hinge region and along the southern limb of the F_3 Manitouwadge synform in the thickest preserved section of supracrustal rocks. Deformation and metamorphic recrystallization have resulted in a paucity of way-up indicators on outcrop scale. However, in the area of Willroy (W1–W6) and Geco (G1–G3) mines, Zn-Cu ratios of orebodies and the position of footwall hydrothermal alteration zones and of a subvolcanic trondhjemite (*see* below) indicate southward younging. The stratigraphic sequence in this area dips subvertically, and shows a progression from mafic volcanic rocks at the base (north), overlain by interlayered felsic volcanic rocks and iron-formation, overlain by metagreywacke (south). This sequence is repeated along the southern limb of the Manitouwadge synform by the F_2 Agam Lake syncline. Two belts of volcanic rocks, hereafter referred to as "inner" and "outer" with respect to the easterly plunging F_3 fold, show a progression from mafic to felsic rocks toward the greywacke (*see* Fig. 3–9 for representative illustrations of the lithological units). Whereas economic mineralization is known only in the inner volcanic belt, felsic rocks are interlayered with iron-formation in both. The synvolcanic trondhjemite (unit At) which intrudes the base of the sequence, in the present configuration occupies a structural position in the core of the F_3 Manitouwadge synform. In the inner belt, three discrete mappable bodies of coarsely quartz-porphyritic felsic rocks (unit AfQ) are interlayered with iron-formation (units Aip, Ais, Aib) and spatially associated with massive sulphide deposits. In the outer volcanic belt, aphyric felsic rocks (unit Af) are interlayered with iron-formation. Mafic rocks (units Am, Amg, Amv) are more abundant in the outer volcanic belt than in the inner, occurring in the latter as screens or septa in synvolcanic trondhjemite and interleaved with felsic metavolcanic rocks along the transitional contact zone.

The Dead Lake suite (unit AD), an enigmatic package of interleaved foliated gabbro, diorite, and layered mafic to intermediate rocks of unknown origin, forms several semicontinuous zones in the inner trondhjemite. The Dead Lake suite includes a distinctive group of strongly magnetic, melanocratic rocks characterized by hornblende-magnetite ± plagioclase ± garnet ± clinopyroxene ± sulphide minerals (Fig. 10). The melanocratic rocks show local transitions on centimetre- to outcrop-scale to mesocratic, garnet ± magnetite ± hornblende trondhjemite, which is transitional to typical leucocratic trondhjemite (Zaleski et al., 1995b). Similar rocks are present in sporadic exposures in the mafic volcanic unit near Gaug Lake in the outer volcanic belt, suggesting that the Dead Lake suite is also repeated by the Agam Lake syncline.

Uranium-lead zircon geochronology on felsic volcanic and subvolcanic rocks supports the correlation of volcanic units across the Agam Lake syncline. Aphyric felsic breccia from the outer volcanic belt gave an age of 2722 ± 2 Ma (Zaleski et al., 1994, 1999), within error of 2720 ± 2 Ma muscovite schist at the Geco mine interpreted as an altered felsic volcanic rock (Davis et al., 1994). Foliated trondhjemite sampled north of the Willroy and Geco mines gave an age of 2720 ± 2 Ma, confirming our field interpretation of subvolcanic intrusion.

Extensive zones of orthoamphibole-cordierite-garnet gneiss (unit Aog) near the mafic-felsic transition in the inner volcanic belt, and to a lesser extent in the outer volcanic belt, are interpreted as synvolcanic hydrothermally altered, alkali-depleted, Fe-Mg-enriched rocks, modified by high-grade metamorphic recrystallization and deformation (Fig. 11). The precursors to alteration, mafic and interlayered mafic-felsic rocks near the transitional mafic-felsic contact, are still recognizable in less altered enclaves mostly on the margins of the unit and to the northeast further from known deposits. Near the contact with orthoamphibole-cordierite-garnet gneiss, trondhjemite locally contains disseminated garnet and folded seams of orthoamphibole, garnet, and biotite, suggesting that the trondhjemite was also affected by incipient hydrothermal alteration. On the basis of these observations, the trondhjemite was interpreted as part of a dynamic hydrothermal system in which the intrusion provided heat for driving hydrothermal circulation, and continued to rise intruding its own halo of hydrothermally altered rocks (Zaleski and Peterson, 1995). Surface mapping and subsurface data show that orthoamphibole-garnet rocks form a semiconformable sheet of regional extent, mantling synvolcanic trondhjemite and folded by the F_3 Manitouwadge synform. Orthoamphibole-garnet gneiss extends semicontinuously for at least 30 km from Rabbitskin Lake on the northern limb of the Manitouwadge synform, around the hinge of the fold to the Willroy–Geco area, east to the Hucamp zone of subeconomic mineralization (#17), and beyond to the Gavan mines (#18) and Falconbridge zones (#19). In the outer volcanic belt, orthoamphibole-garnet assemblages are found locally in a discontinuous zone in mafic metavolcanic rocks near the northern contact with felsic metavolcanic rocks and metagreywacke.

The orthoamphibole-cordierite-garnet rocks, equivalent to synvolcanic footwall alteration zones associated with volcanogenic massive sulphide deposits in less metamorphosed terranes, lie north of the Nama Creek (NC), Willroy (W1–W6), and Geco (G1–G3) deposits. The Geco orebodies increase in Zn/Cu from north to south, characteristically a stratigraphic-upwards zonation in volcanogenic massive sulphide deposits (Suffel et al., 1971). The position of the footwall alteration with respect to the deposits and the southward increase in Zn/Cu have been used to infer southward younging in the Willroy–Geco area (Suffel et al., 1971; Friesen et al., 1982). The northern position of the synvolcanic trondhjemite intrusion is consistent with exposure of progressively deeper levels of a volcano-plutonic edifice in that direction in the inner volcanic belt.

Quartz-muscovite ± sillimanite schist, sillimanite-knot felsic schist, and quartzose schist (units Aam, Aas, Aaq) are interpreted as the products of aluminous-potassic and silicic synvolcanic hydrothermal alteration (Fig. 12; Zaleski and Peterson, 1995). Sillimanite-muscovite-quartz schist is found close to massive sulphide deposits, mainly to the south of orebodies in the Willroy–Geco area and enveloping the Geco main orebody (G1). Two zones of sillimanite-bearing felsic schist converge to the east near the Geco mine, where they are interpreted to be separated by an early, low-angle fault (Garnet Lake fault, *see* below). The northern zone grades easterly from sillimanite-knot schist to sillimanite-muscovite-quartz schist consisting of alternating thin quartz-rich and muscovite-rich layers with sillimanite forming sprays on the foliation surface. Near Willroy, the southern belt consists of thinly layered quartzofeldspathic schist that becomes more muscovitic and silicic to the east, merging with the northern belt and grading to a sulphidic muscovite-biotite quartzose schist in the Geco area. Felsic volcanic rocks lying along strike and in less altered enclaves are interpreted as the protolith of the altered rocks.

Near the hinge region of the Manitouwadge synform in the Willecho area (E1–E3), sillimanite-knot felsic schist is interleaved (on a metre scale) with nonsillimanitic felsic schist, straight gneiss, and sheared pegmatite. Similar rocks occur sporadically to the south of Willecho, associated with iron-formation that can be traced continuously to the Willroy area. At a few localities, thinly layered quartz-porphyritic felsic tuff or tuffaceous metasedimentary rocks contain abundant sillimanite that coalesces into sillimanitic layers.

Three types of iron-formation (units Aib, Ais, Aip) are present in the Manitouwadge belt: a) quartz-magnetite-silicate banded iron-formation, b) magnetite-silicate iron-formation, and c) sulphidic iron-formation consisting of disseminated or stockwork pyrite and/or pyrrhotite in quartz-magnetite-silicate host rocks. Quartz-magnetite-silicate banded iron-formation is by far the most abundant type (Fig. 7, 8). Magnetite-silicate iron-formation is mainly present near the contacts of banded iron-formation, especially near the northern contact (the stratigraphic footwall) of the thickest iron-formation. Sulphidic iron-formation rarely forms mappable units, but occurs mainly in the transition from quartz-magnetite-silicate banded iron-formation to massive sulphide (e.g. Timms and Marshall, 1959).

Monotonous metagreywacke and biotite-hornblende schist (Fig. 9a) lie between the inner and outer metavolcanic belts, occupying the centre of the F_2 Agam Lake syncline along the southern limb of the F_3 Manitouwadge synform. The maximum age of sedimentation of 2693 Ma, constrained by U-Pb dating of detrital zircon grains, is at least 25 Ma younger than the age of felsic volcanism associated with Cu-Zn mineralization (Zaleski et al., 1999). The nature of the contact with adjacent metavolcanic rocks is obscured by intrusions, metamorphic recrystallization, and deformation, but it is either an unconformity or an early (pre- to syn-D_2) fault.

Very fine-grained to aphanitic, laminated felsic rocks, referred to as straight gneiss (Fig. 13), were mapped as semicontinuous outcrop-scale layers and lenses. In the Willroy–Geco area, straight gneiss lies in a zone along which iron-formation and other units are truncated and, across which the sequence quartz-porphyritic felsic rock, iron-formation (with massive sulphide mineralization), sillimanite-muscovite-quartz schist, is repeated. Based on these observations, straight gneiss is interpreted as annealed mylonite marking early ductile faults (*see* below). The protolith to straight gneiss is mainly felsic volcanic rocks and, in some cases, pegmatite.

Away from the hinge region of the Manitouwadge synform, supracrustal rocks are increasingly attenuated and invaded by intrusions, and unambiguous identification of protolith becomes difficult. Undivided mafic to intermediate rocks, locally with garnetiferous zones, define the northern limb of the Manitouwadge synform and related macroscopic folds to the north. Orthoamphibole-bearing rocks, well exposed west of Rabbitskin Lake, trend easterly into the east-northeasterly trending Rabbitskin Lake fault. Further east along the northern limb of the Manitouwadge synform, orthoamphibole-garnet rocks outcrop west of the hinge region of the Blackman Lake antiform associated with sphalerite-bearing iron-formation at the Jim Lake occurrence (#21). In the vicinity of the Blackman Lake and Jim Lake folds, the greenstone belt is represented by layered metavolcanic rocks with minor iron-formation, and by foliated medium- to coarse-grained amphibolite that could be recrystallized volcanic, subvolcanic, or plutonic rocks. The Jim Lake synform is partly defined by zones of mafic to intermediate inclusions in foliated tonalite and pegmatite. Inside the Manitouwadge synform, the Dead Lake suite forms a marker unit that can be traced in outcrop and as an aeromagnetic high (Geological Survey of Canada, 1997) along the northern limb of the synform and around the Blackman Lake antiform.

On the southern limb of the Manitouwadge synform, the easternmost exposure of orthoamphibole-bearing rocks lies about 4 km east of Wowun Lake. To the east, exposure is poor; however, a prominent aeromagnetic anomaly continues the same trend to the Falconbridge zone (#19), and the unit was intersected by drilling (unpub. data, Noranda Mines Ltd., Geco Division, 1984). The outer belt of mafic metavolcanic rocks can be traced as a southerly diverging zone of inclusions in foliated plutonic rocks. South of Thompson Lake, the area of the Banana Lake antiform is poorly exposed and no supracrustal rocks outcrop. Foliations in plutonic rocks are folded, and supracrustal rocks are exposed to the south in the Faries Lake belt (Williams and Breaks, 1990a, 1996). East of Thompson and Banana lakes near the eastern extremity of the map area, orthoamphibole-garnet-cordierite gneiss, mafic schist, and garnet-magnetite ± hornblende ± clinopyroxene rocks resembling the Dead Lake suite define macroscopic folds with a northerly trending enveloping surface.

QUETICO SUBPROVINCE

Metagreywacke in the Quetico Subprovince is indistinguishable from that in Manitouwadge greenstone belt, except for the difference in metamorphic grade, as shown by pervasive migmatitic segregations in the Quetico metagreywacke (Fig. 9b). Locally, thin silicate and sulphide iron-formation, ranging from several centimetres to 10 m in width (e.g. McKay, 1994), are intercalated with migmatitic metagreywacke. Iron-formation widths as shown on the map are exaggerated for legibility. In the area of the Jim Lake synform, there is a compositional gradation from hornblende-dominated schist, interpreted to be of volcanic or volcaniclastic origin, to hornblende-biotite metagreywacke. The depositional age of Quetico greywacke, constrained by U-Pb dating of detrital zircon grains, is less than 2690 Ma, permitting correlation of Quetico greywacke with greywacke on the southern limb of the Manitouwadge synform in the Wawa Subprovince (Zaleski et al., 1999).

STRUCTURE AND METAMORPHISM

The structural evolution can be modelled by four phases of ductile deformation (D_1-D_4). The deformation history is based on field observations of planar (S) and linear (L) fabric elements, their inter-relationships, and their relationships with respect to mesoscopic folds (F), coupled with map-scale interpretations. Our deformation sequence is generally compatible with that of Williams and Breaks (1989, 1990a, 1996), with differences arising from our detailed mapping of supracrustal rocks and extensive integration of geological and aeromagnetic data (Geological Survey of Canada, 1997).

The oldest fabric elements recognized include modified bedding, contacts, volcanic flow horizons, and transposed sheets or layering in plutonic rocks and in metasomatically altered rocks. These are subparallel to tectonic fabric elements, that is, subparallel to laminations in straight gneiss (annealed mylonitic layering, S_1), to the dominant mineral foliation (S_2), or to the oldest migmatitic segregations (S_2) in the Quetico Subprovince. The dominant foliation (S_2) is typically a composite fabric comprising transposed layering and laminations (S_0-S_1), and layer-parallel mineral schistosity (S_2). The schistosity (S_2), and a strong lineation (L_2) on the schistosity surface, are defined by the preferred crystallographic orientation and shapes of high-grade metamorphic minerals including mica, amphibole, cordierite, and sillimanite. Mineral lineations (L_2) are commonly parallel to a stretching lineation defined by rodding of mineral aggregates and elongate sillimanite knots, and prolate primary features such as clasts, pillows, and phenocrysts.

The dominant S_2 planar and L_2 linear fabrics are widely distributed and their relationships to mesoscopic and macroscopic folds were used to classify fold generations. In general, F_2 folds deform compositional layering and modified bedding, and the dominant foliation and lineation are parallel to F_2 axial planes and fold axes, respectively. Key relationships supporting an episode of D_1 deformation are preserved locally in the hinge regions of F_2 folds where folded mylonitic layering (S_1) is oblique to S_2 axial planar fabrics. F_3 folds, including the Manitouwadge synform, deform the dominant D_2 fabrics and, in some cases, are associated with weakly developed crenulation microfolds (F_3) and crenulation cleavage (S_3). F_4 folds are typically kinks at high angle to the dominant foliation and, locally, are strongly developed in schistose rocks and associated with crenulation cleavage (S_4).

Metamorphic grade increases northward culminating in an orthopyroxene-granulite zone in the Quetico Subprovince (Williams and Breaks, 1990a). Thermobarometry in granulite assemblages indicates peak metamorphic conditions of 680–770°C and 4–6 kbar (Pan et al., 1994). In the southern Manitouwadge belt, thermobarometry has resulted in estimates of 600°C and 3–5 kbar (Pan and Fleet, 1992) and 650°C and 5–7 kbar (Petersen, 1984). The regional gradient is marked in the Manitouwadge belt by a change from muscovite-sillimanite-quartz schist on the southern limb of the Manitouwadge synform to sillimanite-microcline-quartz schist near the hinge region. In the absence of evidence for melting, this transition is consistent with the high temperatures and with low pressures of less than 4–5 kbar (e.g. Spear, 1993).

With increasing metamorphic grade toward the north, the dominant planar fabric is increasingly recrystallized and is commonly defined by weak mineral foliation and transposed compositional layering, which in the Quetico Subprovince, includes modified bedding and migmatitic segregations. Mineral and/or stretching lineations are subtle or absent. Especially in the Quetico Subprovince, mesoscopic folds (F_3) that deform early migmatitic layering (S_2) show development of axial planar mineral foliations (S_3). A hornblende ± biotite foliation (post-D_3 pre-D_4) transects the dominant fabrics at a high angle.

D_1 and D_2 are particularly important for understanding stratigraphic relationships in the area of known economic deposits, the geometry of the 'Geco mine horizon', and the internal complexity of the greenstone belt. In the Willroy–Geco area, the sequence, quartz-porphyritic felsic rocks, iron-formation (with massive sulphide deposits), sillimanite-muscovite-quartz schist, is repeated across an interpreted D_1 fault (Garnet Lake fault) marked by zones of straight gneiss. The Garnet Lake fault divides the Nama Creek–Willroy–Geco area into two blocks and results in repetition of mineralized horizons (Zaleski and Peterson, 1995; Peterson and Zaleski, 1999). The fault geometry and presence of mylonitic layering (annealed S_1) are consistent with a ductile fault with relatively minor displacement (hundreds of metres to 1 km) at low angle to stratigraphic contacts. The fault continues eastward in sillimanite-muscovite-quartz schist through the Geco area, to highly strained iron-formation and straight gneiss exposed near the Hucamp zone (#17) east of Wowun Lake. Northwest of Willroy, the D_1 fault separates an area of complex folding, involving iron-formation and felsic rocks in the Willecho area and south, from an area of more continuous orthoamphibole-garnet gneiss and trondhjemite to the northeast. North of the Willecho deposits, quartz-porphyritic felsic rocks, iron-formation, and sillimanite-knot felsic schist are repeated by a fold that is transected by the dominant S_2 fabric and, hence, probably an F_1 fold.

D_2 deformation produced folds with curved hinge lines, including sheath folds, on map and outcrop scale (Peterson and Zaleski, 1994, 1999). The southernmost iron-formation in the inner volcanic belt is considerably thickened by F_2 folding and, in the Geco area, it is much invaded by concordant foliated tonalite dykes or sheets of probable D_2 age. In the complex area between Nama Creek and Willecho, a macroscopic F_2 fold repeats iron-formation and the D_1 Garnet Lake fault in a closed structure (approximately 4 km long and 1 km wide). The intrafolial, rather than repetitive, character of the structure and the nearly coaxial relationship of D_2 and D_3 lineations and mesoscopic fold axes are best explained by an F_2 sheath fold, rather than an F_2-F_3 interference pattern (Peterson and Zaleski, 1999). The Willecho deposits and subeconomic sulphide occurrences (#7 and #8) lie near or on the folded repetition of the fault.

On the southern limb of the Manitouwadge synform, the lithological sequence of mafic volcanic rocks, felsic volcanic rocks interlayered with iron-formation, sedimentary rocks, was interpreted as a stratigraphic succession repeated by an early syncline (Suffel et al., 1971; Robinson, 1979), here called the F_2 Agam Lake syncline. A possible consequence of F_2 fold repetition of sequences across the southern limb of the F_3 Manitouwadge synform is that the mineralized and altered intervals of the Willroy–Geco area may be repeated in the outer volcanic belt, assuming that they were not removed by erosion or faulting along the contact with younger greywacke. The sporadic zones of orthoamphibole, garnet, and minor cordierite in mafic rocks in the outer belt near the contact with interlayered felsic rocks and iron-formation are interpreted as synvolcanic alteration zones correlative with altered rocks in the Willroy–Geco area.

The dominant foliation and mineral lineations, defined by peak metamorphic minerals in the Manitouwadge belt and folded by F_3 folds on map and outcrop scale, are consistent with D_2 fabric development during peak metamorphism. Toward the north, evidence of recrystallization subsequent to D_2 deformation increases. In the Quetico Subprovince and near the subprovince boundary, migmatitic segregations are both folded by, and cut across, folds attributed to D_2 deformation. Ubiquitous mesoscopic Z-folds and dextral kinematic indicators support oblique dextral shear during D_2 deformation. Minor structures deform migmatitic layering and are transected by migmatitic segregations, suggesting that peak metamorphism and migmatization were associated with progressive deformation and the development of F_3 folds near the subprovince boundary. These observations imply a protracted metamorphic history, and diachronous cooling, with cooling from peak temperatures predating D_3 deformation in the Manitouwadge belt and postdating D_3 deformation in the Quetico Subprovince (Zaleski et al., 1995a). This interpretation is supported by U-Pb zircon ages on plutonic rocks. Strong D_2 fabrics in the 2687 ± 2 Ma Loken Lake pluton, folded by the Manitouwadge synform, are cut by 2680 +4/-3 Ma foliated granite, bracketing the D_2 fabrics and, by inference peak metamorphism, to the interval ca. 2687–2680 Ma (Zaleski et al., 1999). In the Wawa–Quetico boundary region, the 2679 ± 2 Ma Everest Lake pluton and the 2680 ± 2 Ma Nama Creek pluton show evidence of migmatization.

D_2 fabrics are well developed in synvolcanic trondhjemite, early phases of the Black Pic batholith and in the Loken Lake pluton. Macroscopic F_2 synformal 'keels', account for repetitions of supracrustal rocks about pluton-cored antiformal culminations. For example, our preferred interpretation of the mafic and orthoamphibole-cordierite-garnet rocks east of Thompson and Banana lakes involves repetition of altered rocks and trondhjemite by an F_2 synformal keel. The Loken Lake pluton, characterized by an $L_2 \geq S_2$ fabric, is interpreted to occupy an F_2 antiformal fold.

Easterly plunging F_3 folds, the Manitouwadge synform, Blackman Lake antiform, and Jim Lake synform, dominate the regional map pattern and involve migmatitic greywacke continuous with that of the Quetico Subprovince. The axial surface of the Manitouwadge synform dips to the south, resulting in shallow to moderate southerly dips of layering and foliation on the northern limb, and near-vertical to moderate southerly dips on the southern limb (Fig. 14). F_3 folds deform D_2 fabrics and, in general in the Manitouwadge belt, S_3 axial planar fabrics are weakly developed. Although L_2 linear fabrics are typically nearly coaxial with F_3 folds, they show systematic variation consistent with reorientation by F_3.

D_4 deformation is mainly manifested as kinks and crenulations, open warps of F_3 axial traces, and transposition of F_3 axial surfaces, for example in the Wawa–Quetico boundary region. The northwestern contact of the Manitouwadge belt to the Nama Creek pluton was the locus of post-D_3 ductile shearing, sinistral in map view, along the D_4 Nama Creek shear zone. Near this zone, structural and aeromagnetic trends are discontinuous, and outcrop-scale F_3 folds and earlier fabrics are strongly transposed into L > S tectonite. In the southeastern area of the Manitouwadge belt, the Banana Lake antiform, previously considered to be an F_3 fold (Williams and Breaks, 1996), is tentatively reinterpreted to be an F_4 fold. Its orientation and style are consistent with either an F_3 or an F_4 fold. However, D_4 development is supported by the 2677 ± 2 Ma age of the Banana pluton, which apparently postdates D_3 deformation and yet contains a tectonic fabric (S_3) folded by the Banana Lake antiform.

A number of brittle-ductile to ductile faults were previously identified by Pye (1957), Milne (1974), and Williams and Breaks (1990a). The Agam Lake fault (Pye, 1957) forms a pronounced strike-parallel topographic lineament, mostly in metagreywacke, but juxtaposing metagreywacke and mafic volcanic rocks along its western extremity. In metagreywacke, it corresponds to a change in aeromagnetic signature, suggesting possible involvement of volcanic rocks in the subsurface. The Rabbitskin Lake fault forms a broad lineament defined by topographic and aeromagnetic lows. The inferred fault apparently truncates or attenuates orthoamphibole-bearing rocks, and may be responsible for the strong attenuation of the northern limb of the Manitouwadge synform, implying sinistral movement in map view. The Agam Lake fault and Rabbitskin Lake fault, and two faults west and southwest of Garnet Lake, are apparently folded by the Manitouwadge synform.

High-angle faults are marked by low aeromagnetic and low topographic lineaments, and by displacement of lithological units and aeromagnetic trends. The northerly trending Cadawaja and Fox Creek faults show apparent sinistral displacement and, in the case of the Fox Creek Fault, intersected by underground workings at the Geco mine, 60 m of left-lateral and east-side-up displacement is recorded (Pye, 1957; Brown et al., 1960). In general, the trends of faults are subparallel to those of Proterozoic Matachewan and Marathon dykes, that is northwesterly and northerly, respectively. Dykes are commonly intruded along faults, or along some segments of faults and, in some cases, dykes and faults cannot be discriminated on the basis of aeromagnetic signature.

AGE AND STRUCTURAL RELATIONSHIPS OF PLUTONIC ROCKS

The Black Pic batholith comprises a range of plutonic rocks from diorite to granite to layered gneissic rocks, commonly with several generations of intrusions represented on a single outcrop. The magmatic and deformation history of the region was partly addressed by U-Pb dating of zircons in plutonic rocks (Zaleski et al., 1999). The oldest recognized phase of the Black Pic batholith, 2689 ± 2 Ma monzodiorite (Fig. 15), which varies to granodiorite and quartz diorite, has a tectonic foliation folded by the Manitouwadge synform. The contact to the Manitouwadge belt is a transitional zone of mafic metavolcanic rocks and monzodiorite sheets involved in tight folds and, in many cases, cut by younger foliated tonalite and aplite-pegmatite. Inside the Manitouwadge synform, the 2687 ± 2 Ma Loken Lake pluton is a foliated microcline-megacrystic granodiorite, commonly with an L > S tectonic fabric (Fig. 16). Both the Black Pic monzodiorite and Loken Lake pluton are interpreted as pre- to syn-D_2 intrusions.

Several intrusions, all with tectonic fabrics interpreted as late-D_2 to syn-D_3, have emplacement ages of ca. 2680–2675 Ma. The Nama Creek pluton, 2680 ± 2 Ma microcline-megacrystic granodiorite to monzodiorite, forms a long sinuous body along the margin of Manitouwadge belt and is folded by the F_3 Blackman Lake antiform. The foliation of the 2677 ± 2 Ma Banana monzodiorite pluton is folded around the F_4 Banana Lake antiform. Everest Lake pluton underlies an elongate area, slightly modified here from Williams and Breaks (1990a), along the Wawa–Quetico boundary. Its northern contact consists of a wide zone in which monzodiorite to diorite sheets are interleaved and deformed together with Quetico paragneiss (Fig. 17). Both the paragneiss and the monzodiorite sheets have abundant *in situ* anatectic segregations, implying that migmatization, at least in part, postdated the 2679 ± 2 Ma emplacement of the pluton.

WAWA–QUETICO SUBPROVINCE BOUNDARY

The Wawa–Quetico boundary in the Manitouwadge area is transitional on the basis of lithological, structural, and metamorphic criteria. The similarity in depositional age constraints and in composition between metagreywacke in the Manitouwadge greenstone belt and that in the Quetico Subprovince, and the folding of the latter together with metavolcanic rocks in the Jim Lake antiform, argue for correlation of the sedimentary sequences across the subprovince boundary. There is a northward change from macroscopic F_3 folds with broad hinge regions and northeasterly trending axial planes that dip toward the south, to tight F_3 folds with subvertical dips and east-west trends parallel to the dominant structural trends of the Quetico Subprovince (Fig. 14). The increased transposition and increased D_3-D_4 strain toward the Wawa–Quetico boundary may partly reflect the contribution of the thermal gradient to ductility contrasts during metamorphism.

ECONOMIC GEOLOGY

The Geco deposit was by far the largest in the Manitouwadge belt (Table 1A), producing 55.9 Mt of ore during its lifetime with an overall grade of 1.9% Cu, 3.8% Zn, and 47 g/t Ag (H. Lockwood, written comm., 1994). Combined production from the Willroy, Nama Creek, and Willecho deposits, until the closure of the Willroy mine in 1977, was 8.7 Mt with a grade of 0.9% Cu, 4.9% Zn, and 50 g/t Ag. Except for Nama Creek, each deposit comprised several massive, semimassive, or stockwork sulphide orebodies of varying Cu, Zn, and Pb grades and ratios. In terms of classification based on Cu-Zn-Pb, the Manitouwadge belt collectively fits Franklin's (1986) Cu-Zn group 1a, which includes the deposits of the Abitibi greenstone belt, the Norwegian Caledonides, and other areas dominated by basaltic volcanism (Zaleski and Peterson, 1995).

On the basis of Cu-Zn-Pb proportions, nature of mineralization and relationships to iron-formation and alteration zones, the orebodies of the Manitouwadge camp can be divided into three main types. Firstly, Cu-rich stockwork and disseminated orebodies are hosted by orthoamphibole-cordierite-garnet gneiss or sillimanite-muscovite-quartz schist (Geco 4/2 Cu and Main disseminated zones, Willroy 1 and 6). Secondly, massive and semimassive Zn-Cu(-Pb) orebodies are associated with iron-formation horizons interleaved with sillimanite-muscovite-quartz schist or quartz-porphyritic felsic rocks (Geco 8/2 Zn zone and Main orebody, Willroy 2, 3, 5, Nama Creek, and Willecho 1, 2, 3). Thirdly, massive and semimassive Zn-Pb(-Cu) orebodies are hosted by iron-formation along the south side of sillimanite-muscovite-quartz schist (Geco zincian iron-formation (not shown) and Willroy 4). With some exceptions related to D_1 fault movement, the spatial distribution of orebodies defines a tendency to more Zn-rich and Pb-rich deposits toward the south.

The orebodies are conformable to the moderately to subvertically dipping host rocks, and elongate with shallow to moderate easterly plunges subparallel to the dominant lineation. The massive sulphide zone of the Geco main orebody is thickest in the hinge of the easterly plunging Z-shaped 'Geco drag fold' (Friesen et al., 1982), inferred to be an F_3 or later fold on the basis of folded foliation.

Numerous other sulphide occurrences, the more important of which are shown on the map, have been investigated in the past by surface work and drilling (Tables 1B, 2). The Delmico E and F sulphide occurrences (#7 and #8), intersected by several drill holes along a strike-length of about 800 m, define a zone containing up to 0.18% Cu associated with iron-formation (Simard and Knight, Mining Consultants and Zurowski, 1954; Pye, 1957). The position of the zone, near the trace of the interpreted D_1 fault, suggests that it lies in the same stratigraphic interval as the economic mineralization, and may represent sulphides remobilized during ductile deformation. To the south, the Delmico D occurrence (#6) has up to 0.13% Cu, and the Granges 1 occurrence (#9) has up to 0.41% Zn, in graphitic, semimassive to stockwork sulphide zones near the contact between felsic volcanic rocks and metagreywacke (Pye, 1957; Keast, 1991). North of the axial trace of the Manitouwadge synform, the Man-Echo, Minnova 1 and 2, and McIntyre occurrences (#2–#5), with minor Cu and up to 0.43% Zn (Pye, 1957; McIntyre Porcupine Mines Ltd., 1967; INMET Mining Inc., unpub. data, 1991), consist of three subparallel zones of semimassive and disseminated sulphides associated with iron-formation and sillimanite-knot felsic schist. While precise correlations are difficult, the mineralization and associated rocks are similar to those of the Willecho area and the Delmico occurrences. The Rabbitskin Lake occurrence (#1) is hosted by sillimanitic, garnetiferous, and orthoamphibole-bearing rocks intersected by several deep drill holes collared 0.5–1 km southwest of Rabbitskin Lake (Noranda Incorporated (Geco Division), 1982). The occurrence is shown projected to a probable approximate surface location. The host rock lithology and high Cu/Zn suggest that the mineralization lies on the same horizon as the Geco 4/2 Cu and Willroy 1 and 6 orebodies. East of the Geco mine, the Hucamp occurrence (#17) (Pye, 1957), with up to 0.27% Cu and 2.78% Zn intersected by drilling, has been viewed as an extension of the 'Geco mine horizon' (H. Lockwood, pers. comm., 1993).

In the outer volcanic belt, the Granges 2, Delmico B, and Granges 3 occurrences (#11–#13) consist of semimassive and stockwork sulphides associated with iron-formation and felsic volcanic rocks along a strike-length of more than 1 km. At the Delmico B occurrence (#12), up to 0.17% Cu was intersected by drilling in the 1950s (Simard and Knight, Mining Consultants and Zurowski, 1954; Pye, 1957). Later investigation by Granges Inc. showed up to 0.34% Cu in surface samples and 0.13% Cu in drill core (Keast, 1991). The Granges 2 and 3 occurrences (#11 and #13), with 0.09–1.1% Zn in drill core and more than 1% Cu in surface samples (Keast, 1991), are apparently extensions of the same zone. The Agam Lake zone (#14), containing up to 0.10% Zn (Simard and Knight, Mining Consultants and Zurowski, 1954) in metagreywacke along the Agam Lake fault, possibly represents sulphides remobilized during faulting. West of the Agam Lake zone, where the Agam Lake fault juxtaposes metagreywacke and mafic metavolcanic rocks, the General Engineering Co. Ltd. occurrence (#10) (Pye, 1957) has a semicontinuous strike length of about 800 m, with assay values typically ranging from 0.12–2.4% Cu in surface samples and up to 1.3% Cu in drill core (Keast, 1991).

On the regional scale, the 'Geco mine horizon' has been traced easterly to the Hucamp, Gavan Mines Ltd., and Falconbridge zones (#17–#19), the last with up to 0.62% Cu, 2.96% Zn, 1.89% Pb, and 51 g/t Ag (Table 2). The One Otter Lake (East) and Jim Lake (East Larry Lake) occurrences (#20–#21) are also interpreted as lying on the same horizon, in the case of the One Otter Lake occurrence, through repetition by an F_2 synformal keel. All of the above occurrences are associated with orthoamphibole-bearing rocks. The Swill Lake occurrences (#28–#32) in the outer hinge region of the Manitouwadge synform lie in the outer volcanic belt. The Swill Lake West and South showings (#28, #30–#32) are hosted by quartz-rich felsic volcanic rocks with minor iron-formation (not shown at the scale of the map) within the thick mafic sequence. They define a sporadically mineralized zone, with up to 0.13% Cu and 0.91% Zn, over a strike length of 3 km. The Swill Lake East occurrence (#29) lies in a cummingtonite-garnet-bearing zone in mafic metavolcanic rocks. Inside the Manitouwadge synform, the area of the Straight Lake occurrence (#22) is poorly exposed, but aeromagnetic trends suggest continuity with the Dead Lake suite and, hence, a lower stratigraphic position possibly near the base of the synvolcanic trondhjemite.

In the Quetico Subprovince, several minor Cu ± Zn occurrences (#23–#27) are associated with thin sulphidic zones in silicate iron-formation and, in one case (Husak Road 3, #25), with local mafic rocks.

ACKNOWLEDGMENTS

Hugh Lockwood, Battle Mountain Gold, formerly Chief Geologist at Noranda's Geco mine was instrumental in the initiation of the Manitouwadge project, and contributed greatly to its success by facilitating the exchange of information and the development of ideas. Otto van Breemen, Geological Survey of Canada, has worked with us on geochronology and contributed to our understanding of temporal relationships. Ken Buchan and Richard Ernst, Geological Survey of Canada, lent their expertise in the interpretation of diabase dykes and faults. Mark Smyk, Thunder Bay Resident Geologist's Office, Ontario Geological Survey, searched the files for unpublished information on mineral occurrences. Noranda Minerals Inc., INMET Mining Inc., Granges Inc., and Al Turner provided access to unpublished maps and reports. Wouter Bleeker and John Henderson, Geological Survey of Canada, greatly improved the maps and notes with their incisive reviews.

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Figure 3a. Laminated mafic schist, showing boudinage and truncations of sheared layering, typical of highly strained mafic metavolcanic rocks (unit Amv). Photograph by E. Zaleski. GSC 1998-013Q

Figure 3b. Layered mafic metavolcanic rocks (unit Amv) near the northwestern margin of the Manitouwadge greenstone belt showing F_3 S-folds tightened by the Nama Creek shear zone. Tonalitic veins cut across folds in the mafic rock, but are also folded. Photograph by E. Zaleski. GSC 2000-008A

Figure 4. Highly strained, interlayered mafic and felsic metavolcanic rocks (unit Amf), with boudinaged pegmatite and quartz veins. The outcrop forms an enclave of weakly altered rocks in the orthoamphibole-bearing rocks of unit Aog south of Cracknell Lake. Photograph by E. Zaleski. GSC 2000-008B

Figure 5a. Coarse monolithic aphyric felsic breccia (unit Af) in the outer volcanic belt north of Gaug Lake interpreted as a proximal volcanic deposit. Fragments are 10–30 cm. The matrix composition varies from biotitic felsic to dominated by calc-silicate minerals (garnet, amphibole, epidote). Fragments are approximately 10–30 cm across. Photograph by V. Peterson. GSC 1998-007A

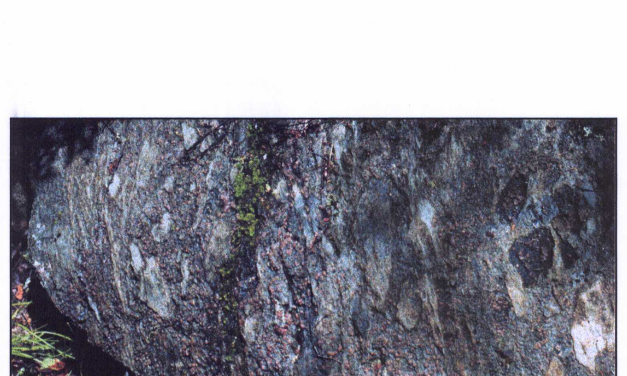

Figure 5b. Coarse heterolithic breccia in the outer volcanic belt north of Gaug Lake. The fragments comprise felsic (unit Af) volcanic and garnet-hornblende clasts, the latter similar to the matrix of some monolithic felsic breccia. The matrix contains abundant garnet and hornblende. Photograph by V. Peterson. GSC 1998-013J

Figure 6. Coarsely quartz-porphyritic felsic breccia (unit AfQ) in the Willroy area cut by a concordant foliated tonalite dyke. In the breccia, both clasts and matrix contain variable amounts of muscovite, biotite, magnetite, and garnet, interpreted as indicating minor synvolcanic hydrothermal alteration. Photograph by E. Zaleski. GSC 1998-013HH

Figure 7. F_2 folds in banded iron-formation (unit Aib) with intraformational breccia of segmented quartzose layers in a dark silicate-magnetite matrix. Note the competence of the quartzose layers with respect to silicate-magnetite layers. Photograph by E. Zaleski. GSC 2000-008C

Figure 8. Folded contact between banded iron-formation (above) and felsic schist (below) in the hinge region of the macroscopic F_2 fold southwest of the Nama Creek deposit. Photograph by V. Peterson. GSC 1998-013GG

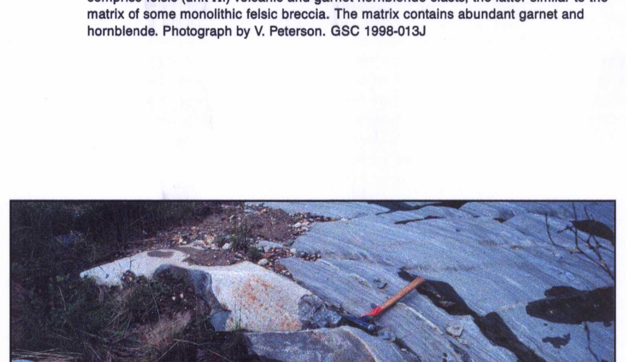

Figure 9a. Metagreywacke (unit Awb) in the centre of the Agam Lake syncline in the Manitouwadge belt, with modified bedding cut at low angle by a foliated tonalite dyke. Both dyke and metagreywacke show the dominant S_2 layer-parallel schistosity. Photograph by E. Zaleski. GSC 2000-008D

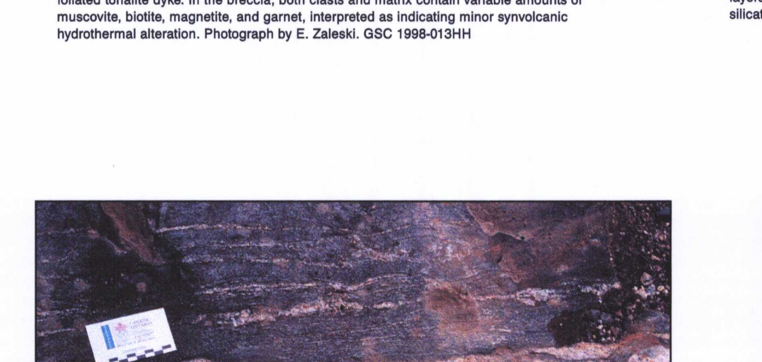

Figure 9b. Migmatitic metagreywacke (unit Awg) in the Quetico Subprovince with coarse-grained tonalitic leucosome defining boudinaged layers and isoclinal folds. Photograph by E. Zaleski. GSC 2000-008E

Figure 10a. Dark, mottled hornblende-garnet-magnetite rock of the Dead Lake suite (unit AD), intruded by trondhjemite (unit At). Photograph by E. Zaleski. GSC 1998-013AA

Figure 10b. The Dead Lake suite (unit AD), dark amphibolite enclaves have ameboid to pillow-like shapes, and a hornblende-rich garnetiferous margin to the contact with light-coloured trondhjemitic rock. Garnet in the selvedge grades in size, from coarse near the margin to finer toward the interior of the enclaves. Photograph by E. Zaleski. GSC 2000-008F

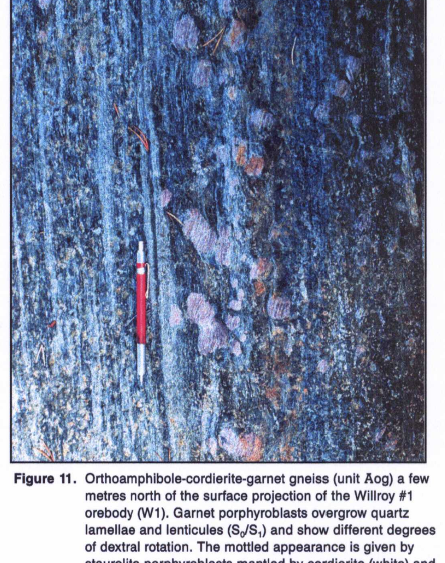

Figure 11. Orthoamphibole-cordierite-garnet gneiss (unit Aog) a few metres north of the surface projection of the Willroy #1 orebody (W1). Garnet porphyroblasts overgrow quartz lamellae and lenticules (S_0/S_1) and show different degrees of dextral rotation. The mottled appearance is given by staurolite porphyroblasts mantled by cordierite (white) and surrounded by coarse-grained, blue iridescent orthoamphibole. Photograph by V. Peterson. GSC 2000-008G

Figure 12a. Sillimanite-muscovite-quartz schist (unit Aam) south of the Willroy #1 orebody (W1). The prominent white-weathering spots are sillimanite knots. Photograph by E. Zaleski. GSC 1998-013O

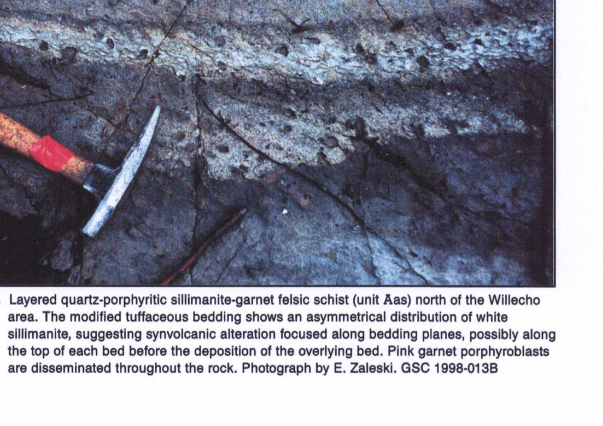

Figure 12b. Layered quartz-porphyritic sillimanite-garnet felsic schist (unit Aas) north of the Willecho area. The modified tuffaceous bedding shows an asymmetrical distribution of white sillimanite, suggesting synvolcanic alteration focused along bedding planes, possibly along the top of each bed before the deposition of the overlying bed. Pink garnet porphyroblasts are disseminated throughout the rock. Photograph by E. Zaleski. GSC 1998-013B

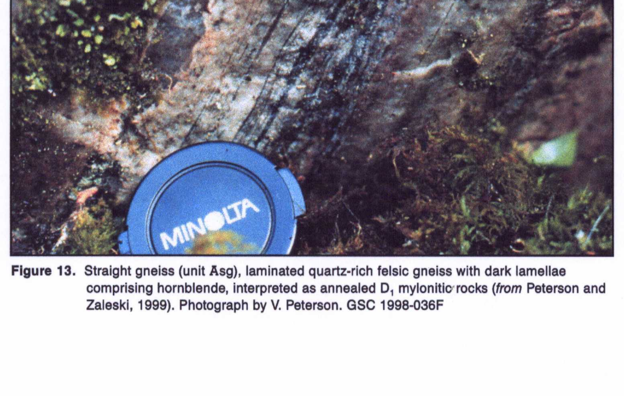

Figure 13. Straight gneiss (unit Asg), laminated quartz-rich felsic gneiss with dark lamellae comprising hornblende, interpreted as annealed D_1 mylonitic rocks (*from* Peterson and Zaleski, 1999). Photograph by V. Peterson. GSC 1998-036F

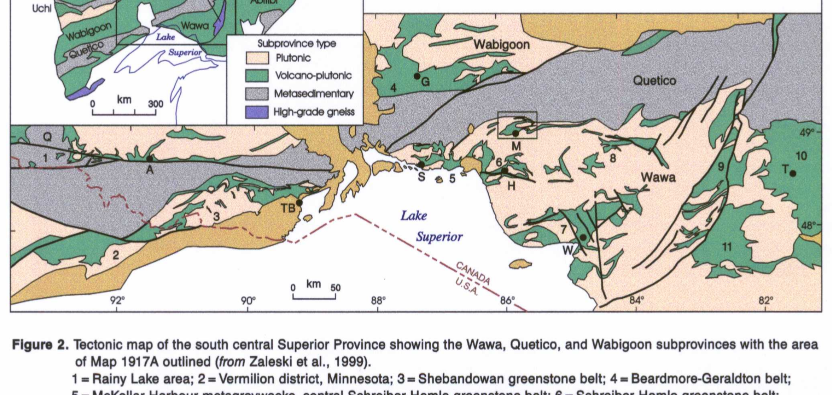

Figure 2. Tectonic map of the south central Superior Province showing the Wawa, Quetico, and Wabigoon subprovinces with the area of Map 1917A outlined (*from* Zaleski et al., 1999).
1 = Rainy Lake area; 2 = Vermilion district, Minnesota; 3 = Shebandowan greenstone belt; 4 = Beardmore-Geraldton belt;
5 = McKellar Harbour metagreywacke, central Schreiber-Hemlo greenstone belt; 6 = Schreiber-Hemlo greenstone belt;
7 = Michipicoten greenstone belt; 8 = Dayohessarah-Kabinagami greenstone belt; 9 = Kapuskasing structural zone;
10 = western Abitibi greenstone belt; 11 = Swayze greenstone belt; Q = Quetico Fault; A = Atikokan; TB = Thunder Bay;
S = Schreiber; G = Geraldton; M = Manitouwadge; H = Hemlo; W = Wawa; T = Timmins.
Adapted from Ontario Geological Survey (1991a, b) and Percival (1989). The inset shows the subprovinces of the southern Superior Province after Card and Ciesielski (1986), and the area detailed in the tectonic map.

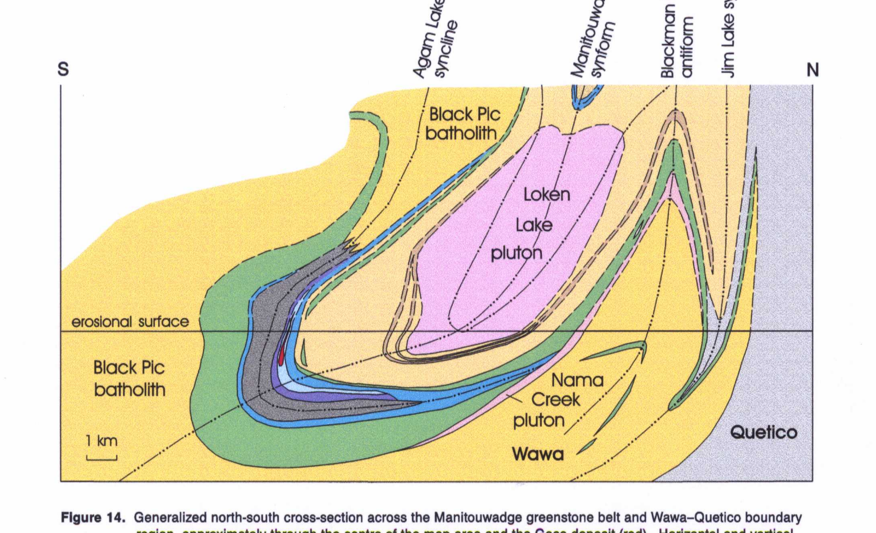

Figure 14. Generalized north-south cross-section across the Manitouwadge greenstone belt and Wawa–Quetico boundary region, approximately through the centre of the map area and the Geco deposit (red). Horizontal and vertical scales are equal. Unit colours match those on the map.

Figure 15. Relationships among phases of the Black Pic batholith south of the Manitouwadge greenstone belt. The oldest phase, foliated plagioclase-porphyritic monzodiorite (unit ABm) is cut by several generations of weakly foliated to massive granitic and aplitic intrusions. Photograph by E. Zaleski. GSC 2000-008H

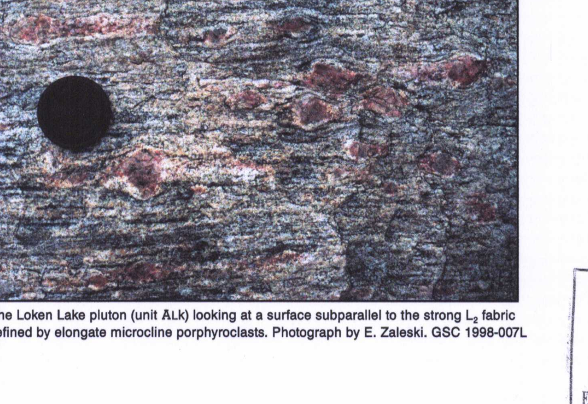

Figure 16. The Loken Lake pluton (unit ALk) looking at a surface subparallel to the strong L_2 fabric defined by elongate microcline porphyroclasts. Photograph by E. Zaleski. GSC 1998-007L

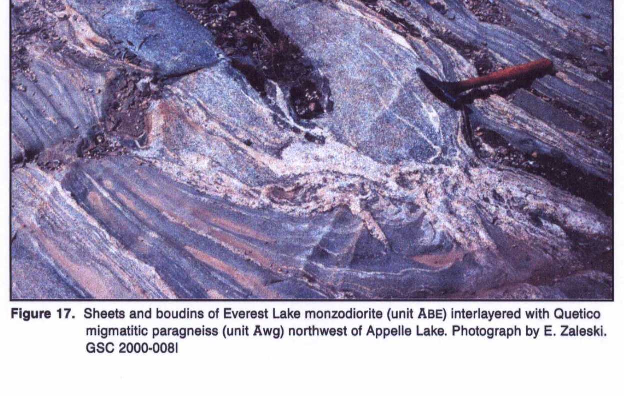

Figure 17. Sheets and boudins of Everest Lake monzodiorite (unit ABE) interlayered with Quetico migmatitic paragneiss (unit Awg) northwest of Appelle Lake. Photograph by E. Zaleski. GSC 2000-008I

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Figures and descriptive notes to accompany Map 1917A
Recommended citation:
Zaleski, E. and Peterson, V. L.
2001: Geology, Manitouwadge greenstone belt and the Wawa–Quetico subprovince boundary, Ontario; Geological Survey of Canada, Map 1917A, scale 1:25 000.

1917A (Figure)

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