Ontario

Summary of Field Work and Other Activities 1997

Ontario Geological Survey
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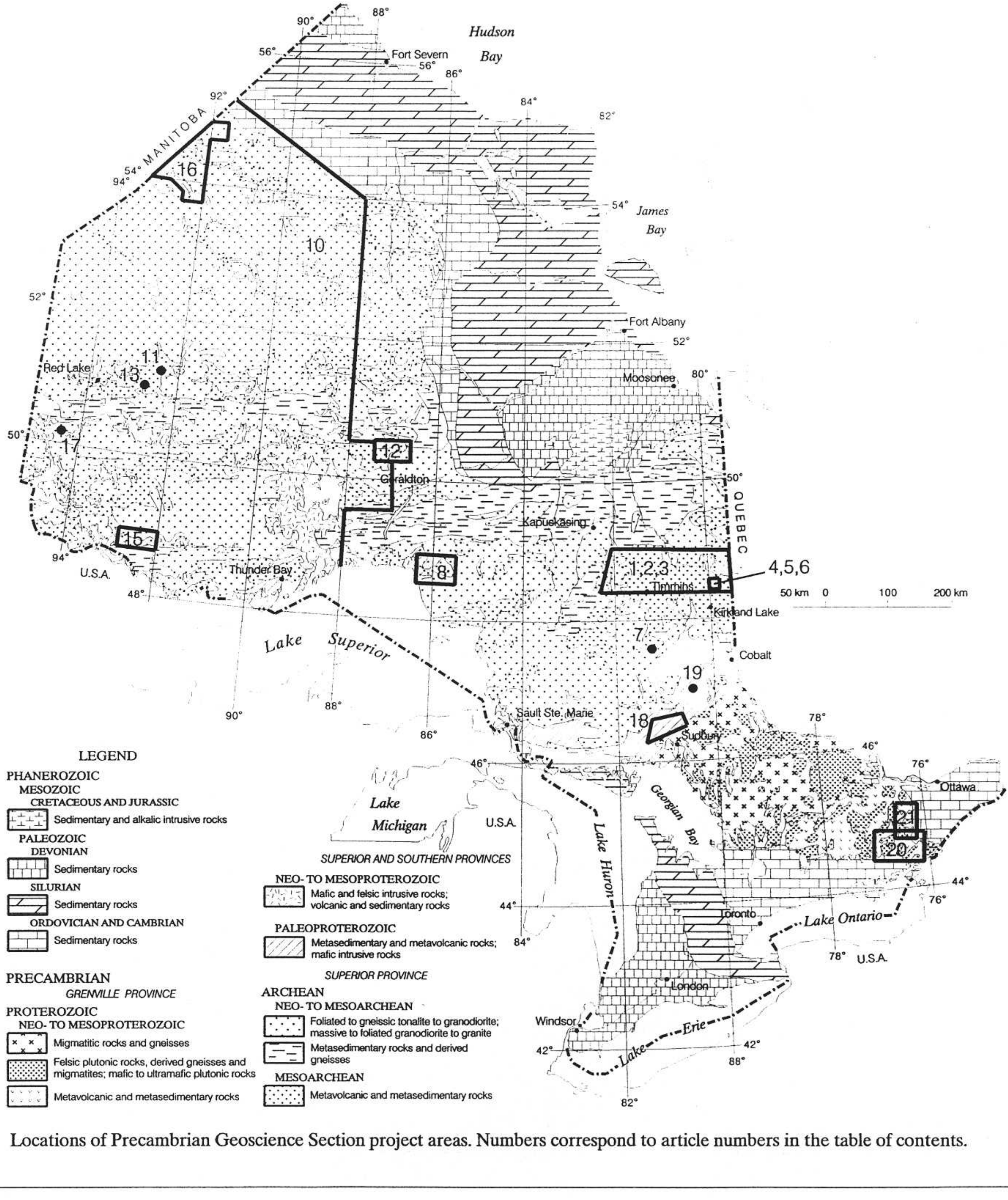

Locations of Precambrian Geoscience Section project areas. Numbers correspond to article numbers in the table of contents.

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Summary of Field Work and Other Activities 1997

Ontario Geological Survey
Miscellaneous Paper 168

edited by J.A. Ayer, C.L. Baker, D.G. Laderoute, P.C. Thurston

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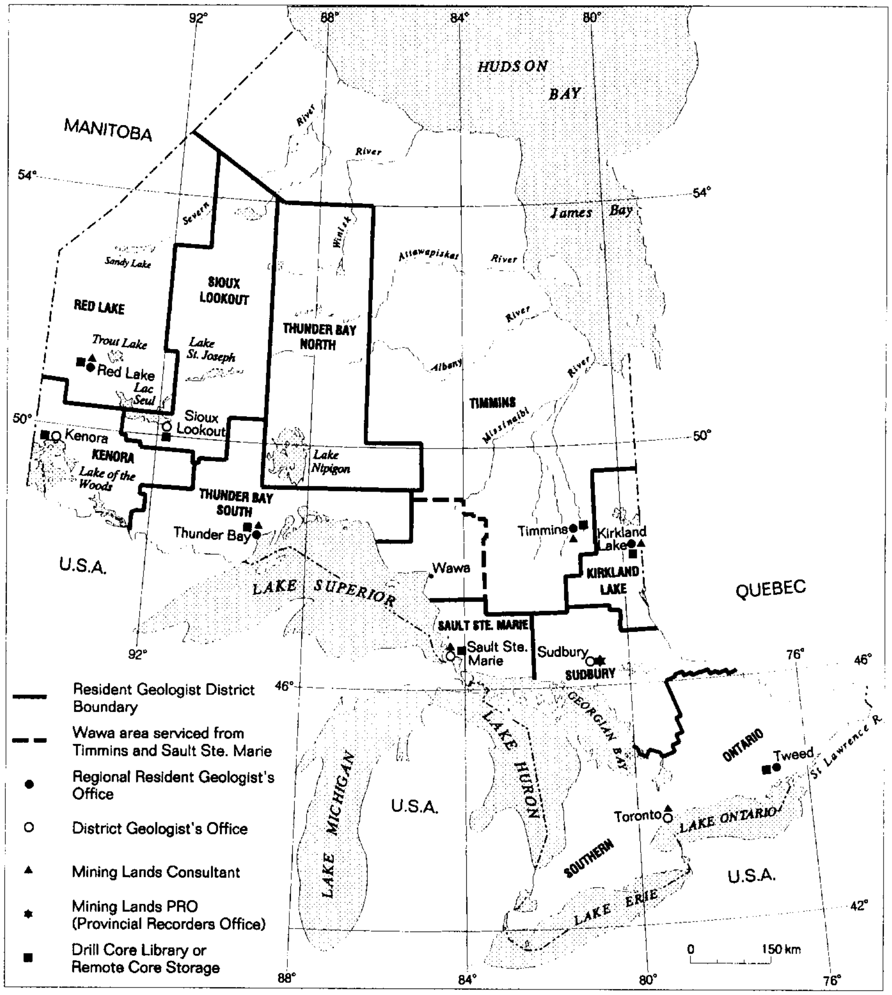

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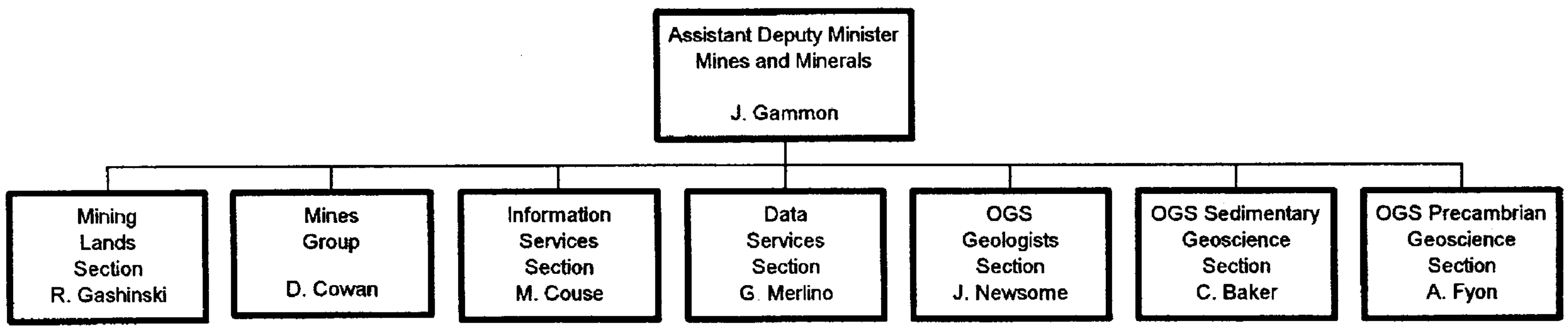

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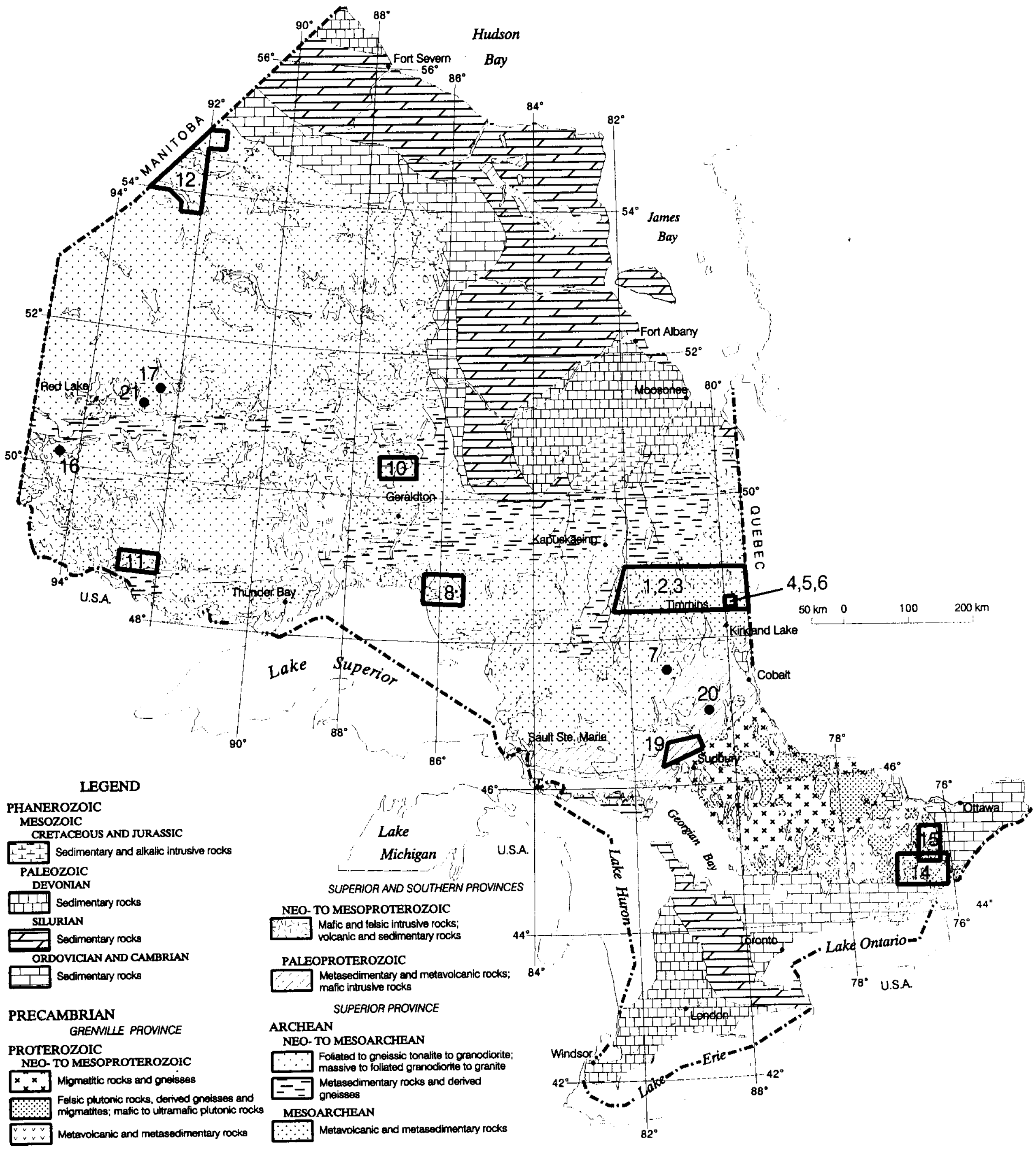

Locations of Precambrian Geoscience Section project areas. Numbers correspond to article numbers in the table of contents.

1. Project Unit 95–24. Geological Compilation of the Abitibi Greenstone Belt in Ontario: The Correlation of Metallogenic Potential with Stratigraphy

J.A. Ayer[1], N.F. Trowell[1], Z. Madon[1] and F. Corfu[2]

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INTRODUCTION

This multi-year and multi-component compilation project will produce a series of 1:100 000 geological maps covering the Abitibi greenstone belt (AGB) in Ontario in hardcopy and digital formats (Ayer and Trowell 1996). The northwest compilation sheet covering the area around Timmins will soon be released and work has started on the northeast sheet (Figure 1.1) with expected completion in 1998. This compilation will serve to identify areas for future mapping projects and will be used as a basis for tectonostratigraphic interpretation of this mineral rich area.

The geochronological component of the project is designed to complement past geochronological work (*see* e.g., Corfu 1993), to help resolve tectostratigraphic problems and to improve our understanding of the relationships of the metallogeny to stratigraphy and structural elements. Geochronological evidence indicates that the mineral deposits of the Abitibi Subprovince were episodically deposited over a 50 million year period from about 2730 to 2680 Ma (Lacroix 1996). Thus a knowledge about the distribution of stratigraphic units which host, or are associated with the deposits, will provide a valuable exploration tool by highlighting areas with potential for new deposits.

Stratigraphic models for the AGB have been developed over the past 70 years. Early mapping resulted in a simple two-fold subdivision consisting of older Keewatin Series volcanic and sedimentary rocks unconformably overlain by sedimentary rocks and alkalic volcanic rocks of the Timiskaming Series. A more formalized, belt-wide stratigraphy consisting of supergroups, groups and formations was developed in the early 1980s (*see* MERQ–OGS, 1983). By the late 1980s, an increased focus on structural geology, geochronological results and trace element geochemical data led to the application of plate tectonic models to the Archean and consequently to the application of the assemblage concept to Abitibi stratigraphy (Jackson and Fyon 1991; Jackson et al. 1994). In this model, packages of stratigraphic units representing similar depositional environments were defined as lithotectonic assemblages, thus allowing portrayal of lithostratigraphic/tectonic maps in which contact relationships could be either conformable, unconformable, fault bounded and possibly allochthonous. In the 1990s, mapping programs extended into the less well known parts of the Abitibi Subprovince including the Swayze greenstone belt (SGB) and the Montcalm greenstone belt (MGB), and the clay belt areas north of Timmins within the AGB. Results of this mapping and an extensive geochronological sampling program focussed on the SGB recognized rock types and stratigraphy identical to those in the central part of the AGB (Heather et al. 1995, 1996). In addition, the careful analysis of the different zircon populations within individual samples, collected in the Swayze program, indicated that younger units may contain inherited zircons with ages similar to those of the underlying older units. These observations led to a return to a more traditional stratigraphic model, in which the Keewatin assemblages were deposited in an autochthonous "layer-cake" succession with their current complex map pattern distribution developed through the interplay of multiphase folding and faulting that occurred prior to and during the deposition of the Timiskaming assemblage.

NEW GEOCHRONOLOGICAL RESULTS

As a part of this compilation project samples from the Northwest sheet area were submitted for U-Pb analysis of zircons by Fernando Corfu at the Royal Ontario Museum (ROM). Results of a number of the samples have been received to date (Figure 1.2).

Two samples were selected to test the limits of the extension of the base metal rich Kidd–Munro assemblage west of the Kidd Creek deposit. Extensive geochronology has previously established the distribution of the 2714 to 2717 Ma assemblage in the immediate vicinity of the Kidd Creek base metal deposit (Bleeker and Parrish 1996; Bleeker et al. in press). Zircons from rhyolite tuff breccia from the central part of Reid Township give a relatively imprecise age with a minimum of 2717 Ma and indicate the assemblage continues into central Reid Township. A significantly younger rhyolite flow with an age of 2703 ± 2 Ma from southern Mahaffy Township is within error of the 2706 ± 2 Ma for rhyolite from Southeast Reid Township (Barrie and Davis, 1989). Both are similar to the Kamiskotia complex rhyolite ages (Corfu 1993). This data suggests the Kidd-Munro assemblage is bracketed to the north and south by Kamiskotia-like ages in southern Reid and Mahaffy townships respectively and thus narrows into the central part of Reid Township.

A sample was also collected to test the age of the massive sulphide-bearing stratigraphy west of the Matagami River fault. Zircons from a dacite tuff sample in southeastern Thornburn Township yielded an age of 2719.5 ± 1.5

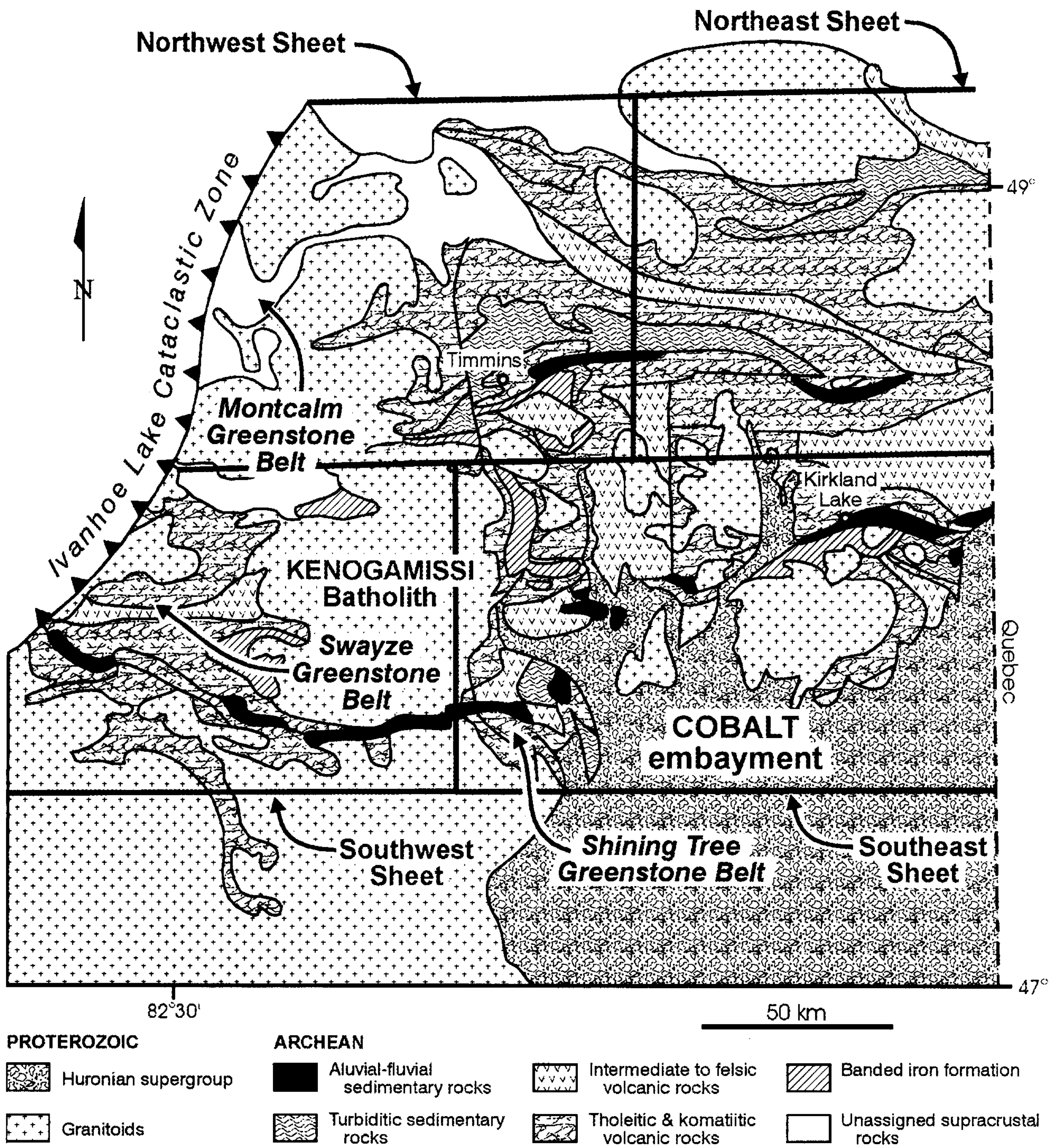

Figure 1.1. General geology of the Timmins area with the locations of new geochronolgy samples.

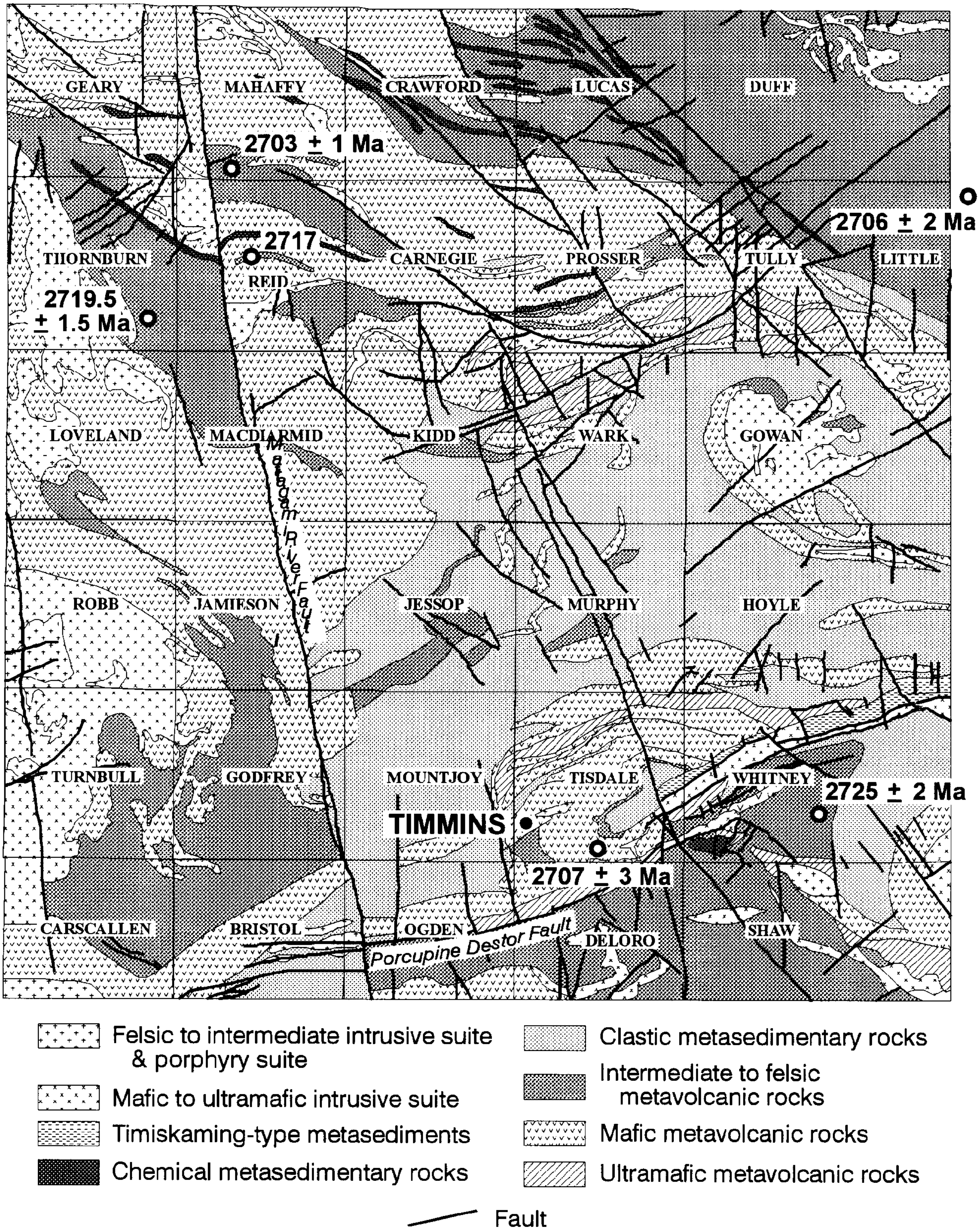

Figure 1.2. Stratigraphic assemblages of the western Abitibi Subprovince.

Ma (see Figure 1.2). The sample occurs within a sequence of calc-alkaline mafic to felsic metavolcanic rocks locally containing massive sulphide mineralization and chloritoid-bearing, hydrothermally altered rocks. Depending on whether the upper or lower error limits are utilized, the age might represent either a Deloro Group age, which would better fit its calc-alkaline rock types, or a Kidd–Munro age, or possibly, a previously unrecognized assemblage age. Further geochronological sampling is required to more fully determine the age distribution of this assemblage.

A sample was collected to test the absolute age of the well established stratigraphy in the Timmins area (Pyke 1982). Calc-alkaline felsic volcanic rocks of the Krist Formation, correlated with the Upper Tisdale Group, were dated at 2698 ± 4 Ma (Corfu 1993). However, the middle Tisdale had not previously been dated because their mafic composition typically did not yield sufficient zircons. As part of this project, a sample of medium-grained, massive mafic volcanic rock from the 99 unit of the Vipond Formation of the Middle Tisdale Group yielded magmatic zircons with an age of 2707 ± 3 Ma. The unit overlies the komatiites of the Lower Tisdale Group in Tisdale Township in the southern limb of the Timmins synclinorium (see Figure 1.2). This age thus demonstrates correlation of the Tisdale Group across the Porcupine–Destor Fault (PDF) as indicated by an age of 2707 ± 3 Ma from a dunite feeder dike intruding the Deloro Group volcanic rocks in the Shaw Dome and an age of 2706 ± 2 Ma from an intermediate crystal tuff in the Marker Horizon (Corfu 1993) overlying the dominantly komatiitic Bowman Group, both lying south of the PDF. Collectively the above data indicates that komatiitic volcanism occurred in at least two different time intervals in the central Abitibi: (1) in the Kidd-Munro assemblage at about 2714 to 2717 Ma, and (2) in the Tisdale-aged rocks at about 2707 Ma.

Little is known about the absolute age of the supracrustal rocks in the MGB. Zircons from a calc-alkaline rhyodacite lapilli tuff intercalated with mafic to ultramafic volcanic rocks in northeastern Belford Township give an age of 2710 ± 2 Ma (Figure 1.3). The sample is within the lower error limit of the Lower Tisdale Group and further suggests the widespread distribution of this age in the Abitibi Subprovince. More geochronological results from other MGB samples are pending and should help to further define the stratigraphy of this poorly exposed portion of the Abitibi Subprovince.

Results of three unpublished samples (also analyzed by the ROM) were donated to the project by Cominco Ltd. A quartz phyric lapilli tuff from Whitney Township yielded a typical Deloro Group age of 2725 ± 2 Ma (*see* Figure 1.2). Felsic tuff from the southwestern margin of the Stoughton–Roquemaure Group in northeastern Little Township give an age of 2706 ± 2 Ma (*see* Figure 1.3). This age correlates well the Tisdale Group (see above) and further demonstrates the widespread distribution of these Tisdale-ages in the Stoughton–Roquemaure, Kamiskotia, Bowman and Kinojévis groups. A sample of felsic flow collected from Mahaffy Township, from a different unit in the same general area as the Mahaffy Township sample collected for this project (see above), gives an identical, but even more precise, age of 2703 ± 1 Ma.

CORRELATION OF ABITIBI STRATIGRAPHY AND METALLOGENESIS

Volcanogenic Massive Sulphide Deposits

Geochronological results indicate that there are at least four distinct VMS epochs within the western AGB (*see* Figure 1.3). Each epoch has distinctive lithological associations which can help to categorize it even if the host rocks have not been dated. The deposits also have spatial/genetic associations with different types of chemically distinctive felsic volcanic suites identified as FII, FIIIa and FIIIb type rhyolites (Lesher et al. 1986, Parker and Ayer, this volume).

The oldest VMS mineralizing event occurs in calc-alkaline mafic to felsic volcanic rocks commonly capped by regional scale BIF units. Currently dated units of this type range from 2725 to 2730 Ma and include the Deloro Group and the Hunter Mine Group in the AGB (Corfu 1993) and the Hanrahan, Marion and Cummingham groups in the SGB (Heather et al. 1996). Two distinct types of VMS mineralization are found within these units; (1) massive sulfide deposits in mafic to felsic calc-alkaline volcanic rocks spatially associated with FII type felsic volcanic rocks and synvolcanic intrusions. A good example of this deposit type is the Normetal deposit of northwestern Quebec, which yielded about 11 million tonnes of 5% Zn and 2% Cu, and (2) base metal mineralization in sulphide facies iron formations representing proximal exhalative mineralization localized within regional-scale oxide facies iron formations. The Shunsby deposit in Cunningham Township in the SGB is an example of this deposit type. While only subeconomic quantities of base metals have been found in this deposit type to date in the western Abitibi, the potential for economic concentrations may exist as the Manitouwadge sulphide deposits occur within more regional oxide facies iron formations in similar aged rocks within the Wawa Subprovince (Zaleski et al. 1995).

The second oldest VMS epoch occurs within the Kidd–Munro assemblage dated at 2714 to 2717 Ma (Bleeker and Parrish 1996, Bleeker et al. in press). Deposits include the giant Kidd Creek Mine with over 150 million tonnes of Cu, Zn and Ag ore and a number of smaller deposits in Munro Township (Figure 1.3). Deposits of this age occur in dominantly tholeiitic mafic volcanic rocks and are spatially associated with the FIIIb rhyolites and komatiites. Coeval relationships between the komatiites and rhyolites at Kidd creek have lead to speculation that the mineralization may also have had a genetic relationship with komatiitic magmatism (Barrie, in press). Geochronological results to date indicate Kidd–Munro aged rocks

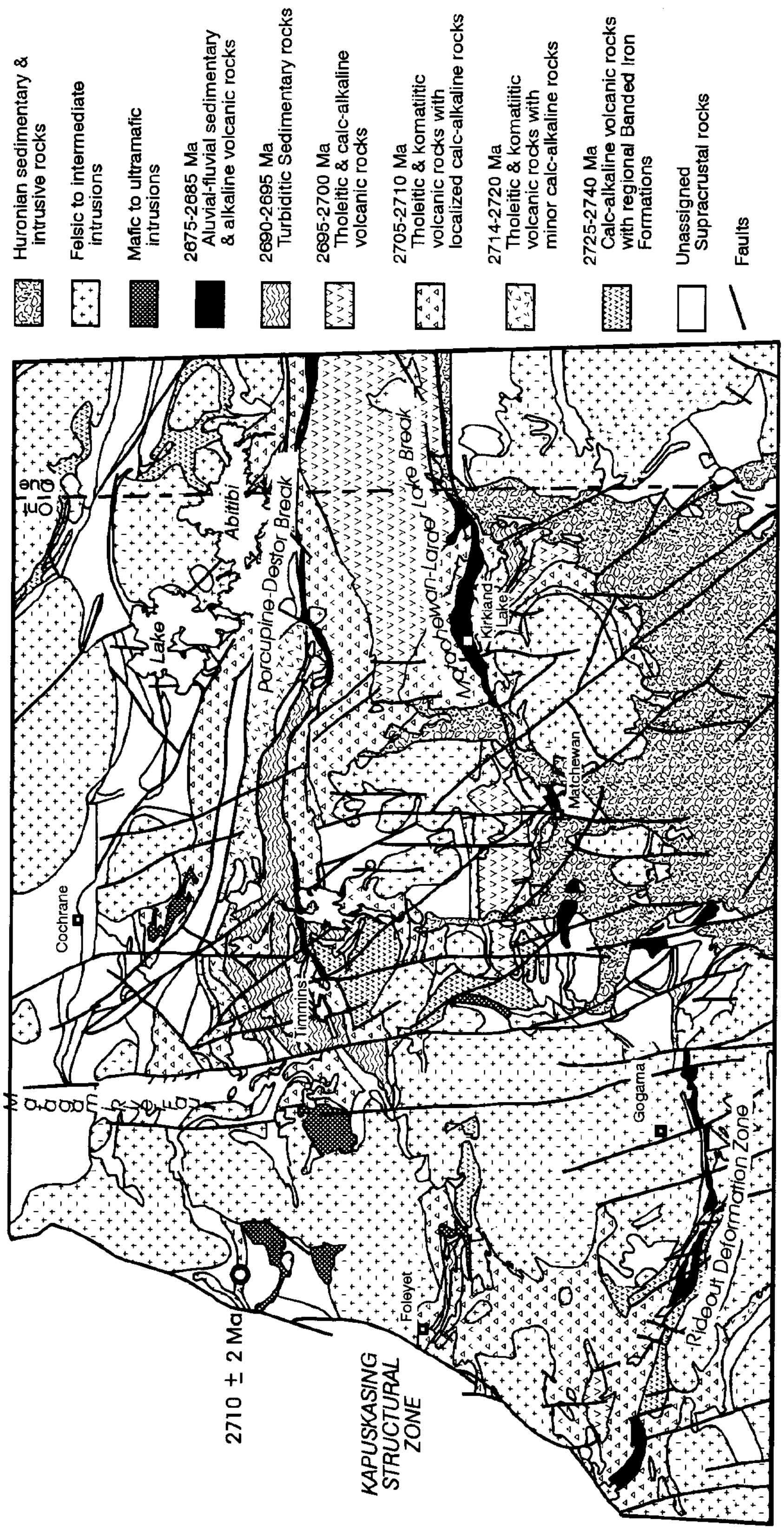

Figure 1.3. The southern Abitibi greenstone belt in Ontario, modified after Jackson, Fyon and Corfu (1994).

in the northern and southern extremities of the SGB (Heather et al. 1995; 1996).

The third VMS episode occurred at about 2705 Ma and is exemplified by the deposits at Kamiskotia and in the Val d'or area in Quebec (Corfu 1993). The Kamiskotia deposits are associated with FIIIb rhyolites, tholeiitic basalts and coeval gabbroic cumulates. As discussed above, units of this age appear to be widespread and also includes the Tisdale, Stoughton–Roquemaure, Kinojévis, and Larder Lake groups within the AGB (Corfu 1993) and possibly the Horwood Lake and October Lake groups in the SGB (Heather et al. 1995; 1996).

A fourth and final VMS episode occurred at around 2700 to 2698 Ma and are exemplified by the Noranda camp deposits occurring within the Blake River Group (Corfu 1993). The deposits occur in calc-alkalic to tholeiitic volcanic sequences with a spatial association with FIIIa type rhyolites. Deposits of this age have not been found in Ontario to date, but the Blake River Group extends westerly from Noranda and volcanic rocks of this age are also found in the Skead Group and the Krist Formation in the AGB and the Swayze–Dore Group in the SGB.

Magmatic Ni–Cu

Magmatic Ni-Cu deposits are correlated with three different epochs of mafic to ultramafic magmatism in the SAB (see Figure 1.3). The oldest is associated with komatiites and differentiated ultramafic to mafic sills in rocks of the 2714 to 2717 Ma Kidd–Munro assemblage (Corfu 1993). The Alexo deposit in Dundonald Township is an example of this type.

The second epoch is also associated with komatiitic magmatism but it occurs in the Lower Tisdale-aged rocks which are about 5 to 10 million years younger (see above). This stratum appears to be have been more productive and includes the Langmuir and Redstone deposits in the southern part of the Shaw dome and the Texmont deposit south of the Adams pluton.

The youngest Ni-Cu event occurs within the Montcalm gabbroic complex in the MGB with an age of 2702 ± 2 Ma (Barrie et al. 1990). This age is most similar to that of the Blake River Group. The geochemical characteristics of the complex also show similarities to the mixed calc-alkaline and tholeiite patterns of the Blake River Group with fractionated, calc-alkaline-like REE patterns in gabbro and pyroxenite and unfractionated, tholeiitic-like patterns in the peridotite (Barrie et al. 1990; McTavish 1996). McTavish (1996) identified a second gabbroic complex in Strachan Township of the MGB with very similar REE patterns which may also be prospective for Ni-Cu.

Gold

Theories about the origin of gold mineralization in the Abitibi Subprovince have gone through many incarnations from the dominantly structural models up to the late 1970s, to a syngenetic, exhalative model comparable to that of VMS deposits in the late 1970s and early 1980s, and finally to the present diversity of three different deposit types (Robert and Poulsen 1997) including: (1) the exhalative, synvolcanic type associated with stratabound base metal sulphides (e.g., Horne and Bousquet deposits), (2) intrusion related deposits (e.g., Hollinger–McIntyre and Matachewan deposits) and (3) mesothermal vein type deposits (e.g., Dome and Kerr Addison).

Type 1 deposits appear to be most abundant within the Blake River Group volcanic rocks in Quebec, but rocks of this age also occur in Ontario (see above) and may also be prospective for the synvolcanic type of gold deposits. Significantly-sized gold deposits of types 2 and 3 have a strong spatial relationship to crustal scale fault systems such as the Kirkland Lake–Larder Lake fault (KLF) and Porcupine–Destor faults (PDF) (Hodgson and Hamilton 1989). Geographic correlation also occurs between these types of gold deposits, the crustal fault systems and the rocks of the Timiskaming Group (*see* Figure 1.3). The dominantly coarse clastic sediments and alkalic volcanic rocks of the Timiskaming Group represent clastic sedimentation and volcanism unconformably deposited on the older Keewatin units and are probably genetically related to movements on these breaks (Mueller and Donaldson 1992). Geochronology on the Timiskaming units indicates deposition at about 2675 to 2680 Ma (Corfu 1993).

There may also be a more subtle spatial correlation of an older and more widespread sedimentary sequence with the Timiskaming Group, crustal scale faults and the type 2 and 3 gold deposits (*see* Figure 1.3). These older sedimentary sequences consists predominantly of turbidites and are best exemplified by the Porcupine Group in the Timmins area. Contact relationships and geochronology suggest these units were diachronously deposited on underlying volcanic units with a range of ages at around 2695 to 2690 Ma (Corfu 1993, Bleeker et al., in press) and are thus 15 to 20 million years older than the Timiskaming Group. Sedimentary sequences of this age have now also been identified in the SGB indicating an even wider distribution than was previously recognized (Heather et al. 1995, 1996). The spatial association of these older sedimentary units with the regional breaks suggests that they may represent distal sedimentation related to early faulting while the Timiskaming Group may represent proximal sedimentation related to late stage reactivations along the crustal–scale fault systems.

CONCLUSIONS

The Abitibi in Ontario has a current annual production rate of more than $800 million per year for base and precious metals. However, it is also a mature mining area and because of the amount of past work, new base metal discoveries will probably be located at depth and will require improved targeting criteria. These criteria include the larger targets presented by rock types such as the high silica felsic volcanic rocks, komatiites, hydrothermal alteration systems and favourable stratigraphy.

Recently there have been a number of gold discoveries outside of the traditional gold mining areas of the ABG. These discoveries should encourage more exploration in these "frontier-like" areas. Repetition on the standard themes on geological controls on gold mineralization are indicated at Thornloe and Bristol townships which suggest the fertile PDF has been sinistrally offset 5 to 6 km along the north-trending Mattagami River fault west of Timmins (*see* Figure 1.3). A number of gold discoveries have recently been found to be associated with fault structures in areas such as the SGB and Shining Tree. Documented auriferous fault systems in the northern part of the SGB are on strike with the PDF east of the Kenogamissi batholith (Ayer 1995). In the southern Swayze, the Rideout deformation zone is the locus of a number of occurrences and deposits. There has been speculation that this fault may be the on-strike extension of the KLF (Heather et al. 1995; 1996). If this is the case, then the Shining Tree area is critical for establishing its continuity. Thus the question remains does the KLF continue west of Matachewan into the Halliday area where Timiskaming-like rocks have been identified and possibly further west across the Kenogamissi batholith into the central Swayze? Or has it been rotated southward into the Shining Tree area? We should be better able to answer these questions in a few years as we continue our investigations in the Shining Tree area (*see* Johns, this volume).

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2. Project Unit 95-24. Using Radarsat Data for Geoscientific Applications, Abitibi Greenstone Belt, Ontario

Z. Madon, N.F. Trowell, and J.A. Ayer

Ontario Geological Survey, Precambrian Geoscience Section

INTRODUCTION

A multiyear project (Ayer and Trowell 1996) to produce four 1:100 000 scale geological compilation maps covering the southern Abitibi Greenstone Belt in Ontario (Figure 2.1) is presently underway (*see* Ayer et al. this volume).

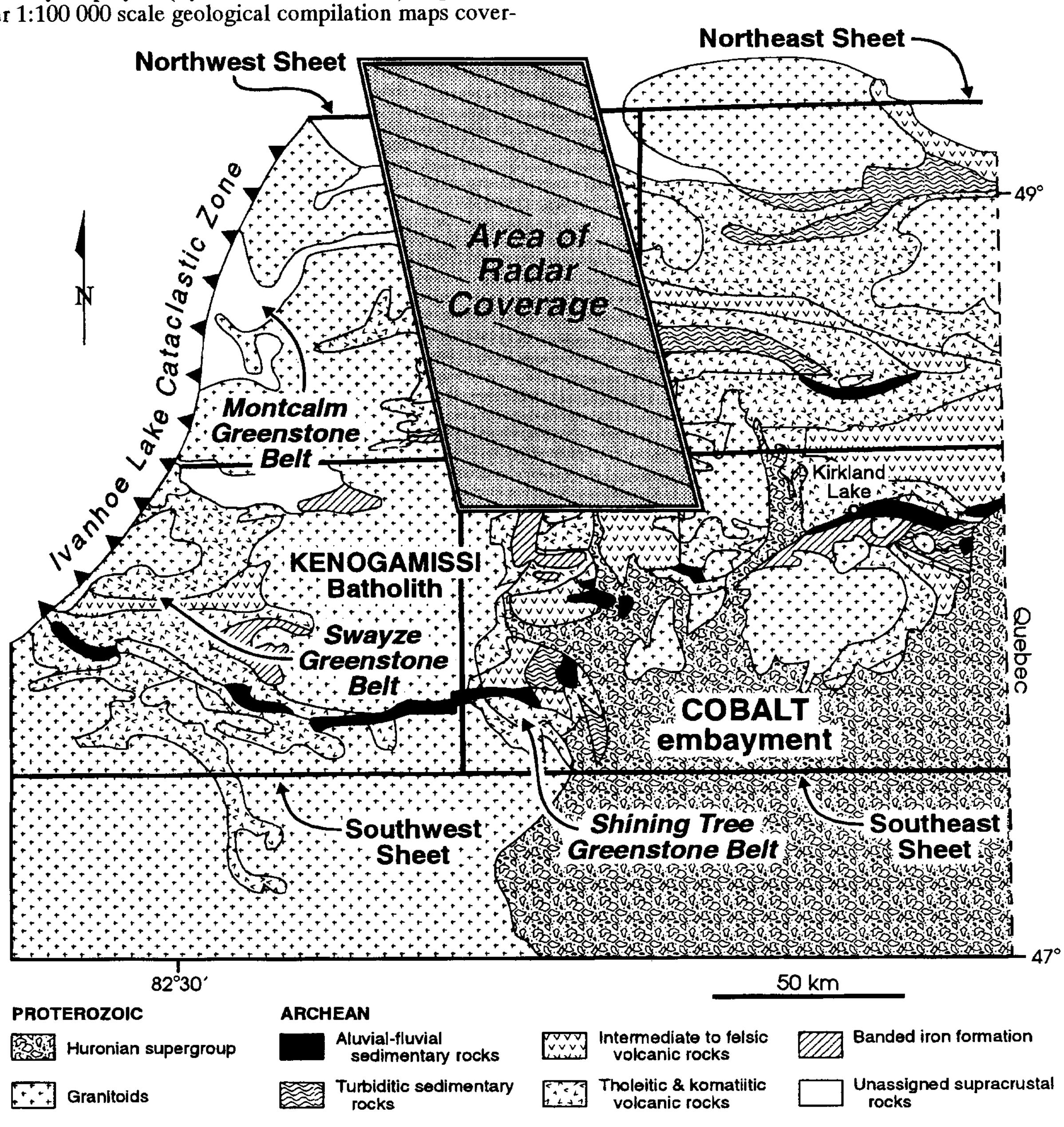

Figure 2.1. The southern Abitibi greenstone belt in Ontario.

The first map to be completed in the fall of 1997 will cover the Timmins area (Northwest Sheet, Figure 2.1).

In 1997, the Ontario Geological Survey received Radarsat digital radar data covering most of the Timmins–Kirkland Lake portion of the Abitibi Greenstone Belt. This data was received under ADRO (Application Development and Research Opportunity) Project 662 from the Canadian Space Agency.

A key scientific objective of ADRO Project 662 is to integrate Radarsat data with geological, geophysical and other remotely sensed datasets and to enhance the geological interpretation of the Abitibi Greenstone Belt in Ontario. The suitability of Radarsat imagery to geological problems will be evaluated across a variety of bedrock and surficial terrain. Specific objectives include mineral potential assessment, tectonic interpretation, exploration method development and mapping of surficial deposits.

This summary presents a preliminary structural investigation of the Timmins area using Radarsat data.

GENERAL GEOLOGY

The southern Abitibi greenstone belt extends well into northwestern Quebec and is terminated to the west by extensive granitoid complexes along the Ivanhoe Lake Cataclastic Zone. This study confines itself to the general Timmins area (*see* Area of Radar Coverage, Figure 2.1).

ACQUISITION AND PROCESSING OF THE RADARSAT DATA SET

Landsat and SPOT satellites use the sun as their energy source and record the visible to near infra-red light spectrum (0.4 µm to 12 µm). They can effectively image the Earth's surface during daylight hours but cannot penetrate cloud cover. Radar satellites, on the other hand, transmit their own signal and can produce earth images both day and night. Because radar waves are approximately 10 000 times longer than visible light waves, they easily penetrate cloud cover and tend to accentuate the Earth's topography. The ability to enhance landscape features make Radarsat imagery an important dataset for a variety of geological applications, including bedrock mapping, surficial mapping, mineral exploration and geological hazard identification.

Radar images record the portion of transmitted radar waves that return to the satellite, known as backscatter. The amount of backscatter is a function of both terrain parameters – the attitude or geometry of the surface, its roughness, and its dielectric properties and system parameters – radar wavelength, radar polarization, incidence or illumination angle and "look" direction of the radar beam. Radarsat has two fixed "look" directions, 098° in ascending orbit and 278° in descending orbit.

The processed radar image is a single channel display of greyscale tones that range from black (no backscatter) to white (maximum backscatter) on a typical computer monitor. Calm water bodies or flat, smooth terrain (pavement) reflect nearly all the incident energy away from the satellite and tend to produce dark grey to black tones. Because water has a relatively high dielectric constant, wet or swampy ground will generally return darker tones than dry ground. Topographic ridges that are manifestations of structural lineaments or faults will return either light tones if facing the satellite "look" direction or dark tones if facing away from the satellite "look" direction. Any ridges parallel to the "look" direction will be less discernable.

The Radarsat data received under ADRO Project 662 has the following parameters: the images were acquired using a Standard 7 beam mode meaning that the incidence angle for the radar beam was between 45° and 49°, a range considered optimal for detecting subtle differences in relief. Nominal resolution is 30 m although the images were all resampled to 12.5 m. Each image covers an area of approximately 100 km by 100 km. The image illustrated in this report was acquired with the satellite in ascending mode and is thus "east-looking".

Subsets of two images covering the area of interest were stitched together and georeferenced to Ontario Base Map (OBM) 1:20 000 digital topographic data. The georeferenced data was then Gamma filtered to remove the inherent "speckle" found in all radar imagery. The Gamma filter algorithm removes much of the speckle while retaining any edges or sharp feature. Finally, the image was scaled down from its original 16 bit radar values (0 to 65 536) to 8 bit values (0 to 255) and "stretched" using a linear algorithm. Images are stretched to make more effective use of the entire greyscale range. The processed image is illustrated in Figure 2.2.

PRELIMINARY GEOLOGICAL INTERPRETATION

The overall lack of prominent edges in the radar image can be explained by the very flat and extensively till–covered terrain around Timmins (*see* Figure 2.2). Lakes and rivers are shown quite clearly as are areas of high moisture such as the tailings pond at the metallurgical site east of Timmins (Figure 2.3). The bright return corresponding to Timmins itself is typical of urban areas with buildings that produce elevated backscatter while the checkerboard pattern west of Timmins is typical of agricultural fields. The dark cross-shaped feature north of Timmins is the regional airport and illustrates the lack of backscatter from very smooth, flat runways.

Figure 2.3 is a composite of radar imagery overlain by a vector file of known and interpreted faults and lineaments for the area. In general, it would appear that there is little indication in the radar imagery of these features.

Locally, structurally controlled drainage patterns confirm the presence of north and northwest trending lineaments; for example, portions of the Matagami River Fault. The Destor–Porcupine Fault is not visible to radar because it generally lacks a strong topographic signature and because it is oriented almost parallel to Radarsat's look direction.

A good example of the east-looking geometry of the satellite is shown by the bright east side of the Kidd Creek

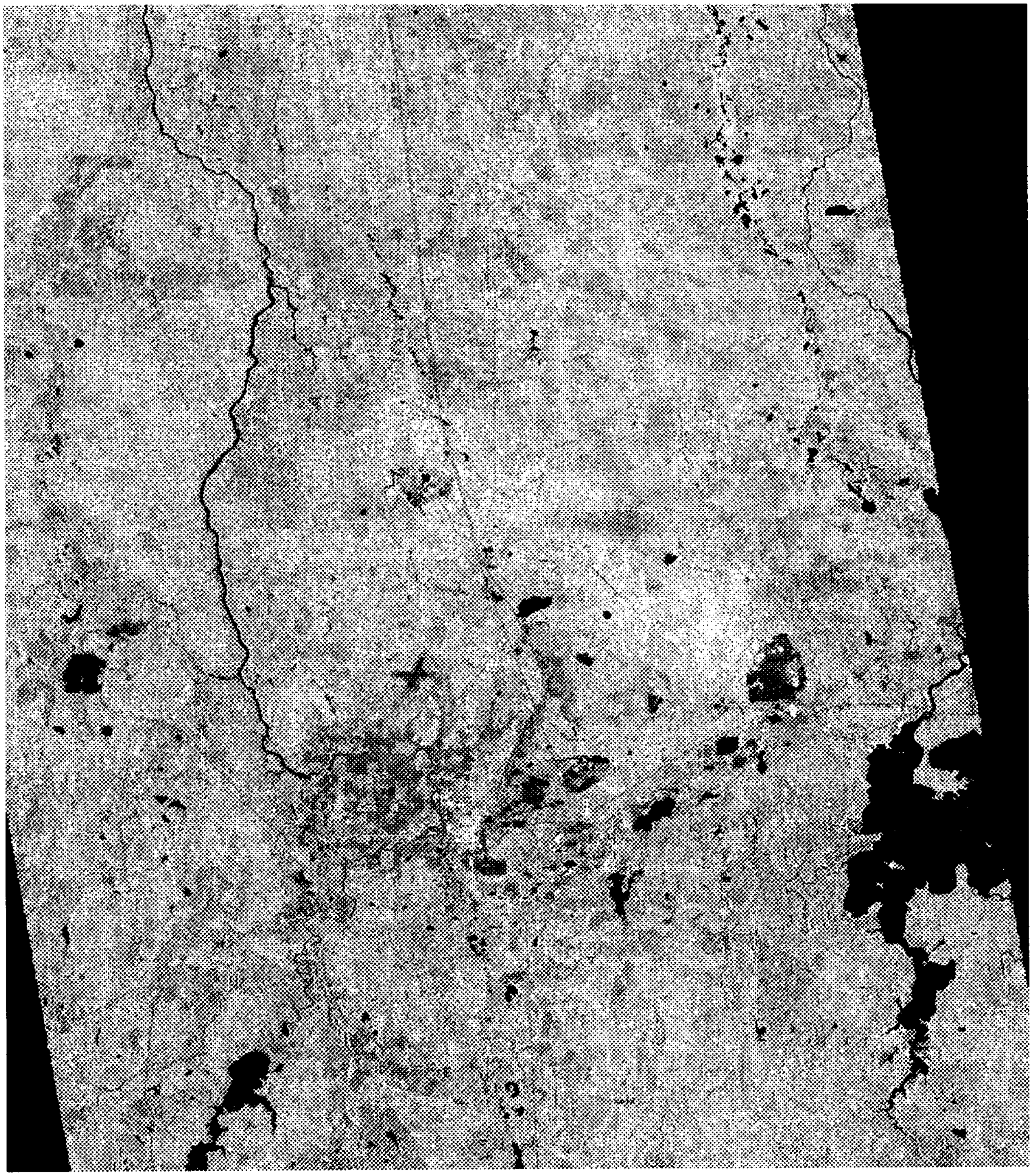

Figure 2.2. Radar imagery for the Timmins area. The base of the image is 55km long.

K100 pit, indicating high backscatter, and the dark west side, indicating an area in Radarsat's "shadow". The same pit in descending mode would display the exact opposite effect.

PLANNED CONTINUATION OF THE PROJECT

Future plans include creating and comparing mosaics of all ascending-mode and descending-mode radar imagery to

Figure 2.3. Radar imagery for the Timmins area overlain by known and interpreted faults and lineaments.

the Quebec–Ontario border. To the east where there is more relief, it is expected that the radar imagery will better delineate major faults and lineaments. As well, we intend to evaluate various low-pass (averaging) and high-pass (edge-enhancing) filters to enhance subtle structural features.

In the coming years, a more thorough examination of the radar data for the entire Abitibi Greenstone belt in Ontario will be used to examine the geomorphologic expression of regional-scale bedrock geological structures.

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3. Project Unit 96–00. The Kidd–Munro Extension Project: Synopsis of Field Work in the Southeast Dundonald Area

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INTRODUCTION

The Kidd–Munro Extension Project is designed to: 1) provide a detailed architectural framework for the komatiite-rich volcanic terrane of the southern Abitibi subprovince in Ontario and Quebec, with emphasis on volcanic facies of komatiite flows (including high magnesium basalts, many of which are contaminated komatiites), and rhyolite volcanic centres; 2) correlate the Kidd Creek stratigraphic succession with other successions on scales of kilometres, tens of kilometres and ultimately across the southern Abitibi subprovince, using volcanology, structural geology, chemostratigraphy, and U-Pb geochronology; and 3) develop exploration criteria specific to this terrane to help locate targets for large volcanogenic massive sulphide (VMS) and nickel deposits. The project is sponsored jointly by five mineral exploration companies, the Geological Survey of Canada and the Ontario Geological Survey.

In Year 1 (June 1, 1996 to July 1, 1997), the geology, geochemistry, galena Pb isotope systematics and U-Pb geochronology were investigated in four areas: Dundonald and western Clergue townships; a twelve township area in the Iroquois Falls area, from Fox–Stimson–Sweatman townships in the north to Calvert–Teefy–Rickard townships in the south ("Fox–Stimson area"); northeast Langmuir township, and the Kidd Creek deposit area (Figure 3.1). Analyses are complete for eight U-Pb zircon geochronology samples and for the 98 least altered samples of volcanic rocks submitted for high precision whole rock geochemistry. Geological maps of Dundonald and western Clergue townships (1:20 000 scale), and the Fox–Stimson area (1:50 000 scale) are complete. This summary focuses on the stratigraphy and mineralization in SE Dundonald township only.

STRATIGRAPHY IN SOUTHEAST DUNDONALD TOWNSHIP

Dundonald and western Clergue townships have a komatiite-rich stratigraphic succession that is tentatively correlated with komatiites in the Kidd Creek footwall (Barrie, in press) on the basis of regional airborne magnetic maps. The area has significant nickel mineralization which has been drilled recently. Much of the drillcore has been made available for this study. Southeast Dundonald Township in the vicinity of the Dundonald mafic-ultramafic intrusion has good exposure.

In SE Dundonald Township, the stratigraphic succession is dominated by the Dundonald sill, a 20 km by 0.8 km mafic-ultramafic intrusion. The sill has been folded into a W-shape. This fold is open to the WSW exhibiting ENE trending, isoclinal to tight folds, with sub-vertical to steeply north-dipping axial planes. The northern fold is well-defined, and is termed the Dundonald sill anticline. An ESE trending fault with hundreds of metres of sinistral horizontal displacement is present near the Dundonald sill in the nose of the west-facing anticline (Davis 1997). Splays from this fault with SE trends are evident in the anticlinal nose of the Dundonald sill and in strata up-section. Exposure and drill information are limited in the rest of the township. Airborne magnetic patterns are interpreted to reflect more open folds. Bedding or ultramafic sills have NE trends along the NE shore of the eastern lobe of Frederick House lake.

A generalized stratigraphic column for SE Dundonald township is given in Figure 3.2. The Dundonald sill has been described by Naldrett and Mason (1968). It has a medium-grained cumulate peridotite base, with pyroxenite layers, and locally with olivine-rich layers that contain up to 60% relict olivine and up to 6% chromite. Naldrett and Mason (1968) described the peridotite as having an olivine-rich base approximately 230 m thick composed of 40 to 60% relict olivine, with the remainder clinopyroxene. The olivine-rich basal section is overlain by approximately 200 m of pyroxenite that is nearly 100% clinopyroxene or relict pyroxene. Modal layering on a centimetre-scale has been noted locally. There is a relatively abrupt contact over 1 to 2 metres into medium-grained magnesium gabbro cumulate with plagioclase as a cumulus phase. Minor platinum group element enrichment up to 0.6 ppm PGE in surface exposures of the gabbro has been reported (Falconbridge internal report). The upper parts of the gabbro contain up to 10 modal % Fe-Ti oxides. Naldrett and Mason (1968) described the presence of minor quartz and potassium-feldspar, with trace titanite, zircon and apatite in the upper gabbro, and local granophyric textures. Minor amounts of dacitic xenoliths are present locally in the upper gabbro. Textures are more varied in the upper 50 metres, ranging from aphanitic to sub-pegmatitic with plumose clinopyroxene to 3 cm.

The Dundonald sill is overlain by dacite/rhyolite, komatiite, argillite and basalt. Plagioclase porphyritic dacite agglomerate with up to 40% medium- to fine-grained plagioclase directly overlies, and is cut by, the sill. Quartz and plagioclase phyric rhyolite with flow banding and spheru-

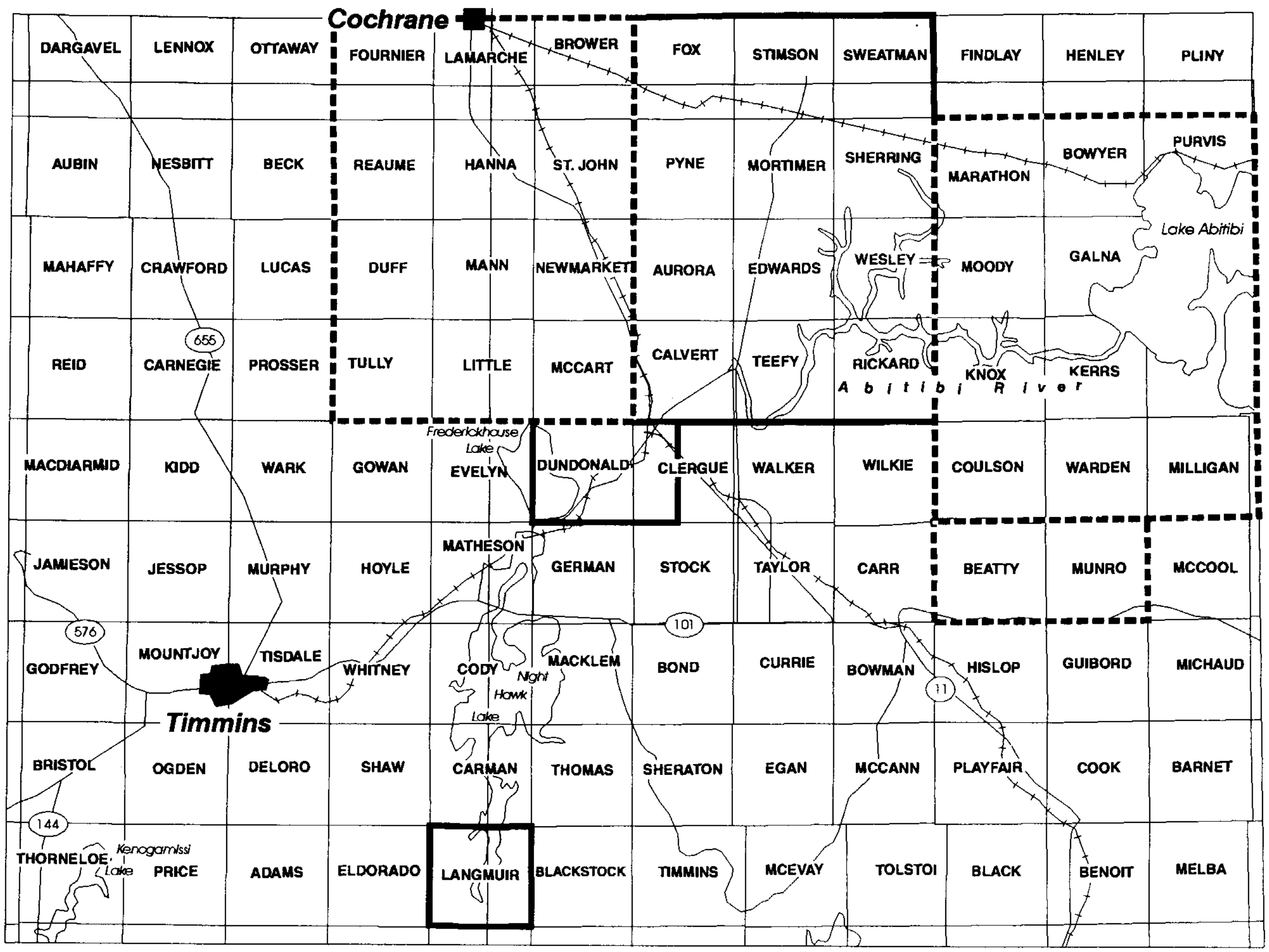


Figure 3.1. Location of Year 1 (heavy solid outlines) and Year 2 (dashed outlines) study areas.

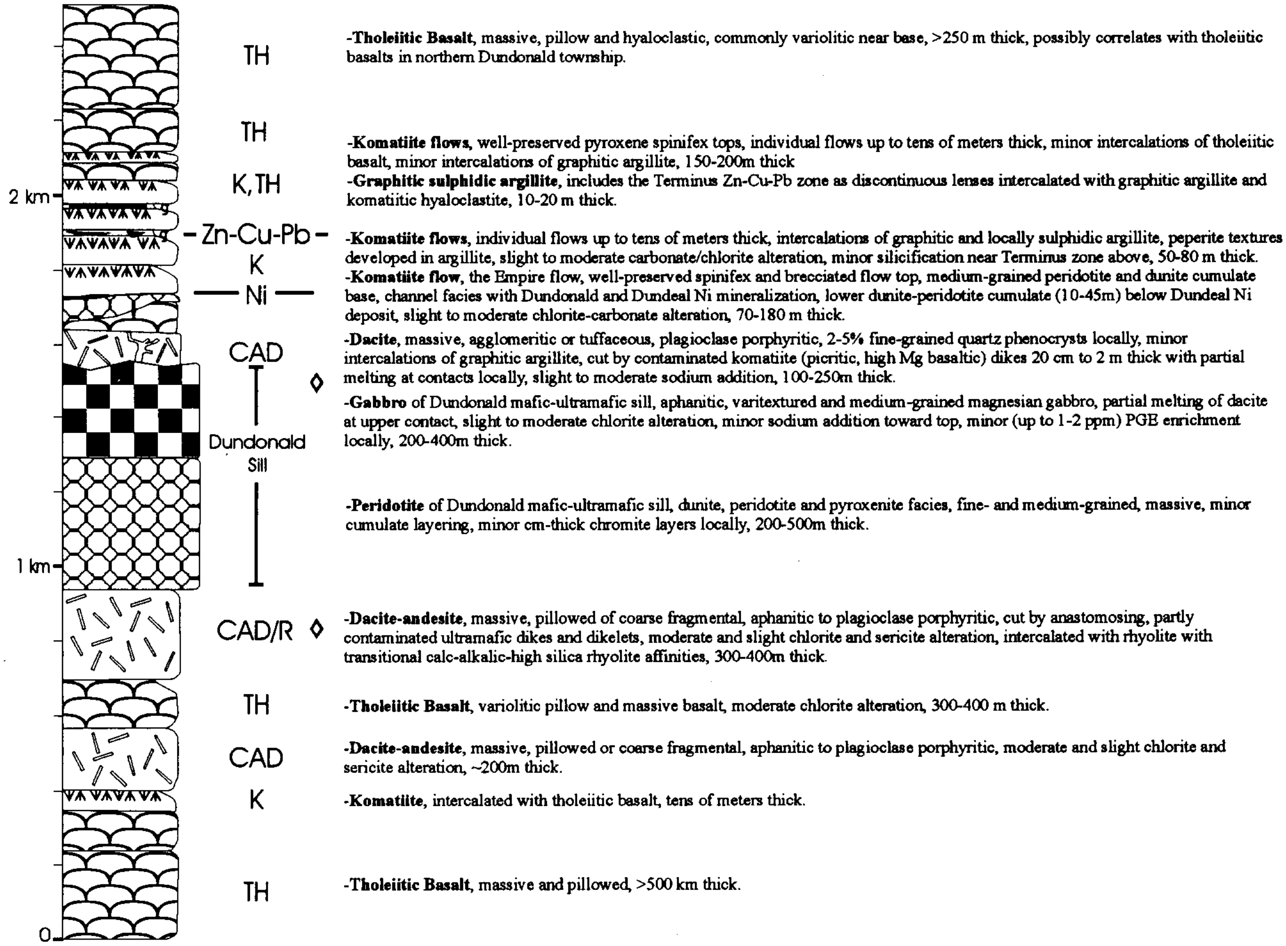


Figure 3.2. Descriptive stratigraphic column for SE Dundonald Township.

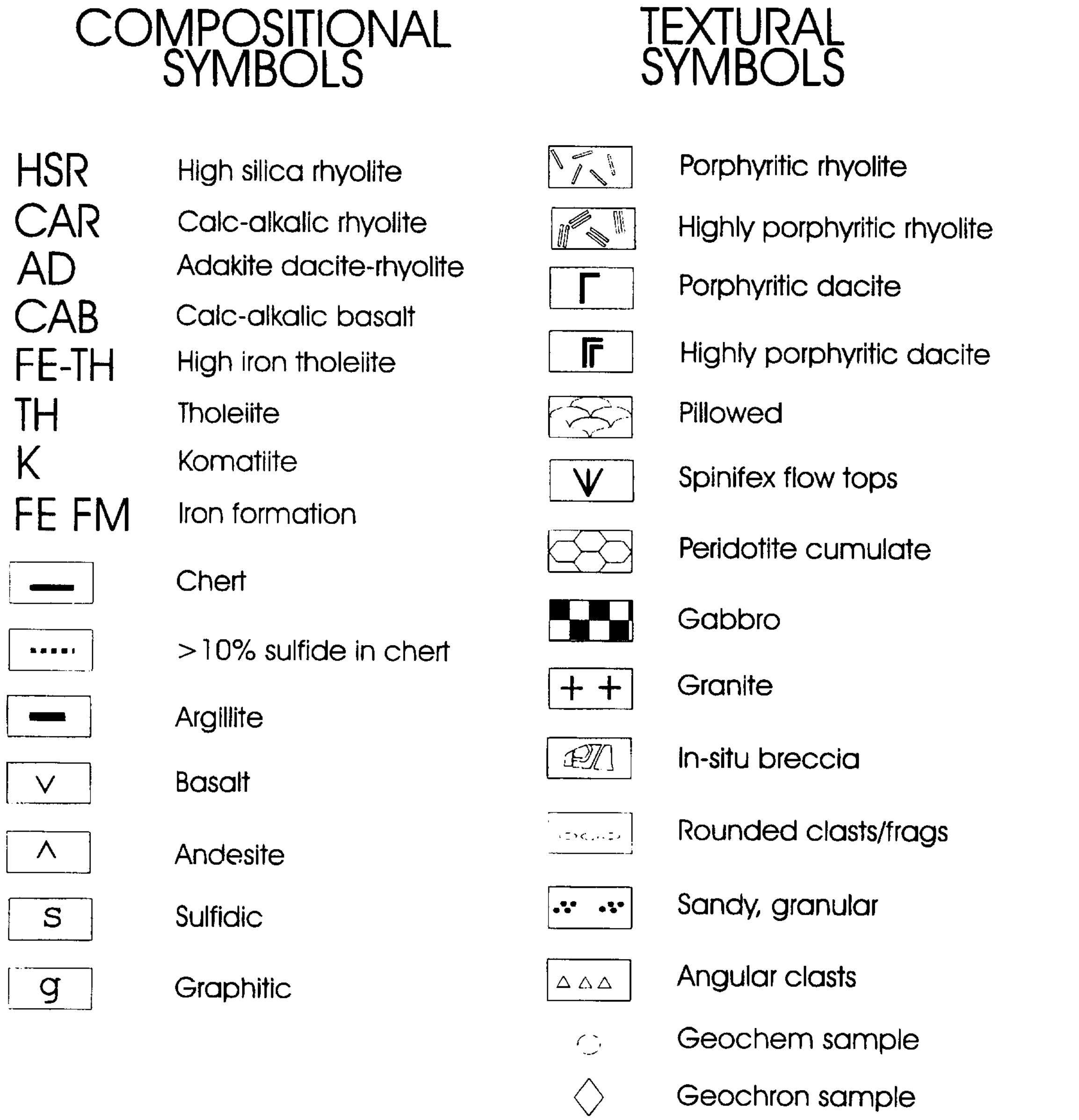
litic textures locally (Photo 3.1) is present in the southern Dundonald sill area. The dacite is cut by minor basaltic and picritic dikes with partial melt textures at their margins locally that probably represent contaminated komatiite (Photo 3.2). Minor graphitic argillite is cut by the dacite and the komatiite, and also has partial melting and peperite textures in contact with both volcanic rock types (Photos 3.3 and 3.4).

Overlying the dacite is the Empire flow, a 70 to 180 m thick composite komatiite flow that contains the Dundeal nickel occurrence north of the Dundonald sill, the Dundonald South nickel deposit on a south-facing limb of the Dundonald sill; and possibly, the Alexo nickel deposit to the NW at the township border (Davis 1997). Within the Empire flow, a dunite cumulate several tens of metres thick is present beneath much of the Dundeal nickel mineralization. Above the mineralization is a medium-grained olivine-rich peridotite to dunite cumulate section 40 to 100 m thick, overlain by aphanitic to fine-grained peridotite and pyroxenite with minor gabbroic sections. At the top are flow top breccias and olivine spinifex layers intercalated with graphitic argillite.

Above the Empire flow are intercalated, thinner komatiite flows and graphitic, locally sulphide-rich argillite. Graphitic, sulphide-rich argillite contains appreciable Zn ± Cu ± Pb ± Ag mineralization along two horizons which comprise the Terminus zone, described below. Massive and pillowed, and locally variolitic basalts overlie the komatiite units. The Nickel Island nickel occurrence in the southwestern part of Frederick House Lake is within variolitic basalts up-section from the komatiites. Within these overlying units in drillcore in the centre of the township, a distinctive, amphibole-bearing dacite dike was encountered. This rock type may be related to strata of similar composition in Little and Duff townships (B. Berger, personal communication).

Nickel Mineralization

The Alexo nickel deposit was a small nickel producer in the first half of the twentieth century (52 000 tonnes at



4.5% Ni and 0.5% Cu from 1912 to 1919; also a few thousand tonnes production in 1943) from the surface and from limited underground workings (Baker 1917; Davis 1997). The deposit is within a dunitic core of a peridotitic komatiite flow several tens of metres thick, that is broadly along strike with the Dundeal deposit 3 km to the SW, and may be within the Empire flow that is host to the Dundeal and Dundonald south deposits. The deposit occurs within and over the banks of a probable thermal erosion channel into footwall pillowed andesites. Minor massive sulphide underlies semi-massive and net-textured sulphide within the dunite core of the flow.

The geochemistry and metallogeny of Alexo nickel deposit and the host komatiite flows have been studied extensively (e.g., Barnes 1984, 1985; Dupre et al. 1984; Brugmann 1987). Recent drilling across the deposit stratigraphic section encountered hangingwall fine- and medium-grained, olivine-rich peridotite, several highly talc-carbonate altered zones; and then footwall pillowed, amygdular andesite/basalt. A parallel drillhole 150 m along strike encountered variolitic basalt, then several stacked komatiite flows tens of metres thick. Here the komatiite flows reflect the effects of supersolidus metasomatism that results in pale green, chalky rodingite. A third drillhole cut parts of the footwall stratigraphic succession, with intercalated graphitic argillite, pyroxenitic komatiite and variolitic basalt.

The Dundeal nickel occurrence is on the north flank of the Dundonald sill anticline, near the base of the Empire flow. It is along strike with the Alexo nickel deposit 3 km to the NE, and with the Dundonald south deposit 1.5 km to the SW on the opposite side of the Dundonald sill anticline. The mineralization is within serpentinized or rodingitized mesocumulate dunite or olivine-rich peridotite. The sulphides are generally net-textured or as thin veinlets. pyrrhotite and pentlandite, with minor pyrite, chalcopyrite, and violarite. The sulfide content is surprisingly low in many places, with 1 to 3% Ni corresponding to 3 to 12% sulphide. Some sulphur has probably been lost during serpentinization, but it is unlikely that the mineralization was originally semi-massive or massive. The sulphur content of the nickel mineralization is low in comparison to most komatiite-hosted nickel deposits outside of the Dundonald area.

The stratigraphy of the Dundonald South nickel deposit (previously known as the Dundonald deposit) is similar to that of the Dundeal deposit to the north, and includes, from base to top, the Dundonald sill, dacites, and peridotitic/pyroxenitic komatiites intercalated with graphitic argillites and possibly with dacites. The geology is complicated by two episodes of faulting, one interpreted to be synchronous with the folding event and parallel to the WSW-trending fold axes, and a later, WNW-trending sinistral fault that cuts the folds. The dacite that is apparently intercalated with the nickel-bearing komatiite flows is believed to be juxtaposed with the flows by early faulting.

Drilling in the 1960s to 1970s (>100 drillholes) outlined a significant resource with an average grade of approximately 1.5% Ni in five zones; and more recent drilling has extended the mineralized horizons (Green and MacEachern 1990). Each of the five zones of mineralization are at the contact of peridotitic komatiite with other rock types. The sulphide assemblage is pyrrhotite, pentlandite, heazlewoodite, millerite, violarite, and other trace phases; and is usually net-textured within meso- to orthocumulus, medium- to coarse-grained amoeboidal olivine. Sulphide contents are up to 25%, but are generally at much lower levels; semi-massive sulphide is rare, and massive sulphide is apparently absent. Where the komatiite is in contact with graphitic argillite, "interflow ore" may be present, which apparently has a higher nickel tenor (Muir and Comba 1979).

Photo 3.1. Flow-banded, spherulitic rhyolite, from south of the Dundonald sill anticline.

Photo 3.2. Komatiitic basalt (contaminated komatiite) dike cutting dacite. The dacite has partial melt textures: irregular, cuspate-lobate contact, and wispy terminations in the basaltic material.

Photo 3.3. Dacite (lighter colour) cuts graphitic, sulphide-rich argillite with peperite textures that indicate intrusion into wet, unconsolidated sediments.

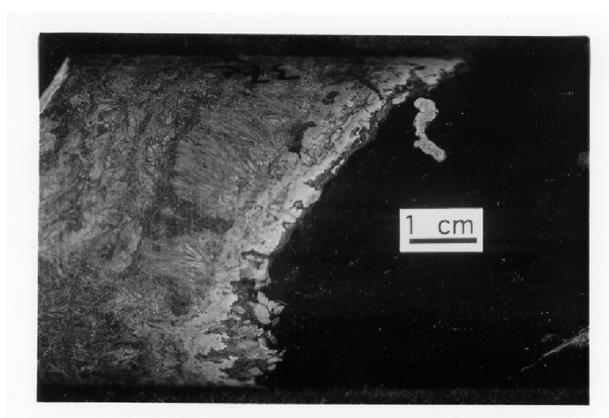


Photo 3.4. Komatiite (lighter colour)-graphitic argillite contact. Komatiite has centimetre-scale bladed olivine spinifex, and irregular contact indicating partial melting of argillite.

Nickel Island is a small, approximately 125 m by 75 m, island in the southeastern part of Frederick House Lake in central southern Dundonald township. It is underlain by variolitic hyaloclastic, pillowed or massive basalt/magnesian basalt (contaminated komatiite?). These units are apparently up-section from the Empire flow which is host to the Dundeal nickel mineralization and the Dundonald south nickel mineralization in the Dundonald sill area approximately 3 km to the east. Minor sulphide occurs up to 2% as disseminated blebs locally on the western shore of the island. The varioles are almost exclusively concentrated in pillow rims and in hyaloclastitic matrix to pillow breccia and pillows. Bedding generally dips to the north at 65° to 75°. Facing directions are predominantly to the north, although many of the pillows are sub-equant and spherical, and approximately 35% have apparent facing directions to the south or west. Drilling in the 1960s found numerous intersections of 1 to 3 m with 0.6 to 1.8% Ni, with disseminated to semi-massive sulphide intersections in hyaloclastitic basalt. Given the Hollinger descriptions and the lack of significant sulphide at the surface, the nickel tenor in sulphide would appear to be high. A common feature to all the nickel deposits and occurrences in Dundonald township is that they have a relatively high nickel tenor in the sulphide in comparison to nickel deposits of the Shaw Dome area.

Volcanogenic Massive Sulphide Mineralization: The Terminus Occurrence

The Terminus Zn ± Pb ± Cu ± Ag zone is graphitic and sulphide-rich argillite and brecciated komatiite flow tops on the northern flank of the Dundonald sill anticline. The main Terminus zone horizon is 150 to 200 m up-section from the Dundeal nickel horizon, and up-section 50 to 100 m above the top of the Empire flow. It is characterized by semi-massive and locally massive sulphide mineralization as bedded and nodular pyrite and pyrrhotite, with bedded and veined sphalerite, galena and chalcopyrite. Secondary Zn-Cu zones are present within interflow graphitic, sulphide-rich argillite within 50 m of the main Terminus zone horizon. The best intersection is 7.53% Zn and 1.37% Cu per 10 m (Falconbridge DDH 25-20) also has 0.1% Pb, 1.1 ppm Au and 29.1 ppm Ag. The Zn mineralization is discontinuous along strike and up-dip as shown by drilling with penetration points on the main Terminus horizon spaced at 25 to 100 m. The encompassing komatiite and komatiitic basalt flows exhibit weak to moderate chlorite alteration, and minor silicification in the vicinity of the best mineralization.

Massive pyrrhotite with a trace of chalcopyrite over 5.3 m was encountered at the dacite-komatiite contact overlying the western nose of the Dundonald sill anticline (MNDM Assessment files). This mineralization is considered to be VMS style, and to be coeval with Terminus zone mineralization.

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4. Project Unit 97–01. Geological Investigations Along Highway 101, East of Matheson

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This multi-year project is designed to improve the geological database along Highway 101, especially in areas covered by overburden in the vicinity of the Porcupine–Destor deformation zone (PDDZ). This year, work was concentrated in the Harker–Holloway townships area (Figure 4.1) and involved examination of outcrop, diamond-drill core and assessment files. The work was carried out in conjunction with structural (Luinstra, this volume) and alteration (Ropchan, this volume) studies at Battle Mountain Gold Incorporated's Holloway gold mine. Previous mapping and interpretation of the area is provided by Satterly (1949, 1951, 1953), Jensen (1978, 1982a, 1982b), Jensen and Langford (1985) and Jackson and Fyon (1991). Readers are referred to these authors for detailed discussions of the geology of the map area.

A number of observations made this summer will serve to refine existing maps and aid future interpretation of the area. Mafic metavolcanic flows dominate the Kinojevis assemblage south of Highway 101 and are interbedded with wacke and graphitic argillite units that are more numerous than previously portrayed. These metasedimentary units are generally moderately to strongly foliated and are more deformed than the mafic metavolcanic rocks. Northeast-striking (070°) faults are inferred to be coincident with some of the metasedimentary units.

Intermediate and felsic metavolcanic rocks north of Highway 101 were previously correlated with the 2730 Ma Hunter Mine Group in Quebec (Jensen and Langford 1985). Calc-alkalic feldspar porphyry and related autoclastic and pyroclastic breccia deposits interpreted to represent a volcanic vent underlie the southern part of Rand Township (Jensen and Langford 1985). These rocks were dated at 2713 ± 2 Ma (Corfu 1993), which is correlative with the Kidd–Munro assemblage. Drill data indicate that the feldspar porphyry extends east into Lamplugh Township.

Intermediate and felsic metavolcanic rocks that occur on the south limb and in the core of a syncline in northern Harker and Holloway townships extend farther south than previously indicated. These feldspar phenocrystic deposits underlie peridotite and gabbro of the Ghost Range (2713^{+7}_{-5} Ma Corfu 1993), are contiguous with similar felsic rocks in northern Garrison Township and may be contiguous with the feldspar porphyry in Rand Township. These rocks will be sampled to determine their geochronology in the near future.

Andesitic and dacitic epiclastic and pyroclastic rocks are interbedded with wacke and argillite in the central parts of Stoughton, Frecheville and Lamplugh townships. Drill data indicate that these deposits are composed of amygdaloidal, plagioclase and pyroxene phenocrystic clasts in a tuffaceous matrix of similar composition. They are remarkably similar to intermediate metavolcanic rocks correlated with the Duff–Coulson–Rand assemblage in the Monteith area approximately 30 km to the west (Berger 1996). Mafic metavolcanic rocks separate these deposits from, and preclude their direct correlation with, other intermediate and felsic rocks north of Highway 101.

Metasedimentary rocks that occur within the PDDZ are of two types. Turbiditic wacke, argillite and minor laminated iron formation are most abundant and are isoclinally folded in northern Garrison Township. Massive, featureless air-fall tuff is a distinct rock type in this area and may be correlative with similar rocks in Guibord Township approximately 20 km to the west. Drill data near the Holloway Mine indicate that wacke and argillite are strongly sericitized and silicified, and display strong foliation and crenulation cleavage. Stratigraphy is south younging in this area.

Polymictic conglomerate, interbedded sandstone and rare argillite comprise the second metasedimentary rock type in the PDDZ. The conglomerate is thickest (approximately 25 m) at the Holloway Mine, where clasts are composed of aphanitic and phaneritic syenite, plagioclase and pseudo-leucite(?) porphyry, red jasper, iron formation and rare ultramafic clasts. Only the ultramafic rocks occur locally, indicating a distal provenance source for the majority of the clasts. The feldspathic sandstone is massive, with red jasper clasts common. In many drill holes it has been confused with turbiditic wacke. Conglomerate and sandstone are weakly to strongly hematized and commonly display weak to moderate foliation. These rocks are correlated by the author with Timiskaming-type metasedimentary rocks similar to those at Kirkland Lake and Hislop Township (40 km to the west).

Ultramafic metavolcanic rocks occur throughout the PDDZ as cumulate and spinifex-textured flows and as green mica-carbonate altered schist. These rocks are more abundant than previously portrayed and occur in the structural footwall of the Holloway Mine and along the north contact of the metasedimentary rocks in Garrison Township. The ultramafic rocks are important marker units in the stratigraphy and based on their distribution provide strong evidence that fault-modified isoclinal folding is prevalent in the PDDZ.

Syenite and monzonite intrusions in Harker and Garrison townships also have pyroxenitic, gabbroic and lamprophyric phases associated with them. Where these rock types are undeformed, as at the Iris gold occurrence in southern Harker Township (*see* Figure 4.1), they are easy to recognize. Where they are deformed in the PDDZ, however, they were not previously recognized or they were mapped as diabase and mafic flows. Explorationists should be aware that these intrusive rocks are present in the PDDZ and that they cannot be used for stratigraphic correlation in the map area.

Some general observations regarding structure and gold mineralization are relevant to the map area. Stratigraphy is consistently southward younging in the Kinojevis assemblage south of the PDDZ. However, reversals in stratigraphic facings subparallel to first-generation spaced cleavage occur within and immediately north of the PDDZ, indicating that isoclinal folds are present. Widely spaced subhorizontal F_2 folds overprint first-generation cleavage in the Holloway Mine and also appear to postdate alteration and gold mineralization (Luinstra, this volume). In many places, northerly (345° to 015°) spaced cleavage and faults crosscut first-generation structures. These faults

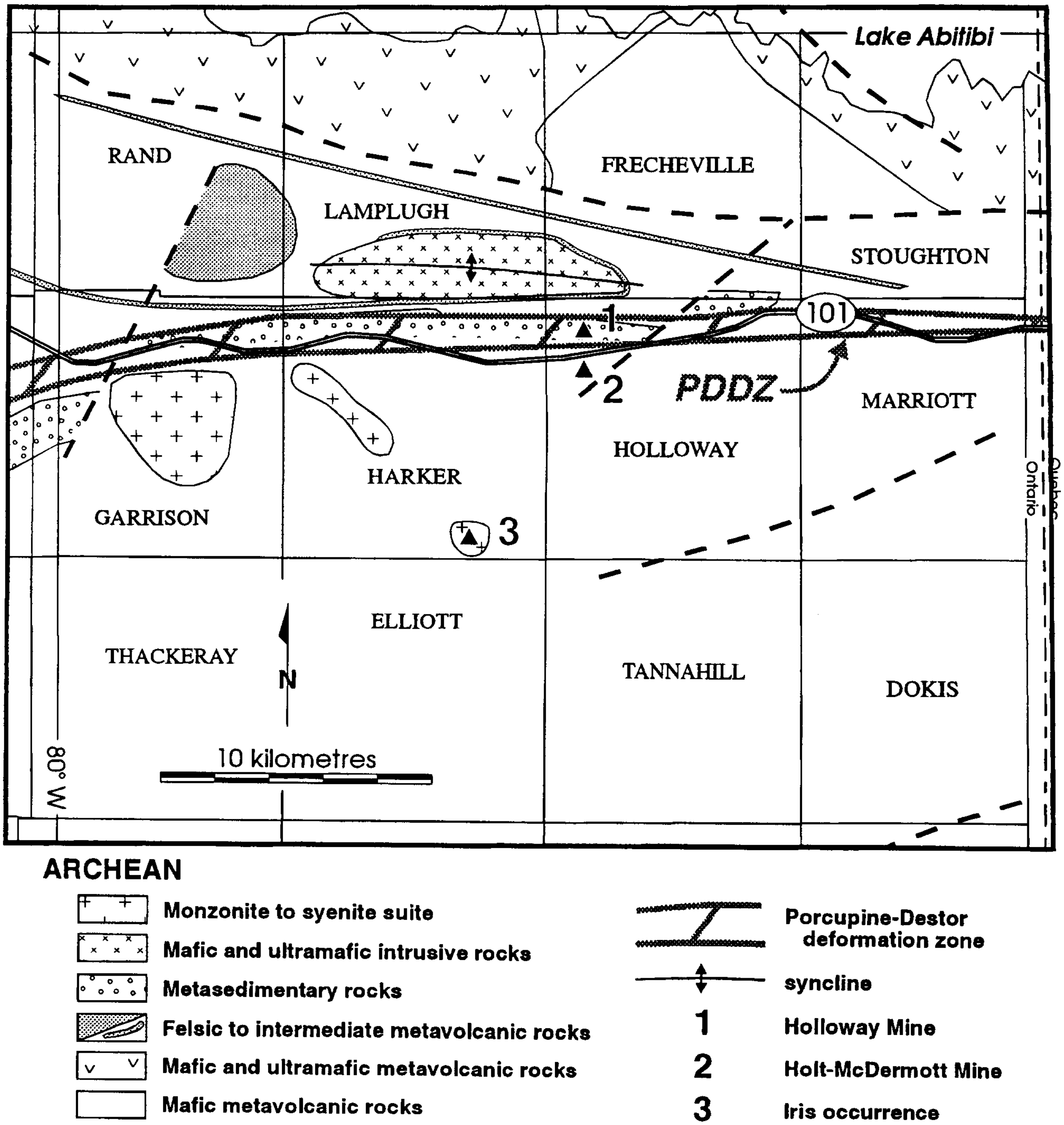

Figure 4.1. General geology, Harker–Holloway townships area.

display east-side-down and sinistral displacement that has locally modified the distribution of rock types and gold mineralization in the Holloway Mine area.

The PDDZ is characterized by several discrete faults separated by weakly to moderately deformed rocks. The easterly striking, southerly to vertically dipping faults vary from a few centimetres to a few metres in width, contain rubbly fault gouge and/or strongly foliated rock and locally transpose rock units. Rare kinematic indicators and lineations indicate that late reverse south-over-north movement occurred on many of the faults. Shearing was not observed in the area and the faults appear to represent zones of flattening. Subhorizontal structures hosting gold mineralization at the Holt–McDermott Mine suggest that the faults may become listric at depth.

Gold mineralization occurs in hydrothermal alteration zones at or near faults within the PDDZ. Gold accompanies albite, sericite, hematite and pyrite alteration that Robert (1997) inferred was related to syenite intrusions. Further study is required to determine if the alteration zones are folded or faulted into their present locations, and the paragenetic sequence of mineralizing events. Gold is associated with syenite intrusions at the Iris occurrence in southern Harker Township approximately 8 km south of the PDDZ. Here, gold occurs in quartz veins within the syenite and in northwesterly striking faults in the Kinojevis assemblage. Pyroxenite and lamprophyre occur around the margins of the syenite and their role in localizing gold mineralization requires further study.

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5. Project Unit 9600–00. Structural Investigations of the Holloway Mine and Vicinity

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This two-year project is aimed at documenting the structural geology and the structural setting of the Holloway Gold Mine. The project represents the MSc thesis of Luinstra, supervised by Benn, and the work has been undertaken in collaboration with the Ontario Geological Survey (OGS) and Battle Mountain Canada Inc. The mine is situated about 15 km west of the Ontario–Quebec border along Highway 101, on a splay of the Porcupine–Destor deformation zone (PDDZ). Detailed geological and structural mapping and microstructural analyses are being carried out to demonstrate the key structural elements associated with the Holloway deposit, to establish the timing of mineralization with respect to structural events, to determine the structural controls on the deposit, and to provide a description of the PDDZ in the vicinity of the mine. The study is being carried out in conjunction with regional mapping by the OGS (Berger, this volume) and a study of alteration (Ropchan and Fowler, this volume). Previous geological maps and interpretations of Holloway township were provided by Satterly (1953), Jensen (1982a,1982b), and Jensen and Langford (1985).

Initial field work was carried out by Luinstra over a period of 14 weeks during the summer of 1997. Six weeks were spent on a general survey of the surface between Garrison and Marriott townships, becoming familiar with the regional geology and assisting with OGS mapping. Four weeks were spent underground assisting the mine's geology department personnel and becoming familiar with the rock types associated with the deposit, through drill-core logging and underground mapping. An additional 4 weeks were spent preparing detailed structural maps of the deposit in 2 key areas (Figure 5.1), collecting samples for microstructural analyses, and compiling and plotting data. The preliminary results indicated a complex structural signature, with strong deformation highly localized within specific rock types. Several days of additional field work are planned for the autumn of 1997. Thin sections cut from oriented samples are being prepared for microstructural analyses. These will be carried out during the winter in order to better document fine-scale evidence of deformation phases, including transposition, and the timing of mineralization with respect to structural development. These data should further our understanding of the structural geometry of both the Holloway mine and the PDDZ in the area.

Figure 5.1 is a simplified profile of the mine, modified from Couture and Robert (1997). The lithological units define a south-dipping monocline. The footwall of the deposit is composed of ultramafic flows characterized by spinifex textures and intense fuschite and carbonate alteration. A first-generation penetrative foliation (S_1) is strongly developed in this unit. It strikes east-west and dips steeply south, and can be correlated with the principal regional foliation (Berger, this volume). Exposure of this unit underground is rare because of the incompetency of the rocks, which renders excavation hazardous. The upper 5 m of the ultramafic unit is strongly sheared in the "Footwall Contact Shear Zone" that Guy (1996) suggested could represent the conduit zone for mineralizing fluids.

The ore bodies are hosted by a discontinuous unit composed of hyaloclastites (Guy 1996) situated structurally above the ultramafic unit. These rocks are characterized by intense albitic alteration and gold mineralization. No macroscopic fabric was observed in the ore bodies, suggesting that the alteration associated with mineralization may have overprinted and effaced the S_1 foliation.

The ore bodies and the ultramafic unit are overlain by a sequence of tholeiitic mafic volcanic rocks, mostly pillowed, with some intercalated massive flows, characterized by the presence of leucoxene and a variable degree of sericitic and albititic alteration. In the areas mapped in detail, the massive flows are concentrated near the top of the unit. Similar pillowed and massive mafic volcanic rocks are found structurally overlying the conglomeratic unit (*see* Figure 5.1; *see also* Guy 1996). The pillowed basalts overlying the ultramafic unit are characterized by strong sericitization and a well-developed S_1 foliation. S_1 is deformed by subhorizontal crenulations with a shallow eastward plunge, an undulating subhorizontal S_2 crenulation cleavage is also locally developed. Interflow metasedimentary rocks, predominantly greywackes and mudstones with rare argillites, occur throughout the mafic volcanic units. S_1 foliation, crenulations and the S_2 foliation are strongly developed in the sedimentary units.

The structure of the deposit and the above-described units suggests that the stratigraphy has undergone a great deal of isoclinal folding and transposition during the formation of the S_1 foliation (D_1 structural event). Evidence for transposition includes the lateral discontinuity of the deposit and lithological units, which pinch out to the east and west (out of the plane of Figure 5.1), the presence of intrafolial folds within the sedimentary rocks, the presence of highly sheared zones at many lithological contacts, and the fact that S_1 is generally parallel to all lithological contacts and bedding. Further evidence of isoclinal folding and transposition of primary structures is documented at the regional scale by Berger (this volume). The recognition of transposition at all scales is of primary importance since it indicates that bedding, where it is preserved, is not a marker of the depositional plane.

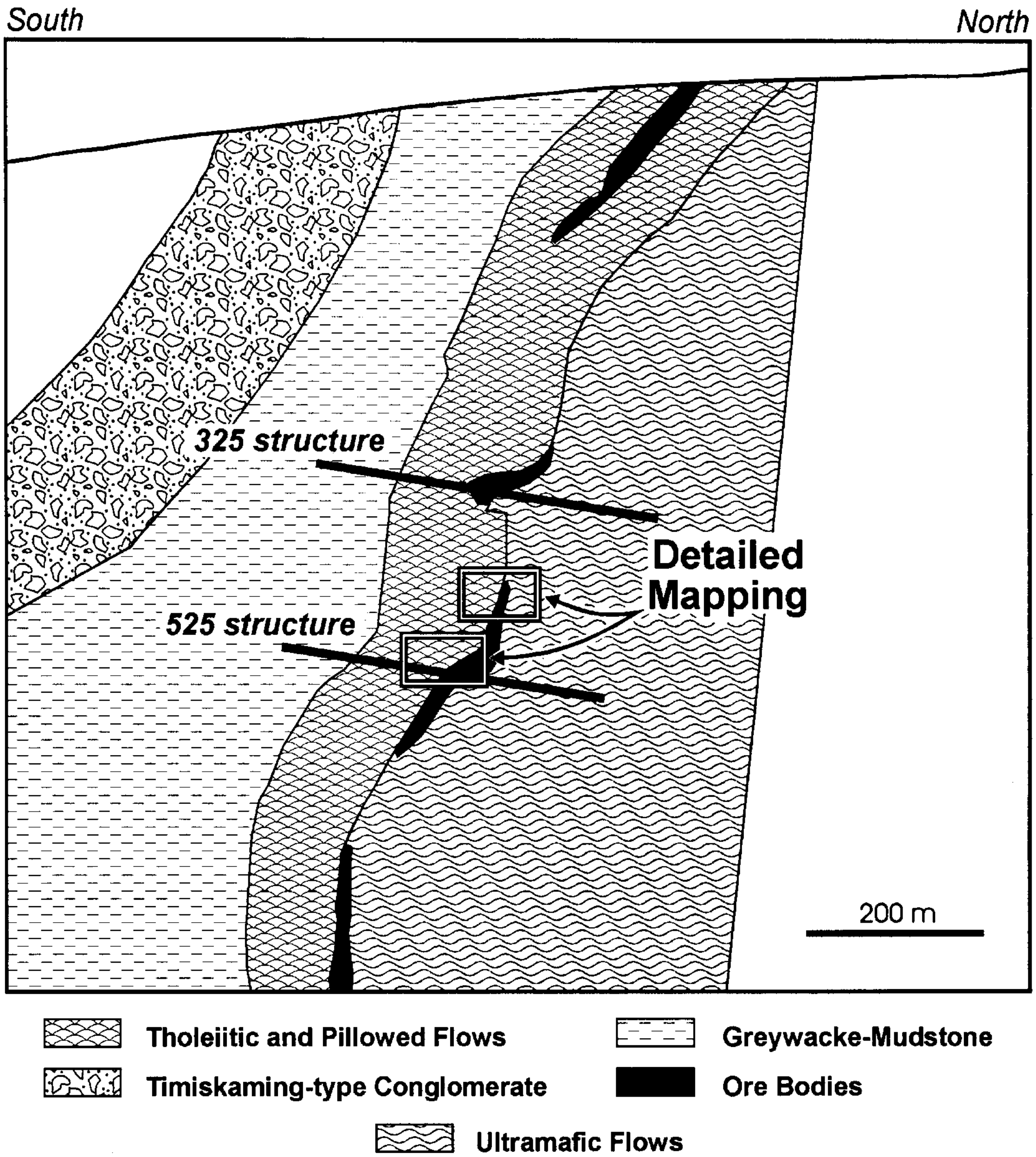

Figure 5.1. Cross section, looking west through the Holloway Deposit.

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6. Project Unit 96–01. Lithogeochemical Characterization of Gold-Associated Alteration, Garrison to Marriot Townships

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Gold mineralization associated with Fe-rich tholeiitic metavolcanic rocks, and the Destor–Porcupine deformation zone (DPDZ) has long been recognized in Garrison, Harker, Holloway and Marriot townships. Despite this, economic concentrations have only been found in the past few years, and little is known about the details of the mineralizing process. The purpose of this research project is to shed light on the lithogeochemical controls of gold mineralization. This may lead to increased efficiency in the exploitation of known deposits, and also provide tools applicable to future exploration programs.

The project involves the collaboration of the Geology Department, University of Ottawa (UO), Battle Mountain Canada Inc. (BMC) and the Ontario Geological Survey (OGS). The area of study consists of an east-west trending region which extends for more than 15 km from northern Garrison Township to the northeast corner of Marriot Township, and also includes an area of equivalent rock units further to the south in the vicinity of Harker Lake. The project is carried out in conjunction with regional mapping by the OGS (Berger, this volume) and a study of the structural controls on gold (Lunistra and Benn, this volume). The project consists of a master's thesis by Ropchan and posters presented at the Northeastern Regional Symposiums to be held in the spring of 1998 and 1999.

The Holloway mine of BMC celebrated its grand opening on May 30, 1997. It is located adjacent to Highway 101, approximately 60 km east of Matheson and 65 km north of Kirkland Lake. The Holloway mine occurs a few hundred metres north of the southern branch of the DPDZ. While Barrick Gold's Holt–McDermott mine ocurrs to the south of the DPDZ. The gold mineralization at the Holloway deposit occurs within a silicified-albitized-sulphidized zone known as the Lightning Zone. The Lightning Zone is hosted by mafic metavolcanic rocks at or near the contact with underlying ultramafic metavolcanic rocks. Variolitic, mafic metavolcanic rocks may be favourable hosts for gold mineralization because they are iron-rich and deform in a brittle manner making them relatively permeable and reactive hosts (Jones 1992).

The Lightning Zone is a "blind deposit" and was discovered using a program of systematic surface diamond drilling undertaken from 1986 to 1988. The general geology of the Holloway gold deposit, has been described by Guy (1996). Massive, pillowed, variolitic, autobrecciated basaltic flows and hyaloclastite horizons in the mine area have undergone extensive alteration including silicification, albitization, sericitization, carbonatization, sulphidization and some hematization.

The goals of this lithogeochemical study are to: 1) identify the lithogeochemical characteristics of unaltered and altered ore-bearing rock types and determine the changes associated with the mineralizing process, 2) determine which rock types and alteration types are favourable hosts to mineralization; and, 3) determine the role of textural elements and physical rock properties such as primary or hydrothermal brecciation in the mineralizing process.

The 1997 field season focussed on reconnaissance work in the southwestern Abitibi Greenstone Belt and the collection of samples from within the Holloway mine. In addition, samples were taken from sections of diamond drill core which intersected correlative units in the vicinity of the mine. Particular attention was paid to sampling mineralized rocks and their least altered equivalents so that mass balance techniques can be used to investigate elemental mobility. Approximately 100 thin sections and another 100 samples are in preparation for geochemical analysis. The data will be used to determine the chemical and mineralogical changes in the hydrothermal alteration zones as the ore zone is approached both vertically and laterally. Further mapping and sampling of a well-exposed hyaloclastite-debris flow east of Harker Lake in Harker Township, as first described by Jones (1992), is underway to better understand apparently similar hyaloclastite in the Holloway mine sequence.

During the second field season, regional work will focus on collecting more samples from Garrison to Marriot townships. Also, during the two year project, a database compiled by Kirkland Lake resident geologist Gerhard Meyer, consisting of 144 samples will be further interpreted using Gresens (1967), and other techniques. An additional database of approximately 250 samples is being provided by BMC's exploration division.

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7. Project Unit 96–03. Reappraisal of the Geology of the Shining Tree Area (Tyrrell Township), Districts of Sudbury and Timiskaming

G.W. Johns

Ontario Geological Survey, Precambrian Geoscience Section

INTRODUCTION

Active mineral exploration in the Shining Tree area and advances in concepts of Archean geology prompted the initiation of a multiyear study to re-evaluate the geology and mineral potential of this mineral-rich portion of the southern Abitibi greenstone belt. The area is bounded by latitude 47°29′30″ to 47°45′30″N and longitude 80°55′ to 81°27′30″W, comprising the townships of Asquith, Cabot, Churchill, Connaught, Fawcett, Kelvin, Knight, Leonard, Macmurchy, Miramichi, Natal and Tyrrell. The area was mapped for the Ontario Geological Survey in the early 1970s by M.W. Carter, who produced several detailed geological maps and reports culminating in a 1:50 000 compilation map and report (Carter 1987).

The author spent 6 weeks in 1996 examining cross sections through the Archean rocks (Johns 1996). Based on these observations, several changes were made to the interpretations portrayed by Carter (1987). The Archean rocks were tentatively subdivided into two packages (Figure 7.1): package 1—a lower, probably Keewatin-aged, package consisting of mafic to intermediate metavolcanic rocks and felsic flows and clastic rocks with a subpackage containing komatiitic flows, and package 2—an intermediate pyroclastic to epiclastic package of unknown age disconformably overlying package 1 (*see* Figure 7.1). Both packages have been intruded by gabbros, possibly of early Proterozic age.

Four weeks were spent in 1997 examining the rocks in Tyrrell Township and in parts of Knight, Macmurchy and Natal townships. The rocks have been further subdivided and contacts have been reinterpreted (Figure 7.2). The designation of packages 1 and 2 has been retained until further data are collected. In addition, rocks interpreted to be Timiskaming-type sediments unconformably overlying package 1 metavolcanics have been outlined in southern Tyrrell Township.

GENERAL GEOLOGY

Package 1

Package 1 (*see* Figure 7.2) has been further subdivided in Tyrrell Township and comprises basaltic to peridotitic komatiite, mafic to intermediate flows, felsic to intermediate flows and pyroclastic rocks, interflow sedimentary rocks, chert-pyrite-magnetite ironstone and gabbro.

KOMATIITES

Komatiitic metavolcanic rocks were not extensively mapped south of Knight Township by Carter (1987). However, scattered ultramafic outcrops have been observed by the author in Tyrrell Township—south of Milly Lake, east of Breeze Lake, along the Hydro Creek Fault—and have been reported south of Porphyry Lake (Jamie Walker, Shining Tree Resources, personal communication, 1997) and south of Hare Lake. Except for the outcrops in the Milly Lake area, these rocks are altered actinolite and talc-chlorite schists and have few primary features preserved, although spinifex and olivine cumulate have been observed.

The ultramafic rocks are interbedded with mafic metavolcanicrocks and are interpreted to strike in a northwest direction (*see* Figures 7.1 and 7.2).

MAFIC TO INTERMEDIATE METAVOLCANIC ROCKS

Mafic to intermediate metavolcanics are well preserved, with only minor amounts of deformation and alteration evident. Primary structures include pillows, pillow breccia and hyaloclastite, autoclastic breccia, amygdules and variolites. Although the strike is locally variable, they appear to have an overall northwesterly trend.

INTERMEDIATE TO FELSIC METAVOLCANIC ROCKS

These rocks, comprising flows, autoclastic breccias, and pyroclastic and volcaniclastic units, are found both in the north, around Highway 560, and in the southwest part of Tyrrell Township. Volcaniclastic rocks generally have fragments in the tuff to lapilli tuff size range and appear to be primary in mode of deposition.

CHEMICAL METASEDIMENTARY ROCKS

Pyritiferous black and red chert outcrops in the southwest part of Tyrrell Township at the boundary between mafic and intermediate to felsic metavolcanics. An 8 m thick pyritiferous black chert unit capping a felsic breccia was also observed north of Porphyry Lake. The black cherts may have been the source of chert clasts found in the Timiskaming-type sediments described below.

Package 2

Package 2 rocks, as defined in Johns (1996), were not found in Tyrrell Township.

Timiskaming-type Metasediments

Timiskaming-type metasedimentary rocks have been observed in the south-central part of Tyrrell Township and as thin units along the Hydro Creek Fault. Where the contacts

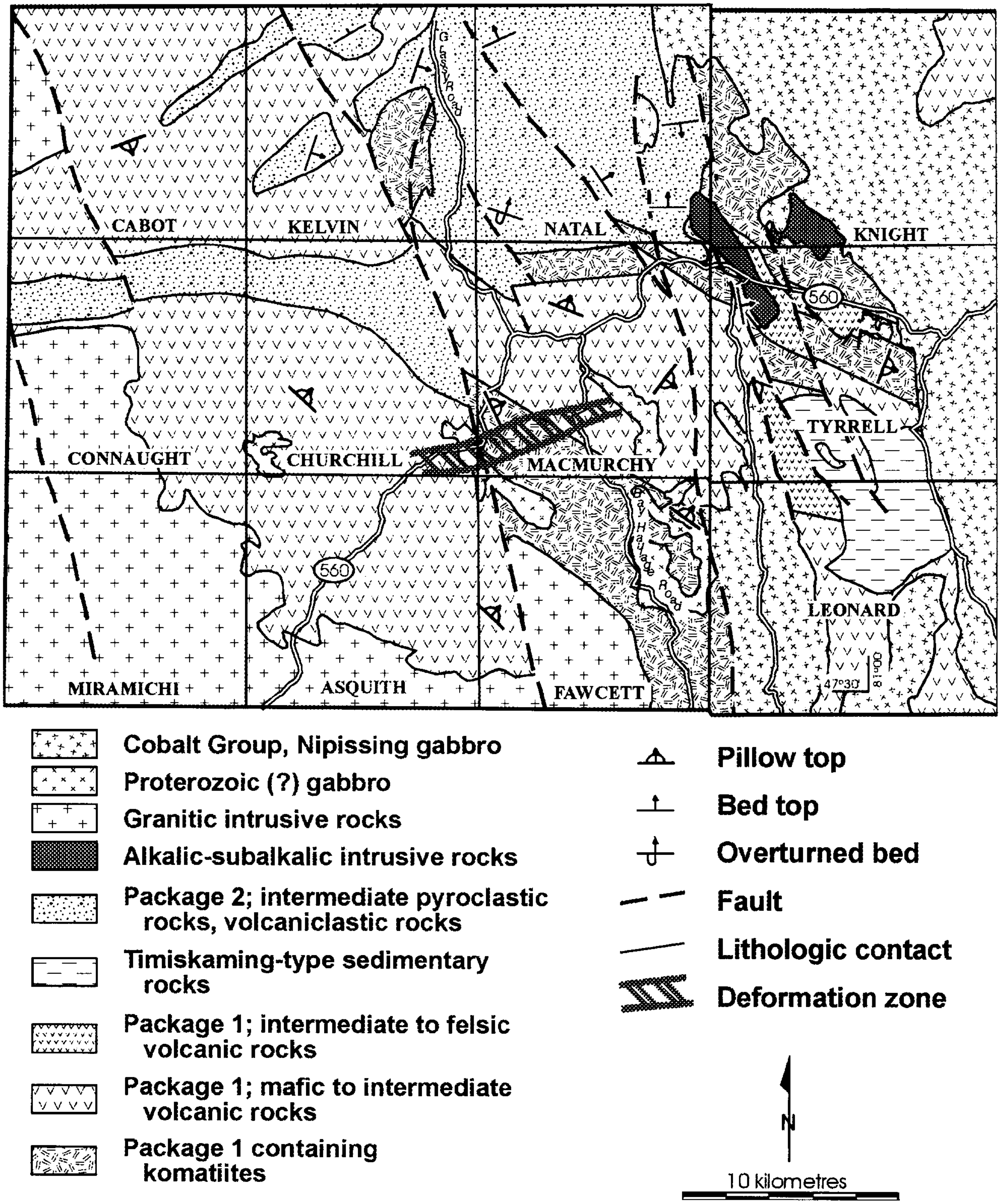

Figure 7.1. General geology of the Shining Tree area. Package 1 rocks may represent Keewatin–aged rock types. Package 2 is younger and comprises both calc-alkalic and alkalic rock types. Tyrrell Township has been *modified from* Johns (1996, Figure 7.1) to reflect the geology shown in Figure 7.2.

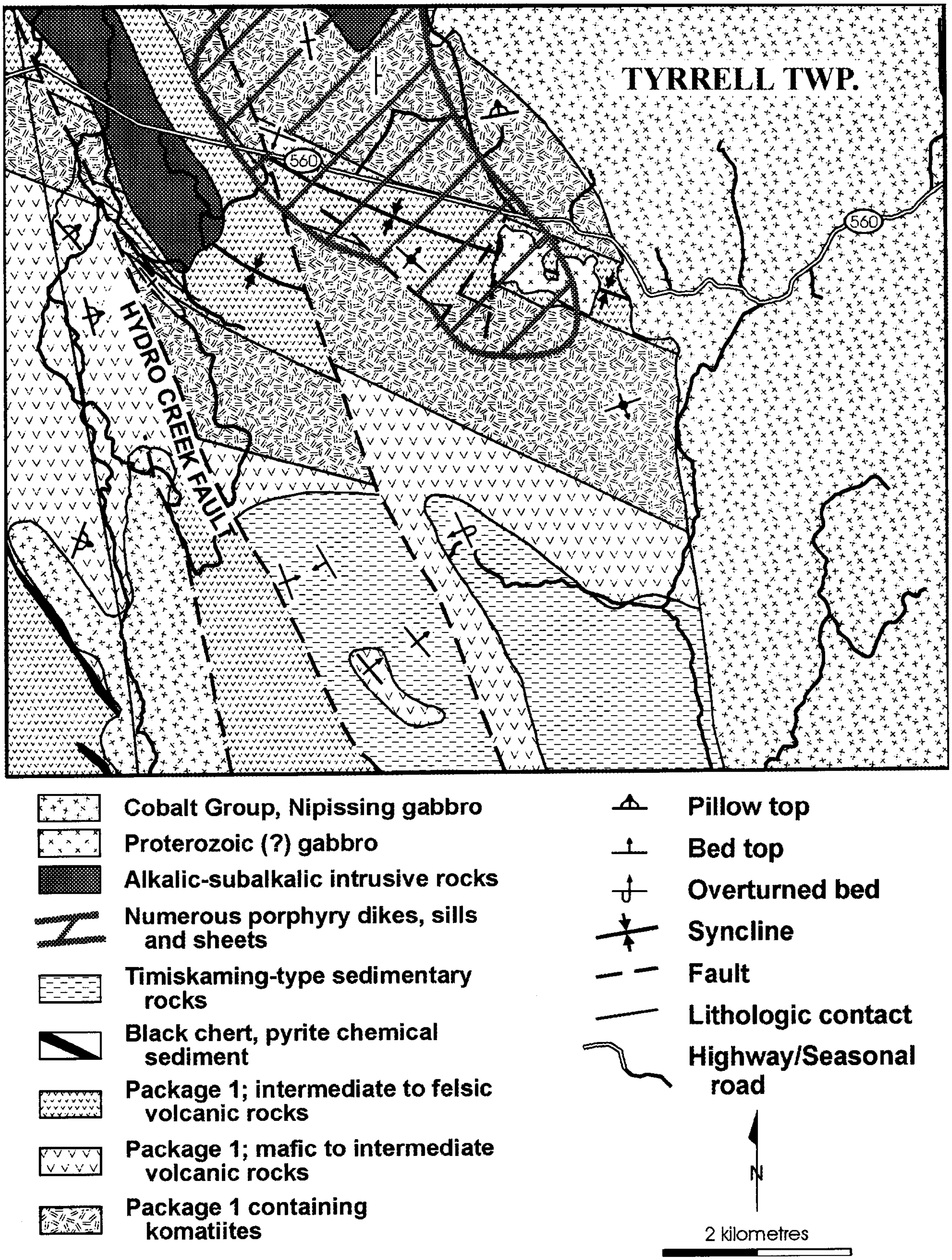

Figure 7.2. General geology of Tyrrell Township. The hatched pattern indicates the area that is rich in feldspar, hornblende-feldspar and hornblende porphyry.

are well exposed, they demonstrate unconformable relationships with the underlying mafic and komatiitic metavolcanic rocks.

The sediments are massive, coarse, angular to subangular quartz-feldspar arenite with lenses, sheets and single-clast layers of conglomerate. Clasts comprise rounded metavolcanic and intrusive rocks and angular black, grey and red chert. The red jasper clasts locally contain laminae of magnetite. Bedding planes are not obvious and very rapid deposition by debris flow is suggested by scouring of the underlying bedding planes. Primary features, such as bedding, grading and cross-bedding, are rare, but minor laminated argillite beds are found. Grain sizes in the unit fine to the north.

Intermediate Porphyry Dikes and Sills and Sheets

The area around Porphyry Lake (*see* hatched pattern on Figure 7.2) has been flooded with feldspar, hornblende-feldspar and hornblende porphyry. In many outcrops, these are the predominant rock types. Crosscutting relations suggest that the feldspar porphyry is the oldest. The hornblende-bearing porphyries may be coeval with the hornblende monzonite to monzodiorite Milly Creek Stock.

Alkalic to Subalkalic Intrusive Rocks

Fine-grained to very fine grained, brick–red, hornblende syenite sills and dikes are common, intruding both package 1 and package 2 rocks. The largest of these bodies is an elongate intrusion in northwest Tyrrell Township. It has a coarser grained monzonitic core that is exposed in its southern tip north of Hare Lake. In the Milly Lake area and in Natal Township, similar rocks exhibit possibly extrusive-like features, and more work will be required to further subdivide them.

The southern lobe of the Milly Creek Stock is exposed in north-central Tyrrell Township and comprises euhedral hornblende monzonite to monzodiorite. It is medium-grained inequigranular and contains xenolith trains of the surrounding country rock.

Metamorphism

Except for the higher grade contact metamorphic aureoles around the external granitic batholiths, the grade of metamorphism is generally lower greenschist to subgreenschist. Fine volcanic textures, such as perlitic cracks in felsic hyaloclastite, have been preserved.

Structure

Deformation is restricted to discrete zones that divide the area into individual blocks, which exhibit little evidence of internal deformation.

Carter (1987) has shown many fold axes on his 1:50 000 synoptic map. Many of these are suspect as they were not confirmed due to a lack of stratigraphic top markers and, as such, they are not shown on Figures 7.1 and 7.2. The continuation of a syncline in eastern Natal Township (Carter 1987) is interpreted to occur within the intermediate to felsic rocks of package 1 in northern Tyrrell Township. The axis of the syncline curves from south-southeast to southeast and is offset by northwest-trending faults (*see* Figure 7.2).

Northwest faulting, common in the Shining Tree area, is interpreted to offset stratigraphy in Tyrrell Township. The Hydro Creek Fault and splays from it (*see* Figure 7.2) are related to gold mineralization and intense alteration. In some locations, there appears to be intense carbonatization but little ductile deformation. Ductile deformation appears to be more intense on the splay faults.

Implications for Mineralization

Carter (1987 and references therein) has outlined the mineral deposit types found in the area. Currently, gold is the subject of intense exploration in Tyrrell Township. Areas of interest include lands in the former Temagami Land Caution and along the Hydro Creek Fault.

A recently completed lake sediment and water geochemical survey (Hamilton 1997) included all of Knight, Leonard and Tyrrell townships and an additional 29 townships to the north, south and east. Significant gold and nickel anomalies were noted in all three townships. Anomalies in arsenic and base metals were noted in Tyrrell Township.

North-northwest faults and northwest-trending cross faults are prospective for gold. Robert (1997) discusses gold mineralization associated with syenitic stocks and dikes. The syenite to monzonite intrusive rocks in the area should be examined for their gold potential, especially when associated with deformation and alteration.

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8. Project Unit 94–42. Regional Geological Studies in the Hemlo Greenstone Belt

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INTRODUCTION

The Hemlo gold deposit lies roughly at the centre of the Hemlo greenstone belt (Figure 8.1) and has been the focus of considerable study and debate (Muir 1997). Alteration, multiple deformation events and amphibolite facies metamorphism have complicated interpretation of the deposit and its host rocks. In order to improve the understanding of the regional geological setting of the deposit, the Ontario Geological Survey initiated several regional thematic studies (see reports in the 1995 and 1996 Summary of Fieldwork). The purpose of this project is to provide the regional structural and metamorphic framework of the deposit and to characterize the geochemistry of metavolcanic rocks. Fieldwork during the 1997 field season focussed on the northern and eastern portions of the greenstone belt. This report summarizes some structural, metamorphic and lithologic observations made during 1997.

STRUCTURAL GEOLOGY

Deformation Stages

The structural history of the greenstone belt can be generalized into two main stages (e.g., Jackson 1995, 1997), that are comparable to D_2 and D_3 events developed by Zaleski et al. (1995) for the Manitouwadge greenstone belt. The first stage resulted in the development of a penetrative foliation defined by medium-grade metamorphic minerals. This foliation is, in general, parallel to unit boundaries and pluton and batholith contacts. A second stage of deformation resulted in the folding of this early fabric, the

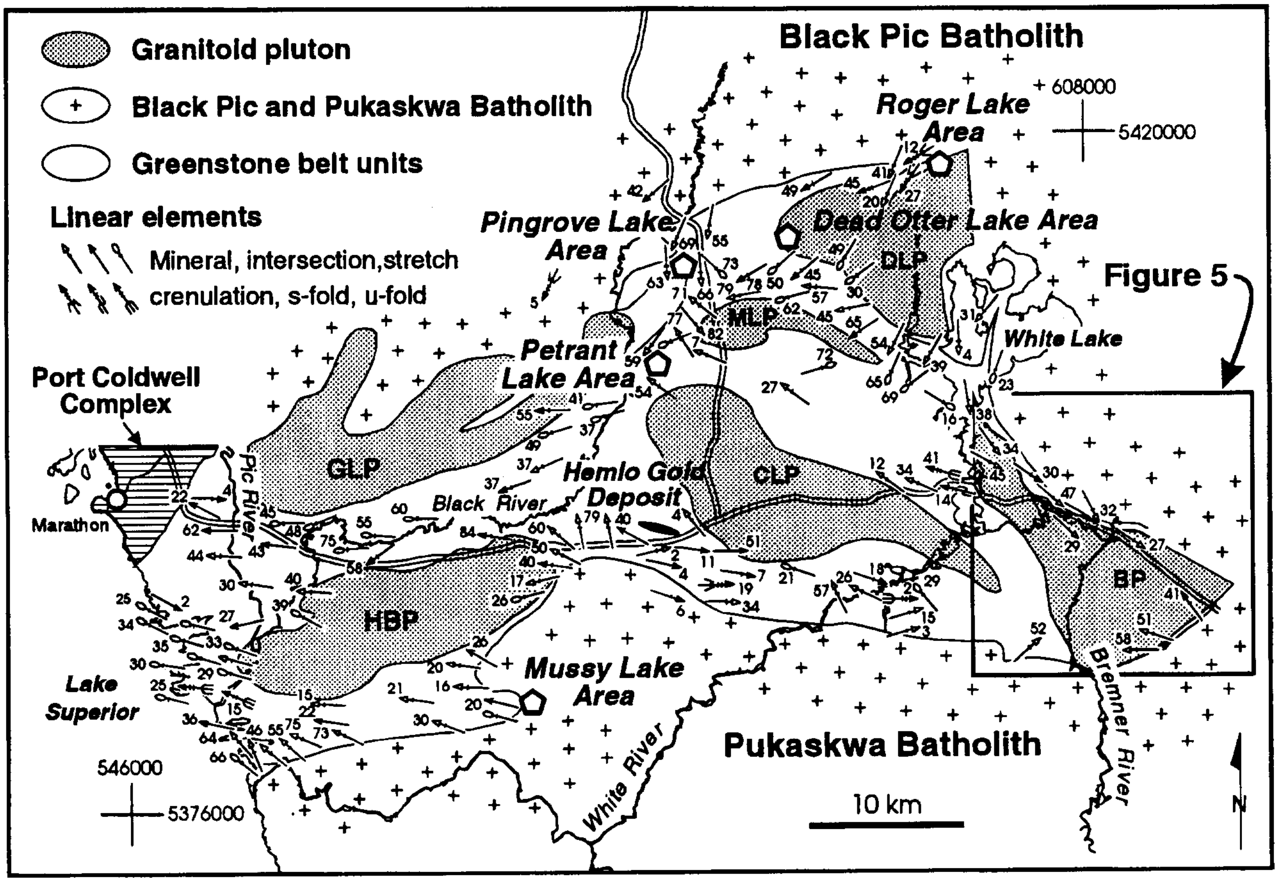

Figure 8.1. Generalized geology of the Hemlo greenstone belt. Outline of Figure 8.5 shown at east end of belt. Abbreviations: GLP = Gowan Lake Pluton; HBP = Heron Bay Pluton; CLP = Cedar Lake Pluton; MLP = Musher Lake Pluton; DLP = Dotted Lake Pluton; BP = Bremner Pluton (see text for discussion of Bremner Pluton). This structural history is similar to that developed by Zaleski et al. (1995) for the Manitouwadge greenstone belt.

granite-greenstone belt boundary, metamorphic zones, and some plutons internal to the greenstone belt. Both stages may consist of several discrete or protracted deformation events. At present, however, structures will be referred to as D_1 and D_2 structures. It is not yet known if all D_2 structures are correlative; however, they all post-date D_1 structures and display similar structural styles. Figures 8.2 and 8.3 illustrate relationships at the western end of the Heron Bay Pluton. Here, the early foliation defines trajectories subparallel to the pluton boundary (*see* Figure 8.2). The early foliation and the pluton boundary appear to be folded with a related crenulation cleavage (*see* Figure 8.2). Metamorphic zones also mimic the pluton boundary (*see* Figure 8.3), indicating that the pluton likely contributed heat to the metamorphism and crystallization of the early D_1 strong foliation. Observations at the eastern end of the pluton margin, however, indicate that country rocks adjacent to the pluton contain a D_1 foliation that is cut by granitoid material. This material is folded and contains a weak foliation parallel to D_1 foliation in the country rocks. Collectively, these observations suggest that the Heron Bay Pluton was emplaced late during D_1 and was folded along with regional metamorphic zones during D_2.

Similar observations were made in the northern portion of the greenstone belt. In the Roger Lake and Dead Otter Lake areas, the greenstone belt boundary displays a cuspate-lobate geometry. In the Roger Lake area, the greenstone belt terminates in a narrow, cuspate, synclinorial form (Milne 1968). Detailed structural observations in the Roger Lake area are similar to those from the Mussy Lake area (Jackson 1995). An early strong foliation appears to be folded and crenulated in the cuspate closure. A crenulation cleavage is roughly axial planar to the closure. This suggests that the closure is a cuspate D_2 fold. In the Dead Otter Lake area Milne (1968) mapped an antiform cored by biotite granodiorite of the Dotted Lake Pluton. In this area, the Dead Otter Lake Anticline folds a penetrative mica foliation (see foliations on map 2147 of Milne, 1968) and is also interpreted as a regional D_2 structure.

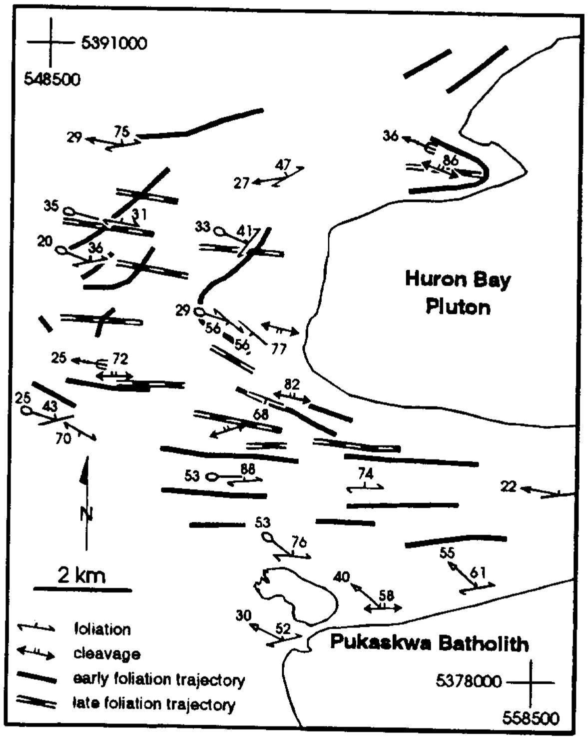

Figure 8.2. Schematic structural relationships observed west of the Heron Bay Pluton. See Figure 8.1 for linear symbols.

Lineation Patterns

Previous results indicated a general westward plunge to linear elements in the greenstone belt (Jackson 1995). Further work during 1997 indicates that while this is generally valid west of White Lake, it is not true east of White Lake (*see* Figure 8.1). East of White Lake, linear elements plunge east or southeast toward the Bremner Pluton (newly defined; see description below). However, at the eastern boundary of the Bremner Pluton, linear elements again plunge to the west. These plunge variations may be attributed either to primary variation in stretching and mineral growth orientation, or alternatively, to secondary folding.

NORTHERN GREENSTONE BELT:

North of Musher Lake Pluton

The intermediate to felsic units immediately north of the Musher Lake Pluton are difficult to interpret because of ambiguous contact relationships and non-diagnostic textures. Many of these rocks are massive feldspar-, quartz-, and quartz-feldspar porphyritic units that lack obvious bedding. Fragmental units are locally present, but their relationship to the volumetrically dominant massive units is unclear. Milne (1968) mapped this sequence of rock chiefly as metavolcanic, however, a significant proportion of it could be intrusive porphyritic rock.

The transition from the pillowed basalt sequence to the intermediate to felsic rock sequence is marked by laterally extensive units of metasedimentary and/or metavolcanic rock, including magnetite-chert iron formation and compositionally heterogeneous, thinly-bedded units.

Figure 8.4 illustrates two pseudo-stratigraphic sections from north of the Musher Lake Pluton 2.5 km apart along strike. The sections represent the transition from metabasalt of the Dead Otter Lake area into the intermediate to felsic rocks delineated by Milne (1968). Despite the lateral separation of 2.5 km, several units within the "mixed unit" at this transition (see Figure 8.4) appear correlative, and include: 1) a lower unit of laminated to thinly bedded rocks including mafic, felsic, and intermediate compositions; 2) a non-magnetic metabasite; 3) a middle unit of magnetite-chert iron formation; 4) a unit above the iron formation that includes intermediate feldspar phyric, massive, to fragmental rocks and sericite schist; and 5) an upper feldspar-porphyritic intermediate unit. Both sections also contain varying amounts of quartz-porphyry which in the eastern section appear to intrude metabasaltic units. Mapping this fall is aimed at resolving interpretation of the intermediate to felsic porphyritic units.

Petrant Lake Area

East of the Musher Lake Pluton, in the Petrant Lake area (Milne 1968), there is a succession that, from north to south, includes: 1) ultramafic and mafic volcanic? rocks; 2) quartz-phyric, muscovite-rich, fragmental rocks commonly with 1% to 5% disseminated sulphide; 3) metapelite; 4) and, interbedded metawacke and metaconglomerate. Top determinations in the metasedimentary rocks indicate the succession is southward younging, although, there is local folding and shearing. The contact between the ultramafic and quartz-phyric rocks was not observed. The contact between the quartz-phyric fragmental rocks and metapelitic rocks is gradational and interpreted to be a sedimentary contact. The quartz-phyric fragmental rocks, then, are interpreted as metavolcanic, or resedimented metavolcanic rocks. The metapelite unit is overlain conformably by wacke and conglomerate. Conglomerate clasts in this area are dominated by various intermediate, hornblende-feldspar-phyric clasts. The conglomerates also contain some magnetite-chert iron formation clasts and rare granitoid clasts. The clast population indicates a derivation from rocks similar to those exposed north of Musher Lake and in the Pinegrove Lake area. Furthermore, these observations indicate that the clastic metasedimentary rocks along the north limb area are younger than, and derived from, the metavolcanic rocks. Interestingly, mafic metavolcanic clasts were not identified. This may indicate either extremely local provenance, or, at the time of deposition, the mafic metavolcanic rocks were largely covered by an apron of intermediate to felsic rocks. Although an unconformity below the Petrant Lake sedimentary rocks has not been documented, this clastic succession bears some resemblance to sedimentary sequences mapped as "Timiskaming" elsewhere in the Superior Province.

EASTERN END OF THE HEMLO GREENSTONE BELT

Supracrustal Rocks

In general, the higher metamorphic grade and greater degree of strain at the eastern end of the Hemlo greenstone belt makes unit definition and recognition of rock protolith difficult. Nevertheless, greenstone belt units can be recog-

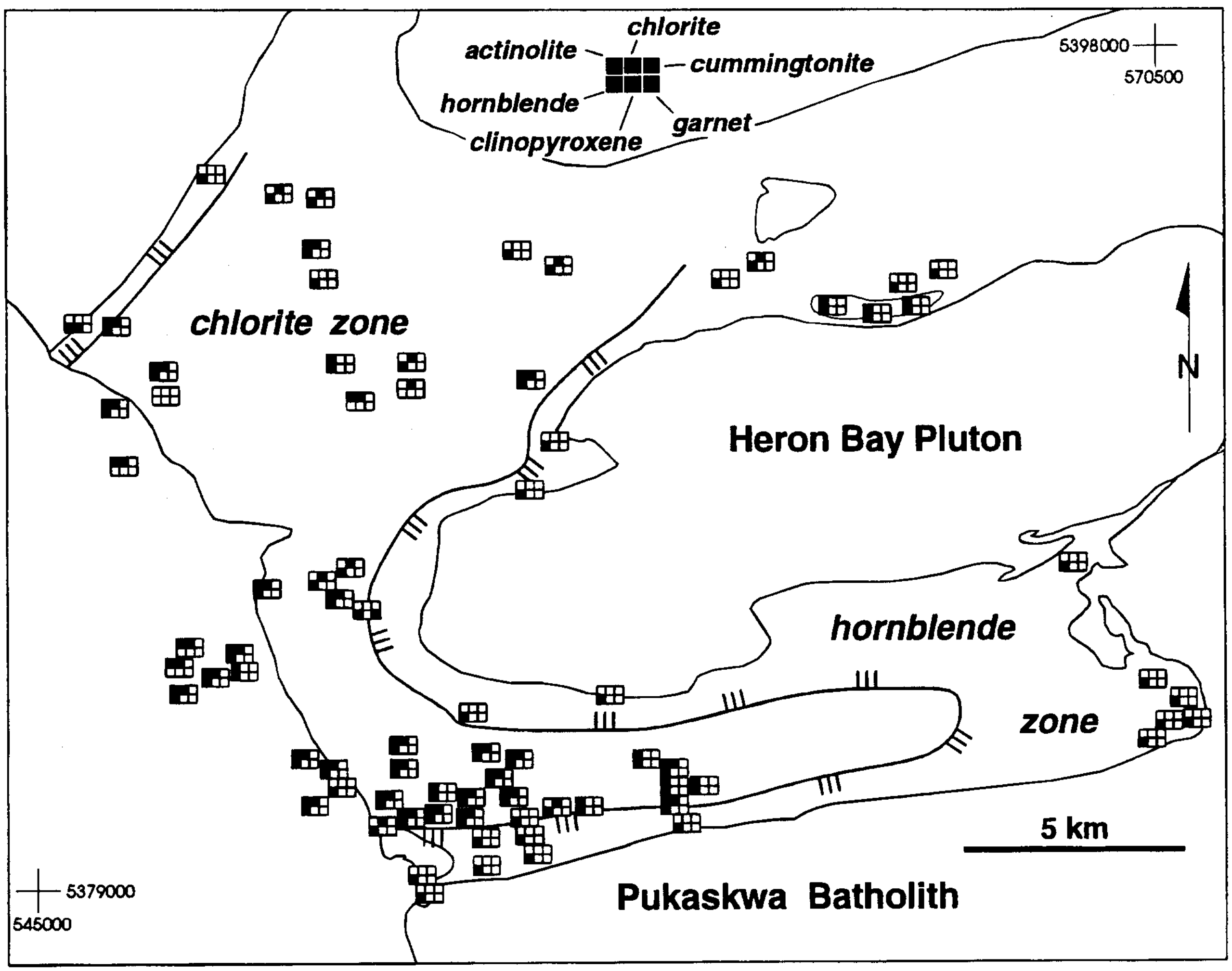

Figure 8.3. Generalized metamorphic mineral assemblages in metabasites from west of the Heron Bay Pluton. The chlorite zone is defined by the presence of chlorite and actinolite. The hornblende zone lacks prograde metamorphic chlorite and generally does not contain actinolite.

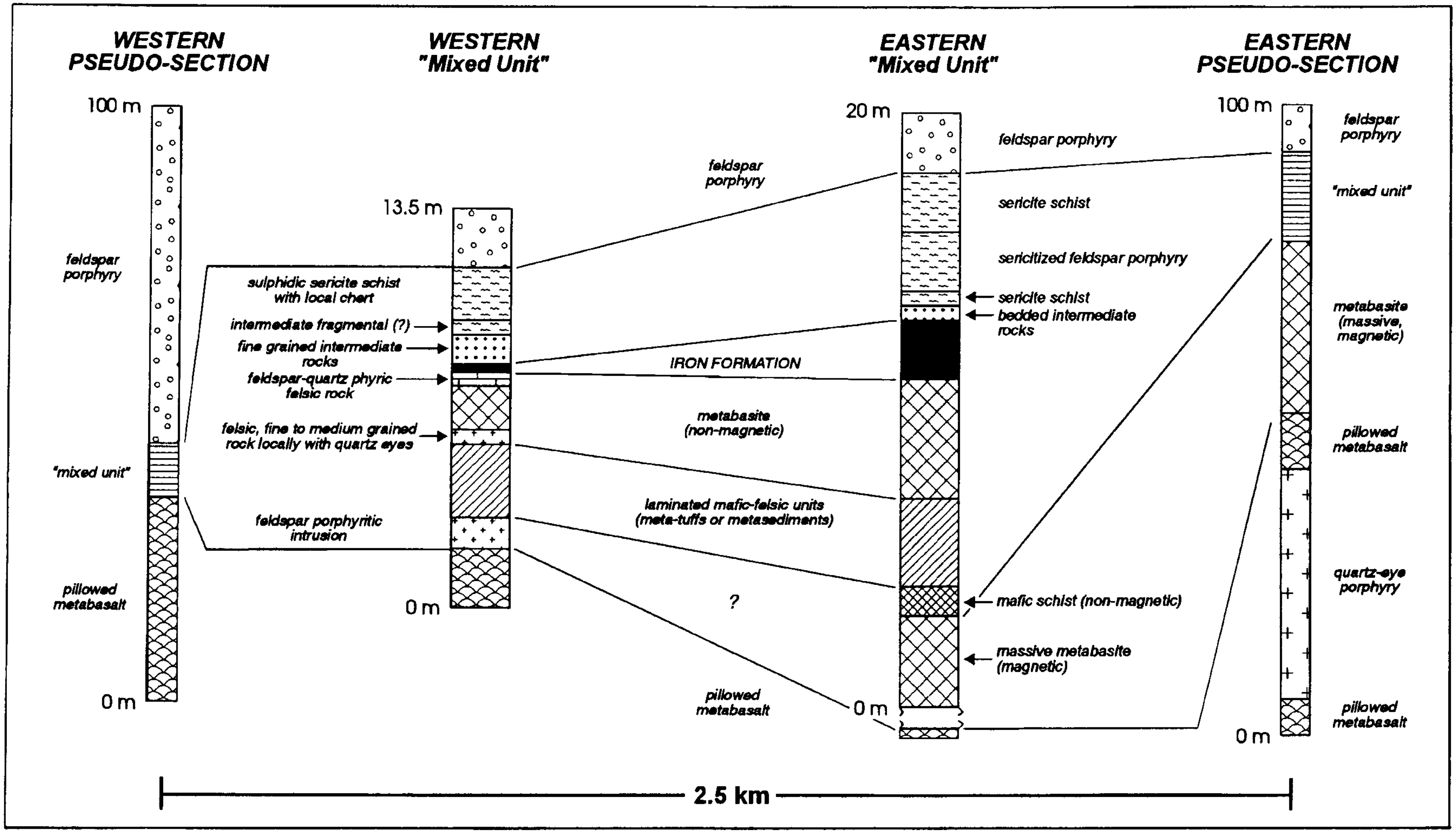

Figure 8.4. Generalized pseudo-stratigraphic sections from north of the Musher Lake Pluton at the boundary between mafic and intermediate to felsic rocks (see Milne (1968) for regional geological setting and distribution of units).

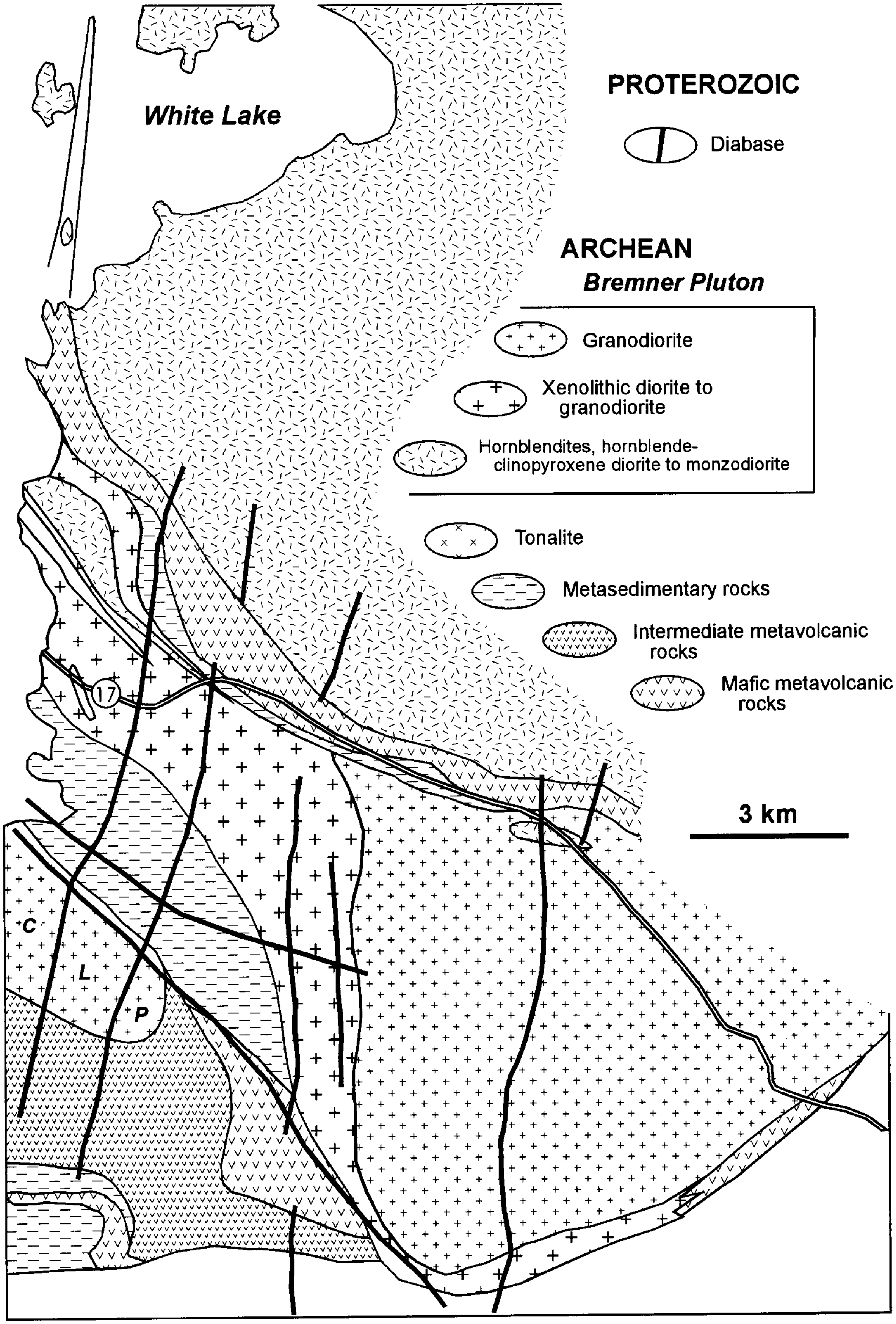

Figure 8.5. Reconnaissance geology of the eastern end of the Hemlo greenstone belt. The southwestern portion of the area is generalized after Siragusa (1984) and unpublished assessment file maps.

nized, and extended further east than previously recognized. In addition, a relatively large granodiorite-diorite-hornblendite intrusive complex was identified and is herein informally named the Bremner Pluton. This pluton is described below.

Units identified by Siragusa (1984) on the eastern shore of White Lake can be extended southeastward for over 10 km. Supracrustal units mapped at the eastern end of the greenstone belt include (Figure 8.5): 1) highly strained pillowed basalt and minor ultramafic rocks including one outcrop of spinifex-textured rock; and 2), a thin sliver of metapelite and polymictic metaconglomerate. In Figure 8.5, a narrow sliver of mafic metavolcanic rock occurs between the Bremner Pluton and the Pukaskwa Batholith. These rocks locally have highly strained pillows and are intruded by granodioritic, tonalitic and granitic to pegmatitic sheets and veins. There is insufficient mapping at present to constrain the relationship of this unit to the mafic unit extending southeast from White Lake (Figure 8.5).

Bremner Pluton

Greenstone belts in the Superior Province often have a late stage of magmatism characterized by rocks bearing some resemblance to shoshonites, sanukites and or appinites. Although a direct link to gold mineralization is not proven, rocks of this magmatic association are often, although not necessarily, spatially associated with Au mineralized greenstone belts. The Bremner Pluton at the East end of the greenstone belt displays field relationships similar to so-called sanukitoid rocks mapped elsewhere in the Superior Province (Stern et. al. 1989).

The Bremner Pluton extends southeastward from White Lake for approximately 18 km. Units of this pluton extend across White Lake (Sirgusa 1984; Milne 1968); however, further mapping and correlation is required. The pluton then is likely much larger than the outline depicted in Figures 8.1 and 8.5. Consequently, the name and geometry of this body should be regarded as preliminary and subject to change.

Three principal components comprise the pluton. The volumetrically least abundant component is megacrystic hornblendite and hornblende megacrystic diorite to monzodiorite. Locally the hornblendites display cumulate layering defined by variation in grain size and hornblende orientation. Hornblende megacrystic diorite to monzodiorite consists of 60 to 95 % hornblende 0.5 to 1 cm in diameter. Intercumulus(?) minerals (5% to 40%) include 1 to 2 mm plagioclase, clinopyroxene, potassium-feldspar, and locally quartz. The second mappable component consists of xenolithic, hornblende diorite to granodiorite. Xenoliths constitute 10% to more than 50% and consist of mafic diorite to quartz diorite. This unit is gradational into the third

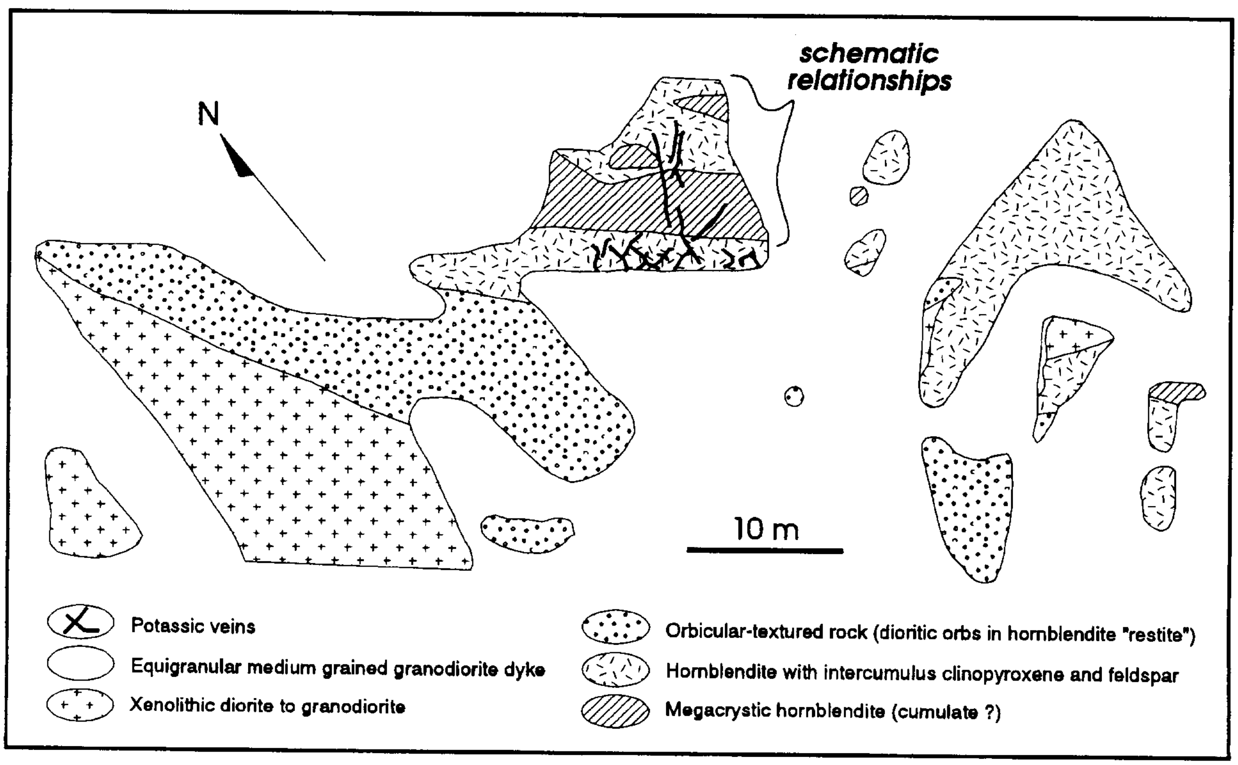

Figure 8.6. Sketch of outcrop-scale relationships of hornblendites and related rocks to granodioritic rocks of the Bremner Pluton (see text for discussion of units).

component, foliated to non-foliated hornblende granodiorite.

The hornblendite and hornblende-megacrystic diorite to monzodiorite bodies exhibit a peculiar crystallization sequence. Biotite inclusions in the cores of hornblende crystals suggest biotite preceded hornblende. Intercumulus(?) clinopyroxene would seem to indicate clinopyroxene followed hornblende. This is the opposite of Bowen's reaction series and would seem to require special fluid and/ or physical conditions of crystallization.

Several well-exposed outcrops reveal systematic temporal and spatial relationships between the various components (Figure 8.6). The oldest units are the hornblendites which are both gradational into, and intruded by, the hornblende-megacrystic clinopyroxene-bearing diorite. Adjacent to the hornblende megacrystic clinopyroxene-bearing diorite are orbicular-textured dioritic to hornblende granodiorite. These leucocratic orbs are set in a mafic hornblende matrix, or mesh. The orbicular textured rock is gradational into xenolithic diorite to granodiorite. The xenolithic component of the pluton is gradational into hornblende granodiorite which ordinarily contains fewer than 5% xenoliths. Finally, several outcrops indicate a spatial and mineralogical link to late potassic veins consisting primarily of potassium-feldspar, but also locally containing hornblende and clinopyroxene. Hornblende and clinopyroxene in these veins is not retrogressed, suggesting that the veins formed at a high temperature and may be related to late-stage fluid evolution of the pluton.

IMPLICATIONS FOR EXPLORATION

Reconnaissance mapping at the eastern end of the Hemlo greenstone belt indicates that supracrustal rocks can be extended a considerable distance east of White Lake. Further detailed mapping is required to better define map units and their potential to host mineralization.

The intermediate to felsic rocks mapped by Milne (1968) along the north limb of the greenstone belt contain a significant proportion of massive feldspar-phyric and quartz-phyric to quartz-feldspar phyric units. Locally these rocks are potassium altered, pyritiferous, and schistose. Aluminous metapelites and aluminous schists are also locally present. This rock and alteration association is, in a general way, similar to some aspects of the Hemlo gold deposit area.

Sedimentary rocks along the north limb of the Hemlo greenstone belt may be equivalent to "Timiskaming" rocks mapped elsewhere in the Superior Province. Work is underway to define the age and source material for these conglomerates and wackes.

The Brenmer Pluton bears some resemblance to rocks mapped as sanukitoids elsewhere in the Superior Province and may represent a late magmatic event in the greenstone belt capable of generating potassium-rich fluids responsible for sericite alteration. Geochemistry and age dating is underway to clarify the significance of this type of magmatism.

ACKNOWLEDGMENTS

M. Smyk (Thunder Bay Resident Geologist's Office) generously discussed numerous aspects of Hemlo greenstone belt geology and provided the author with information related to the greenstone belt. Battle Mountain Gold (Manitouwadge Office) is thanked for grid location maps, and discussions related to the geology of the northern limb of the greenstone belt.

S. Richards provided enthusiastic assistance throughout the 1997 field season.

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9. Project Unit 93–12. Kimberlites of Ontario

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INTRODUCTION

Work on kimberlites of Ontario is currently concentrated on occurrences within the James Bay Lowlands (Figure 9.1). Sampling has been completed and analytical work is in the final phase. Interpretation and report preparation will begin during the coming year. Within the James Bay region, early Jurassic kimberlites are concentrated in the area of the Attawapiskat River and Precambrian kimberlites are widely dispersed southwest, west and northwest of the younger intrusions (Figures 9.2 and 9.3).

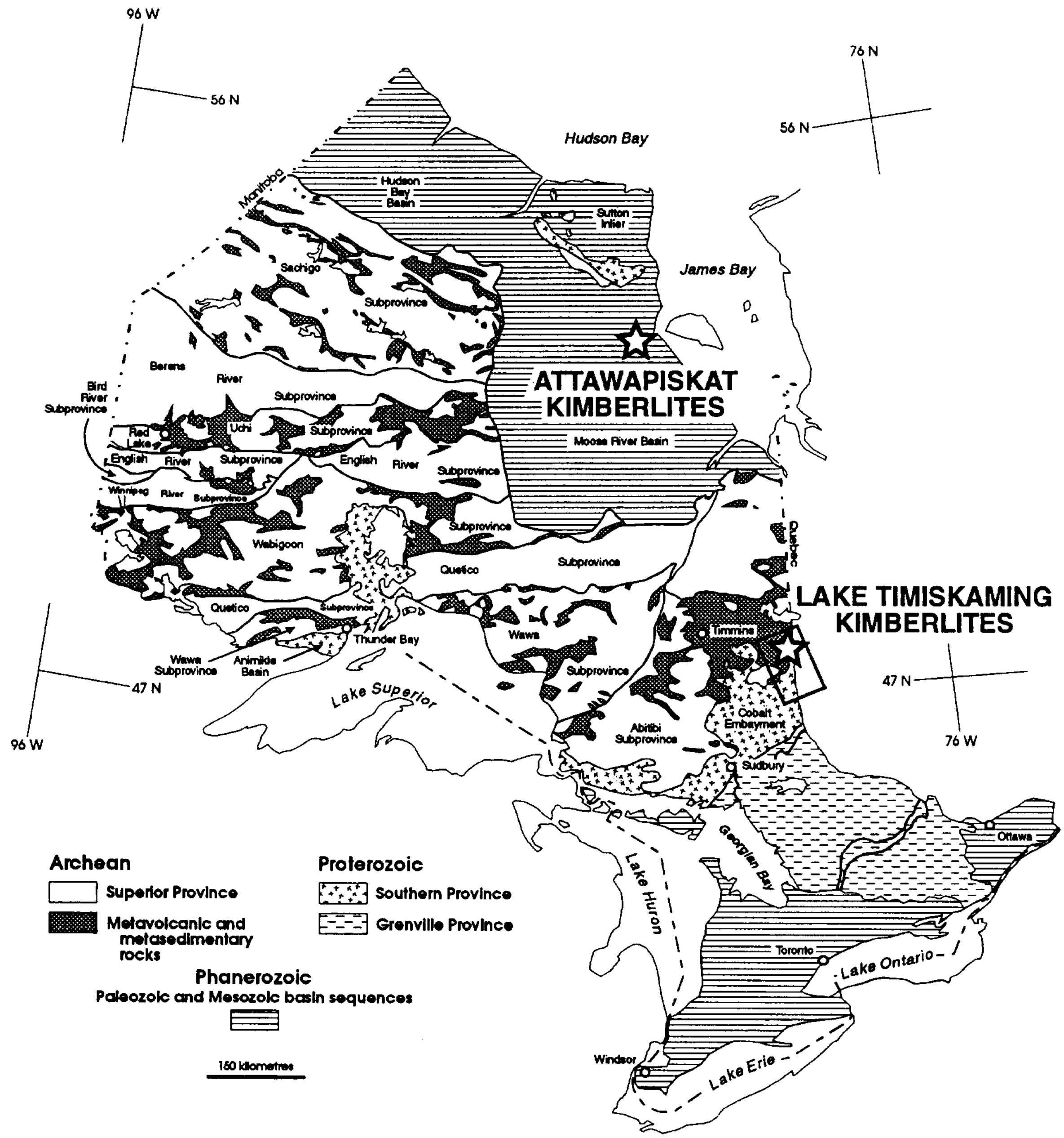


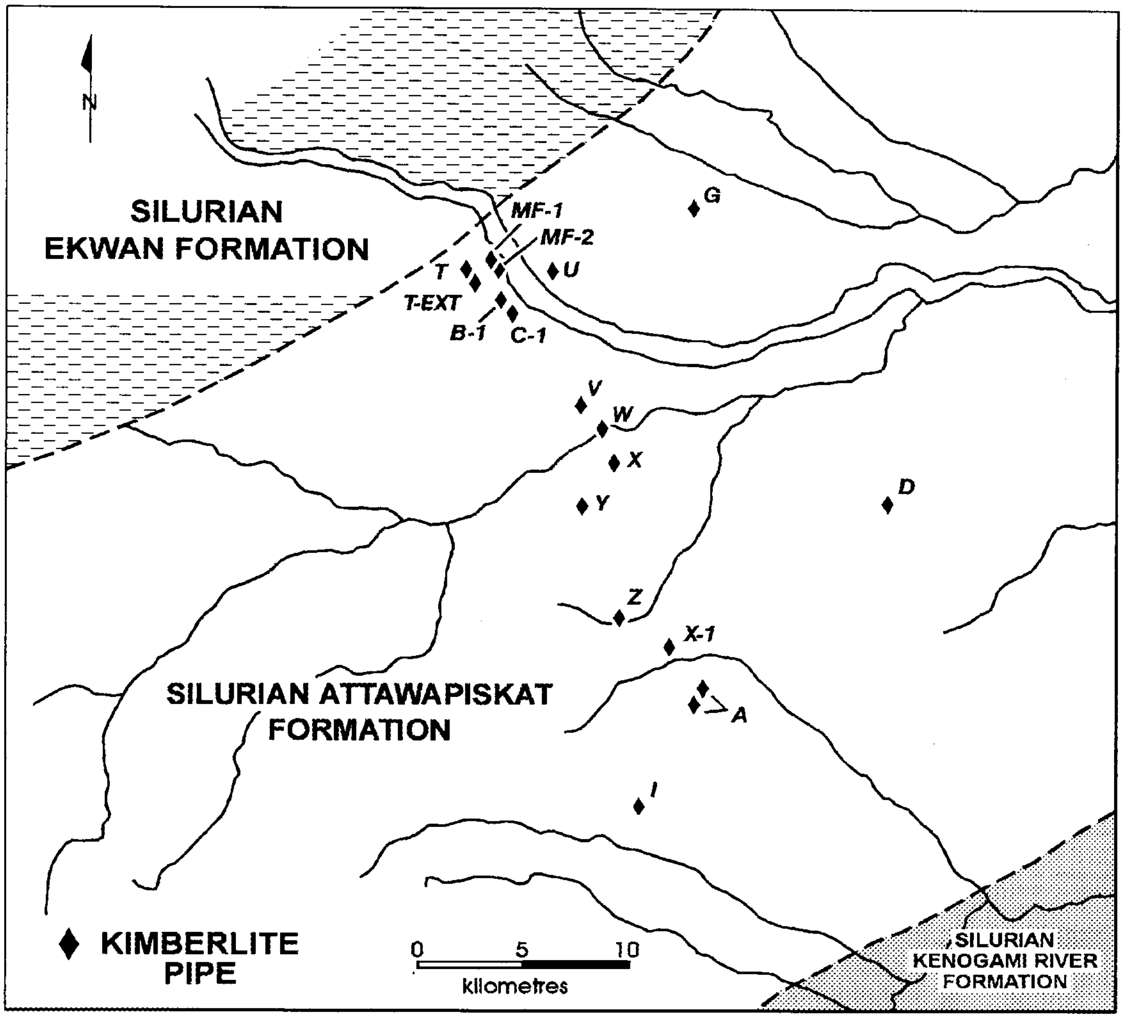
Figure 9.1. Index map showing location of kimberlite occurences within the James Bay Lowlands.

GEOCHRONOLOGY

An extensive effort has been made to date the known kimberlite pipes of the James Bay region as part of this study. An attempt has been made to isotopically date each of the known early Jurassic kimberlite pipes in the area. However, a general absence of perovskite inhibits use of the U-Pb isotopic system and extensive alteration of micas prevents use of the Rb-Sr technique. Thus, only two kimberlite pipes have proven dateable using the U-Pb method on perovskite. The MacFadyen–1 pipe yielded two isotopic ages of 177.1 ± 2.0 and 177.3 ± 1.8 Ma and Charlie–1 gave an isotopic age of 180.0 ± 1.6 Ma (L. Heaman, University of Alberta, unpublished data, 1996–1997). These isotopic ages are very close; however, it should not be assumed that undated pipes have essentially equivalent ages. Within the Lake Timiskaming Structural Zone, isotopic dating using U-Pb and Rb-Sr methods indicates that kimberlite emplacement spanned approximately 30 Ma and is later than the James Bay occurrences (Sage 1996). Therefore, it is assumed that there is a similar spread of isotopic ages for the early Jurassic Attawapiskat pipes.

Five Precambrian kimberlites have been identified to date. They are known as Kyle Lake 1 through 5. Kyle Lake 1 contains abundant mica but perovskite could not be found. A Rb-Sr isotopic age of 1100 ± 40 Ma (L. Heaman, University of Alberta, unpublished data, 1995) has been obtained on the mica. This places it within the age range of development of the midcontinent rift or tectonic activity associated with the Grenville Deformation Zone (Paces and Miller 1993; Cannon 1994). As all Kyle Lake pipes have undergone serpentinization, the age may not be an emplacement age.

Attempts to date James Bay kimberlites are continuing. Much larger bulk samples are being processed from



A	ALPHA	*G*	GULF-1	*U*	UNIFORM-1	*X-1*	X-RAY-1
	ALPHA-NORTH	*I*	INDIA	*V*	VICTOR-1	*Y*	YANKEE-1
B-1	BRAVO-1	*T*	TANGO-1	*W*	WHISKEY-1	*Z*	ZULU
C-1	CHARLIE-1	*T-EXT*	TANGO-EXTENSION	*X*	X-RAY	*MF-1*	MACFADYEN-1
D	DELTA-1					*MF-2*	MACFADYEN-2

Figure 9.2. Sketch map showing distribution of known early Jurassic kimberlite pipes near the Attawapiskat River.

four of the early Jurassic pipes and additional isotopic studies are continuing on Kyle Lake kimberlite pipes 1, 2 and 3.

STRUCTURE

The early Jurassic pipes intrude through the Paleozoic cover rocks and, even though covered by younger deposits, are essentially exposed at the surface. The Precambrian pipes are overlain by the Paleozoic rocks and are not exposed at the surface. Location and identification of both Jurassic and Precambrian pipes are accomplished by airborne and ground magnetic surveys followed by drilling.

The early Jurassic kimberlites lie in an elongated northwest-trending cluster near the Attawapiskat River, whereas the Precambrian kimberlites appear to be widely dispersed. However, the apparent absence of clustering of the Precambrian kimberlites may be a result of the difficulty associated with prospecting for them beneath the overlying younger Paleozoic rocks. The strong northwest trend to the cluster of early Jurassic pipes has been noted by Sage (1996) and most likely reflects control by bedrock structures parallel to subparallel to the trend of the Sutton Inlier and to the aeromagnetically interpreted Winisk River Fault (Riley 1979). These northwest trends are perpendicular to the Cape Henrietta Arch and to the trend of the Grenville Deformation Zone, located far to the southeast, and may have resulted from compressional forces related to their development. The early Jurassic kimberlite pipes may lie within the Winisk River Fault, a structure likely representing a zone of intense deformation and faulting within the Superior Province, separating the Winisk Subprovince to the northeast from the Sachigo Subprovince to the southwest (Riley 1979; Thurston et al. 1991; Thurston and MacFadyen 1992). The early Jurassic kimberlite cluster occurs at the intersection of the Winisk River Fault and a northeast-trending aeromagnetic feature most likely representing one or more diabase dikes with a less pronounced aeromagnetic trend than the Winisk River Fault (Ontario Geological Survey 1991). This northeast-trending aeromagnetic feature is of continental scale and can be traced from James Bay southwest to Lake Nipigon (Ontario Geological Survey 1991). The importance of crosscutting structures to larger regional trends as possible controls for kimberlite emplacement was noted by Sage (1996) for kimberlites associated with the Lake Timiskaming Structural Zone trend. In the Michipicoten area of eastern Lake Superior, olivine diabase dikes displaying northeast trends are of Proterozoic age and are likely associated with midcontinent rifting (Sage 1994).

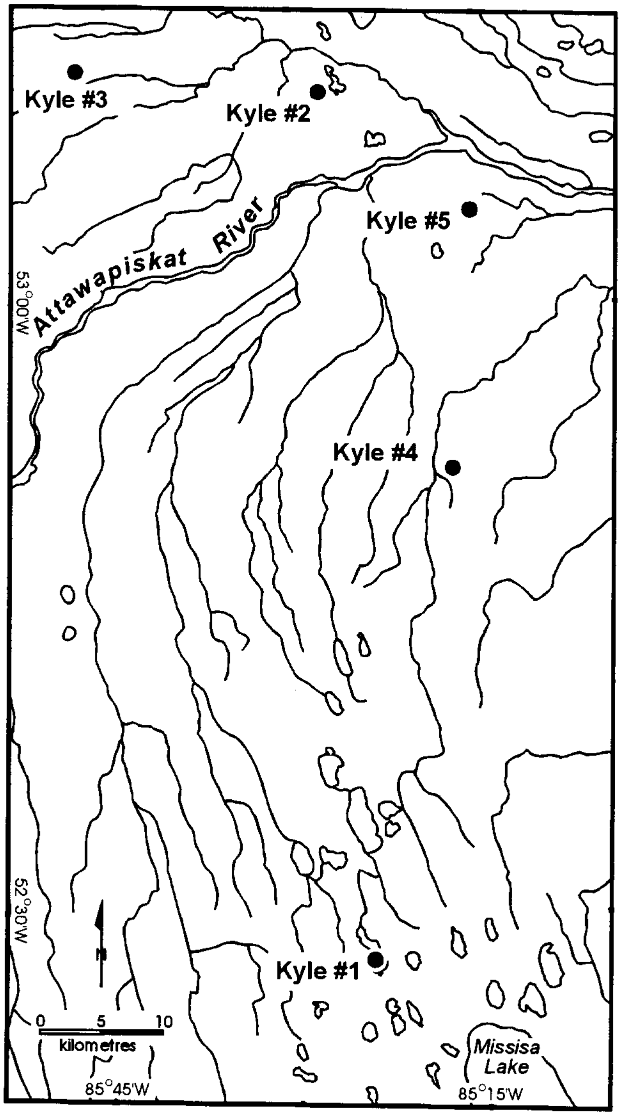


Figure 9.3. Sketch map showing distribution of known Proterozoic kimberlite pipes within the James Bay Lowlands.

GEOLOGIC OBSERVATIONS

The author has not observed samples of wall rock that host the early Jurassic pipes. KWG Resources Inc. encountered two distinct varieties of granitic rock at Kyle Lake kimberlite pipes 1, 3 and 4. One variety consists of massive, homogeneous granodiorite and the second variety consists of a gneissic-textured tonalite. Although the relationships between the two are somewhat speculative, the author considers the massive variety to represent a younger phase than the gneissic-textured variety.

Riley (1979) describes the Winisk Subprovince terrane northeast of the Winisk River Fault as consisting of porphyritic, pyroxene-bearing granitic rock of quartz monzonite composition. Southeast of the Winisk River Fault, in the Sachigo Subprovince, Riley (1979) describes the rocks as consisting of trondhjemite (tonalite) and granodiorite, with inclusions of metamorphosed volcanic and sedimentary rocks.

ECONOMIC GEOLOGY

The author is uncertain as to whether diamond has been recovered from all early Jurassic kimberlites identified by Monopros Ltd. However, KWG Resources Inc. has reported (D. MacFadyen, KWG Resources Inc., personal communication, 1996) diamond from the MacFadyen-1 pipe and the author assumes diamond is present in other pipes of similar age. Diamond is present in Kyle Lake kimberlite pipes 1 and 3. In Kyle Lake kimberlite pipe 1, diamond occurs in quantities that have warranted testing for diamond content and quality (N. Novak, KWG Resources Inc., personal communication, 1996).

Many geophysical targets remain to be identified and it is likely that many more Precambrian and early Jurassic kimberlite pipes will be found in the region. The potential for locating diamond deposits in the region is excellent.

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10. Western Superior NATMAP: Tectonic Evolution and Mineral Potential of Archean Continental and Oceanic Blocks

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INTRODUCTION

A NATMAP (National Mapping Program) project has been initiated in the western Superior Province of Ontario and Manitoba with the objective of determining the distribution and contact relationships between old (earlier than 2.8 Ga) continental, and younger (ca. 2.7 Ga) oceanic/arc crustal fragments, a key element in advancing understanding of the tectonic evolution and mineral potential of the region. In the existing tectonic framework, the linear subprovinces of the western Superior are regarded as the fundamental tectonic building blocks, accreted at ca. 2.7 Ga, but this fails to explain the widespread presence of 3.0 to 2.8 billion-year-old crust in greenstone belts of predominantly juvenile oceanic origin. This collaborative research program will integrate new 1:50 000 and existing mapping, geochemistry and geochronology in 3 key areas. In the central Wabigoon and western Uchi subprovinces, we aim to provide a tectonostratigraphic context for economic volcanogenic massive sulphide (VMS) and gold deposits, as well as regional geological control for interpretation of seismic corridors of the Western Superior LITHOPROBE transect. The same integrated approach will be extended into frontier areas to the north, where the North Caribou terrane abuts younger greenstone sequences of the Sachigo Subprovince.

The Superior Province is regarded as a global benchmark of late Archean evolution by virtue of its large extent, where the scale of ancient tectonic features can be assessed, and its well-preserved supracrustal sequences, that faithfully record its depositional environments. Recent interpretations of its tectonic development regard accretion of juvenile arc terranes at ca. 2.7 Ga as instrumental in formation of Earth's largest Archean craton and its rich mineral endowment. Keystones of these models include lithotectonic interpretation of volcanic-plutonic belts as island arc assemblages, metasedimentary belts as accretionary prisms, plutonic belts as Andean arcs, and older (2.8 to 3 Ga) cratonic blocks as microcontinental fragments. Application of plate-tectonic models to the Superior Province has had significant impact on exploration concepts, particularly in relating VMS potential to the geodynamic setting of volcanism.

The conclusion that plate tectonics operated in the late Archean has fundamental impact on the general understanding of Earth's evolution, but remains controversial. Critics point to the absence of key plate-tectonic indicators such as ophiolites, melanges and fore-arc basins, and favour a primitive style of vertical, plume-related crustal growth. Such widely divergent views can be tested by establishing relationships between the older "microcontinental" blocks, present in most subprovinces of the western Superior, and the younger sequences. In a plate-tectonic framework, the older blocks would represent rifted fragments of a protocraton that were tectonically reassembled with juvenile sequences at ca. 2.7 Ga, whereas in static interpretations, the younger sequences were deposited directly on older, pan–Superior basement. Resolution of these contrasting views will have direct impact on mineral exploration. For example, current models for generation of volcanogenic massive sulphide (VMS) deposits require oceanic settings, in particular back-arc regions, that provide an environment of sustained high heat flow and fluid circulation through metal-rich juvenile crust. Similarly, gold-bearing structures are commonly spatially associated with boundaries between crustal elements of differing age; definition of these domains may target exploration activity. It is key for both tectonic and economic reasons to inquire how and when continental (3 to 2.8 Ga) and "oceanic" (2.77 to 2.70 Ga) crustal components and their mineral endowments became incorporated into the western Superior craton.

Many opportunities exist for interagency collaboration and logistical cooperation. The Ontario Geological Survey (OGS) has several ongoing mapping projects, the Manitoba Geological Services Branch (MGSB) has initiated "Operational Superior", the Western Superior LITHOPROBE transect is establishing three-dimensional control on subprovince structure, and the Geological Survey of Canada (GSC) has a long-standing interest in the Superior Province. The NATMAP program takes advantage of the expertise and logistical opportunities provided by each of these agencies and the LITHOPROBE program to address the old/young theme in 3 different subprovinces.

Problems Under Consideration

Research topics can be grouped into first- and second-order problems based on their importance with respect to the central theme. The first-order problem concerns the nature of assembly of the western Superior Province at ca. 2.7 Ga. Current models view the North Caribou terrane as a 2.8 to

3.0 billion-year-old protocratonic nucleus onto which juvenile arc terranes were accreted from the north and south. Subprovince boundaries are viewed as fundamental sutures separating tectonic entities that were independent until final assembly at ca. 2.7 Ga. But, blocks of 3.0 to 2.8 billion-year-old crust within the Wabigoon and Uchi subprovinces have remarkably similar lithostratigraphic assemblages and ages to sequences of the North Caribou terrane, suggesting that they may be derived from a single older protocraton. Whether the southern blocks represent fragments rifted off after 2.8 Ga and reassembled at ca. 2.7 Ga, or a continuous basement to the younger sequences, is an outstanding question. Its resolution depends on identifying the extent of well-mapped and dated sequences and defining their interrelationships. Representative areas north and south of the North Caribou block have been chosen to address this question. Several mining camps of the western Superior Province are located in proximity to boundaries between older and younger sequences. The Red Lake gold camp in the Uchi subprovince and Sturgeon Lake VMS camp of the Wabigoon subprovince require re-evaluation in the context of tectonic problems and the metallogenic questions outlined above.

Second-order questions cascade from the first-order questions. For example, if the older crustal fragments are related, what insight does modern information on each of the fragments bring to the 3.0 to 2.8 billion-year history of the Superior Province? At present, the fragmentary record reveals early (3.02 to 2.93 Ga) arc activity followed closely by platformal conditions, deformation by 2870 Ma and renewed volcanism at 2840 to 2800 Ma. More information on sequences and relationships within these blocks will provide constraints on tectonic models for this period. Additional second-order questions may become viable once the first-order tectonic framework is established. A significant problem concerns controls on gold mineralization. The important Red Lake, Bissett, Musselwhite and Little Stull Lake deposits share characteristics including proximity to boundaries between crust formed before 2.8 Ga and crust formed ca. 2.7 Ga, localization in late structures, and association with Timiskaming-type sedimentary and volcanic sequences. However, the regional controls on gold mineralization in western Superior are not well understood. Improved resolution of the regional tectonostratigraphic framework will directly affect metallogenetic models for gold. Study of the younger juvenile sequences and their interrelation with older basement will also shed light on controls of massive sulphide mineralization.

Methodology

The principal method used is a team approach integrating geological mapping, geochronology and geochemical studies of supracrustal and plutonic rocks. The teams, housing a variety of expertise from the MGSB, OGS, GSC and universities, will be active in several subproject areas over the life of the project to take advantage of logistical and collaborative opportunities.

In greenstone belts, mapping will establish whether contacts between older (>2.8 Ga) and younger (ca. 2.7 Ga) sequences are conformable, unconformable or tectonic as well as the extent of these sequences, in addition to allowing comparisons of the structural geometries and chronologies of younger and older sequences. Important components of this work will be U/Pb geochronology and isotopic and trace-element geochemistry of ca. 2.7 billion-year-old felsic volcanic and sedimentary units to assess contributions from older sources, as well as examining VMS potential of rhyolites through establishing eruption temperatures. Boundaries between crust older than 2.8 billion years and ca. 2.7 billion-year-old blocks may be cryptic if invaded by young plutons. Elucidation of such relationships will require an innovative combination of mapping, geochronological and isotopic tracer studies of granitoid regions to define the extent of younger and older plutonic phases, as well as to constrain the character of older crustal input. The GSC's sensitive high resolution microprobe (SHRIMP) facility will be instrumental in detection of inherited zircons from both volcanic and plutonic units.

The program has been developed as a co-operative undertaking of the GSC, OGS and MGSB. Planning took place within each organization through consultations with in-house staff, university collaborators and industry clients, and through a three-day workshop, that focussed the theme of the program, defined key project areas, and assembled teams with appropriate expertise. Areas were chosen based on a variety of scientific and logistical criteria: 1) integration with ongoing programs; 2) presence of both older (>2.8 Ga) and younger (ca. 2.7 Ga) rock packages; 3) good exposure, adequate previous mapping and U/Pb zircon dates; 4) potential for preservation of relatively low-strain domains; 5) geographically widespread areas representative of their respective subprovinces; and 6) presence of a variety of mineral deposit types. The areas are described below:

CENTRAL WABIGOON–WESTERN WABIGOON SUBPROVINCE INTERFACE

The extent of older (>2.8 Ga) crust in the central Wabigoon subprovince is not well established, and the nature of contacts with ca. 2.7 billion-year-old sequences to the east and west is undefined. An ongoing OGS project to study the southern part of the interface will be complemented by GSC work in the Savant–Sturgeon belt to the north. The GSC and OGS projects will provide a geological framework for interpretation of the main LITHOPROBE north-south corridor, and link thematically to a project, led by the OGS, east of Lake Nipigon supporting the Beardmore–Geraldton LITHOPROBE line.

WESTERN UCHI BELT

OGS and GSC mapping programs in the Birch–Uchi–Confederation lakes area will emphasize structure, stratigraphy and gold mineralization. This area straddles the North Caribou–Uchi–English River subprovince interfaces and will allow detailed field and laboratory study of the complex relationships among 3 major tectonic entities in relatively accessible and well-exposed sequences. Results will support this western LITHOPROBE transect line.

SACHIGO–NORTH CARIBOU BOUNDARY IN THE STULL–KISTIGAN LAKES AREA

The hypothesis that the North Caribou terrane represents the continental nucleus for accretion at 2.7 Ga to the north will be tested by mapping and structural analysis in the Stull–Kistigan and Oxford lakes area. The NATMAP contribution in this region will complement MGSB field studies through additional mapping, geochronology and geochemistry of volcanic and plutonic rocks to examine their age, origin and tectonic history. Initially, this will involve a field component as well as laboratory analysis of archival material. Additional resources may be directed toward bedrock studies in northern Ontario, including targeted geochemical studies of northern greenstone belts to determine geodynamic settings.

Work Plan

Work commenced in 1997 in the central Wabigoon subprovince. M. Sanborn-Barrie and T. Skulski (GSC) worked in the central Sturgeon belt in the East Bay area, integrating new and existing data on stratigraphy, structure and mineralization; Skulski is examining the extent of crustal recycling in supracrustal assemblages through geochemical (whole rock and Sm/Nd isotopes) and geochronological means (conventional and SHRIMP U/Pb dating). J. Whalen (GSC) initiated a project to map granitoid plutons and study their petrogenesis, focussing on the extent of crustal recycling as determined by geochemistry, tracer isotopes and U/Pb geochronology. J.A. Percival (GSC) mapped a structural transect to the east, examining relationships between granitoid rocks and the Savant–Sturgeon belt on the west and the Obonga belt on the east. Mapping projects led by the OGS are underway in western Wabigoon granitoids and greenstones to the south by D. Stone (OGS), and in the central-eastern Wabigoon by G.M. Stott (OGS) and J.R. Parker (OGS). The new information from all sources for this region will be immediately useful in the interpretation of LITHOPROBE seismic-refraction (1996 acquisition) and seismic-reflection (1997 acquisition) lines which transect the central Wabigoon subprovince. In the North Caribou–Sachigo boundary region, ongoing mapping projects in adjoining areas near Stull–Kistigan lakes by D. Stone and M.T. Corkery (GSC) were augmented by the participation of J. Whalen and T. Skulski (GSC). Reconnaissance geochemistry and SHRIMP geochronology will complement the new field studies in providing age control and an assessment of crustal recycling. To the west in Manitoba, S. Lin will be mapping potentially gold-bearing structural "breaks" and their geological context. Beginning in 1997, geological and geophysical information including LITHOPROBE sections will be assembled into a GIS package by J.Harris (GSC).

Work also commenced in 1997 in the Birch–Uchi–Confederation lakes area, through projects by C. van Staal (GSC) and J. Devaney (OGS). Collaboration with LITHOPROBE in interpretation of the western seismic corridor, as well as interaction with supporting geoscience studies such as structural analysis, detrital zircon studies, sedimentology and granitoid geochemistry, will complement NATMAP activities.

In 1998, work is projected to continue in the central Wabigoon, western Uchi and North Caribou–Sachigo regions. In greenstone belts of the North Caribou block, reconnaissance geochemical studies of volcanic rocks will also be initiated. Mapping will continue in the central, eastern and western Wabigoon.

In 1999, the principal focus in the south will be on the western Uchi Subprovince. Collaborative work will continue in the central and western Wabigoon subprovince, as well as in the north, including the Stull–Kistigan and Oxford–Knee lakes belts.

In 2000, work will continue in the western Uchi belt of Ontario and Manitoba, central and western Wabigoon, and northern regions. Depending on the reconnaissance results from the north, additional problem areas may be identified as mapping targets. Preliminary assessment suggests that the Island Lake belt (Manitoba) and Sandy Lake belt (Ontario) may be areas of key importance based on the probable presence of older and younger supracrustal rocks.

In the final year of the project (2001), compilation products will be assembled, including 1:100 000 maps of the central Wabigoon, western Uchi, and Stull–Kistigan regions. Global synthesis products, incorporating the new tectonic framework for the western Superior Province, will take the form of a 1:500 000 map, produced in parallel with a volume of research papers and CD-ROM releases.

11. Project Unit 97–10. Sedimentological Studies of the Birch Lake Area, Western Uchi Subprovince

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INTRODUCTION

The Birch–Uchi Archean greenstone belt, part of the western Uchi Subprovince (Stott and Corfu 1991), is an area that contains formerly productive copper-zinc and gold mines and numerous metallic mineral occurrences (Parker and Atkinson 1992), including a significant gold-fluorite deposit (Springpole Lake; *see* Barron 1996) that is at an advanced stage of exploration.

The present study is designed to provide additional knowledge of the bedrock geology of the north-central part of the Birch–Uchi greenstone belt, specifically the Birch Lake area, which will be useful in making an improved evaluation of the region's economic mineral potential. Using the most recently published geological maps and reports concerning the Birch Lake area (Thurston et al. 1981; Thurston 1986; Good 1988; Beakhouse 1989; Beakhouse and McNeil 1989; Beakhouse et al. 1989) as a foundation, the new mapping of the approximately 400 km^2 study area consists largely of sedimentologically oriented description and interpretation of the fragmental (meta-) sedimentary and (meta-) volcanic lithofacies in the Birch Lake area, which are part of the Confederation Assemblage of Stott and Corfu (1991). This project is designed to clarify whether or not: 1) the copper-zinc ore-bearing horizon of the former South Bay Mine, located in the southwest part of the Birch–Uchi greenstone belt, might also be present in the northern, Birch Lake portion of the belt; and 2) the various conglomeratic units represent small pull-apart basins, tectonically late features with a potential for gold mineralization along any basin-bounding fault zones.

The sedimentological focus of this project is intended to complement structural studies within the same greenstone belt (by C. Van Staal, Geological Survey of Canada), which together will comprise part of a multiyear NATMAP project (Canada's National Geoscience Mapping Program) in the western Uchi Subprovince. This NATMAP project will provide a new tectono-stratigraphic analysis of the evolution of the Birch–Uchi greenstone belt and related stages of mineralization.

GENERAL GEOLOGY

The southern to central Birch Lake region examined in this study can be subdivided into four lithologically based areas (Figure 11.1): 1) a northwest area of felsic volcanic rocks bounded by deformation zones; (Beakhouse 1989); 2) a northeast area of intermediate pyroclastic rocks, related wacke and iron formation (Good 1988; Beakhouse and McNeil 1989) minor basaltic units, and two conglomeratic units; 3) a complex, south-central area predominantly composed of wacke, with numerous relatively small units (not shown) of gabbro, basalt, felsic porphyry and polymict conglomerate (for details, *see* Beakhouse et al. 1989) and 4) a southwest area of polymict conglomerate with minor finer grained subunits (not shown) and a sigmoidal lens of rhyolitic rocks.

The stratigraphy of the map area will not be well understood until structural studies reach an advanced level. However, the polymict conglomerate units (discussed below) appear to be late, probably fault- and unconformity-bounded units. For example, in the southwest part of the map area, based on clast composition (including basal beds) and map patterns, the predominantly conglomeratic sequence is interpreted to be lying on a highly faulted, partly unconformable surface atop older felsic volcanic rocks.

Two of the more economically interesting aspects of the complex and varied geology of the Birch Lake area are briefly discussed below.

NORTHERN FELSIC-INTERMEDIATE VOLCANIC ROCKS AND RELATED SEDIMENTARY ROCKS

In the central Birch Lake area, a western area with a concentration of rhyolitic rocks and related porphyries (*see* area 1 in Figure 11.1) contrasts with pyroclastic to sedimentary strata to the east (*see* area 2 in Figure 11.1). In the western area, lava facies (massive, flow banded, autobrecciated), pyroclastic rocks and associated feldspar porphyry bodies define a felsic volcanic centre (Beakhouse 1989). Deformation of the porphyritic intrusions is marked by discrete deformation zones and quartz-vein systems (brittle fracture fills), some of which are spatially related to gold mineralization (e.g., west Birch Lake: Beakhouse et al. 1989).

To the east (*see* area 2 in Figure 11.1), pyroclastic to volcaniclastic intermediate rocks consist of commonly coarse, poorly sorted, feldspar crystal tuff and coarser lapilli tuff to lapillistone (white weathering, mostly oligomict, intermediate to felsic clasts). As is the case in many greenstone belts and volcanic successions (Cas and Wright 1987; McPhie et al. 1993), the typically poorly bedded tuff to lapillistone can be interpreted as thick beds or units (beds 10 cm to tens of metres thick) deposited by pyroclastic (hot) or sedimentary (cold) mass flow processes in more volcanic source-proximal settings. In contrast with the above, the volcaniclastic units are more thinly layered, "better stratified" zones (laminae or beds 1 mm to 1 m thick) that likely represent variable degrees of sedimentary reworking, particularly via current flows, including transport to more distal settings. Rare sites with magnetite (iron formation) clasts and one outcrop with detrital magnetite and several very rusty clasts show that some erosion of exhalite horizons occurred. Adjacent sedimentary units (*see* area 2 of Figure 11.1, and a few kilometres to the east: *see* Good 1988) of thinly bedded wacke with common graded bedding and minor magnetite iron formation suggest a high degree of sedimentary reworking of volcanic to volcaniclastic source areas, such as the area presently exposed to the west, and the magnetite iron formation present in both the pyroclastic and sedimentary units suggests that exhalative chemical sedimentation may have spanned an original volcanic to sedimentary facies change. No sub-ex-

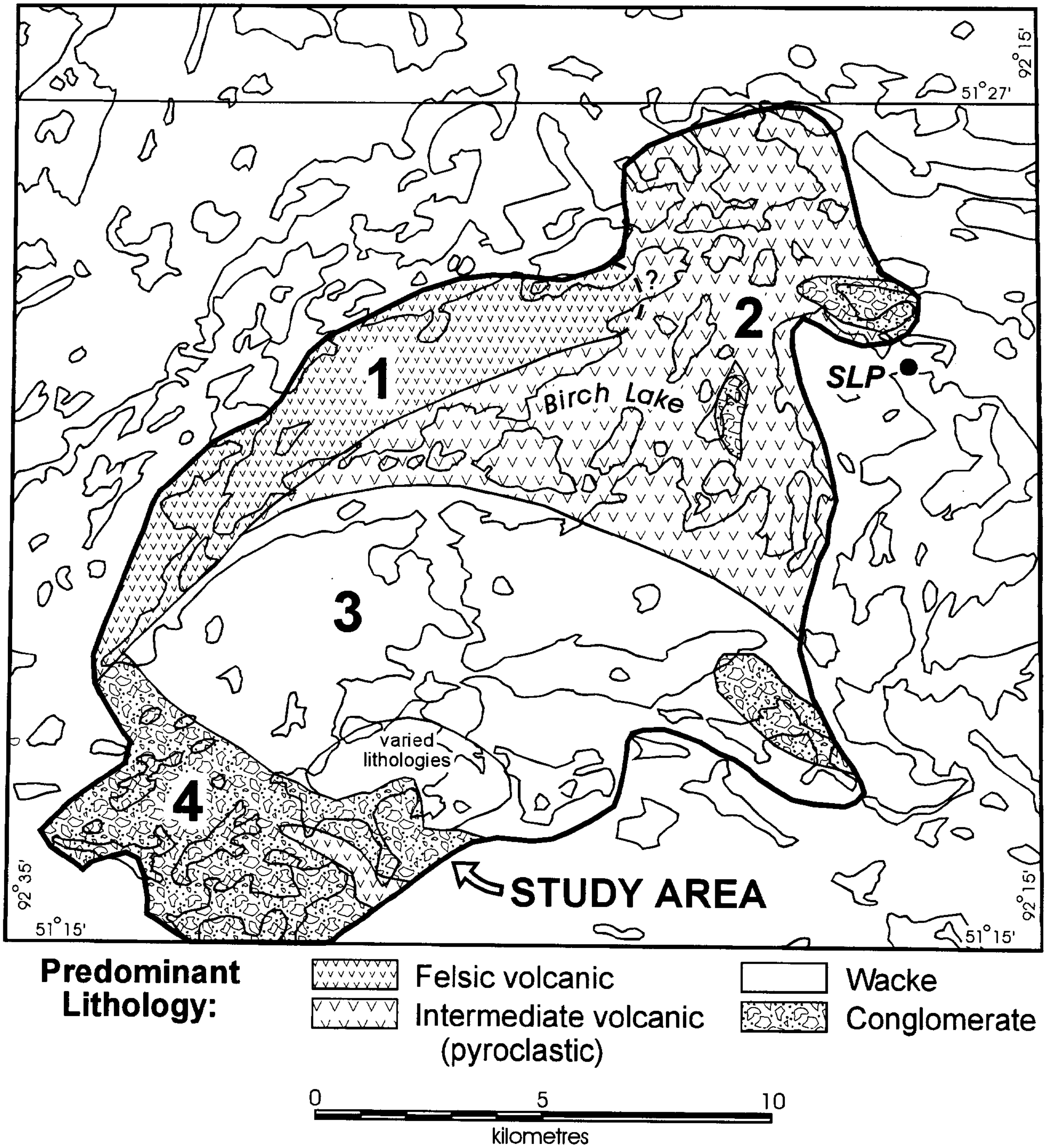

Figure 11.1. Simplified lithological map showing four studied areas composed predominantly of: 1) felsic volcanic rocks; 2) intermediate pyroclastic to sedimentary rocks; 3) wacke ("varied lithologies" subarea consists of gabbro, felsic porphyry, felsic tephra and flows, and polymict conglomerate) and 4) polymict conglomerate; see text for details. SLP = Springpole Lake gold prospect.

halite (footwall) alteration zones have been recognized in the map area. No epithermal breccia dikes and pipes, which are thought by Barron (1996) to be present at the Springpole Lake prospect beyond the east margin of the map area, were identified in the present study.

POLYMICT CONGLOMERATE UNITS AND RELATED FACIES

Tectonized stratigraphic units of clast-supported polymict conglomerate (*see* Figure 11.1; Good 1988; Beakhouse et al. 1989) are very coarse (cobbles common, few boulders), with minor thin sandstone interbeds (rare cross-beds, ripples) and features such as fining-up sequences (metres thick) and rare small channels, and are likely proximal braided river deposits (e.g., criteria of Hein 1984; Nemec and Steel 1984). Locally, a subfacies of fine pebble conglomerate with better sorted clast frameworks and well-rounded clasts suggests deposition in more distal fluvial, lacustrine or shallow marine environments. Within the predominantly conglomeratic units, thick horizons (tens of metres or more) of sandstone-mudstone, interpreted as lacustrine or marine deposits, probably record episodes of transgression (e.g., transition of conglomerate to mudstone or wacke-siltstone via submergence) and progradation (e.g., coarsening- and thickening-upward sequences tens of metres thick) in the most distal parts of the former (sub-) basins. Small areas or basins filled with fan-delta or braid delta successions can contain such a range of proximal to distal facies and prograded and retrograded intervals (Ethridge and Wescott 1984; McPherson et al. 1987; for Archean examples, *see* Nocita and Lowe 1990; Mueller et al. 1991).

The composition of the clasts in the polymict conglomerate beds is a very felsic suite of predominantly felsic volcanic and feldspar porphyry clasts and lesser amounts of quartz, chert and magnetite (iron formation) and very rare gabbroic clasts. Granitoid and basalt clasts are very rare to locally absent. This clast provenance reflects derivation from highly local sources, from within the Birch–Uchi greenstone belt (e.g., in the Birch Lake area, rhyolite and felsic porphyry units are presently adjacent to some of the conglomeratic units), with little input from the presently belt-marginal areas of older granitoids and basalt.

The variation over small areas (kilometre scale) from proximal fluvial to distal aquabasinal (lacustrine/marine) lithofacies units, the local provenance of the clasts and the limited strike extent (mostly only kilometres long) of the conglomeratic stratigraphic units suggest deposition in a series of late orogenic, small transtensional pull-apart basins. Linear, strike-parallel units of (meta-) gabbroic rocks (in the South Bay area; *see* Beakhouse et al. 1989) may represent mafic intrusions along syntectonic, transtensional megafractures, but this hypothesis requires further detailed study. Atkinson and Storey (1997) proposed a volcanic vent complex and caldera-infilling sediment hypothesis to account for the geology of the most southern exposures of conglomerate and rhyolite, but the sedimentological and volcanological observations made during the present study do not support their hypothesis. Finer resolution of the late-stage tectonic and sedimentary events must await a more advanced level of structural analysis of the northern Birch–Uchi greenstone belt.

Pull-apart basins are bounded by fault zones, and because such a setting is becoming increasingly recognized as a good gold exploration target, the poorly exposed margins of the conglomeratic units and the deformation zones in the vicinity should be further investigated for their gold potential (e.g., late quartz veins in regional strike-slip zones).

ACKNOWLEDGMENTS

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12. Project Unit 95–13. Geology and Mineralization of the O'Sullivan Lake area, Onaman–Tashota Greenstone Belt, East Wabigoon Subprovince

G.M. Stott and J.R. Parker

Ontario Geological Survey, Precambrian Geoscience Section

INTRODUCTION

The O'Sullivan Lake map area (NTS 42L6/NE, 42L7/NW, 42L10SW) occupies the northeast part of the Onaman–Tashota greenstone belt in eastern Wabigoon Subprovince (Figure 12.1) and is about 390 km^2 in size. The area is bounded to the north by the English River Subprovince, a metasedimentary migmatite terrane, and to the south by the Esnagami pluton (*see* Figure 12.1). A six-week reconnaissance survey of the bedrock geology of the O'Sullivan Lake area (Figure 12.2) was made at 1:20 000 scale, as part of a multi-year mapping program covering a cross-section through the Onaman–Tashota greenstone belt. The map area is located 30 to 40 km north-northwest of Nakina on the CN Railroad line. Boat access to O'Sullivan Lake is available at a public boat launch on the Kawashkagama River. The south part of the belt can be accessed from the Maun Road, a logging road extending eastwards from the Anaconda Road, which is an unpaved northward extension of Highway 643. A substantial glacial moraine underlies the Anaconda Road and separates the O'Sullivan Lake area from the rest of the Onaman–Tashota greenstone belt. Extensive glacial sand deposits cover the northeast part of the map area, particularly northeast of Muriel Lake.

Significant findings from the present survey are as follows:

1. The greenstone belt contains a much more substantial volume of intrusive rocks than previously recognized. Intrusive rocks consist of tabular sheets of gabbro and felsic porphyry dikes and sills. The south part of the belt contains the largest volume of intrusive rocks dominantly consisting of gabbro sills.
2. Almost all of the gabbro, the felsic porphyry and fine-grained felsic dikes and sills are interpreted to be late tectonic and comagmatic with the Esnagami pluton. Shear zones related to the pluton show south-side-up sense of shear. The structural effect of this pluton is limited, since it does not appear to produce significant strain in the adjacent greenstone belt.
3. Most of the shear zones, gold and sulphide mineralization, and associated alteration correspond to the regional scale deformation which we relate to microplate-collision that affected the English River and northernmost Wabigoon subprovinces. This structural domain extends south for about 10 km from the north margin of the Wabigoon Subprovince. Shear zones within this domain commonly show north-side-up sense of shear. A zone of more intense deformation along the northern part of the belt is narrow, up to 300 m wide, and displays oblique right-handed and north-side-up sense of shear. The authors have observed this style of deformation near other greenstone-subprovince boundaries: in the north half of the Shebandowan greenstone belt west of Thunder Bay; in the Detour Lake area of the northern Abitibi belt; and in the Lake of the Woods area of the western Wabigoon Subprovince.
4. A post-collision pluton of hornblende quartz diorite-syenite-granite straddles the English River Subprovince boundary near Sheff Lake. This suturing pluton will provide a minimum age for the tectonized boundary between the greenstone belt and the English River metasedimentary terrane.
5. An electromagnetic conductor traced along the south part of the belt is a narrow 1 to 10 m unit of sulphidized mafic metavolcanic flows. It is locally associated with thin units of intermediate tuff, lapilli tuff, argillite, limestone, iron formation and chert.

GENERAL GEOLOGY

Our mapping of the O'Sullivan Lake area confirms the general observations of previous government surveys by Kindle (1932), Moorhouse (1955) and Inasi (1981). Detailed geological maps produced by exploration companies are available from the assessment files (Resident Geologist's office, Thunder Bay) for areas around Sheff Lake and Muriel Lake.

Most of the greenstone belt consists of pillowed to massive tholeiitic basaltic flows with minor, narrow units of pillow breccia and hyaloclastite. Pillows are typically large with thick selvages. Vesicle fillings and amygdules are commonly absent in the mafic flows which is generally indicative of deep water deposition. Interflow metasedimentary rocks are absent at O'Sullivan Lake but increase in abundance in the vicinity of Rodin, Casper and Muriel lakes. Narrow, discontinuous, east-striking units (less than 10 m thick) of intercalated limestone, chert, argillite, iron formation, intermediate to felsic tuff and heterolithic lapilli tuff are interlayered with pillowed and massive mafic flows.

A relatively thin unit of intercalated dacitic to rhyolitic tuff, lapilli tuff, tuff breccia and pyroclastic breccia is located along the north margin of the belt. This pyroclastic unit has been traced east from the west side of O'Sullivan

Lake (where it is buried beneath a glacial moraine) to south east of Superb Lake and east of Sheff Lake (*see* Figure 12.2). It may continue along the north margin of the belt, northeast of Muriel Lake, but this part of the belt is also overlain by glacial sand. The tuff is typically composed of beds of moderately contrasting composition, with some hornblende-garnet-rich lenses, possibly derived from synvolcanic iron-enrichment alteration of some layers. Primary bedding and transposed bedding are evident from subtle contrasts in composition and the stratabound presence of lithic clasts and feldspar grains. Tuff breccia units at Sheff and Elka lakes are poorly sorted and heterolithic, reflecting a mix of source material, perhaps as debris flow. The pyroclastic unit may correlate with the thick, folded tuffaceous pile at Marshall Lake, 32 km west of O'Sullivan Lake.

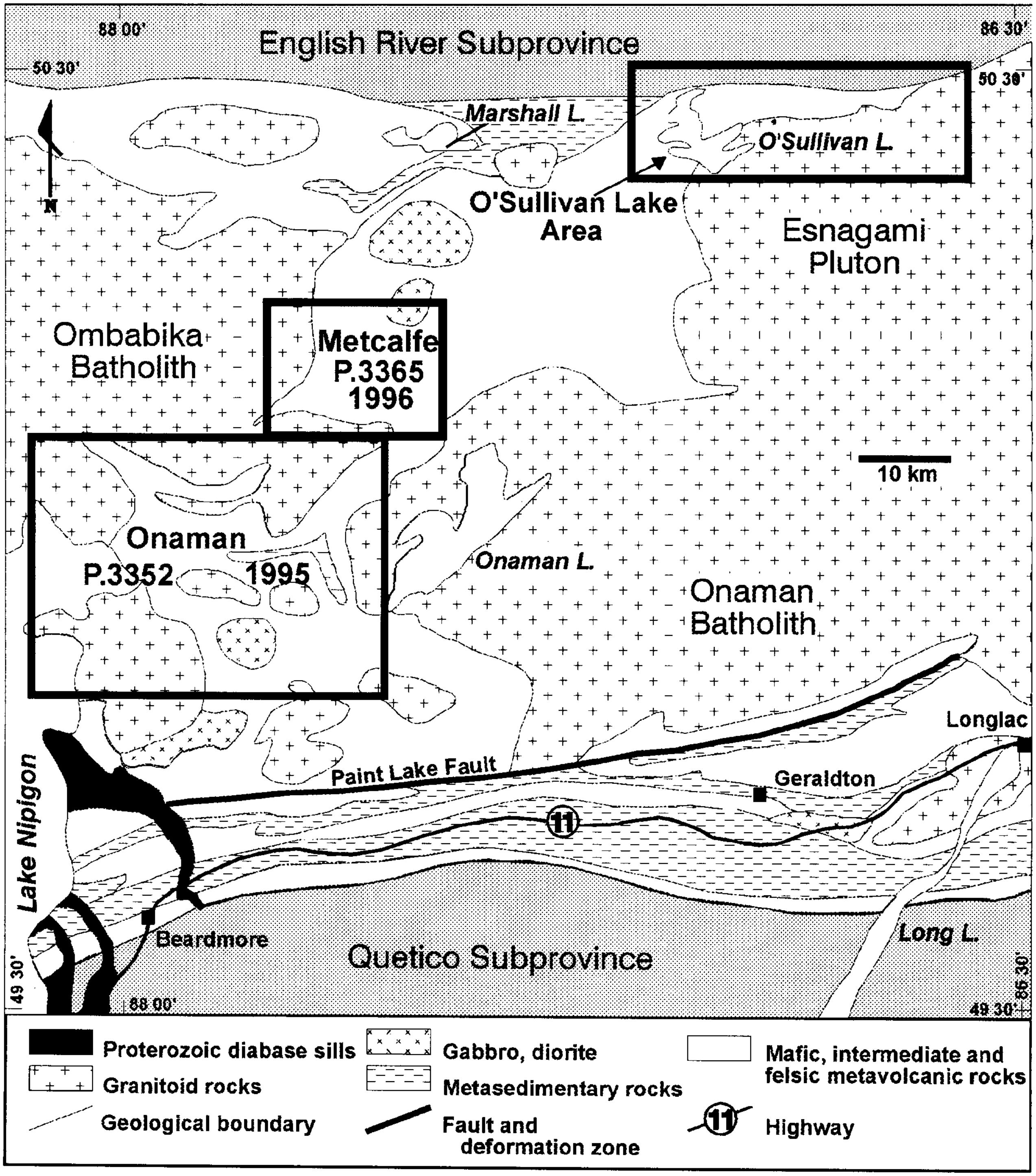

Figure 12.1. Location of the O'Sullivan Lake map area in the Onaman–Tashota greenstone belt, East Wabigoon Subprovince. Previously completed map areas, with their preliminary map numbers, are also outlined.

The pyroclastic unit is in sharp parallel contact with typical metasedimentary wackes and pelites of the English River Subprovince. Both the tuffaceous and metasedimentary rocks are highly strained and locally display mylonite fabrics. The English River metasedimentary rocks are composed of thickly bedded feldspathic wacke with some biotite-rich pelitic layers. The metasedimentary rocks are intruded by weakly foliated peraluminous granitoid rocks or diatexite. The peraluminous granitoids have a distinctive chalky white weathered surface with medium to coarse grain size and numerous patchy pegmatoid phases. A large granitoid body, situated between Maytham and Queenston lakes (*see* Figure 12.2) contains abundant coarse muscovite, pink to lilac garnets and small enclaves (less than 1 m) of metasedimentary rock.

The Esnagami pluton (*see* Figure 12.2) south of the belt, is a homogeneous body of quartz porphyritic tonalite that appears to be a large crescent-shaped intrusion between the greenstone belt and an older tonalite gneiss terrane to the south (Stott 1984). It contains hornblende ± biotite near its northwest margin on O'Sullivan Lake but contains only biotite in most of the intrusion. Fine-grained biotite commonly forms aggregates that resemble pseudomorphic relicts of hornblende, which might reflect auto-metamorphic processes. The pluton typically contains no pegmatite or other granitic dikes but does contain abundant joints and late extension fractures that are sealed with white quartz. This pluton is accompanied by a petrographically identical stock on Hurd Lake, northeast of O'Sullivan Lake, and thick sill-like intrusions southeast of Superb Lake and northwest of Northeast Arm on O'Sullivan Lake (*see* Figure 12.2).

These intrusions are accompanied by apparently comagmatic gabbro and felsic porphyry dikes and very fine-grained felsite dikes. The porphyry and felsite dikes generally transect the gabbro. Some of the felsite dikes may be misidentified as rhyolite, particularly where they intrude parallel to basaltic flows, for example south of Muriel Lake, but their intrusive character is generally evident. Gabbro within the Esnagami pluton occurs as inclusions, as foliation-parallel thick sheets, as folded dikes and as later, straight dikes with chill margins against the tonalite. The Esnagami pluton and associated intrusions are late tectonic and are similar to the quartz porphyritic tonalite and accompanying gabbro of the Onaman pluton (Stott and Morrison 1995); and similar to the Jackson pluton and associated Dyer–Oboshkegan gabbro at Metcalfe Lake (Stott and Parker 1996). The only contrast with these pre-

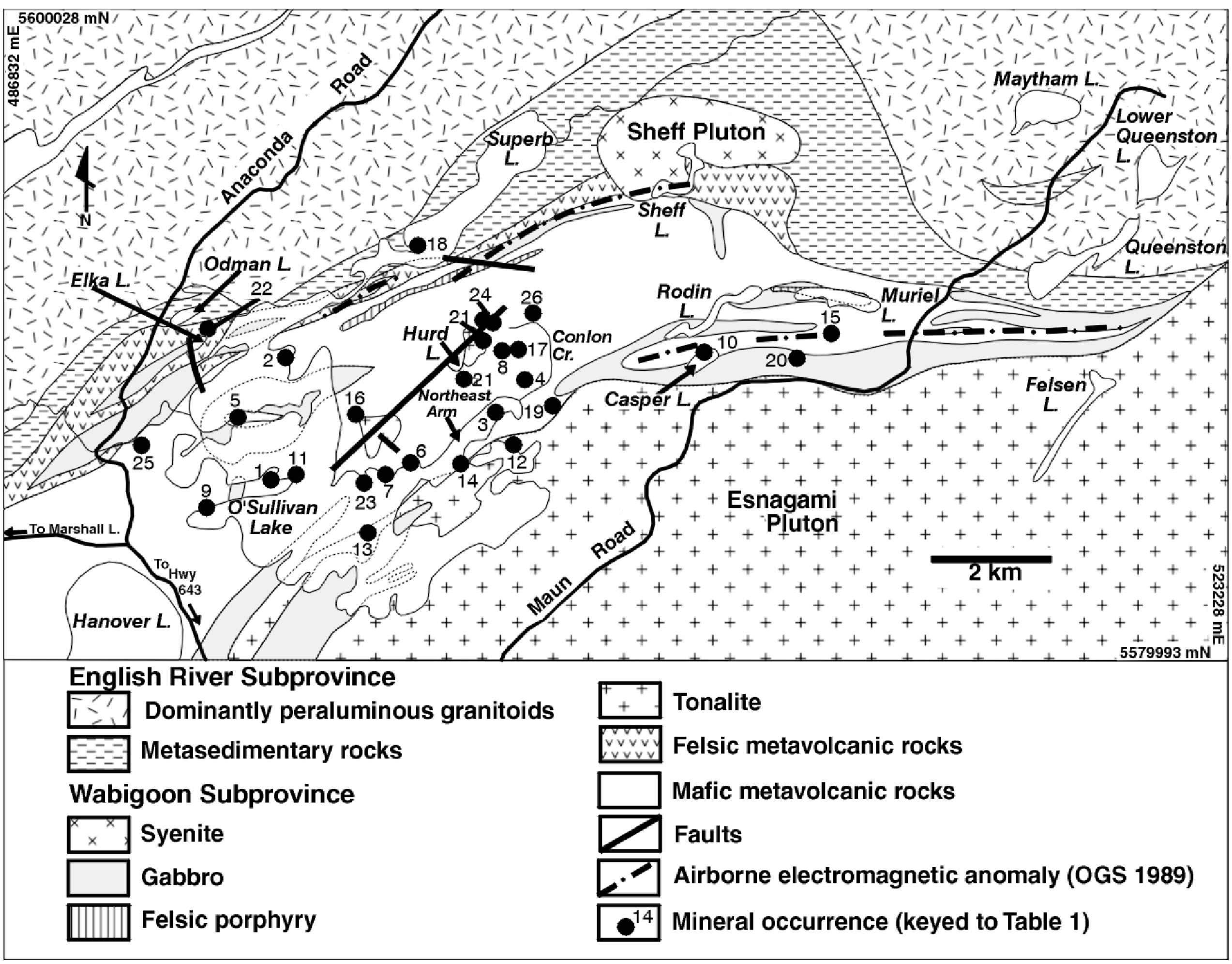

Figure 12.2. General Geology and location of mineral occurrences in the O'Sullivan Lake area. Location numbers for the occurrences correspond to the list of occurrences Table 12.1.

vious areas is that the Esnagami pluton, gabbro and porphyry dikes predate a subsequent period of deformation recorded across the map area and restricted to the northern 10 to 15 km margin of the subprovince.

A late tectonic pluton at Sheff Lake overlaps the boundary with the English River Subprovince (*see* Figure 12.2). This intrusion is cored by potassium feldspar megacrystic granite with an outer phase that ranges from brick-red hornblende syenite to quartz monzonite. It deflects the adjacent volcanic strata on its west and east margins.

STRUCTURAL GEOLOGY

The structural geology (Figure 12.3) of the O'Sullivan Lake belt is characterized by a folded sequence of pillowed basalts. The basaltic rocks are well preserved in the southern half of the belt, with good stratigraphic top indicators generally facing north. Regional scale reversals in pillow top directions are observed on the lake and in sections of the belt further east. Two reversals of stratigraphic facing reflect the presence of axial traces of major fold repetitions of the pillowed basaltic flows. Flattening strain increases

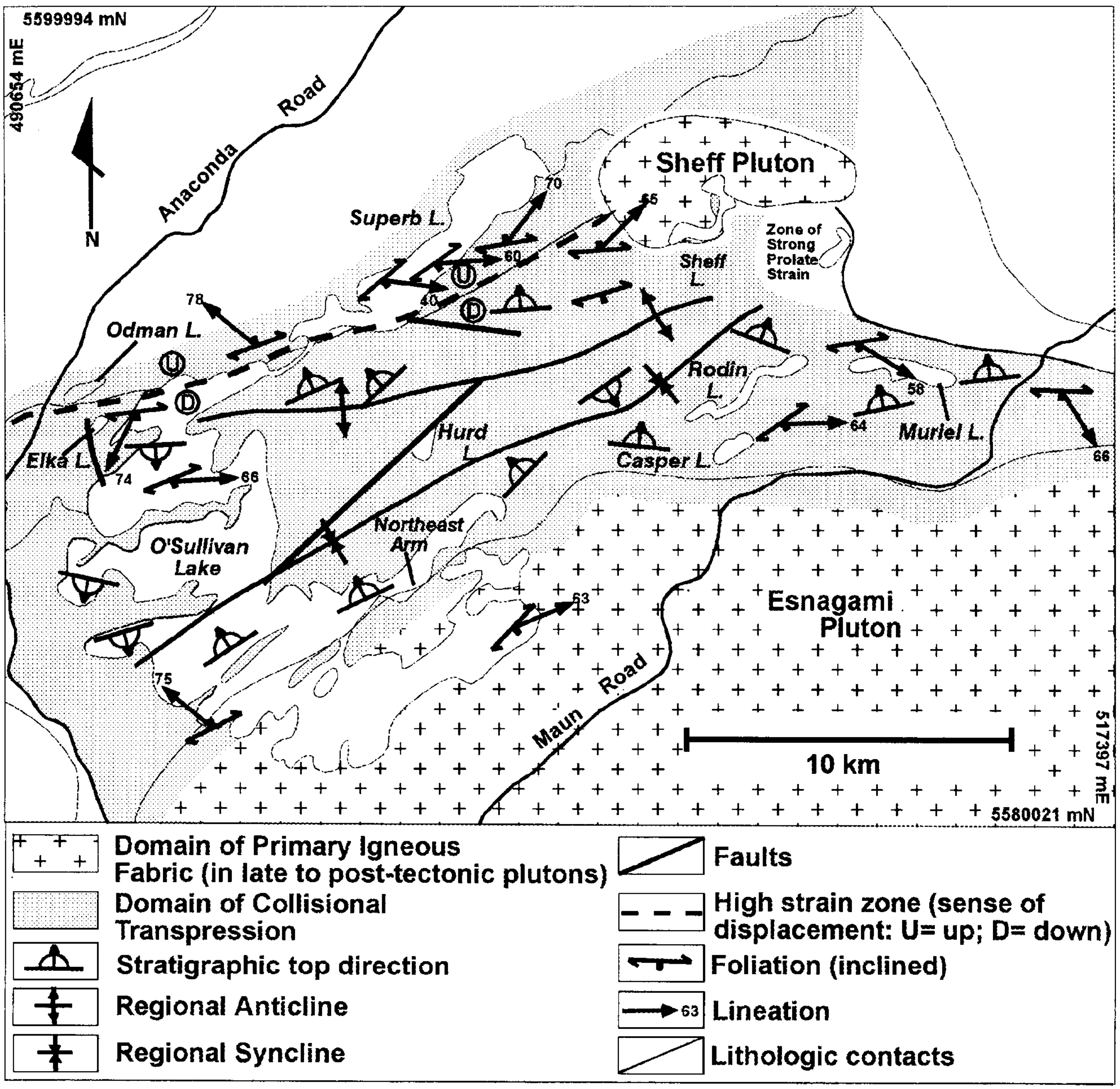

Figure 12.3. Structural geology of the O'Sullivan Lake area.

close to the Esnagami pluton but the contact strain aureole produced by the pluton is limited. Very few high strain zones close to the pluton show south-side-up sense of shear that would typically occur in a strain aureole in the adjacent host rocks during emplacement of the pluton. Instead, most high strain zones, including some within the margin of the pluton, show north-side-up shear sense, produced after the emplacement of the Esnagami pluton and arising from regional northward tectonic uplift. In the northern half of the belt, the rocks are more deformed and show some rotation of pillows consistent with flexural slip of volcanic strata. Deformation is most pronounced along the northern edge of O'Sullivan Lake and along Superb Lake, notably illustrated by the high strain recorded in the pyroclastic unit. The tuff beds are highly attenuated and discontinuous with transposed layers only a few centimetres thick. Some of the discontinuous thin beds resemble small disk-like bombs.

Gabbro locally displays areas of undeformed ophitic texture that grades to a more common, weak to moderate penetrative mineral foliation. In addition, narrow, straight to anastomosing shear zones become more prevalent towards the northern part of the belt. In the east part of the belt, southwest of Queenston Lake, the north margin of the belt is marked by a highly strained gabbro intruded by sheets of fine-grained felsite dikes parallel to the foliation.

Shear zones across the map area generally show north-side-up sense of shear consistent with the fabric observed along the sheared boundary with the English River Subprovince. Shear zones and strong flattening of basaltic pillows are more prevalent in the northernmost part of O'Sullivan Lake compared to the rest of the belt. This is consistent with the authors' observations along similar subprovince boundaries such as the northern margins of both the western Wabigoon Subprovince and the Shebandowan belt in the western Wawa Subprovince. Shear sense indicators are reliably identified across the entire width of the belt and most commonly include oblique foliations, shear bands and rotated clasts.

Overall, the dominant style of deformation consists of buckle folding of pillowed basalt, with weak penetrative strain and narrow high strain zones in the south part of the belt, and stronger penetrative strain and more abundant high strain zones in the north part of the belt. With few exceptions (close to the Esnagami pluton) virtually all high-strain zones show evidence of north-side-up sense of shear, consistent with northward tectonic uplift as a consequence of regional-scale, orogenic collision between superterranes (subprovinces).

METAMORPHISM AND ALTERATION

In general, metamorphic grade within the map area increases from greenschist to amphibolite grade from O'Sullivan Lake in the west to Muriel Lake in the east where the greenstone belt narrows and pinches out (*see* Figure 12.2). Amphibolite grade rocks are also located in the thermal contact aureoles of stocks and plutons and at the subprovince boundaries. Most amphibolite grade rocks are recrystallized, granoblastic and consist of relatively unaltered prograde mineral assemblages except where they are sheared and deformed with variable retrograde alteration to actinolite, chlorite, carbonate and sericite. Prograde metamorphic mineral assemblages along the margin of the Esnagami pluton, at O'Sullivan Lake, are commonly retrograded to chlorite-carbonate due to strong deformation that postdates peak metamorphism. Further east, on Rodin Lake and south of Muriel Lake, thin interflow units of amphibolitized tuff and lapilli tuff contain porphyroblastic metamorphic minerals such as garnet, andalusite and minor staurolite. Wacke and pelitic metasedimentary rocks of the English River Subprovince contain almandine garnet or more commonly, retrograded andalusite, cordierite and staurolite.

Variably pervasive calcite carbonate alteration is common in mafic metavolcanic rocks throughout O'Sullivan Lake. Calcite also occurs in interpillow spaces and along pillow selvages with quartz and along late fractures and shear zones in metavolcanic rocks and gabbro. Iron carbonate alteration is associated with gold and sulphide mineralization and occurs as iron carbonate flooding in sheared mafic metavolcanic rocks; as discontinuous shear-parallel veins; or as thick, 1 to 5 m wide, north-striking extension veins. The majority of iron carbonate alteration is distributed along the margin of the Esnagami pluton at O'Sullivan Lake and in shear zones adjacent to porphyritic felsic dikes. Abundant iron carbonate occurs locally along the north shore of Northeast Arm on O'Sullivan Lake.

Chlorite alteration occurs on foliation planes in sheared and carbonatized mafic metavolcanic rocks and gabbro and in alteration haloes adjacent to quartz and quartz-chlorite veins. Sericite is common in sheared felsic intrusive rocks, felsic metavolcanic rocks and chert.

Albite-epidote alteration is common in metavolcanic rocks and late gabbro intrusions adjacent to the Esnagami pluton and is locally pervasive. This alteration also occurs in large pods and patches; along pillow selvages; and along late fractures and joints. An unusual albite breccia was observed at Casper and Muriel lakes where angular fragments of mafic metavolcanic rocks are embedded in an albite matrix. Some albite and epidote in the pillowed basaltic flows may be due to synvolcanic seawater alteration; however, it's difficult to distinguish between synvolcanic alteration and late alteration associated with the Esnagami pluton.

Strong potassium feldspar alteration was observed in felsic metavolcanic rocks adjacent to the composite, syenitic pluton at Sheff Lake. Potassium feldspar alteration occurs pervasively throughout the rocks and in late fractures with epidote.

Synvolcanic iron enrichment of coarse pyroclastic rocks was observed at Elka and Sheff lakes. The alteration has been metamorphosed to a prograde assemblage of fine- to medium-grained, dark green to black hornblende ± pink garnet porphyroblasts ± magnetite in amphibolite grade lapilli tuff to tuff breccia. The alteration has replaced the matrix of the pyroclastic rocks and partially replaced some clasts. Identical alteration has been recognized in rhyolitic autobreccia at Metcalfe Lake (Stott and Parker 1996) and in pyroclastic rocks at Toronto Lake (Berger 1992).

MINERALIZATION

Gold, lithium and some minor base metal occurrences have been the focus of mineral exploration at O'Sullivan Lake. The Consolidated Louanna gold mine has been the only producing mine in the area. About 70 000 tons of ore grading 0.22 ounce gold per ton was milled between 1983 and 1984 (Mason and White 1986). The locations of mineral properties are indicated on Figure 12.2 and their characteristics are summarized in Table 12.1.

SYNVOLCANIC SULPHIDE MINERALIZATION

Sulphidized, pillowed and massive mafic metavolcanic flows intercalated with felsic tuff to lapilli tuff, argillite, limestone and iron formation form a distinct stratigraphic horizon along the south margin of the greenstone belt. Several properties such as the Holland–Chellew and De Laporte occurrences are located along this horizon (*see* Figure 12.2).

On airborne geophysical maps the sulphide-rich horizon appears as a discontinuous, east-striking conductive anomaly (OGS 1989) that extends east from Casper Lake to the north end of Felsen Lake for a strike length of approximately 25 km (*see* Figure 12.2). Sulphidized mafic flows with rusty weathered surfaces contain 5 to 25% fine-grained disseminated pyrrhotite, pyrite and minor chalcopyrite. Interflow metasedimentary units also contain abundant disseminated pyrrhotite and pyrite. Samples taken from sulphide-rich rocks at the De Laporte occurrence, north of Casper Lake, assayed 0.21 and 0.14 ounce gold per ton with elevated copper and zinc values (AFRI File 42L07NW0021, Assessment Files, Resident Geologist's office, Thunder Bay). The sulphide-rich mafic flows are also associated with weak to strong albitization. Albite is concentrated in pillow selvages; in albite breccia; and in abundant albite and epidote lenses or pods within the mafic flows. Other sulphide-rich mafic flows have been mapped along Northeast Arm on O'Sullivan Lake in the vicinity of the Copper Jim occurrence (*see* Figure 12.2). The sulphide-rich horizons may have formed during synvolcanic hydrothermal activity that deposited iron sulphide minerals and some chemical sediment at the seafloor.

GOLD

The majority of gold properties are located in the south part of O'Sullivan Lake in close proximity to the margin of the Esnagami pluton or adjacent to the Hurd Lake fault (*see* Figure 12.2). These occurrences consist of extensional and shear-parallel quartz veins in northeast-striking, vertical, late shear zones localized along lithologic contacts between felsic, porphyritic dikes and mafic metavolcanic rocks or gabbro. Strong shearing occurs along the margin of the pluton in quartz porphyritic tonalite and pillowed mafic flows. Gold–bearing veins are typically narrow and host minor amounts of disseminated pyrite ± chalcopyrite ± arsenopyrite ± sphalerite ± galena. Sheared wall rocks are pyritic and moderately to strongly altered to chlorite, sericite and calcite ± iron carbonate. Some sheared mafic flows host thin lenses of chalcopyrite and pyrite along foliation planes. Large iron carbonate veins also host gold–bearing extensional quartz veins.

SKARN AND SULPHIDIZED IRON FORMATION

The Muriel Lake occurrence (*see* Figure 12.2) consists of two separate showings formerly known as the J.Perry and Galena Vein occurrences (Kindle 1932). These consist of large stripped and trenched areas on deformed, pillowed mafic flows interlayered with northeast-striking sulphidized iron formation and a 5 m thick unit of recrystallized limestone. The metasedimentary and metavolcanic rocks are intruded by thick, deformed gabbro and quartz porphyry dikes. The limestone is partially skarnified with irregular calc-silicate pods up to 1.6 m in size consisting of large pink to dark brown garnets, green diopside crystals, acicular actinolite–tremolite and fine–grained, granular quartz. The calc–silicate pods host disseminated chalcopyrite and pyrite. The sulphidized iron formation has been thickened by tight folding and consists of sericitized, recrystallized chert interlayered with semi-massive and disseminated, medium-grained pyrite with minor chalcopyrite, sphalerite and galena. Pyrite also occurs as small nodules and in massive aggregates. Variable and erratic gold, silver, copper, zinc and lead values have been reported from these occurrences ranging from anomalous values to 12% Cu, 3.3% Zn, 3.6% Pb, 0.05 ounce gold per ton and 45.0 ounces silver per ton (Kindle 1932; File 2.15360, Assessment Files, Resident Geologist's office, Thunder Bay).

LITHIUM

An occurrence of spodumene (a lithium pyroxene)-bearing muscovite granite pegmatite occurs on a peninsula at Superb Lake (*see* Figure 12.2). This pegmatite dike is 2.5 m wide and is exposed along its length for 15 m. It trends approximately 250° and obliquely cuts thickly bedded greywacke of the English River metasedimentary suite. The dike is zoned inward from fine- to medium-grained muscovite granite including pale greenish spodumene crystals aligned perpendicular to the dike walls, to a 1 m wide core containing very coarse grained muscovite granite pegmatite with randomly oriented spodumene crystals up to 35 cm long. No evidence of mineralization occurs in the host rock. The dike is one of several muscovite granite pegmatite dikes seen on this peninsula but the only one observed to contain spodumene. Less evolved muscovite granite pegmatite, commonly containing garnets, occurs widely just north of the greenstone belt within the English River Subprovince. No pegmatite dikes were observed to occur within the greenstone belt.

Table 12.1. Summary of mineral occurrences in the O'Sullivan Lake area. Occurrence numbers in the table correspond to the location numbers on Figure 12.2.

Name (Commodity)	Host Lithology(ies)	Local Structures	Mineralization	Wall Rock Alteration
1. **Camdeck (Au)**	mafic flows, felsic quartz porphyry dike	shear zone strikes 244°/90°	diss. py, cp in shear-parallel quartz veins in felsic dike	ser, Fe-carb
2. **Chimo (Au)**	mafic flows	shear zone strikes 280°	diss. py, apy, po, cp, sp, gn in sheared tuffaceous zone	ab, chl, cal
3. **Conlon 1 (Au)**	mafic flows, felsic quartz porphyry dikes	north-side-up, dextral shear zone strikes 220°	diss. py in extension quartz veins and iron carbonate veins; diss. py in felsic dike	ser, chl, Fe-carb, cal
4. **Conlon 2 (Au)**	gabbro, felsite dikes	moderately foliated 205°/90°	diss. py in host rocks and on fractures	ep, cal on fractures
5. **Consolidated Louanna mine (Au)**	mafic flows, felsic quartz porphyry dike	wide, NE-striking north-side-up, dextral shear zone steep NW-plunging lineations	diss. apy, py, po, cp, sp and visible gold in host rocks and quartz veins (Moorhouse 1956)	chl, Fe-carb, cal, ser, Fe-carb veins
6. **Conwest (Au)**	mafic flows, felsic quartz-feldspar porphyry dikes	NNE-striking shear zones; N-striking Fe-carb vein	no sulphide minerals observed; extension quartz-chlorite veins	Fe-carb, cal, chl, ser, Fe-carb vein
7. **Copper Jim (Cu,Au)**	mafic flows, felsic quartz-feldspar porphyry dikes	weak fracturing and narrow local shear zones	diss. po, py, cp in mafic flows; sulphide minerals also on fractures and in quartz veins	ab, ep; weak chl and cal; Fe-carb veins
8. **Croteau (Au)**	mafic flows, gabbro felsite and tonalite dikes	moderate NNE- striking foliation	diss. py and py on fractures in host rocks	ep, weak cal and ser
9. **Cryderman (Au)**	mafic flows, felsic quartz porphyry dike	shear zone strikes 68°/85°	diss. py in host rocks, quartz and iron carbonate veins	chl, Fe-carb, ep and Fe-carb veins
10. **De Laporte (Cu, Au)**	sulphidized mafic flows and interflow tuff	moderate fracturing; weak to moderate foliation 255°/90°	diss. po, py, cp in mafic sulphidized flows and interflow tuffs	ab, ep and cal ab-breccia
11. **Farley Is. (Ag, Au)**	mafic flows, gabbro, felsite dikes	shear zone strikes 230°/74°	diss. py, asp, cp, gn, sp in sheared host rocks and extension quartz-carbonate veins	chl, ser, strong Fe-carb and Fe-carb veins
12. **Gagnon (Au)**	mafic flows, felsic porphyritic dikes	wide NE-striking shear zone	diss. py, cp in sheared host rocks and in extension quartz veins; diss py, cp and alteration in tonalite	strong chl, Fe-carb
13. **Harlow Is. (Au)**	quartz porphyritic tonalite	strong, NE-striking foliation	diss. gn in narrow quartz veins (Moorhouse 1956)	ser, cal
14. **Hogan–Newman (Ag)**	mafic flows, felsic porphyry dike	strong, north-side-up NE-striking shear zones	diss. py, gn, sp, cp in quartz veins (Moorhouse 1956)	chl, ser, cal, Fe-carb
16. **Kowkash Gold (Au,Cu)**	mafic flows	weakly fractured host rocks; narrow south-side-up sinistral shear zone strikes 160°/90°	diss. po, cp in narrow, folded, extension quartz veins; diss. sulphide minerals in wall rocks as well	chl,cal in shear zone; ep in fractured rocks

Name (Commodity)	Host Lithology(ies)	Local Structures	Mineralization	Wall Rock Alteration
17. Lacana (Au)	mafic flows	narrow shear zone strikes 182°/90°	diss. py, cp in shear parallel, crack–seal quartz vein; diss. py in host rocks	chl, ser and heavy cal in shear zone
18. Lithium (Li)	pegmatite dike intrudes English River meta–sedimentary rocks	pegmatite dike strikes 250°	zoned pegmatite dike containing abundant pale green spodumene crystals; pegmatite hosts muscovite	none observed
19. Melly Lake (Cu)	mafic flows, quartz porphyritic tonalite	wide, north–side–up dextral shear zone strikes 216°/90° at tonalite/metavolcanic contact	diss. py, cp in sheared host rocks and in extension quartz veins; diss py, cp and alteration in tonalite	strong chl, ser, cal, Fe– carb and Fe– carb veins
20. Muriel Lake (Cu,Ag,Zn,Au)	mafic flows, felsic porphyritic dikes, gabbro, interflow metasediments	strongly deformed host rocks; shear zone strikes 230° to 265°	strong py and minor cp, sp, gn in sulphidized iron formation; diss. cp, py in calc–silicate pods in skarnified limestone	chl, ser, ab, ep and sulphidization
21. New Athona (Cu,Ag,Au)	mafic flows,felsic feldspar porphyry dike	moderately fractured host rocks	diss. py, po, cp in fractured mafic flows	ep, ab
22. Odman Lake (Au)	mafic flows, felsic feldspar porphyry dike	strong shear zone strikes 250°/90°	diss. py,po in sheared, rusty mafic flows	grt, ep, ab
23. Ovansull (Au)	gabbro, felsic quartz porphyry dikes	sheared and folded host rocks; shear zone strikes 274°/90° N–striking Fe–carb vein	diss. py, cp in host rocks	chl, ser, strong Fe–carb; wide Fe–carb vein
24. Peterson (Au)	mafic flows	strong, south–side–up sinistral shear zone strikes 50°/80°	diss. py, po, cp in sheared mafic flows and in extension and shear parallel quartz veins	chl, ser, cal
25. Shields (Au)	mafic flows, gabbro	shear zone strikes 236°/85°	diss. py, sp in wall rocks and veins; extension and shear– parallel quartz veins (Mason and White 1986)	chl, cal
26. Warren (Cu)	mafic flows, gabbro felsic porphyritic dikes	strong shear zone strikes 240°/60°	diss. py, cp in sheared mafic flows and gabbro	chl, cal

ABBREVIATIONS: *ab –albite, apy –arsenopyrite, cal –calcite, chl –chlorite, cp –chalcopyrite, E –east, ep –epidote, Fe–carb –carbonate, gn –galena, grt –garnet, N –north, NE –northeast, NNE –north–northeast, po –pyrrhotite, py –pyrite, ser –sericite, sp –sphalerite.*

SEQUENCE OF EVENTS AND CRITERIA

1. Volcanism and some associated hydrothermal alteration (epidote pods, calcite carbonatization and sulphidization).

2. Early deformation and folding of the volcanic strata to produce large-scale synclines and anticlines evident from the reversals in facing directions of pillowed basaltic flows across the width of the belt.

3. Intrusion of the Esnagami pluton and associated gabbroic intrusions and felsic porphyry dikes. Related shear zones provide evidence of south-side-up sense of displacement. The intrusions produce very little evidence of contact strain upon the adjacent volcanic rocks but are host to shear zones related to later dominant collisional deformation.

4. Collision along the northern margin between superterranes, now represented by subprovinces, producing regional shortening of strata coupled with narrow shear zones. A few major shear zones have been iden-

tified along the margin of Esnagami pluton. These shear zones show evidence of north-side-up sense of displacement. Displacement of the English River terrane upwards, relative to the Onaman–Tashota greenstone belt, exposed clastic metasedimentary rocks of a higher metamorphic grade represented by the presence of andalusite, staurolite and garnet. Accompanying this stage is the introduction of hydrothermal fluids along some shear zones across the O'Sullivan Lake area, producing alteration assemblages that include chlorite associated with iron carbonate and quartz veins. Examples of this mineralizing event are the Consolidated Louanna gold mine and shear zones near the Esnagami pluton.

5. Late stage intense shortening, transposed folding and right-handed transcurrent shear occurs along and close to the subprovince boundary, affecting particularly the ductile tuffaceous and metasedimentary rocks of northern O'Sullivan and Superb lakes.
6. Retrograde metamorphism near the subprovince boundary is evident from the alteration of andalusite and staurolite porphyroblasts in the metasedimentary rocks. Large peraluminous muscovite-garnet-bearing granite pegmatite bodies and related granite plutons developed within the English River metasedimentary terrane. Some more evolved pegmatite bodies are lithium-rich and contain coarse spodumene crystals, exemplified by the lithium-pegmatite dike on Superb Lake (*see* Figure 12.2). The pegmatite is unaffected by and postdates the collisional deformation.

RECOMMENDATIONS FOR MINERAL EXPLORATION

Narrow shear zones across most of the O'Sullivan Lake area show evidence that they were produced during a major period of deformation. We relate this deformation to the collision between terranes, that form the present subprovinces, during the final assembly of the Archean Superior Province. This deformation is observed within a broad domain along the northern part of the Onaman–Tashota greenstone belt near the English River Subprovince. Consequently, like the Shebandowan belt, the northern half of which shows similar structures related to this style of collisional deformation, the northern part of the Onaman–Tashota greenstone belt has the potential of preserving a record of hydrothermally mineralized shear zones related to this late stage of deformation.

Gold exploration should continue to be focussed along iron carbonatized shear zones adjacent to the Esnagami pluton and along the Hurd Lake fault. A previously undocumented iron carbonate-flooded shear zone was mapped along the northwest shore of a small oval lake a few hundred metres east of Conlon Creek.

The east-striking sulphide-rich horizon in the east part of the map area should also be thoroughly prospected for base metal and gold mineralization. More limestone and sulphide-rich interflow metasedimentary rocks were mapped west of Casper Lake during this survey.

Finally, the English River–Wabigoon subprovince boundary should be thoroughly prospected for more lithium and rare element pegmatite dikes. A large muscovite-bearing granitoid body, situated between Maytham and Queenston lakes, might represent a fertile granite mass that is parental to rare earth element pegmatites, based on the presence of abundant muscovite and sodic feldspar in the intrusion (F.W. Breaks, OGS, personal communication, 1997).

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13. Structural Analysis at the Woman–Confederation Assemblage Boundary, Western Birch–Uchi Greenstone Belt: Progress Report

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INTRODUCTION

Many greenstone belts in northwestern Ontario are composed of rock assemblages that differ greatly in absolute age (Ontario Geological Survey 1992). The structural geology of metavolcanic-metasedimentary rocks exposed along boundaries between assemblages remains to be analyzed in detail. Such analysis may aid in discriminating whether the jump in protolith age at assemblage boundaries resulted mainly from dislocation of rock masses or long breaks in deposition. Under the auspices of LITHOPROBE (Western Superior Transect) and the Ontario Geological Survey, we are studying the ductile deformation of rock units at the Woman–Confederation assemblage boundary in the west-central part of Birch–Uchi greenstone belt, Western Uchi Subprovince (Stott and Corfu 1991). The western boundary of this greenstone mass (Figure 13.1), also called the Confederation Lake belt (Fyon and Lane 1985), lies about 75 km east of the town of Red Lake in northwestern Ontario.

At the present erosion level, Confederation assemblage rocks compose most of the greenstone belt (*see* Figure 13.1) and may have been thrust northward onto the rocks of the Woman assemblage (Stott and Corfu 1991). Alternatively, the geologic map pattern may be early-stage regional folding about north-south axes, resulting in a large synclinorium on a 50 km scale (Fyon and Lane 1985;

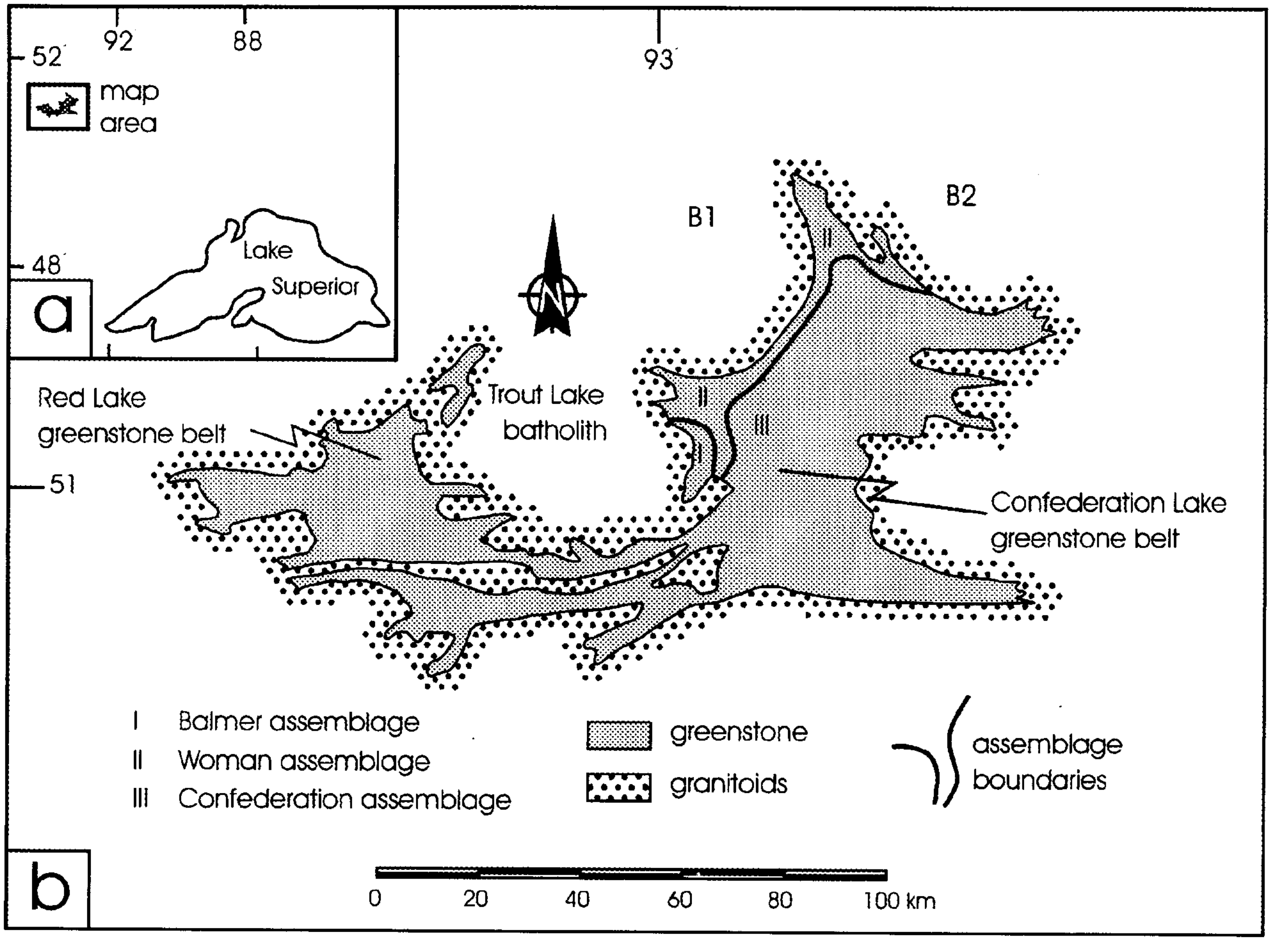

Figure 13.1. Woman–Confederation assemblage boundary, western Birch–Uchi greenstone belt.

Thurston 1985). Structural data from the assemblage boundary contacts, which are well exposed in the Woman Lake area, will facilitate testing tectonic hypotheses and constrain the origin of the age gap at the assemblage boundary.

LITHOTECTONIC PATTERN

In the southern part of Woman Lake, the assemblage boundary is marked by a unit of strained stromatolitic marble about 100 m thick (Hofmann et al. 1985; Thurston 1985). The marble is underlain by a unit of felsic metavolcanics (Thurston's 1985 formation H). This metavolcanic unit, which is characterized by flow laminae and other primary features marking the paleohorizontal plane, has been traced into the northernmost bay of Woman Lake. However, no marble outcrops are known in the northern half of Woman Lake (Goodwin 1967; Thurston 1985). If present at all, the marble must be relatively thin, that is, less than 5 m thick at shoreline localities with excellent rock exposure. In all parts of Woman Lake, the hanging wall of the assemblage boundary contains three prominent rock units composed, respectively, of mafic metavolcanics with relict pillows, fragmental intermediate metavolcanics and polymictic metaconglomerates with locally dominant greywackes (Thurston 1985, Map 2498). The geologic map pattern of all units in the walls of the assemblage boundary attests to an open subvertical s-fold (interlimb angle = 90°), which encompasses the prominent ironstone horizon of the Woman assemblage (Thurston 1985, Map 2498). The large s-fold, whose short limb lies in Goodall Township, is indicative of a sinistral component of north-south shear strain, distributed across rocks of both assemblages. This seems compatible with the idea of northward displacement of Confederation assemblage rocks (Stott and Corfu 1991).

DEFORMATION EFFECTS

Primary structural features, such as varioles, pillows, lapilli and pebbles, occur in the lithologic units of both assemblages. Their present geometry attests to markedly heterogeneous strain on a kilometre scale. The direction of maximum total extension is subvertical at most localities, but its tectonic significance is unclear. The maximum and minimum diameters of strained varioles are, respectively, parallel to the mineral lineation and normal to the main foliation (Crews et al., in press). Similarly, the principal axes of the shape fabric of pebbles and lapilli are approximately parallel to the principal axes of mineral shape fabrics, but the tectonic significance of this parallelism is unclear because the structural history of the belt is not well known.

Previous workers (Thurston and Breaks 1978; Fyon and Lane 1985; Thurston 1985) recognized that the rocks of the Birch–Uchi greenstone belt were deformed repeatedly. Early regional deformation created the first-order north-south synclinorium and lower-order horizontal folds on a kilometre scale (Fyon and Lane 1985; Thurston 1985). The large s-fold delineated in the Woman Lake area is subvertical and probably formed at an advanced stage of tectonism. However, the main foliation and associated total-strain fabrics are axial-planar to the s-fold. This is difficult to reconcile with two folding events (Hudleston 1976) unless the early folding created chevron structures in which the strain was confined to narrow hinge zones. (Such zones may now coincide with topographic troughs filled with Quaternary sediment.)

Throughout the west-central Birch–Uchi greenstone belt, subvertical mineral foliation strikes northeasterly and amounts to a component of sinistral shear strain parallel to the north-south assemblage boundary (Crews et al., in press). This strain was accompanied by north-south buckle shortening of the boundary and its wall rocks, but need not have included a large component of vertical extension.

DISCUSSION

The northward transportation hypothesis (Stott and Corfu 1991) implies a difference in horizontal displacement of many kilometres between the two assemblages. Such a displacement difference may predate the ductile deformation and greenschist-facies metamorphism of Confederation assemblage rocks (Thurston and Breaks 1978; Thurston 1985). By contrast, the open s-fold in the assemblage-boundary walls on Woman Lake precludes the possibility of late-stage tangential shear of very large magnitude. The processing of structural data obtained in 1997 may allow us to discern whether the tangential ductile shear was severe at the assemblage boundary, before the inception of the open s-fold. Evidence for a high transverse gradient of tangential shearing would support a scenario of early ductile emplacement of Confederation assemblage rocks.

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14. Project Unit 95–17. Distribution of Evolved Rhyolites in the Superior Province, Ontario

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INTRODUCTION

Geochemistry of rhyolites is increasingly used by explorationists to: 1) differentiate tectonic environments of Archean metavolcanic rocks; and 2) distinguish between barren and Volcanic-hosted massive sulphide-productive metavolcanic assemblages. Therefore, an on-going compilation project has been initiated to build a database and document the distribution of evolved, felsic metavolcanic rocks associated with volcanic–hosted massive sulphide (VMS) mineralization in the Archean Superior Province of Ontario (Figure 14.1, Table 14.1).

VMS deposits in the Superior Province occur within metavolcanic assemblages ranging in age from 2738 to 2700 million years old (Fyon et al. 1992). These assemblages have formed in extensional tectonic environments such as, thickened, bimodal oceanic rift terranes and primitive, tholeiitic to calc–alkaline rifted island arcs (Galley 1995). VMS deposits in the Superior Province are associated with felsic volcanic centres in two different metavolcanic assemblage types: 1) bimodal successions of intermediate to felsic flows and pyroclastic rocks representing stratovolcanoes or central volcanic complexes (i.e., South Bay and Mattabi deposits); and 2) komatiite-tholeiite assemblages composed of ultramafic, mafic, intermediate and felsic metavolcanic rocks (i.e., Potter and Kidd Creek deposits)(Fyon et al. 1991). A close association also exists between rhyolites and VMS deposits because rhyolites are commonly extruded from high-level magma chambers along synvolcanic faults that also serve as conduits for focussed discharge of metal-bearing hydrothermal fluids (Galley 1995; Franklin et al. 1981).

The application of lithogeochemistry has aided in the identification and exploration of these specific metavolcanic assemblages in which VMS are deposited. The interpretation of lithogeochemical data using various discriminant diagrams, chondrite-normalized REE patterns and REE-trace element ratios helps to distinguish between barren and VMS-productive metavolcanic assemblages and defines tectonic environments were large VMS deposits are located (Galley 1995; Lesher et al. 1986; Barrie et al. 1993). The geochemistry of rhyolites, in particular, is commonly used to identify VMS-productive metavolcanic assemblages. A brief review of the classification and geochemistry of barren and productive rhyolites follows below. Readers should refer to the referenced papers for more detailed information.

GEOCHEMISTRY OF ARCHEAN FELSIC METAVOLCANIC ROCKS

Archean felsic metavolcanic rocks are subdivided into FI, FII and FIII types based on their trace element geochemistry. The subdivisions are based on variations in trace element abundances and ratios that are related to various petrogenetic processes such as fractional crystallization of basaltic magmas and partial melting of earlier formed hydrated, mafic crust (Fyon et al. 1991; Condie 1976, 1981; Lesher et al. 1986; Galley 1995).

Type FI felsic metavolcanic rocks are dacitic to rhyodacitic with steep chondrite–normalized REE patterns; weakly negative to moderately positive Eu anomalies and high Zr/Y ratios (9–31)(Lesher et al. 1986). Lesher et al. (1986) consider Type FI rocks to be barren of significant VMS deposits and derived from deep magma chambers where fractional crystallization has taken place. These magma chambers were buried too deep to function as effective heat sources for convective mineralizing hydrothermal systems required for the development of a VMS deposit (Lesher et al. 1986). These type of magmas are also commonly formed in compressional subduction settings (Lentz 1997).

Type FII felsic metavolcanic rocks are rhyodacitic to rhyolitic with gently sloping REE patterns, variable Eu anomalies and moderate Zr/Y ratios (6 to 11)(Lesher et al. 1986). Type FII felsic metavolcanic rocks occur in VMS-productive successions at the Mattabi and Lyon Lake deposits at Sturgeon Lake and at the Geco deposit at Manitouwadge (Lesher et al. 1986; Zaleski et al. 1995). These metavolcanic rocks are considered to be derived either from high-degree partial melting of a crustal source or fractional crystallization of an intermediate parent magma (Lesher et al. 1986).

Type FIII felsic metavolcanic rocks are rhyolites and high–silica rhyolites that occur in VMS–productive metavolcanic successions throughout the Superior Province (i.e.; the Kidd Creek and Kamiskotia deposits in the Abitibi greenstone belt and the South Bay deposit in the Birch–Uchi greenstone belt)(Fyon et al. 1991). There are also several locations in the Superior Province (*see* Figure 14.1 and Table 14.1) where FIII rhyolites are known to host small occurrences of massive sulphides but economic VMS deposits have not yet been discovered (i.e., Mine Centre, Rice Bay–Fort Frances, Straw Lake and Strathy–Chambers townships).

Type FIII rhyolites are characterized by relatively flat REE patterns and are subdivided into FIIIa and FIIIb sub–

types. FIIIa rhyolites have moderately negative Eu anomalies and low Zr/Y ratios (4 to 7); while FIIIb rhyolites have strong negative Eu anomalies and low Zr/Y ratios (2 to 6)(Lesher et al. 1986). Type FIII rhyolites are derived from subvolcanic, high-level magma chambers that are the source for overlying metavolcanic rocks. These high-level chambers are also considered to be the heat source for convective mineralizing hydrothermal systems (Lesher et al. 1986).

Barrie et al. (1993) defined a specific high-silica rhyolite type (Group I)that hosts more than 50% of the VMS deposits in the Abitibi subprovince including the Kidd Creek and Kamiskotia deposits. This rhyolite is characterized by elevated, flat REE patterns with negative Eu anomalies, high-silica values (greater than 73%), Zr/Y ratios less than 5 and Rb/Sr ratios greater than 1 (Barrie et al. 1993). These high-silica rhyolites may have been derived from partial melting of hydrated basaltic rocks and may

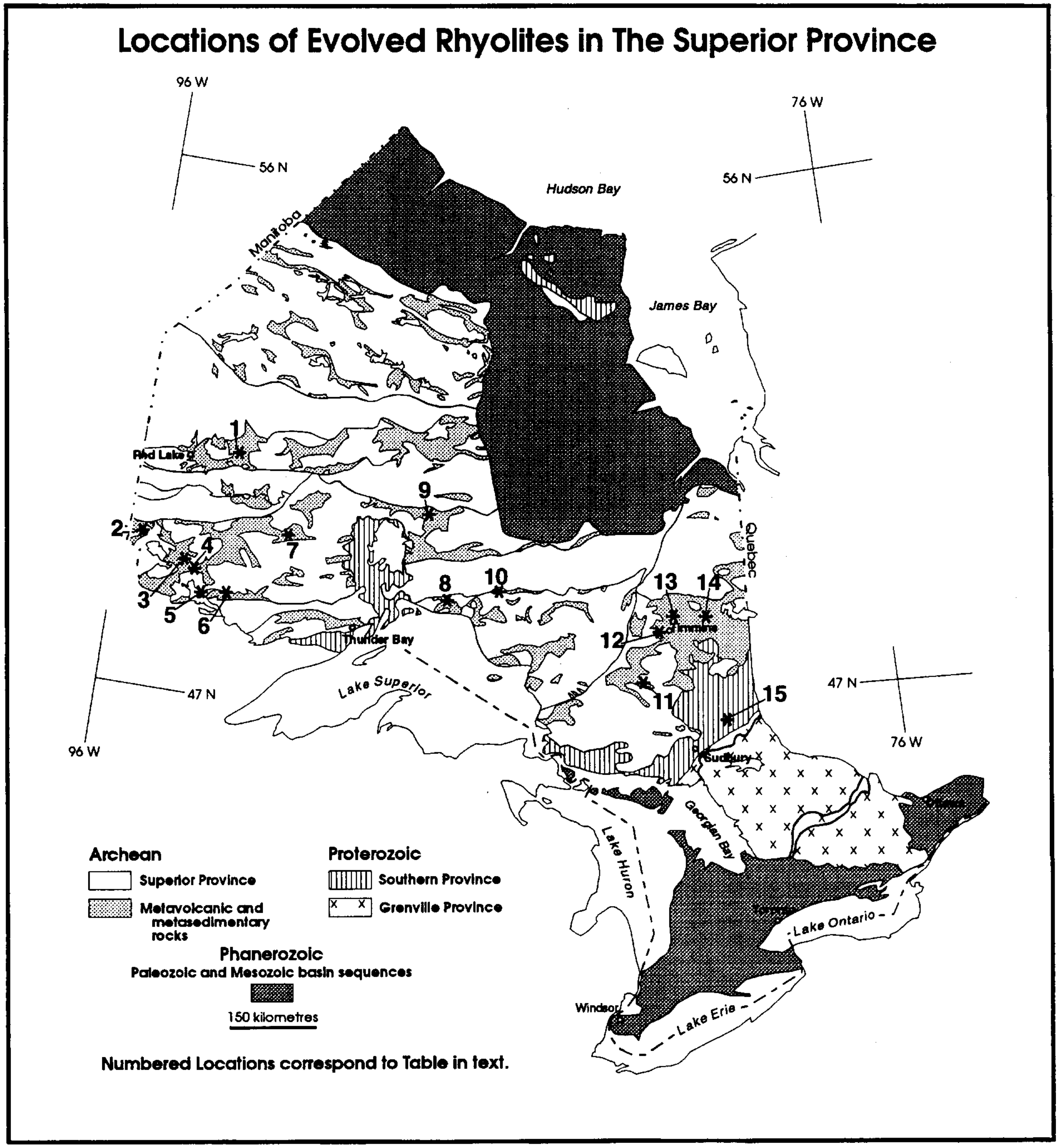

Figure 14.1. Locations of evolved rhyolites in the Archean Superior Province, Ontario.

Table 14.1. Documented locations of evolved rhyolites in the Archean Superior Province, Ontario.

Location	Rhyolite Type	Associated VMS Deposit	U/Pb Age (Ma)	References
1. South Bay–Confederation Lake	FIII	South Bay mine	2738	Thurston & Fryer 1983
2. Lake of the Woods–Zig Zag Is.	FII	none	2719	Ayer & Davis 1997
3. Phinney–Dash lakes	FIII	Freeport & Loydex occurrences	2711	Davis & Edwards 1986; Edwards & Hodder 1991
4. Straw Lake	FIII	none	n/a	Edwards 1983
5. Rice Bay–Fort Frances	FIIIb	Pocket Pond & McTavish occurrences	2727	Davis et al. 1989; Parker et al. 1992
6. Mine Centre	FIIIb	Pidgeon prospect	2728	Davis et al. 1989; Parker et al. 1992
7. Sturgeon Lake	FII	Mattabi & Lyon Lake mines	2736	Davis et al. 1985; Lesher et al. 1986
8. Winston Lake	FII/FIII	Winston Lake mine	n/a	Schandl & Gorton 1991; Schandl et al. 1991a
9. Marshall Lake	n/a	Billiton prospect	n/a	Amukun 1989
10. Manitouwadge	FII	Geco mine	2720	Zaleski et al. 1995
11. Swayze–Chester twps.	FII	Shunsby prospect	2731	Heather et al. 1996
12. Kamiskotia	FIIIb	Kamiskotia mine	2705	Barrie et al. 1993
13. Kidd Rhyolite	FIIIb	Kidd Creek mine	2715	Barrie et al. 1993
14. Beaty–Munro twps.	FIII	none	2714	Barrie et al. 1993
15. Strathy–Chambers twps.	FIII	none	n/a	Fyon & Crocket 1986

have been emplaced at very high temperatures of approximately 900°C (Barrie et al. 1993; Barrie 1995).

The location of known Type FII and FIII felsic metavolcanic rocks in Ontario are indicated on Figure 14.1. Table 14.1 summarizes references and U/Pb zircon age dates (if available) for each location.

The authors would appreciate input from readers who are aware of other locations in Ontario of FII or FIII rhyolites that do not appear in Figure 14.1 and Table 14.1.

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15. Project Unit 95–14. Geology of the Mine Centre–Manion Lake Area, Northwest Ontario

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INTRODUCTION

The Mine Centre–Manion Lake area is situated in the southern Wabigoon Subprovince and adjacent Quetico Subprovince approximately midway between Fort Frances and Atikokan in northwest Ontario. This area has a long history of prospecting and geologic investigations (e.g., Lawson 1913) dating back over a century. Previous work has however, focussed on the main greenstone belts in the south with less attention paid to northern parts of the area.

Although the Wabigoon Subprovince is made up of greenstone belts and plutons of mainly Neoarchean age (Blackburn et al. 1991), geochronologic studies (e.g., Davis and Jackson 1988) have determined that supracrustal and plutonic rocks of the central Wabigoon Subprovince, which lies to the east including the Atikokan–Lumby Lake area, are Mesoarchean. The Mesoarchean domain represents a significant area of older crust in the Wabigoon Subprovince however the contact relations of the older domain and its possible extension into the present area are not established. The present survey was initiated to provide an integrated geologic map both in aid of modern mineral exploration and to help define major litho-structural subdivisions of the Wabigoon Subprovince.

PREVIOUS WORK AND GENERAL GEOLOGY

Recent geologic investigations include those of Fumerton (1984), Shanks (1994), Wood et al. (1980a, b) and Harris (1974) who mapped adjoining blocks in southern parts of the present area (Figure 15.1) from Calm Lake to Redgut Bay of Rainy Lake. Blackburn (1973) mapped the areas of Otukamamoan Lakes and northern Redgut Bay.

The present area is one of varied and complex geology and can be broadly subdivided into three domains including the Wabigoon, Wabigoon–Quetico boundary and Quetico domains.

Wabigoon Domain

The area north of about 48°46′ (see Figure 15.1) is representative of the volcano-plutonic Wabigoon Subprovince. In the north, belts of highly metamorphosed supracrustal rocks are interspaced with tonalite gneiss and felsic plutons. Supracrustal rocks are mainly amphibole gneisses that probably originated as mafic volcanic flows however variably migmatized sandstone-siltstone sequences, iron formation and intermediate to felsic volcanic fragmental rocks are also present.

Supracrustal belts are complex in shape. They can be broad or narrow and commonly bifurcate or anastomose. They variably join with larger greenstone sequences to the south, grade to tonalite gneiss or taper to discontinuous chains of inclusions. Belts of supracrustal and gneissic rocks wrap around oval to lenticular plutons of biotite tonalite giving rise to conspicuous oval structures (see Figure 15.1). Examples of oval structures are cored by the Joe, Hillyer Creek and Spawn plutons. Foliations in some plutons such as the Joe pluton, dip outward on all sides implying an overall domed shape to the oval structure.

Biotite tonalite, tonalite gneiss and supracrustal sequences are intruded by suites of felsic igneous rocks including peraluminous granite (muscovitic white granite), hornblende tonalite, biotite granite and heterogeneous intermediate to felsic rocks of the sanukitoid suite. Largest of the late igneous bodies is the White Otter batholith that extends beyond the northeast corner of the area. Sanukitoid intrusions such as at Otukamamoan Lake and Redgut Bay may be the youngest plutonic suites. Archean rocks are cut by a north trending Proterozoic gabbro dike tentatively correlated with the Kenora–Fort Frances swarm (Osmani 1991).

Also present in the Wabigoon domain are possibly two generations of igneous rocks compositionally variable from anorthosite to gabbro and diorite. Coarse grained, strongly foliated to lineated anorthosite to gabbroic anorthosite occurs at Manion Lake, southwest of Manion Lake in the Hillyer Creek pluton and at several localities east of Manion Lake. At Manion Lake, ovoid plagioclase crystals and aggregates of crystals attain 5 cm size. Anorthositic rocks appear to occur as inclusions in biotite tonalite and are cut by dikes of most other igneous rocks.

A tapered, oval body, immediately west of the Joe pluton (see Figure 15.1) is compositionally variable from hornblende tonalite at margins to gabbro or diorite in the core with local possibly ultramafic inclusions. Although crosscutting relations are lacking, this intrusion is texturally distinct and possibly younger than the anorthosite. Two mafic intrusions, the McPherson Lake Gabbroic Stock of Fumerton (1984) and the Bennett Creek Stock of Shanks (1994), occur west of Calm Lake at the south side of the Wabigoon domain. The crescentic Bennett Creek Stock is of gabbroic to peridotitic composition and is closely associated with mafic to possibly ultramafic volcanic sequences.

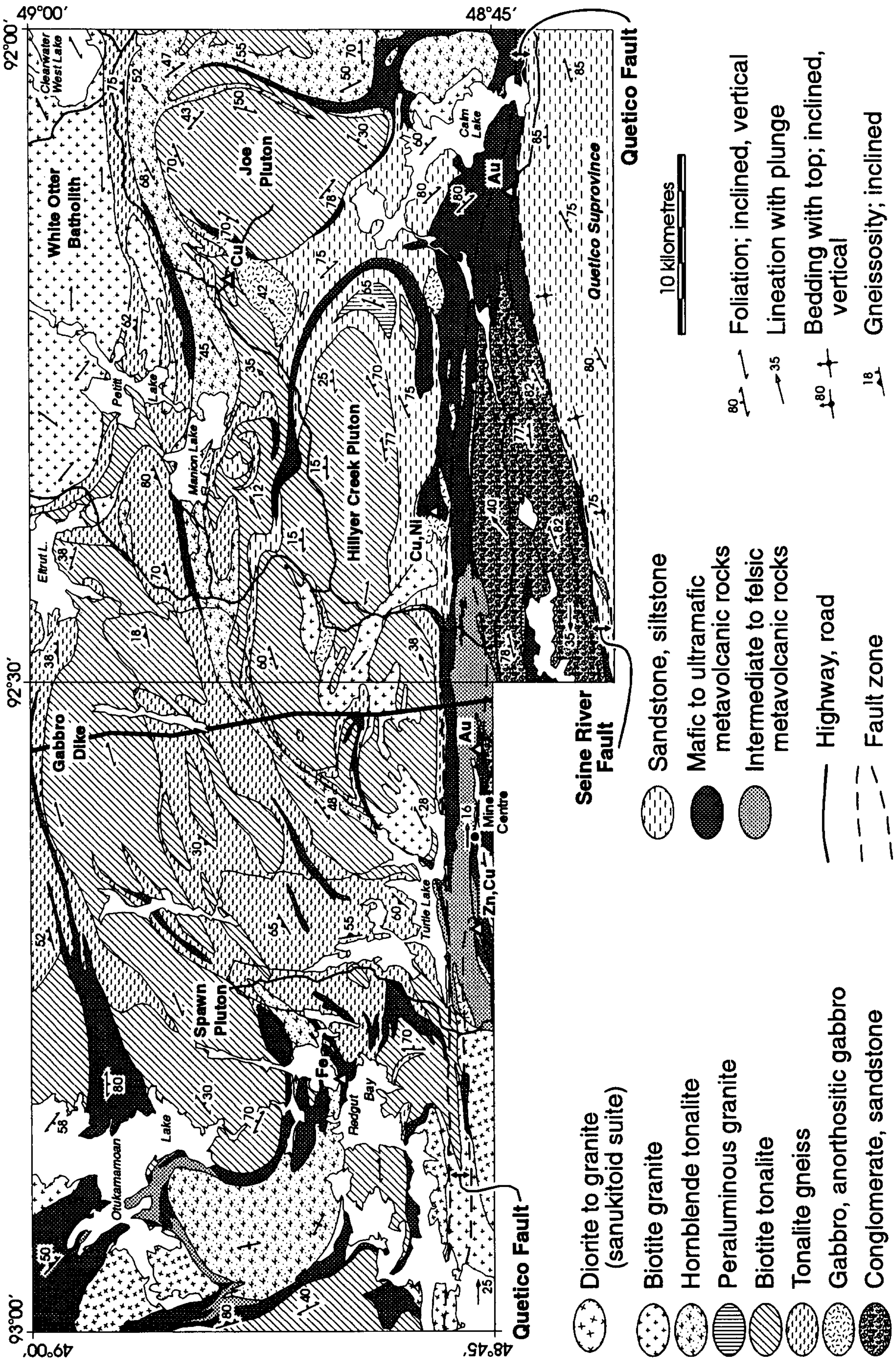

Figure 15.1. Geology of the Mine Centre–Manion Lake area, northwest Ontario.

Wabigoon–Quetico Boundary Domain

The Wabigoon–Quetico boundary domain is underlain by mainly supracrustal rocks of the southern Wabigoon Subprovince and broadens westerly from Calm Lake. The domain is bounded on the north by the Quetico fault zone and on the south by the Seine River fault zone; these faults merge west of Calm Lake (*see* Figure 15.1).

Poulsen (1986) described the Wabigoon–Quetico boundary domain as a fault-bounded wedge or wrench zone. A broad spectrum of mafic, intermediate and felsic volcanic flows, tuffs and breccias and associated gabbros occur within the domain and have been extensively described by earlier workers. These sequences are intruded by tonalite sills, biotite granite and heterogeneous monzodiorite to granite between Mine Centre and Redgut Bay. At the eastern apex of the wrench zone, volcanic strata are unconformably overlain by conglomerate and sandstone of the Seine Group. Poulsen (1986) interpreted the Seine Group as alluvial-fluvial sediments that accumulated in pull-apart basins developed at fault bends and junctions of fault splays.

The Quetico and Seine River faults are up to several kilometres wide (*see* Figure 15.1). Within these zones, clasts are stretched, supracrustal rocks are strongly foliated to schistose and greenschist-facies minerals such as chlorite, sericite and carbonate are prevalent. In contrast, biotite granite at Redgut Bay is extensively fractured and brittlely deformed by the Quetico fault.

Quetico Domain

The Quetico domain occupies the extreme southeast corner of the area and is underlain by turbiditic sandstone–siltstone sequences of the Quetico Subprovince. Metamorphic grade increases southward from greenschist facies at the Quetico–Wabigoon boundary. Graded beds in Quetico sediments young north at most localities near the boundary.

EXTENT OF OLDER CRUST IN THE WABIGOON SUBPROVINCE

The Wabigoon–Quetico boundary domain and Quetico domain have had extensive geochronologic studies summarized by Davis et al. (1989) and Davis et al. (1990). Three precise U-Pb zircon dates on volcanic rocks between Calm Lake and Redgut Bay are in the range 2722 to 2727 Ma; all dates have errors of less than 5 Ma. Deposition of Quetico sediments is bracketed between 2692 Ma, the age of a discordant dike, and 2698 Ma, the age of the youngest detrital zircon. Equivocally, deposition of the Seine Group is bracketed between 2686 Ma, the age of an intrusion thought by Davis et al. (1989) to postdate deposition of the Seine Group, and 2696 Ma, the age of a clast.

The Wabigoon domain has had little geochronologic research except for the White Otter batholith dated at 2685 Ma (D. Davis, Royal Ontario Museum, personal communications, 1994). The anorthositic inclusions appear, on the basis of crosscutting relations, to be the oldest rocks in the Wabigoon domain. Biotite tonalite and tonalite gneiss are also relatively old however, field relations cannot distinguish whether these rocks are Mesoarchean or Neoarchean. Detrital zircons as old as 3059 Ma in Quetico sediments (Davis et al. 1989) indicate a Mesoarchean source however, it is unclear whether the source of the detrital zircon grains lies in the Wabigoon domain or elsewhere.

Greenstone sequences of the Wabigoon–Quetico boundary domain extend continuously east from the present area through Steep Rock Lake to Finlayson Lake. West of Calm Lake the volcanic rocks have Neoarchean ages whereas at Finlayson Lake, felsic volcanic strata are dated at 2932 Ma (Tomlinson et al. 1996). The boundary between Neoarchean and Mesoarchean supracrustal rocks is somewhat arbitrarily chosen to be at Calm Lake (Stone et al. 1997) however accurate definition of this boundary together with the boundary between Neoarchean and Mesoarchean plutonic rocks requires further geochronologic work.

RECOMMENDATIONS FOR MINERAL EXPLORATION

The Mine Centre–Manion Lake area has significant potential for gold and base metal mineralization. In summarizing the setting of known gold showings, Poulsen (1984) noted that gold occurs with quartz, carbonate and sulphides in a variety of rock types that are sheared and altered to greenschist facies minerals. The present survey has defined broadly sheared and altered zones associated with the Quetico, Seine River and subsidiary faults (*see* Figure 15.1) most of which occur within or at margins of the Wabigoon–Quetico boundary domain. Further, carbonate alteration and quartz-carbonate vein development are enhanced in areas of complex deformation such as where major faults join. Such areas occur 5 to 10 km west of Calm Lake where the Seine River fault merges with the Quetico fault and about 5 km west and southwest of Mine Centre where a possible splay fault, which lies south of the present area (*see* Figure 15.1) merges with the Quetico fault.

Alteration and vein development seem to be well developed at lithologic contacts in the fault-junction zones. An example from west of Calm Lake is the Mayflower showing (Fumerton 1984) where mafic metavolcanic rocks at the east end of a small granite stock are intensely carbonatized. West of Mine Centre, a quartz porphyritic tonalite sill (Mudge Lake intrusion of Wood et al. 1980b) in gabbroic and volcanic rocks is intensely altered to sericite + quartz + carbonate and is recommended for gold exploration.

Three types of base metal mineralization are distinguished. The first consists of massive pyrite and pyrrhotite with minor chalcopyrite associated with metavolcanic belts in the Wabigoon domain. The sulphide mineralization probably represents metamorphosed iron formations; several examples are exposed as gossan zones on the shores of Redgut Bay.

Base metal sulphides occur with mafic intrusive rocks. A small gabbroic anorthosite body west of Manion Lake is mineralized with vein-like aggregates of pyrite, pyrrhotite and chalcopyrite. Metavolcanic rocks in contact with the Bennett Creek stock, located south of the Hillyer Creek pluton (*see* Figure 15.1) are mineralized with pyrite, pyrrhotite, magnetite and chalcopyrite within a zone 1.5 km by up to 16.3 m wide (Shanks 1994). Relatively large and previously undefined bodies of gabbroic anorthosite at Manion Lake and of gabbro immediately west of the Joe pluton (*see* Figure 15.1) are recommended for base metals and platinum group metals.

Stratabound iron sulphides, sphalerite and chalcopyrite are associated with mafic to felsic volcanic sequences at Mine Centre. Typical mineralization at the Port Arthur Copper Mine consists of discrete seams, 1 to 20 cm wide, of sulphides separated by barren chloritic volcanic rocks. Poulsen (1984) noted nine occurrences of the Port Arthur Copper type in the Mine Centre–Fort Frances area and recommended exploration in greenschist-altered portions of felsic volcanic sequences such as extend approximately 10 km east and west of Mine Centre in the present area.

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16. Geology of the Sachigo, Stull and Yelling Lakes area: an overview

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INTRODUCTION

This report summarises results of regional mapping in the Sachigo, Stull and Yelling lakes area approximately 350 km north of Red Lake, Ontario. The area spans several major greenstone belts and intervening plutonic areas at the north side of the Superior Province. Largely due to remoteness, limited geologic investigations and mineral exploration have been carried out in the area. The present survey provides a revised set of geologic maps to assist mineral exploration and as a basis for unravelling magmatic and tectonic evolution of the northern Superior Province.

PREVIOUS WORK

Previous geologic investigations are rare. Downie (1937), Meen (1937) and Satterly (1937) travelled major lakes and rivers of the area and defined greenstone belts at Ponask, Sachigo and Stull lakes. The present area was remapped by Bennett and Riley (1969) at a scale of 1 inch to 2 miles. Corkery (1981) mapped the Little Stull Lake area.

REGIONAL GEOLOGY

Elongate over a distance of 120 km, the study area (Figure 16.1) provides a geologic transect of the most northerly part of the Superior Province in Ontario. The transect crosses four major west to northwesterly striking greenstone belts and intervening plutonic domains.

Greenstone Belts

SACHIGO BELT

The Sachigo belt extends northwesterly from Sachigo Lake to Ponask Lake (see Figure 16.1) attaining a maximum width of 8 km. North of Ponask Lake, the Sachigo belt is separated by a narrow unit of biotite tonalite from a 2 km wide greenstone sequence that extends westerly through Pierce Lake to Red Sucker Lake, Manitoba.

At Sachigo Lake, the belt is made up of basaltic lavas showing large oval south-younging pillows. Komatiitic flows are interlayered with the basalts. At Ponask Lake, the greenstone belt tapers and highly strained felsic and mafic volcanic units are interleaved. Volcaniclastic dacites to rhyolites occupy the northwest end of the belt. Conglomerate containing tonalite clasts and komatiite occur at the north side of the belt at Ponask Lake; although these rocks occur in close proximity to each other, their mutual contact is not exposed.

At Pierce Lake, strongly foliated amphibolite-facies mafic volcanic rocks are layered with thin units of fine sandstone and siltstone. Also present, at scattered localities on the north side of the belt are komatiitic rocks, tonalite conglomerate and coarse buff marble, which are similar to supracrustal sequences at Ponask Lake and are typical of platform sequences (Thurston and Chivers 1990).

STULL LAKE BELT

The Stull Lake belt is the largest and most lithologically diverse greenstone belt. It is part of a chain of greenstone belts extending 200 km east-southeasterly to Big Trout Lake and attains 12 km width at Stull Lake. Stone and Pufahl (1995) divided the belt into four panels on the basis of lithology and structural facing (*see* Figure 12.1 of Stone and Pufahl 1995). The northern panel, composed of north-younging pillowed mafic flows and thin bedded sandstone–siltstone sequences, extends northwesterly through Little Stull Lake (*see* Figure 16.1) whereas the three southern panels extend westerly through Twin Lakes.

Panel 2 consists of mainly south-younging dacitic to rhyolitic tuffs, lapilli tuffs and associated epiclastic rocks and minor mafic flows. Southeast of Stull Lake, this and possibly other panels are intruded by a heterogeneous diorite to granodiorite intrusion. Panel 3 is composed of south-younging boulder conglomerate, cross-bedded sandstone and massive, moderately well-sorted, cobble-pebble conglomerate. These alluvial fan deposits are probably correlative with coarse sandstone at Little Stull Lake (T. Corkery, Manitoba Energy and Mines, personal communications, 1997). Panel 4 is not unlike Panel 1 and consists of north-younging pillowed basaltic flows and deep–water sandstone–siltstone sequences.

Strata of the Stull Lake belt are cut by numerous faults (*see* Figure 16.1). In places, such as between Panels 1 and 2, faults appear to mark the boundaries of panels although the kinematics of the faults is poorly known. Possibly, the panels of the Stull Lake belt represent assemblages that have been tectonically amalgamated and whose boundaries are largely tectonic in nature. Relative ages of panels are poorly constrained beyond the observation that conglomerates of Panel 3 contain clasts of most other units in the belt and must be relatively young in age.

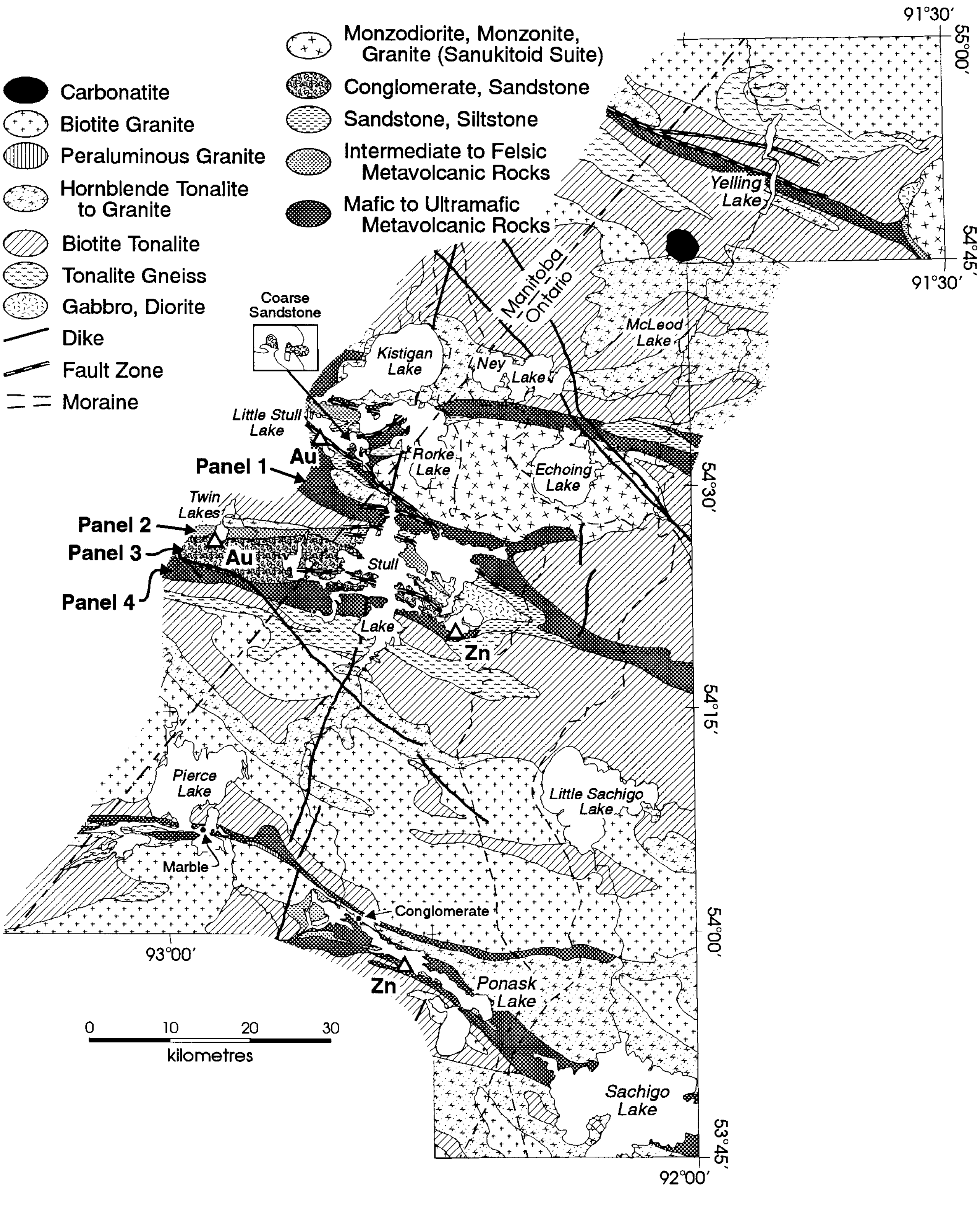

Figure 16.1. Geology of the Sachigo, Stull and Yelling lakes area, northern Superior Province. Geology of the Little Stull Lake area is compiled from unpublished maps by T. Corkery, Manitoba Energy and Mines.

WESTERN ELLARD BELT (LITTLE STULL BELT)

The western Ellard belt is largely overlain by the Sachigo Moraine and is inferred, on the basis of aeromagnetic maps (GSC 1967a) and limited drill data (e.g., Canadian Nickel Company, Bonnell Lake area; Assessment Files, Resident Geologist's Office, Red Lake), to extend westerly from northeast of Echoing Lake, to Little Stull Lake (*see* Figure 16.1). Rare outcrops and boreholes east of Echoing Lake expose gneissic mafic volcanic rocks and lesser clastic sediments and intermediate tuffs. Bennett and Riley (1969) mapped conglomerate in this area.

At Little Stull Lake, the belt is composed of mafic pillowed lavas and turbiditic sediments in fault contact with intermediate to felsic tuffs, breccias and associated epiclastic volcanic rocks (T. Corkery, Manitoba Energy and Mines, personal communications, 1997). A feldspar porphyry intrusion is dated at 2717 ± 3 Ma (Davis and Moore 1991).

YELLING BELT

Although poorly exposed, the Yelling belt crosses Yelling Lake (*see* Figure 16.1) and maintains a width of a few kilometres. The belt is composed of gneissic, amphibolitized mafic volcanic flows and possible ultramafic volcanic rocks. East of Yelling Lake, a narrow, northerly arm of the belt envelopes a lensoid body of medium-grained gabbro. Intermediate, epiclastic rocks occur at the southeast end of the belt.

The Yelling belt follows a prominent aeromagnetic low (GSC 1967b) and is flanked on the north side by north-dipping mylonite zones. The Yelling belt lies at the trace of the Kenyon fault of Osmani and Stott (1988).

Plutonic Rocks

TONALITIC SUITE

The tonalitic suite is composed of essentially biotite tonalite to granodiorite. Although several varieties of tonalite are distinguished by variation in grain size and mineralogy, rocks of the tonalitic suite are typically medium to coarse grained, white to grey and foliated to massive.

The tonalitic suite occurs widely in forms ranging from small dikes to large batholiths. Biotite tonalite is cut by most other plutonic suites but can be variable in age. For example, early tonalite plutons shed detritus into platform-sequence conglomerates of the Sachigo belt, whereas other tonalite bodies intruded greenstone belts such as at Stull Lake.

GNEISSIC SUITE

Gneisses are heterogeneous and hybrid rocks typically composed of several varieties of leucocratic to mesocratic tonalite and granodiorite and amphibolite arranged in complexly banded and commonly folded patterns. At the mafic end of their compositional spectrum, gneisses grade through amphibolite gneiss to mafic metavolcanic rocks and at the felsic end, grade to rocks of the tonalite or granite suites. Gneisses occur in belt-like domains. Major occurrences are south of the Stull Lake belt and in the Yelling Lake area (*see* Figure 16.1).

PERALUMINOUS SUITE

Rocks of the peraluminous or S-type suite are massive, coarse grained to pegmatitic white leucocratic granite. They contain a few percent of one or both of muscovite and biotite and can have accessory garnet, tourmaline, blue-green apatite and cordierite. Peraluminous granites are rare occurring as small bodies within and adjacent to the Sachigo and Stull Lake greenstone belts.

HORNBLENDE SUITE

The hornblende suite includes a spectrum of hornblende-bearing rocks compositionally variable from tonalite to granite. Hornblende tonalite is a dark grey, coarse grained, granular mesocratic rock locally grading to quartz diorite. Lensoid inclusions of diorite and amphibolite are common in hornblende tonalite. Potassium-feldspar tends to occur as megacrysts in the hornblende suite. Hornblende granodiorite and granite are coarse grained and red with blocky potassium-feldspar megacrysts. Intrusions of the hornblende suite are elongate and occur adjacent to greenstone belts such as the Sachigo belt (*see* Figure 16.1).

GRANITE SUITE

Rocks of the granite suite range from granodiorite to granite with biotite as the main mafic mineral. Typical granites are massive to weakly foliated, medium to coarse grained, inequigranular to locally potassium feldspar megacrystic and white to pink with a few percent biotite. Granitic intrusions are heterogeneous, commonly having large inclusions of tonalite and variably sharp to gradational contacts. Granite is concentrated in the south part of the area (*see* Figure 16.1) forming several large oval to northwesterly elongate batholiths adjacent to the Sachigo belt. Granite also underlies the extreme north end of the area.

SANUKITOID SUITE

Intrusions of the sanukitoid suite can be compositionally variable from monzodiorite and monzonite to granodiorite and granite. Monzodiorites and monzonites are massive to foliated, grey to reddish, medium grained mesocratic rocks containing hornblende and clinopyroxene and oval ultramafic (hornblendite) inclusions. Granodiorite to granite phases are red, coarse grained and slightly potassium feldspar megacrystic with a few percent hornblende or biotite.

A large oval intrusion of the sanukitoid suite occurs at Echoing Lake and a second intrusion extends east of the map area at Yelling Lake (*see* Figure 16.1). Sanukitoid intrusions tend to have strong aeromagnetic anomalies, particularly associated with monzodioritic phases. These intrusions are possibly the youngest of the major plutonic suites.

Proterozoic Rocks

Archean rocks are intruded by dikes and a carbonatite stock of Proterozoic age. A discontinuous to *en echelon* gabbro dike strikes approximately 015° through the Stull Lake area (*see* Figure 16.1). Where exposed, the dike is composed of variable fine to coarse grained pyroxene gabbro and attains a width of up to 100 m. The dike has a strong aeromagnetic anomaly (GSC 1967a) and is tentatively grouped with the 1883 Ma Molson swarm (Osmani 1991). Although unexposed, northwesterly striking dikes are identified from aeromagnetic maps and are tentatively grouped with the 1267 Ma Mackenzie swarm (Osmani 1991).

North of MacLeod Lake (*see* Figure 16.1) an intrusion of approximately 4 km diameter is distinguished by an oval aeromagnetic anomaly (GSC 1967a, b). The intrusion is unexposed however drift prospecting by Bennett and Riley (1969) and examination of exploration drillcore by Sage (1987) indicates that the intrusion is a carbonatite composed of mainly sovite and silicocarbonatite with minor narrow bands of magnetite. Biotite from the Carb Lake carbonatite is dated using K-Ar methods at 1826 ± 97 Ma (Sage 1987).

QUATERNARY GEOLOGY

The Sachigo Interlobate Moraine forms a prominent discontinuous ridge of sand and gravel that extends northerly through the area (*see* Figure 16.1) and locally rises 100 m above adjacent lakes. Although the main central moraine ridge is typically of a few kilometres width, it is flanked by broad, thick aprons of silt and clay that blanket bedrock over distances of up to 20 km on each side of the moraine. Glaciolacustrine clay and silt are extensive east of the moraine in the area of Sachigo Lake and Little Sachigo Lake. West of the moraine such as in the area of Stull Lake and in the north such as at Yelling Lake, bedrock is overlain by tan-brown silty till that typically contains abundant pebbles of Paleozoic rocks.

The direction of glacial motion is markedly different on either side of the moraine. East of the moraine, striae and drumlins are oriented at about 240° whereas to the west, such as at Pierce Lake, glacial striae trend approximately 170° with rare local evidence of a probably earlier southwesterly direction.

Mineral Potential

Two gossan zones, identified during regional mapping show anomalous concentrations of zinc. A sample from a metre-wide zone in mafic metavolcanic rocks south centrally on Ponask Lake (*see* Figure 16.1) was assayed at 1705 ppm Zn and samples from narrow (0.1 m wide) zones southeast of Stull Lake yield more than 5000 ppm Zn with lower concentrations of Cu. Zinc at the latter showing occurs as disseminations and veins of sphalerite with clinozoesite and chlorite.

Komatiites at Ponask and Sachigo Lakes have an assemblage of magnesite+talc+serpentine+chlorite with up to 2% chromite and magnetite in the form of euhedral, disseminated crystals with minor iron-sulphide, chalcopyrite, pentlandite and Cu-Ni arsenide. This mineralogy implies that the ultramafic components of the Sachigo greenstone belt, has potential for Cu-Ni and Cr mineralization. Further, the soft dense ultramafic rocks such as at northwest Ponask Lake may be suitable for carving.

Greenstone sequences in the Stull Lake area host two important gold occurrences. Noranda Exploration Limited defined 3 500 000 t grading 2.7 to 15.8 ppm Au in four zones at Twin Lakes, Manitoba (*The Northern Miner*, April 8, 1991, p.20). Limited exposures suggest that the mineralized zones are confined to sheared and carbonate altered alluvial-fan conglomerate and felsic rocks of probable volcanic origin. The conglomerates are extensive in the Stull Lake belt and sheared and altered parts of these units are recommended for gold exploration. An independent type of gold mineralization occurs on the southwest side of Little Stull Lake, Manitoba where Westmin Resources Limited and Tanqueray Resources Limited outlined 750 000 t grading 10.3 ppm Au (Report to Shareholders, Tanqueray Resources Limited, September 1991). The mineralization occurs where a composite mylonite zone cuts mafic volcanic and gabbro sequences at Little Stull Lake. Regional mapping has traced the faulted supracrustal sequences southeasterly into the Rapson Bay area of Stull Lake (*see* Figure 16.1) where they may provide an environment for gold mineralization analogous to that of Little Stull Lake.

Peraluminous granite at the north side of the Sachigo belt from Pierce Lake to Ponask Lake (*see* Figure 16.1) is a potential source of rare metal mineralization including Li, Be, Ta, REEs and Nb. These peraluminous granite bodies are possible extensions of pegmatitic granites at Red Sucker Lake, Manitoba, which have associated rare metal mineralization (Chackowsky and Cerny, 1984). The carbonatite intrusion north of McLeod Lake (*see* Figure 16.1) is a second potential source of rare metal mineralization. Although unexposed and poorly explored, Bennett and Riley (1969) noted synchysite and ancylite in boulders overlying the intrusion.

In aid of mineral exploration, a total of 61 samples of till and beach sand were collected from various parts of the area in 1995 through 1997 and are analyzed for gold grains, and indicator minerals of kimberlite and metamorphosed massive sulphide deposits. Results of the survey will be published following completion of analytical work.

TECTONIC EVOLUTION

Relatively well-studied greenstone belts in the southern Superior Province are interpreted as tectonically stacked composites of supracrustal assemblages (Stott and Corfu 1991). The greenstone belts and subprovinces of the southern Superior Province are thought to have been assembled in the Neoarchean by successive accretion of terranes outboard and southward from the North Caribou Terrane—a Mesoarchean core of the northwest Superior Province (Thurston, Osmani and Stone 1991). The present study provides new information on the northern Superior Province and raises several points in comparing evolution of this area with that of the south.

Firstly, northern greenstone belts appear to be composed of multiple assemblages, some of which have mutual faulted boundaries. This invites the interpretation that northern greenstone belts could have grown by accretion of allochthonous and autocthonous terranes not unlike what occurred in the south.

The Sachigo belt is unique among northern greenstone belts in having examples of platform assemblages such as are common in Mesoarchean belts. This suggests that at least parts of the Sachigo belt are older than other northern belts and alludes to a process of south to north accretion in the northern Superior Province. Northerly dipping mylonites of the Kenyon fault are consistent with late, north-south shortening and imbricate stacking of the craton margin, possibly at a late stage in the accretionary process.

Alluvial fan conglomerate and sandstone of the Stull Lake belt are not unlike the Seine Group sediments at the Quetico–Wabigoon Subprovince boundary (see Stone and Halle, this volume). The clastic sediments probably were deposited in pull-apart basins developed in continental strike-slip zones and suggest comparable processes of late transpression on both the south and north sides of the Superior craton.

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17. Project Unit 93–11. Rare-Metal Exploration Potential of the Separation Lake Area: an Emerging Target for Bikita-Type Mineralization in the Superior Province of North Western Ontario

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ABSTRACT

Rare-metal class pegmatites of the complex-type and petalite-subtype represent the most desirable target for tantalum, cesium, rubidium and ceramic-quality petalite in Archean terrain settings. However this deposit-type is one of the most difficult exploration targets owing to lack of responsiveness to airborne geophysical systems and the difficult and exotic mineralogy of the pegmatites. Geological, mineralogical, structural and some preliminary chemical features are given for the Big Whopper pegmatite system, discovered by the authors in 1996 and which is now the largest petalite pegmatite system in Ontario.

Current economic interest is focussed upon the petalite potential which retails at US$270 per ton of concentrate. The widest part of the Big Whopper Pegmatite averages 37% petalite over 60 m which is comparable to the world's premiere petalite deposit at the Bikita Pegmatite of southern Zimbabwe. The tantalum potential is also considered significant as wodginite, the chief ore mineral for Ta at the Tanco Mine of southeastern Manitoba, is not only widespread in the Separation Lake area, but also exhibits compositional variation unlike any other pegmatite group on a global scale. Cesium, a metal of growing economic importance, also has high exploration potential as pollucite, the only ore mineral for the metal, has recently been verified in the area. A flow-chart scheme for exploration in glaciated, Archean shield terrain of the northern hemisphere is presented. Delineation of rare-metal exploration targets is partly a function of an in-depth knowledge of the geology, mineralogy and bulk chemistry of "fertile" granite/pegmatite systems, which are typically peraluminous and of a S-type heritage. The Separation Rapids pluton represents a classic example of a fertile granite. Detection of lithium exomorphic dispersion halos in host-rocks, which are typically mafic metavolcanic, is an effective exploration tool, both on a reconnaissance and detailed scale. Metasomatic selvedge chemistry is advocated owing to its ability to detect evolved pegmatites even though the difficult and exotic mineralogy of the pegmatite may be unrecognized during the initial phase of investigation.

INTRODUCTION

Rare-metal class pegmatites of the complex-type and petalite sub-type are the most desirable targets with respect to tantalum, cesium, rubidium and ceramic-grade petalite. However, petalite pegmatites are rare and only comprise about 2% of the complex-type (Cerny and Ercit 1989) and hence represent a very difficult and elusive exploration target. Subsequent to the discovery of the significantly large Big Whopper Pegmatite (Breaks and Tindle 1996 b,c), the Separation Lake area has experienced a significant increase in exploration interest for ceramic grade petalite, tantalum and cesium. The principals include exploration firms Avalon Ventures Limited, Champion Bear Resources and Tanco Exploration coupled with several local prospectors. To date, 60 new rare-metal mineral occurrences have been established by our work. This work was strongly supported by an extensive electron microprobe analytical data-base of the economically important oxide minerals which now comprise approximately 1000 analyses completed by A.G.Tindle at The Open University. All bulk chemical analyses used in this report were conducted by the Geoscience Laboratories of the Ontario Geological Survey, unless otherwise indicated.

GEOLOGICAL SETTING

The Separation Rapids pegmatite group lies almost entirely within the Separation Lake metavolcanic belt (SLB), which in this part of the Superior Province, constitutes the boundary zone between the high grade, metasedimentary-dominant English River Subprovince (ERS) to the north (Breaks 1991; Breaks and Bond 1993) and the granite-to-nalite-dominant Winnipeg River Subprovince (WRS) to the south (Beakhouse 1991); see Figure 17.1. The SLB conceivably represents a highly attenuated, easterly extension of the Bird River metavolcanic-metasedimentary belt of Manitoba (Cerny et al. 1981) which has an age span of 2740 to more than 2844 Ma (Timmins et al. 1985; Turek et al. 1996). The Bird River–Separation Lake belt system is noteworthy in being the locus for one of the highest concentration of rare-metal pegmatite mineralization in the Superior Province coupled with probably the greatest number of complex-type, petalite-subtype pegmatite occurrences in Canada (Cerny et al. 1981).

On the basis of a striking similarity in geological setting, age of emplacement and mineralogy, the Separation Rapids pegmatite group is regarded as the easterly extension of the Winnipeg River–Cat Lake pegmatite field of Manitoba into adjacent Ontario.

RARE-METAL MINERALIZATION

The various rare-metal mineral occurrences that constitute the Separation Rapids Pegmatite Group are now divisible into two distinct clusters that are both spatially related to the Separation Rapids pluton (Figure 17.2) and are herein named:

1. eastern sub-group (2.5 km^2)
2. southwestern sub-group (7.5 km^2).

Geological and mineralogical characteristics of the eastern pegmatite subgroup have been previously reported (Breaks and Tindle 1994; Breaks and Pan 1995; Breaks and Tindle 1996 (a,b); Breaks et al. 1996, Tindle and Breaks 1996). The most recent summary of mineralogy is given in Table 17.1. However, less information has been released to date on the southwestern pegmatite subgroup owing to its more recent discovery (Breaks and Tindle, 1996 b,c). The following section will therefore provide a summary of the detailed field investigations conducted on the southwestern pegmatite group which is now covered by claim-groups of Avalon Ventures Limited, Tanco Exploration and A. Mowat/P. Thorgrimson.

Big Whopper Pegmatite System

The pegmatite system (Figure 17.3) comprises 5 relatively large petalite pegmatite lenses (6 by 56 m to 12 by 122 m) and swarms of much thinner pegmatites, mostly 1 to 10 m thickness, that occur *en echelon* to these lenses. The presence of this smaller pegmatite population also characterizes the extreme eastern part of the zone (east part of Avalon claim 1178349 and the adjacent claim to the east of Tanco Exploration). For the entire population of petalite pegmatites, a 1350 m strike length and maximum breadth

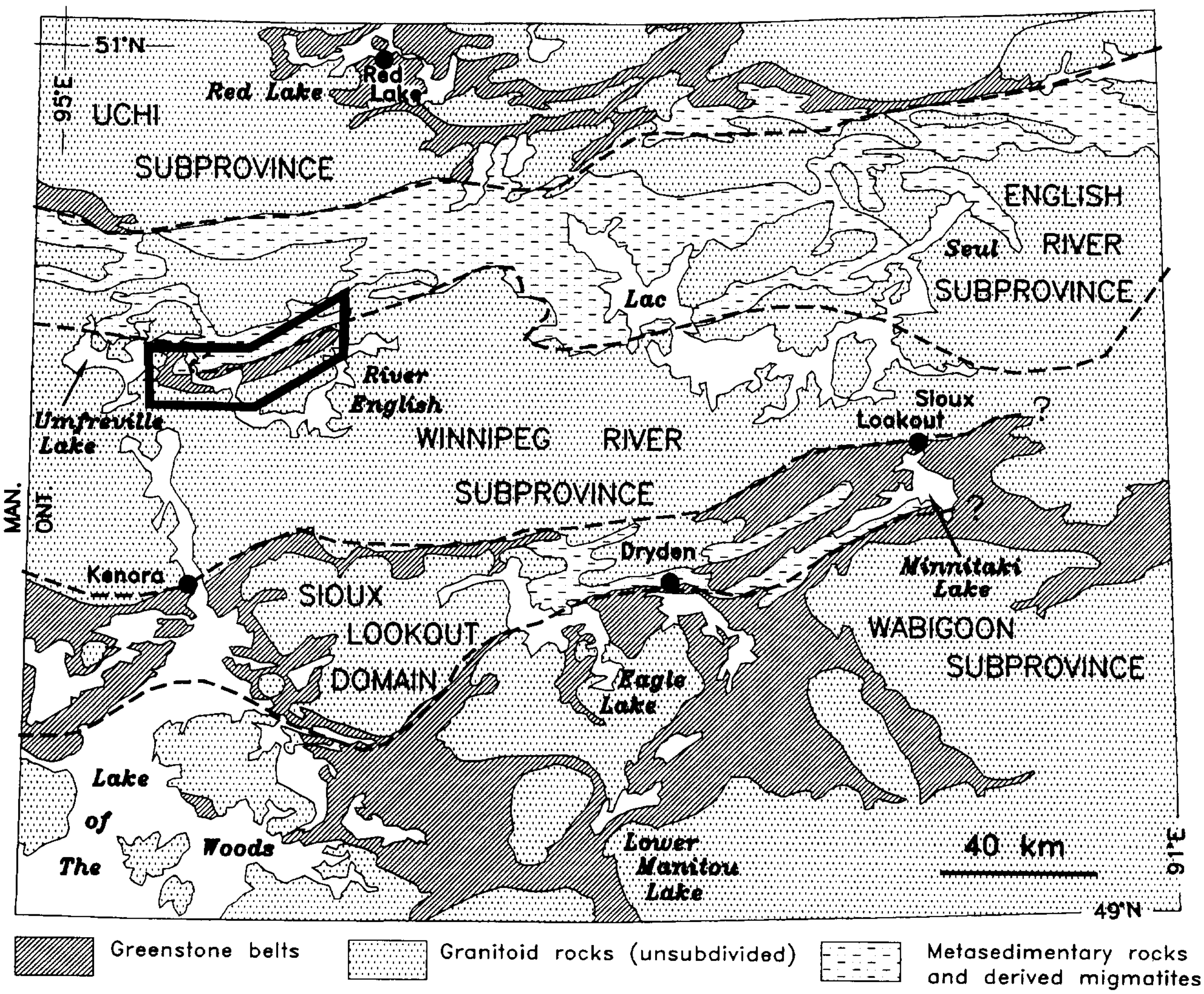


Figure 17.1. Location of Separation Lake area.

of 160 m has been defined, making this, by far, the most significant lithium-rich complex-type pegmatite system ever found in Ontario.

The most impressive part of the mineralized zone is a single mass named the Big Whopper Pegmatite, lensoid in plan which is at least 350 m in strike length and up 60 m thick. To the west of this large pegmatite mass, the zone narrows significantly such that a 15 m breadth is apparent (Avalon Ventures Ltd., news-release, August 21, 1997). This WSW-striking zone of petalite pegmatites extends from the main mass for a distance of 750 m to the west and comprises 4 pegmatite lenses (*see* Figure 17.3):

Great White North Pegmatite: 27 by 55 m

Bob's Pegmatite: 15 by 84 m

Swamp Pegmatite: 6 by 56 m

West Pegmatite: 12 by 122 m.

The western limit for the Big Whopper pegmatite system is not definitively established due to poor exposure beyond the West Pegmatite. Dispersion of lithium in mafic metavolcanic rocks, however, has been established on the claim-block of A. Mowat and P. Thorgrimson adjacent to Avalon Ventures Ltd. claim 1178306 and situated about 500 m west of the West Pegmatite (*see* Figure 17.3). Here it was noted that several *en echelon* fractures were subtly coated with holmquistite, possibly attesting to a nearby lithium-rich pegmatite source. Narrow aplite dikes at the same locality contain scant, locally emerald-green beryl crystals up to 3 by 4 mm.

Internal Zonation

Within the Big Whopper Pegmatite, petalite principally occurs in two rock units:

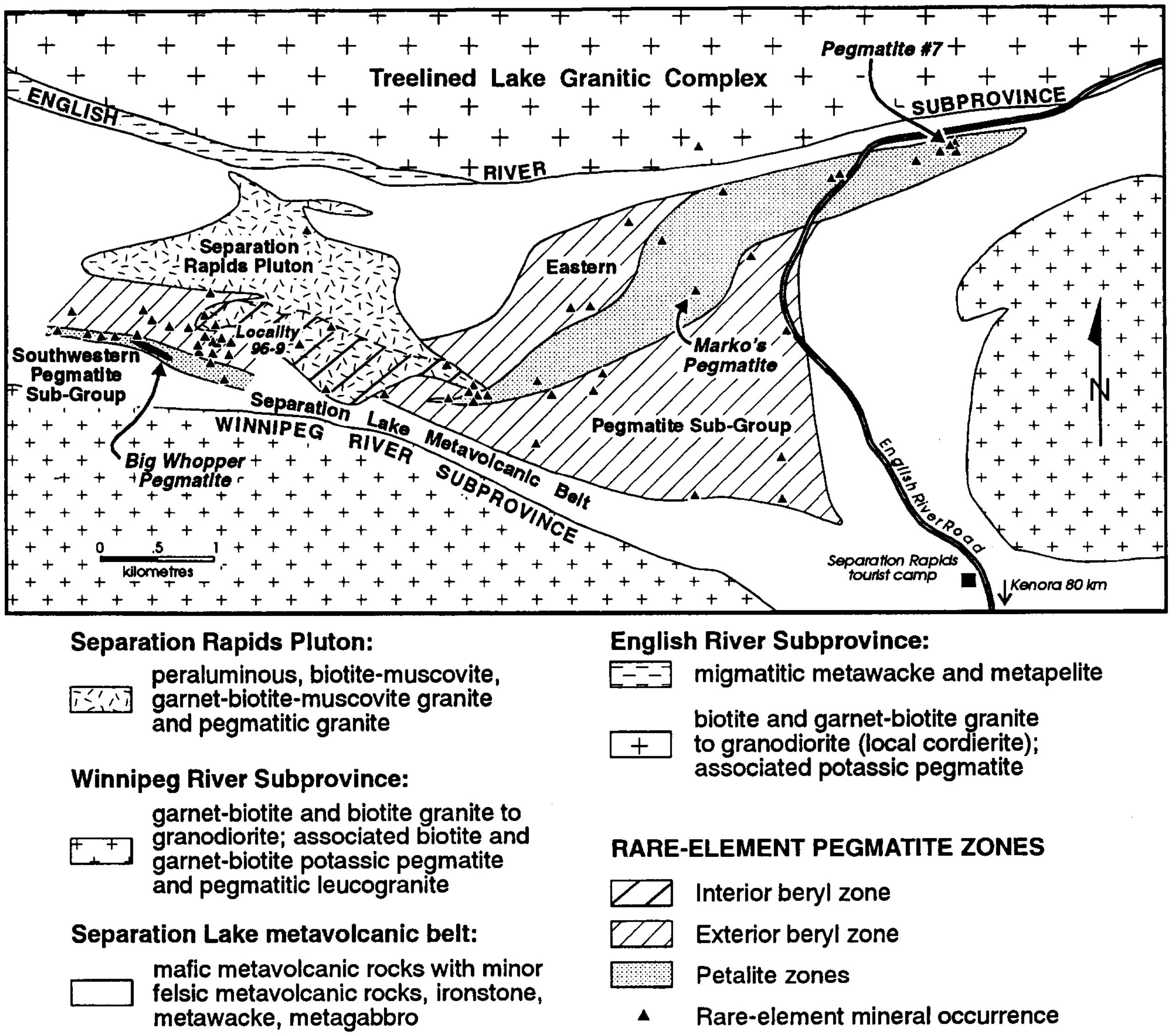


Figure 17.2. General geology of the Separation Lake metavolcanic belt and adjacent parts of English River and Winnipeg River subprovinces (after Blackburn and Young 1994a, b) and distribution of rare-metal pegmatite sub-groups in relation to Separation Rapids pluton (parent granite).

Table 17.1. Separation Rapids Mineralogy.

	1	2	3	4	5	6	7
Fe-columbite		•	•	•			(•)
Fe-tantalite	• ?		(•)	•			
Mn-columbite					•	•	•
Mn-tantalite	• ?				•	•	•
Fe-wodginite			•	•			(•)
Wodginite				(•)	•	•	•
FeTi wodginite							•
Ti wodginite							•
Microlite				•	•	•	•
Stibiomicrolite				•			•
Bismutomicrolite					•		
Uranmicrolite				•			
Stibiobetafite							•
Cassiterite	•	•	•	•	•	•	•
Strüverite							•
Ilmenite		(•)					
Scheelite				(•)			
Uraninite				•			
Gahnite	•	•	•				
Nigerite				•			
Sphalerite		•					
Pyrite		•	• ?	•		•	
Löllingite				•		•	
Arsenopyrite		•	• ?	•	• ?	•	•
Chalcopyrite		•	•	•			
Fluorapatite		•	•	•	•	•	•
Monazite		•	•	•		•	
Xenotime			•	• ?			
Alluaudite		•					
Purpurite				•			
Zircon		•	•	•		•	
Allanite		•					
Epidote		•		•		•	
Fluorite		•	• ?		•		
Topaz	•				•		
Beryl		•	•	•	•	•	•
Tourmaline	•	•		•	•	•	• ?
Garnet	•	•	•	•		•	
Cordierite	•	•					
Amphibole		•					
Biotite	•	•	(•)		• ?		
Zinnwaldite		• ?	• ?	• ?	• ?	• ?	
Li Mica		•	•	•	•	•	•
Muscovite	•	•	•	•	•	•	•
Albite	•	•	•	•	•	•	•
K feldspar	•	•	•	•	•	•	•
Quartz	•	•	•	•	•	•	•
Spodumene						•	
Petalite				•		•	
Pollucite				• ?		• ?	

1 = Treelined Lake granitic complex, a potential source of the Separation Rapids pluton;
2 = Separation Rapids pluton; 3 = Beryl pegmatites (Fe-rich suite);
4 = Petalite pegmatites (Fe-rich suite); 5 = Beryl pegmatite (Mn-rich suite);
6 = Petalite pegmatites (Mn-rich suite);
7 = Wall zone of Marko's pegmatite - a Petalite pegmatite (Mn-suite).
(•) implies only found in one sample; ? questionable

1. Potassium-feldspar-petalite assemblage (mino quartz and muscovite)
2. Monomineralic lenses in garnet-muscovite aplite.

The first unit contains the large bulk of petalite with modal range for the mineral between 22 and 47 % and averages 37 % over 60 m, as estimated by the authors from the increment bulk Li_2O analyses of Avalon Ventures (Don Bubar, president, Avalon Ventures Ltd, personal communication 1997).

This assemblage commonly grades into zones that reveal alternation of the potassium-feldspar-petalite assemblage with lenses of much finer-grained, muscovite aplite.

The second unit is not common and is characterized by pink petalite layers, 2 to 4 cm thick, hosted within an orange garnet-quartz-muscovite-albite aplite.

Narrow dikes, 10 cm to 1 m thickness, which are common in the easternmost part of the pegmatite system demonstrate a consistent internal zonation:

1. narrow albitite border zones, and,
2. central core zone with quartz-albite-petalite assemblage.

Such zonation may also characterize some of the larger pegmatite bodies, at least locally. Within the eastern part of the Great White North Pegmatite a 30 cm thick albitite border zone envelops a quartz-potassium-feldspar-petalite core zone. Furthermore, 30 cm thick dikes, which have been emplaced within 1 to 3 m thick mafic metavolcanic screens present within the Big Whopper Pegmatite, reveal an identical internal zonation to that in the small dikes found immediately west of the Great White North Pegmatite.

There is very little evidence of albite-rich replacement masses. Irregular, vein-like patches up to 5 to 15 cm by 60 cm composed of mauve mica-quartz-albite (local garnet) were observed in a petalite-rich unit at extreme eastern exposure of Big Whopper Pegmatite.

MINERALOGY

The vast majority of original pegmatite minerals in the Big Whopper pegmatite system have been variably modified by strong ductile deformation which has induced flattening and recrystallization of the petalite and development of spindle-to lens-shaped potassium-feldspar. Approximately 90 to 95% of the original petalite crystals have been pervasively recrystallized and converted into a polygonal, net-like mosaic of secondary, medium- to coarse-grained petalite crystals which are typically demarcated by a delicate, fibrous intergrowth of quartz and spodumene needles (Photo 17.1). Better preservation of primary assemblages

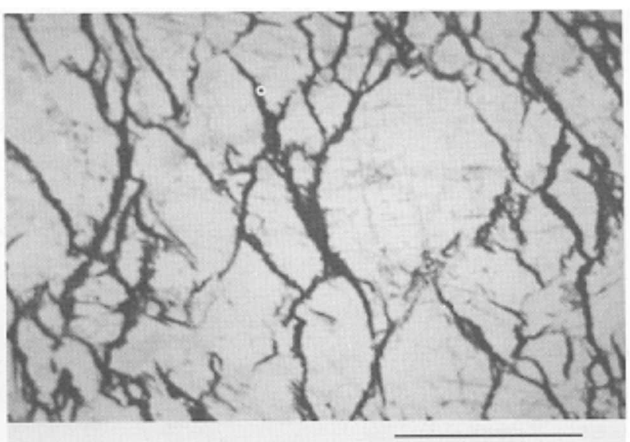


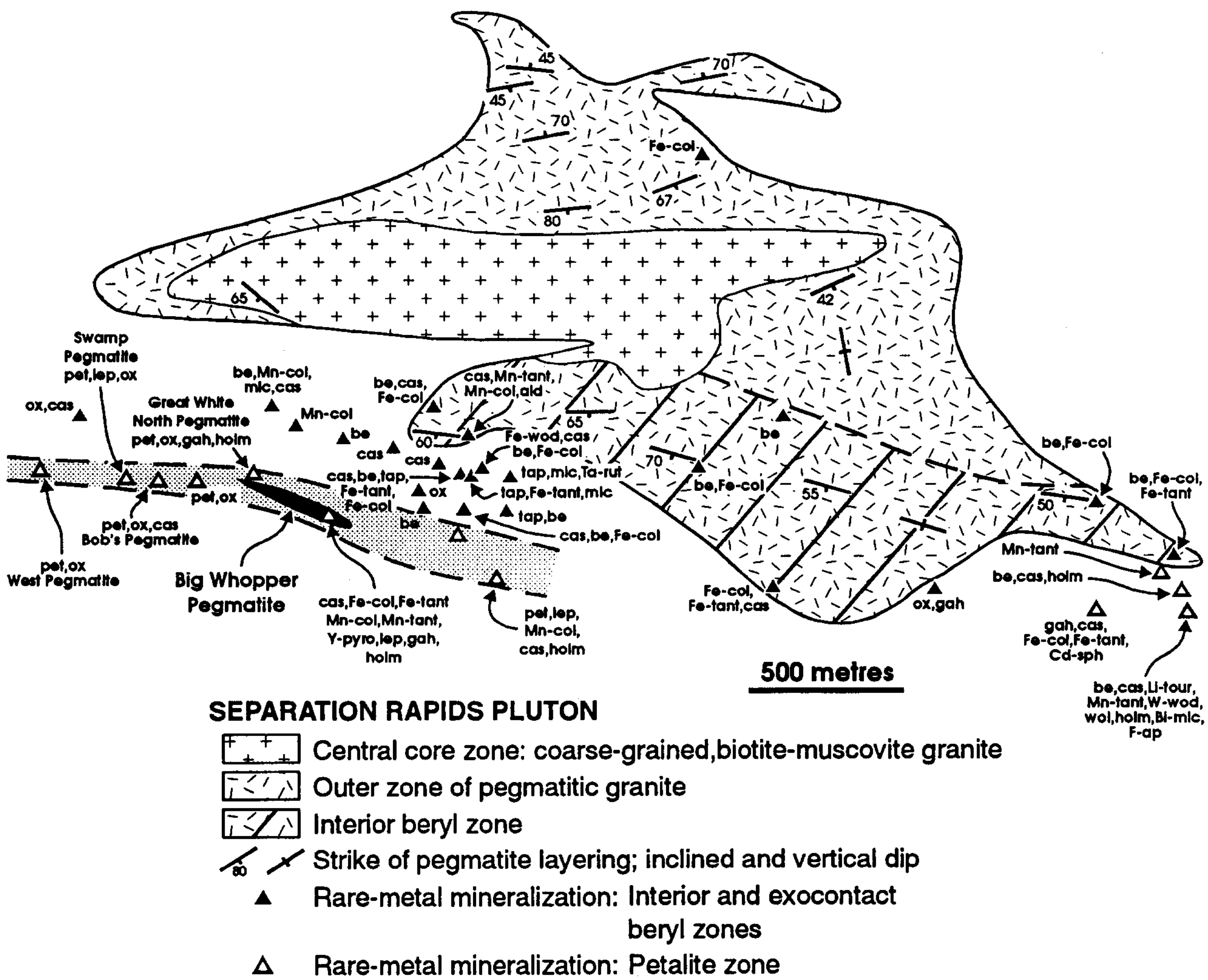
Photo 17.1 Strongly recrystallized petalite from Pegmatite #7, Champion Bear claim–group. The dark, interconnected veins represent a secondary intergrowth of very fine-grained spodumene and quartz whereas the white areas comprise unaltered petalite. Bar=2mm.

is locally apparent in several of the narrow *en-echelon* pegmatite dikes where more typical "log-shaped" to blocky petalite crystals and perfectly preserved light green beryl and blocky potassium-feldspar are notable.

Colour of the petalite at the Big Whopper Pegmatite, is a characteristic translucent, light pink on fresh blast pieces that changes to light brown on the weathered surface. Grey and milky-white petalite is also apparent, particularly where recrystallization is extensive. Pink petalite is rare (Deer et al. 1963) and has previously been reported only in complex pegmatites of the Karibib–Usakos area in Namibia (von Knorring 1970, p. 173). The chromophore responsible for the pink may possibly be trace levels of Mn^{2+}. Within the four other pegmatite lenses situated to the west, the colour of petalite is typically a translucent milky white.

Potassium-feldspar is white to grey and contains between 1 and 1.4 % Rb.

Quartz is notably low in the entire Big Whopper pegmatite system. Both the potassium-feldspar-petalite and aplite units contain 5 to 10% quartz. However, the low modal abundance of quartz does not necessarily infer a deficiency of SiO_2 nor presence of quartz-rich segregation units at depth that are apparently absent in surface expo-



ald	alluadite	gah	gahnite	ox	oxide minerals not identified by electron microprobe
be	beryl	holm	holmquistite	pet	petalite
Bi-mic	bismutomicrolite	lep	lepidolite	Ta-rut	tantalum rutile
cas	cassiterite	Li-tour	lithian tourmaline	tap	tapiolite
F-ap	fluorapatite	mic	microlite	W-wod	tungsten wodginite
Fe-col	ferrocolumbite	Mn-col	manganocolumbite	wol	wolframite
Fe-tant	ferrotantalite	Mn-tant	manganotantalite	Y-pyro	yttropyrochlore
Fe-wod	ferrowodginite				

Figure 17.3. Rare-metal pegmatite zones and mineral occurrences of the southwest sub-group, Separation Lake area.

Table 17.2 Representative electron microprobe analyses of oxide minerals from the southwestern pegmatite sub-group of the Separation rapids group.

Sample	93–260	94–15	96–9	96–29C	96–29G	96–53	96–81
Na_2O							0.23
CaO			0.02		0.58		14.93
Al_2O_3							
FeO	0.46	10.33	14.28	0.99		11.73	0.30
MnO		4.13	0.05	15.49		3.92	0.41
TiO_2		2.53	4.32	0.30	0.09	0.26	
Nb_2O_5	15.63	13.36	9.10	31.78	36.44	22.36	8.77
Ta_2O_5	68.39	54.32	70.79	51.04	12.79	60.75	72.70
SnO_2	0.17	11.74	1.63			0.07	0.20
WO_3	0.27		0.41	0.67	1.44	0.47	0.30
PbO		2.45	0.04		0.97	0.51	0.39
ThO_2			0.06		0.39		0.46
UO_2		0.20	0.09		2.18		0.08
Sb_2O_3	0.02				0.03	0.12	0.69
Bi_2O_3			0.04				
Sc_2O_3		0.23	0.05		0.08	0.52	
Y_2O_3					20.92		
F					0.26		0.43
Cs					0.05		0.28
H_2O^+					24.21		
TOTAL	99.46	99.44	100.88	100.27	100.29	100.71	99.70

93–260: Manganotantalite from beryl-cassiterite-muscovite-quartz-cleavelandite assemblage (most evolved unit of Separation Rapids pluton).

94–15: Ferrowodginite from beryl-cassiterite-bearing sodic pegmatite dike in beryl zone. Ferrocolumbite also present.

96–9: Ferrotapiolite from 30 cm thick albitite dike in beryl zone. Microlite and struverite also present.

96–29C: Manganotantalite from 1 m thick dike of cassiterite-purple mica-quartz-albite related to Big Whopper Pegmatite.

96–29G: Yttropyrochlore from patches of albite-rich replacement material in muscovite-quartz-potassium-feldspar-petalite unit of Big Whopper Pegmatite. Also present: ferrotantalite, ferrocolumbite, manganocolumbite, manganotantalite and cassiterite.

96–53: Ferrotantalite from 1 km thick dike of biotite-muscovite-garnet-sodic pegmatite from the beryl zone. Rock also contains beryl, cassiterite, and ferrocolumbite.

96–81: Garnet-chlorite-biotite-quartz-albite dike from the beryl zone, 30 cm thick, in beryl zone. Rock also contains tapiolite and ferrotantalite.

Analyses done by A.G. Tindle at the Open University using a Cameca SX–100 electron microprobe.

sures. Petalite is silica-rich compared to spodumene and crystallization of petalite under relatively low pressure conditions (1.5 to 4 kilobars: London 1984) consumes much of the silica that would otherwise end up as quartz in lithium-rich melts that crystallize in the spodumene stability field (Stewart 1978).

Light green spodumene is rare in the Big Whopper pegmatite system and solely occurs in small domains associated with quartz within a 30 cm wide garnet-cassiterite-potassium-feldspar-petalite dike situated near Bob's Pegmatite. The overall paucity of primary spodumene in the pegmatite system implies that the crystallization path for the precursor Lithium-rich melts was below 1.5 to 4 kilobars, depending upon temperature of the pegmatitic melt, as inferred by the experimental work of London (1984).

Accessory minerals in the petalite pegmatites include light orange to red-brown garnet, blue-green apatite, dark green gahnite, and dark brown to black oxide minerals, and rare dark green-black tourmaline. The Sn, Ta and Nb bearing oxide minerals generally occur as inconspicuous, fine-grained specks and may reach up to 0.5 by 1.2 cm. The limited electron microprobe work undertaken to date has confirmed cassiterite, ferrocolumbite, ferrotantalite, manganotantalite, microlite and rare yttro- and yttrian-pyrochlore (Table 17.2). Dark green gahnite is scarce and up to 5 mm in diameter.

Fine-grained, purple mica is locally evident in aplite zones as at locality 96–13 (*see* Figure 17.3), and at the Big Whopper and Swamp Pegmatites (*see* Figure 17.3). There is no confirmation to date whether this mica is lepidolite or lithian muscovite. Light orange garnet, likely spessartine-rich, is pervasive. Holmquistite occurs as dark purple needles that developed during at least two episodes of fluid migration into the mafic metavolcanic host-rocks, defined on the basis of structural evidence (see below).

STRUCTURAL GEOLOGY

The petalite zone pegmatites are pervasively overprinted by a ductile shear fabric with kinematic indicators that consistently reveal a dextral sense of rotation (Z-folds, potassium-feldspar megacrysts with clockwise sense of rotation and back-rotated boudins of small associated dikes).

In zones of pervasive emplacement of narrow petalite pegmatite dikes, there is local evidence that compressional deformation led to boudinage and isolated dike remnants. Some of the originally interconnected dikes show evidence of isoclinal folding of connecting segments between associated dikes.

The deformation fabric is likely the result of a substantial, north-south directed compressional event that induced flattening and boudinage in the pegmatite bodies and mafic metavolcanic host-rocks. Timing of the deformation relative to pegmatite evolution can be constrained from two episodes of lithium-exomorphism. An early event of lithium-rich fluid migration into the host-rocks is evident as tightly folded veins that possess axial planes concordant to the foliation surface. However, evolution of the Big Whopper Pegmatite outlasted this deformation as a second event of lithium-fluid movement into the host-rocks post-dates the folding as it occurs as planar fracture fillings that cross-cut the folded holmquistite veins.

COMPARISON TO BIKITA-TYPE RARE-METAL MINERALIZATION

Several mineralogical features suggest that the rare-metal pegmatites of the Separation Lake area bear a similarity to those at the Bikita area of southern Zimbabwe, which is currently the world's premiere petalite deposit (Cooper 1964):

1. dominance of petalite as the chief lithium aluminosilicate mineral; primary spodumene is rare in the SLB (spodumene at the Bikita deposit appears mostly secondary after the breakdown of petalite),
2. abundance of cassiterite
3. presence of topaz
4. paucity of tourmaline
5. presence of lepidolite
6. presence of pollucite.

It is interesting to note that the true mineable width (41 to 59 m) at the Al Hayat sector of the Bikita Mine, where most of the petalite production has originated (Copper 1964), is comparable to the 60 m breadth of petalite mineralization exposed in the widest part of the Big Whopper Pegmatite.

ECONOMIC GEOLOGY

Three commodities of economic significance are currently of exploration focus in the Separation Lake area: petalite, cesium and tantalum.

Petalite

The greatest interest at present is directed towards exploration evaluation of the area's petalite deposits, as the apparent global scarcity of viable petalite deposits, combined with its value in the specialized lithium ceramic industry, has recently generated a price rise to US$270 per ton for petalite concentrate (D. Bubar, president, Avalon Ventures Ltd., personal communication, 1997).

Fairly consistent Li_2O values are apparent across most of the Big Whopper Pegmatite, where contents varied between 0.97 to 2.00%, and averaged 1.58 % over 58.9 m in Trench 1, equivalent to an estimated petalite content of 37%. Furthermore, the average Li_2O content and calculated percent petalite in the four main pegmatite masses that represent most of the strike length of the Big Whopper pegmatite system is remarkably consistent (D. Bubar, president, Avalon Ventures Ltd., personal communication, 1997):

Apatite is rare in the Big Whopper Pegmatite which is an important observation as P_2O_5 is a deleterious constituent in petalite concentrates utilized in the ceramic industry; bulk analyses for P_2O_5 at Trench 1 revealed scant levels of this component (range: 0.03 to 0.22; average: 0.055 % P_2O_5: D. Bubar, president, Avalon Ventures Ltd, personal communication 1997).

The petalite potential is also considered excellent in the eastern pegmatite sub-group (*see* Figure 17.2) where the mineral has been documented at eleven pegmatites distributed within a 0.8 by 5 km area (Breaks and Tindle 1994). Most notable is Marko's Pegmatite, a 8 by 130 m lens-shaped mass which occurs on the claim-group of Champion Bear Resources and represents the best example of an internally-zoned pegmatite within the SLB. Two core zone units contain up to 95% white to grey petalite, which indicate that exceptional concentration processes for lithium were achieved in pegmatites emplaced in this particular part of the SLB.

Tantalum

An important commodity to consider in exploration of SLB is tantalum, the price of which has recently increased to $US40 per pound (for a concentrate that contains 40%

Table 17.3. Average Li_2O contents and calculated percent petalite across important pegmatites of the Big Whopper rare-metal system.

Pegmatite	Percent Li_2O/width	Calculated % Petalite
Big Whopper Pegmatite	1.58 % / 59.8 m	37%
Great White North Pegmatite	1.78 % / 14.3 m	41%
Bob's Pegmatite	1.67 % / 15.2 m	39%
West Pegmatite	1.56 % / 8.3 m	36%

Ta_2O_5) owing to a current global supply deficit of at least 400,000 pounds per annum (D. Bubar, president Avalon Ventures Ltd., personal communication, 1997). Wodginite ($MnSnTa_2O_8$), the chief ore mineral at the Tanco Mine, Canada's only primary producer of tantalum (Cerny et al. 1996), is widespread in the Separation Lake area and confirmed within eight different pegmatites (Tindle et al., in press).

The chemical variation in wodginite from the Separation Lake area is very extensive, encompassing the species wodginite (ss), ferrowodginite, titanowodginite and two possible new species ferrotitanowodginite and wolframowodginite (Tindle et al., in press). The variation with respect to the A- and B- cation sites (Figure 17.4) and the C-site (Tindle, unpublished data) is more extensive than has been any found elsewhere on a global basis, and is illustrative of a highly evolved rare-metal pegmatite system in regards to its Ta and Nb contents. This variation implies a significant exploration potential for tantalum in the Separation Lake area.

Other tantalum-bearing minerals present in the Separation lake pegmatites (*see* Table 17.1), also contribute to the bulk Ta_2O_5 values. The ranges of Ta_2O_5 contents along with those of the wodginite group are given Table 17.4.

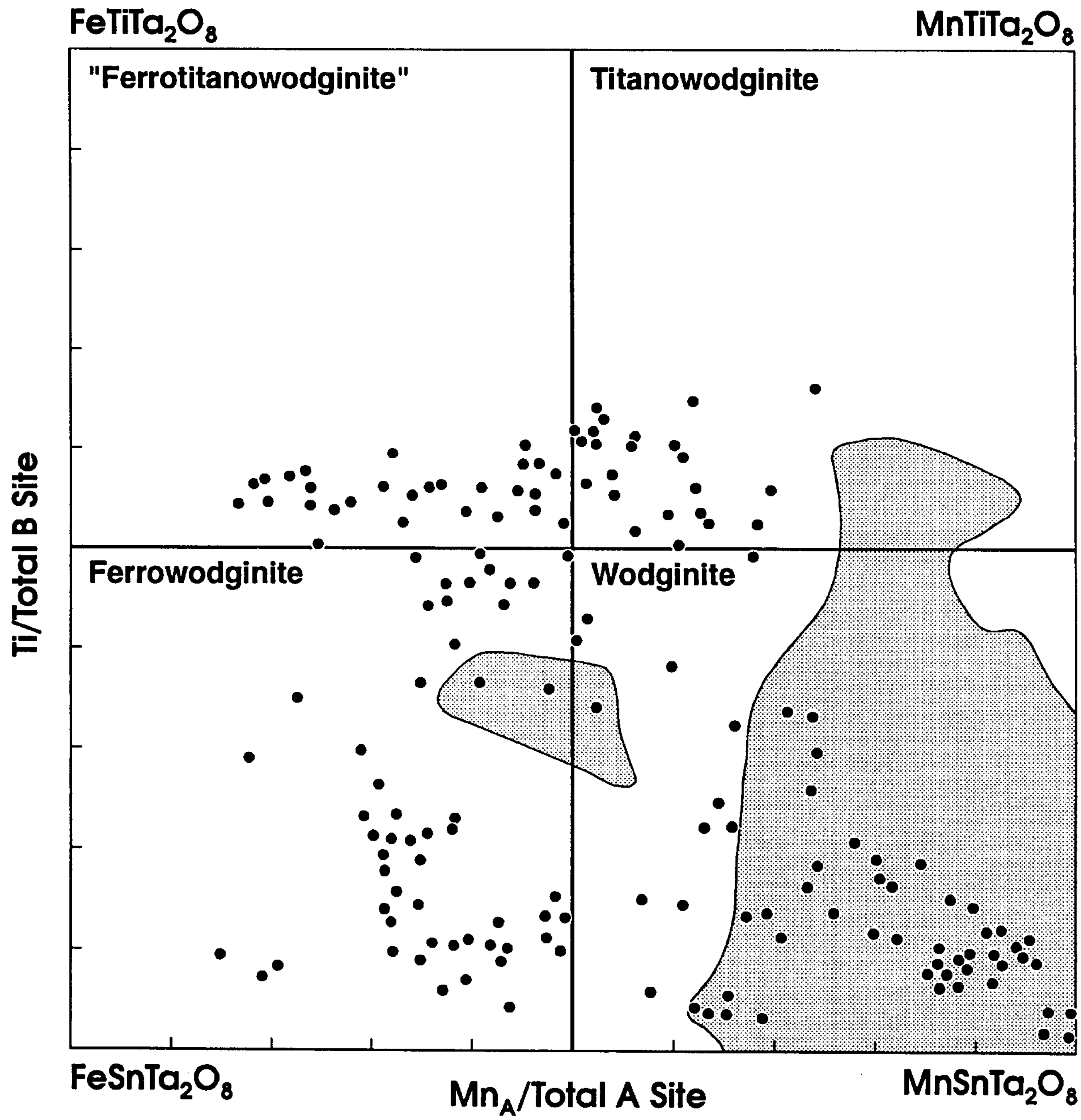


Figure 17.4. Classification quadrilateral for Separation Lake area wodginites (Tindle et al. in press). Shaded areas represent variation of 163 analyses of wodginite from the Tanco Mine, Manitoba (Ercit et al.1992, p.616).

Significant Ta_2O_5 bulk assay results encountered to date from the Separation Lake area are presented in Table 17.5.

Cesium

Cesium has recently found new application as cesium formate, an efficient deep-drilling solution in the petroleum industry (Ramsey and Shipp 1996). A cesium extraction plant is currently under construction at the Tanco Mine which will produce cesium and by-product rubidium from pollucite (Cerny et al. 1996, p.50–51). Pollucite $[(CsNa)_2Al_2Si_4O_{10}.H_2O]$, the only ore mineral for cesium, has been confirmed by X-ray diffraction at Marko's Pegmatite on the claim-group of Champion Bear Resources, where a single, 3 by 4 cm crystal has been located in the beryl-muscovite-albite-quartz wall zone (Photo 17.2). This represents only the fourth known pollucite occurrence in Ontario and demonstrates that physio-chemical conditions necessary for formation of this rare mineral, indicative of extreme fractionation (Cerny et al. 1985), was achieved at least locally in the Separation Lake area pegmatites. Hence, the exploration potential for cesium should be considered in the area.

EXPLORATION FOR RARE-METAL PEGMATITE MINERALIZATION

This deposit-type is amongst the most difficult to explore for in Archean terrains such as that represented by the Superior Province, which partially explains why the prolific rare-metal mineralization of the Separation Lake area remained elusive until recently. The difficulty in exploration for rare-metal mineral deposits is partly a reflection of the lack of responsiveness to airborne geophysical systems and the limited usefulness of ground geophysical surveys. Discovery of new deposits in the Superior Province thus requires an in-depth knowledge of regional geology, tectonics and high grade metamorphism and its controlling influence in the generation of anatectic plutons, concentration of rare-metals and important associated volatiles such as H_2O, F, B and PO_4.

Figure 17.5 presents a possible exploration sequence to consider in the exploration for rare-metal deposits in glaciated terrains such as that of the Canadian shield. In the reconnaissance phase of investigation, there are two aspects that are particularly effective:

Table 17.4. Range of Ta_2O_5 in Ta-Nb bearing oxide minerals from the Separation Lake area.

	$\%Ta_2O_5$
microlite	50–72%
columbite-tantalite	13–83%
wodginite	45–69%
tapiolite	70–82%
cassiterite	0.6–9%
struverite	24–42%

1. Recognition of parent granite plutons
2. Lithium-lithochemistry of metavolcanic host-rocks.

The Big Whopper pegmatite system was discovered utilizing a combination of the following:

1. recognition of parent granite and its internal fractionation trends, on bulk chemical and mineralogical basis (potassium-feldspar),
2. detection by of highly evolved, Mn-tantalite minerals in cleavelandite-rich pods (sample 93–260: Table 17.2) within the parent granite proximal to Big Whopper pegmatite system by electron microprobe analysis,
3. detection of exomorphic dispersion halos in mafic metavolcanic host-rocks, augmented by metasomatic selvedge data.

Search for Parent Granites

Identification of chemically- and mineralogically-specialized granites, if exposed, is very important in exploration as this will greatly reduce the area of search. If a parent granite can be located, then the area of investigation can be much more focused as the derivative rare-metal pegmatite swarms are typically distributed over 10 to 20 km^2 and proximal to such plutonic centres.

A classic example of a parent granite is the Separation Rapids pluton, which is the most chemically-evolved peraluminous granite mass yet found in the Winnipeg River–Cat Lake pegmatite field (Figures 17.6 and 17.7). It is exceptional that the maximum degree of fractionation for the SRP in terms of Cs and K/Rb ratios in potassium-feldspar almost overlaps with the lower end of the highly-evolved field for pegmatites of the Bernic Lake group in Manitoba, which contains the Tanco pegmatite (Cerny et al. 1981). The Bernic Lake Pegmatite Group is considered the most evolved pegmatite group in the entire field.

The following attributes are notable for prospective parent granite plutons:

1. small areal extent, typically greater than 10 km^2
2. textural and grain-size heterogeneity (commonly referred to as "pegmatitic granites" (Cerny et al. 1981)

Photo 17.2. First occurrence of pollucite found the Separation Lake area. The cavity situated below the 2.5 cm diameter coin contains a subhedral pollucite crystal contained in a beryl-muscovite-albite-quartz assemblage of the wall zone of Marko's Pegmatite (Champion Bear claim-group).

Table 17.5. High grade tantalum bulk analyses from the Separation Rapids Pegmatite Group.

$\%Ta_2O_5$	Rock Type	Pegmatite	Claim-Holder
1% T_2O_5 grab sample	Albite-rich replacement pods with cassiterite, wodginite and Mn-tantalite that overprint central petalite core zone.	Marko's Pegmatite	Champion-Bear Resources
0.22 % Ta_2O_5 (channel sample)	Primary wall zone unit rich in albite with fluorapatite, cassiterite and minor wodginite and uranmicrolite.	Pegmatite # 7	Champion Bear Resources
0.16 % Ta2O5 (grab sample)	Albitite dike (11.0 % Na2O with tapiolite, Ta-rutile and microlite.	Locality 96-9	Tanco Exploration/Gossan Resources

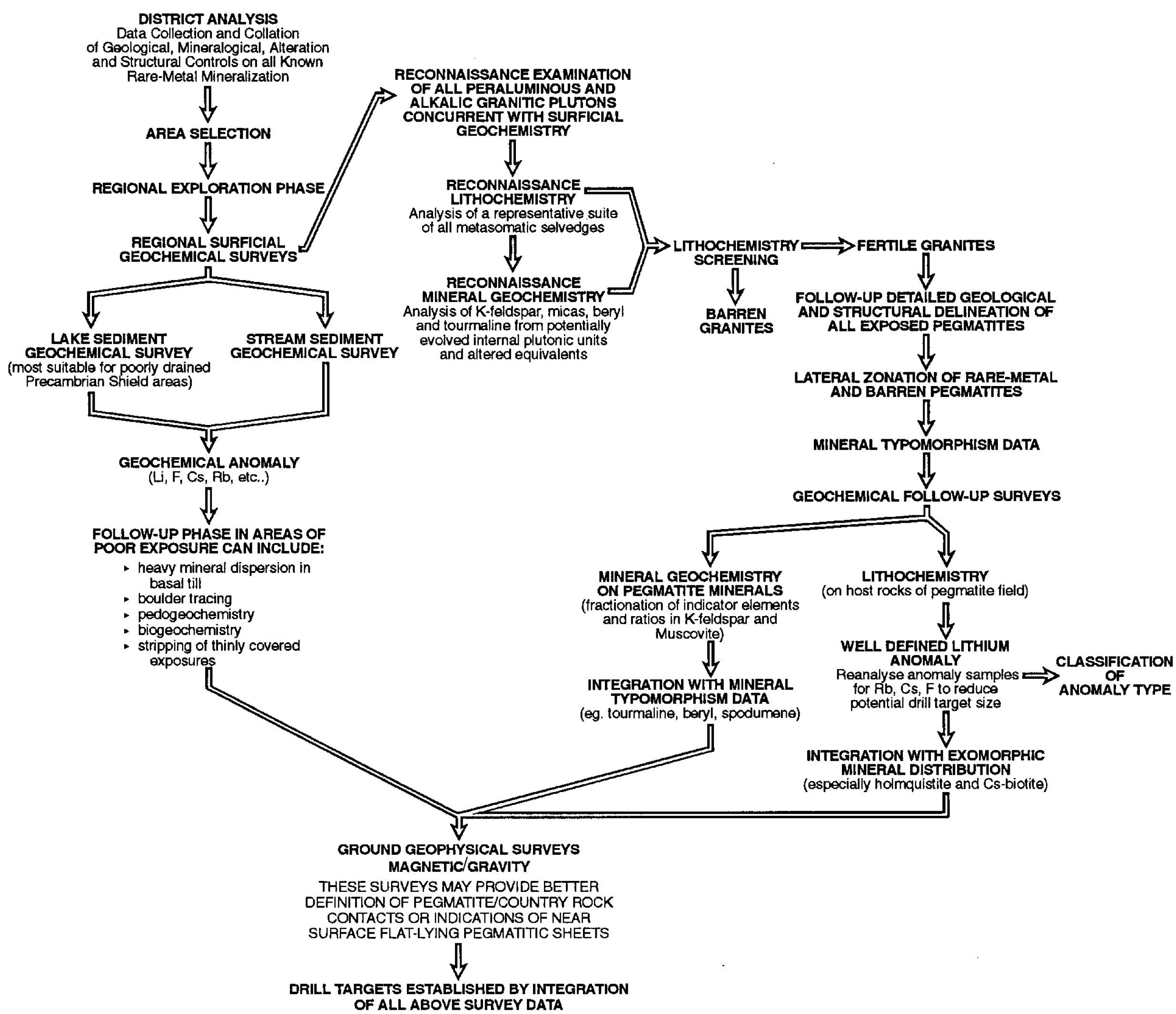


Figure 17.5. Suggested exploration scheme for rare-metal mineralization in glaciated Archean shield terrain.

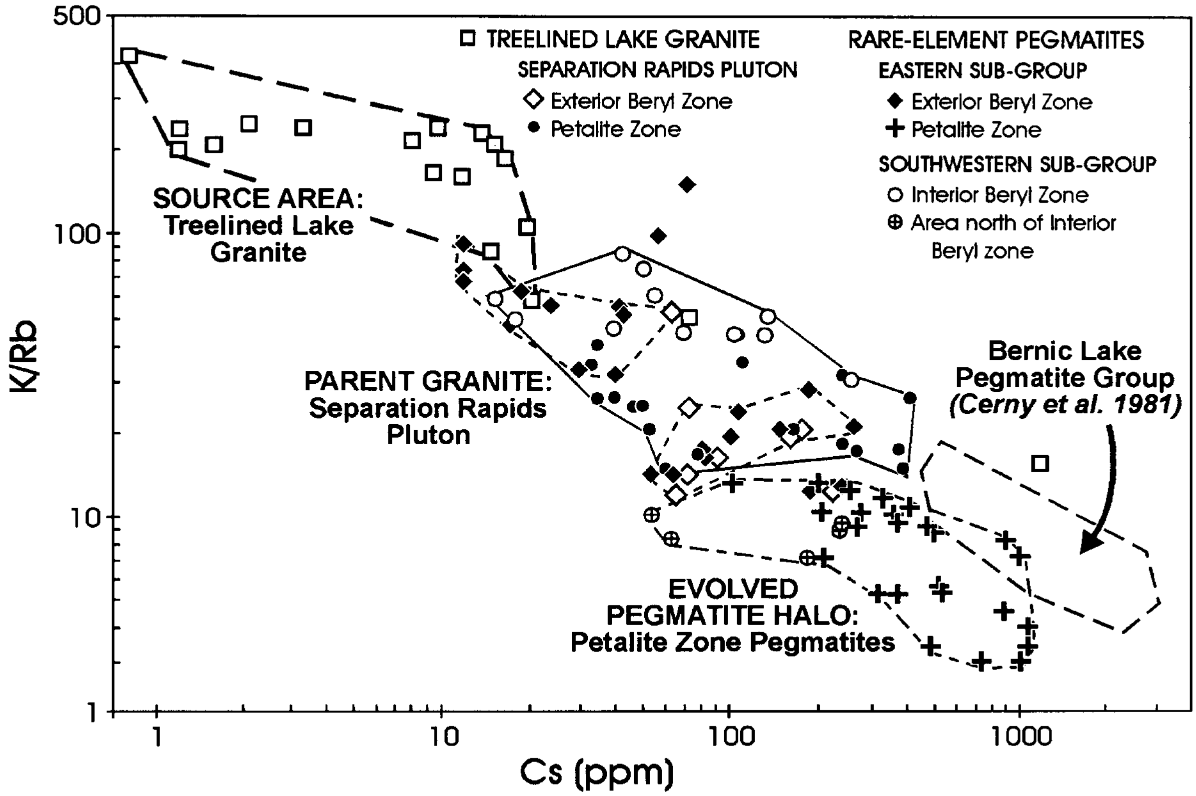


Figure 17.6. K/Rb versus Cs variation in potassium-feldspar from peraluminous granite and related rare-metal pegmatites of the Separation Lake area.

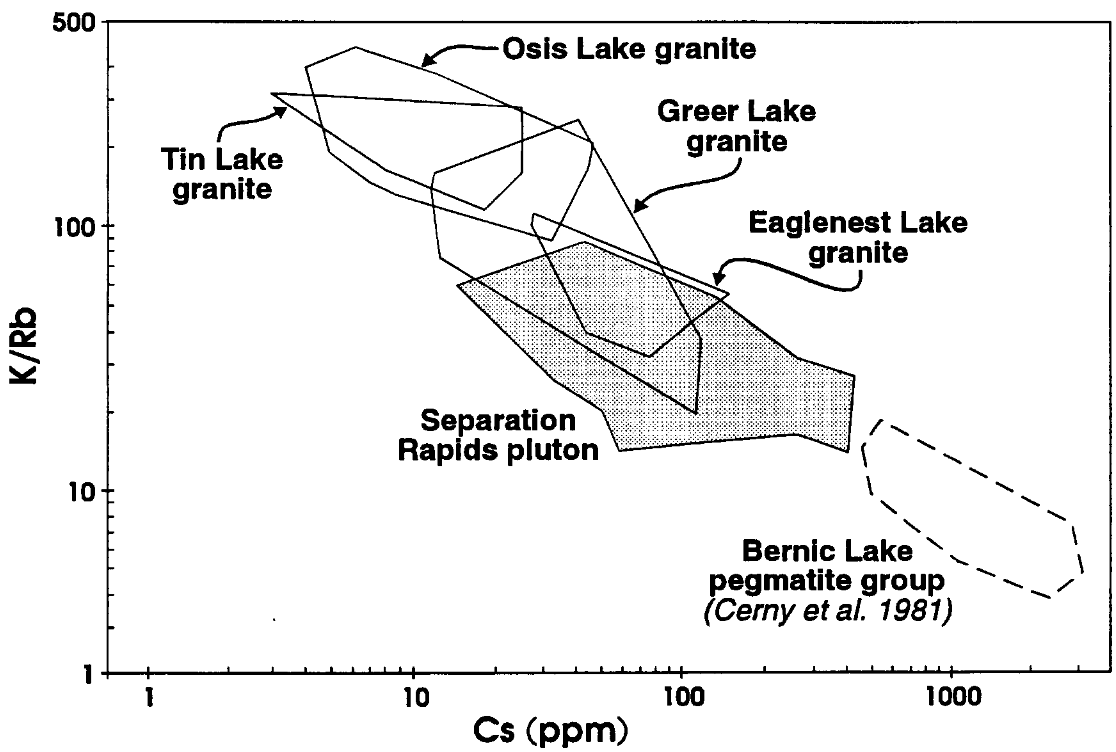


Figure 17.7. Fields of K/Rb versus Cs variation for potassium-feldspar from peraluminous granite plutons considered to be parental to rare-metal pegmatites in the Cat Lake–Winnipeg River Pegmatite Field

3. diagnostic peraluminous accessory and varietal minerals (e.g., primary muscovite, cordierite, aluminous biotite, garnet, tourmaline; rare beryl and topaz)
4. rare-metal minerals may be locally present (e.g., beryl, columbite, Li-tourmaline).

In the SRP, internal chemical fractionation trends were found to be particularly valuable in assessing where in the immediate mafic metavolcanic host-rocks to search for the exocontact rare-metal pegmatite swarms. Such trends are best detected by Rb and Cs contents in blocky potassium-feldspar which both reveal strong increase towards the south-central and southeastern margins of the Separation Rapids pluton (Figure 17.8). The maximum levels of these metals within the pluton closely corresponds to the commencement of the eastern and southwestern pegmatite subgroups (*see* Figure 17.2).

Tantalum Niobium Bulk Chemical Variation

Data for Ta and Nb are presented in Figure 17.9 and comprise bulk rock and internal units from the complete spectrum of peraluminous magmatism in the Separation Lake area, viz, the fractionation sequence Treelined Lake granite→Separation Rapids pluton→exocontact beryl subtype pegmatites→petalite subtype pegmatites. In most crustal materials, Ta and Nb exhibit strong geochemical coherence with the average crust Nb/Ta of 11.4 (Taylor and McClennan 1985). The peraluminous granites/pegmatites of the Separation Lake area, however, reveal strong fractionation of Ta relative to Nb such that the Nb/Ta exhibits a significant range of 0.05 to 8.4.

Most granites of the Treelined Lake granite complex (TLG) form a cluster near the average crustal Nb/Ta ratio ($mean_{15}$ = 14.5; range = 6–34) whereas the SRP samples are more evolved as the Nb/Ta ratios are generally significantly lower ($mean_{17}$ = 4.3; range = 0.8 to 8.4). The Separation Rapids pluton data falls into two clusters, that is, one that comprises mainly coarse-grained granites of the central core zone and a second cluster with higher Ta and Nb levels which are dominantly units of the outer pegmatitic granite zone of the pluton. The Nb/Ta ratio of 6.8 in the rare-metal-enriched, cassiterite-topaz sodic pegmatite at locality 94–84 indicates significant fractionation, which led to accumulation of rare metals and fluorine in residual pegmatitic melts, was attained locally in the TLG. The similarity of the Nb/Ta of 6.8 in the TLG to ratios of pegmatitic granite units of the nearby SRP supports the contention that the SRP represents evolved residual pegmatitic melt derived from the TLG.

Exocontact pegmatites that lie in the petalite zones of the Southwest and Eastern Pegmatite subgroups and situated adjacent to the Separation Rapids pluton, comprise a cluster of more fractionated rocks, with a Nb/Ta ratio range of 0.5 to 2. It is notable that two samples from the most evolved parts of the SRP, at localities 93–262 and 96–72, also plot within this data group. Extremely low Nb/Ta (0.1 to 0.05) characterize various units of petalite pegmatites in which Na greatly dominates over K, such as albitites, saccharoidal aplites and sodic pegmatites. Levels of Ta of economic importance (650 to 1600 ppm) are given locality reference in Figure 17.9 (94–44t, 96–9 and 96–53). It is also noted that these analyses along with 96–31 (Figure 17.9) exhibit Nb/Ta so extremely fractionated (less than 0.2) that even the range for tantalum ore deposits is exceeded, as exemplified lepidolite-tantalite rare-metal pegmatites of Russia (Smirnov 1976).

Lithium Lithochemistry

The late-magmatic history of pegmatite systems commonly led to the egress of fluids that metasomatically-deposited anomalously-high levels of K, Rb, Li, in the host-rocks. In exploration, lithium is particularly useful as it represents the most mobile exomorphic element in most rare-metal mineralized systems (Trueman and Cerny 1982) and commonly forms halos many times larger that the pegmatite bodies themselves. The most extensive lithium anomaly associated with rare-metal pegmatite mineralization delineated to date in Ontario, at 100 to 750 m breadth by greater than 7 km, was documented by Pryslak (1981) in the Dryden area (Breaks 1989) and provides an excellent example of the exploration value of Lithium-lithochemistry. Mean level of Li in mafic metavolcanic rocks from Superior Province of Ontario not known to contain rare-metal mineralization is 16 ppm (Breaks 1989, p.314).

Results of a preliminary survey that evaluated extent of Li dispersion in mafic metavolcanic rocks adjacent to the southwestern contact of the SRP are shown in Figure 17.10. The significant Li anomaly that surrounds the Big Whopper pegmatite system is commonly marked by Li values that exceed 80 ppm with a maximum of 245 ppm. The anomaly extends west from the southwest contact of the SRP (Tanco Exploration claim-group) on to claim 1178349 of Avalon Ventures Limited, a minimum distance of 2 km.

Metasomatic Selvedges

These refer to narrow zones of highly altered metavolcanic host-rocks that lie immediately adjacent to a pegmatite mass. These domains, typically 1 to 3 cm thick and exceptionally up to 30 cm thickness, originate via intense metasomatic interaction of pegmatitic fluids with typically mafic metavolcanic host-rocks. These selvedges are typically recognizable as schistose, biotite-rich mineralogical domains that contrast from nearby hornblende-plagioclase assemblages of less altered mafic metavolcanic rocks.

As the chemistry of these domains "reflect the internal mineralogy of the spatially associated pegmatite" (London 1992, p.528), there is immediate application to mineral exploration as analysis of such materials can give the explorationists a quick idea as to what metals should be expected in a given pegmatite body. This is particularly important if many of the difficult and exotic minerals within a given pegmatite body are not recognized in the initial investigation phase. Figure 17.11 reveals highly anomalous cesium

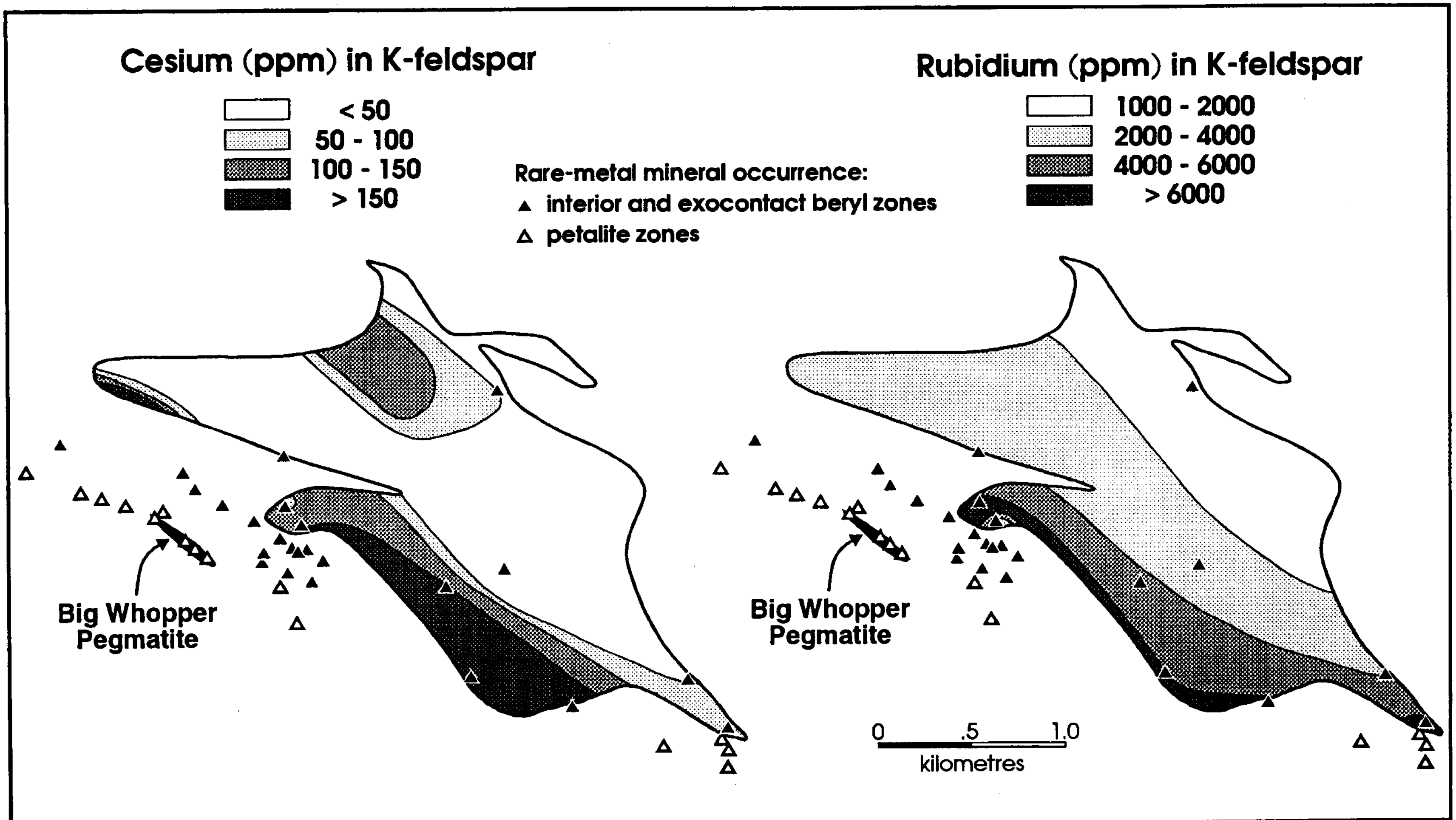


Figure 17.8. Variation of rubidum and cesium in potassium-feldspar within the Separation Rapids pluton.

levels (range: 1000 ppm to 1.4 %) were concentrated in metasomatic selvedges in pegmatites that comprise the eastern part of the Big Whopper system. Such concentrations imply the presence of cesium-rich minerals such as pollucite within the southwest pegmatite subgroup. Cesium contents of 1 % and above in metasomatic selvedges elsewhere in the SLB (Marko's Pegmatite up to 1 % Cs) and in the Dryden area (1.6% Cs: Breaks, 1989, p.332) closely correlate with the presence of pollucite zones in the adjacent rare-metal pegmatite system.

RECOMMENDATIONS FOR FUTURE MINERAL EXPLORATION

The following recommendations derive from the work undertaken to date in the Separation Lake area:

1. significant tantalum- and cesium-rich mineralization could lie at depth within the eastern part of the Big Whopper pegmatite system as exposed on claim 1178349 of Avalon Ventures Limited and the adjoin-

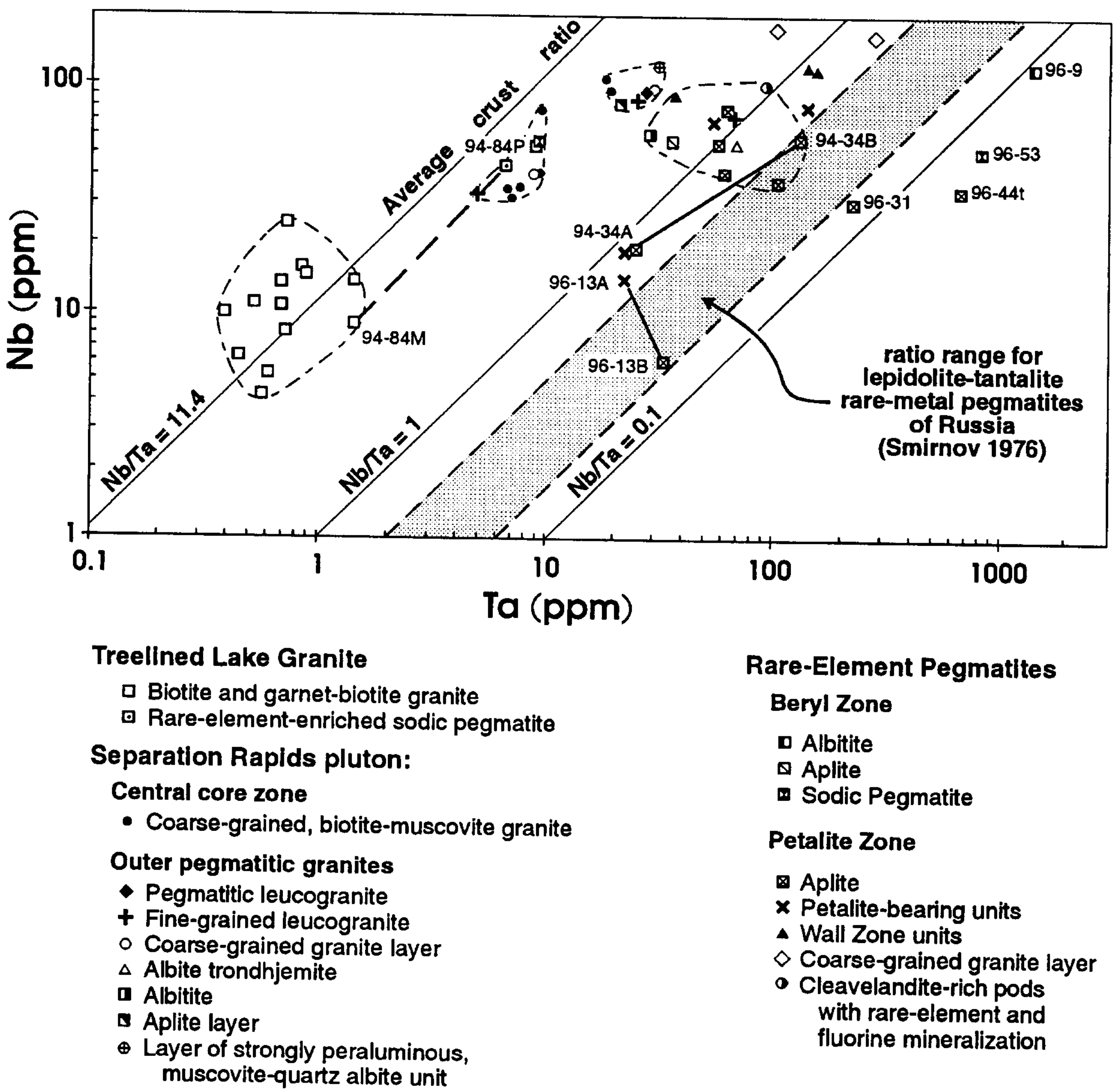


Figure 17.9. Ta versus Nb in various units of rare-metal pegmatites and peraluminous granites of the Separation Lake area.

ing claim of Tanco Exploration. The potential for tantalum is indicated by the presence of ferrowodginite and tapiolite in this area coupled with one of the highest bulk concentrations of tantalum yet encountered in the SLB (locality 96–9 on Tanco Exploration ground: Figure 17.2, Table 17.5). This high value is mainly attributed to tapiolite (*see* Table 17.2) which also has been found in three other proximal pegmatites in the beryl zone. Furthermore, extreme fractionation of tan-

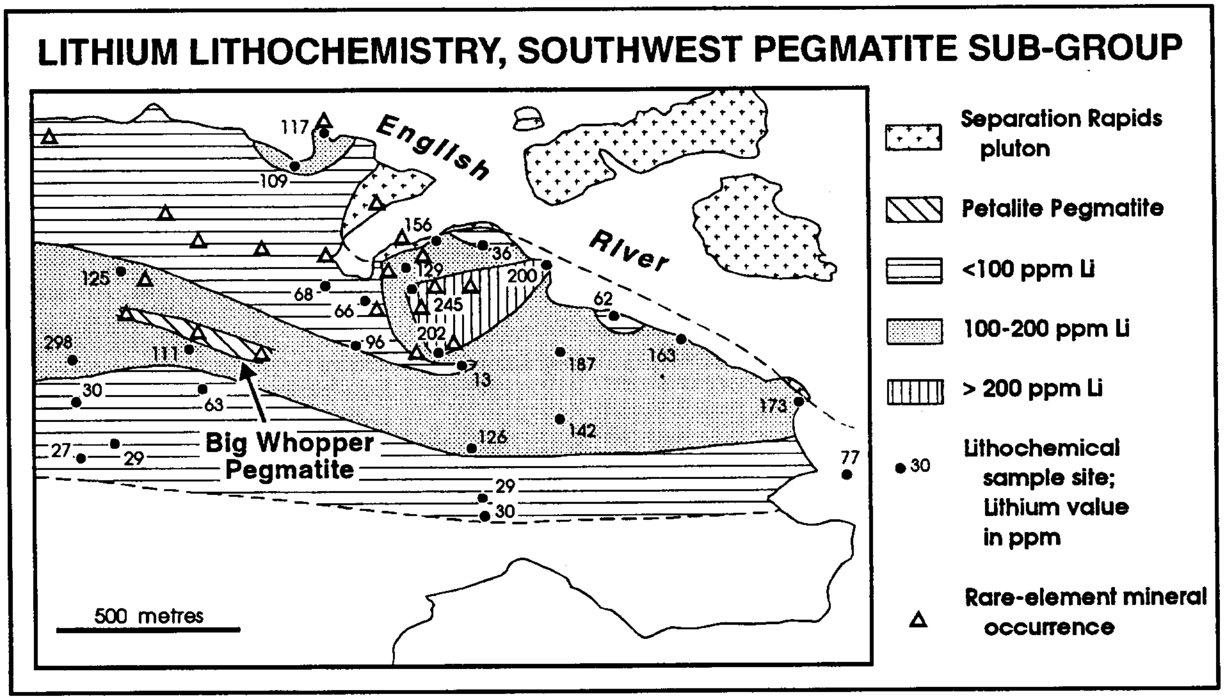


Figure 17.10. Lithium variation in mafic metavolcanic host-rocks to rare-metal pegmatites of the eastern part of the Southwestern Pegmatite Subgroup.

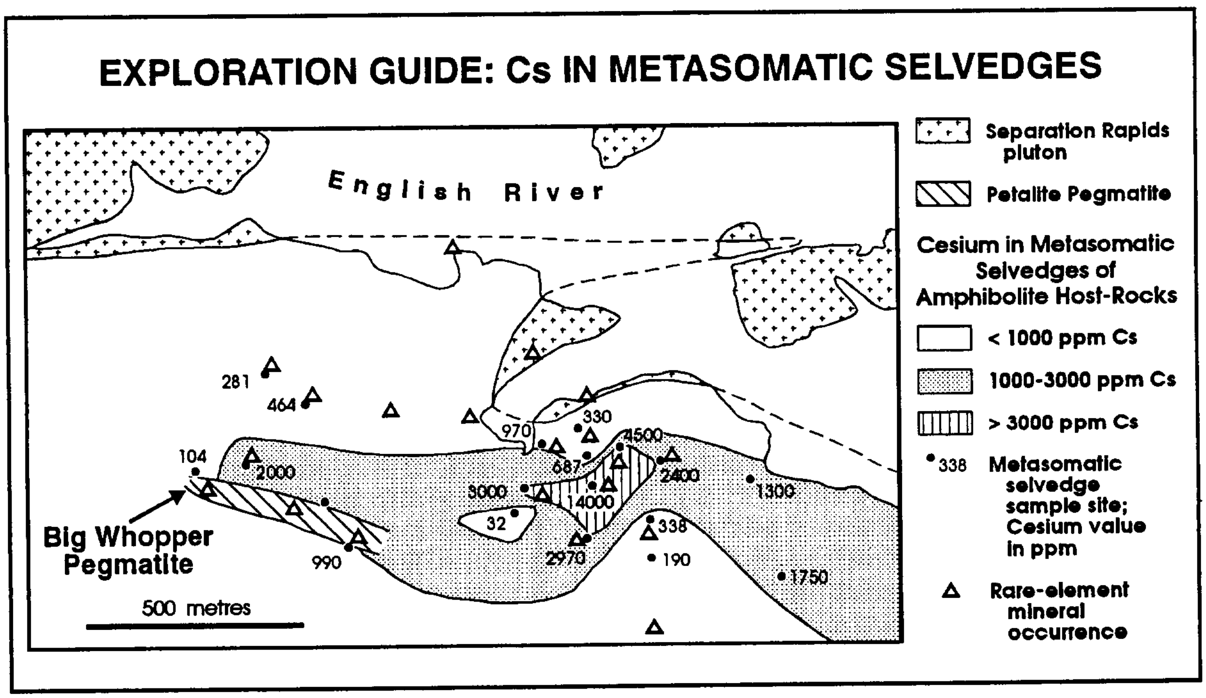


Figure 17.11. Cesium in metasomatic selvedges in southeastern rare-metal pegmatite subgroup.

talum relative to niobium has been established in this area.

2. examination of the cesium content in metasomatic selvedges is recommended as an exploration tool.

3. other areas of SLB merit exploration for other potential rare-metal pegmatite swarms, which to the authors' knowledge have not been explored for rare-metal mineralization:

a. **Selwyn Lake area** where Morris (1996; his Figure 8) has documented local concentrations of gahnite in basal till samples. Gahnite, although present in several varied mineralization environments, is characteristic of peraluminous granite-pegmatite systems (Tindle and Breaks in press). Gahnite is widespread in the Separation Lake area and has been documented in the Treelined Lake granite, Separation Rapids pluton and rare-metal pegmatites in the eastern sub-group (Breaks and Pan 1995; Tindle and Breaks in press) and this work (Big Whopper and Great White North Pegmatites). Presence of gahnite with chemistry indicative of a rare-metal pegmatite source occurs in basal till of the Selwyn Lake area and therefore indicates that this area should be given exploration attention for petalite pegmatites.

b. **Ryerson-Routine lakes area**: Breaks et al. (1975) reported several occurrences of muscovite-bearing peraluminous granites in this area. These granites, which could be potentially parental to rare-metal mineralization, occur at three scattered localities proximal to a 20 km strike-length of the narrow, easterly extension of the Bird River Belt into Ontario, (i.e., with the following latitude/longitude locations: 50°22'33"N/95°07'45"W; 50°22'51"N/95°01'13"W; 50°22'40"N/94°50'43"W).

c. **Helder Lake area**: The tapering easterly part of the SLB and associated enclaves in nearby granitic rocks, between Longitude 94°28'W east to Helder Lake represents good exploration ground for further discoveries of rare-metal pegmatite bodies, as the northeastern limits of the eastern rare-metal pegmatite subgroup is as yet undefined. It is important to note that the highest degree of fractionation in any pegmatite body in the SLB was documented at Pegmatite #7 (Champion Bear Resources claim-group) as revealed by potassium-feldspars whose Rb contents exceeded the upper analytical limit of 3.5% Rb. Hence pegmatites further to the northeast of Pegmatite #7 could exist that also express a similar degree of extreme fractionation.

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18. Geological Setting of Offset Dikes and Allied Hypervelocity Impact Studies within the Sudbury Structure — UNB Sudbury Research Program

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INTRODUCTION

The UNB Sudbury Research Program, which commenced in 1991, currently comprises a team of five (four graduate students and supervisor). The primary focus is to establish the geological setting of the radial and concentric offset dikes that emanate from the main mass of the Sudbury igneous complex (SIC). From the association of these dikes with Sudbury Breccia (pseudotachylyte) and with radial and concentric fracture/fault systems, it is clear that the origin of the dikes is connected with the generation and modification stages of impact basin formation that took place at approximately 1.85 Ga. In particular, the research aims to identify those processes that operated during the modification stage, where target rock behaviour was dominated by gravitationally-driven crater collapse. Ten offsets are known (Figure 18.1) and these can be subdivided into radial (e.g., Copper Cliff, Worthington) and concentric (e.g., Hess, Manchester) variants.

At present, three concentric offsets are being studied in detail: Hess in the North Range (C.R. Wood. M.Sc.), and Frood–Stobie (R.G. Scott, Ph.D.) and Manchester (J.P. O'Connor, M.Sc.) in the South Range (*see* Figure 18.1). Work on the Whistle–Parkin (radial) Offset will commence in 1998. In addition, an investigation of shatter cones, primarily focussed in the South Range, is nearing completion (H.M. Gibson, Ph.D.).

THE FROOD–STOBIE (SOUTHERN) BRECCIA BELT

The Frood–Stobie breccia belt is a subconcentric arc of pseudotachylyte (*see* Figure 18.1), ranging from 0.1 to over 1 km in width, and reaching approximately 45 km in length (Scott et al. 1996). It abuts the SIC in the vicinity of the Kirkwood Mine in the east (Garson Township), and at the abandoned Victoria Mine in the west (Denison Township). It also connects to the SIC via an embayment/funnel structure in the Little Stobie and Mount Nickel Mines area (Blezard Township). The belt is cut by the Copper Cliff radial Offset Dike. Exposure is relatively good to the east of the Copper Cliff Offset (where extensive sampling has been carried out for magnetic and petrochemical work), but is poor to the west of it. Outcrop in Graham and Waters Townships is typically limited to boulders in low-lying, marshy terrain, as originally noted by Speers (1957). However, the full extent of the belt is well expressed as a 120 nT high in regional aeromagnetic data. The reason for the high is not yet clear, but it is probably due to the paramagnetic susceptibilities of ferromagnesian silicates that are both concentrated and aligned within the pseudotachylyte matrix.

The belt consists of subrounded to rounded, clasts and large blocks of metasedimentary and metavolcanic rocks of the approximately 2.3 Ga Huronian Supergroup (Debicki 1990). These inclusions range from several millimetres to tens of metres in size and they are set within a dark, fine-grained recrystallized matrix. The inclusions and matrix together comprise Sudbury Breccia, also known as Frood Breccia, which we now know is a form of pseudotachylyte (Dressler 1984; Thompson and Spray 1996). The matrix comprises quartz + biotite + plagioclase + potassium-feldspar + ilmenite, with minor pyrite and pyrrhotite. Zircon is ubiquitous and easily detected via pleochroic haloes in biotite. The matrix of the pseudotachylyte is annealed, with no melt glasses detectable (if ever present). The matrix is locally massive, but is more typically found strongly foliated as defined by biotite. The biotite foliation may present a primary flow structure, or a metamorphic overprint formed during the Penokean (1.9 to 1.7 Ga) and/or Grenvillian ($\sim$1 Ga) orogenies. Ongoing textural and geochronological ($^{40}Ar/^{39}Ar$) work will help to resolve this.

The belt hosts one of the world's largest deposits of Ni-Cu-PGE ore, the Frood–Stobie mine complex, which has been in production for more than a century. Deposits at the Kirkwood, Little Stobie and Victoria mines have also contributed economic significance to the belt.

The Ni-Cu ore is commonly associated with quartz diorite bodies that are, in turn, hosted by the pseudotachylyte. However, in contrast to the more typical offset relationships found at Sudbury, the prime association at Frood–Stobie is with pseudotachylyte rather than quartz diorite; the latter being volumetrically subordinate. The ores are primarily composed of massive to disseminated chalcopyrite, pyrrhotite and pentlandite, with minor associations of numerous rare PGE phases (e.g., froodite; $PdBi_2$).

The Frood–Stobie pseudotachylyte belt was derived by the frictional comminution and melting of wall rocks, most probably during large displacement seismogenic faulting (superfaulting, Spray 1997). Such fault behaviour may be the result of gravity-induced transient cavity collapse, which leads to the slumping of the crater walls into the impact melt sheet.

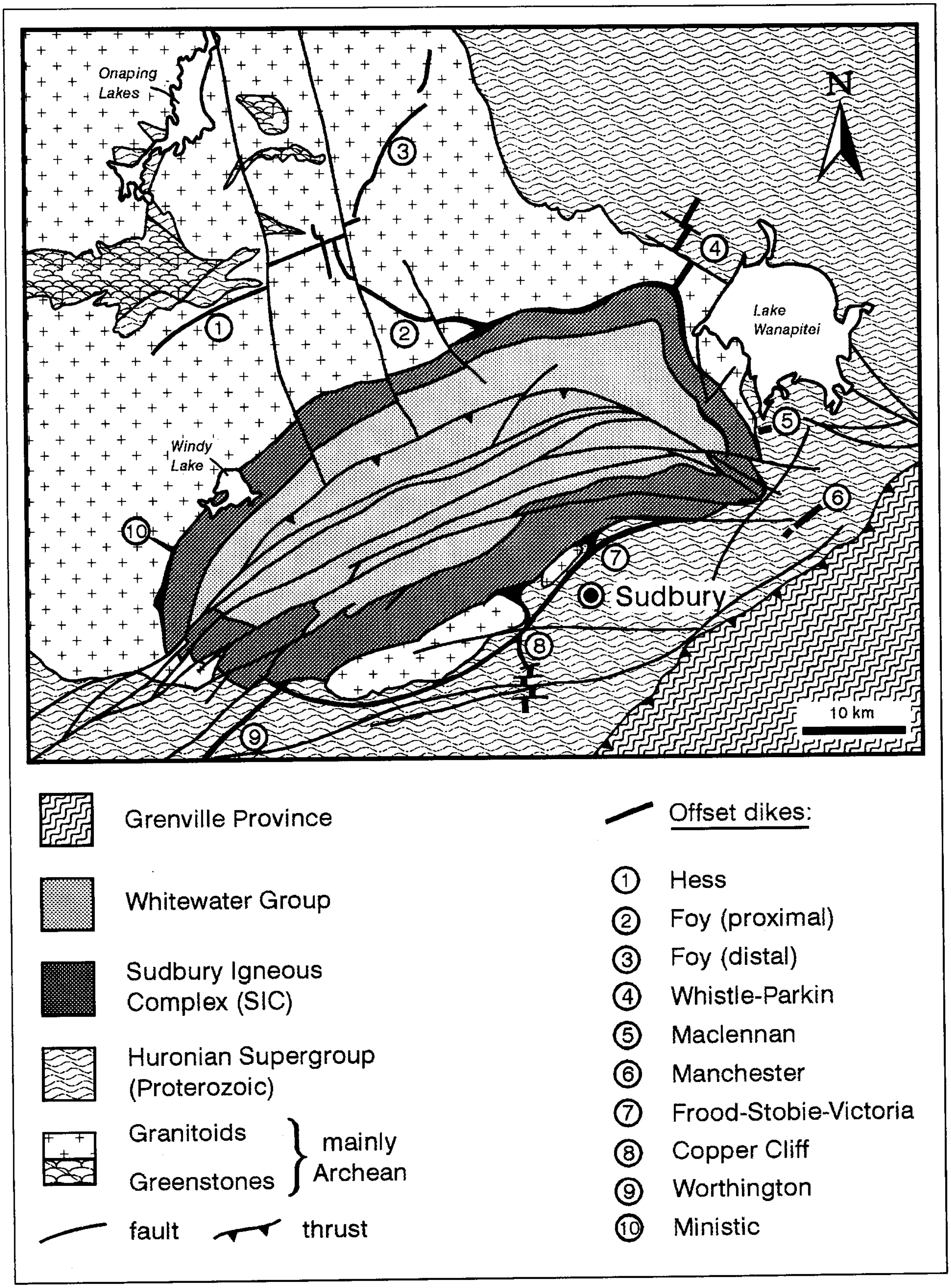

Figure 18.1. Simplified geology of part of the Sudbury Structure indicating known offset dike locations and their names. Note that many of the offsets extend further than previously mapped.

THE HESS OFFSET DIKE

The Hess Offset occurs as a subconcentric dike located 13 to 15 km NNW of the base of the Sudbury Igneous Complex (SIC) within predominantly Archean granitoids of the Sudbury impact structure. It comprises so-called quartz diorite, allied to the magmatic rocks of the SIC, and is locally mineralized. The Hess body appears mineralogically distinct from the more typical quartz diorite offsets of the Sudbury Camp — it is generally less quartz-rich. The offset extends from at least as far as Clear (formerly Hess) Lake in the west (just east of Cartier), to east of the radially-oriented Foy Offset, for a total strike distance of approximately 23 km. Its thickness is 10 to 30 m and it is commonly found in association with Sudbury Breccia (pseudotachylyte). The nature of displacement on the post-impact reactivated, NNW-trending, Fecunis Lake and Sandcherry Faults indicates that Hess dips steeply to the south.

Previous work in the North Range suggested that the Hess Offset occurs at the northern margin of a pseudotachylyte-rich annulus surrounding the SIC (Thompson and Spray 1994, 1996). Critically, this implied that Hess could "line" the annulus margin and hence be more extensive than originally mapped (Card and Innes 1981). This project therefore sought to map and trace out the full extent of Hess (Wood et al. 1997), the result being that Hess has been extended approximately 8 km west of its previously determined limit (Card and Innes 1981). The common association of the Hess Offset with Sudbury Breccia (pseudotachylyte) indicates that Hess does indeed delineate a subconcentric fault system that defines either (1) part of the collapsed and modified northern margin of the transient cavity of the Sudbury impact structure, or (2) the northern margin of the peak ring. The pseudotachylyte occurs as discrete veins (up to 0.5 m wide and as mm to microscopic veinlets), allied to broader zones of more cataclastic deformation. The larger pseudotachylyte veins are typically subparallel to the Hess Offset, whereas the finer veinlets are more anastomosing.

Major, trace and REE chemistry of selected Hess samples clearly indicates an affinity with the SIC. The primary mineralogy is quartz + plagioclase (labradorite rimmed with oligoclase) + pyroxene (usually found altered to actinolite) + hornblende + biotite. Opaque phases include pyrite, pyrrhotite, pentlandite and chalcopyrite, with minor amounts of argentiferous pentlandite ($FeNi_8AgS_8$), michenerite (PdBiTe) and hessite (Ag_2Te). Secondary (deuteric) phases include titanite, epidote, chlorite and actinolite. The magmatic source of the Hess Offset is unclear: it may be fed laterally from the proximal Foy Offset (*see* Figure 18.1), which is directly connected to the SIC, or it may be fed underneath via a listric fault system which connects at depth to the lower levels of the SIC. Field work indicates that the distal Foy is in turn fed by Hess (*see* Figure 18.1). The Hess Offset is of interest because it is the most distal concentric offset known. As such, studying it can throw light on the nature of impact-related fracturing and faulting in target rocks well beyond the SIC.

THE MANCHESTER OFFSET DIKE

The Manchester Offset dike is located 4 to 5 km SE of the SIC within Huronian metasedimentary footwall rocks. Although it was mapped as a basic to intermediate dike-like body in the 1950s (Thomson 1959), it was only recognized as an SIC-related offset in the 1970s (Grant and Bite 1984). The dike is subconcentric to the SIC and is up to 30 m wide. It strikes discontinuously for at least 10 km and dips about 60° to the SE. A thicker, better exposed zone, approximately 5 km in length, is centred within the 10 km strip. Manchester is hosted by a broad zone of Sudbury Breccia (pseudotachylyte), the southern limit of which is, in part, defined by the so-called Falcon Fault, which was post-impact generated or reactivated. The host pseudotachylyte zone is up to 350 m thick. Contacts between the pseudotachylyte and the dike are generally sharp, with the dike being slightly chilled against the pseudotachylyte. The dike comprises the assemblage quartz + plagioclase + alkali feldspar + amphibole + biotite. Granophyric and myrmekitic intergrowths are particularly common. Clinopyroxene relics also occur. The dike is a quartz diorite and, although clearly genetically related to the SIC, is more siliceous than many of the other offsets of the Sudbury structure. This may reflect the effects of assimilating the quartzo-feldspathic (Huronian) wall rocks.

Critical to this study is the original mode of connection between the Manchester Offset and the SIC, as there is no apparent physical attachment between the two at present exposure levels (O'Connor and Spray 1997). Penokean faulting has dismembered the Manchester Offset and field studies cannot yet constrain the magma emplacement direction (i.e., whether lateral or vertical). If a lateral connection to a radial offset cannot be found, then the implication is that Manchester was emplaced from below, or from above, via SIC-concentric listric faulting initiated during collapse of the transient cavity some time after hypervelocity impact.

SHATTER CONES

Shatter cones have been studied extensively in the South Range of the Sudbury Structure over the last four years. One of the objectives of the study was to establish diagnostic criteria for the field identification of shatter cones. The following is a summary of results (Gibson and Spray 1997).

Shatter cones are commonly described as being conical, striated fracture surfaces formed as a result of hypervelocity impact (Dietz 1960). Other structures having similar, but not identical, morphological elements include blast fractures, natural percussion marks, slickensides, wind-abrasion structures, and cone-in-cone structures.

A true shatter cone must possess three basic elements: (1) a conical, or part conical, fracture surface; (2) ridge and groove striations that diverge from an apex or central striae; and (3) a penetrative, rather than a surficial, distribution in the host rock.

Blast fractures are true fracture surfaces, but they are not conical. Most commonly, they consist of a radiating array of planar fractures. Percussion marks results from the impact of cobbles and boulders on one another within a rapid flow regime (typically fluvial). These can possess conical fracture surfaces that may include crude striations, so their morphology is superficially similar to that of shatter cones. However, percussion marks are restricted to the exposed impact surface, so they are not a penetrative structure. Slickensides have ridge and groove striations similar to those of a shatter cone. However, the fracture surface is planar to subplanar, and not conical. Nor do slickensides exhibit diverging striations like shatter cones. Cone-in-cone structures are not fracture surfaces, but are displacive growths of calcite formed within a carbonate-rich sediment. As such they possess a characteristic internal structure that is distinct from that found in shatter cones (e.g., cone-shaped oriented crystal growth and development rather than a conical fracture system). Conical structures formed as a result of wind abrasion lack a fracture surface and are spatially restricted to outcrop surfaces facing the prevailing wind direction at the time of formation.

If care is taken, the above evidence can be used to distinguish true shatter cones formed by hypervelocity impact from other cone-like structures at the mesoscopic scale (i.e., in the field). At the microscopic scale (e.g., using a scanning electron microscope), shatter cones may be further distinguished by the localization of planar deformation features (PDFs) in the vicinity of cone surfaces (Hargraves and White 1996), as well as by the presence of spherules (vapour condensates) and high-pressure polymorphs indicative of shock (Gibson and Spray, in press).

ACKNOWLEDGMENTS

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19. Metallogenic Potential of the Nipissing Diabase: New Approaches to Ascertaining the Mineral Potential

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INTRODUCTION

This project is part of a PhD thesis at the University of Western Ontario, under the supervision of N. MacRae (University of Western Ontario) and R. Keays (Laurentian University). The thesis is directed toward ascertaining the potential for economic concentrations of Cu-Ni-PGE (platinum group element) metals in the rocks of the Nipissing Diabase and will involve a minimum of two field seasons (1997 and 1998) in the area between Sault Ste. Marie and the west shore of Lake Temagami. Field work will involve detailed geological mapping of specific Cu-Ni-PGE occurrences and lithogeochemical sampling of the Nipissing Diabase and immediately adjacent rock units.

PREVIOUS WORK

Much of the early detailed work on the petrology, structure and mineralization of the Nipissing Diabase and associated metasedimentary and metavolcanic rocks was concentrated in the Cobalt–Gowganda region (e.g., Bowen 1910; Collins 1910; Hriskevich 1968; Jambor 1971; Conrod 1989). By the 1980s, there was increased interest in the Nipissing Diabase westward toward the Sudbury and Sault Ste. Marie areas, with particular attention toward its potential as a host to platinum group elements (PGEs), and/or copper, and/or nickel (e.g., Lightfoot et al. 1986; Rowell and Edgar 1986; Lightfoot et al. 1987; Lightfoot and Naldrett 1989). The current project builds on the early work, but will also supplement more recent contributions (e.g., Lightfoot et al. 1993; Lightfoot and Naldrett 1996) and introduce new approaches that will be of use in exploration for Cu-Ni-PGE-rich sulphides that are both in and associated with the Nipissing Diabase.

GENERAL GEOLOGY

The Nipissing Diabase forms a significant igneous component of the Southern Province of the Precambrian Shield, occupying about 20% of the outcrop area. The intrusive bodies are considered to be a product of rift-related magmatism and were emplaced into Archean and early Huronian sedimentary rocks as a series of undulating sills, and less commonly as dikes; subsequent erosion produced isolated basins and arches, representing the lower and upper parts of the sills respectively (Jambor 1971). The intrusions consist primarily of gabbros (gabbro, quartz gabbro, hypersthene gabbro), with subordinate diabase and granophyre. Lightfoot and Naldrett (1996) refer to the intrusions collectively as the Nipissing Gabbro Intrusions of the Nipissing Magmatic Province.

Numerous high-grade showings and deposits of Cu-Ni-PGE sulphides and gold occur within rocks of the Nipissing Diabase or are proximal to the intrusive contacts of the Nipissing Diabase and surrounding country rocks. The distribution of known prospects extends from the Whitefish Falls area (Card 1976), southwest of Sudbury, to Janes Township (Dressler 1979), southwest of Lake Temagami. Showings of Cu-Ni-PGE sulphide mineralization are observed at or near the basal contacts within the basins, as isolated podlike bodies in the middle to upper arches, and as shear-zone and quartz-carbonate vein-related deposits in both the basin and arch portions of the sills. Gold prospects and economic gold deposits have been found in association with the Nipissing Diabase. The gold deposits are either hosted within the metasedimentary rocks themselves (e.g., Card et al. 1975) or are associated with contact regions between the Nipissing Diabase and sedimentary rocks. Skarn deposits, primarily found at the contacts between gabbroic rocks of the Nipissing Diabase and calcareous metasedimentary rocks, are not as well documented as sulphide occurrences, but also show excellent potential as targets for gold exploration.

ECONOMIC POTENTIAL

The impact of the meteorite that produced the Sudbury Igneous Complex induced melting of the upper crust and generated a melt sheet that presumably had a composition corresponding to that part of the upper crust from which the melt sheet was derived (Lightfoot et al. 1997). At the time of impact (~1.85 Ga), the Nipissing Diabase and metasedimentary rocks of the Huronian Supergroup constituted the bulk of the rocks in the area. Assuming that the ores of the Sudbury Igneous Complex were derived from the upper crust, it is probable that the rocks of the Nipissing Diabase, and its associated sulphides, contributed to the inventory of Cu-Ni-PGEs in the Sudbury Igneous Complex. This suggests that the Nipissing Diabase hosted at least some of the protores of the Sudbury Igneous Complex, distinguishing them as excellent targets for Cu-Ni-PGE exploration.

To date, exploration and development of the nickel and copper ores in the Sudbury Igneous Complex have diverted any serious attempts to assess the potential for economic accumulations of copper and/or nickel and/or platinum group element sulphides in rocks of the Nipissing Diabase. For the past 30 years, it has primarily been the grass-roots prospector who has conducted exploration of the Nipissing Diabase, with only sporadic interest on the part of major and junior mining companies. The result has been a haphazard assessment of the potential of the Nipissing Diabase to host economic deposits of Cu-Ni-PGE sulphides. Nonetheless, this erratic approach has resulted in the discovery of several new occurrences and has expanded our understanding of many of the known Cu-Ni-PGE prospects. What is now required is a systematic evaluation of the sulphide occurrences within the Nipissing Diabase to develop an exploration model that is useful to both the prospector and the major and junior mining companies.

OBJECTIVES

One of the most important aspects of this study is to determine whether or not the magmas of the Nipissing Diabase were sulphur saturated or sulphur undersaturated at the time of magma formation. If the magmas were sulphur saturated, they would have been depleted of ore-forming chalcophile and/or siderophile elements (i.e., Cu-Ni-Au-PGEs) and would not be considered capable of producing economic Cu-Ni-PGE deposits (e.g., Keays 1995). However, if the Nipissing Diabase magmas were sulphur undersaturated, it is expected that they would have kept their full complement of chalcophile and/or siderophile elements.

When the magmas became sulphur saturated, either through contamination from sulphur-rich sediments or through an increase in the silica content of the magma, they would have formed sulphides that were strongly enriched in nickel, copper, gold, platinum group elements and other highly chalcophile and/or siderophile metals. These sulphides would have formed massive magmatic sulphide deposits and/or disseminated sulphide mineralization; subsequent remobilization of the sulphides may also have led to the development of hydrothermal gold and/or Cu-PGE deposits. The most effective way to test the sulphur-saturation model is through systematic lithogeochemical sampling of both mineralized and nonmineralized rock units, followed by a geochemical comparison of the two sample suites (cf. Hoatson and Keays 1989; Keays 1995).

The aims of this project are as follows: 1) Characterize known occurrences of Cu-Ni-PGE sulphide mineralization in the Nipissing Diabase. This will include a description of the host gabbroic rocks and immediately adjacent sedimentary rocks. 2) Determine the ore-forming potential of the Nipissing Diabase magmas, and in particular the formation of economic accumulations of Cu-Ni-PGE sulphides. This will include determination of Pd/S, Pd/Se and Pd/Cu ratios from both mineralized and nonmineralized rock units. 3) Determine the controls on sulphide mineralization, including an assessment of the sulphur fugacity of the magmas and evidence for contamination based on light rare earth element, $^{87}Sr/^{86}Sr$ and S/Se ratios. 4) Identify and assess the effectiveness of various elements as pathfinders for mineralization. 5) Elucidate the petrogenesis of the Nipissing Diabase and establish the tectonic environment in which the intrusions were emplaced.

The outcomes of this research project will be to 1) develop a model that explains the distribution of the Cu-Ni-PGE metals that is of general use in the exploration for Cu-Ni-PGE sulphide ores in diabasic magmas; 2) quantify the physical and chemical controls on platinum group element fractionation as they relate to the sulphur fugacity of parent magmas and the degree of contamination; and 3) further develop analytical techniques that are applicable to Cu-Ni-PGE sulphides through the use of microbeam techniques such as secondary-ion mass spectrometry (SIMS), proton-induced X-ray emission (PIXE) and electron-probe microanalysis (EPMA).

CURRENT PROGRESS

During the past field season (1997), regional and detailed sampling was completed. Regional sampling extended from the Basswood Lake intrusion, near Wharncliffe (Wells Township), to Macbeth and Clement townships, southwest of Lake Temagami, and as far north as the Benny greenstone belt, north of Cartier. Detailed geological mapping and sampling was carried out at several sulphide occurrences in Janes, Kelly, Waters, Louise, Nairne and Porter townships. Samples are being processed at the Geoscience Laboratories in Sudbury. The 1998 field season will involve additional detailed geological mapping and sampling of both barren and sulphide–bearing Nipissing Diabase.

ACKNOWLEDGMENTS

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20. Project Units 92–05 and 94–07. Graphical Representation of the Geochemistry of Metapelitic Rocks, with Examples from the Grenville Province, and Implications for the Protolith of Frontenac Terrane Gneiss

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INTRODUCTION

Rocks in Frontenac terrane have generally been regarded as a metamorphosed stable shelf sequence consisting originally of limestones and dolostones, siltstones and shales, and quartzites (e.g., Wynne-Edwards 1967). Recently, the nature of this sequence has been questioned; in particular, whether the carbonate rocks were indeed part of a coherent stratigraphic succession including the quartzitic and pelitic gneisses (Hildebrand and Easton 1995). In addition, petrographic studies reported elsewhere in this volume (Buckley et al., this volume) have prompted a re-evaluation of existing geochemical data on the Frontenac gneisses with the goal of elucidating the protolith of these rocks.

GEOCHEMISTRY

Approximately 90 major element analyses exist for various mineralogical types of Frontenac gneisses from the three major gneiss units mapped by Wynne-Edwards (1967). Representative analyses are listed in Table 20.1, along with similar units from other areas.

When compared to average shale and wacke (*see* Table 20.1, samples 1 and 2; Figure 20.1), many of the Frontenac gneisses, particularly the clinopyroxene (unit 5 of Wynne-Edwards 1967) and the two-pyroxene gneisses, are notable in their higher CaO and lower Al_2O_3 contents (*see* Table 20.1, samples 6, 7 and 8; Figure 20.1b) compared to typical shales. They most closely resemble recent fore-arc sands (*see* Table 20.1, sample 3; Figure 20.1) and amphibolite facies calcic metapelites and metaconglomerates of the Flinton Group, in particular the Fernleigh Formation and the Ompah and Kaladar conglomerates (*see* Table 20.1, samples 9, 11 and 12). This is also reflected in the chemical index of alteration (CIA) ($[Al_2O_3/Al_2O_3 + CaO–CaO^* + Na_2O + K_2O] \times 100$, where CaO^* = CaO in carbonate minerals) values for the calcareous sediments, metasediments and Frontenac clinopyroxene gneisses, which are abnormally low (less than 55, the value for unweathered igneous rocks) due to the greater CaO content of these rocks. In contrast, typical shales have CIA values over 70, generally in the 75 to 85 range (e.g., *see* Table 20.1, sample 1). Cordierite-bearing and other gneisses of Frontenac terrane have CIA values that fall in the range of typical shales (e.g., *see* Table 20.1, sample 5).

In order to display the distinctive character of the Frontenac gneisses, a ternary plot of CaO - Al_2O_3 - Na_2O + K_2O is used (*see* Figure 20.1). This is not a plot normally used to portray the chemistry of sedimentary or other rocks, but was constructed by the author in an attempt to discriminate between calcic pelites and the more aluminous character of typical pelites. The diagram is constructed to best display the balance between the main components present in shales, notably the dominant elements in clay minerals (Al_2O_3, Na_2O and K_2O) and calcic materials (CaO). The boundaries shown in Figure 20.1 are based on the distribution of modern shales and wackes, compiled from several sources. Additional work is needed to ascertain if this diagram can be used to discriminate between tectonic settings for shale deposition.

As a test group, carbonate and calc-silicate rocks and calcareous aluminous pelites of the Flinton Group are shown in Figure 20.1a, which shows effective separation of the various rock types. In addition, the Flinton Group contains associated quartzites, which are not displayed in Figure 20.1a (they plot in the pelite field). Also shown in Figure 20.1a are examples of some representative shales compiled from the literature.

The Frontenac gneisses also plot into two distinct fields (Figure 20.1b). One field is dominated by clinopyroxene ± hornblende ± hypersthene-bearing gneisses characterized by CaO contents greater than 3.0 wt %, whereas the other contains cordierite ± garnet ± sillimanite ± hypersthene-bearing gneiss, biotite gneiss and quartzofeldspathic gneiss, which are all characterized by lower CaO contents and higher Al_2O_3 contents than the clinopyroxene gneisses. Figure 20.2 shows a similar separation into 2 groups when magnesium content is used instead of alkali content, and also shows that the cordierite-bearing gneisses are slightly more magnesium rich than many of the Flinton Group pelites. Figure 20.3, an AFM plot, shows a similar separation into two groups, with the cordierite-bearing and other gneisses falling in the range of typical shales, and the Flinton Group calcic pelites and the clinopyroxene gneisses lying in the same field. Based on this

Table 20.1. Representative and average analyses of Frontenac gneisses, shale composites and Flinton Group calcic pelites.

	1	2	3	4	5	6	7	std	8	9	10	11	12
SiO_2	62.80	69.20	61.50	68.90	59.05	57.69	60.42	6.27	63.47	49.91	27.98	49.89	58.24
TiO_2	1.00	0.70	0.00	0.00	1.05	0.69	0.67	0.32	0.61	0.65	0.35	0.52	0.86
Al_2O_3	18.90	15.00	15.20	12.10	18.63	12.87	12.44	3.25	8.20	11.25	5.55	9.54	10.33
Fe_2O_3	0.00	0.00	0.00	0.00	2.64	2.45	3.55	2.57	2.77	1.33	0.62	0.91	0.00
FeO	6.50	4.80	6.90	6.50	5.15	2.07	1.72	0.49	1.42	4.69	2.36	3.39	4.40
MnO	0.11	0.00	0.00	0.00	0.04	0.10	0.09	0.05	0.08	0.08	0.09	0.11	0.07
MgO	2.20	1.90	3.80	3.00	3.70	5.65	4.87	2.55	6.60	7.10	6.98	5.72	3.69
CaO	1.30	2.20	6.70	4.90	0.36	10.92	8.72	4.47	11.50	9.67	25.92	13.81	14.37
Na_2O	1.20	2.40	3.80	2.60	1.46	4.56	3.93	1.43	1.11	1.80	0.45	1.79	0.90
K_2O	3.70	3.50	1.40	1.50	6.02	1.42	2.91	2.06	0.77	3.61	1.87	2.45	3.02
P_2O_5	0.16	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.14	0.14	0.12	0.16
CO_2	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	1.43	7.43	31.11	9.87	3.58
LOI	6.00	0.00	0.00	0.00	1.27	0.00	0.00	0.00	0.67	8.45	24.65	11.14	4.63
Total	97.87	99.70	99.30	99.50	98.57	98.42	99.33	1.81	97.96	97.66	96.96	98.12	99.62
CIA	75.30	64.94	56.09	57.35	71.16	43.23	44.63	10.54	40.69	59.52	70.52	53.84	41.25
Mg #	37.62	41.36	49.53	45.13	46.70	70.20	61.43	31.27	75.04	68.25	81.00	70.78	59.91

Abbreviations: LOI = Loss on ignition; CIA = chemical index of alteration (see text for details); std = standard deviation

Samples:

1. *average post-Archean shale, Taylor and McClennan (1985)*
2. *average Late Proterozoic shale, Taylor and McClennan (1985)*
3. *average recent forearc sand, Taylor and McClennan (1985)*
4. *average recent forearc mud, Taylor and McClennan (1985)*
5. *corderite gneiss, Frontenac terrane, sample H90, Wynne-Edwards and Hay (1963)*
6. *clinopyroxene gneiss, Frontenac terrane, sample K743, Krause (1970)*
7. *average clinopyroxene gneiss, Frontenac terrane, n=41, Krause (1970)*
8. *clinopyroxene-scapolite gneiss, Frontenac terrane, sample 14, Wynne-Edwards (1967)*
9. *calcic pelite, Fernleigh Formation, Mazinaw terrane, 91RME-0110*
10. *calc-silicate, Myer Cave Formation, Mazinaw terrane, 91RME-0113*
11. *calcic pelite, Fernleigh Formation, Mazinaw terrane, 91RME-0136*
12. *matrix, Kaladar conglomerate, Mazinaw terrane, 95RME-0081*

preliminary analysis, it would appear that many of the Frontenac gneisses are calcic, even though most of these rocks would not be described as calc-silicate rocks, and are not characterized by substantive CO_2 contents (*see* Table 20.1). In the case of both the Flinton Group calcic pelites and the Frontenac clinopyroxene gneisses, it is not clear whether the source of the excess calcium in these rocks is the result of primary carbonate content, with CO_2 lost during metamorphism, or reflects a mafic provenance that included calcic minerals such as hornblende, pyroxene and epidote (e.g., fore-arc muds and sands, *see* Table 20.1, samples 3 and 4). Both the Flinton Group rocks and the Frontenac gneisses are associated with true calc-silicate rocks, as well as marbles, suggesting that if CO_2 loss was important in generating these rocks, the effect was localized.

IMPLICATIONS

1. The obvious implication of the existence of the two compositional types is that some of the Frontenac gneisses were derived from calcic rather than aluminous shales. This suggests that in addition to an inner shelf environment, deposition of the protolith of the clinopyroxene gneiss could have occurred marginal to the outer shelf if the calcic nature of these rocks is due to higher original carbonate contents (Einsele 1992). Thus, deposition of the clinopyroxene gneisses may have been separated in time and space from quartzite and/or carbonate deposition. Alternatively, if the higher CaO content of the clinopyroxene gneiss reflects a mafic provenance (e.g., metamorphosed or weathered mafic volcanics), then a stable shelf setting

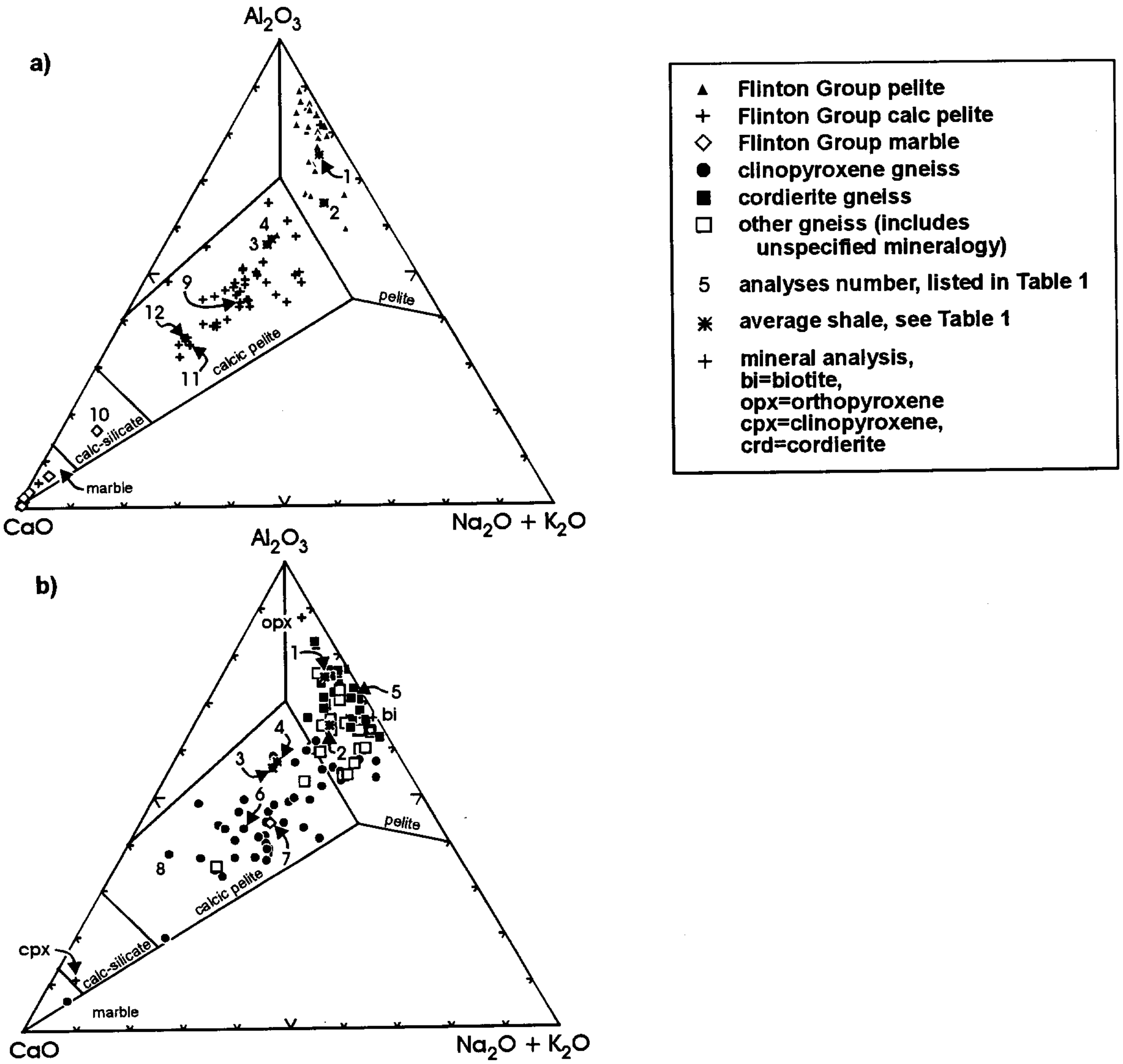

Figure 20.1. a) CaO - Al_2O_3 - $Na_2O + K_2O$ plot for Flinton Group pelite, calcic pelite, calc-silicate and marble (data from Easton (unpublished data, 1990–1997) and Van de Kamp (1971)). Subdivisions based on Easton (unpublished data, 1997). b) CaO - Al_2O_3 - $Na_2O + K_2O$ plot for Frontenac gneisses (n = 90). Data from Wynne-Edwards and Hay (1963), Wynne-Edwards (1967), Reinhardt (1968), Krause (1970) and Marcantonio et al. (1990).

for deposition of the Frontenac metasedimentary rocks is unlikely. In either case, determining the stratigraphic relationship between gneiss, marble and quartzite in Frontenac terrane is critical to interpreting the depositional setting(s) of these rocks.

2. Wynne-Edwards and Hay (1963) attributed the distribution of cordierite in the Frontenac gneisses to "lime-poor, magnesia-rich rocks which are less commonly represented in the geological column." Figures 20.1b, 20.2 and 20.3 suggest, rather, that the cordierite bearing units consist of fairly typical pelitic rocks, possibly somewhat alumina poor, that are indeed typical of the "geological column." Additional chemical data on the Frontenac gneisses will help elucidate any bulk-rock chemical controls on the distribution of metamorphic minerals throughout Frontenac terrane.

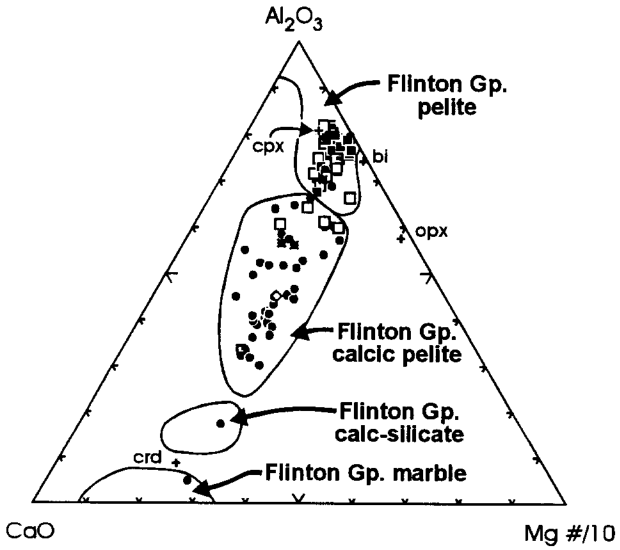

Figure 20.2. CaO – Al_2O_3 – Mg #/10 plot for Frontenac gneisses showing that they are not notably magnesium rich compared with Flinton Group pelites. Legend as in Figure 20.1.

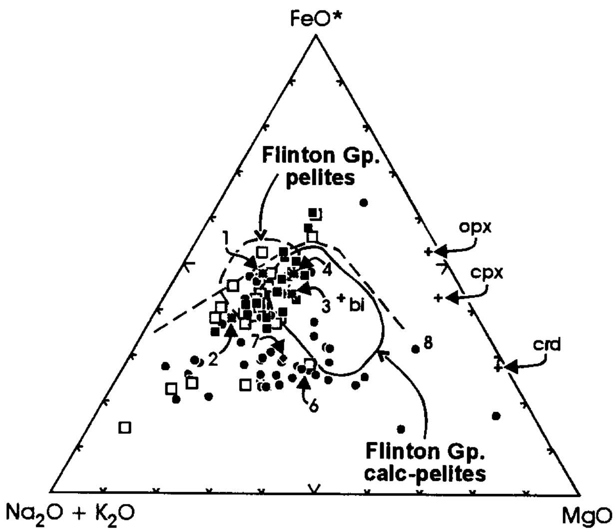

Figure 20.3. AFM plot for Frontenac gneisses. The field of calcic pelite of the Flinton Group is shown for reference. Legend as in Figure 20.1.

3. Petrogenetic grids based on calcic and potassic pelites should be used in metamorphic studies in Frontenac terrane, rather than the more commonly used potassic-based grids.

4. The economic implications of these results are unclear. If both the carbonate rocks and the calcareous gneisses were deposited in a marginal shelf environment, then the zinc potential of the carbonate rocks might be lower than if they were formed in a shallow shelf, where sabkha environments might be present. Potential for sedimentary-hosted exhalative deposits might also be reduced. This would not affect the potential for skarn and manto zinc mineralization in Frontenac carbonates related to younger plutonic rocks as discussed in Easton (1995).

5. Future work on the geochemistry of the Frontenac gneisses, including trace and rare earth element analyses, is planned in order to address some of the points noted above.

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21. Project Unit 94–07. P–T Conditions, Metamorphic History, and Sharbot Lake – Frontenac Terrane Relationships in the Carleton Place and Westport Map Areas, Grenville Province

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INTRODUCTION

The nature of the Sharbot Lake – Frontenac terrane boundary is the subject of recent debate (cf. Davidson and Carmichael 1997; Hildebrand and Easton 1997). Is it 1) a single discrete shear zone (Maberly shear zone of Davidson and Ketchum 1993), 2) a complex mélange of materials (Elzevir–Frontenac boundary zone of Forsyth et al. 1994) or 3) a folded thrust that juxtaposes low-grade marbles against high-grade gneisses (Hildebrand and Easton 1995)?

In an effort to further our understanding of this boundary, a metamorphic study of gneissic and other rocks in the Carleton Place and Westport map areas (Figure 21.1) began in 1997. This study complements previous mapping (Reinhardt et al. 1973; Easton 1988; Easton and Hildebrand 1994) and metamorphic (Ewert 1977) and geochronologic studies in the Carleton Place area (Corfu and Easton 1997). This study has had the added benefit of expanding the range of mineral phases that can be reliably analyzed by microprobe at the Geoscience Laboratories.

GEOLOGY

The geology of the Carleton Place area is summarized in Figure 21.2. Samples from the Carleton Place area are mainly from the Wolf Grove structure, which includes a variety of amphibolites, orthogneisses and migmatitic gneisses. The geology of the Westport area has been described by Wynne-Edwards (1967). Samples were collected from the Westport area because there is a paucity of thermobarometric studies from Frontenac terrane.

MINERAL ASSEMBLAGES AND TEXTURES

A petrographic summary of samples used in this study is presented in Table 21.1. Several of the Carleton Place amphibolites (e.g., 97RME–0006, 97RME–0013A) contain typical upper amphibolite facies metamorphic assemblages; namely, hornblende and plagioclase, locally with garnet or clinopyroxene or both. Some amphibolite samples contain more distinctive mineral assemblages. For example, sample 97RME–0012 contains 3 amphiboles in equilibrium: hornblende, anthophyllite and gedrite. Hornblende predominates, displaying subhedral prismatic crystals up to 2 mm long. Anthophyllite has a slender (almost fibrous) prismatic form and is finer grained than the hornblende (up to 1 mm). In several places, anthophyllite appears to be replacing hornblende around its edges or overgrowing it, suggesting that it grew later than the hornblende. Gedrite occurs as very pale green, small (less than 0.7 mm), anhedral crystals. Other minerals present are garnet, plagioclase and quartz. Other samples with multiamphibole assemblages are 94RME–0005 and 94RME–0021.

Sample 94RME–0011 from the Wolf Grove structure is noteworthy in that it shows textural evidence for a complicated metamorphic history, with the mineral assemblage used in the P–T determinations (*see* Tables 1 and 2) pseudomorphing large (5 to 15 mm) hexagonal crystal forms that most likely were once garnet.

Sample 97RME–0029 is a migmatitic biotite gneiss from Frontenac terrane in the Carleton Place area. In addition to relatively coarse-grained plagioclase, quartz and potassium-feldspar, it also contains trace amounts of riebeckite, and very fine-grained relict clinopyroxene crystals. Preliminary scanning electron microscope (SEM) work indicates that this clinopyroxene is sodic, suggesting that it may have originally been aegirine. Sample 94RME–0015, from the same unit as 97RME–0029, lacks riebeckite, but does contain a few bright green clinopyroxene crystals that might also be aegirine. In addition, both samples contain minor amounts of calcite, titanite and epidote. The mineralogy suggests a possible calcareous sediment protolith, consistent with the zircon population present in sample 94RME–0015 (Corfu and Easton 1997).

Petrographic examination of samples collected from the Westport area reveals a complex metamorphic history. Sample 97RME–0023B, from unit 5 of Wynne-Edwards (1967), has a garnet–cordierite–potassium-feldspar–biotite–sillimanite assemblage. The garnet and cordierite are porphyroblastic, and both have rounded or irregular edges. The medium-grained matrix is composed of quartz, plagioclase and potassium-feldspar. Very fine-grained anhedral hercynite occurs as relict inclusions along with corundum within the cordierite. In some cases, the hercynite ap-

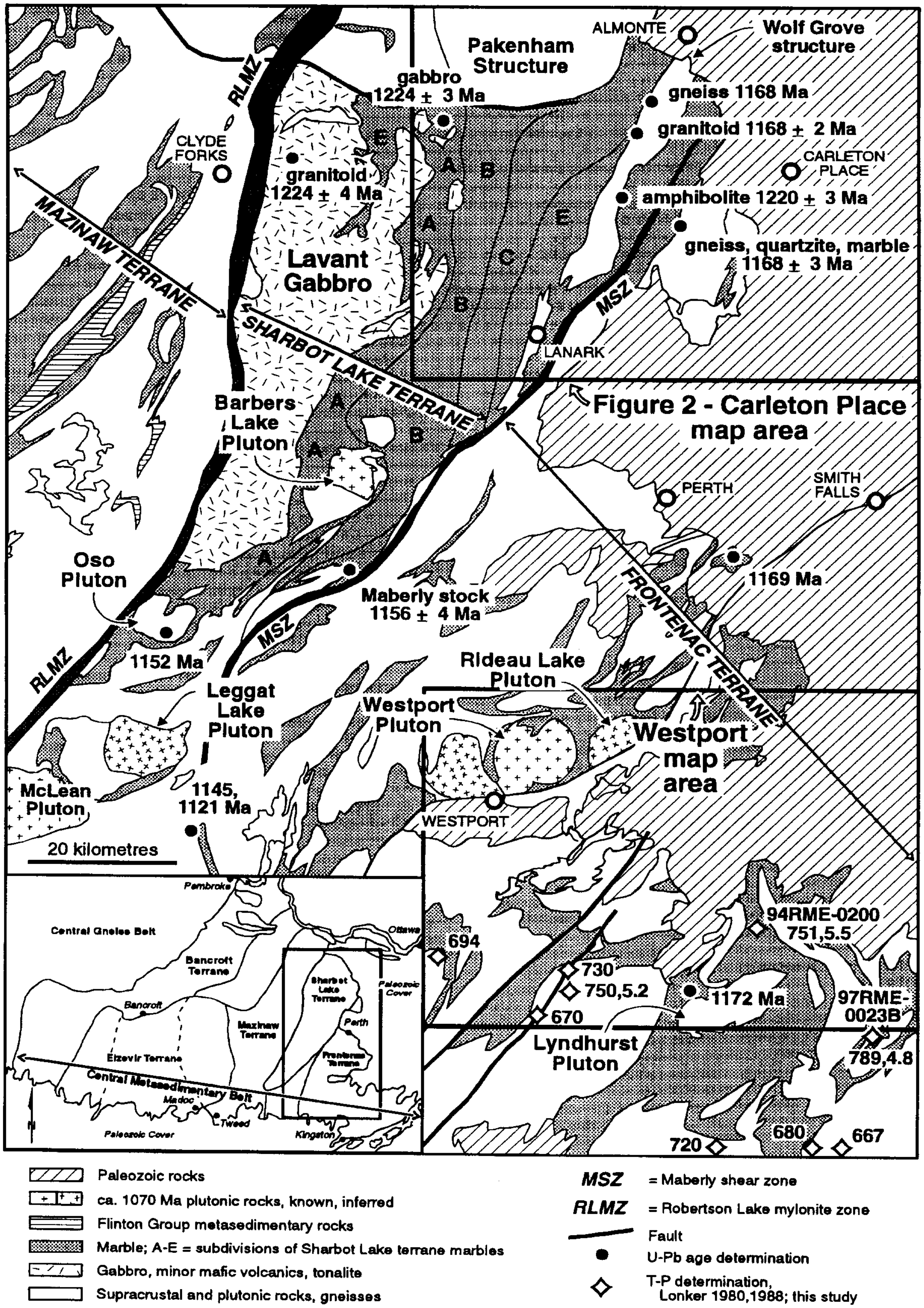

Figure 21.1. Geology of eastern Ontario showing the location of the Carleton Place and Westport map areas, and the location of samples from the Westport area. P–T data from the Westport area from Lonker (1980, 1988) are also shown. U-Pb ages are from Corfu and Easton (1997) and Mezger et al. (1993).

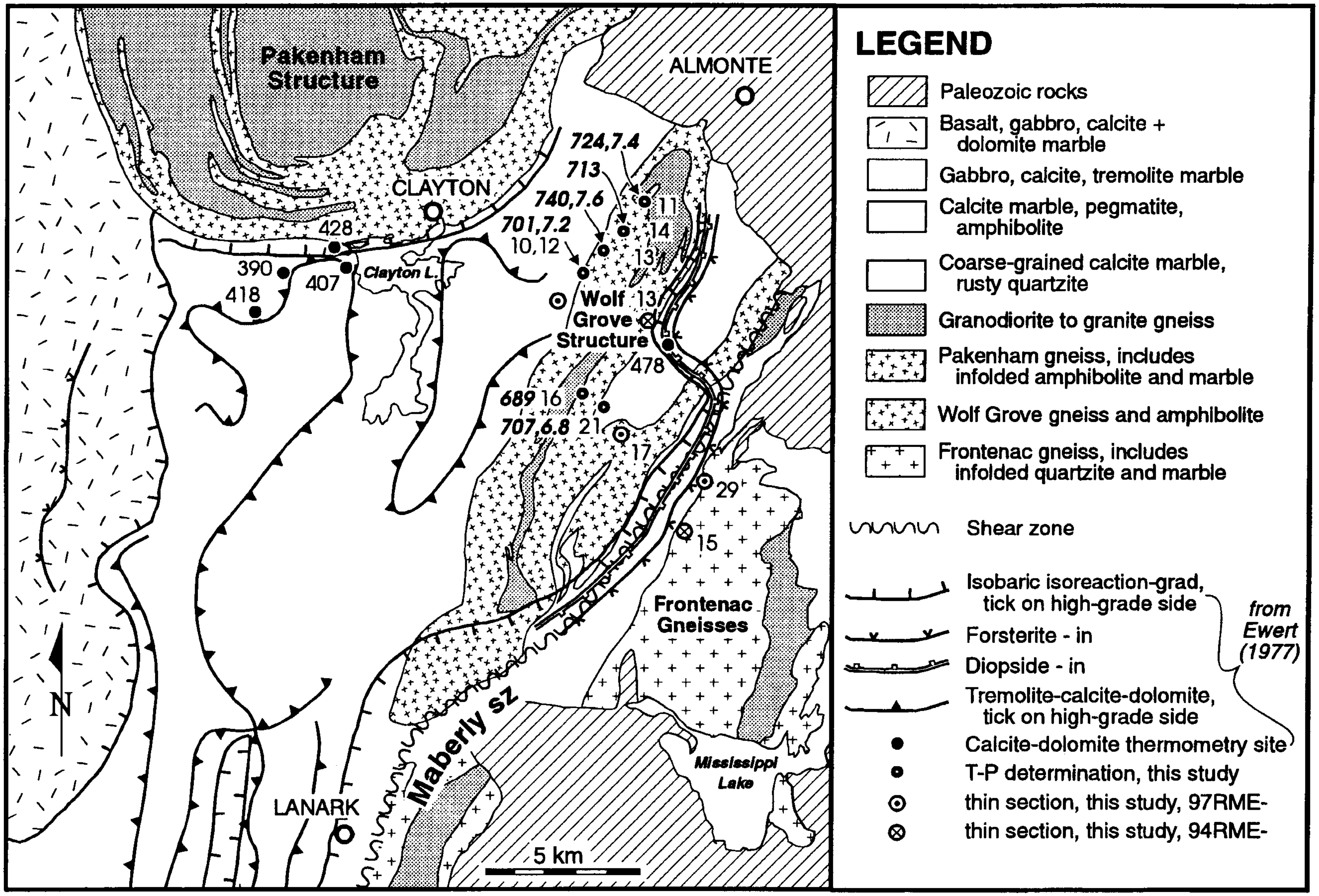

Figure 21.2. Geologic sketch map of the Carleton Place map area (*after* Reinhardt et al. 1973) showing the location of samples used in this study. Mineral isograds in carbonate rocks are from Ewert (1977). P–T results shown are summarized from Table 21.1.

pears to replace the corundum. Sillimanite occurs as abundant radiating inclusions within garnet. Sillimanite inclusions are also found within plagioclase and cordierite. Sample 97RME–0023B–2 contains a fine-grained slender prismatic crystal included in a cordierite grain. Given that the mineral has a blue-purple to colourless pleochroic colour scheme, it has tentatively been identified as grandidierite, which has previously been identified from this locality (Carmichael et al. 1987). Sample 94RME–0200, from unit 2 of Wynne-Edwards (1967), is similar to the pre-

Table 21.1. Petrography of samples used in this study.

SAMPLE NUMBER	UTM EAST	UTM NORTH	ROCK TYPE	KEY MINERALS PRESENT[1]	SIGNIFICANT INCLUSIONS & COMMENTS
Carleton Place Area					
97RME–0006	399850	5002800	Amphibolite intercalated with marble	Hbl–pl–cpx–qtz	
97RME–0012	400695	5003518	Para-amphibolite	Hbl–pl–bt–grt–ath–ged–qtz	Section 1
94RME–0005				Hbl–pl–bt–grt–ath	Section 2
97RME–0010	400695	5003518	Protomylonitic pegmatite	Pl–qtz–ksp–bt–grt–ms	
97RME–0013A	400982	5003831	Amphibolite	Hbl–pl–gt–bt–qtz	Greenschist facies overprint
97RME–0014	401467	5004310	Granodioritic migmatitic leucosome	Qtz–ksp–pl–bt–grt	Metamorphism between 1168(zrn) and 1148 Ma(mnz) (Corfu and Easton 1997)
94RME–0002				Pl–qtz–bt–ksp–grt	
94RME–0011	402149	5005145	Migmatitic gneiss	Pl–qtz–ksp–cpx–grt–bt–hbl	Replacement assemblage in pseudomorph is cpx-grt-pl-qtz
94RME–0013	404113	5002694	Migmatitic gneiss	Pl–qtz–ksp–cpx–grt–bt–hbl	
97RME–0016	400350	4999075	Garnet-rich mafic inclusion in migmatitic granodioritic gneiss	Grt–qtz–bt–pl	
94RME–0021	399572	4998153	Siliceous gneiss	Pl–bt–qtz–ath–grt–cum–(hbl)	Optical identification, only of cum, hbl
97RME–0017	402600	4997000	Amphibolite intercalated with marble	Cpx–hbl–scp–pl–bt	
94RME–0015	403336	4995196	Migmatitic biotite gneiss	Ksp–bt–qtz–pl	Metamorphism at 1168 Ma (zrn), Corfu and Easton (1997)
97RME–0029	404350	4996500	Migmatitic biotite gneiss,	Qtz–pl–ksp–bt–cpx–rbk–(ep)–(cal)	Fresh outcrop, same unit as sample 94RME–0015
Westport Area					
94RME–0200	408850	4936350	Pelitic gneiss	Crd–qtz–grt–bt–ksp–hc	Unit 2, Wynne-Edwards (1967); sil as inclusions in crd and grt
97RME–0023B1	416000	4927200	Leucosomal vein within migmatitic pelitic gneiss	Qtz–crd–ksp–pl–grt–bt	Unit 5, Wynne-Edwards(1967); Sil in grt & crd; hc-cdm in crd; hc in crd; cdm with hc. Unidentified purple mineral (grandi dierite?)
97RME–0023B2				Crd-qtz-pl-grt-bt-ksp	

[1]*minerals in order of decreasing abundance, brackets indicate mineral is present only in trace amounts. Abbreviations after Kretz (1983).*

vious sample, but does not contain any plagioclase or corundum. Furthermore, potassium-feldspar in this rock occurs as fine-grained rims (or coronas) around the cordierite grains and hercynite is partially armoured by cordierite.

MINERAL CHEMISTRY

Representative microprobe analyses from several selected samples are presented in Table 21.3. In general, the garnets from all samples analyzed were almandine rich, with lesser amounts of pyrope, grossular and spessartine. In samples 94RME-0011 and 97RME-0014, however, garnets are relatively rich in spessartine (up to 8 wt %). Compositional zoning profiles were obtained for each garnet by analyzing approximately 30 to 40 points across each crystal. Zoning profiles are generally flat, typical of high-grade metamorphic garnets, with an increase in the Fe/Mg ratio at the rim, which is interpreted to be retrograde re-equilibration during cooling.

Biotite compositions were quite varied, with the magnesium-number (100Mg/(Mg + Fe)) ranging from 45 to 76 and Ti contents ranging from 2 to 5 wt %. Plagioclase cores are generally anorthitic, with increased amounts of albite toward the rims. The cordierite magnesium-number ranged from 75 to 78 in sample 94RME-0200. Sample 97RME-0023B-1 had a slightly lower magnesium-number, ranging from 69 to 72. Hornblendes are most commonly tchermakitic hornblende or tchermakite, and less commonly ferroan-pargasitic hornblende (Leake 1978).

P–T CONDITIONS OF METAMORPHISM

The results of thermobarometric work are summarized in Table 21.2 and Figure 21.2, and are thought to represent peak or near-peak conditions of metamorphism. These values were obtained by using the inner rim composition of the garnet, matrix or armoured biotite, and the core analyses of other minerals present.

Temperatures were estimated using the garnet–biotite exchange thermometer of Ferry and Spear (1978), Hodges and Spear (1982) and Indares and Martignole (1985), as well as the hornblende–plagioclase thermometer of Holland and Blundy (1994) (*see* Table 21.2). The temperatures obtained using Ferry and Spear (1978) averaged 683 ± 26 and 793 ± 50°C for the Carleton Place and Westport areas respectively (*see* Table 21.2). Hornblende–plagioclase temperature estimates for amphibolites in the Carleton Place area average 718°C, which is only slightly higher than the results obtained using the Ferry and Spear (1978) thermometer.

Metamorphic pressures of garnet-bearing amphibolites were estimated using the hornblende–plagioclase–garnet barometer of Kohn and Spear (1990). Results averaged 6914 ± 1300 bars for rocks in the Carleton Place area.

Both pressure and temperature estimates were also obtained using the multiequilibria program TWEEQU (Berman 1991). This program plots all possible equilibria for a given set of phase components, with the compositions of

Table 21.2. Summary of P-T determinations of samples from the Carleton Place and Westport map areas (*see* Figures 21.1 and 21.2 for sample locations).

Sample	TWEEQU(vs 1.02)[1]		Grt–Bt Temperatures (°C)			Hb-Pl [5]	Hbl-Pl-Grt[6]
	P bars	T °C	H & S[2]	F & S[3]	I & M(2)[4]	T°C	P bars
Carleton Place Area				@7.5 kbar		@7.5 kbar	@725°C
97RME-0012 7219	701	-		-	702	5683	
97RME-0013A 7565	740	-		-	705	6815	
97RME-0014 -	-	757	713	743	-	-	
97RME-0011 7350	724	762	679	776	747	8243	
97RME-0016 -	-	730	689	654	-	-	
94RME-0021 6835	707	723	651	641	-	-	
Average	7242±306	718±18	743±19	683±26	704±66	718±29	6914
Westport Area			@5 kbar		@5 kbar		
97RME-023B1 4761	789	844	828	625	-	-	
94RME-0200 5500	751	787	757	643	-	-	
Average	5131±522	770±27	816±40	793±50	634±13		

[1]*Berman (1991).*
[2]*Calibration of Hodges and Spear (1982.)*
[3]*Calibration of Ferry and Spear (1978).*
[4]*Calibration of Indares and Martignole (1985), model 2.*
[5]*Calibration of Holland and Blundy (1994), average of edenite–tremolite and edenite–richterite thermometers.*
[6]*Calibration of Kohn and Spear (1990), average of Fe and Mg end-member reactions.*

Table 21.3. Representative mineral chemistry.

	Grt			Pl			Bt		Ksp	Cpx	Crd	Sil	Hc	Hbl	Ath	Ged
Sample	**94RME-0011**	**97RME-0023B-1**	**97RME-0012**	**94RME-0011**	**97RME-0023B-1**	**97RME-0012**	**94RME-0011**	**97RME-0023B-1**	**94RME-0011**	**94RME-0011**	**97RME-0023B-1**	**97RME-0023B-1**	**97RME-0023B-1**	**97RME-0012**	**97RME-0012**	**97RME-0012**
SiO_2	37.52	37.20	38.20	58.11	57.90	56.69	36.74	35.20	65.48	51.55	47.44	35.70	0.23	44.87	53.03	5.72
Al_2O_3	20.99	21.44	22.44	26.47	26.46	26.91	15.82	16.87	18.16	1.89	34.01	63.01	55.70	13.90	4.28	13.73
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.12	b.d.	b.d.	b.d.	b.d.	0.13	b.d.	b.d.	b.d.
V_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.21	n.d.	n.d.	n.d.
TiO_2	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	4.22	5.33	b.d.	0.24	b.d.	b.d.	b.d.	1.56	b.d.	0.50
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.22	n.d.	n.d.	n.d.
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.16	n.d.	n.d.	n.d.
Fe_2O_3	n.d.	n.d.	n.d.	0.20	b.d.	0.12	n.d.	n.d.	b.d.	n.d.	n.d.	0.96	3.96	n.d.	n.d.	n.d.
FeO	22.48	34.10	25.55	b.d.	b.d.	b.d.	16.59	19.03	b.d.	10.62	7.02	b.d.	33.05	12.77	18.66	17.76
MnO	7.76	0.42	1.38	b.d.	b.d.	b.d.	0.26	b.d.	b.d.	1.61	b.d.	b.d.	b.d.	0.24	0.48	0.45
MgO	3.79	5.34	9.29	b.d.	b.d.	b.d.	12.37	9.50	b.d.	12.06	8.56	b.d.	4.14	13.35	19.97	16.90
CaO	7.89	1.32	3.49	8.74	8.64	9.55	b.d.	b.d.	b.d.	21.03	b.d.	b.d.	b.d.	9.25	0.47	0.83
Na_2O	n.d.	n.d.	n.d.	6.68	6.59	5.92	b.d.	b.d.	0.41	0.64	0.31	b.d.	n.d.	1.81	0.77	1.83
K_2O	n.d.	n.d.	n.d.	0.26	0.10	b.d.	10.10	10.03	16.31	b.d.	b.d.	b.d.	n.d.	0.27	b.d.	b.d.
BaO	n.d.	n.d.	n.d.	b.d.	b.d.	0.10	b.d.	b.d.	0.48	b.d.	b.d.	b.d.	n.d.	b.d.	b.d.	b.d.
Cl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.11	0.13	n.d.	n.d.	n.d.	n.d.	n.d.	b.d.	b.d.	b.d.
TOTAL	100.43	99.82	100.35	100.46	99.69	99.29	96.21	96.21	100.84	99.64	97.34	99.67	98.80	98.02	97.66	97.72

Abbreviations

b.d. concentration below detection limit

n.d. concentration not determined

Analyses by Geoscience Laboratories, Sudbury, using a JEOL 6400 scanning electron microscope equipped with a Link EXL–Energy Dispersive Spectrometer using the following operating conditions: 2.5 nA beam current, 20 kV accelerating voltage, natural and synthetic standards, and a ZAF–4 collection routine. Spot analyses were collected for 100 s for all minerals except plagioclase, which was raster scanned to minimize Na loss. Domains were selected for analysis to maximize the number of phases in a small area (1–2 mm) to increase the likelihood of obtaining equilibrium conditions. In general, 3 analyses were conducted for each major mineral phase per domain, which were than averaged for thermobarometry calculations.

the analyzed minerals determining where in P–T space these equilibria will be located. Ideally, all reactions will pass through one point, indicating that the chosen mineral compositions were in equilibrium at that pressure and temperature. Figure 21.3 illustrates the results for four of the samples listed in Table 21.2.

Figure 21.3A is from the multiamphibole garnet amphibolite discussed earlier (97RME-0012). The phases used were garnet, plagioclase, hornblende and quartz. Figure 21.3B shows the plot obtained from sample 94RME-0011 using the phases clinopyroxene, garnet, biotite, plagioclase, potassium-feldspar and quartz. In general, the average P–T for Carleton Place area rocks is 7242 ± 306 bars and 718 ± 18°C, consistent with results obtained using other thermobarometric methods.

TWEEQU plots obtained from the garnet-cordierite rocks in the Westport area are shown in Figure 21.3C and 3D. The phases used for Figure 21.3C were garnet, biotite,

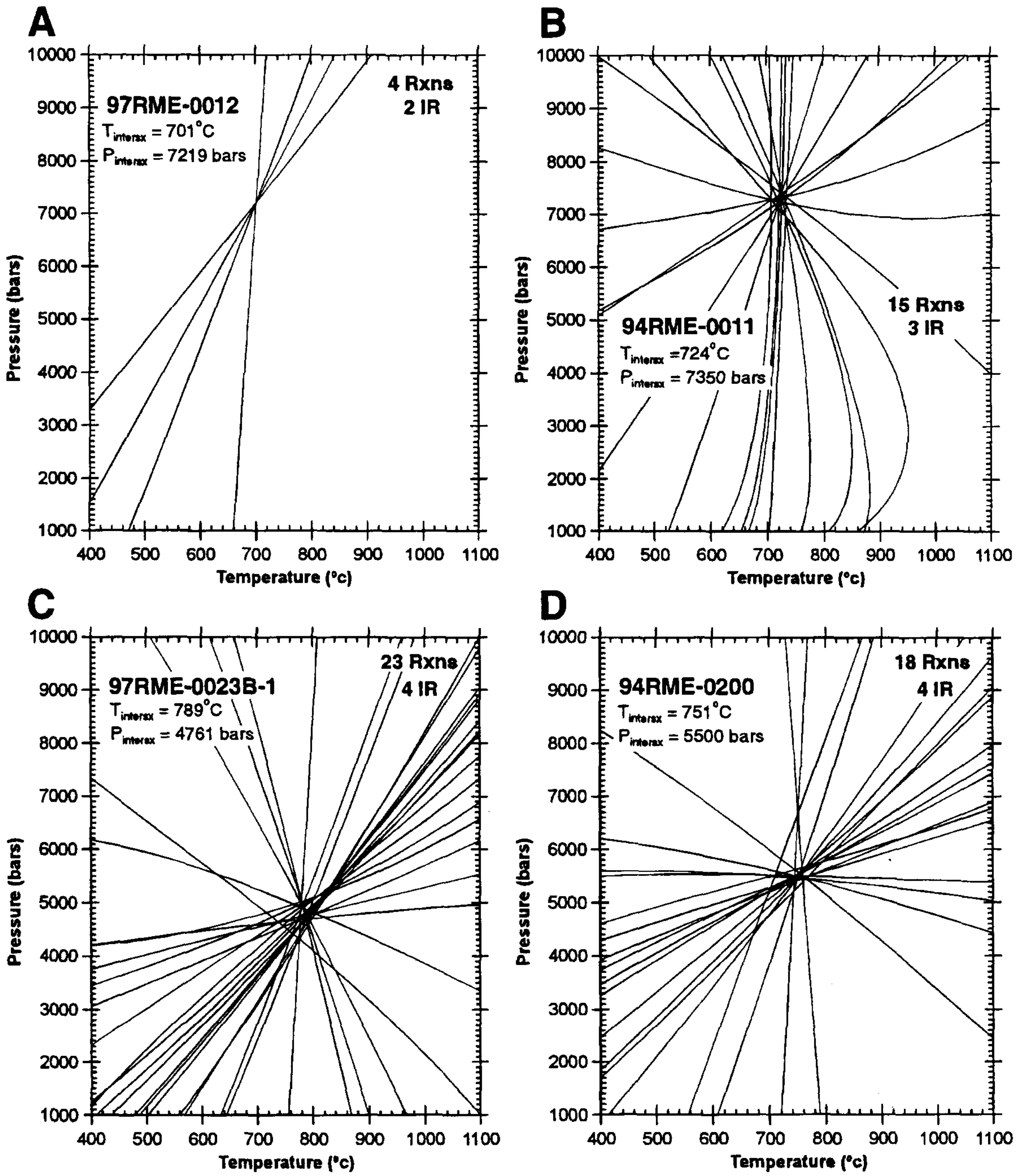

Figure 21.3. Examples of P–T results obtained using the program TWEEQU (version 1.02, Berman 1991). Samples 94RME-0011 and 97RME-0012 are from the Wolf Grove structure; samples 97RME-0023B-1 and 94RME-0200 are from the Westport area. Abbreviations: Rxns, reactions; IR, independent reactions; Intersx, average pressure and temperature values calculated using the program intersx.exe. Ideal water activity used in all plots, except for 97RME-0021 which did not include water.

cordierite, hercynite (armoured in cordierite), quartz, plagioclase and sillimanite (armoured in plagioclase). The same phases were used for Figure 21.3D, except for plagioclase, which was not present. The average P–T estimate for Westport area rocks is 5131 ± 522 bars and 770 ± 27°C. This is in good agreement with the estimate of 5200 bars and 750°C obtained by Lonker (1988) from the same area.

DISCUSSION

P–T conditions based on thermobarometry (*see* Table 21.2; Figure 21.3) indicate near-peak metamorphic conditions of approximately 7.2 kilobars and 718°C for all major rock units in the Wolf Grove structure. The pressure estimate is supported by the presence of the divariant assemblage hornblende-anthophyllite-almandine in sample 97RME–0012, which, based on the P–T grid of R. Berman (Geological Survey of Canada, written communication, 1997), is stable at pressures above 7.3 kilobars in the temperature range of 670 to 710°C. Sample 94RME–0021 also contains cummingtonite, in addition to hornblende-anthophyllite-almandine. This assemblage is univariant, marking the lower pressure stability limit of the hornblende-anthophyllite-almandine subassemblage, where hornblende + anthophyllite + almandine = cummingtonite. U–Pb geochronology by Corfu and Easton (1997) indicates that metamorphism in the Wolf Grove area occurred between 1168 and 1148 Ma.

In contrast, P–T conditions for the Frontenac terrane are approximately 5 kilobars and 760 to 790°C, based on both our data and data of Lonker (1980, 1988) (*see* Figure 21.1). The pressure estimate is supported by phase relations constrained by the petrogenetic grid of Xu et al. (1994). The upper pressure limit is constrained by the equilibrium biotite + sillimanite + quartz = cordierite + potassium-feldspar + garnet. The presence of the low-pressure subassemblage cordierite-potassium-feldspar-garnet with sillimanite relics in samples from the Westport area suggests that metamorphic pressures were below approximately 6.1 kilobars at 770°C. Similarly, the lower pressure limit is constrained by the equilibrium biotite + garnet + quartz = cordierite + orthoamphibole + potassium-feldspar, with the high-pressure subassemblage being biotite-garnet-quartz. This suggests pressure conditions lying above 3.7 kilobars at 770°C. U-Pb studies by both Corfu and Easton (1997) and Mezger et al. (1993) indicate that metamorphism occurred in the Frontenac terrane at ca. 1168 Ma.

Temperature estimates using both TWEEQU and garnet–biotite thermometry appear to be slightly high when compared with various petrogenetic grids. According to the grid of Berman (Geological Survey of Canada, written communication, 1997), the divariant assemblage biotite-almandine becomes unstable in favour of the assemblage cordierite-orthopyroxene-potassium-feldspar at approximately 740°C and 5 kilobars. Further work is necessary to explain these discrepancies.

Furthermore, the apparent "collapse" of equilibria in the TWEEQU phase diagrams (*see* Figure 21.3C and 3D) using the relict phases hercynite and sillimanite is problematic, given that both are no longer in contact with the matrix anywhere in the sample. In the case of hercynite, which is typically armoured in cordierite, the dominant reaction is Fe–Mg exchange. Because this equilbrium is largely temperature dependent, the exchange must be continuing between hercynite and the surrounding cordierite as the temperature decreases, even though the hercynite is armoured. Therefore, it is suggested that we are sampling equilibrium, rather than relict, hercynite compositions.

IMPLICATIONS

To date, the closest thermobarometry to the Sharbot Lake – Frontenac terrane boundary within Frontenac terrane is located roughly 42 km from the Maberly shear zone (*see* Figure 21.1). Consequently, it is not known if metamorphic pressures remain relatively constant in this interval or increase to the north-northwest. The occurrence of the assemblage garnet - cordierite ± sillimanite throughout this interval, to within 2 km of the Maberly shear zone, suggests that pressures do not rise above 6 kilobars in northern Frontenac terrane.

The P–T results suggest that there is roughly a 2 kilobars pressure, and a minor (50°C) temperature, difference between rocks of the Wolf Grove structure and Frontenac terrane. As noted earlier, geochronologic constraints suggest that metamorphism in both areas was coeval (Corfu and Easton 1997). Currently, this pressure difference does not exclude any of the models for the nature of the Sharbot Lake – Frontenac terrane boundary outlined in the introduction. It does, however, suggest that if the Wolf Grove gneisses are part of Frontenac terrane, they represent a different structural level than that exposed south of the Maberly shear zone. It also raises the possibility of considerable metamorphic displacement across the Maberly shear zone regardless of the model. Metamorphic data from the Pakenham structure and from Frontenac terrane immediately adjacent to the Maberly shear zone are needed in order to better understand this boundary.

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Sedimentary Geoscience Section

22. Project Unit 92–19. Geology of the Beaverton Map Area, Durham and York Regional Municipalities and Victoria County Municipality, Ontario

P.J. Barnett

Ontario Geological Survey, Sedimentary Geoscience Section

INTRODUCTION

Field investigations into the geology of the Beaverton area were undertaken this past summer (Figure 22.1). The area investigated is covered by the National Topographic System 1:50 000 scale Beaverton (31D/6) map sheet. The work is part of the Oak Ridges Moraine NATMAP Program (Canada's National Geoscience Mapping Program) being carried out in co-operation with the Geological Survey of Canada (Barnett 1996).

The Beaverton area was previously mapped by Deane (1950). The current work builds on this information as well as previous work completed by the author in adjacent areas to the south along the Oak Ridges Moraine. A summary of the main geological findings of the previous work can be found in Barnett (1995).

GEOMORPHOLOGY

The area examined this past summer borders Lake Simcoe. It lies within the Simcoe lowlands and Peterborough drumlin field physiographic regions of Chapman and Putnam (1984).

The landscape in the northern half of the area is strongly bedrock controlled and consists of a series of low cuestas dipping gently to the south, becoming higher and more continuous toward the south. The southern half consists of isolated streamlined hills, or uplands, bordered by a low relief plain. In the eastern part, the uplands are large and are cut by deep, steep-walled, flat-floored valleys (tunnel valleys). In the west, these valleys are much broader and upland areas stand as isolated hills. Local relief along upland margins is on the order of 20 m.

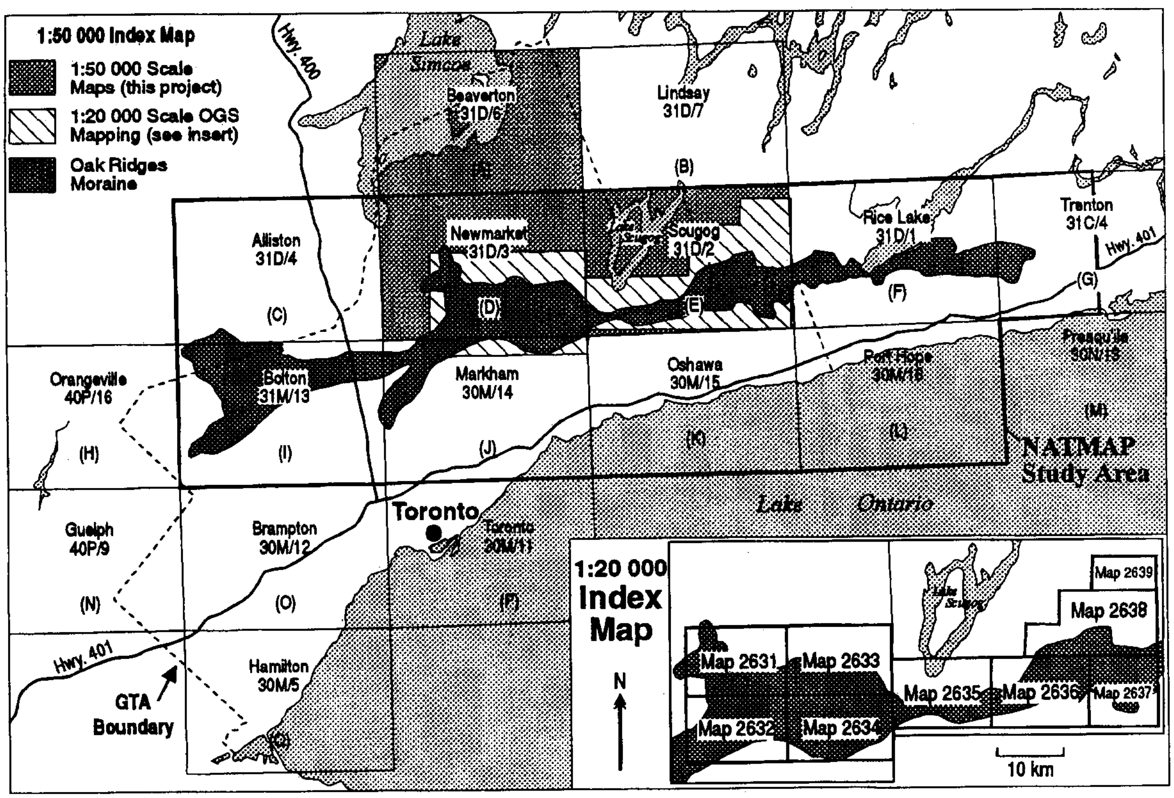

Figure 22.1. Index map of Ontario Geological Survey 1:20 000 and 1:50 000 scale Quaternary geology maps and Geological Survey of Canada Open File (NATMAP-GTA) 1:50 000 scale glacial geology map series for the Oak Ridges Moraine (NATMAP) and Greater Toronto Area (GTA) areas (map areas A-Q). Oak Ridges Moraine outline after Chapman and Putnam (1984).

Drumlins occur on upland surfaces and eskers occur in valley bottoms and on upland margins and surfaces. Major esker ridges are observed around Cannington and east of Sunderland. West of Pefferlaw, several eskers occur. Here, however, their form has been modified by postglacial lake processes or they are buried beneath glaciolacustrine sediments, making their identification solely on morphology difficult.

Shorebluffs, wave-cut platforms and beach bars, spits and tombolos are common geomorphic forms in the area. The most prominent shoreline features are associated with a major transgression, associated with the establishment of glacial Lake Main Algonquin. Shoreline features of this lake rise from an elevation of approximately 240 m at Sutton to over 250 m, 5 km northwest of Argyle. In places, several multiple beach ridges occur.

STRATIGRAPHY

Paleozoic rocks of Ordovician age underlie the Beaverton area. They outcrop or occur beneath a thin cover of Quaternary sediments throughout much of the northern half of the area and on the islands of Thorah and Georgina in Lake Simcoe. The farthest south bedrock was observed was along Pefferlaw Creek at the bridge in Pefferlaw.

The bedrock consists of thinly bedded fossiliferous limestone and shale of the Simcoe Group (Verulam and Lindsay formations of Johnson et al. 1992). Where more resistant limestone beds overlie shale-rich sequences, north-facing cuestas form. One long linear feature interpreted as a pop-up (horizontal stress release feature in bedrock) deforms a glacial Lake Algonquin shoreline northwest of Argyle.

Quaternary sediments overlie the Paleozoic rocks in the Beaverton area. In the southern part of the study area, 2 tills were identified. The older, a fine-grained (clayey silt) till, is exposed on an ancestral wave-cut platform of glacial Lake Main Algonquin at Island Grove and along the eastern side of Snake Island. The younger till is coarse grained (stony, sandy silt to silty sand till) and is correlated to the Newmarket Till of Gwyn and DiLabio (1973).

The Newmarket Till has a regional distribution. It occurs on the uplands in drumlins and is the only till observed in the northern half of the area. Here, it can be seen resting directly on the bedrock surface. The Newmarket Till appears to be absent along the valleys that dissect the uplands. However, it may be deeply buried by younger glaciolacustrine sediments in the low-lying areas.

Sand- and gravel-rich glaciofluvial sediments are observed beneath, within and above the Newmarket Till. Ice-contact sand and gravel deposits occur in the form of eskers, mega-ripples, pendant and eddy bars, and discontinuous sheets primarily within and along the margins of tunnel valleys. These deposits are the products of large subglacial meltwater flood(s) that created the network of tunnel valleys in south-central Ontario.

The Beaverton area was inundated by large proglacial lakes during deglaciation. Glaciolacustrine sediments occur throughout the map area and overlie the sediments mentioned previously. Shorelines of high-level lakes (Schomberg Ponds) occur in the Newmarket and Scugog areas (Barnett 1995, 1996); however, only their basin sediments record their existence in the Beaverton area.

The basin sediments consist of fine-grained deposits (sand, silt and clay) that occur in discontinuous sheets in the lower parts of the uplands but are thicker and more continuous within the lowlands and valleys. Glaciolacustrine sediments immediately overlying the Newmarket Till are rhythmically bedded sands, silts and clays that contain numerous glacially derived debris flows (flowtills) and ice-rafted debris. The debris flows and ice-rafted debris both decrease in abundance upward. Individual rhythms also tend to become thinner and finer upward.

A large channel cut into the fine-grained rhythmites and filled with sand is located near Beaverton. The channel was probably cut during the Kirkfield low-water stage of glacial Lake Algonquin and filled during the transgression to the Main Algonquin level. The channel fill consists of a fining-upward sequence of sands to silts, dominated by climbing ripple drift packages.

Nearshore deposits and features consist of shorebluffs, wave-cut platforms and deposits of sand and gravel that occur in beach ridges, bars, spits and tombolos. Most highly developed shoreline features are associated with Lake Main Algonquin. Extensive wave-cut platforms with boulder lags occur along the northern ends of uplands south of Lake Simcoe and attest to the erosive power of lake processes during a major transgression. Gravel and sand beach ridges and spits commonly extend from the margins of wave-cut platforms and the base of shorebluffs. Extensive beach deposits have developed from and along esker ridges within some of the valleys west of Pefferlaw.

Areas of very fine sand and silt that occur in low-lying areas east of Lake Simcoe are interpreted as being lacustrine sediments deposited in a nonglacial lake—an ancestral Lake Simcoe.

ACKNOWLEDGMENTS

The author would like to thank the many residents of the Beaverton area who granted access to their land and, in particular, the Chippewas of Georgina Island. The assistance of David Mate (senior assistant) and Jennifer Nistico and Steve Leney (junior assistants) during this past summer's field work is also acknowledged.

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23. Quaternary Geology Mapping and Overburden Sampling, Woman Falls – Wakusimi River Area, Northeastern Ontario

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INTRODUCTION

Kimberlite is recognized as the primary host rock for diamond. A suite of heavy minerals (chrome pyrope garnet, chromite, magnesium-rich ilmenite and chrome diopside) are commonly associated with kimberlite and are referred to as kimberlite indicator minerals (KIMs). A Quaternary geology mapping and modern alluvium sampling program conducted by the Ontario Geological Survey (Morris 1990, 1991, 1992a, 1992b, 1994, 1995, 1996, 1997; Morris, Murray and Crabtree 1994a, 1994b; Morris, Crabtree and Pianosi 1997) in the Wawa area, northeastern Ontario, was successful in defining the types and distribution of KIMs. The Kapuskasing Structural Zone (KSZ) underlies the Wawa region and is thought to be a suitable structure for hosting kimberlite (Boland and Ellis 1989). The KSZ extends northeast from Wawa through the Woman Falls – Wakusimi River area, south of Kapuskasing (Figure 23.1)

Quaternary geology mapping, in conjunction with a modern alluvium and till sampling program, was initiated in the Woman Falls – Wakusimi River area to establish the occurrence of KIMs. Modern alluvium was the principal material sampled; some till and coarse-grained glaciolacustrine material were also sampled. In addition to KIMs, magmatic massive sulphide indicator minerals (MMSIMs™) and gold grains were picked from heavy mineral concentrates. MMSIMs (anthophyllite, chalcopyrite, chromite, gahnite, hypersthene, olivine, red epidote, red rutile, ruby corundum, sapphirine, spessartine and staurolite) are indicators of polymetallic deposits associated with migmatized terrain; gahnite is also used to identify rare element pegmatites. Geochemical analysis of surface till samples will provide data useful for base metal, rare element pegmatite, gold and phosphate exploration.

Quaternary geology mapping provides a framework for understanding the distribution of the data derived from the overburden materials. In addition, mapping has identified aggregate resources critical in the development of road infrastructure for the local forestry industry.

The Woman Falls – Wakusimi River area is represented on two 1:50 000 scale National Topographic System maps. The western part of the study area is covered by the Woman Falls (42G/2) map sheet and the eastern part by the Wakusimi River map sheet (42G/1). The area is bounded by longitudes 83°00′ and 82°00′W and latitudes 49°00′ and 49°15′N.

PHYSIOGRAPHY

This area is located north of the Great Lakes – Hudson Bay drainage divide and all surface drainage flows north into James Bay. There are two major drainage basins within the area. Flow from these basins is through the Kapuskasing and Groundhog rivers.

The Woman Falls – Wakusimi River area is part of the Abitibi Uplands subregion of the James physiographic region (Bostock 1976). This region, and much of the study area, is underlain by crystalline Archean rocks and has a broad rolling surface that rises gently from the Hudson Bay Lowland.

Much of the topography in the study area is subtle; local relief is only 85 m. Bedrock outcrops in the western and eastern parts of the area, as well as along parts of the Kapuskasing and Groundhog rivers.

BEDROCK GEOLOGY

The bedrock geology of the area consists of 5 bedrock types (Ontario Geological Survey 1991). These include: 1) a gneissic tonalite suite consisting of tonalite to granodiorite with minor supracrustal inclusions; 2) a granodiorite to granitic suite consisting of massive to foliated granodiorite to granite; 3) the Casselman greenstone belt consisting of mafic to intermediate metavolcanic rocks; 4) a metasedimentary suite consisting of wacke, arkose, argillite, slate, marble, chert, iron formation and a minor component of metavolcanic rocks; and 5) a migmatized suite consisting of supracrustal, metavolcanic and minor metasedimentary rocks, as well as mafic and granitic gneisses.

There is also a series of northeast-trending faults. Two of these faults, which are part of the KSZ, control the orientation of the Kapuskasing and Groundhog rivers.

QUATERNARY GEOLOGY

All of the glacial landforms and materials in the map area are thought to have been formed and deposited during the Wisconsin glaciation. Ice flow direction across the area is defined by striae and drumlinoid features. Three sets of striae were observed. Striae orientated 120° are the youngest and are observed on many outcrops in the western and southwest parts of the map area. Striae orientated 160 to 180° were observed at only 2 sites—one northwest of the study area and the other in the extreme southwest-central part of the map area. The 120° ice flow eradicated striae orientated 160 to 180° on the outcrop to the northeast, except on a protected lee-side face. A third set of striae orientated approximately 220° was observed on many outcrops in the east and southeast parts of the map area. This set of striae is also truncated and eroded by striae orientated 220°. The relative age relationship between the 160 to 180° and 220° flow events is not clear.

There are 2 sets of drumlinoid features in the area. The first set is largely restricted to the northeast portion of the study area and is generally aligned at 120°. The second set is located in the northwestern and western parts of the map area and is generally orientated at 220°. The drumlinoid features are composed primarily of till, although several are cored by streamlined bedrock and at least one is composed of sand and gravel.

Three different types of tills were identified within the study area. A pebbly, sandy till consisting of thin, wavy beds interpreted as subglacial flows was observed in only one section. The second type of till, a deformation till, was observed in 2 sections where it directly overlies fine-grained glaciolacustrine materials. The third till, a flowtill, was observed in several sections and encountered throughout the study area in test pits and soil probes. In 2 sections, this flowtill was 4 to 6 m thick. This till makes up much of

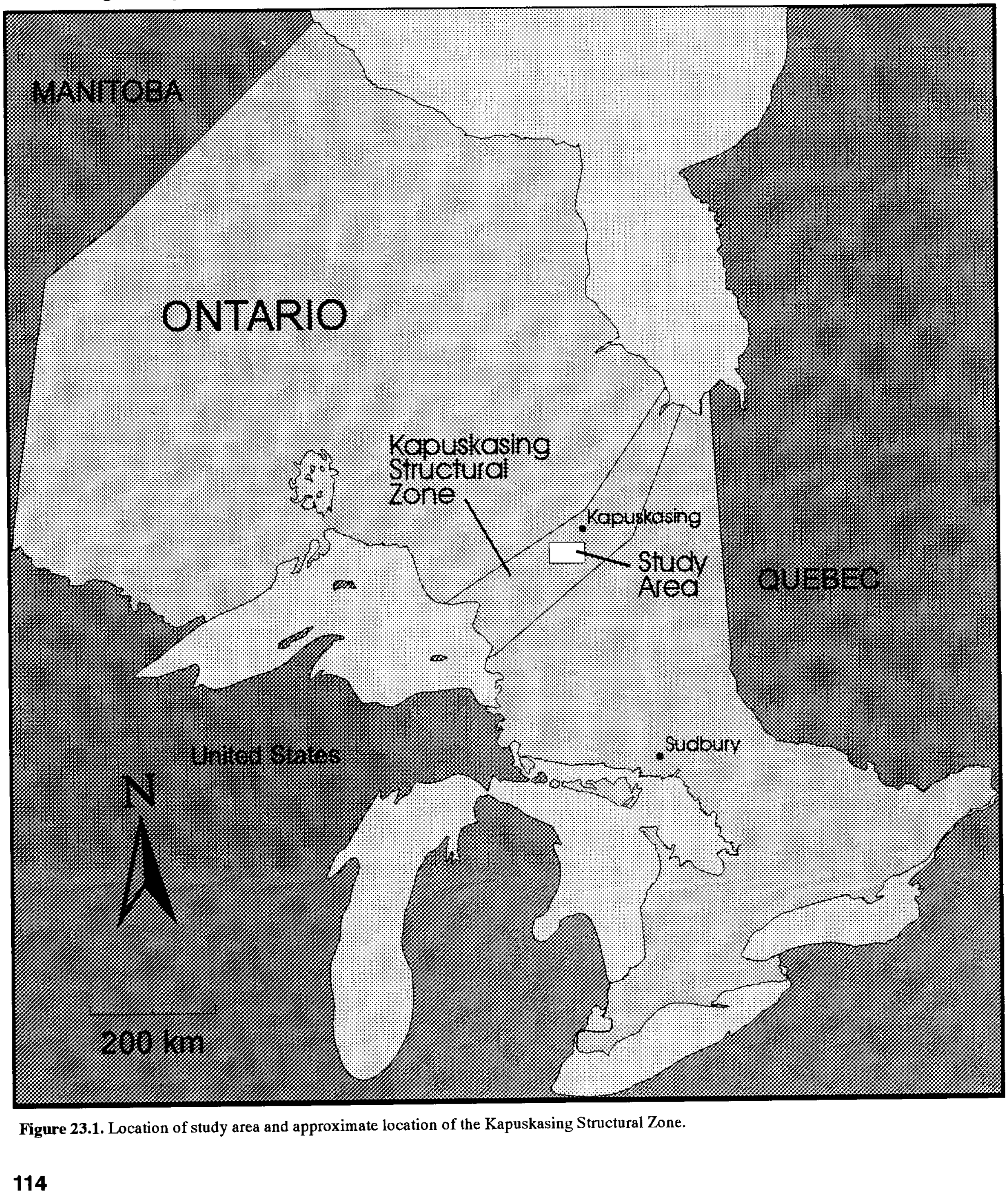

Figure 23.1. Location of study area and approximate location of the Kapuskasing Structural Zone.

the till plain covering the central part of the study area and was likely deposited during deglaciation.

Landforms associated with deglaciation include a till plain, recessional moraines and eskers. The till plain, consisting largely of flowtill, covers much of the central part of the study area and is locally thick. Recessional moraines are subtle features, rarely higher than 4 to 5 m above the till plain. The moraines are sinuous, up to 1 km long and trend westerly. The majority are concentrated in the north-central part of the study area.

A few small eskers (less than 1 km in length) were identified within the study area. There are, however, 2 major eskers. The Remi Lake esker extends south from Remi Lake into the north-central part of the study area. This esker is capped by silty clay. A second prominent esker system extends east across the Kapuskasing River, above Woman Falls, then southeast, paralleling the surrounding drumlinoid ridges. This esker is not covered by fine-grained material.

The oldest glaciolacustrine material consists of a sand and gravel deposit underlying fine-grained glaciolacustrine silts and clays. This was observed at 1 site in a gravel pit west of the Groundhog River. The fine-grained glaciolacustrine silts and clays were observed in section at 2 sites and occasionally along the banks of the Groundhog and Kapuskasing rivers. Within the 2 sections, this fine-grained unit consisted of alternating beds of silt and clay-rich materials. Arguably, they may be varves, but many of the beds were badly disturbed by loading.

An upper fine-grained glaciolacustrine unit, observed in the Kapuskasing River section and occasionally in soil probes and pits in the western half of the study area, overlies flowtills. This unit consists of varved silts and clays. In the lower and upper parts of the unit, the silt beds are up to 1 cm thick and the clay beds are millimetres thick. In the middle part of the unit, the silt beds are up to 4 cm thick, with the clay beds up to 1 cm thick. The unit is generally 2 m thick.

Several small pockets of sand and gravel are scattered throughout the central part of the study area. These deposits may be proglacial subaquatic fans associated with recessional moraines. The deposits are covered by flowtills.

A dense, massive silty clay diamicton caps much of the stratigraphy within the study area. This diamicton is structureless, compact and essentially pebble free. This material may be related to ice flow associated with the formation of the drumlinoid features.

PRELIMINARY RESULTS

A total of 205 modern alluvium, 94 till and 15 coarse-grained glaciolacustrine samples were collected. Modern alluvium was collected from as many streams and rivers as possible. Overall, a very good distribution of samples was collected from the entire study area. To direct till sampling, a hypothetical 5 km^2 grid was placed over the area and as many grids as possible were sampled. Coarse-grained glaciolacustrine material was collected from as many gravel pits as could be reached.

To date, the suite of kimberlite heavy mineral indicators identified includes garnet (chrome pyrope), chrome diopside, chromite, magnesium-rich ilmenite and olivine. In addition, MMSIMs identified include gahnite, chalcopyrite, red rutile, ruby corundum and sapphirine.

The Quaternary mapping program has defined several different types of coarse-grained glaciolacustrine deposits and identified several new potential aggregate deposits. These types of deposits are critical for the area as there is an acute shortage of aggregate for construction. In addition, this type of material has the potential to be used in products ranging from asphalt to concrete. The identification of fine-grained glaciolacustrine material may also be useful as liners for dams and landfill sites.

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24. Project Unit 97–05. Aggregate Resources Inventory of the Eastern Part of the Regional Municipality of Sudbury

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INTRODUCTION

During the summer of 1997, an aggregate resources assessment of the eastern part of the Regional Municipality of Sudbury was undertaken by the Sedimentary Geoscience Section. The study area covers 23 townships or approximately 210 000 ha (Ontario Ministry of Municipal Affairs and Housing and the Association of Municipal Clerks and Treasurers of Ontario 1997) (Figure 24.1). The area is covered by parts of the Venetian Lake (41I/14), Milnet (41I/15), Chelmsford (41I/11), Capreol (41I/10), Copper Cliff (41I/6) and Coniston (41I/7) 1:50 000 scale map sheets of the National Topographic System (NTS).

The purpose of the investigation was to delineate the aggregate deposits within the study area and to assess the quality and quantity of the sand and gravel resources. This information is required for infrastructure development and general construction applications, as well as for land-use planning.

BEDROCK GEOLOGY AND PHYSIOGRAPHY

The most prominent geological feature in the report area is the Sudbury Structure. It is a large oval-shaped structure measuring approximately 60 km in length and 23 km in width; its long axis is oriented in a northeasterly direction (Dressler 1984).

The Sudbury Structure consists of the Sudbury Igneous Complex, largely granophyre, quartz gabbro and norite; the overlying Sudbury Basin assemblage, which contains breccias, mudstones, wackes and sandstones of the Whitewater Group; and the brecciated footwall rock that occurs along the outer edges of the Sudbury Igneous Complex. Ni-Cu-PGE (platinum group element) mineralization occurs primarily along the contact of the Sudbury Igneous Complex and the surrounding footwall rocks, as well as in offset dikes that both radiate out from and trend parallel to the outer edges of the Sudbury Igneous Complex (Bajc 1992).

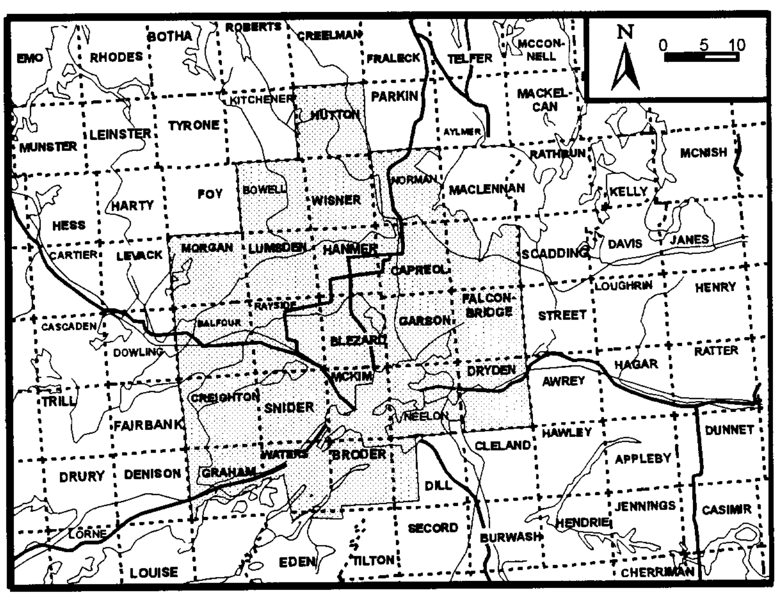

Figure 24.1. Townships within the Regional Municipality of Sudbury that were part of the 1997 study area.

The Sudbury Igneous Complex and the brecciated footwall rock form the physiographic region informally referred to as the "rim." Local relief varies from about 30 m along the south rim to over 60 m along the north rim. Rugged upland bedrock knobs characterize this area (Burwasser 1979).

The central part of the structure, the Sudbury Basin, is filled with glaciolacustrine sediments. The "valley," which is underlain by the relatively flat–lying Onaping, Onwatin and Chelmsford formations, is a flat to gently undulating glaciolacustrine plain with local relief generally less than 15 m. Most of the relief is attributable to the outcrop pattern caused by broad warpings of the Chelmsford Formation, as well as downcutting of the Vermilion River through the glaciofluvial and glaciolacustrine sediments (Burwasser 1979).

Archean granites, granitic gneisses and metavolcanic rocks of the Superior Province lie to the northwest of the Sudbury Structure. The predominantly clastic Huronian succession, with some metavolcanic rocks of the Southern Province, surrounds the remaining portions of the basin (Dressler 1984).

SURFICIAL GEOLOGY

During the Pleistocene Epoch, all of Ontario was covered by a succession of ice sheets. There were definitely two and probably more major ice advances, each separated by interglacial periods. The last glacial stage, referred to as the Late or Classical Wisconsinan, began approximately 23 000 years before present (Barnett 1992).

During this period, a thin, discontinuous cover of till was deposited throughout the study area by glacial ice that advanced in a south to southwesterly direction (Boissonneau 1966, 1968; Burwasser 1979). This sandy till generally exists as a thin veneer over bedrock, although in several areas thicknesses of up to 40 m are known to exist (Burwasser 1979). The thicker till accumulations are usually associated with east-trending morainic ridges deposited during temporary halts of the melting ice front. One such moraine, the Cartier 1 Moraine, extends across the report area from Hanmer to Hart townships. It exhibits local relief generally between 6 and 30 m (Boissonneau 1968).

As the glacial ice retreated northward, sinuous esker ridges were formed in the report area. These ridges are generally 3 to 6 km long and are situated in bedrock depressions (bedrock controlled). The eskers, consisting of stratified sand and gravel, were deposited by meltwater flowing in tunnels under the ice or in re-entrants at the ice front. They often rise between 5 and 30 m above the surrounding terrain. The eskers generally trend in a southerly or southwesterly direction.

Several deposits of undifferentiated ice-contact stratified drift were deposited close to the ice front as it melted; many of the deposits are associated with esker systems. These ice-contact deposits display a hummocky topography (Burwasser 1979).

Outwash features in the report area were deposited by meltwater flowing from the ice margin. The outwash primarily consists of well-stratified, uniformly bedded sand and gravel. Outwash is one of the most widespread glaciofluvial sediments in the study area and has been a traditional source of aggregate material.

As the ice front melted back to a position north of the Sudbury Basin, the basin, along with low-lying areas in the southern part of the report area, was inundated by glacial lake water. Where glaciofluvial systems entered the lake along the north rim of the basin, broad glaciolacustrine deltas were formed. These deltaic deposits, often more than 30 m in height, are relatively flat features with steep frontal slopes. Along these slopes, terraces were developed as water levels lowered in the lake (Boissonneau 1968; Burwasser 1979). Well-stratified, uniformly bedded sand and gravel are exposed in several pits developed in the deltas. The major deltaic deposits, located in Morgan, Lumsden and Hanmer townships, are well situated with respect to local aggregate markets.

Glaciolacustrine sediments are widespread throughout the Sudbury Basin. In the deeper waters of the glacial lake, massive and/or varved silt and clay were deposited. Glaciolacustrine sediments, consisting largely of silty fine sand, were laid down in the shallower areas of the lake. These glaciolacustrine sands are generally too fine for most aggregate uses. In places, glaciolacustrine material overlies ice-contact sediments.

Erosional activity has been minimal since the disappearance of the ice sheet and lowering of glacial lake water to present-day levels. Organic deposits have been developed in depressions in the land surface. Alluvium has been deposited along the courses of existing creeks and rivers.

AGGREGATE POTENTIAL

Highly weathered, brittle and friable Precambrian bedrock, which appears acceptable for low-specification aggregate use, is common within the report area. There are also many areas that are underlain by more massive, hard and durable rock, which appears suitable for a variety of aggregate applications.

At one site, within the Sudbury city limits, gabbroic rock has been found suitable by the Ontario Ministry of Transportation (MTO) for use in Portland cement concrete. At this site, the gabbro was stockpiled as waste rock from a tunnel excavation. Factors that would influence quarry development in this gabbroic rock include the size of the intrusion; the amount of impurities, such as mineralization; and the abrasive nature of these rocks on crushing equipment. Similarly, the gabbroic rocks of the Sudbury Igneous Complex are also potential sources of aggregate, although information is lacking on the suitability of this rock type.

The granitic rocks in the report area are also potential sources of quality aggregate. These rocks are usually hard and relatively homogeneous, but brittle varieties can occur and should be avoided in aggregate use. Massive, coarse-grained felsic plutonic and gneissic rocks with high mica, feldspar and quartz contents may have bonding problems.

The smooth cleavage and fracture surfaces of the minerals hinder the adhesion of asphalt and Portland cement concrete mixes. This problem can often be circumvented by weathering the rocks for a period of time in stockpiles or by adding chemicals (anti-stripping agents) that erode the smooth surfaces and allow better adhesion. Rogers (1985) reports that some granitic rocks can slowly react with alkalies from Portland cement concrete, resulting in concrete deterioration.

Within the report area, considerable latitude exists in choosing sites for potential bedrock extraction as there are extensive areas where bedrock is exposed at or near the surface. Areas in which excessive overburden thicknesses would restrict bedrock extraction are generally located within the Sudbury Basin.

Although the Precambrian bedrock in the area may meet MTO specifications for concrete aggregate, it may not be accepted by the MTO for use in Portland cement concrete, which will be exposed to de-icing salts. Radioactive mineralization may also occur locally within some rock types in the area and these rocks should be avoided during extraction.

Any site proposed for quarry development should be thoroughly tested before extraction commences. The Precambrian rocks may vary in quality over relatively short distances and may be alkali-reactive with Portland cement concrete mixes.

Certain by-products of bedrock mining and processing have also been used as alternative aggregate sources in the Sudbury area. For 40 years, slag from the area has been used as railway ballast and it is considered to be excellent for this use (Emery 1978). Finely ground nickel slag may also have potential as a pozzolana for use with Portland cement fills and could be used for binder in base stabilization in road construction (Emery 1978).

MTO has also tested the suitability of nickel slag from the Sudbury area for use as granular subbase. Because of the uniform smooth characteristics of the slag, compaction was difficult as the lack of fine particles did not allow the material to bind easily. Provided that fine material can be blended economically with the slag, or that the slag can be crushed finely enough not to require the addition of large quantities of fines, it has the potential for use as aggregate. Slag is hard, exhibits good drainage characteristics and forms little dust. Nickel slag is much heavier that gravel; consequently, it is more costly to haul. Nickel slag is not well suited for concrete use because its smooth nature would prevent good bonding with cement and it is too heavy to use in bridge construction (Chojnacki and Ryell 1960). Proposed changes to MTO specifications may mean that previous testing on nickel slag will have to be updated.

In the Sudbury area, excellent sources of aggregate material are eskers and other glaciofluvial ice-contact features, as well as outwash and deltaic deposits. The townships along the northern and eastern parts of the study area, particularly the glaciofluvial complex around the Sudbury airport, have large potential supplies of aggregate. Some of the sand and gravel material cannot be used in Portland cement concrete mixes because of an alkali–reactivity problem. The central and southern parts of the study area have less aggregate potential.

In the central and southern parts of the study area, small sand and gravel pits have been developed in lee-side cavity fill deposits. These deposits have often formed on the south side of bedrock topographic highs and have provided granular material for local projects.

Till is usually not well suited for aggregate use as it often contains excess fines and abundant cobbles and boulders. However, it may be a suitable source of fill in some locations. In some cases, the till has been reworked by glacial lake water removing some of the finer material.

In addition to delineating the aggregate resources and assessing the quality of the material, this study will also establish updated estimates of the quantity of aggregate available for future development and extraction.

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25. Project Unit 97-02. Atikokan–Lumby Lake High-Density Regional Lake Sediment and Water Survey, Northwestern Ontario

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INTRODUCTION

Field work for a high-density lake sediment and water geochemical survey of the Atikokan–Lumby Lake area was carried out between July 21 and August 19, 1997. Atikokan is located approximately 160 km west of Thunder Bay (Figure 25.1). The survey covered NTS (1:50 000) areas 52B/13, 52B/14, 52G/3 and most of 52B/15.

Lake sediment and water samples were collected at 2150 sites for an average of 1 sample per 1.7 km^2. The Atikokan–Lumby Lake area was selected for this type of geochemical survey due to recent increased exploration and claim-staking activity in the area, spurred on by the exploration success at the Hammond Reef gold property and new mapping and interpretations by the Ontario Geological Survey (Stone and Pufahl 1995; Stone and Halle 1996).

Some of the lakes in the southern half of the study area were sampled during the national geochemical reconnaissance (NGR) lake sediment program. This program was undertaken during the late 1970s by the Geological Survey of Canada (Friske et al. 1990) at a relatively low density of 1 sample per 13 km^2.

BEDROCK GEOLOGY

The most recent mapping of the area was completed by Stone et al. (1992), Stone and Pufahl (1995) and Stone and Halle (1996). The center of the study area is dominated by the 25 km by 70 km Marmion Lake batholith. Surrounding this batholith are the Sapawe, Steep Rock, Finlayson and Lumby Lake greenstone belts. These rocks, including the Marmion Lake batholith, are dominantly of Mesoarchean age (older than 2900 Ma). They therefore are some of the oldest rocks within the Wabigoon Subprovince. The Quetico

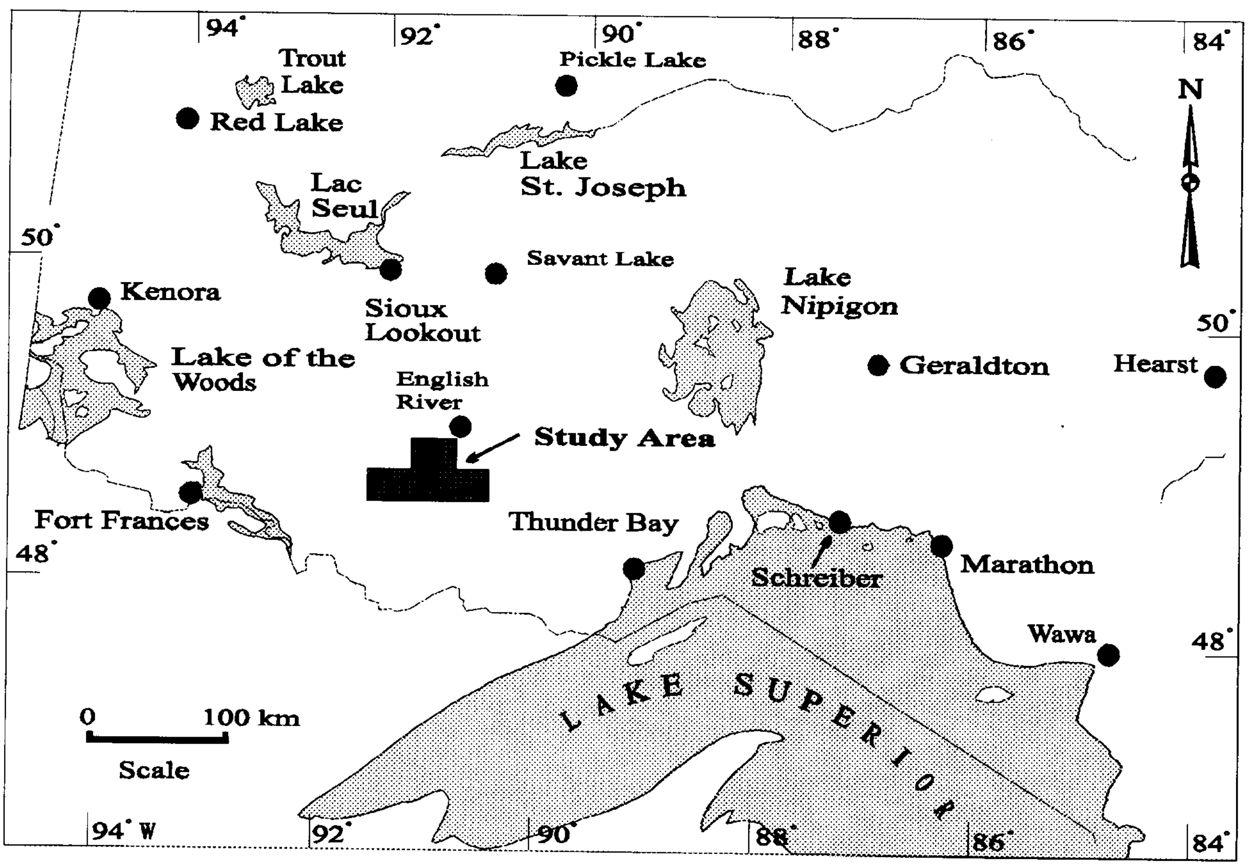

Figure 25.1. Location map of the Atikokan-Lumby Lake sediment and water survey area.

Fault, which marks the boundary between the Wabigoon and Quetico Subprovinces, is located along the southern edge of the study area.

Numerous gold occurrences are known within the Atikokan–Lumby Lake area (Wilkinson 1982, Schneiders and Dutka 1985). Most of these occurrences are located within or near the margins of the Marmion Lake batholith. Most gold showings are spatially associated with northeast-trending shear/fault structures (Lavigne and Scott 1995). For example, the Hammond Reef gold property of Pentland–Firth Ventures Ltd. is located within the northeast-trending Sawbill Bay deformation zone. The deformation zone that hosts the Hammond Reef mineralization has been traced for approximately 5 km (Lavigne and Scott 1995).

PHYSIOGRAPHY AND QUATERNARY GEOLOGY

Gentle topography characterizes the study area, with local relief rarely exceeding 50 m. Typically, relief over greenstone belts is more complex and rugged than over areas of granitic bedrock; the latter is characterized by rounded hills and shallow slopes.

Systematic detailed Quaternary geological mapping has not been conducted over the Atikokan–Lumby Lake area. Reconnaissance Quaternary mapping (1:506 880) was completed by Zoltai (1965). Engineering terrain maps, at a scale of 1:100 000, were produced for the region in 1980 (Mollard and Mollard 1980a, 1980b). A more recent regional compilation of the Quaternary geology of the area has been completed by Barnett et al. (1991). These sources indicate that surficial materials within the Atikokan–Lumby Lake area consist predominantly of a thin discontinuous veneer of drift (till) over bedrock. Modern fluvial deposits occupy major river valleys, such as along the Seine River. Glaciolacustrine sand, silt and clay occur locally. The Eagle–Finlayson Moraine and the Steep Rock Moraine, consisting of glaciofluvial sand and gravel, are located in the southern portion of the study area, trending southeasterly.

SAMPLING METHODS

Organic lake sediment samples were collected from a helicopter float, using a redesigned and improved gravity corer. This corer was designed to improve sampling speed by operating more reliably and obtaining a larger size of sample than the previous OGS sampler.

In order to avoid anthropogenic influences and water-sediment interface effects (i.e., increased Mn due to anoxic conditions that result in secondary accumulation of base metals), only deep sediment (greater than 20 cm below the sediment surface) was collected. This sediment better reflects the effects of natural geochemical inputs that may be traced to local geology.

Lakewater samples were collected at a depth of 0.5 m from shallow lakes (less than 3 m deep) and at a depth of 2 m from deep lakes (greater than 3 m). A semiautomated water-sampling apparatus, developed by the OGS, was utilized during the 1997 field season. The apparatus consists of a submersible pump, a flow cell (for measurement of parameters such as pH, conductivity, oxidation-reduction potential and dissolved oxygen), a sample-bottle tray and various hoses and pinch valves. Water was pumped from the lake and allowed to purge the sampling system prior to the collection of a water sample and the recording of water quality parameters. Water samples were kept cool after collection and processed (filtered and acidified) within 24 hours after collection.

A GPS receiver was utilized to record accurate sample-site positions. A customized database application operated on a pen-based computer was used to record sample descriptions and observations. Data from the water quality probe were also monitored and recorded with the pen-based computer.

The improvements in sample equipment and procedures used during the 1997 field season resulted in significant cost savings over previous years. On average, 24 lakes were sampled per hour of helicopter time, resulting in a daily (8 hour day) average of 192 sample sites. This is approximately twice as fast as the 1996 field season.

SAMPLE PREPARATION AND ANALYTICAL METHODS

Lake sediment samples were placed in breathable fabric bags and allowed to partially air dry prior to shipment to the laboratory. The samples were then freeze dried (to retain volatile elements) and sieved to obtain the less than 80 mesh (<177 mm) size fraction. Laboratory analysis includes nitric-aqua regia digestion followed by inductively coupled plasma-mass spectrometry (ICP-MS) to determine approximately 50 trace elements. Mercury is determined by cold vapour-flameless atomic absorption spectrometry. Nitric acid-aqua regia digestion attacks all sample matrix constituents, except for silicate minerals, and therefore is considered a nonselective, relatively strong, partial extractant.

Approximately 15 gm of sample pulp are pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA) for Au and a suite of 34 other elements. Quality control will be monitored through the use of sample pulp duplicates and certified reference materials. Loss-on-ignition (LOI) is determined at 500°C, using an automated gravimetric technique.

Water samples are passed through 0.45 mm syringe filters and acidified to 1% ultrapure nitric acid within 24 hours of collection. Analysis of water includes direct aspiration ICP-MS to determine approximately 50 elements including major cation and anion species. Quality of the analyses is monitored through the use of sample duplicates, certified reference standard SLRS–3 and blanks.

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26. Project Unit 97–01. High Density Regional Lake Sediment and Lake Water Geochemical Survey of the Shining Tree Area

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INTRODUCTION

A high density, helicopter-supported lake sediment and lake water sampling program was carried out during the 1997 field season over a 2480 km^2 area in northeastern Ontario. The map boundaries are irregularly shaped (Figure 26.1), with the village of Shining Tree located in the southern portion of the map area. This work follows a 1996 study (Hamilton 1997) completed to the east and a 1995 study (Bajc et al. 1996) to the north. With the completion of this project, the high density lake sediment and water sampling survey will have covered a contiguous area of approximately 7000 km^2 in northeastern Ontario.

The Shining Tree geochemical survey area includes all of the following townships: Asquith, Burrows, Cabot, Churchill, Connaught, Doon, Fawcett, Halliday, Kelvin, Kemp, MacMurchy, Midlothian, Miramichi, Mond, Natal, Nursey, Sothman and Yarrow, and parts of Amyot, Bannockburn, Browning, Brunswick, Emerald, Hutt, Londonderry, Mattagami, Montrose, Moyer, Ogilvie, Powell, Semple, Sheard and Togo townships.

OBJECTIVES

The sampling is part of an ongoing surficial geochemistry program carried out by the Ontario Geological Survey (OGS). This year's field area encompasses the Shining Tree greenstone belt and part of the southern Abitibi greenstone belt. The objectives of the program were to assess the background concentrations of over 40 elements in lake water and sediment to provide a high density geochemical database for use as

- a geochemical resource to aid exploration by the mineral exploration community
- a regional measure of natural and anthropogenically induced background concentrations.

REGIONAL SETTING

The Shining Tree greenstone belt is an extension of the southern Abitibi greenstone belt (*see* Figure 26.1). It is made up of Archean-aged steeply dipping supracrustal rocks striking northwest, west or southwest. It is composed of intercalated felsic to ultramafic metavolcanic flows with relatively minor amounts of interspersed clastic metasedimentary rocks. Plutonic rocks dominate along the south, southwest and northwest margins, but make up less than a third of the map area. To the northeast, largely flat-lying metasedimentary rocks of the Huronian Supergroup dominate. A small but important part of the southern Abitibi greenstone belt occurs along the northeastern margin of the map area. Most of the mines and former mines of the Matachewan gold camp are located in this area. Near Shining Tree, numerous old gold mines and shafts also exist. The largest of these was the Rhonda Mine. The bedrock geology of most of the southern half of the study area is currently the subject of a compilation project (Johns, this volume).

Alcock (1991) has mapped the Quaternary geology of most of the southern half of the study area in detail. The rest of the study area has been mapped on a 1:100 000 scale (Roed 1979; Roed and Hallett 1979a, 1979b). Quaternary deposits in the south-central portion of the area are thin and discontinuous over bedrock, with the exception of eolian dunes. Several moderate-sized south-trending esker complexes occur in the study area, but significant ice-contact stratified drift occurs in only 2 locations: southeast of Shining Tree and northeast of Sinclair Lake in the north-central part of the study area. Significant morainal complexes have also been mapped in these areas. The predominance of bedrock or thin till-dominated terrain makes this area ideal for lake sediment geochemical exploration.

FIELD PROGRAM

The OGS employed new sample collection and data recording equipment and protocols during the 1997 field season. Lake sediment samples were collected using a newly designed gravity corer but following standard OGS collection protocols (Fortescue 1988). These included sampling the portion of the sediment core below 20 cm to lessen the possibility of anthropogenic or diagenetic bias in the data. The new sampler retrieved more than double the amount of deep sample, thereby eliminating the need for 2 or 3 drops to obtain a large enough sample.

Water samples were collected from a depth of 2 m where lake depth allowed. Otherwise, samples were collected from just below the water surface. New, semi-automated water sampling equipment allowed water to be collected at the same time sediment was being collected. A small PVC submersible pump pumped water into the helicopter where a series of solenoids directed the water first into a drain, then into the sample bottle and finally though a flow-cell. This allowed simultaneous recording of pH, electrical conductivity, dissolved oxygen, temperature and oxidation-reduction potential. Samples were kept in ice-filled coolers for a period of less than 24 hours until they could be filtered (using 0.45 μm filters) and preserved by acidification to 1% nitric acid. Colour was measured in the field within 24 hours of sampling using a Pt-Co unit-calibrated colour wheel.

Sample notes were taken using a pen-based computer with custom-designed computer forms and dialog boxes. This aided in taking standardized notes and reduced sampling time. Geographic positioning system (GPS) location was recorded with the touch of a button on the sample

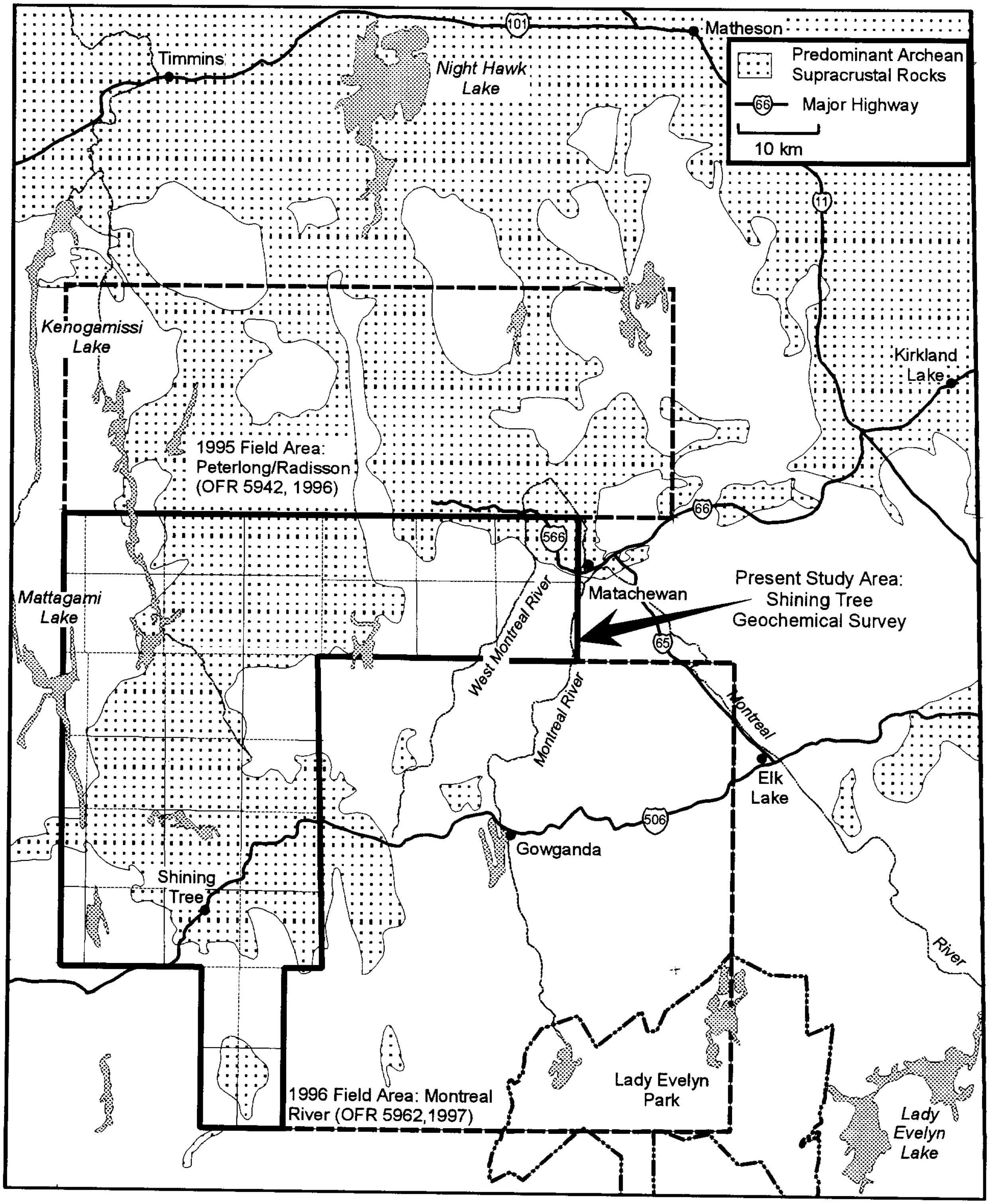

Figure 26.1. Shining Tree geochemical survey area.

form. Other data collected included lake depth, a description of the sample location, and the colour, texture, maturity and terrigenous content of the sediment.

These improvements succeeded in halving last year's sample time of 5 minutes per sample, thereby halving helicopter sample collection costs.

Samples are currently being prepared and analyzed according to protocols outlined in Hamilton (1997).

PRELIMINARY RESULTS

A total of over 1800 lake sediment samples and 2000 water samples were collected from almost every lake and pond in the study area. This resulted in a density of about 1 sediment sample per 1.4 km^2 and 1 water sample per 1.25 km^2. Chemical results are not yet available. Normally, results from OGS geochemical surveys are published within 12 to 18 months of completion of field work.

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27. Project Unit 97–07. An Evaluation of Peat and Shallow Groundwater for the Detection of Deeply Buried Mineralization: Case Studies from the Shoot Zone and Victoria Creek Gold Deposits, Northeastern Ontario

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INTRODUCTION

Large areas of highly prospective ground concealed by thick sequences of glacial deposits are situated across much of northern Ontario. In these areas, conventional surface geochemical methods are not particularly effective exploration tools. Over the past few years, the Ontario Geological Survey (OGS) has been evaluating a number of sample media and new geochemical techniques for the detection of mineralization situated within these terranes. Selective leach soil surveys have been undertaken at 7 sites, six of which are situated within the Abitibi greenstone belt of northeastern Ontario (Jackson 1995; Bajc 1996, in press). At four of these sites, preliminary water geochemical investigations were performed (Hamilton et al. 1995; Jackson 1995). At all of these sites, selective leach soil geochemical anomalies, spatially associated with buried mineralization, have been identified to varying degrees. Investigations at one of these sites, the St. Andrew Goldfields Shoot Zone gold deposit, are ongoing. Earlier studies include:

1. surface sampling of mineral soils and peat and analysis by enzyme leach and mobile metal ion (MMI) selective extractions;
2. a detailed, three-dimensional investigation of subsurface stratigraphy;
3. investigation of the lateral and vertical variation in chemistry of the major stratigraphic units using enzyme leach and conventional analytical digestion techniques;
4. determination of groundwater flow patterns and physical parameters of the various aquifers and aquitards underlying the property; and
5. sampling and analysis of groundwater in the major hydrostratigraphic units.

In conjunction with this work, a detailed water and soil geochemical investigation was carried out jointly by the Geological Survey of Canada (GSC) and the OGS at the Victoria Creek gold deposit situated east of Kirkland Lake (McClenaghan et al. 1997). Samples of vegetation, humus, and B- and C-horizon mineral soils were taken on well-drained upland lines transecting mineralization. Samples of shallow groundwater were also collected along a line that passes through a wetland over the mineralization. A spectrum of total and partial extractions was applied to the soils and the groundwater was analyzed directly.

A MODEL

Of all the data collected at both sites, responses from the poorly drained peatlands were the most encouraging. Clear and well-defined multielement anomalies were identified in groundwater at Victoria Creek and in peat at the Shoot Zone. Anomalies take the form of twin peaks (rabbit ears) straddling mineralization or single peaks directly over mineralization depending upon the element measured. At the Victoria Creek gold deposit, pH forms one of the sharpest anomalies and is defined by a strong rabbit-ear response, that is, hydrogen ion concentration forms a distinct apical anomaly.

The element anomaly patterns at both sites suggest the potential for electrochemical transport of elements from mineralization (Hamilton, unpublished data). This is supported by the overburden at both sites being too thick and too young to have allowed metals diffusing along concentration gradients to have reached the surface. Data from the Shoot Zone have shown that transport by groundwater advection would also be impossible because of downward gradients and slow groundwater velocities. Transport in gaseous complexes is also unlikely because gases do not typically exist as a separate phase below the water table; and the water table in the peat is at the surface.

It is postulated that an electrolytic conductor exists at these two sites based on adsorbed hydrogen ions in overburden materials. This conductor effectively extends an existing electronic conductor in rock (probably graphite or graphitic argillite) up to the surface. The objective of this year's field work was to investigate further the electrochemical cells that are suspected to be controlling the mobilization and deposition of anomalous metals at these two sites. In particular, the mechanism by which charge is transferred through overburden, in the absence of an electronic conductor, was investigated.

CURRENT STUDY

The 1997 field work was undertaken jointly by the OGS and the GSC with the goal of verifying previous observations at both sites and extending the geochemical coverage laterally outwards from initial survey lines. At the Shoot Zone deposit, both peat and shallow groundwater were collected from the same locations at 20 m spacing along 2 grid lines and at 10 m spacing along 1 grid line. At Victoria Creek, samples were taken at 20 m spacing along 2 lines.

Water was collected from shallow piezometers inserted approximately 1 m into the peat and filtered on site using in-line filters. The pH of the water was measured shortly after collection. Metals and major ions will be analyzed at the GSC Methods Development Laboratory. Surface and basal, humified peat samples were collected using a stainless steel Swedish auger and sidewall sampler respectively. Care was taken to minimize the amount of wood and root material included within the peat samples. The shallow and deep peat samples were collected at the Shoot Zone to investigate the vertical variation in geochemical response. Only shallow samples were collected at the Victoria Creek property because of the thin peat cover present at the site. Peat samples will undergo instrumental neutron activation analysis (INAA) and aqua regia inductively coupled plasma emission spectroscopy (ICP–ES), as well as an extraction selective to the metals chelated to humic and fulvic acids that form during the humification of plant matter. The Na-pyrophosphate digestion releases only those metals scavenged by humic and fulvic acids and should therefore provide a measure of the lateral variability of aqueous mobile ion concentration within the surface environment of wetlands. The relationship between peat and water geochemistry will be investigated to further advance the electrochemical cell model presented above.

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28. Project Unit 90–30. Joint Orientation Trajectories in South–Central Ontario

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INTRODUCTION

Mapping and analysis of joints, faults and lineaments in the Paleozoic cover and Precambrian basement are being carried out to investigate the post-Paleozoic structural and tectonic history of southern Ontario (Figure 28.1). Preliminary analysis of the area from Georgian Bay to Kingston indicates that joint sets and major lineaments have common orientations, and are self-similar between the outcrop and regional scales (Andjelkovic and Cruden 1997). There is surprising uniformity in the orientation and pattern of joints observed in the field and lineaments detected from satellite imagery. Three major joint sets oriented NNE-NE, ENE and SE occur throughout the study area in addition to locally occurring joint sets.

Field work in 1997 focussed on obtaining additional measurements of joint populations from Precambrian and Paleozoic outcrops throughout the study area and on de-

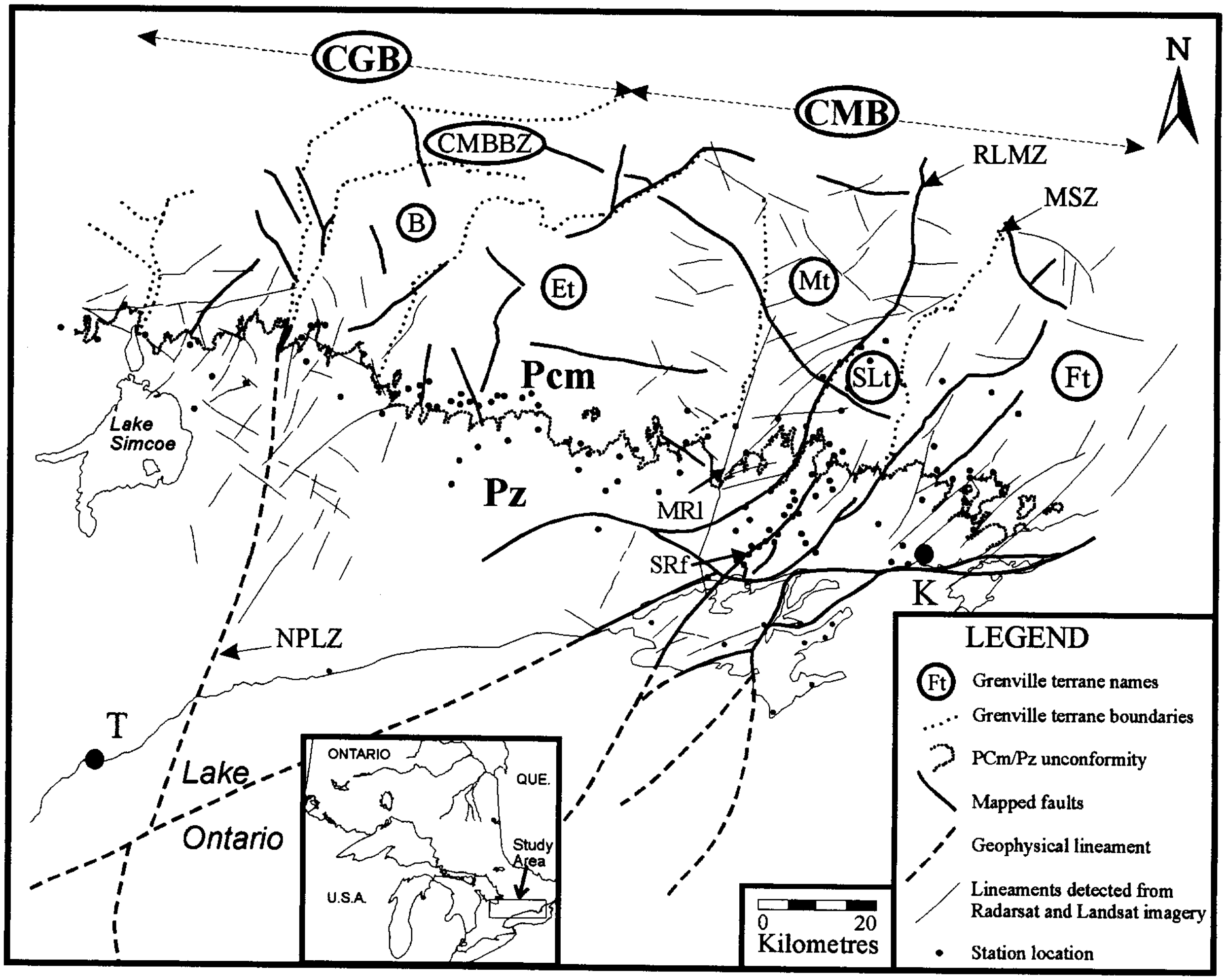

Figure 28.1. General geology of south–central Ontario showing faults and geophysical lineaments from Ontario Geological Survey (1991a, 1991b), location of joint mapping stations, and lineaments identified with satellite imagery in this study. Key: Pz=Paleozoic; Pcm=Precambrian; CGB=Central Gneiss Belt; CMB=Central Metasedimentary Belt; CMBBZ=Central Metasedimentary Belt Boundary Zone; B=Bancroft terrane; Et=Elzevir terrane; Ft= Frontenac terrane; Mt=Mazinaw terrane; Slt=Sharbot Lake terrane; NPLZ=Niagara–Pickering linear zone; RLMZ=Robertson Lake mylonite zone; MSZ=Maberly shear zone; Srf=Salmon River fault; Mrl=Moira River lineament; T=Toronto; K=Kingston.

tailed mapping of joints in the Campbellford–Madoc area. The major objective of this work was to better delineate a previously detected north-trending boundary in the regional joint pattern characterized by a transition from rocks containing NNE-trending joints to rocks containing NE-trending joints (Andjelkovic et al. 1996). This boundary is thought to mark a major change in structural style in the underlying crystalline basement (Andjelkovic and Cruden 1997). It may correspond to the western branch of the Elzevir–Frontenac boundary zone (EFBZ) (Forsyth et al. 1994) or to the boundary between Elzevir and Mazinaw terranes (*see* Figure 28.1; Cureton et al. 1997).

Additionally, 1997 field work focussed on detailed mapping of joints and field evaluation of lineaments that appear to cross the Paleozoic–Precambrian unconformity. Notable examples include the southern extension of Robertson Lake mylonite zone and the Salmon River fault (*see* Figure 28.1).

METHODOLOGY

A total of 6356 measurements of joints have been collected from 100 outcrop and quarry localities in the Paleozoic and 1516 measurements from 37 outcrop localities in the Precambrian (*see* Figure 28.1). Joints sets were defined by examination of rose diagrams (or propeller plots) of joint measurements for the entire region. The class interval used for counting the orientation data was 15° and the resulting rose diagrams were refined using a Gaussian smoothing function. Joint orientation data were grouped into the sub-areas presented in Table 28.1 and Figure 28.2. Once ranges of joint sets were classified, peak trends were identified at each station according to their intensity of occurrence. Using the program Spheristat®, the map area was divided into 28 km diameter circles, within which each set of peak trends was spatially averaged. The spatially averaged peak trends were plotted and used to construct a map of regional joint trajectories (Figure 28.3).

PRELIMINARY RESULTS

Three joint sets, trending NNE-NE, ENE and SE, occur regionally. In addition, two joint sets, trending ESE and NNW are developed locally.

NNE-NE-Trending Joint Set

The NNE-NE-trending joint set is the most dominant set in the Paleozoic, accounting for 32% of all measurements. This set is the second most dominant set in the Precambrian making up 25% of the joints observed.

The NNE-NE joint set may be sub-divided into two geographically based populations. In the western and central parts of the study area, NNE-trending joints are a major set in the Paleozoic (*see* Table 28.1). For this part of the study area, this joint set ranges between 011° and 042° with a peak trend of 024° (*see* inset A in Figure 28.2). However, there is an apparently abrupt change in the orientation of joints from west to east in the vicinity of Campbellford–Madoc. In the eastern part of the study area, the NNE-trending joint set is replaced by a NE-trending set which ranges between 020° and 065° with a peak of 042° (*see* inset B in Figure 28.2). This abrupt transition, or break, trends approximately NNE and crosses the Paleozoic–Precambrian boundary between Madoc and Tweed. To the south, this break appears to swing towards a more westerly trending orientation. However, data are currently insufficient to accurately position this feature.

In the Precambrian, the NNE-NE-trending joint set is the second most common set in most of the areas mapped (*see* Figure 28.2; Table 28.1); orientations range from 014° to 062° (*see* Table 28.1). This set shows a similar behaviour to that in the Paleozoic, with a shift from a NNE-trend in the west to a NE-trend in the east. The dividing line marking the shift is oriented approximately NNE in the Madoc-Tweed area (*see* Figure 28.3). Additional work is required to better delineate the position of this boundary north of the Paleozoic–Precambrian unconformity. Data grouped from the area west of this boundary has a peak trend of 026°, whereas data to the east exhibits a peak trend of 047° (*see* insets C and D in Figure 28.2).

In most areas trajectories of this joint set pass smoothly across the unconformity, indicating a continuity of this joint set from Precambrian basement to Paleozoic cover (*see* Figure 28.3). However, there are apparent minor deflections of trajectories across the unconformity, especially in the Stony Ridge–Balsam Lake area. It is currently unclear whether these deflections are significant or simply artifacts of the data processing.

ENE-Trending Joint Set

In the Paleozoic the ENE-trending joint set has the best defined peak (081°) and narrowest range (065° to 089°) (Andjelkovic et al. 1996). It is the most common or second most common set in the eastern half of the area except for the Napanee region where it is masked by a local ESE-trending set. The ENE-trending set becomes more prominent southward towards the shoreline of Lake Ontario to which it is sub-parallel (*see* Figures 28.2 and 28.3).

In the Precambrian, the ENE-trending set has a peak trend of 080° and range between 074° and 087°. It is the major set in the Stony Ridge area (*see* Table 28.1 and Figure 28.2). To the east in the Madoc and Westport areas, the ENE-trending set is the second most common joint set.

Trajectories of the ENE-trending joint set are continuous across the Paleozoic–Precambrian unconformity (*see* Figure 28.3). Despite this generally uniform pattern, the ENE-joint trajectories exhibit several apparent minor deflections. One of these corresponds to the observed break in the NNE-NE-trending trajectories.

SE-Trending Joint Set

The SE-trending joint set exhibits a constant orientation throughout the area, although its frequency of occurrence is highly variable (*see* Table 28.1). Its range in Paleozoic rocks is between 122° and 160°, with a peak at 138°. This set is quite prominent in the Orillia to Balsam Lake areas in the west. However, it seems to be replaced by the ESE-trending joint set in the Buckhorn–Lakefield area (*see* Fig-

Table 28.1 Summary of joint orientation data in Paleozoic and Precambrian rocks in study area. Range in orientation is listed for each joint set. Order of prominence of joints sets is indicated (e.g., 1st, 2nd, 3rd) for each area. Also see propeller plots in Figure 28.2.

			Areas											
Paleozoic joints sets	**Azimuth Range**	**%**	**Orillia**	**Carden**	**Toronto**	**Balsam Lake**	**Buckhorn**	**Lakefield**	**Campell–ford**	**Madoc**	**Napanee**	**Prince Edward Cty**	**Kingston**	**Total**
NNE–NE	011–064	32	2	1		1	2	3	1	3	2		3	
ENE	065–089	19	3	2	1	3	3	1	2	1	3	1	1	
SE	122–160	20	1	3	2	2			4	2	4	2	5	
NNW	343–010	10								5			4	
ESE	090–120	19					1	2	3	4	1		2	
Total measurements:			358	374	163	739	250	668	402	430	1351	620	1001	6356

			Areas						
Precambrian joint sets	**Azimuth Range**	**%**	**Balsam Lake**	**Buckhorn**	**Stony Ridge**	**Madoc**	**Kaladar**	**Westport**	**Total**
NNE–NE	014–062	25	2	2	3		2	3	
ENE	074–087	15		3	1	2		2	
SE	122–158	27	1	4		1	1	1	
NNW	343–010	11				3			
ESE	090–120	22		1	2		3		
Total measurements:			70	309	190	143	491	313	1516

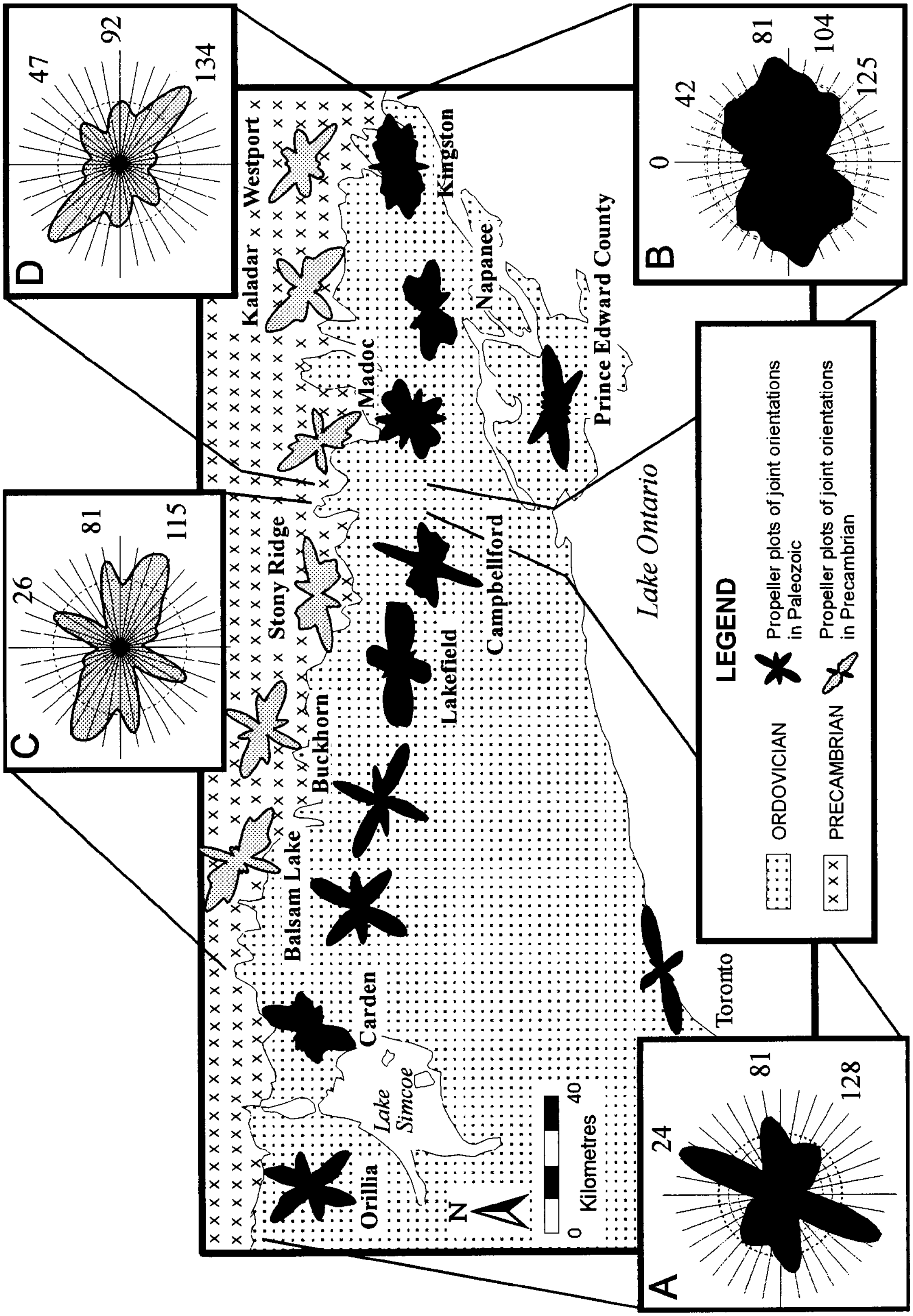

Figure 28.2. Propeller plots of joint orientations in Paleozoic and Precambrian terrains grouped into sub-areas (see Table 1) and into four sub-regions (inset A, B, C and D).

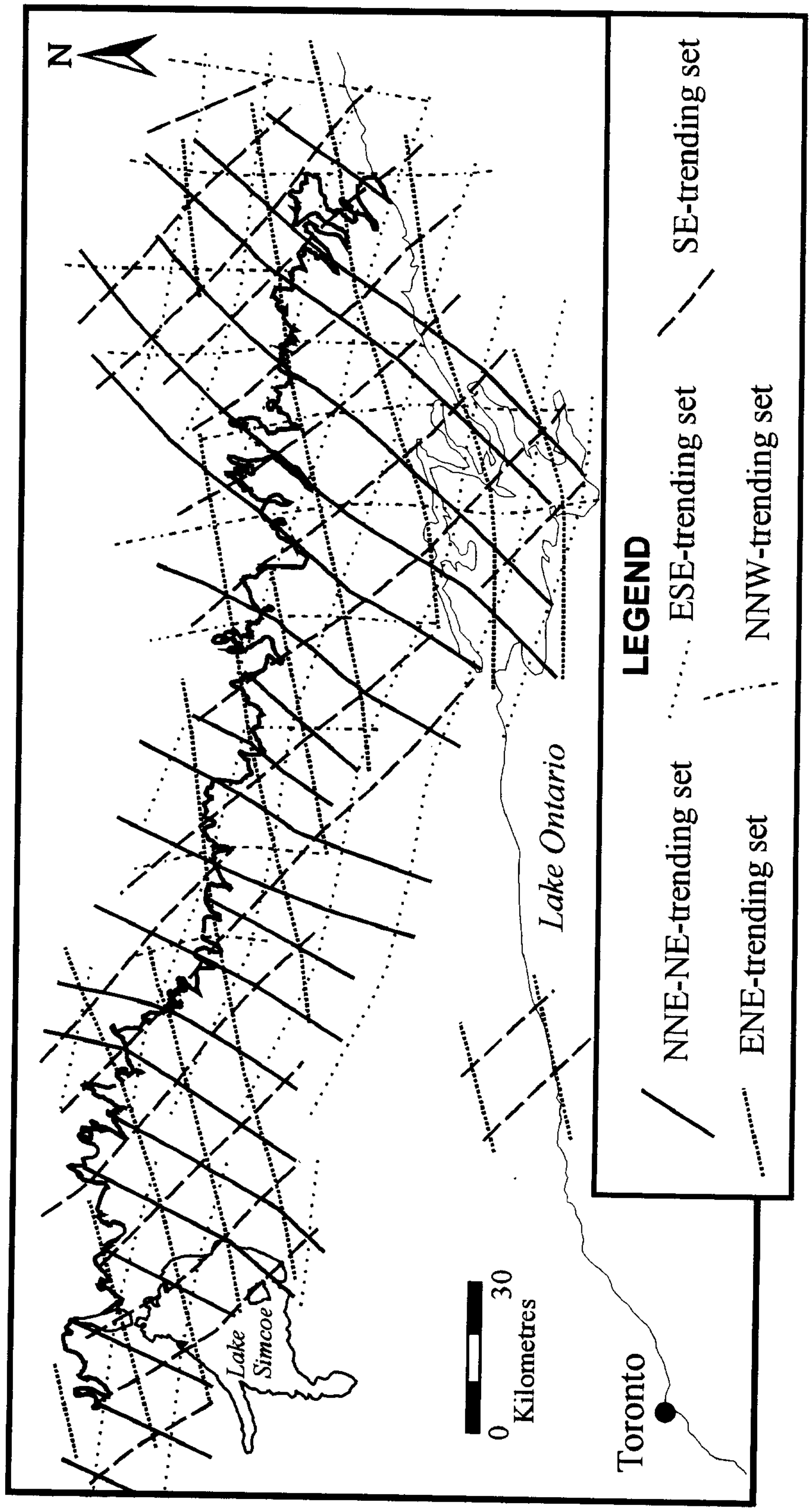

Figure 28.3. Joint set trajectories in the study area.

ure 28.2). Its greatest deviation from the mean occurs in the Campbellford–Madoc area where it has a peak of 148° (*see* Figure 28.2). In the eastern part of the area, from Madoc to Kingston, this is a minor set with a peak of 126°. The trajectories of this set show only minor deflections and are continuous across the Paleozoic–Precambrian unconformity (*see* Figure 28.3).

The SE-trending joints are the dominant set in the Precambrian with a range of between 126° and 158°, and a peak at 135°. SE-trending lineaments are also dominant in the Precambrian of this area (Lowman et al. 1992; Spitzer 1981; Sanford et al. 1984).

Local Joint Sets

NNW- and ESE-trending joint sets are developed locally throughout the region (*see* Table 28.1; Figures 28.2 and 28.3) and dominate the regional sets at some localities. The NNW-trending set in Paleozoic rocks has a range between 343° and 010°, with a peak of 002° (*see* Table 28.1). It is present in the central part of the region (e.g., at Buckhorn; Figure 28.2) and becomes more frequent to the east. In the Precambrian, this set has the same range but a peak of 348° (*see* Table 28.1).

The ESE-trending set in the Paleozoic terrain is the most dominant set in the Buckhorn and Napanee areas and is the second most common in the Lakefield and Kingston areas (*see* Table 28.1). Orientations range between 090° and 120° with a peak at 102°. This set is difficult to differentiate from the ENE-trending set in the Lakefield and Kingston areas (*see* Figure 28.2), and from the SE-trending set in the Campbellford area.

In the Precambrian rocks, the ESE-trending set has the same range as its equivalent in the Paleozoic strata. It is the most prominent set in the Buckhorn area, both north and south of the unconformity.

The ESE-trending joint trends vary slightly in the Paleozoic rocks, ranging from approximately 100° in the Lakefield area, to approximately 118° in the Campbellford area and back to approximately 100° in the Belleville–Napanee areas (*see* Figure 28.3).

Trajectories of the ESE-trending and NNW-trending sets, in the areas where they have been established, do not change significantly across the Paleozoic–Precambrian unconformity (*see* Figure 28.3).

DISCUSSION

Joints in the Paleozoic display similar trends across the region (*see* Figures 28.2 and 28.3; Table 28.1). Despite local differences in their frequency of occurrence the NNE-NE-, ENE- and SE-trending joint sets occur regionally.

Although less data are currently available, joint sets exhibit a similar pattern in the Precambrian. Furthermore, trajectories of both regional and local joint sets generally continue without change in orientation across the Paleozoic–Precambrian unconformity. These results suggest that jointing in the Precambrian basement and Paleozoic cover rocks is related. Considering the complex pre-Paleozoic tectonic and uplift history of the Precambrian basement (Easton 1992), it is reasonable to assume that some jointing in the Precambrian must have occurred prior to Ordovician sedimentation and that at least some of the joint sets that occur in the Paleozoic were inherited from pre-existing sets. The chronology and mechanisms of joint set formation in the area will be the focus of further research.

Despite the regional uniformity of joint orientations several changes in the pattern of joints are observed (see Figure 28.3). These can be viewed as structural breaks in the joint pattern. Given the correlation between joints in the basement and cover, it is reasonable to suggest that they may be related to changes in basement structure.

The most obvious change in joint pattern occurs as a transition from NNE-trending to NE-trending joints across a cryptic, approximately NNE-trending break located in the Campbellford–Madoc area (*see* Figures 28.2 and 28.3). Further analyses will show if this transition occurs across a narrow or a broad zone.

Known basement structures that could be linked to this NNE-trending break are the Robertson Lake mylonite zone (Easton 1992), the Elzevir–Frontenac Boundary Zone (Forsyth et al. 1994) (which is approximately coincident with the Sharbot Lake terrane in Figure 28.1) and the Elzevir–Mazinaw terrane boundary (Cureton et al. 1997). As defined by currently available data, the observed break in joint trajectories lies closest to the sub-Paleozoic projection of the Elzevir–Mazinaw boundary and also to the prominent Moira River lineament. Further work is required to investigate a possible link between this break in joint orientation and these basement structures.

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29. Project Unit 90–30. Subsurface Study of Middle Ordovician Strata Near Lake Simcoe: A Preliminary Report

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INTRODUCTION

Middle Ordovician strata in the Lake Simcoe area (Figure 29.1) in south-central Ontario were cored and geophysically logged as part of an ongoing investigation by the Ontario Geological Survey (OGS) into the nature and distribution of alkali-carbonate reactive beds (e.g., Armstrong and Rhéaume 1993; Armstrong 1995). The primary objective of the current project is to conduct a detailed sedimentological and diagenetic investigation into the origin into the carbonate rocks in these strata using the core obtained from the OGS drilling program.

The Middle Ordovician strata in the Lake Simcoe area consist of, in ascending order, the Shadow Lake, Gull River, Bobcaygeon, Verulam and Lindsay formations (Figure

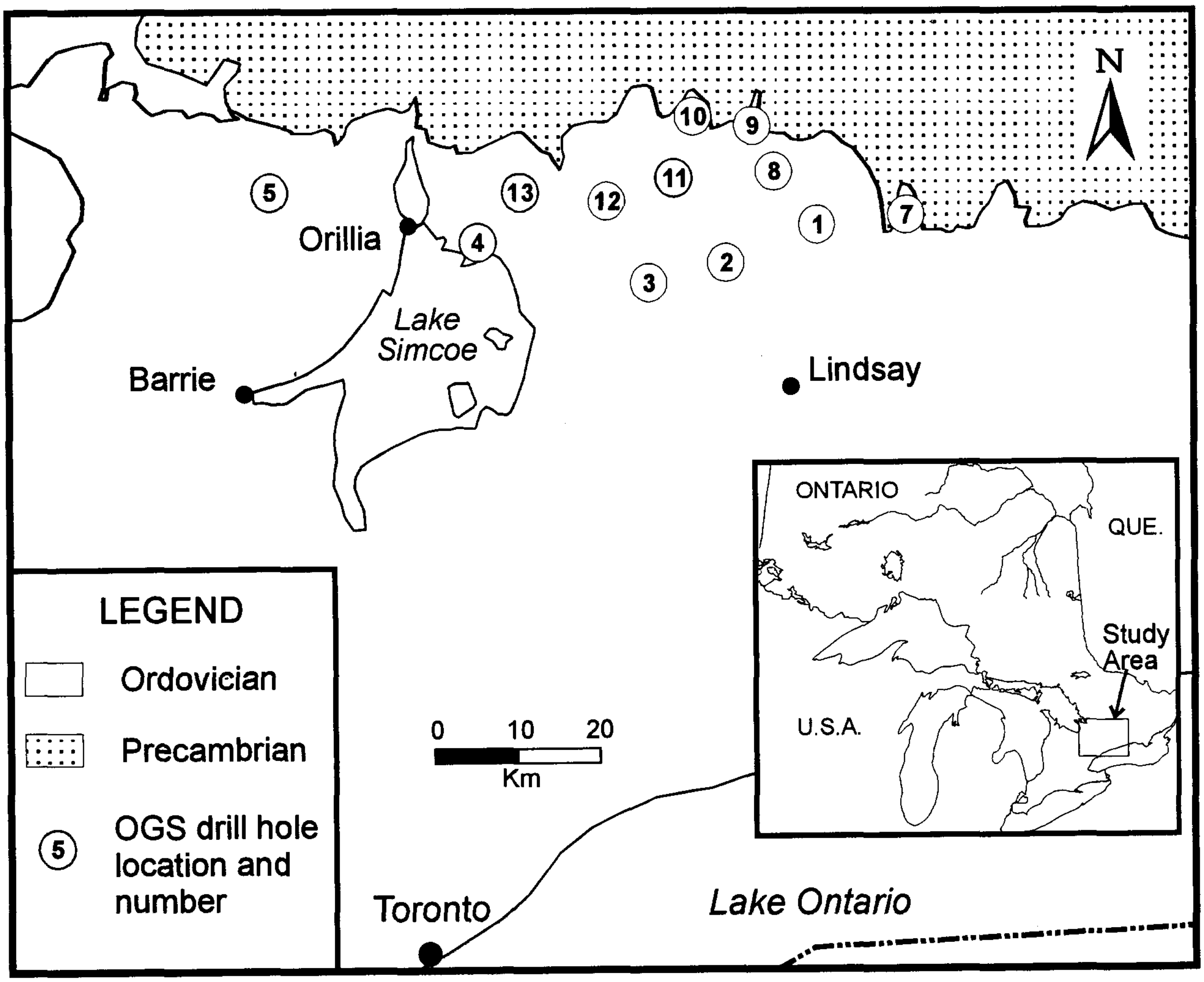

Figure 29.1. General bedrock geology of south-central Ontario showing the locations of OGS drill holes.

29.2). These units record the Middle Ordovician transgression of the Tippecanoe Sea over the Precambrian surface. All of the OGS drill holes were continuously cored into Precambrian basement and all but one were collared in the lower member of the Bobcaygeon Formation or a higher stratigraphic unit (Armstrong and Rhéaume 1993). The study reported on here focusses on the Blackriveran age portion of the Ordovician section, that is, from the lower Bobcaygeon down to the Shadow Lake Formation (*see* Figure 29.2)

These rocks contain lithofacies that represent deposition in a variety of shallow marine settings. There is abundant and varied evidence for event sedimentation, likely resulting from storms, as well as a range of discontinuity surfaces most readily interpreted as representing varying degrees of early seafloor cementation (i.e., hardgrounds). Although aspects of the sedimentology of these rocks, including both storm sedimentation and hardground formation, have been treated previously in outcrop-based studies (e.g., Wilkinson et al. 1982; Brett and Brookfield 1984; Brookfield 1988; Noor 1989), the available suite of cores offers an unprecedented opportunity to assess sedimentation and diagenesis on a regional scale using a well-spaced and consistently high-quality record.

In addition, although still a topic of some controversy, these rocks and coeval strata located farther to the east in the St. Lawrence Lowlands have been suggested to represent deposition under temperate water conditions (e.g., Brookfield 1988; Lavoie 1995). The systematic study of these rocks, particularly their microfacies, will enable vigorous testing of the above hypothesis. Integration of the results of this study with recently completed theses carried out at Queen's University on correlative rocks in the Kingston area (McFarlane 1992; Brown 1997) will provide a better understanding of the correlation and regional characteristics of these units. This study will also help in determining the origin of alkali-carbonate reactive beds in south-central Ontario.

North American Series	North American Stages	Southwestern Ontario (Sanford 1961)		Lake Simcoe Area (Liberty 1969; Russell and Telford 1983)			Depositional Environments (Melchin et al. 1994)
Upper Ordovician (Cincinnatian)	Maysvillian		Blue Mountain Fm.			Blue Mountain Fm.	deep shelf
			Collingwood Fm.	Simcoe Group		Collingwood Mb.	
	Edenian	Trenton Group	Cobourg Fm.		L	Lindsay Formation	shallow shelf
Middle Ordovician (Champlainian)	Trentonian		Sherman Fall Formation		U	Verulam Formation	shallow shoal
					L		deep shelf
			Kirkfield Formation		U	Bobcaygeon Formation	shoal - shallow shelf
					M		lagoon - protected shelf
	Blackriveran	Black River Gp.	Coboconk Fm.		L		shoal - shallow shelf
			Gull River Fm.		U / M / L	Gull River Fm.	lagoon tidal flat
			Shadow Lake Fm.	Basal Gp.		Shadow Lake Fm.	supratidal

Figure 29.2. Stratigraphy and depositional environments of Ordovician strata in southern Ontario (*modified after* Melchin et al. 1994). L, M and U refer to lower, middle and upper members respectively.

METHODOLOGY

This study is based on the examination of 12 logged cores, 50 polished slabs and 321 thin sections. Cores were logged at a 10 cm scale, recording lithology, sedimentary and diagenetic fabrics, type and degree of bioturbation, and the abundance and diversity of fossils. Polished slabs were used to more closely examine rock fabrics and other aspects not as easily observed on sawn, unpolished surfaces. Uncovered thin sections were stained with Alizarin Red-S and potassium ferricyanide to differentiate calcite from dolomite and ferroan from nonferroan carbonate. These thin sections were subsequently covered using a spray-on plastic coating. Additional analysis of polished thin sections may be carried out by microprobe at the University of Western Ontario to identify problematical mineral phases. Integration of core, slab and thin section information will enable the generation of a series of cross sections across the study area and will allow more detailed correlation beyond the study area.

PRELIMINARY RESULTS

Ten cores were logged at the core laboratory in the Willet Green Miller Centre in Sudbury and an additional 2 cores were examined at the Ministry of Northern Development and Mines office in London. The following descriptions are based on core and thin section examinations carried out to date and on information from the published literature.

Shadow Lake Formation

The Shadow Lake Formation is the lowermost Ordovician unit in the study area, resting unconformably on the Precambrian basement. Its thickness is extremely variable, ranging from absent over Precambrian topographic highs to 12 m thick in Precambrian surface depressions (Liberty 1969). In the cores examined in this study, thicknesses ranged from 2 to 9 m.

The Shadow Lake Formation consists of immature, arkosic conglomerates and sandstones that grade upward into dolomitic or calcareous sandstones, terrigenous mudstones and silty to sandy dolostones or limestones. Commonly, these units are poorly sorted and contain abundant clasts of quartz, feldspar, and igneous and metamorphic rock. The formation is unfossiliferous and thickly bedded and exhibits colours ranging from red-green to grey and buff-brown.

Sedimentary structures include horizontal planar lamination and cross-lamination, mud cracks, normal grading and amalgamated surfaces. Burrows and bioturbation are common and are responsible for the red and green colour mottling seen in parts of the formation (Noor 1989).

These strata were deposited in a nearshore zone during the advance of the Tippecanoe Sea. The sediments were deposited in a low-energy environment, extending outward from the Precambrian source area, in a fanlike, deltaic setting (Liberty 1969). A combination of very low regional gradient and Precambrian topography resulted in the low energy regime that was interrupted periodically by storm events (Melchin et al. 1994).

Gull River Formation

The contact between the Shadow Lake Formation and the overlying Gull River Formation is gradational and can be recognized by the transition from the red-green siliciclastic beds of the Shadow Lake Formation to the buff-brown dolostone and limestones of the Gull River Formation. The change commonly occurs over a vertical distance of 0.5 m. The thickness of the Gull River Formation in the cores varies from 14 to 32 m. The formation consists predominantly of medium- to thin-bedded lime mudstones, with minor dolomitic limestone, dolostones and silty to shaly carbonates near the base. Locally, oolitic beds, domal stromatolites, calcareous shales and rare bentonites are found. Colours include light green, buff-brown, tan and white.

Sedimentary features are abundant and diverse. Fenestral fabrics, cryptalgal laminations, desiccation cracks, and vertical and U-shaped burrows are commonly found in the lower laminated and unlaminated lime mudstones and dolostones. Bedding contacts are commonly marked by the presence of stylolites, shaly seams, hardgrounds and firmgrounds. Diagenetic features include moldic pores resulting from the dissolution of platy gypsum crystals.

Fossils in the lower part of the formation are generally rare, consisting mainly of ostracode and trilobite remains. In the upper part of the formation, fossils are more abundant and include gastropods, trilobites, bivalves, bryozoans, brachiopods and tabulate corals (e.g., *Tetradium*), but diversity remains low. The topmost beds of the Gull River Formation are the most bioclastic interval within the formation. They also contain the algae *Girvanella* as grain coatings.

Lime mudstones and cryptalgal laminites in the lower Gull River Formation represent deposition in a hypersaline, supratidal to intertidal flat, grading into a restricted lagoon setting (Melchin et al. 1994). Periodic storms interrupted this otherwise quiet–water setting. The increased fossil content higher up in the formation represents a shift to a more open marine setting with subtidal lagoonal conditions (Melchin et al. 1994). The presence of glauconite–filled burrows, phosphatic clasts, and diversely fossiliferous intraclastic and peloidal wackestones and packstones may indicate brief open subtidal conditions.

Lower Bobcaygeon Formation

Liberty (1969) defined the lower contact of the Bobcaygeon Formation as the gross lithologic change between the "lithographic" limestones of the Gull River Formation and the fine- to medium-grained, grey limestones of the lower member of the Bobcaygeon Formation. Winder et al. (1975), Noor (1989) and Carson (1981) all proposed different stratigraphic locations for the contact, however, and it remains a controversial issue. For the purpose of this study, the contact is deemed to be located where mudstones and wackestones of the uppermost Gull River Formation change to packstones and grainstones of the lower Bobcaygeon Formation.

The lower member of the Bobcaygeon Formation is approximately 3 to 11 m thick in the Lake Simcoe area, consisting of pale grey to brown-grey, medium- to thick-bedded, bioclastic and/or peloidal grainstones, packstones and wackestones. Grain sizes range from silt to fine sand in peloidal grainstones to 5 to 10 mm in bioclastic grainstones. Calcareous algal oncolites, micritized grains, intraclasts and large bioclasts are common throughout the formation. Fossils are abundant and diverse, and include tabulate and rugose corals, gastropods, bryozoans, brachiopods, stromatoporoids, bivalves, nautiloids, trilobites and calcareous algae. This formation contains a variety of sedimentary structures, including planar, ripple and trough cross-laminations, burrows and moderate bioturbation. Diagenetic features include hardgrounds, silicified fossils and chert horizons.

The lower member of the Bobcaygeon Formation is interpreted to represent a complex of offshore sandshoals on a shallow marine shelf (Melchin et al. 1994), as indicated by the diverse fauna, algal-coated grains, current-produced structures and lack of lime mud.

FUTURE WORK

To date, approximately 20% of the thin sections have been systematically examined. Once thin section examination is complete, it will be possible to identify the spectrum of facies and microfacies present in these rocks. Integration of core, slab and thin section information with data from previous studies will allow reconstruction of the paleoenvironments of the lower Middle Ordovician units in the study area. The detailed core logs will provide a high-resolution record with which cyclicity in these rocks can be assessed and compared to small-scale cycles described from coeval strata in the Kingston area. The results of this study will also provide a clearer understanding of the relationship between storm sedimentation, seafloor cementation and cyclicity.

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Resident Geologists' Section

30. Recommendations for Exploration in the Thunder Bay North Regional Resident Geologist's Area

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INTRODUCTION AND EXPLORATION ACTIVITY

Thunder Bay North Regional Resident Geologist's Area includes the Beardmore–Geraldton District (G.D. White, District Geologist) and Sioux Lookout District (G. Seim, District Geologist). In 1997, approximately 100 exploration programs were undertaken in Thunder Bay North, of which 40 were funded under the Ontario Prospectors Assistance Program (OPAP).

RECOMMENDATIONS FOR EXPLORATION (BEARDMORE–GERALDTON DISTRICT)

The Brookbank deformation zone, Barton Bay lithotectonic zone (Bankfield–Tombill fault) and Watson Lake fault represent tectonic targets that have potential to host significant gold mineralization. The deformation zones are ductile–brittle fault systems displaying an alteration and mineral assemblage including iron carbonate, silica, tourmaline, potassium feldspar, hematite, fuchsite, pyrite, arsenopyrite and pyrrhotite.

Recent gold discoveries in the Metcalfe–Knucklethumb Lake felsic metavolcanic sequence have enhanced the exploration potential of this area. East-trending deformation zones host auriferous, disseminated to massive, pyrite-bearing porphyry units and visible gold in crack-seal vein systems. The same felsic metavolcanic package extends north and northeast from Oboshkegan Lake to Kowkash station on the CNR mainline.

The northern portion of the Onaman–Tashota belt and the English River Subprovince and East Uchi Subprovince will be accessed, over the next 10 years, by new logging roads, constructed under the Nakina North and Ogoki Timber Management agreements. Potential exploration targets include the following:

1. The Uchi Subprovince, which has produced over 17 million ounces of gold, is a potential target. For the first time, roads will access the east portion of the Uchi Subprovince, an area with a good geological and exploration database.
2. The East English River Subprovince has not been geologically mapped in detail. The opportunity exists for new gold, base metal and diamond discoveries in previously unrecognized metavolcanic rocks.
3. The Attwood Lake–Melchett metavolcanic–metasedimentary belts may be the same lithological assemblages (G.M. Stott, OGS, personal communication, 1997), as indicated by structural and geological interpretation .

Houghton–Clarke Elmhirst Property

The main portion of the Houghton–Clarke Elmhirst property is located approximately 25 km northeast of Beardmore, in south-central Elmhirst Township. The property consists of 72 contiguous claims in 10 blocks, aligned along a southerly trend. It is currently held by Beardmore prospectors F. Houghton and L. Clarke, and was recently optioned by a junior mining company (1997). Access to the main occurrences is via Highway 11, travelling 23 km east to Highway 801 (the Paint Lake road) then north for 11.5 km to the Paint Lake haul road. The centre portion of the claim group is located roughly 4 km northeast along this road.

The area containing the Houghton–Clarke property, which is underlain by granodioritic rocks, has seen very little exploration activity compared to the surrounding metavolcanic terrain. An exception is the Oliver Severn occurrence to the east, a highly mineralized (pyrite, chalcopyrite) gold-bearing vein system within an altered metavolcanic xenolith. This property was first trenched and diamond drilled in 1935 by Oliver Severn Gold Mines Limited. From 1989 to 1990, Noranda Exploration Company, Ltd. conducted an extensive exploration program over the same occurrence that involved detailed geological mapping, stripping, rock sampling and several geophysical surveys.

Outside the northeast boundary of the Houghton–Clarke property and within the metavolcanic sequence, an extensive amount of work was conducted by several groups, from 1971 to 1980, over what is known as the Milestone–Kengate option. Carling Copper Mines Limited completed extensive geological mapping and sampling, 2 geophysical surveys, and 31 diamond- drill holes over several copper-zinc-gold occurrences on the property. In 1987 and 1988, E. Maruska explored what was known as the Coyle Lake property, which covered the north and northwest portions of the present day (1997) Houghton–Clarke claim group. An airborne, magnetic and VLF electromagnetic survey, geological mapping, stripping and trenching were done during that period. The current Houghton–Clarke property was staked in 1995, with extensive prospecting and sampling conducted until its option in 1997.

The centre portion of the Coyle Lake granodioritic stock underlies the entire Houghton–Clarke ground. This is one of three late Archean intrusive bodies underlying the surrounding townships, which are located in the extreme southern part of the Onaman–Tashota metavolcanic belt. Intermediate to felsic metavolcanic rocks dominate this area. The southern boundary of the property lies only 1.5 km north of the Paint Lake fault. Much of the exploration work to date has focussed on a major northeast-trending break or fault zone traversing the main, south-central portion of the claim group (it is this fault that hosts the Oliver Severn occurrence to the northeast). Several, less well-defined parallel and cross-cutting structures or shear zones have also been uncovered to the northwest. Grab samples collected along these structures by both the owners and the Thunder Bay North Resident Geologist Program staff assayed from 0.03 to 0.11 ounce per ton gold (Resident Geologist's Files, Beardmore–Geraldton District, Thunder Bay) (Bruce 1936; Mackasey 1976; Mackasey and Wallace 1978). The granodiorite at these sites becomes finer grained relative to granodiorite away from the deformation zones, is highly sheared with prominent sericite–chlorite alteration and contains 1 to 2% disseminated pyrite. Some of the zones contain recrystallized quartz-vein material. Specular hematite and fine-grained magnetite mineralization is also associated within some of these shear horizons, however, its importance to gold mineralization has yet to be determined.

RECOMMENDATIONS FOR EXPLORATION (SIOUX LOOKOUT DISTRICT)

The Sioux Lookout Deformation Zone

Observations made by the Sioux Lookout District Geologist during this and past field seasons suggested that there is an as-yet undocumented deformation zone that traverses the length of the Sioux Lookout greenstone belt. This suspected deformation zone hosts many of the 68 documented gold occurrences found within the greenstone belt. This deformation zone trends east-northeast from south of the Goldlund deposits to the Misfit Lake area, where it adopts a more easterly trend. East of Neepawa Island, on Minnitaki Lake, the deformation zone trends east-northeast once again, and projects to the Black Lake–Clamshell Lake area.

During the summer of 1997, the Sioux Lookout District Geologist visited 4 gold occurrences in the Sioux Lookout greenstone belt. These were the Floregold occurrence, the Bonanza vein (Black Lake), the Misfit Lake occurrence, and the Miles Lake (Claim KRL 30579) occurrence. None of these 4 occurrences is directly associated with a mapped fault. However, significant and wide zones of deformation and alteration are associated with these gold occurrences.

The Floregold occurrence and the Bonanza vein are found at the northeast end of the Sioux Lookout greenstone belt. The Floregold occurrence consists of a series of high-grade, quartz-carbonate-sulphide (pyrite, sphalerite, chalcopyrite, galena) veins hosted in strongly sheared, mafic to felsic metavolcanic rock and quartz porphyry. The Bonanza vein is actually a zone of pervasive iron-carbonate alteration hosting many quartz-carbonate-sulphide veinlets, 1 mm to 30 cm wide and 1 to 3 m in length. Recent drilling by Placer Dome Canada Ltd. indicates that the Bonanza vein occurs in a wide zone of intense shearing and iron-carbonate alteration. The visit to these 2 occurrences, taken with previous work in the area, suggested the existence of a deformation zone that trends northeast and whose width extends from Botsford Lake in the northwest to Clamshell Lake in the southeast.

The Misfit Lake gold occurrence is located about 23 km southwest of Sioux Lookout. It is found on the south side of the Minnitaki Lake Road (formerly Highway 72), south of Misfit Lake. Chisholm (1951) described the Misfit Lake gold occurrence as follows:

> A stockwork of narrow quartz stringers is exposed on a altered tuff or spherulitic horizon in the lavas. The zone is about 15 feet wide and strikes northeast. About half of the rock in the zone is made up of quartz. Mineralization consists of fine pyrite and tourmaline. Gold values reported by the company from the drilling and channel-sampling on surface were low. The best reported value was 0.1 ounce per ton in gold across a width of 6 feet located underneath the surface exposure.

The lavas that host the Misfit Lake occurrence are strongly deformed. "Siliceous" rock, 3 to 5 m north of the occurrence outcrop, previously mapped as tuff by Johnston (1969), was interpreted by the Sioux Lookout District Geologist to be a mylonite. The spherulitic lavas northeast of the occurrence are intensely sheared, the spherules are extremely flattened. An examination of the outcrops on the shores of Misfit Lake indicated that the strong deformation extends at least to the north shore of the lake. About 1 km east of the occurrence is a microwave tower sitting upon a large outcrop. The mafic lavas here are strongly deformed and contain lenticular pods of more siliceous rock cut by deformed quartz veins. Quartz-tourmaline veins form distinct ladder veins through one of the lenticular pods of siliceous rock. To the south of the Misfit Lake occurrence, Johnston (1969) noted several small faults on the north shore of Pickerel Arm of Minnitaki Lake. These faults parallel the shearing noted near the occurrence. These observations made around the Misfit Lake gold occurrence suggested the presence of a wide (> 2 km) deformation zone that trends east-northeast through this area.

Along Highway 72 between the Misfit Lake occurrence and the Miles Lake occurrence, which is 29 km southwest of Sioux Lookout, the roadside outcrops all exhibit intense shearing. Many of these outcrops exhibit weak to intense pervasive iron-carbonate alteration. The highway trends about 050° along this stretch while the strike of the shearing averages 070°. Observations made along the highway suggested that the deformation zone described at Misfit Lake extends southwest towards the Goldlund deposit.

Geological mapping should be done to confirm the presence of this suggested deformation zone. Gold exploration along this deformation zone should concentrate on areas of competency contrasts including the contacts between metavolcanic and metasedimentary rocks and early felsic intrusions. The flexure points of the deformation zone to the west of Misfit Lake and to the east of Neepawa Island on Minnitaki Lake are also important areas to prospect.

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31. The Continuing Investigation of the Gold Potential of the Goodchild Lake Area, Schreiber–Hemlo District

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The Goodchild Lake area (Figure 31.1) is situated in a north-trending portion of the Schreiber–Hemlo greenstone belt northeast of Marathon. This area is underlain by mafic to felsic metavolcanic rocks, with smaller amounts of clastic and chemical metasedimentary rocks and serpentinized ultramafic rocks (Milne 1967).

The gold and base metal potential of the area has been promoted over the last several years, most recently by Schnieders and Smyk (1995, 1996, 1997). This, in part, led to the staking of several hundred claim units in early 1997; several option agreements have been signed or are pending. The area is again a focus for grass–roots prospecting activity and gold exploration.

Follow-up prospecting and geological reconnaissance by staff of the Resident Geologist Program in 1997 have reaffirmed previous gold assays, have led to the discovery of new occurrences, and have generated ideas about other prospective targets. Part of the 1997 survey was designed to investigate and ground-truth areas adjacent to 7 small lakes where sampling had returned anomalous gold values in lake-bottom sediment collected by P. Friske of the Geological Survey of Canada (GSC) in June, 1996 (P. Friske, GSC, personal communication, 1997). Six of these anomalous lakes, situated roughly south of Pukatawagan and Goodchild lakes, had not been sampled previously. Only Smoke Lake, which yielded anomalous samples in both the 1978 reconnaissance and detailed, 1996 follow-up surveys, had been sampled before.

Two quartz-vein-hosted gold occurrences described by the authors last year (Schnieders and Smyk 1996, 1997) were resampled on Smoke Lake. The Smoke Lake Float occurrence, from which fine, visible gold has been noted, again returned multi-ounce-per-ton gold values. The occurrence on the north side of Smoke Lake, discovered by the authors in 1996, returned 0.33 ounce gold per ton in a grab sample of one vein; a 30 cm chip sample returned 0.11 ounce gold per ton across another vein.

Reconnaissance prospecting by the authors in 1997 has also revealed evidence of gold mineralization approximately 1 km northeast of Smoke Lake. This area, like Smoke Lake, is underlain by mafic metavolcanic flows which are locally pillowed, carbonatized and mineralized with pyrite, pyrrhotite ± epidote. Narrow, but persistent, sulphidic banded iron formations occur within the mafic flows. Both east–trending and north-trending fabrics are developed. These rocks are flanked to the north by granitic rocks that constitute the southern part of the Beggs Lake stock. This small, elliptical stock consists dominantly of equigranular, hornblende-quartz monzonite (Milne 1967). Two grab samples collected in the stock near its contact with the metavolcanic rocks returned 0.02 and 0.03 ounce gold per ton, respectively. Both samples were carbonatized, cut by quartz ± carbonate veinlets and contained fine-grained, disseminated pyrite. One sample also contained a fine-grained, grey metallic mineral that was tentatively described as galena or as a telluride mineral.

The Wire Lake shear zone (Schnieders and Smyk 1995, 1996, 1997) hosts a number of gold occurrences along a strike length of 2.5 km. Resampling of the South Lake and North Hill zones on the property of Gregor Goldfields Corp. in 1997 returned values in grab samples of 0.26 and 0.21 ounce gold per ton, respectively. This long, persistent shear zone proves that large, gold-mineralized structures are developed in the Goodchild Lake area.

The recent discovery of many new gold occurrences and anomalously gold-enriched lake-bottom sediments suggests that the potential for finding additional auriferous rocks is high. The small catchment areas associated with the majority of the "anomalous" lakes point to a local source for the gold. Till sampling in an up-ice direction from these lakes would help to narrow the possible source area. Prospecting activities should focus on their shorelines and on feeder and outlet creeks, as well as on areas near known gold occurrences. The contact zones of the Beggs Lake stock and other granitic intrusions should also be investigated.

Known occurrences are typically quartz vein hosted or are in sheared and/or altered rocks which contain veins. Carbonatization, epidotization, silicification, sericitization and biotitization are most commonly associated with these occurrences; pyrite is ubiquitous.

It is the authors' belief that prospecting and subsequent exploration will lead to the discovery of more gold occurrences in the Goodchild Lake area. Prospectors and explorationists should utilize high-quality, lake-bottom sediment, geochemical surveys to identify prospective areas. A report documenting the results of a 1996 lake-bottom sediment sampling survey conducted by Dyer (1997) was recently released. This report, covering much of the Schreiber–Hemlo greenstone belt from Rossport to west of Hemlo, provides valuable exploration targets.

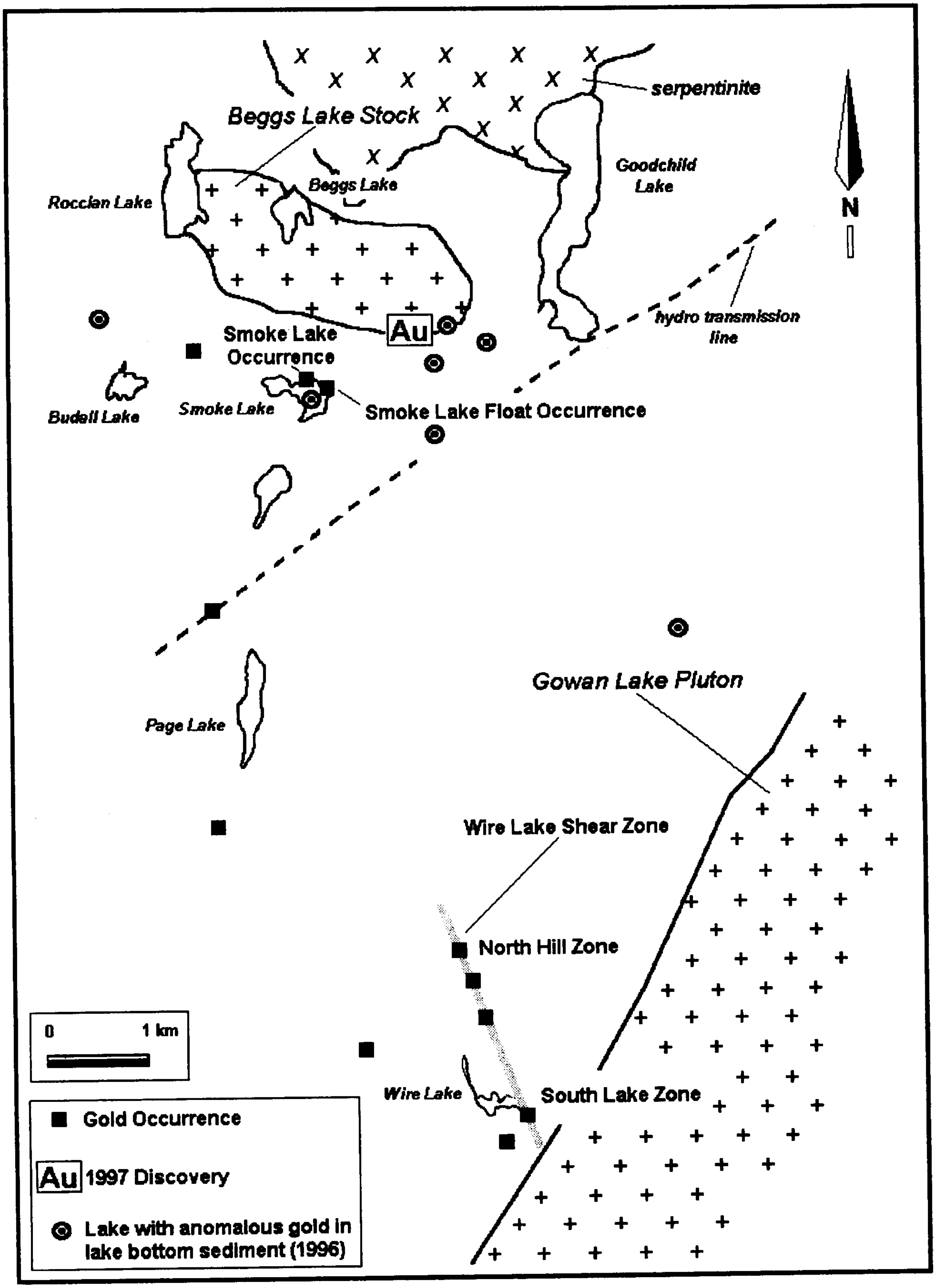

Figure 31.1. Gold occurrences in the Goodchild Lake area. Granitic rocks are denoted by hatching (+); metamorphosed supracrustal rocks are not shaded. Geology *after* Milne (1967).

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CONVERSION FACTORS FOR MEASUREMENTS IN ONTARIO GEOLOGICAL SURVEY PUBLICATIONS

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 02	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.308 0	cubic yards	1 cubic yard	0.764 555	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 908 8**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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