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PHYSICAL VOLCANOLOGY, HYDROTHERMAL ALTERATION AND MASSIVE SULPHIDE DEPOSITS OF THE STURGEON LAKE CALDERA (FIELD TRIP B3)

by

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INTRODUCTION

The south Sturgeon Lake area of northwestern Ontario (Fig. 1) is underlain by a well preserved, though partially eroded, Archean submarine volcanic caldera. This caldera is host to five massive sulphide deposits (Mattabi, F-Group, Sturgeon Lake Mine, Creek Zone and Lyon Lake)(Fig. 2, Table I) as well as numerous subeconomic massive sulphide occurrences. The Sturgeon Lake Mine, F-Group and Mattabi deposits were depleted of reserves in 1981, 1984 and 1988 respectively, whereas production at the Lyon Lake and Creek Zone deposits ceased in 1991.

Table I. Grade and tonnage figures of the ore deposits in the south Sturgeon Lake area.

Deposit	Tonnage* (10^6 tons)	Zn %	Cu %	Pb %	Ag o/t
Mattabi	12.55	8.28	0.74	0.85	3.31
F-Group	0.38	9.51	0.64	0.58	1.92
Sturgeon Lake	3.95	6.53	1.24	0.63	3.42
Lyon Lake & Creek Zone	3.17	8.67	1.26	0.99	4.50

* Production grade and tonnage figures

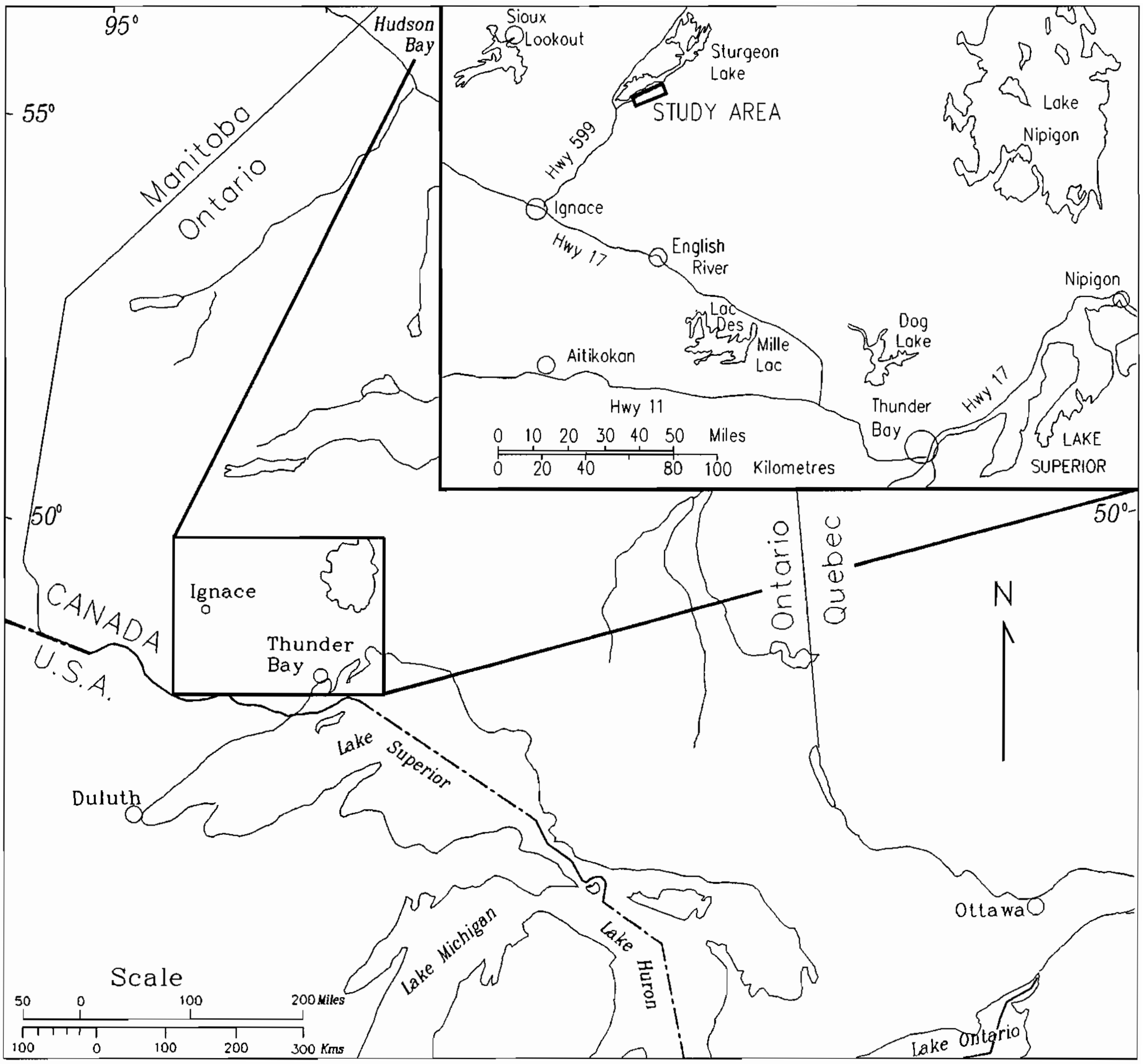

Figure 1. Location of the south Sturgeon Lake area.

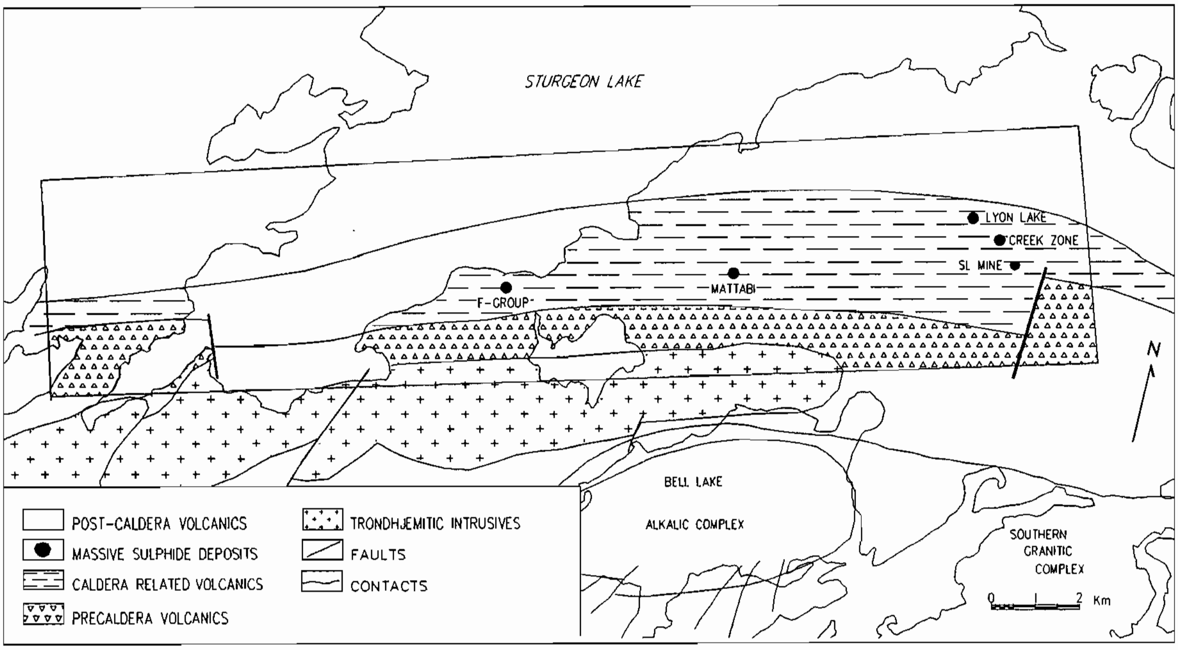

Figure 2. Generalized geological map illustrating the regional extent of the Sturgeon Lake Caldera Complex.

The combination of well preserved volcanic textures, a variable 55° to 90° dip of a north-facing, essentially homoclinal volcanic sequence and more than 600,000 m of diamond drilling over an apparent 4,500 m stratigraphic interval presents the opportunity to examine successive stages of caldera evolution. This includes initial subaerial-shallow subaqueous collapse, subaqueous silicic explosive volcanism and ore formation, and terminal dome building with sedimentary and lava flow fill and burial.

The main purpose of this field trip is to illustrate the physical volcanology of an ancient, ore-hosting caldera and to stress the importance of volcanism and synvolcanic structures in controlling the occurrence and location of hydrothermal alteration assemblages and volcanogenic massive sulphide deposits.

REGIONAL GEOLOGY

The south Sturgeon Lake area is located within the Archean Wabigoon volcano-sedimentary greenstone belt within the Superior Province. The Wabigoon subprovince is bounded to the north by the English River Gneiss Belt and to the south by the Quetico Gneiss Belt (Trowell and Johns, 1986). The volcanic and sedimentary rocks of the area have been subjected to regional greenschist facies metamorphism with almandine-amphibolite assemblages found locally (Trowell, 1974).

Detailed mapping of the volcanic rocks in the south Sturgeon Lake area coupled with the relogging of 200,000 m of diamond drill core (with emphasis on the physical volcanology of the rocks) has led to the recognition and description of a well preserved Archean submarine caldera complex. This complex, which has been named the Sturgeon Lake Caldera (Morton et al., 1988, 1989, 1990), is approximately 30 km in strike length and contains up to 4500 m of caldera fill material. Five separate, major ash flow tuff units have been defined, and each can be traced for kilometers across the complex with individual thicknesses ranging from 100 to more than 1200 m. Based on the stratigraphic distribution and thickness of the five ash flow tuff units and associated debris flow deposits, it is believed that the Sturgeon Lake Caldera consists of a series of smaller nested or overlapping calderas and that each ash flow unit is associated with a collapse event. This interpretation is supported by studies of more recent caldera complexes which show that major ash flow tuff units are related to individual collapse events and that nested or overlapping calderas are common (Cas and Wright, 1987).

Based on detailed stratigraphic mapping and core logging, numerous synvolcanic faults have been defined. Synvolcanic faults with major stratigraphic displacement (>150 m) may represent individual caldera boundaries. In general the eastern and western margin of the complex has been located and the back (northern) bounding wall has been partially defined. A series of late, north-south-trending dip-slip faults has broken the complex into a number of blocks that allow the caldera complex to be observed at different stratigraphic levels. Individual volcanic and intrusive rock units are traceable across the faults, but thicknesses change dramatically (Fig. 3). As well, late east-west- and northwest-trending faults coupled with an east-west folding event (part of the Kenoran Orogeny?) have, along caldera margins, affected the upper part of the sequence causing minor displacement of the upper pyroclastic flow units and the Sturgeon Lake Mine, Lyon Lake and Creek Zone ore bodies. Although much of this deformation has been taken up by caldera fill sedimentary rocks, shear zones are common in the massive to amygdaloidal lava flows located north and east of these ore bodies. Zircon ages of the ash flow tuff deposits and late caldera margin dome lavas yield a similar age of 2,735 m.y. ± 1.5 m.y. (Davis et al., 1985).

A large, sill-like intrusion (Beidelman Bay Complex) has a similar age to the felsic volcanics and represents, in part, the magma chamber for the eruptive material. This intrusive body can be traced along strike for 20 km and has an average width of 2.5 km. Its composition varies from trondhjemite to quartz diorite with feldspar and quartz ± feldspar porphyry phases. The Beidelman Bay intrusive complex also hosts minor occurrences of porphyry copper-molybdenum type mineralization, and the upper portions locally contain stringers of zinc-silver mineralization. A mafic (gabbroic-quartz dioritic) dyke- to sill-like intrusion occurs across the length of the caldera complex (Fig. 3) and may represent a ring dyke complex.

Hydrothermal alteration is widespread within the complex and in the upper part of the Beidelman Bay intrusion. Discrete assemblages of alteration and metamorphosed alteration minerals form zones that are a) widespread and largely conformable to the volcanic stratigraphy, b) locally lens- or pod-like beneath sulphide occurrences and deposits and c) narrow and elongate, cross-cut stratigraphy and are associated with synvolcanic faults (Groves, 1984; Hudak, 1989; Jongewaard, 1989; Morton et al., 1988; Morton and Franklin, 1987).

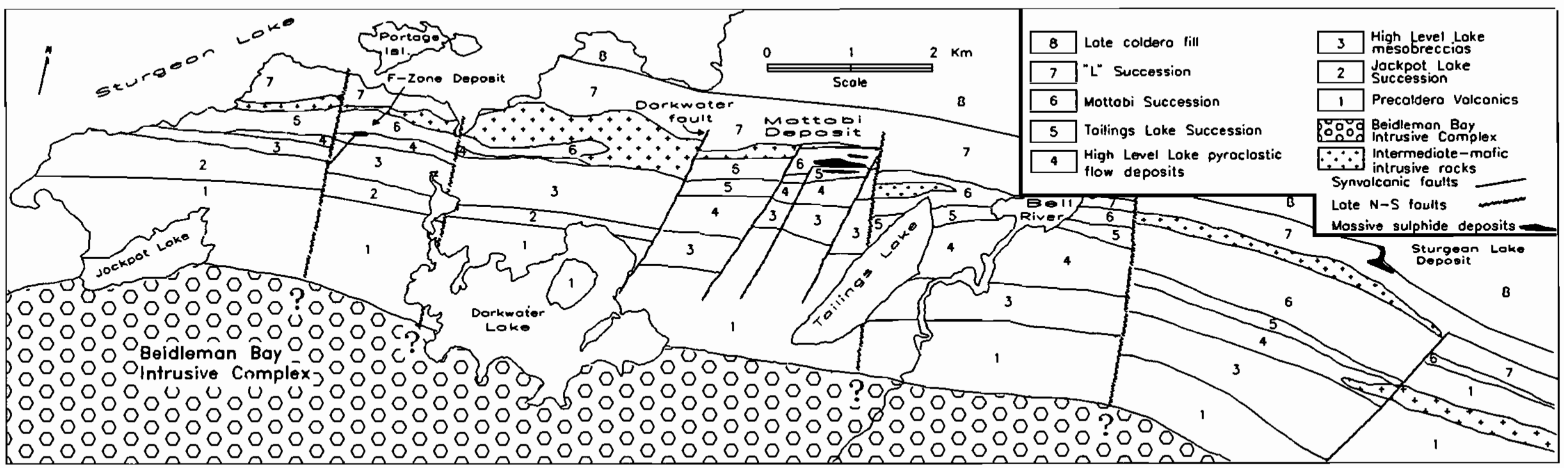

Figure 3. Simplified geological map of the Sturgeon Lake Caldera Complex. The western margin of the complex is 5 km west of Jackpot Lake and beneath Sturgeon Lake.

PHYSICAL VOLCANOLOGY OF THE STURGEON LAKE CALDER COMPLEX

Precaldera Volcanism (Unit 1, Figs. 3 and 4)

Precaldera volcanic rocks, referred to as the Darkwater Succession, have been interpreted to represent part of a large subaerial-subaqueous shield-type volcano composed of a thick sequence of basalt lava flows, scoria-tuff cone and debris flow deposits, with minor amounts of interlayered rhyolitic lava flows and pyroclastic fall deposits (Groves et al., 1988, Morton et al., 1988, 1990). The basaltic lavas beneath and lateral to the caldera complex are composed of amygdaloidal to massive flows which commonly exhibit brecciated and scoriaceous tops; pillow lavas and hyaloclastites have been identified only along the eastern margin of the caldera leading to the interpretation that the mafic lavas are dominantly subaerial (Groves et al., 1988). The scoria and tuff cone deposits represent part of a field of small, monogenic volcanos which formed on the upper flanks of the major shield edifice. One of these has been described in detail (Groves et al., 1988) and all are interpreted as subaerial to shallow subaqueous deposits formed from magmatic and phreatomagmatic eruptions. Caldera collapse caused large blocks and smaller clasts of these lavas and scoria-tuff cone deposits to slide into the caldera where they now form a major component of the various mega-and mesobreccia units (Unit 3).

Jackpot Lake Succession (Unit 2, Figs. 3 and 4)

Pyroclastic flow and fall deposits of the Jackpot Lake Succession overlie the precaldera volcanic rocks and represent the initial pyroclastic eruptions that led to the first caldera collapse event. These pyroclastic rocks vary from 50-300 m thick and are most abundant in the Jackpot Lake area; they thin eastwards and appear to terminate north of Darkwater Lake (Fig. 3). The extent of these rocks westward, beneath Sturgeon Lake, is not known. The pyroclastic deposits vary from massive to well-bedded and are composed predominantly of fine grained, aphyric ash tuff. Small quartz crystals (<1 mm, 1%) occur locally and are typically angular and splintered or broken; subround-irregular shaped pumice comprises from 1 to 50% of the rocks and is typically recrystallized to small quartz mosaics. The ash-size matrix is composed of interlocking mosaics of quartz and feldspar with a wide variety of secondary alteration minerals. Locally these deposits are separated by thin debris flow units and associated fine grained sedimentary rocks indicating that the eruptions were episodic.

High Level Lake Succession (Units 3 and 4, Figs. 3 and 4)

The High Level Lake Succession has been subdivided into two units: a) mesobreccia and b) quartz crystal-rich and pumice-rich pyroclastic flow deposits. Precaldera volcanic rocks and the Jackpot Lake pyroclastic units are immediately overlain by coarse heterolithic breccias that are interlayered with, and grade upwards into, quartz crystal ash flow tuff deposits. The breccias have a strike length of at least 22 km and exhibit rapid changes in thickness from 80 to more than 900 m.

The breccia deposits (Unit 3) are composed of block-and lapilli-size clasts of mafic and felsic volcanic rocks which are mineralogically and chemically similar to underlying precaldera and Jackpot Lake pyroclastic units. Recognizable clasts are poorly sorted and vary from measurable blocks 70 m by 40 m down to matrix-size material; typical size is 3 to 25 cm. Detailed mapping and core logging also indicates that there are large blocks of the Darkwater scoria-tuff cone deposits that are more than 1 km in length and 300 m in thickness. Matrix material to the clasts varies from abundant alteration and metamorphosed alteration minerals (chloritoid, iron carbonate, andalusite, pyrophyllite, sericite, chlorite) to a composition very similar to the interlayered and overlying ash flow tuffs. Overall the composition of this unit is basaltic-andesitic. In the upper 5-50 m the breccias contain sparse quartz crystals and lapilli-size pumice.

These breccia deposits are similar to heterolithic breccias (mega- and mesobreccias) described by Lipman (1976, 1989) from calderas in the San Juan Mountains. In the Sturgeon Lake Caldera Complex these coarse heterolithic breccias are believed to represent debris derived from caldera walls as collapse occurred; collapse and breccia formation were simultaneous with eruption and deposition of the High Level Lake quartz crystal ash flow tuff. Thick deposits of mesobreccia have been related to catastrophic caldera subsidence of a kilometer or more (Lipman, 1976, 1989). Such catastrophic collapse in the Sturgeon Lake area could readily have moved the floor of the

Sturgeon Lake Caldera from an initial subaerial-shallow subaqueous environment to a deeper submarine environment.

The High Level Lake ash flow tuff deposits (Unit 4) represent the second pyroclastic event associated with the caldera complex and can be subdivided into two separate units: a) a lower quartz crystal-rich rhyolite (average SiO_2 of 74%) and b) an upper pumice-rich dacite (average SiO_2 of 67%). The quartz crystal ash flow tuff forms lenses (up to 1000 m in strike length by 100 m thick) within deposits of mesobreccia and an 80-300 m thick unit which overlies the mesobreccia. The contact between the mesobreccia and the quartz crystal-rich rhyolite is gradational and is marked by a gradual upward increase in the size and percentage of quartz crystals and a marked decrease in the number of lithic clasts (< 5%). The ash flow deposits are composed of 3-25% broken and angular quartz crystals (.8-2 mm), which locally are enclosed by 0.1 to 0.8 mm thick recrystallized ash rims, and 5-30% silicified and/or carbonated lapilli-size pumice. The ash rims surrounding the quartz crystals suggest the presence of water in the eruptive environment.

These quartz crystal-rich ash flow tuffs grade upward into quartz-crystal poor, pumice-rich ash flows that vary from 50 to 370 m in thickness. These massive deposits are composed of 35-75% silicified and/or chloritoid-andalusite-pyrophyllite-rich lapilli-size pumice and 5-25% mafic and chlorite-carbonate-rich lithic fragments set in a fine-grained quartz-rich matrix. The upward change in composition from rhyolite to dacite, decrease in quartz crystals, massive nature of the deposits and the presence of abundant pumice can be interpreted to represent rapid eruption of magma from a zoned or layered, gas-rich magma chamber.

The quartz crystal unit can be traced for 20 km across the caldera, whereas the pumice-rich unit is not observed west of the major northeast-trending synvolcanic fault (Darkwater fault). This fault has an apparent offset of 400 m and forms one side of a major topographic depression that hosts the ore lenses of the Mattabi massive sulphide deposit. The pumice flow ponded within but did not fill this depression.

Tailings Lake Succession (Unit 5, Figs. 3 and 4)

The High Level Lake pumice flows represent the end of the second explosive eruptive cycle and are overlain by 60-400 m of subaqueous debris flow deposits and bedded epiclastic rocks. Like the High Level Lake pumice flows, rocks of the Tailings Lake Succession are not found west of the Darkwater fault; however, they can be traced eastward from this structure for more than 10 km. The debris flow deposits are composed of thick (5-120 m) massive basal units overlain by well bedded sedimentary material which may exhibit grading. The debris flows are composed of clasts derived from the underlying ash flow tuffs and from the precaldera rocks. The size and percentage of clasts increases westward toward the Darkwater fault and, in deep drill holes, downdip toward the back margin of the caldera. Locally the debris flow deposits and associated sedimentary rocks are separated by dacitic ash tuffs and by dacitic to andesitic lava flows; these units only rarely crop out and are primarily observed in drill core. The ash tuffs are aphyric and fine-grained, have SiO_2 contents that range from 65 to 77% and TiO_2 contents that are consistently greater than 0.6%; they have locally undergone intense hydrothermal alteration. These rocks range from 5 to 80 m in thickness and are the host rocks to the Mattabi E ore lens. The lava flows range in thickness from 10 to 50 m and vary from massive to amygdaloidal and brecciated; locally these rocks are feldspar-phyric.

The debris flow deposits represent the periodic avalanching of material from caldera walls, whereas the ash tuffs indicate sporadic eruption of felsic material, most likely along leaky ring(?) fractures. The uppermost debris flows are composed of more than 60% precaldera mafic volcanic and High Level Lake ash flow tuff clasts, and are interlayered with abundant ash deposits. These units appear to represent renewed activity at caldera margins which immediately preceded the eruption of the overlying Mattabi ash flow tuffs.

Mattabi Succession (Unit 6, Figs. 3 and 4)

The Mattabi Succession represents the third and most voluminous eruptive event within the caldera, forming deposits that exceed 1200 m in thickness. The deposits can be traced across the caldera complex for more than 20 km and directly overlie debris flow or ash deposits of the Tailings Lake Succession east of the synvolcanic Darkwater fault; they overlie the High Level Lake quartz-rich ash flow tuff and mesobreccia deposits west of this structure. East of the Darkwater fault the Mattabi ash flow tuffs range from 150-1200 m thick; they thin rapidly west of this structure (with the notable exception of the F-Zone area), ranging in thickness from 20-80 m. It is believed that the Darkwater fault represents one segment of the caldera wall for the Mattabi eruptive event and that deposits west of this structure represent outflow sheets. In the vicinity of the F-Zone ore deposit the Mattabi ash flow tuffs are 125-200 m thick and are believed to have ponded in, and filled, the fault-bounded basin which hosts this massive sulphide deposit (Hudak, 1989).

Based on flow morphology and composition, the Mattabi ash flow tuff succession may be divided into two distinct units: a) a bedded quartz crystal-rich unit and b) a massive to poorly-bedded ash unit. The bedded quartz-crystal rich unit varies from 150 to 1100 m thick east of the Darkwater fault and 20-75 m thick west of the fault. The bedded ash flow tuffs have an average SiO_2 content of 75%, always contain less than 0.5% Na_2O and exhibit a pronounced cyclicity within individual bedded sections. Beds are subdivided into basal quartz crystal- (5-35%) and pumice-rich (5-45%) lower sections overlain by bedded ash deposits which contain sparse quartz crystals (1-3%) and rare pumice. The lapilli-size pumice are well-vesiculated (40-70% amygdules) and, with subangular to irregular shapes, exhibit no evidence of flattening that might be indicative of welding. The lower units, in core from relatively deep diamond drill holes that approach the back wall and eastern margin of the caldera, contain up to 20% precaldera mafic and felsic volcanic clasts and possibly indicate mixing, close to caldera margins, with debris derived from caldera walls.

Detailed core logging in the eastern part of the area (below the Sturgeon Lake Mine) has defined 14 such flow units which vary in thickness from 15 to 180 m; the bedded ash component is 1 to 14 m thick. More than 280 chemical analyses have been completed on these units with one sample collected for about every three meters of stratigraphy. Analyses of standard trace elements clearly and dramatically show that individual flows (bed sets) have high Zr (550-1025 ppm), Y (75-120 ppm) and Nb (30-80 ppm) at and/or near their base, and that these elements gradually decrease upwards towards the ash beds which have low Zr (80-230 ppm), Y (24-45 ppm) and Nb (1-4 ppm) contents; TiO_2 and Ba appear to have opposite trends. This zoning pattern holds true a) whether the qauartz crystals are normally or inversely graded; b) regardless of the size or percentage of quartz crystals found in the basal beds; or c) regardless of the thickness of the beds. At Mattabi the flow units exhibit a similar thickness, composition and chemical zonation with the B, C and D massive sulphide ore lenses situated at breaks between quartz-rich beds in the hanging wall and ash beds in the footwall. Numerous other massive sulphide occurrences are found throughout the lateral and vertical extent of this unit, making it a prime exploration target.

The bedded quartz-crystal deposits are overlain by massive, very fine-grained ash flow tuff deposits which vary from 20 to 150 m in thickness. These units are composed of zero to 2% small (< 1 mm), broken and sliver-like quartz crystals in a quartz-rich matrix; it is not uncommon for these units to be intensely silicified and iron metasomatized. This massive unit is overlain by 5-35 m of bedded, fine-grained ash material which is compositionally and chemically similar to the underlying massive ash flow tuffs. The massive unit contains no known massive sulphide mineralization and lacks the pronounced geochemical zoning exhibited by the bedded deposits. In morphology these units are similar to those described by Busby-Spera (1984) from the Mineral King roof pendant and by Morton and Nebel (1983) from the Wawa area, and represent flow units deposited in a relatively shallow subaqueous environment.

L Succession

This is a complex succession of rocks which range from quartz- and quartz-plagioclase-bearing pyroclastic flow deposits through plagioclase-phyric lava flows and domes to sedimentary sequences. The entire succession ranges from 250 to 1200 m thick with the domes, lava flows and dome related sediments and debris flow deposits making up the bulk of the stratigraphy. The pyroclastic flow deposits form two distinct units, each of which may represent a major pyroclastic eruption (caldera forming ?). The distribution of these pyroclastic rocks and their physical volcanology and alteration is currently the subject of a doctoral thesis (Hudak, in progress). Work completed so far shows that the ash flows associated with the first eruptive event are quartz- and plagioclase-crystal rich whereas the ash flows associated with the second eruptive period were dominantly quartz crystal-rich and contain traces to 5% of K-spar crystals with associated K-spar in the groundmass. These quartz-rich pyroclastic flows are the host rocks for the Sturgeon Lake Mine, Lyon Lake and Creek Zone massive sulphide deposits. Feldspar-bearing lava flows and domes (up to 400 m thick and 3 km long), along with a variety of dome-derived volcaniclastic rocks and debris flow deposits, overlie the pyroclastic flow units. The domes occur close to caldera margins and are believed to represent the last felsic eruptive products associated with caldera formation. Locally iron formation (banded magnetitechert and iron carbonate) and graphitic sedimentary rocks are interlayered with dome-derived volcaniclastic rocks and represent relatively quiet sedimentation and low temperature hydrothermal activity in basins that formed between the growing domes and caldera walls.

The L succession is overlain by extensive basaltic-andesitic lava flows which have been termed the No Name Lake Andesite (at Mattabi) and the Lyon Lake Andesite (at Lyon Lake). Previous workers believed that the No Name Lake Andesite separated the Mattabi and L pyroclastic rocks from what had been termed the NBU rhyolites. It was believed that the NBU rhyolites were the host rocks for the Lyon Lake and Creek Zone ore bodies, and that the Lyon Lake andesite stratigraphically overlaid these ore deposits (Mumin, 1988, Franklin et al., 1977). Detailed volcanological facies mapping and core relogging, along with geochemical studies, now shows that No Name Lake and Lyon Lake Andesites are laterally correlative, and the so called NBU rhyolite can be correlated with rocks formed by the second L pyroclastic eruptive event. The No Name Lake-Lyon Lake basalts and andesites form amygdaloidal to massive flows, pillow lavas, hyaloclastites and scoriaceous rocks and bring an end to caldera pyroclastic activity.

SUMMARY OF THE VOLCANOLOGICAL HISTORY OF THE STURGEON LAKE CALDERA COMPLEX

1) Subaerial basaltic shield volcanism.
2) Subaerial-shallow subaqueous scoria and tuff cone formation as an end stage in the development of the shield volcano.
3) Formation of the ancestral Beidelman Bay silicic, high level magma chamber and initial eruption of the Jackpot Lake pyroclastic rocks along incipient ring(?) fractures.
4) Major eruption of the Jackpot Lake pyroclastic flow and fall deposits, triggering instability and initiating the first caldera collapse event.
5) Eruption of quartz crystal-rich ash flow tuffs along major ring(?) faults, coupled with the avalanching and sliding of precaldera material from growing caldera walls, to form the mega- and mesobreccia deposits and the mixed breccia and pyroclastic units.
6) Continued eruption of pyroclastic material from a zoned magma chamber with a

gradual change from rhyolitic quartz crystal-rich to dacitic pumice-rich material.

7) High temperature hydrothermal activity and the formation of the F-Zone massive sulphide deposit with the High Level Lake quartz crystal units as the host rocks.
8) Periodic movement along old and newly developed ring(?) fractures to form the debris flows and associated bedded epiclastic rocks of the Tailings Lake Succession. This was coupled with the periodic eruption of ash tuffs from the developing ring(?) fracture system.
9) Formation of the E ore lens at Mattabi.
10) Major movement on newly developed ring(?) structures coupled with the eruption.
11) Pulsating subaqueous eruptions to form the bedded Mattabi ash flow tuffs coupled with continuous intense hydrothermal activity and formation of B, C and D ore lenses at Mattabi. The hydrothermal system was active both during and between eruptive pulses.
12) Continuous, shallow subaqueous eruption of the massive Mattabi ash flow tuff and continued lower temperature hydrothermal alteration.
13) Generation of andesitic lava flows and debris flows that separate the Mattabi ash flow tuffs from the first pyroclastic event of the L Succession.
14) Eruption of the lower L pyroclastic units, which are quartz- and plagioclase-phyric and mark the first pyroclastic activity where plagioclase crystals are present. The formation of the subeconomic A zone at Mattabi was associated with this pyroclastic event.
15) Deposition of plagioclase-phyric lava flows and volcaniclastic sediments derived from the L and Mattabi pyroclastic flows.
16) Eruption of quartz crystal-rich, K-spar bearing pyroclastic material (second L pyroclastic event) and renewed high temperature hydrothermal activity leading to the formation of the Sturgeon Lake Mine, Lyon Lake and Creek Zone ore deposits. Block and ash flow deposits within the middle L succession indicate that rhyolitic lava domes were present (possibly along a caldera margin fault to the east) during this stage of volcanism.
17) Reworking of previously deposited volcanic units to form the upper L volcaniclastic sediments and numerous debris flow and turbidite deposits.
18) Lava dome building and periodic dome collapse with reworking and erosion of the domes. Associated with dome formation were iron- and graphite-rich

moat sediments that were related to the last stages of hydrothermal activity in the caldera.

19) Final caldera fill by mafic lavas that represent the start of a new cycle of more quiescent volcanism.

20) Late southeast to northwest shearing relocates the Lyon Lake and Creek Zone ore bodies into their present locations.

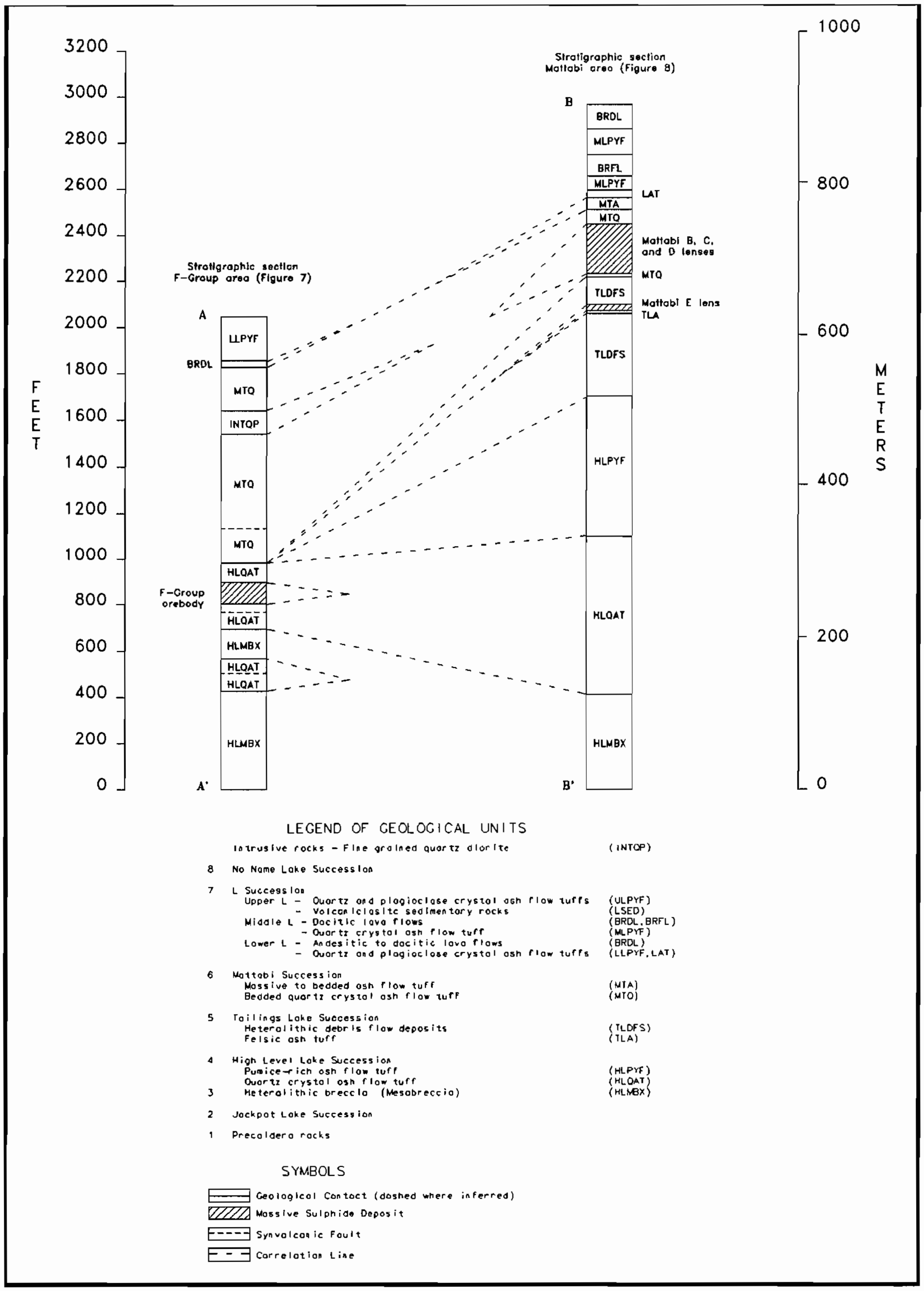

Figure 4. Stratigraphic correlations between the F-Group and Mattabi areas.

HYDROTHERMAL ALTERATION

Hydrothermal solutions, both ore-forming and non-ore-forming, have altered the volcanic rocks associated with the Sturgeon Lake Caldera Complex. Following alteration, these rocks were metamorphosed to greenschist facies. Therefore, the alteration minerals now present are, in part, metamorphosed equivalents of the alteration minerals formed in the hydrothermal system.

Hydrothermal fluids formed five distinct, mappable massive sulphide ore-associated alteration assemblages in the area. From least- to most-altered, these assemblages are: a) widespread, semiconformable carbonatization and silicification; b) widespread, semiconformable iron carbonate ± iron chlorite; c) widespread, semiconformable chloritoid ± iron carbonate and/or iron chlorite; d) lens- to pod-like, locally linear zones of aluminum silicate (pyrophyllite, andalusite, and/or kyanite) + chloritoid; and e) linear cross-cutting, and stratiform zones of aluminum silicate. Late sericite and/or magnesium-rich chlorite alteration locally overprints these five alteration assemblages. Iron formation-associated alteration composed of patches to cross-cutting veinlets of iron carbonate + iron chlorite + magnetite ± garnet ± grunerite is present in the uppermost sections of the L succession.

Iron carbonate ± iron chlorite assemblage rocks contain at least 10% iron carbonate + iron chlorite with less than 5% chloritoid or aluminum silicate minerals. Outcrops which contain abundant iron carbonate are easily identified by their orange to orange-brown stained, commonly pitted surfaces. Staining varies from irregular, lens-shaped patches up to 15 cm in diameter, to veins and veinlets 1-15 mm in width that are aligned parallel to the foliation. Pumice that has been replaced by carbonate can be recognized as rounded to oval, orange-brown stained pits up to 5 cm in diameter which commonly contain rounded to lens-shaped quartz-filled amygdules (10-60%). In thin section, this assemblage contains iron carbonate ± iron chlorite (10-60%), sericite (up to 30%), Mg-rich chlorite (0-50%), and locally, traces of chloritoid or aluminum silicate minerals.

Chloritoid ± iron carbonate and/or iron chlorite assemblage rocks contain greater than 5% chloritoid, and are characterized by the presence of 1-3 mm dark green to black chloritoid prisms and rosettes. The presence of the chloritoid commonly gives the rocks a "salt and pepper" appearance. Locally, chloritoid porphyroblasts occur with sericite (10-

55%) in 1-5 mm wide grey-green veinlets which can be conformable to or cross-cut the strata. Other minerals present include iron carbonate (up to 60%), iron chlorite (2-20%), magnesium chlorite (1-20%) and pyrite (0-12%).

Aluminum silicate + chloritoid bearing rocks typically contain 1-3 mm chloritoid porphyroblasts (up to 33%) in a grey to grey-pink matrix composed of massive pyrophyllite (5-20%), 1-3 mm blocky pink andalusite (0-8%), and/or bluish tabular porphyroblasts of kyanite (0-8%) up to 2 mm long. Chloritoid occurs as 1-3 mm prismatic crystals or rosettes dissementated throughout the rock, or in chloritoid-andalusite-rich veinlets up to 1 cm in width. In addition, iron chlorite (up to 7%), magnesium chlorite (up to 35%), iron carbonate (3-35%), pyrite (trace - 30%) and sphalerite (up to 5%) are also associated with this alteration assemblage.

Rocks containing greater than 5% aluminum silicate minerals (pyrophyllite, andalusite, and/or kyanite) or micaceous pseudomorphs of aluminum silicates with less than 5% chloritoid represent the aluminum silicate assemblage. Generally, rocks bearing this alteration assemblage are light grey to pink in colour. Andalusite is the most commonly observed aluminum silicate mineral, and is present as 1-3 mm grey to pink, blocky to rounded porphyroblasts in micaceous domains. Kyanite occurs in three forms: a) as ragged grains in the matrix of strongly altered, andalusite-rich rocks; b) as subhedral to euhedral grains associated with pyrite, sphalerite, and/or chalcopyrite mineralization; and c) as euhedral, commonly bent blades up to 2 cm in length within or along the margins of quartz ± carbonate veins and veinlets up to 3 cm in width. Other phases present within this assemblage include quartz (10-80%), sericite (0-40%), iron carbonate (0-10%), chloritoid (0-4%), magnesium chlorite (0-30%), pyrite (trace - 15%), and sphalerite (locally up to 7%).

Figure 5 illustrates the distribution of the ore-forming alteration assemblages in the F-Group area. Iron carbonate ± iron chlorite assemblage rocks form a large, semiconformable zone along the southern, eastern, and northern boundaries of the area. Locally, pod-like areas (up to 50 m in diameter) of this assemblage occur within the chloritoid assemblage zone, which exists as a large, semiconformable zone up to 100 meters thick in the hangingwall to the F-Group orebody, and is present as pipe-like alteration zones in the F-Group footwall. More proximal to the mineralization, semiconformable and locally pipe-like zones containing the aluminum-silicate ± chloritoid alteration assemblage are present. Aluminum silicate assemblage rocks are most closely associated with the mineralization at the F-Group deposit. These rocks are distributed in two distinct patterns: a) in linear, 5-30 meter wide, pipe-like zones that trend NNE and cross-cut the stratigraphy; and b) in a broad, semiconformable zone (700 by 500 meters at surface) located both in the footwall and the hangingwall rocks to the F-Group massive sulphide deposit (Hudak, 1989).

Figure 6 illustrates the distribution of ore-forming alteration at the Mattabi deposit. Semiconformable carbonatized and silicified rocks form a broad zone in the lower footwall rocks. This zone is cross-cut by several westward plunging tabular zones outwardly zoned with an aluminum silicate-rich core and aluminum silicate + chloritoid margin. These zones commonly surround synvolcanic fault zones which lead upward to and cross-cut a broad semiconformable zone of aluminum silicate + chloritoid altered rocks, which crudely surrounds the Mattabi deposit. The aluminum silicate-rich tabular zones, associated with the synvolcanic faults, spread out into a semiconformable zone directly beneath and lateral to the deposit. Stratigraphically overlying the deposit is a semiconformable zone of chloritoid ± Fe-carbonate ± Fe-chlorite up to 150 m thick (Walker, 1993).

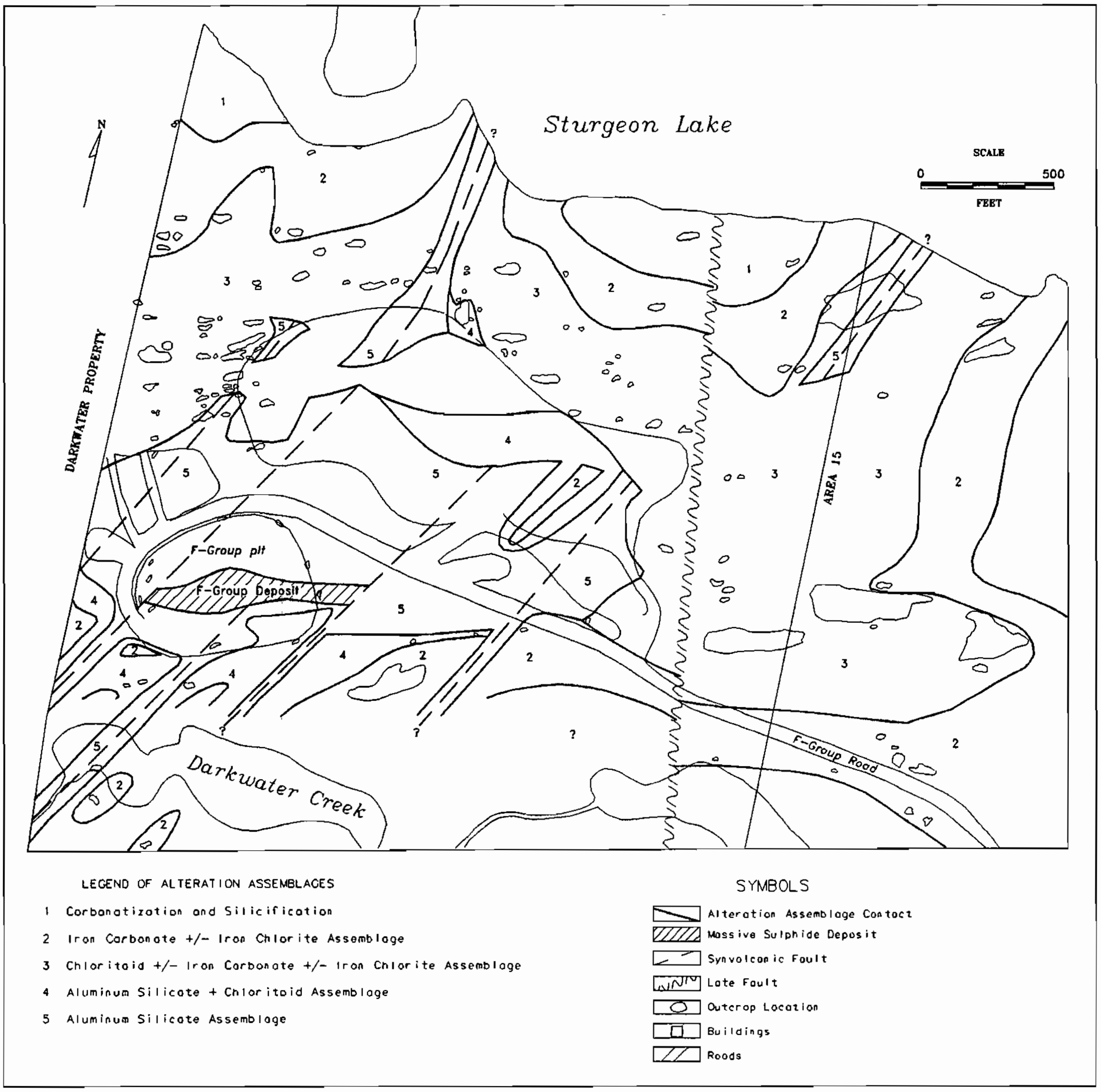

Figure 5. Distribution of ore-forming alteration assemblages associated with the F-Group deposit.

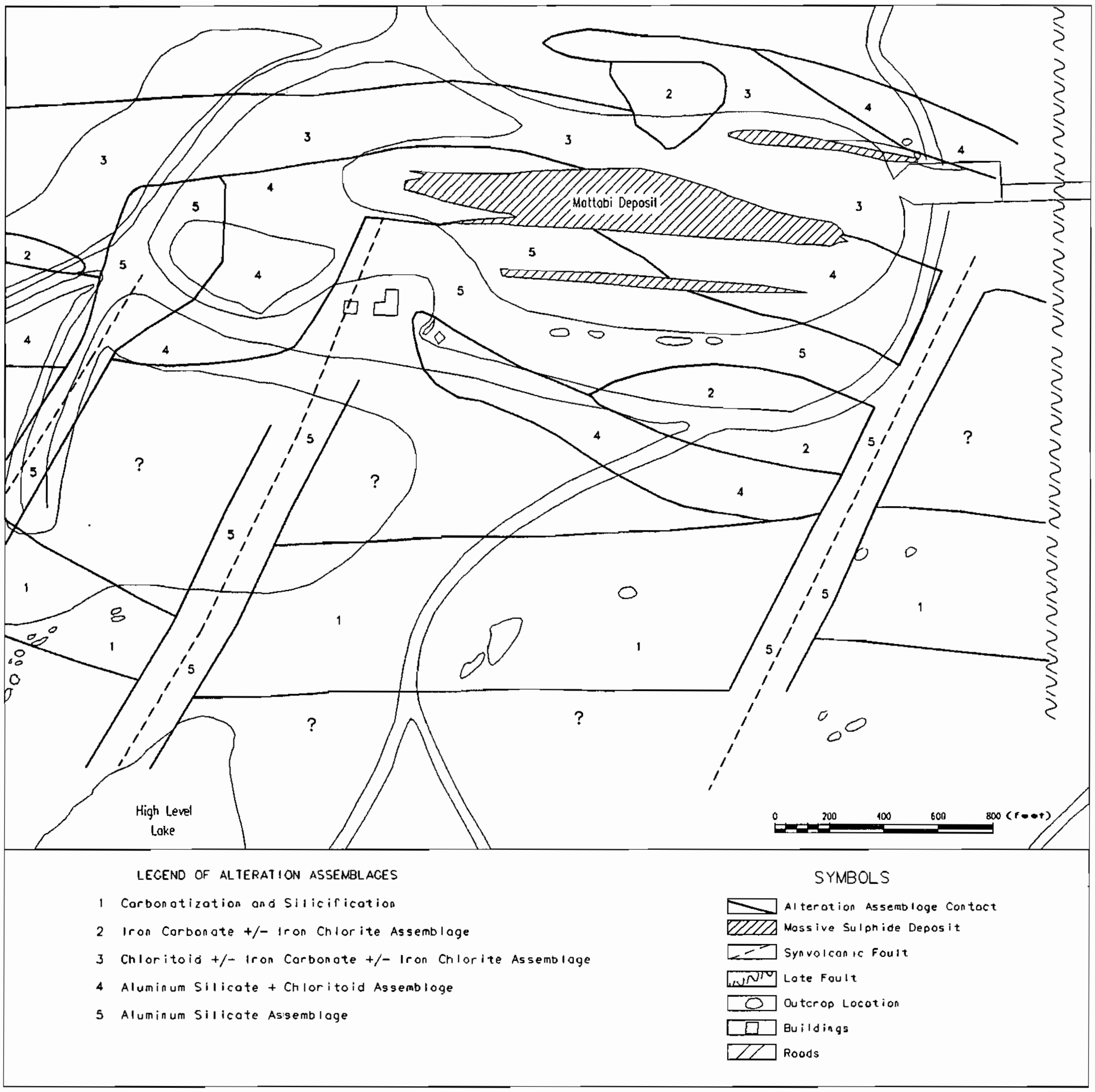

Figure 6. Distribution of ore-forming alteration assemblages associated with the Mattabi deposit.

FIELD TRIP STOP DESCRIPTIONS

F-Group Area

The F-Group volcanogenic massive sulphide deposit was discovered from airborne and ground geophysical surveys combined with exploration diamond drilling conducted by Mattagami Lake Mines in 1969. The orebody was mined from 1981-1984 and yielded 377,565 tons of ore which contained 0.64% Cu, 9.51% Zn, 0.58% Pb, and 1.92 oz/t Ag (M. Patterson, personal communication, 1990).

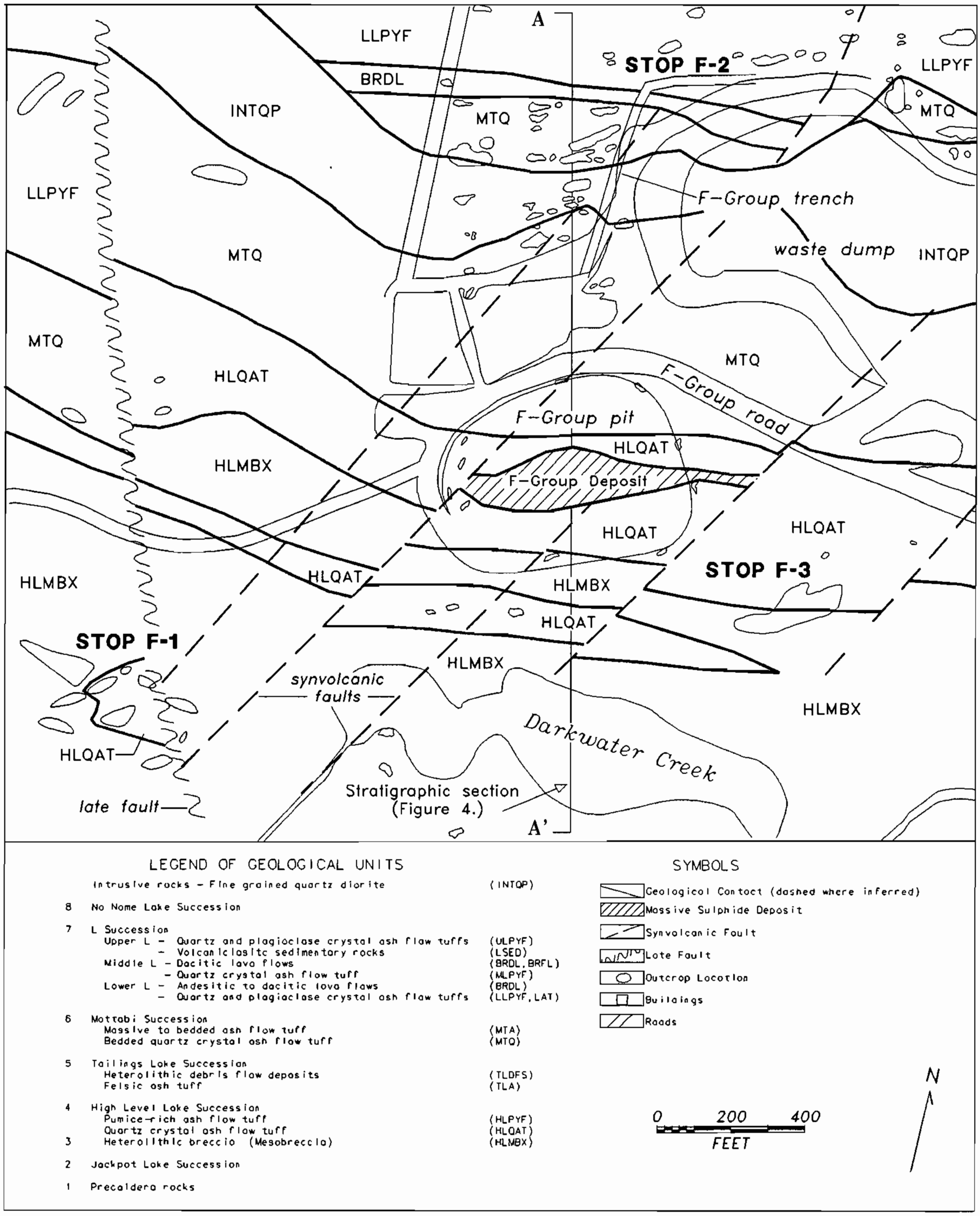

Figure 7. Geological plan map of the F-Group area, with field trip stop locations.

Stop F-1: High Level Lake Ash Flow Tuff And Mesobreccia

At this location (Figure 7), approximately 300 meters southwest of the F-Group pit, intensely altered High Level Lake ash flow tuff and mesobreccia deposits crop out. The High Level Lake ash flow tuff deposits are the host rocks for the F-Group massive sulphide orebody. These rocks vary in colour from grey-green to greyish-pink and contain 5-20% 1 mm quartz phenocrysts in a quartz-rich, locally chlorite-bearing recrystallized ash matrix. Light grey pumice fragments, from 3-20 mm in diameter, are subrounded to oval in shape, and are composed primarily of recrystallized quartz. These fragments typically contain 30-50% <1 mm round to oval quartz-filled amygdules.

High Level Lake ash flow tuff deposits overlie and are locally interlain with mesobreccia deposits. Mesobreccias form from material that slumps off oversteepened walls of a caldera during and after caldera collapse. By definition, these deposits contain fragments dominantly less than 1 m in diameter (Lipman, 1976). Megabreccia deposits are formed more proximal to the caldera wall, and contain fragments generally greater than 1 m in diameter. Mesobreccia deposits which occur in the footwall to the Mattabi orebody (see Stop M-1a) and the Sturgeon Lake Mine are laterally equivalent to the mesobreccia deposits on this outcrop.

At this location, the mesobreccia deposits vary from green to grey-green and contain up to 50% fragments composed principally of three types: a) 5% rounded, 3-10 mm in diameter, amygdaloidal quartz- and sericite-rich fragments interpreted to be pumice;b) 5-10% light grey lapilli-sized subrounded felsic lava fragments; and c) up to 30% rounded to oval, 3-10 mm diameter chlorite-rich amygdaloidal fragments believed to be scoria and amygdaloidal basalt. The matrix to this unit is composed primarily of magnesium chlorite, quartz and sericite.

Both lithological units present in this outcrop have undergone pervasive aluminum silicate alteration. Three different aluminum silicate minerals are present. Andalusite (5-35%) occurs as 1-6 mm equant pink porphyroblasts. In thin section, andalusite is present as ragged, inclusion-rich porphyroblasts with sericite/pyrophyllite rims, and as fresh porphyroblasts that occur in patches and veins up to 5 mm wide. Kyanite is present in two forms: a) as ragged tabular porphyroblasts up to 5 mm in length within the altered matrix of the tuffs; and b) as pale blue blades (3-20 mm in legth) within white to red-brown quartz-iron carbonate veins and veinlets That are up to several cm in width. Pyrophyllite is commonly found along the margins of both the andalusite and kyanite porphyroblasts, and can also occur in veins up to several cm in width as soft, pale green radiating micaceous aggregates. Pyrophyllite is often present where quartz veins intersect kyanite veins. Minor amounts of chloritoid (generally <5%, but locally up to 10%) are associated with these aluminum silicate minerals.

This series of outcrops is believed to be proximal to and part of a synvolcanic fault. These faults are believed to be the channnelways in which high temperature, metalliferous hydrothermal solutions traveled to the seafloor. The aluminum silicate alteration is believed to be produced when these high temperature fluids leached cations from the rocks (for example, during the alteration of feldspar or volcanic glass), leaving them rich in aluminum and silica.

Stop F-2: F-Group Trench

Excavated in 1989, the F-Group reclamation trench was designed to channel runoff waters from the F-Group waste dump into the F-Group pit. Four different lithologies are exposed in this trench: a) dark grey to green, locally amygdaloidal gabbroic to quartz dioritic sill-like intrusion; b) light grey to pink bedded to massive aphyric to quartz-phyric, locally pumice-rich rhyolitic pyroclastic flow deposits of the Mattabi Succession; c) semi massive to massive lenses of pyrite ± sphalerite; and d) grey to grey-green massive quartz ± plagioclase-phyric pyroclastic flows of the "L" Succession. Several alteration assemblages can also be recognized at this locality, including the iron carbonate ± iron chlorite assemblage, the chloritoid assemblage, the chloritoid + aluminum silicate assemblage, and the aluminum silicate assemblage. Structurally, this trench exposes locally highly strained Mattabi Succession pyroclastic flow deposits. It is believed that this deformation is related to splays off the major shear zone that is located to the north beneath Sturgeon Lake.

Stop F-3: Mesobreccia- High Level Lake Pyroclastic Flow Contact

The southern section of stop F-3 (Figure 7), which is located approximately 75 meters southeast of the F-Group pit, is composed in part of heterolithic debris flow deposits that contain a green chlorite-and sericite-rich matrix. These deposits comprise part of the major mesobreccia unit on the regional geology map (Figure 3). Fragments make up 30-70% of this outcrop and are of two types: a) easily recognizable, angular to rounded light grey to pale white felsic lava flow and ash fragments; and b) green, difficult to recognize, lapilli-sized rounded to angular scoria and amygdaloidal basalt fragments. Both types of fragments are believed to have been derived from the underlying precaldera Darkwater Lake Succession rocks.

To the northeast, the mesobreccia deposits become less fragmental, and 1 mm quartz phenocrysts can be observed in the matrix over a zone which varies from 1-5 m in width. This zone represents the gradational contact between the mesobreccia deposits and the overlying quartz-phyric pyroclastic flow deposits. This gradational contact is believed to have formed from mixing of these two units. The contact zone, combined with the interlayering of the High Level Lake ash flow tuff and mesobreccia deposits, suggests simultaneous deposition of these two units. Similar relationships have been documented in mesobreccias that occur in the San Juan Mountains of Colorado (Lipman, 1976).

The light grey quartz- and sericite-rich, recrystallized ash matrix of the High Level Lake ash flow tuffs contains 5-25% 1 mm quartz phenocrysts. Irregular patches and lenses of red-brown iron carbonate alteration vary from 1-10 cm in length and locally comprise 10-15% of the outcrop. In thin section, many of the 1-2 cm carbonate patches appear to be altered pumice.

Mattabi - Area "16"

The Mattabi volcanogenic massive sulphide deposit was discovered by Mattagami Lake Mines in 1969 from follow-up diamond drilling of airborne geophysical anomalies.

The upper sections of the orebody were mined from 1972 to 1980 using open pit methods, and the deeper ore was mined using underground methods from 1980 until reserves were depleted in 1988. The deposit produced 12.55 million tons of ore grading 8.28% Zn, 0.74% Cu, 3.31 oz/ton Ag and 0.85% Pb. The orebody comprised 5 stratiform lenses of massive sulphide ore separated by stringer mineralization or barren host rock. The lenses occurred within three distinct stratigraphic successions (Fig. 9).

Stop M-1: High Level Lake Mesobreccia (HLMBX) Deposits And Quartz Crystal Ash Flow Tuffs (HLQAT)

This series of outcrops is located approximately 500 m stratigraphically below the lower lens of the Mattabi orebody. The southern portion of these outcrops is composed of coarse heterolithic debris flow deposits, which are interpreted to be mesobreccia deposits formed from caldera collapse (See Stop F-1). The far northeastern outcrops (Fig. 8) comprise felsic quartz-phyric pyroclastic flow deposits, which overlie and are interfingered with the mesobreccia deposits and are believed to represent the first intercaldera pyroclastic material. Figure 8 shows the location of the outcrops described below.

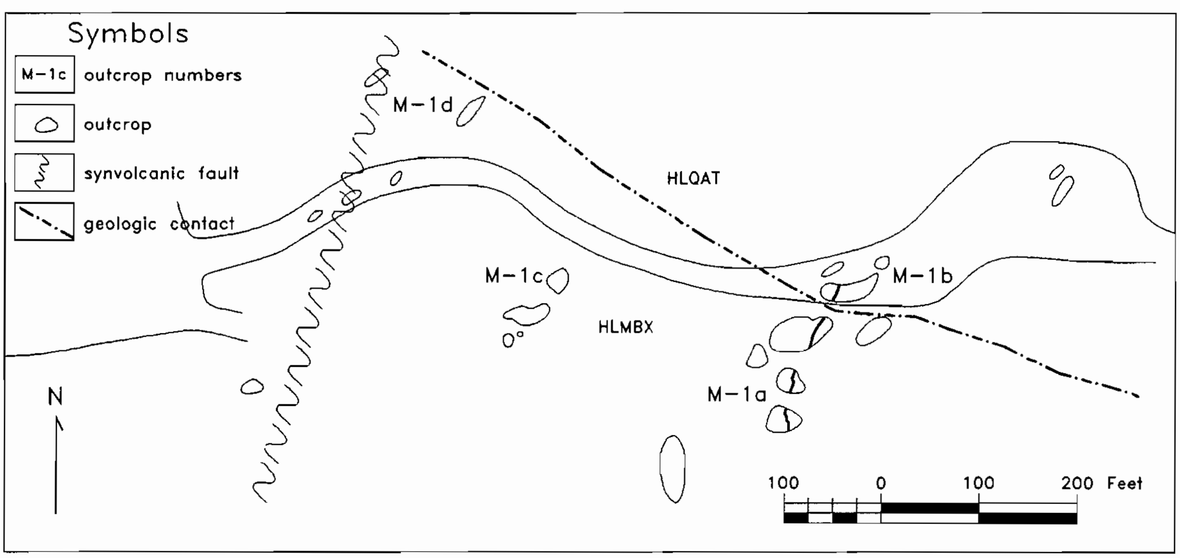

Figure 8. Geological sketch map of the High Level Lake Succession outcrops south of the Mattabi mine (Stop M-1).

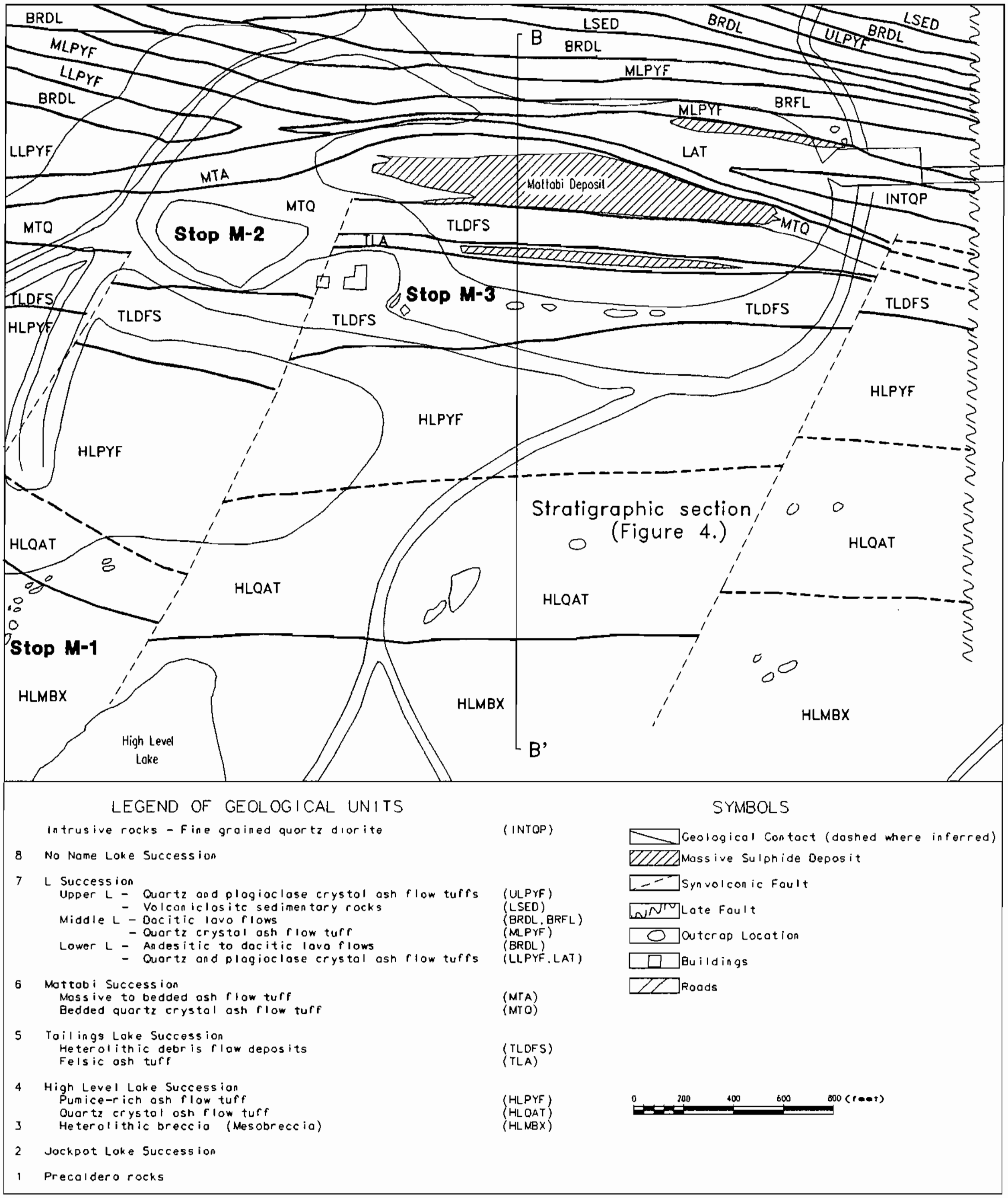

Figure 9. Geological plan map of the Mattabi area, with field trip stop locations.

Stop M-1a: Mesobreccia (HLMBX)

These outcrops consist of coarse heterolithic lithic-rich breccia that contain up to 50% 1-25 cm light-coloured subangular felsic lithic fragments, <10% block-sized pumiceous fragments commonly with silicified rims, and <5% amygdaloidal mafic fragments up to 5 cm in diameter, set in a matrix composed dominantly of alteration minerals. In thin section, the matrix mineralogy consists of 40% fine-grained quartz, 12% chloritoid, 30% Mg-chlorite, 15% sericite ± pyrophyllite and 3% opaque minerals. The northeast section of these outcrops contains an outcrop-sized felsic fragment (>10m) with similar composition and texture as the smaller felsic fragments.

Stop M-1b: High Level Lake Quartz Crystal Ash Flow Tuff (HLQAT)

The HLQAT at this location consists of massive light-tan to grey coloured quartz-phyric ash flow tuff. Quartz crystals (2-5%) range in size from 0.5 to 1.5 mm. In thin section, only "ghosts" of 2-10 mm pumice (20%) can be observed in a matrix composed of recrystallized inequigranular "chunky" quartz (up to 65%), 25% fine sericite, Mg-chlorite (6%), 3% pyrite, and 1% fine opaque minerals. Further to the east, a coarse fragmental texture is observed in outcrops of this unit. The rock consists of coarse (0.5-60 cm) subangular quartz-phyric felsic lithic fragments (60-70%) contained in a matrix petrographically similar to the fragments. This texture has been interpreted as a post-depositional slumpage feature of preconsolidated ash flow tuff. Only minor variations in the alteration mineralogy can be found between the matrix and fragments.

Stop M-1c: High Level Lake Mesobreccia (HLMBX)

This exposure comprises pumice-rich mesobreccia, which contains 20-30% 2-30 cm rounded highly-vesicular (scoria?) fragments and <10% 1-15 cm felsic lithic fragments. The felsic fragments are similar to fragments seen further east (Stop M-1a) and are indicative of the HLMBX unit.

In thin section, the matrix consists of 30% quartz, 20% chlorite, 10% Fe-rich carbonate, 15% sericite ± pyrophyllite, 10% chloritoid, 10% ragged andalusite and 5% opaque minerals. Chlorite alteration increases toward the center of the outcrop where massive chloritic veining up to 50 cm wide occurs.

This chloritic veining is probably the result of fresh seawater recharge into a hot hydrothermal system causing abrupt increases in magnesium content and thus forming chlorite alteration. The quartz-filled tension fractures evident in this outcrop are probably due to volume changes during hydrothermal alteration. Kyanite can be found in these fracture-fillings on the south section of the outcrop. A 10-20 cm wide band of silicified rock, striking N-S, bisects the outcrop. Samples from this band contain 50% quartz, 15% chloritoid, 15% sericite or pyrophyllite (probably replacing andalusite), 8% Fe-rich carbonate, 7% chlorite, 2% relict andalusite, and 2% opaque minerals. This band of more intense alteration probably represents a conduit for upward high- temperature fluid movement, which was later overprinted by sericite (+K) and chlorite (+Mg) alteration.

Stop M-1d: Mesobreccia (HLMBX) And Synvolcanic Fault Zone

This series of outcrops shows a definable, confined and symmetrically zoned increase in alteration intensity through a synvolcanic fault structure within the HLMBX unit. The texture of the HLMBX unit near the synvolcanic fault is strongly overprinted but is still recognizable due to the abundance of relatively unaltered felsic lithic fragments. Alteration in the small outcrop on the road and immediately north of the road consists of 1-4 cm clots of Fe-carbonate-rich material surrounded by anastomosing veinlets of quartz, chloritoid ± andalusite. The dominant change in rock mineralogy from the previous outcrop (M-1c) is an increase in the amount of Fe-rich carbonate and chloritoid.

Stop M-2: Mattabi Ash Flow Tuffs (MTQ)

This outcrop consists of Mattabi Succession quartz crystal ash flow tuff. This exposure contains 10-50% 5-30 mm rounded cherty juvenile felsic fragments, 5-15% 5-30 mm rounded pumice, filled by quartz ± sulphide, and 2-7% 0.5-1.5 mm colourless quartz crystals. The recrystallized altered ash matrix consists of fine quartz (40-50%), chloritoid (10-30%), sericite ± pyrophyllite (15-35%, after andalusite?), andalusite (0-5%) and opaque minerals (1-5%). Lithic fragments consist of quartz ± sericite ± pyrophyllite and the pumice are filled and/or replaced by quartz ± sulphide.

The outcrop shows some alignment of pumice (weathering pits) striking 105° and dipping steeply to the north. This feature may indicate primary bedding.

Stop M-3: Tailings Lake Heterolithic Debris Flow Deposits (TLDFS)

The Tailings Lake Succession consists dominantly of highly-variable heterolithic mafic debris flow deposits (TLDFS) and lesser bedded ash horizons (TLA). The debris flow deposits vary in fragment composition, fragment abundance and bedding characteristics. Three fragment types are dominant: lithic mafic fragments, commonly replaced by chlorite and carbonate (0-50%); fine-grained cherty felsic fragments (0-30%); and rounded pumiceous fragments (0-20%). Bedding is uncommon, but where present, is usually defined by sorting of the various fragment types.

In the outcrop exposure beside the mine ventilation shaft many of the characteristics of the TLDFS unit are conspicuous. This exposure is atypical in its cross-sectional view and in the presence of bedding in the TLDFS unit. Here this unit contains 2-30 mm mafic fragments (5-30% carbonate-replaced weathering pits) and 2-30 mm felsic lithic or pumice fragments (5-30%). In thin section, the matrix consists of 35% quartz, 20% carbonate and 10% andalusite which has been overprinted by 20% Mg-chlorite and 10% sericite ± pyrophyllite. Bedding is defined by sorting of mafic vs. felsic fragments. It appears that mafic fragments are normally-graded and felsic fragments (pumice) are reversely graded. Bedding trends approximately 100° and dips 60-70° to the north.

Stop M-4: No Name Lake Andesite (NNL)

The No Name Lake Succession consists of andesitic pillow lavas, pillow breccias, sheet flows and interflow sedimentary rocks. Only the upper section of this succession is exposed in outcrop; the lower sections are observed only in drill core and appear to consist dominantly of thick amygdaloidal flows.

The first outcrop (behind the core racks) of this stop consists of thin (30-70 cm thick) sheet flows with 5-25% oval-shaped carbonate-filled amygdules (2-30 mm in diameter) generally aligned in the strike direction. In thin section, these rocks are composed of 20% foliated (primary?) fine laths of plagioclase and 15% quartz in a secondary matrix of 40% chlorite, 10% biotite, and 2% epidote.

Pillow breccia and hyaloclastite are exposed in the outcrop east of the water tower. These rocks consist of approximately 25% amygdaloidal pillow fragments (5-50 cm) in a matrix consisting of 30% hyaloclastite and 70% amygdaloidal flows. The pillow breccia fragments contain 10-20% carbonate filled amygdules (now weathering pits) which range in size from 1-4 mm. The hyaloclastite portion of the matrix consists of 0.5-2 cm recrystallized massive angular andesite fragments. The flow portion of the matrix consists of vaguely defined amygdaloidal (20-50% amygdules) flows. Flows become the dominant rock type on the north portion of the outcrop.

Pillowed flows are exposed in the outcrop north of the water tower. This rock consists of well-formed 1-4 m (in the long dimension) amygdaloidal pillows with 25-30%, 1-20 mm carbonate-filled amygdules. The amygdules show a bimodal size distribution; most amygules are 1-4 mm, with another distinct grouping at 5-20 mm. Massive pillow selvages vary from 5-15 cm thick.

AREA “17"

Stop 17-1: Upper “L” Dome Collapse Breccia

Area 17 is located immediately east of the Lyon Lake, Creek Zone, Sub-Creek Zone, and Sturgeon Lake orebodies. The southern one-third of this area is composed of High Level Lake Succession pyroclastic flow deposits, Tailings Lake Succession debris flow deposits and associated sediments, and Mattabi Succession Pyroclastic flow deposits. The central one-third of the area is composed of a complex sequence of rhyolitic to dacitic "L" Succession pyroclastic flow deposits, volcaniclastic sedimentary rocks, and andesitic to dacitic lava flows. The northern one-third of the area is dominated by a dacitic lava dome which is capped by dome-derived debris flow deposits, volcaniclastic sedimentary rocks, graphitic sedimentary deposits, and iron formation (see Figure 10).

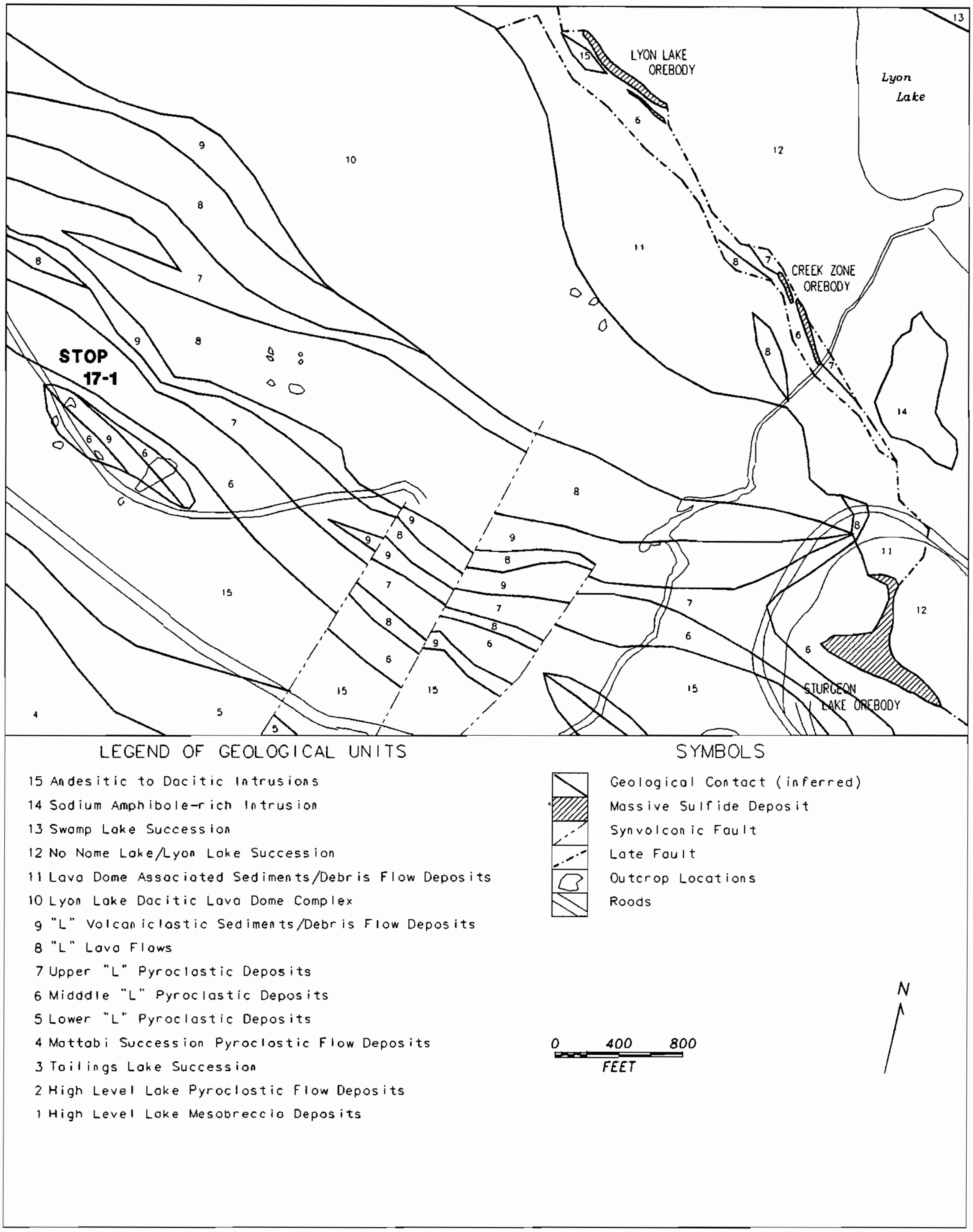

Figure 10. Geological plan map in the vicinity of the Lyon Lake, Creek Zone, and Sturgeon Lake orebodies, with field trip stop location.

This spectacular volcanic breccia is composed of 30-60% subangular to angular, 1-35 cm diameter light grey felsic volcanic fragments which contain 1-5% 1 mm quartz phenocrysts. These fragments are alligned parellel to one another, and in many places, appear as if they can be placed back together with adjacent fragments. Rare sulfide-rich fragments and iron-carbonate-rich fragments (pumice) up to 5 cm in diameter can also be observed. The matrix of this rock is composed of fine grained quartz, iron-chlorite, iron-carbonate, and sericite.

In thin section, the felsic lithic fragments from this outcrop are composed of spherulitic quartz- and K-spar(?)-phyric lava. We believe that this breccia represents a proximal dome collapse breccia or block and ash flow deposit formed from a Middle "L" lava dome that may have been located to the east near the wall of the caldera. A late fault zone located along the northeastern margin of the Sturgeon Lake ore deposit precludes observation of the "L" stratigraphy north and east of this fault.

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