Geology of the Kakinagimak Lake Area, Northwestern Flin Flon Domain (part of NTS 63M/01)

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Abstract

As part of the Flin Flon Targeted Geoscience Initiative III project, geological bedrock mapping of a 150 km² area centred on Kakinagimak Lake (part of 63M/01) was carried out at 1:20 000 scale. This work represents the northward continuation of mapping by the Saskatchewan Geological Survey between 1991 and 1995. The project is integrated with an airborne radiometric and magnetic survey that was flown over a 3141 km² area in late August and early September of 2007.

Supracrustal and plutonic rocks in the Kakinagimak Lake area, metamorphosed to upper amphibolite facies, represent a continuation of the Amisk Collage of the Flin Flon Domain, exposed 40 km to the southeast. About 50% of the area is underlain by granodioritic to tonalitic foliates and gneisses inferred to be circa *1.86 Ga old. The remainder is made up of about 30% migmatitic, generally graphitic sedimentary rocks, and about 20% mafic to felsic volcanic rocks inferred to be >1.87 Ga old. All of these rocks were affected by five ductile deformation events. Primary features are not preserved in the sedimentary or volcanic rocks, but the latter contain abundant evidence of metamorphosed hydrothermal alteration zones, now preserved as garnet-anthophyllite assemblages. Minor amounts of chalcopyrite and Fe-sulphides were encountered in several outcrops. South of Keep Lake, the volcanic succession hosts the Schotts Lake deposit, an approximately four million tonne volcanogenic massive sulphide deposit grading 0.41% Cu and 1.26% Zn. The Keep Lake area is dominated by garnetiferous intermediate to felsic volcanic rocks exhibiting garnet-anthophyllite alteration and local sulphide occurrence. Based on the low ratio of mafic to felsic-intermediate volcanic rocks, the Keep Lake volcanic succession has more similarities to the West Amisk and the Hanson Lake arc assemblages, than the Flin Flon arc assemblage.*

Keywords: *Paleoproterozoic, Flin Flon Domain, Kisseynew Domain, Schotts Lake deposit, volcanogenic massive sulphide deposit, syngenetic alteration, garnet-anthophyllite.*

1. Introduction

This project represents a continuation of the government-funded lithotectonic (*e.g.*, Ashton and Leclair, 1991; Ashton *et al.*, 1993, 1995) and structural studies (*e.g.*, Lewry *et al.*, 1991; Lewry, 1993) carried out in the region between 1991 and 1995. Some of these mapping projects fell under the umbrella of the NATMAP Shield Margin Project, which was initiated in 1991 and was designed to foster an interdisciplinary approach to conducting bedrock and surficial mapping with a primary focus on studying the exposed and sub-Phanerozoic portions of the Flin Flon Belt (Lucas *et al.*, 1999).

This study forms part of the Targeted Geoscience Initiative III project (TGI-3), a joint federal-provincial geoscience initiative that strives to use geoscience as a tool "to help sustain the reserves of base metals in vulnerable established mining communities in Canada" (http://ess.nrcan.gc.ca/tgi/). To date, most of this work has been focused in the immediate Flin Flon area (*e.g.*, MacLachlan, 2006; Simard, 2006). As part of TGI-3, and to complement bedrock mapping, an airborne radiometric and magnetic survey was flown over an approximately 80 x 40 km area between the Tabbernor Fault and the Saskatchewan-Manitoba border in late August and early September of 2007 (dashed line in Figure 1).

The 2007 study area is centred on Kakinagimak Lake, a narrow, river-like, 25 km-long lake with its long axis oriented parallel to the north-trending geological units. It is located about 40 km east of Pelican Narrows and 45 km northwest of Flin Flon. The lake can be accessed via float-equipped aircraft from Pelican Narrows, which can be reached via the Hanson Lake Road (Highway 106) and Highway 135 (Figure 1). Fieldwork using an inflatable boat was carried out from a base camp in File Bay at the south end of Kakinagimak Lake. Relief varies from lake level of Kakinagimak Lake, at about 330 m above sea level, to about 410 m on some of the granitoid ridges. Bedrock mapping of the approximately 150 km² area was carried out by a three-person crew between the beginning of June and the end of August 2007 and consisted of GPS-assisted compass traverses and shoreline mapping. Magnetic

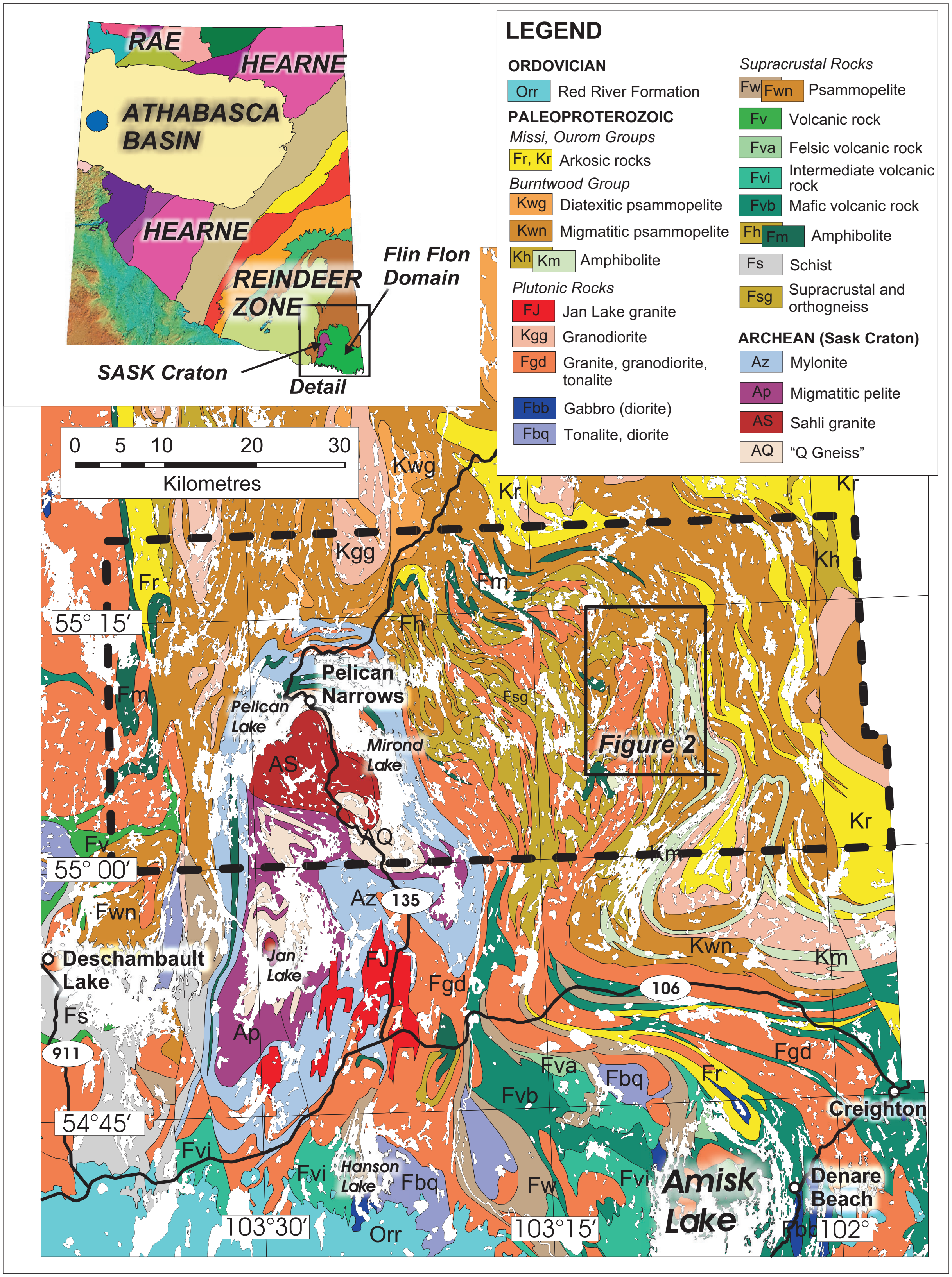

Figure 1 - Location map showing outlines of Kakinagimak map area (solid line; Figure 2) and the airborne geophysical survey (dashed line).

susceptibility measurements were collected at all outcrops, whereas ground gamma-ray spectrometric measurements were only taken on selected shoreline outcrops.

2. Previous Work and Regional Geology

Earliest geological investigations of the larger Pelican Narrows area date back to the early 1900s (McInnes, 1914; Bruce, 1918). Systematic mapping of the area did not commence until the early 1950s (Byers and Dahlstrom, 1954; Cheesman, 1956; Kirkland, 1957; Pyke, 1961) and was accompanied by a considerable amount of base metal exploration activity (*e.g.*, Ministry of Energy and Resources Assessment File 63M01-SE-0042R and summary therein; Coombe, 1991). As part of the 1984 to 1989 Canada-Saskatchewan Mineral Development Agreement, the Geological Survey of Canada (GSC) began a transect across the transition between the southwestern Kisseynew Domain and the northern Flin Flon Domain (*e.g.*, Ashton *et al.*, 1987, 1992). This work was continued by the Saskatchewan government as part of the Wildnest-Tabbernor lakes transect between 1991 and 1996 (Ashton and Leclair, 1991; Ashton *et al.*, 1993; Ashton and Shi, 1994; Ashton *et al.*, 1995) under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990 to 1995. This transect extended across the south end of Kakinagimak Lake. Simultaneously, LITHOPROBE and Flin Flon NATMAP projects were conducted over large parts of the Flin Flon Domain, most of this work being summarized by Syme *et al.* (1998 and refs. therein).

Base metal exploration dates back to the 1950s and saw a revival in the early 1990s due to the work by the Saskatchewan Geological Survey (*e.g.*, Ashton *et al.*, 1993). The area, then known as the 'Attitti Sheet' of the 'Hanson Lake Block', became recognized as a high-grade extension of the Flin Flon Domain. This resulted in a revision of the domainal framework of the province (Saskatchewan Geological Survey, 2003). Recognition of garnet-anthophyllite alteration in the area and reinterpretation of many of the high-grade gneisses as equivalents of the volcanic assemblages of the Flin Flon Domain, led to renewed interest. Companies such as Aur Resources and BHP Minerals started exploration projects in the southeastern Kakinagimak Lake area and applied modern geochemical exploration principles to the search for volcanogenic massive sulphide (VMS) deposits. The Schotts Lake deposit, a 4.5 million tonne (M t) VMS deposit grading 0.41% Cu and 1.26% Zn, originally discovered in the 1950s, is the most advanced exploration target in the area.

The Flin Flon Domain contains 1.92 to 1.87 Ga tectonostratigraphic assemblages, which were amalgamated to form the accretionary 'Amisk Collage' (Lucas *et al.*, 1996), prior to emplacement of younger granitoid plutons and deposition of sedimentary and volcanic successions. Work by Ashton and Leclair (1991) and Maxeiner *et al.* (1995) has shown that lithotectonic assemblages in the Attitti Lake and Hanson Lake areas are similar to parts of the Amisk Collage and likely represent the western extension of the Flin Flon Domain (Ashton, 1999 and refs. therein; Maxeiner *et al.*, 1999b). A foliated to gneissic leucotonalite collected at the south end of Kakinagimak Lake yielded a U-Pb zircon age of 1852 +6/-4 Ma (Heaman *et al.*, 1993), which was interpreted as a crystallization age. This is temporally similar to successor arc plutonism, which affected the 1.92 to 1.87 Ga Amisk Collage (Syme *et al.*, 1998). A sample of a "syn-volcanic(?) tonalite" (Heaman and Ashton, 1996, p109) collected within a larger felsic subvolcanic unit at the southwest end of Kakinagimak Lake yielded $^{207}Pb/^{206}Pb$ ages of 1835 Ma and 1864 Ma, the older of which was interpreted as a minimum crystallization age (Heaman and Ashton, 1996). During the 2007 field season, we collected another sample of a feldspar-porphyritic felsic volcanic rock from the same unit and submitted it for age dating utilizing the GSC's sensitive high-resolution ion microprobe (SHRIMP). The Missi Group, an alluvial-fluvial succession of conglomerate and sandstone unconformably overlying the volcanoplutonic assemblages of the Flin Flon Domain, has been bracketed in the Flin Flon area between 1847 Ma (Ansdell, 1993) and 1842 Ma (Heaman *et al.*, 1992).

A deformed and sheared pegmatite from within the Sturgeon-weir Shear Zone yielded a U-Pb zircon age of 1806 ±2 Ma (Ashton *et al.*, 1992), which was interpreted as a syntectonic emplacement age. A U-Pb zircon age of 1807 +3/-2 Ma from a felsic volcanic rock sampled on southern Attitti Lake was interpreted as a metamorphic age (Heaman *et al.*, 1992). The 1.85 Ga Kakinagimak Lake leucotonalite also provided a titanite cooling age of 1789 ±3 Ma (Heaman *et al.*, 1993).

A metamorphic pressure-temperature study in the Attitti Lake area (Ashton and Digel, 1992) constrained peak metamorphic conditions to about 6.6 to 7.9 kbar and 630° to 725°C using three independent thermobarometric techniques. This is consistent with mineral assemblages and partial melting within pelitic rocks observed in the field, all suggesting upper amphibolite facies conditions (Ashton *et al.*, 1995). Granite and granite pegmatite of the *ca.* 1770 Ma Jan Lake Granite Suite (Macdonald and MacQuarrie, 1978; Bickford *et al.*, 1987; Ashton and Shi, 1994) are widespread in the region.

3. Description of Main Units [1]

The area is predominantly underlain by granodioritic to tonalitic gneisses exposed along the shores of central Kakinagimak Lake (Figure 2). In the south, particularly in the File Bay, Gifford Bay, and Keep Lake areas, the map pattern is dominated by felsic to intermediate volcanic[2] rocks, with subordinate graphitic sedimentary rocks. North of the granodiorite gneisses, in the Cornell Bay to Scott Lake area, calcic and aluminous pelitic to psammopelitic gneisses are most prevalent. North and west of Grindley Lake, mafic volcanic rocks are complexly infolded with the sedimentary rocks.

Since the map area borders recent maps by Ashton and Leclair (1991) to the west and Ashton *et al.* (1995) to the south, their lithological units were largely adopted. Where possible, we mapped into the areas of the previous workers to keep 'map boundary faults' to a minimum.

a) 'Amisk Collage' (1.90 to ~1.87 Ga)

Volcanic and Associated Rocks

A "metamorphic colour index" based on the percentage of mafic minerals in a rock was used in the field to distinguish between mafic (>35), intermediate (35 to 15), and felsic (<15) variants; the term rhyolitic was used for rocks generally having an index of <5, unless they were altered. In general, primary features other than compositional layering have not been preserved within the Kakinagimak volcanic succession due to the upper amphibolite-facies metamorphic overprint and the strong structural transposition. Evidence for syngenetic alteration is characterized by the presence of abundant garnet (regional alteration), garnet-anthophyllite (localized Fe-Mg metasomatism), calc-silicate layers and lenses (quartz-epidote alteration), and extraordinarily high quartz content (silicification).

Dark green to greenish-black **mafic volcanic and volcaniclastic rocks (Mv)** form thin units north of Gifford Bay, where they appear to be intruded by granodiorite. More extensive units of the mafic volcanic rocks can be found south of Keep Lake hosting the Schotts Lake VMS deposit, and northwest of Grindley Lake, where a shallowly northeast-dipping unit covers several square kilometres. The rocks are generally fine grained and layered on a decimetre to metre scale (Figure 3). They contain approximately equal amounts of plagioclase and hornblende, with local enrichment of garnet or clinopyroxene (Figure 4). Hornblende is locally altered to biotite. Trace amounts of sulphides are near ubiquitous. The magnetic susceptibility generally varies between 0.4 and 0.6 (10^{-3} SI), but generally has higher values between 0.6 and 0.8 (10^{-3} SI) with increasing amounts of garnet. Garnet locally reaches 10% of some rocks and helps define metre-scale layering.

With increasing clinopyroxene content, mafic volcanic rocks grade into **mafic calc-silicate rocks (Cm)** such as those east of Dezort Lake. Light greenish grey, dusky green and greenish black mafic calc-silicate rocks are fine grained to rarely medium grained and characteristically heterogeneous, strongly foliated and layered on a 2 to 5 cm scale. They are distinguished by lenses and layers rich in diopside, Ca-rich amphibole, plagioclase and carbonate, within an otherwise homogeneous upper amphibolite facies mafic volcanic rock. Other common minerals include garnet, epidote, and minor quartz. As suggested by Pyke (1961) and Ashton and Leclair (1991), the metre-scale layering observed within the mafic volcanic and calc-silicate rocks likely represents transposed primary layering. The more tightly-spaced laminations defined by calc-silicate minerals are, however, more likely resulting from tectonic transposition of pre-metamorphic quartz-epidote alteration, commonly observed in pillow cores of mafic volcanic flows near Flin Flon (*e.g.*, MacLachlan, 2006).

Intermediate volcanic and volcaniclastic rocks (Iv) form 100 to 500 m thick units extending for several kilometres along the east side of Gifford Bay and east of Keep Lake (Figure 2). The rocks are grey to greenish grey, very fine to fine grained and equigranular, containing 15 to 35% combined hornblende and biotite, with variable amounts of garnet and clinopyroxene, as well as minor sulphides. The sulphides are commonly associated with some of the larger poikiloblastic garnet grains. The rocks are layered on a centimetre to decimetre scale and are locally interbedded on an outcrop scale with their felsic or mafic counterparts and with minor epiclastic rocks. West of Dezort Lake, the interbedded nature of volcanic and epiclastic rocks of intermediate composition is so complex that a separate unit was created (As). For the most part, these rocks are thought to represent the high-grade equivalents of andesitic volcaniclastic rocks. In a few locations, intermediate volcanic rocks are more homogeneous and locally feldspar porphyritic (Figure 5) suggesting that they represent massive flows, sills or minor subvolcanic intrusions.

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[1] Only selected units and important observations and relationships are described in detail in this paper. For comprehensive and systematic descriptions of all units, the reader is referred to the legends on the accompanying maps. Description of rock units follows the IUGS classification of igneous rocks (Streckeisen, 1976) and the classification of metamorphosed clastic sedimentary rocks (Maxeiner *et al.*, 1999a).
[2] The prefix 'meta-' is not used, as all of the rocks have been metamorphosed to upper amphibolite facies conditions.

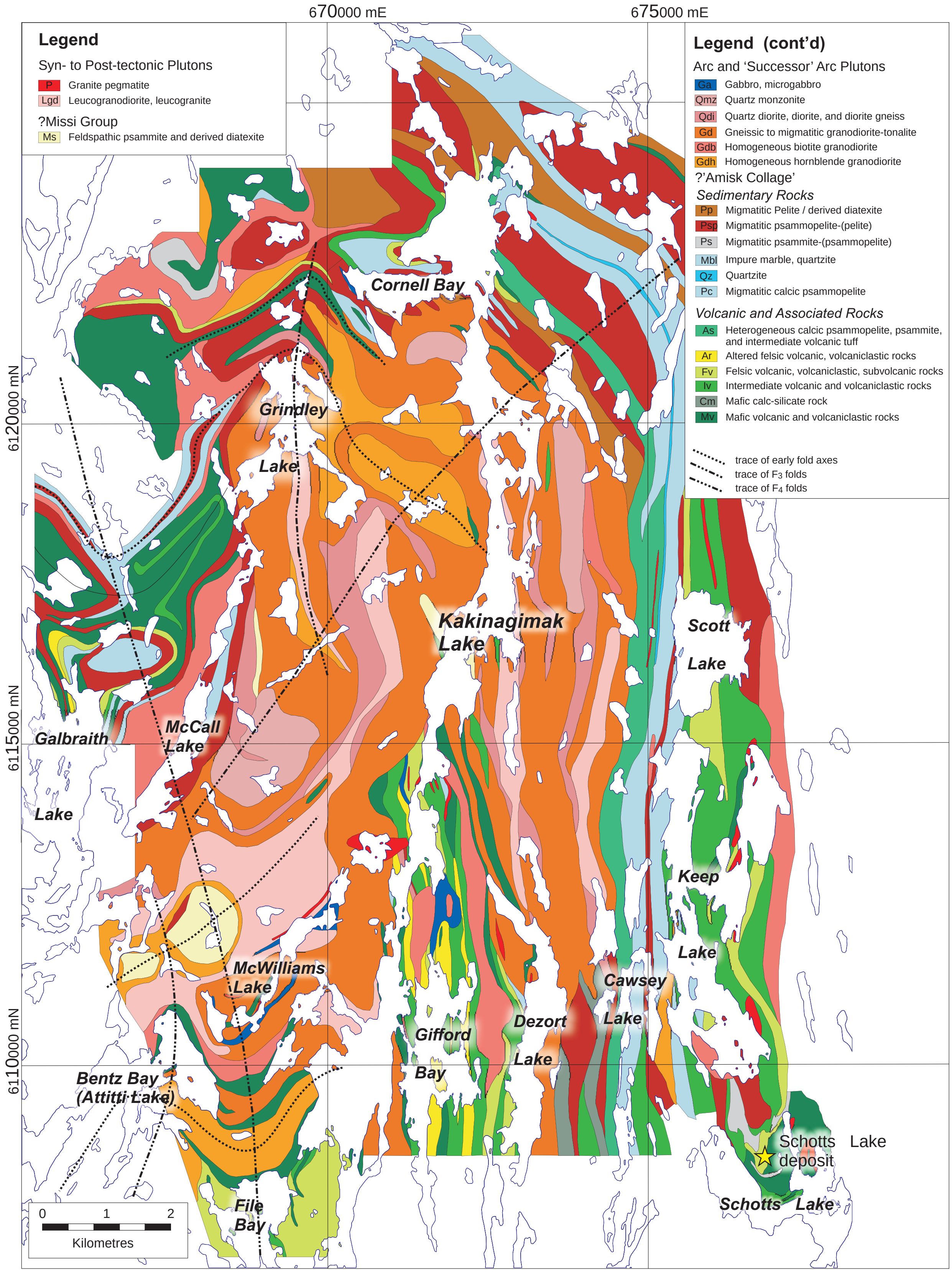

Figure 2 - Simplified bedrock geology of the Kakinagimak Lake area.

Figure 3 - Heterogeneous, possibly pillowed mafic volcanic rock with poorly defined folded layering; northwest of Cornell Bay. Station RM07-55-ST18 at UTM[3] 669573 m E, 6123574 m N.

Fine-grained **volcanogenic rocks of dacitic to rhyodacitic composition (Fv)**, including volcanic, volcaniclastic and subvolcanic varieties, are interlayered on a map scale with intermediate volcanic rocks east of Gifford Bay and east of Keep Lake (Figure 2). Layering is not as prevalent as in the intermediate rocks and is on a decimetre to metre scale. Rare felsic fragmental rocks (Figure 6) were noted at the north end of Gifford Bay. The dacitic rocks are buff to light grey and contain 5 to 15% combined biotite and hornblende with abundant garnet (Figure 7) and local sulphides. The rocks have locally been affected by Fe-Mg metasomatism and these zones are now characterized by enrichment in garnet and anthophyllite representing the equivalent high-grade mineral assemblages. The magnetic susceptibility of the dacitic volcanic rocks typically varies between 0.1 and 0.35 (10^{-3} SI).

Figure 4 - Calc-silicate alteration pod in mafic volcanic rock; note large crystals of garnet (red), diopside (pale green), and hornblende (dark green); north of channel between Gifford Bay and Kakinagimak Lake. Station RM07-27-ST07 at UTM 671122 m E, 6110797 m N.

Figure 6 - Heterogeneous felsic volcanic rock; possibly a rhyolitic tuff breccia; rock has also been affected by silicification and calc-silicate alteration (note dark-coloured calc-silicate lenses); north Gifford Bay. Station RM07-22-ST08 at UTM 671954 m E, 6110192 m N.

Figure 5 - Feldspar-porphyritic intermediate volcanic rock; east Gifford Bay. Station RM07-22-ST04 at UTM 672409 m E, 6109851 m N.

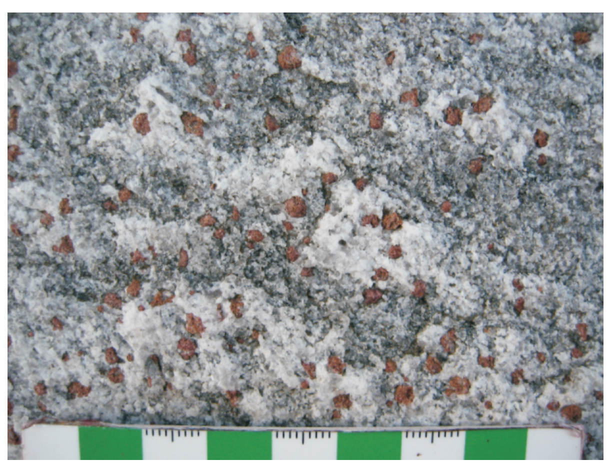

Figure 7 - Highly garnetiferous, altered felsic volcanic rock; Keep Lake area. Station RM07-48-ST19 at UTM 676265 m E, 6111989 m N.

[3] All UTM coordinates are in NAD 83, Zone 13.

A more homogeneous unit of felsic volcanic rock occurs between File Bay and the main part of Kakinagimak Lake, and was interpreted as a subvolcanic intrusion (Ashton and Leclair, 1991). A geochronology sample of this unit collected in 1991 yielded small colourless zircons that provided two multi-grain fractions, which gave $^{207}Pb/^{206}Pb$ ages of 1835 and 1864 Ma (Heaman and Ashton, 1996), the older of which was interpreted as the minimum age of emplacement.

The central part of Gifford Bay is dominated by several 100 to 300 m thick and up to 3 km long units of white to pink, fine-grained felsic gneiss, interpreted as **altered felsic volcanic and volcaniclastic rock** of originally rhyolitic composition **(Ar)**. The rocks are strongly foliated to gneissic and locally extremely siliceous with up to 50% quartz. Mafic minerals, including ubiquitous biotite and local enrichment of garnet, generally account for less than 5% of these rocks. Sillimanite, forming up to 30 cm long lensoid pods, may locally reach up to 30% (Figure 8). Transposed centimetre-thick quartz lenses and ribbons can be found in most outcrops and medium- to coarse-grained granitic leucosome is present in some exposures of the sillimanite-bearing altered rock. Retrograde replacement of sillimanite by muscovite occurs locally. Other minor constituents include sulphides, anthophyllite, and hornblende. Presence of near-ubiquitous sulphides, irregular unit distribution, and the lithological association with other volcanic rocks suggest that the felsic rocks are not sedimentary in origin.

A small unit of very **siliceous sedimentary rocks (If)** is exposed along the west shore of File Bay, in the area previously mapped by Ashton *et al.* (1995), who interpreted them as a succession of chert and minor oxide facies iron formation. The rocks are white, buff to brown, fine grained and bedded on centimetre to metre scale (Figure 9). They are dominated by quartz, with minor amounts of plagioclase, magnetite, graphite, and/or garnet. The unit structurally overlies felsic to intermediate volcanic rocks.

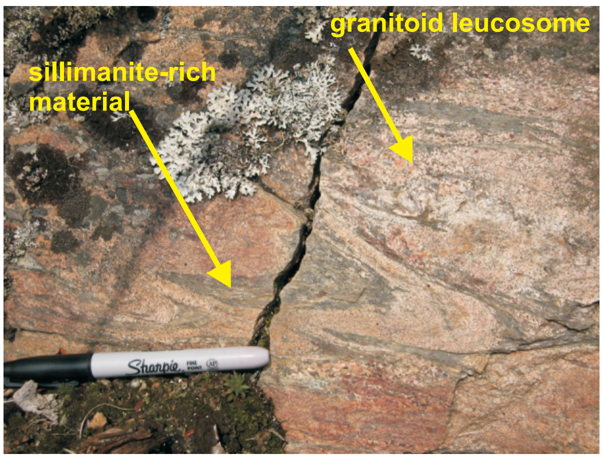

Figure 8 - Rhyolitic felsic volcanic rock with strong enrichment of sillimanite (grey) and development of a granitic leucosome; sillimanite lens was affected by tight F_3 folding; Station RM07-35-ST09 at UTM 671294 m E, 6113521 m N.

Figure 9 - Laminated to thinly bedded cherty sedimentary rocks; northwest side of File Bay. Station RM07-23-ST01 at UTM 668421 m E, 6107305 m N.

An approximately 300 m-thick heterogeneous unit of grey to brown **calcic psammopelite**, **psammite**, **and intermediate volcaniclastic rock (As)** extends for about 15 km from Cawsey Lake to the north end of Kakinagimak Lake. The rocks are fine to medium grained, granoblastic and commonly layered on decimetre to metre scale; generally rocks within this unit have not been affected by partial melting, except for the calcic psammopelite, which commonly contains tonalitic leucosome. The mixed sedimentary rocks differ from the more homogeneous sedimentary rocks (*e.g.*, units Psp, Pp) by containing significant amounts of hornblende which, together with biotite and cummingtonite, forms 15 to 25% of the rock. Garnet, diopside, and graphite are present in minor amounts. This unit is interpreted to represent a transition from predominantly volcanogenic to predominantly epiclastic depositional processes.

Migmatitic Sedimentary Rocks

In addition to the heterogeneous sedimentary-volcaniclastic unit (As) east of Kakinagimak Lake, epiclastic rocks have been identified throughout the area and are intercalated with the volcanic rocks. The sedimentary rocks predominate at the north end of Kakinagimak Lake and between the volcanic successions of Gifford Bay and Keep Lake. Aluminous pelitic to psammopelitic units have been distinguished from a predominantly calcic unit. Most are graphitic and characterized by the presence of 10 to 40% tonalitic to granodioritic leucosome. According to Ashton and Leclair (1991) these ‘aluminous wackes’ are similar to rocks making up much of the southern flank of the Kisseynew Domain and are in part equated with the synvolcanic Welsh Lake assemblage (Ashton, 1990; Ansdell and Connors, 1994). Some of the components may belong, however, to the <1.85 Ga Burntwood Group (*e.g.*, Zwanzig, 1990; David *et al.*, 1996), a deep-water facies equivalent of the Missi

Group making up much of the central parts of the Kisseynew Domain. Earlier attempts to differentiate the two pelitic successions in the Belcher Lake area (Hartlaub *et al.*, 1996), immediately northwest of the current study area, proved difficult and, it was thought, that the synvolcanic volcaniclastic rocks passed gradationally into Burntwood Group rocks. Incidentally, the aluminous rocks are also similar in terms of their composition and structural setting to the *ca.* >1.867 Ga Levesque Bay Assemblage (Corrigan *et al.*, 1999; Maxeiner *et al.*, 2005), exposed on southern Reindeer Lake, structurally sandwiched between >1.86 Ga volcanoplutonic assemblages of the La Ronge Domain and the Burntwood Group of the Kisseynew Domain.

Grey- to brown-weathering **migmatitic pelite and derived diatexite (Pp)** are exposed at the north end of Kakinagimak Lake (Figure 2), where they are interlayered with, and similar to, migmatitic psammopelite (Psp). The rocks are generally gneissic, compositionally variable from pelitic to psammopelitic, and layered on a decimetre to metre scale. The paleosome is generally fine to medium grained, whereas the tonalitic leucosome is medium to coarse grained. The presence and relative abundance of the partial melt component is determined by primary composition of the rock, with pelitic components having more partial melt than their psammopelitic counterparts. The pelitic components have locally succumbed to complete anatexis and the resultant pelitic diatexite is a coarse-grained homogeneous rock with abundant garnet, graphite, and neoblastic plagioclase (Figure 10). Garnet, biotite, and graphite make up between 25 and 35% of the rock, with sillimanite and tourmaline present as local minor components. The magnetic susceptibility is consistently very low, generally varying between 0.2 and 0.3 (10^{-3} SI).

Grey to brown, **migmatitic psammopelite-pelite (Psp)** is by far the most widespread of the epiclastic rock, types. In the Cornell Bay area of Kakinagimak Lake, it forms units up to 1 km thick that extend for several kilometres along strike. Thinner units of migmatitic psammopelite are intercalated on a scale of hundreds of metres with mafic volcanic rocks north and southwest of Grindley Lake, where together they define complex fold interference patterns (Figure 2). On outcrop scale, they are intercalated with minor pelitic and psammitic layers, varying in thickness from 5 to 50 cm. Calc-silicate lenses, up to 20 cm thick and 40 cm long, occur sporadically north of Cornell Bay (Figure 11) and may represent metamorphosed calcareous concretions or boudinaged calcareous layers. The psammopelitic rocks are very similar in appearance to their pelitic counterparts (Pp), but contain less combined biotite, garnet and graphite, generally making up about 15 to 25% of the rock. They also contain less leucosome, generally around 20% (Figure 12).

Migmatitic psammite-psammopelite (Ps) is found in two small units, one northwest of Grindley Lake and one between Keep Lake and Schotts Lake. These grey

Figure 10 - Close-up of garnet and plagioclase porphyroblasts in pelitic diatexite; Cornell Bay area. Station RM07-28-ST03 at UTM 671963 m E, 6121959 m N.

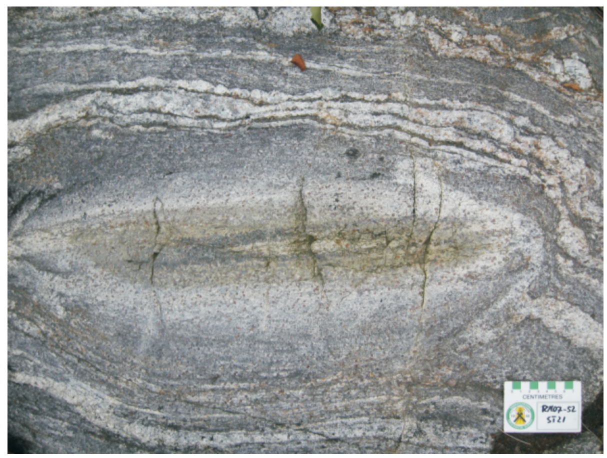

Figure 11 - Migmatitic psammopelite with boudinaged calc-silicate layer; north end of Kakinagimak Lake. Station RM07-52-ST21 at UTM 671200 m E, 6125331 m N.

Figure 12 - Migmatitic psammopelite with 20 to 30% tonalitic leucosome; note isoclinal folding of leucosome and later refolding; north end of Kakinagimak Lake. Station RM07-52-ST19 at UTM 671328 m E, 6124779 m N.

to brownish grey, fine- to medium-grained quartzofeldspathic rocks are of uncertain origin, due to their relatively homogeneous nature, their lack of graphite and sulphides, and their granoblastic texture. Mafic mineral content in these quartz-feldspar-biotite rocks is generally less than 10%. They were interpreted as being of sedimentary origin, as they are locally compositionally layered, associated with graphitic psammopelite, and may contain minor amounts of garnet. Magnetic susceptibility of the psammitic gneisses is generally between 0.15 and 0.2 (10^{-3} SI).

An approximately 500 m-thick unit of grey, greenish-grey to brown weathering, **migmatitic calcic psammopelite (Pc)** extends for 15 km from the north end of Kakinagimak Lake to Schotts Lake (Figure 2) in the south. It structurally overlies a more heterogeneous unit of intercalated calcic psammopelite, psammite, and intermediate volcanic tuff (As). The rocks are fine to medium grained and layered on centimetre to decimetre scale. They are locally interbedded with more aluminous sedimentary lithologies (Pp, Psp), with which they have much in common, including abundant tonalitic leucosome and ubiquitous graphite and garnet. They are distinguished from them by the presence of abundant hornblende (Figure 13), and variable amounts of diopside, carbonate, titanite, K-feldspar, and/or scapolite. Leucosome within the calcic psammopelite commonly contains diopside (Figure 14).

A 20 to 40 m thick unit of **quartzite (Qz)**, extending for a strike length of about 7 km, is interbedded with, and separated out from, the calcic psammopelite (Pc). These white to light greenish grey rocks are fine grained, laminated to thinly bedded, and contain >70% quartz and locally up to 90% quartz, with minor amounts of plagioclase, biotite, as well as local graphite, hornblende and/or diopside. Individual beds of quartzite are between 0.4 and 4 m in thickness. In one location, a quartz-eye–bearing, more feldspathic variant is intercalated on a metre-scale with sillimanite-garnet rich pelite and calcic psammopelite; it may be of igneous origin.

One outcrop of **impure marble and quartzite (Mbl)** in the central Kakinagimak Lake area is exposed along the contact between intermediate volcanic rocks and the larger mass of granodioritic intrusions to the east. The outcrop weathers dark grey, and comprises a thinly bedded carbonate-rich succession with 1 to 5 cm-thick intercalations of white-weathering quartzite (Figure 15). The moderately east-dipping unit is at least 4 to 5 m thick and is capped by a granitic pegmatite, which has preserved this otherwise recessively weathering carbonate-rich unit. Similar rocks are also locally found as minor layers within the migmatitic calcic psammopelite (Pc).

b) Arc and 'Successor' Arc Plutons (?1.88 to 1.85 Ga)

By far the most abundant rock type consists of **gneissic to migmatitic granodiorite-tonalite bodies** (unit Gd), occurring as large masses in the central part of the area

Figure 13 - Abundant hornblende and garnet in migmatitic graphite-bearing calcic psammopelite; southwest of Grindley Lake. Station RM07-50-ST16 at UTM 666733 m E, 6117388 m N.

Figure 14 - Amphibolitized diopside in leucosome of calcic psammopelite; north Kakinagimak Lake. Station RM07-52-ST02 at UTM 671620 m E, 6122524 m N.

Figure 15 - Interbedded succession of impure marble and thin quartzite layers; note tight z-folds in quartzite possibly related to regional F3 synform located to the west; east shore of central Kakinagimak Lake. Station RM07-40-ST05 at UTM 671767 m E, 6114513 m N.

(Figure 2). A leucocratic variety of this inferred >1.85 Ga plutonic suite (Ansdell and Kyser, 1991; Ashton *et al.*, 1995) yielded an ID-TIMS U-Pb zircon crystallization age of 1852 +6/-4 Ma (Heaman *et al.*, 1993) from a sample collected at the south end of Kakinagimak Lake. Farther west, a similar tonalitic gneiss collected 4 km northeast of Pelican Narrows yielded an upper intercept age of 1856 ±3 Ma, which was interpreted as the time of emplacement (Ashton *et al.*, 1999). Based on these ages, it appears as though many of the granitoid plutons in the larger Pelican Narrows area are part of the 1.87 to 1.85 Ga main period of calc-alkaline granodiorite-tonalite-gabbro plutonism commonly observed in the Flin Flon area, where such intrusions are referred to as successor arc plutons (Syme *et al.*, 1998). Some of the more mafic granodioritic rocks may, however, represent older arc plutons.

Light grey to light pinkish-grey, gneissic to migmatitic granodiorite-tonalite (Gd) is heterogeneous because of variable amounts of leucogranodioritic to granitic leucosome, abundant inclusions and schlieren of intermediate to mafic rocks (Figure 16). Some of the mafic 'inclusions' within the granodiorite-tonalite likely represent folded and boudinaged mafic dykes; others are xenoliths of mafic volcanic rocks. Heterogeneous granodiorite-tonalite is generally medium to coarse grained and well foliated with centimetre-scale gneissic layering defined by variation in mafic mineral content and grain size (Figure 17). Hornblende and lesser biotite characteristically account for 10 to 15% of the rock. The heterogeneous gneisses commonly grade into more homogeneous biotite granodiorite (Gdb) and hornblende granodiorite (Gdh), as well as quartz-diorite gneiss (Qdi) and leucogranodiorite (Lgd).

Light pinkish-grey to buff-weathering, **homogeneous hornblende granodiorite (Gdh)** is exposed in a number of localities northwest of Kakinagimak Lake and has gradational contacts with neighbouring heterogeneous migmatitic varieties (Gd). The rocks are medium to coarse grained, weakly to moderately foliated and contain about 10% hornblende with minor amounts of biotite. Units of **homogeneous biotite granodiorite (Gdb)** are identical in outcrop appearance, but contain 10% biotite instead of hornblende. Grey- to buff-weathering **quartz monzonite (Qmz)** is also spatially related to the gneissic granodiorite-tonalite and contact relationships between the two are gradational. The quartz monzonite is medium to coarse grained and characteristically homogeneous, with 10 to 15% coarse-grained hornblende porphyroblasts and 5 to 10% fine-grained biotite. Mafic inclusions and schlieren are locally present. Magnetite is a common constituent in all the granitoid rocks.

Figure 16 - Typical migmatitic gneissic granodiorite-tonalite with layered mafic volcanic xenoliths; island in central Kakinagimak Lake. Station RM07-43-ST05 at UTM 672350 m E, 6117136 m N.

Quartz-diorite gneiss (Qdi) forms 200 to 300 m-thick units within the granodiorite complex (Gd) that are traceable along strike for several kilometres. Contacts with neighbouring granodioritic rock are gradational. The rocks are relatively heterogeneous, typically containing fine-grained mafic inclusions and schlieren (Figure 18), as well as injected granitoid material. They are grey, with a salt-and-pepper texture on weathered surface, medium to coarse grained, and moderately foliated to gneissic. Quartz diorite contains between 5 to 15% quartz, 15 to 25% hornblende > biotite, and minor titanite and magnetite. The unit also includes homogeneous dioritic and quartz-dioritic rocks.

Figure 17 - Granodiorite-tonalite with well-developed gneissic layering; west shore of Kakinagimak Lake just south of Cornell Bay. Station RM07-45-ST21 at UTM 672077 m E, 6120368 m N.

Gabbro and microgabbro (Ga) are exposed as relatively small bodies around McWilliams Lake and north of Gifford Bay. The gabbroic rocks are mottled black and white, fine to coarse grained, and homogeneous to gneissic, with injected granodioritic melt material. Typical samples contain approximately equal proportions of hornblende and plagioclase, with variable amounts of clinopyroxene and biotite. They are likely derived from dykes and minor mafic intrusions, but may include some minor volcanic components.

The gabbroic and dioritic rocks are likely part of the >1.85 Ga plutonic suite as they appear to be closely associated with the granodiorite complex, typically displaying gradational contacts and locally exhibiting well developed foliation and/or gneissosity that is isoclinally folded in places. Cross-cutting relationships between the gabbroic and granodioritic rocks were not observed.

c) ?Missi Group (~1.85 Ga)

A few small units of grey to light pinkish-grey magnetite-garnet bearing quartzofeldspathic rocks are exposed between Bentz Bay of Attitti Lake and the central part of Kakinagimak Lake, and tentatively interpreted as **feldspathic psammite and derived diatexite (Ms)** of the Missi Group. In the Flin Flon area, the group was bracketed between 1847 Ma (Ansdell, 1993) and 1842 Ma (Heaman *et al.*, 1992). Exposures of Missi Group 'meta-arkoses' can be found 10 km to the east and 30 km to the northwest, and are also speculated to exist in the Galbraith Lake area immediately to the west (Ashton *et al.*, 1995). By inference, some of the pelitic and psammopelitic migmatites (units Pp and Psp) may equate with the 1.85 to 1.84 Ga Burntwood Group (Zwanzig, 1990; David *et al.*, 1996), rather than representing synvolcanic detritus.

Two circular units of these quartzofeldspathic rocks can be found west of McWilliams Lake. They are gradational from minor fine- to medium-grained layered quartzofeldspathic gneiss into relatively homogeneous, coarse-grained to pegmatitic, igneous-looking rocks of leucogranodioritic to granitic composition containing ubiquitous garnet (~2%) and magnetite (~2%), with variable amounts of biotite, hornblende, tourmaline, and apatite. Quartz predominates and may locally reach 50% (Figure 19), with K-feldspar and plagioclase each accounting for up to 30% of the rock. Their strongly magnetic nature, the presence of garnet in the predominantly granitic leucosome, and their overall heterogeneous nature with enclaves of layered gneissic rock grading into coarser-grained granitoid, suggest they are diatexites that were possibly derived via partial melting of feldspathic psammites of the Missi Group.

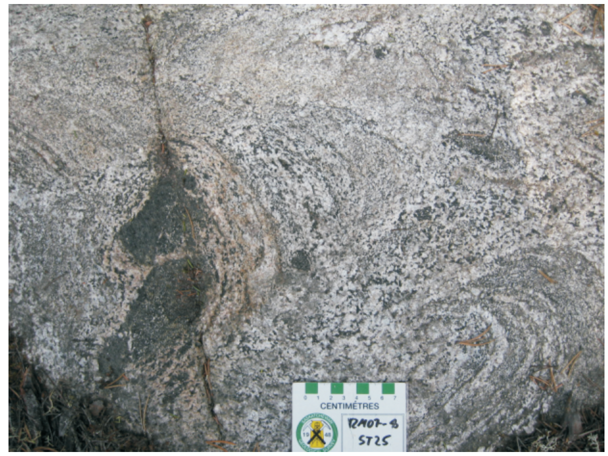

Figure 18 - Heterogeneous quartz diorite gneiss with hornblende-rich quartz dioritic leucosome and mafic inclusions; west of Scott Lake. Station RM07-08-ST25 at UTM 673689 m E, 6114882 m N.

Figure 19 - Magnetite-garnet-quartz–rich diatexite, possibly derived from Missi Group feldspathic psammite; northwest of McWilliams Lake. Station RM07-12-ST02 at UTM 668161 m E, 6112337 m N.

d) Syn- to Post-tectonic Plutons

A relatively extensive suite of white to pink **leucogranodioritic to leucogranitic rocks (Lgd)** underlies large parts of the area west of Kakinagimak Lake and also comprises up to 20% of most gneissic granodiorite outcrops (unit Gd). Leucogranodiorite is medium to coarse grained, homogeneous, and weakly to moderately foliated, grading locally into **granitic pegmatite (unit P)** and gneissic granodiorite (unit Gd). The main mafic mineral is biotite, generally making up less than 5% of most rocks, and magnetite is a common accessory. Based on the overall homogeneous nature of the leucogranodiorite, the generally weakly developed northeast-dipping foliation, and their low colour index, they are interpreted as syntectonic anatectic melt sheets, possibly similar in age to sheared pegmatite dated at 1806 ±2 Ma (Ashton *et al.*, 1992) south of the study area.

Weakly deformed to massive pink granite pegmatite forms concordant sheets and small irregular masses throughout the area (see accompanying map separate). They also occur as numerous conformable transposed dykes about one metre thick. Typical rocks are coarse to very coarse grained and contain several percent biotite, local garnet and rare tourmaline. They may correlate with the *ca.* 1770 Ma Jan Lake Granite Suite (Macdonald and MacQuarrie, 1978).

4. Metamorphism

Based on fieldwork by Ashton *et al.* (1995) and P-T studies by Ashton and Digel (1992) several kilometres to the south, metamorphism in the region reached upper amphibolite facies conditions with estimated pressures of 6.6 to

7.9 kbar and temperatures of 630° to 725°C. A U-Pb zircon age of 1807 +3/-2 Ma (Heaman *et al.*, 1992) obtained from a felsic volcanic rock from the Attitti Lake area, was interpreted as metamorphic and coincides with the age of a syntectonic granitic pegmatite dyke dated at 1806 ±2 Ma (Ashton *et al.*, 1992). This is coeval with the peak of metamorphism in the Hanson Lake and Snow Lake areas, generally constrained between 1804 and 1812 Ma (*e.g.*, Heaman *et al.*, 1994; David *et al.*, 1996; Syme *et al.*, 1998).

In the Kakinagimak Lake area, metamorphism was also in the upper amphibolite facies range. Partial melting is widespread in the granodiorite-tonalite complex (Gd), pelitic to psammopelitic rocks, feldspathic psammites and, to a lesser extent, within the felsic volcanic rocks. The presence of sillimanite in the absence of prograde muscovite within altered felsic volcanic rocks and some of the pelites, implies that conditions exceeded the second sillimanite isograd (*i.e.*, temperatures around 700°C). A stable paragenesis of diopside+hornblende+plagioclase, observed in some of the mafic volcanic and calcic sedimentary rocks, similarly suggests upper amphibolite facies conditions. Widespread sillimanite together with the absence of kyanite, cordierite and orthopyroxene in the area, suggests that pressures were between 5 and 8 kbar, consistent with Ashton and Digel's (1992) findings.

5. Structural Geology

The structural framework for the Pelican Narrows–Attitti Lake area was set out in papers by Lewry *et al.* (1990), Ashton and Leclair (1991), and Ashton *et al.* (1999, 2005) and their findings were largely confirmed in the Kakinagimak Lake area. We identified one extra ductile deformational event (termed D_1) and referred to the earliest deformation described by Ashton *et al.* (2005) as D_0. Early structures (D_0) are defined by compositional layering, attenuation of units, a well-developed biotite and/or hornblende foliation, and gneissic layering. Decimetre-scale isoclinal folds defined by gneissic layering were observed in granodiorite-tonalite gneiss (Gd), quartz-diorite gneiss (Qdi) and mafic volcanic rocks (Mv) and formed during D_1. Map-scale folds of this age have not been recognized.

A subsequent D_2 event produced tight to close minor folds, locally refolding the D_1 isoclines (Figure 20). The axial planes of D_2 folds are generally moderately to steeply northeast dipping with fold axes plunging to the northwest, northeast, and southeast. Axial planar fabrics, most commonly defined by a hornblende foliation and quartz-feldspar flattening, were recognized in several locations. Within the gneissic granodiorite-tonalite unit in the central Kakinagimak Lake area, hornblende and/or biotite foliations, gneissic fabrics and axial planes of D_2 folds are also moderately northeast dipping, and deviate distinctly from the northerly trend of most units (see accompanying map separate). North- to northwest-trending sheets of homogeneous leucogranodiorite in this area are also characterized by a northeast-dipping foliation that is, however, much more weakly developed. This may suggest that these inferred crustal melts were emplaced late during D_2 in an extensional orientation, related to northeast-southwest–directed shortening. Map-scale tight to isoclinal folds southwest of Grindley Lake likely also formed during D_2.

Outcrop- and map-scale D_3 structures include generally close to tight, steeply east-dipping folds with gently north-plunging fold axes (Figure 8). The trace of the F_3 Bentz Bay Antiform (Ashton and Leclair, 1991) extends into the Kakinagimak Lake area, whereas the associated Ewen Lake Synform (Pyke, 1961; Ashton and Leclair, 1991) lies to the west. Both of these structures are map-scale D_3 folds, which are responsible for rotating D_2 outcrop- and map-scale folds in the west. The latest sets of folds in the Pelican Narrows area are open, upright northeast-trending F_4 folds with wavelengths of tens of kilometres (Lewry *et al.*, 1990). In the study area, F_4 is expressed by broad gentle warping of units northeast of Kakinagimak Lake.

Figure 20 - Isoclinal D_1 fold refolded by tight D_3 folds producing fold interference in gneissic granodiorite; west shore of central Kakinagimak Lake. Station RM07-30-ST11 at UTM 670911 m E, 6112104 m N.

6. Ground Spectrometer Data

On August 13, 2007, Sander Geophysics of Ottawa, Ontario began a high-resolution, fixed-wing, airborne, gamma-ray spectrometric and total-field magnetic survey over the northwestern Flin Flon Domain and portions of the Glennie Domain (Figure 1). The survey was funded by the GSC (Natural Resources Canada) as part of the TGI-3 program. It was designed cooperatively by the Saskatchewan Ministry of Energy and Resources and the GSC. The GSC's Radiation Geophysics and Regional Geophysics Sections in Ottawa, under the Northern Resources Development Program, provided contract supervision and quality control to National Gamma Ray Spectrometry (NATGAM) standards.

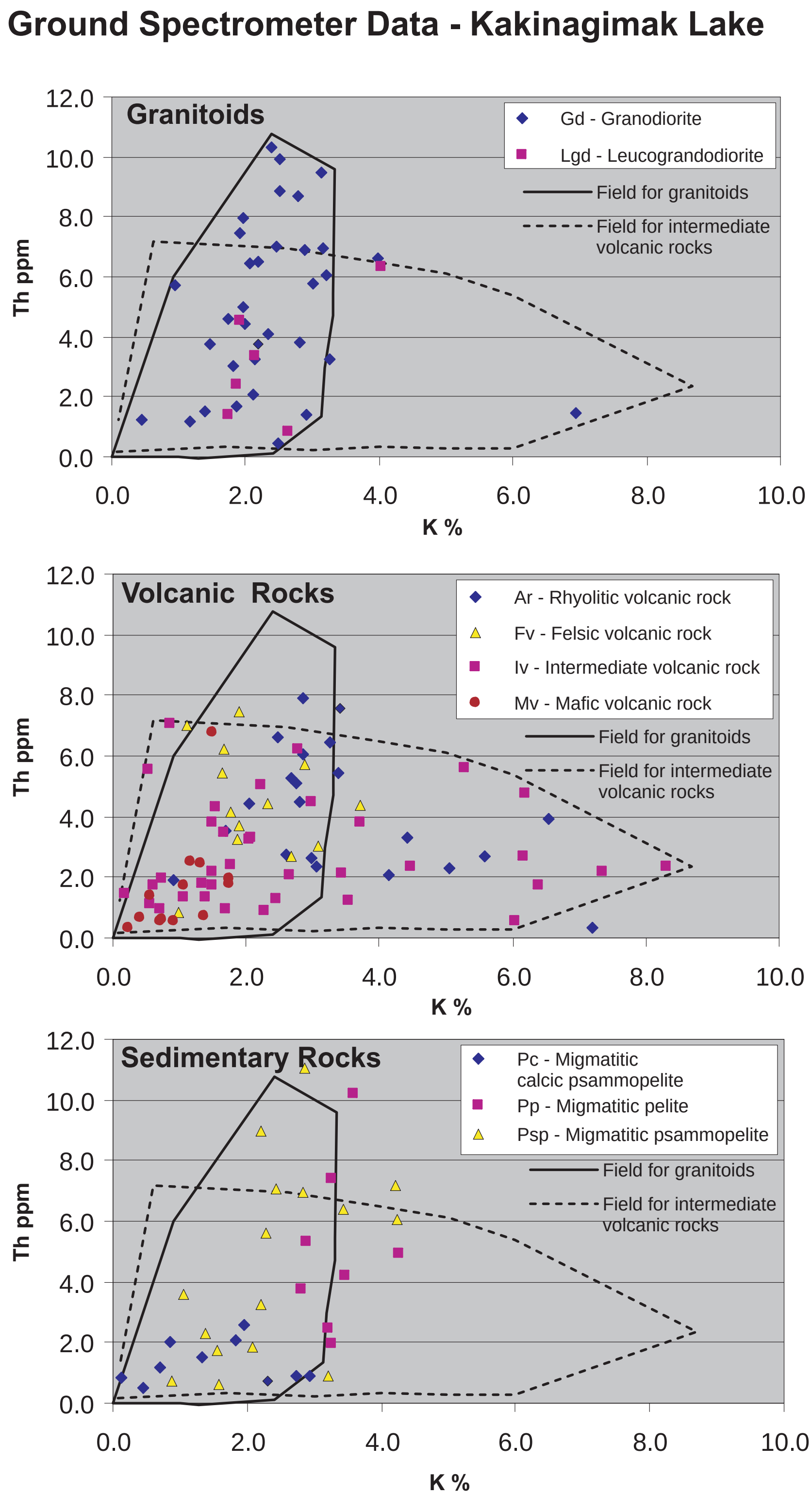

Figure 21 - Plot of ground gamma-ray spectrometric data: average potassium (K) versus equivalent thorium (eTh) concentrations of bedrock for the Kakinagimak Lake area.

The new survey comprises 9889-line kilometres along east- to west-oriented flight lines spaced 400 m apart and north- to south-oriented magnetic control lines spaced 2400 m apart, all flown at a survey altitude of 125 m. Sensors included a large-volume gamma-ray spectrometric detector (NaI, 50 litres downward and 8 litres upward looking) sampling at one-second intervals, and a caesium vapour magnetometer sampling ten times per second. Data acquisition was completed on September 9, 2007. This new data provides improved geophysical and geochemical information that will enhance the understanding of tectonic and metallogenic aspects of the northwestern portion of the Flin Flon Domain, where there is potential to discover additional VMS deposits in close proximity to the Flin Flon smelter.

To aid in the interpretation of the survey, ground gamma-ray spectrometric measurements were collected at 176 sites; magnetic susceptibility measurements were routinely collected at every station. The majority of bedrock lithologies were measured. Average potassium (K) concentrations range from 0.1 to 8%, whereas equivalent thorium (eTh) varies between 0.3 and 13 ppm (Figure 21). The lower K and eTh values came from mafic volcanic rocks (Mv) and calcic psammopelite (Pc), whereas higher values were generally obtained from rhyolitic (Ar) and pelitic rocks (Pp). Some of the intermediate and felsic volcanic rocks display distinctly elevated high K concentrations, possibly a result of alteration.

7. Economic Geology

Mineral exploration in the Kakinagimak Lake area dates back to the 1950s and led to the discovery of the Schotts Lake deposit in 1954. The deposit is located 6 km east of the south end of Kakinagimak Lake (Figure 2). Since its discovery, it has been drilled off to a depth of

266 m and has an indicated mineral inventory of 4.5 M t at 0.41% Cu and 1.26% Zn (Ministry of Energy and Resources Assessment File 63M01-SE-0042R). The last major geological investigation of the deposit began in the early 1990s and culminated with fieldwork carried out by Aur Resources in 1998. The increased exploration activity in the early 1990s was in part brought about by Saskatchewan Geological Survey geologists' findings, which included characterization of the Schotts Lake deposit as a VMS deposit (Pearson, 1986), identification of abundant Fe-Mg metasomatism and sulphide mineralization, and interpretation of the region as an extension of the Cu-Zn-Au-rich Flin Flon Domain (Ashton and Leclair, 1991). BHP Minerals Canada Ltd. staked claim S-99712 in the Gifford Bay area of Kakinagimak Lake, and followed up with geological mapping, sampling, geophysical surveys, and drilling between 1992 and 1994. As a result, they intersected semi-massive sulphide mineralization dominated by pyrite and pyrrhotite, with minor amounts of chalcopyrite and sphalerite. One of the better intersections was drill hole GC-02, which intersected 0.38% Cu and 1.32% Zn between 132.5 and 133.5 m within a sequence of "mafic brecciated gneisses". Elevated precious metal concentrations in narrow intercalated layers of cherty chemical sedimentary rocks were also reported (Ministry of Energy and Resources Assessment Files 63M01-0037 and -0040). According to industry assessment files, there are two alteration zones associated with the massive sulphide lens.

The surface expression of the gossan and surrounding host rocks to the Schotts Lake deposit was investigated during a half-day excursion. Based on that work and the compilation of earlier government and industry maps and reports (Pearson, 1986; Ministry of Energy and Resources Assessment File 63M01-SE-0042R), we conclude that the Schotts Lake deposit is a VMS deposit, situated at the boundary between a mafic volcanic and a felsic volcanic succession close to the core of a northeast-plunging F_3 synform. It has two associated alteration zones: a sillimanite–quartz–?K-feldspar–rich zone located structurally above the massive sulphide lens and an overlying, more distal anthophyllite-garnet-biotite–rich zone. They may represent the original sericitic and chloritic alteration zones, documenting enrichment of K and Fe-Mg, respectively, and an overall depletion of Na and Ca. These types of alteration zones can be situated below and locally above VMS deposits (*e.g.*, Lydon, 1988).

In the remainder of the Kakinagimak Lake area, minor amounts of disseminated pyrrhotite and pyrite are common within felsic to intermediate volcanic rocks in the Gifford Bay and Keep Lake areas. They are closely associated with garnet-anthophyllite rocks (Figure 22), a common expression of Fe-Mg metasomatism typically associated with syngenetic alteration zones surrounding VMS deposits in amphibolite-facies volcanic terranes (*e.g.*, Froese, 1969; Lydon, 1988 and refs. therein; Ashton and Leclair, 1991 and refs. therein).

Relative abundance of potentially rhyolitic volcanic rocks in the central part of the Gifford Bay area in association with widespread evidence of Fe-Mg alteration (Figure 22), K-alteration (Figure 8), and silicification, suggests that this area may have been a hydrothermally active felsic volcanic centre. Based on the low ratio of mafic to felsic-intermediate volcanic rocks, the area has more similarities with the West Amisk (Reilly *et al.*, 1995) and the Hanson Lake arc assemblages (Maxeiner *et al.*, 1999b), than the Flin Flon arc assemblage (*e.g.*, Syme *et al.*, 1998).

Figure 22 - Garnet-anthophyllite alteration in felsic volcanic rocks; east central Keep Lake. Station RM07-48-ST19 at UTM 676265 m E, 6111989 m N.

8. Conclusions

Fieldwork in the Kakinagimak Lake area has led to the following conclusions:

1) As previously suggested (*e.g.*, Ashton and Leclair, 1991), the volcanic succession likely represents an extension of various components of the Amisk Collage. Felsic to intermediate volcanic rocks predominate over their mafic counterparts. Disseminated sulphides occur locally and signs of Fe-Mg metasomatism (garnet-anthophyllite alteration) are abundant.
2) Calcic sedimentary rocks that are closely associated with the volcanic rocks might represent a succession similar to the synvolcanic Welsh Lake assemblage; a thick succession of graphitic pelite and psammopelite may represent outliers of the younger Burntwood Group. Diatexitic feldspathic psammite possibly belongs to the Missi Group.
3) The Kakinagimak Lake area has been metamorphosed under upper amphibolite facies conditions and complexly folded during five ductile deformational events. It is dominated by

granodiorite and granodiorite gneiss, with lesser amounts of sedimentary and volcanic rocks.

4) The Keep Lake area is dominated by garnetiferous intermediate to felsic volcanic rocks, exhibits garnet-anthophyllite alteration, and local sulphide occurrences, and thus represents an interesting exploration target that lies on strike with the Schotts Lake deposit.
5) Based on the low ratio of mafic to felsic-intermediate volcanic rocks, the volcanic succession hosting the Schotts Lake VMS deposit has more similarities with the West Amisk (Reilly *et al.*, 1995) and the Hanson Lake arc assemblages (Maxeiner *et al.*, 1999b), than the Flin Flon arc assemblage (*e.g.*, Syme *et al.*, 1998).

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