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Geology and deformation history around the Ferguson Lake Ni-Cu-PGE deposit, Yathkyed greenstone belt, western Churchill Province, Nunavut

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DESCRIPTIVE NOTES

INTRODUCTION

During the 2003 Field season, 1:20 000 scale bedrock mapping was carried out in the Ferguson Lake area, about 200 km west of Rankin Inlet, in the Kivalliq region of Nunavut. The project was initiated to provide a better understanding of the geology and deformation history of the Ferguson Lake area and to put the known Ni-Cu-PGE deposit into a regional context. The presence of a Ni-Cu deposit at Ferguson Lake was identified by Inco in the early 1950's and a resource of about 7 million tonnes (0.87% Cu and 0.75% Ni) of ore was defined. Since acquiring the property in 1998, Starfield Resources Inc. has completed 42 000 metres of diamond drilling and established an inferred resource of 54.8 million tonnes at a 1% Ni-Cu cutoff (Starfield Resources Inc. News Release June 6, 2003).

Previous geological mapping was conducted by Leggett et al. (1975) around the Ferguson Lake camp (1:30 000), by Bell (1971) in the eastern part of the Ferguson Lake map sheet (NTS 65I; 1:100 000) whereas Eade (1986) mapped the Tulemalu Lake-Yathkyed Lake area (NTS 65J, I; 1:125 000). The study area joins to the south with previous mapping along the Yathkyed greenstone belt (Relf et al. 1997, 1998, 1999; 1:50 000 scale). The study area covers approximately 30 square kilometres around Ferguson Lake (Figs. 1 and 2) and supplements previous internal company maps of the area (e.g. Henderson 1999, Gal 2001).

REGIONAL GEOLOGICAL SETTING

The map area lies within the Hearne Domain of the western Churchill Province, and constitutes the northernmost extension of the Yathkyed greenstone belt (Fig. 1). It is underlain by strongly foliated and lineated, to locally gneissic Archean supracrustal and intrusive rocks metamorphosed to upper amphibolite facies, as well as variably deformed Proterozoic plutons and dykes. Gneissic layering, in large part defined by injected sheets and veins of monzogranite, is most intense in the central part of the map area, and protoliths can only be determined in the north and south. The Ferguson Lake massive sulphide body outcrops along an east-west band across the central part of the map area (Figs. 1 and 2) and is hosted by a hornblendite layer within hornblende diorite.

GEOLOGY OF THE FERGUSON LAKE AREA

Mixed volcanic rocks (unit 1)

Mixed volcanic rocks include bedded tuffs, massive flows and locally pillowed flows. This unit displays cm-scale layers of fine-grained hornblende, chlorite ± garnet-bearing rocks metamorphosed to amphibolite facies grade. The mafic volcanic rocks commonly show thin compositional layering interpreted to represent highly strained and transposed bedding. Amygdaloidal basalt with calcite filled amygdules is locally preserved. Rare remnants of pillow selvages have been identified, although no unambiguous younging directions could be determined. The mafic layers are locally interbedded with felsic volcaniclastic intervals (Fig. 3) that are strongly deformed, exhibit a penetrative foliation or lineation and are locally mylonitized. These lithologies are commonly intruded by monzogranite sheets and veins that are also mylonitized.

Finely banded magnetite-bearing siliceous units, locally associated with the intermediate to felsic volcanic rocks (unit 1), but also observed interbedded with sedimentary rocks (unit 2), were recognized and inferred to represent iron formations. These are typically garnet-rich, range from several centimetres to a few metres thick, and have a gossanous surface expression.

Psammite (unit 2)

Rocks of unambiguous sedimentary origin outcrop in the southern portion of the map area and are continuous along strike with psammitic units mapped by Relf et. al. (1999). The rocks are thickly bedded (cm to dm scale) and are partly migmatized. Although bedding can be locally observed, no convincing younging directions could be determined. Where migmatized, the psammite contains up to 40% quartzo-feldspathic pods, along with aluminosilicate phases such as biotite, cordierite and locally garnet (Fig. 4). Garnet porphyroblasts are typically replaced by cordierite.

Hornblende biotite Gneissic tonalite (unit 3)

Hornblende- and biotite-bearing gneissic tonalite is locally interlayered with hornblende diorite. Contacts with the psammitic unit (unit 2) everywhere appears gradational, and this unit is interpreted as a migmatized and metamorphosed psammite having interlayered mafic volcanic horizons. The gneissic tonalite is distinguished from the gneissic biotite tonalite (unit 7) by the presence of hornblende.

Mixed unit (unit 4)

This has been informally termed the "mixed unit" as it contains numerous interlayered lithologies such as hornblende diorite, hornblende biotite tonalite, hornblendite and abundant monzogranitic to tonalitic sheets and veins (Fig. 5). The relative proportion of each unit is variable, and locally monzogranite sheets comprise over 50% of the exposures.

Hornblende diorite within the "mixed unit" is fine-grained, generally gneissic to strongly lineated, and contains up to 50% plagioclase with less common biotite and garnet. Similarly, the hornblende biotite tonalite is gneissic to foliated, and the proportion of hornblende versus biotite is variable. Concentration of biotite within specific layers is locally accompanied by the appearance of garnet and cordierite. The monzogranite sheets are generally a few centimetres to several metres wide and intrude all of the units described above. Their composition varies from monzogranite to less abundant tonalite. They are coarse-grained to pegmatitic and locally contain garnet and muscovite. These sheets have generally been intruded parallel to the stratigraphy and define the main gneissic fabric. Some pegmatitic monzogranite intrusions cut the main gneissosity (Sgn) and are interpreted as younger intrusive phases.

Hornblendite (Fig. 6) occurs as a layer (interpreted as a sill) within hornblende diorite, and can be up to 75 metres thick. The hornblendite is composed of medium- to coarse-grained hornblende with <10% plagioclase, and small amounts of biotite and/or chlorite. The hornblendite may appear much less deformed than the surrounding rocks, but hornblende grains are commonly preferentially aligned yielding a spaced and irregular foliation also defined by "schlieren" of mica (xenlith?: Fig. 6). This foliation (interpreted as S1) is transposed and folded. Hornblendite is always observed in association with hornblende diorite and invariably hosts the massive sulphide mineralization.

The massive sulphide interval is invariably hosted by the hornblendite (Fig. 7). It consists of 80-90% massive to semi-massive pyrrhotite, with lesser amounts of magnetite and chalcopyrite. Pentlandite is common as an exsolution phase in pyrrhotite and rare marcasite (Fe,Ni) (Se,S) and gersdorffite (Co-sulphides) have been identified (Harris 1999). Clasts of the host rock are common throughout the massive sulphide interval and consist of hornblendite, hornblende diorite and less common garnet feldspar, biotite, chlorite and quartz grains. The clasts range in size from a few millimetres to several centimetres, are subangular and locally aligned parallel to the main fabric. The greatest thickness (45 m) of massive sulphide has been intersected in the central part of the West Zone (Starfield Resources Inc., DDH-FL00-84). In addition, a poorly defined, low-sulphide, PGE-rich interval has been identified structurally below the massive sulphide horizon within the hornblende-biotite tonalite.

Collectively all rocks of unit 4 are strongly deformed and intruded by monzogranite sheets. The hornblendite hosting the massive sulfide interval is spatially associated with hornblende diorite and hornblende-biotite tonalite and exhibits gradational contacts with both lithologies. Unit 4 has a fairly sharp contact with Unit 9, which forms the structural hangingwall to the mineralization. Based on the metal association and the nature of the contacts, the protolith is interpreted as a multiphase or differentiated intrusive body.

Hornblende diorite (unit 5)

The hornblende diorite (zoisetite and garnet) is strongly lineated and weakly gneissic (Fig. 8) and is locally interlayered with fine-grained tonalitic rocks that contain quartz, biotite ± garnet ± cordierite. It is interpreted an amphibolitized intrusive body, but may possibly represent amphibolitized mafic volcanic rocks interlayered with less abundant, strongly migmatized psammite.

Quartz gabbro (unit 6)

The quartz gabbro is a distinctive unit composed mainly of plagioclase and hornblende (+80% plagioclase) and lesser amounts of quartz, garnet and epidote. The rock is variably strained, ranging from coarse undeformed and rounded plagioclase floating in a matrix of hornblende (Fig. 9), to highly foliated and lineated, fine-grained plagioclase with hornblende aligned parallel to the main foliation/lineation. Where highly strained, the quartz-gabbro can be mistaken for medium-grained hornblende diorite (unit 5). Disseminated pyrrhotite ±chalcopyrite mineralization is locally present in this unit.

Gneissic biotite tonalite (unit 7)

Biotite tonalite is gneissic to foliated (Fig. 10) and generally leucocratic, depending on the amount of biotite (up to 25%). It commonly contains decimetre- to metre-scale inclusions of hornblende diorite which are foliated to gneissic and are flattened parallel to the main fabric. The gneissic layering is centimetre- to decimetre-scale and commonly accentuated by coarse-grained to pegmatitic monzogranite sheets up to 50 metres in thickness. These sheets were intruded parallel to the gneissosity (forming an injection gneiss) and commonly outline major folds. In the south of the map area, monzogranite sheets locally contain accessory minerals such as muscovite and garnet and, on this basis, are interpreted as products of partial melting of aluminous crustal protoliths. This unit is folded along with the supracrustal rocks, suggesting that it was emplaced relatively early in the geological history of the area.

Granodiorite (unit 8)

This unit includes all rocks with an overall granodiorite composition. It varies widely in composition from tonalite through predominant granodiorite to less common monzogranite, all of which are characterized by abundant injected monzogranite sheets. Hence, some rocks are likely tonalite, with a higher than normal proportion of feldspars resulting from disaggregation and sheeting of the abundant monzogranite sheets and veins. This unit also includes younger pegmatitic granite (e.g. south of the West Zone).

Gneissic "augen" monzogranite (unit 9)

The "augen" monzogranite is readily distinguished in the field and in drill core as it contains centimetre- to decimetre-scale potassium-feldspar porphyroclasts (Fig. 11). It is commonly interlayered with bands of melanocratic, biotite-rich tonalite and/or hornblende diorite. The "augen" monzogranite is highly strained, being gneissic to strongly foliated (porphyroclastic/mylonite) with feldspar porphyroclasts that acted as rigid grains around which the quartz was strongly flattened to form quartz ribbons. The northern contact of the "augen" monzogranite with rocks of unit 1 is defined by a high strain zone within which the protolith is uncertain. This highly strained unit has been previously termed a "leucititе" by Henderson (1999) and consists of feldspar porphyroclasts (clasts?) within a mica-rich, fine-grained matrix. The contact with the adjacent "mixed unit" (unit 4) is sharp, locally defined by a 10-20 cm wide biotite-rich schistose zone. The "augen" monzogranite has a sharp contact with the structurally underlying "mixed unit" suggesting it intrudes the latter.

Late gabbroic intrusions

Fine- to medium-grained gabbro occurs as dykes, sills and irregular bodies throughout the region. The gabbro is generally massive, but commonly exhibits foliated margins, and discrete shear zones locally occur within the intrusions. The gabbroic intrusions can be up to 50 metres wide and generally cut the regional gneissosity (Sgn) at a low angle. The dykes vary in orientation, but are predominantly oriented east-west and north-south. They are generally weakly magnetic, but some were strongly magnetic, particularly in the southwestern corner of the map area. Some dykes contain cm-scale zoned plagioclase phenocrysts (Fig. 12). These gabbros are interpreted to be part of the Tulemalu-MacQuoid dyke swarm dated at ca. 2.19 (U/Pb baddeleyite; Tella et al. 1997).

Alkaline intrusive rocks (unit 10)

Alkaline intrusions, include syenite plutons, monzonite and quartz-syenite veins and dykes, and abundant lamprophyre dykes. Ovoid syenite plutons range up to 5 kilometres in diameter, and typically contain abundant equant potassium feldspar phenocrysts with subordinate hornblende, biotite, pyroxene and magnetite phenocrysts (Fig. 13). Multiple intrusive phases were observed, varying from fine- to coarse-grained, and from alkali-feldspar dominated to plagioclase- and/or hornblende-rich. A mafic phase of one of the plutons exposed in the northern part of the map area (Fig. 1) appears to be composed mainly of hornblende (after pyroxene?) and clinopyroxene. This mafic intrusive phase of the syenite is cut by a 7 metre wide gabbro dyke with chilled and locally foliated margins. This syenite is locally foliated, the foliation defined by aligned feldspar phenocrysts (Fig. 13) and less commonly by hornblende or biotite. A mineral lineation defined by hornblende was also observed at one locality. The syenites are correlated with the Martell plutonic suite (ca. 1.83; Sandeman et al. 2000 and references therein).

Lamprophyre dykes, also abundant in the map area, range from phlogopite-rich mafic to phlogopite poor felsic varieties and typically consist of a fine-grained feldspathic matrix with phlogopite, hornblende and clinopyroxene phenocrysts (Fig. 14). The dykes are somewhat randomly oriented, but most commonly trend northeast. They vary from centimetre- to metre-scale; the largest dyke mapped having a thickness of about 15 metres. Where the matrix was coarse enough to identify individual grains, the dykes were classified as phlogopite syenite, some of which contain millimetre-scale spheroidal quartz grains. These syenite dykes cut the regional foliation and were locally observed to cut mafic lamprophyre dykes. Felsic varieties are likely cogenetic with the coarse-grained syenite plutons that outcrop in the area, whereas mafic lamprophyre dykes are inferred to correlate with the Christopher Island Formation of the Baker Lake Basin (ca. 1.83 Ga: Tella et al., 1985; Roddick and Miller, 1994; MacCrae et al., 1996).

Quartz-feldspar porphyry dykes (unit 11)

A number of quartz-feldspar porphyry dykes (Fig. 14) were observed on surface and in drill core. These fine- to medium-grained dykes are generally massive but are locally foliated along their margins and have been observed to cut the massive sulphide interval.

STRUCTURAL ELEMENTS

Gneissosity (Sgn)

The earliest fabric recognized to overprint bedding is the gneissosity (Sgn: Fig. 15), which is developed in most of the rocks of the map area. Whether Sgn developed during the early stages of G1, or represents a pre-G1 fabric is uncertain, but we infer that it likely developed prior to G1, as the Sgn is clearly folded by F1 folds. Typically, most of the Sgn resulted from the flattening and transposition of injected monzogranite sheets and, hence, these gneissic rocks are injection and not metamorphic gneisses. However, in the central part of the map area, where the rocks are most intensely deformed, rocks of the "mixed unit" (unit 4) are characterized by metamorphic gneissic layering (Sgn distinct from injection gneissosity). This gneissic layering is generally thinner and less regular than that derived by the injection of monzogranite sheets. Nevertheless, both types of gneissosity are parallel.

G1 structures

F1 folding

An early generation of folds (F1) has been noted at a number of localities (Fig. 16), particularly where the Sgn is subhorizontal. Where the Sgn is moderate to steep, F1 folds are difficult to distinguish from later F2 folds. F1 folds are recumbent and tight to isoclinal, with axial planes that strike approximately east-west and dip shallowly to the north (present-day coordinates: Fig. 16). Owing to the limited number of F1 folds observed, the geometry of the F1 fold belt prior to G2 is uncertain. We suggest, however, that F1 folds were likely shallowly west-plunging with subhorizontal axial surfaces prior to G2.

S1 foliation

The S1 foliation, defined by aligned biotite and/or hornblende and flattened, elongate quartz and plagioclase grains, is almost always parallel to the Sgn, but is rarely observed to be axial planar to the recumbent F1 folds. S1is folded by F2 folds or transposed into the S2 foliation (Fig. 17), and, on a stereonet projection, exhibits a pattern of pole to plane distribution comparable to the Sgn (Fig. 15). The S1 foliation is therefore interpreted as a composite bedding/Sgn/S1 fabric.

L1 structural elements

Stretching (L1s) and mineral (L1m) lineations are well developed in the central-eastern part of the map area within a region characterized by a shallowly plunging, regional-scale fold hinge. The L1m defined by hornblende is best developed in hornblende diorite (unit 5) and quartz gabbro (unit 6), where it plunges both to the east and west (Fig. 18). The L1s is best developed in gneissic tonalite (units 4 and 7) and is defined by extended quartz, plagioclase and melt phase pods (Fig. 16). L1s and L1m are sub-parallel and are themselves sub-parallel to F2 fold axes (Fig. 18). The lineations are interpreted to have developed during G1 and were subsequently rotated into colinearity with the F2 fold axes. Competent layers such as hornblendite are subsequently boudinaged parallel to the subhorizontal lineation (Fig. 19). These structures indicate an important component of extension during G1.

G2 structures

F2 folds

Stereonet data demonstrates that Sgn is folded about F2, defining shallowly southwest plunging folds (Fig. 15). However, macroscopic folds are noted to plunge both to the southwest and northeast (Fig. 20). F2 folds are tight, and shallowly to moderately northeast- and southwest-plunging, with axial surfaces generally steeply dipping to the north (Fig. 21). The doubly plunging nature of the F2 folds is interpreted to reflect the reorientation of F1 folds, and not later cross folding. Mesoscopic F2 fold traces were determined from S2 and Sgn overprinting relationships (clockwise or counterclockwise), gneissic fold asymmetry (Z, S and M folds) and through tracing lithological contacts. The massive sulphide interval is demonstrably folded by F2 folds (Fig. 22).

S2 fabric

S2 foliations, typically defined by aligned biotite and hornblende, are not widely developed. Where observed they most commonly parallel Sgn and S1 foliations and therefore represent a composite S1/S2 fabric. S2 is also observed to have developed at a low angle to G1 fabrics in the hinge zones of F2 folds (Fig. 23). At locations where the rocks are foliated but not gneissic (e.g., quartz gabbro: unit 6), it is difficult to assign a generation to the foliation (i.e., S1 versus S2).

Post-G2 structures

F3 folding

A third generation of folds (Henderson 1999; Gal 2001) display east-west oriented enveloping surfaces and are steeply plunging to the north or south (dependent on the dip of the stratigraphy prior to G3). These low-amplitude folds are open and display metre-scale wavelengths. The F3 event does not significantly affect the geometry of the rocks exposed in the area.

Discrete shear zones

Cm- to dm-scale ductile shear zones identified in the map area are best developed in the schistose chloritic selvages of north-south oriented gabbro dykes and as north-northeast trending zones in gabbroic intrusions. Shear bands in the chloritic zones suggest sinistral displacement. Shear zones having a dextral sense of displacement are less common, are similar to the sinistral shear zones, but typically trend east-northeast. Collectively, these discrete ductile shear zones likely represent a conjugate set indicating northwest-southeast compression (sigma 1).

Brittle faulting

Major northwest-trending dextral faults and east-west-trending faults with unknown sense of displacement (Figs. 1 and 2), are characterized by wide (up to 50 m) cataclastic zones and have been identified in the field and in drill core (e.g. Starfield Resources Inc., DDH-FL00-31). The cataclasites exhibit strong feldpathic alteration with chlorite, epidote, and less common carbonate alteration. Some faults are inferred on the basis of prominent aerial photograph lineaments and by inferred stratigraphic discontinuity.

STRUCTURAL MODEL AND CORRELATION WITH REGIONAL-SCALE DEFORMATION

The deformation history of a number of discrete areas in the vicinity of Ferguson Lake in the Hearne Domain have been previously documented by Relf et al. (1997, 1998 and 1999) in the Yathkyed greenstone belt; by Ryan et al. (1999) in the Gibson Lake-Cross Bay-MacQuoid Lake area; and by Bell (1971) and Eade (1986) in the vicinity of Henik and Ferguson Lakes. Although it is challenging to make regional scale correlations based on the characteristics and orientations of fabrics and folds, we attempt, nevertheless, to correlate the deformational features observed in the Ferguson Lake study area with those documented by Eade (1986) and by Relf and collaborators (1997, 1998, 1999).

The G1 tectonothermal event produced regional-scale, amphibolite grade metamorphism and F1 folding with the development of an associated S1 foliation and L1s and L1m lineations. The gneissic layering (Sgn) may have developed during an early stage of G1, but it more likely developed pre-G1. F1 folds are recumbent with axial planes dipping shallowly to the north, and are interpreted to have developed as a result of north-over-south thrusting with an east-west maximum extension component coaxial with L1 lineations. Relf et al. (1998) documented an early southeast-directed reverse thrust event along the Tyrrell shear zone (a northeast-trending Archean structure in the Yathkyed greenstone belt) possibly contemporaneous with a bedding-parallel foliation. This deformation is interpreted to have resulted from regional shortening and has been dated at ca. 2.62 Ga (K. MacLachlan, personal communication, 1998). G1 deformation in the Ferguson Lake area is possibly contrative with the early thrusting documented by Relf et al. (1998).

G2 produced large-scale, doubly plunging folds with northeast striking axial planes, likely developed as a result of northwest-southeast oriented compression. The map-scale fold pattern is complex, plunging both to the northeast and southwest, and inferred to reflect the interference of F1 folds. The block diagrams in Figure 24 portray the post-G2 geometry of the region (present-day configuration), but excludes the effects of subsequent F3 folding and ductile-brittle faulting. F2 folding in the Yathkyed belt, exposed immediately to the south (Relf et al. 1997, 1998, 1999) shares similar characteristics and kinematics with G2 in the Ferguson Lake area. To the south, S2 foliation development and peak metamorphism have been dated at ca. 2.55-2.50 Ga (MacLachlan, personal communication, 1998). The F2 folding at Ferguson Lake is correlative with the first regional-scale folding event of Eade (1986).

G3 produced open, low-amplitude, nearly upright folds resulting from east-west compression. Although they were noted throughout the map area, these folds did not affect the overall geometry and disposition of the rocks. F2 folds described by Eade (1986) as broad open flexures are inferred to correlate with F3 folds at Ferguson Lake although the orientations of the fold axes are distinct. This difference may be explained by variation in the orientation of preexisting structures. F3 folds with large wavelength are also documented in the Yathkyed greenstone belt (Relf et al. 1999) but no timing constraints are currently available.

East-northeast and north-northeast oriented discrete shear zones define a conjugate set and indicate a maximum compression component oriented approximately northwest-southeast. This shearing is late in the geological history, occurring after the intrusion of the gabbro dykes correlated with the Tulemalu swarm. In the Yathkyed belt, normal dextral shearing along the Tyrrell shear zone was constrained to have occurred at ca. 1.82 Ga (K. MacLachlan, personal communication, 1998). The development of the discrete shear zones in the Ferguson Lake area may be correlative with this Proterozoic event.

Brittle faults transect all of the map units. Northwest trending faults commonly show an apparent dextral displacement, whereas east-west trending faults have an unknown sense of displacement. Northwest-trending brittle faults having a dextral sense of displacement were documented in the Yathkyed belt and environs by Relf et al. (1999) and Eade (1986). The latter author also documented a number of east-west faults characterized by south-side-down movement. One of these faults is likely a continuation of the east-west fault mapped in this investigation (labeled "Fc" on Fig. 2).

IMPLICATIONS FOR TIMING OF MINERALIZATION

The Ferguson Lake Ni-Cu-PGE ore zone is hosted by hornblendite. The hornblendite shows gradational contacts with hornblende diorite and hornblende-biotite tonalite. As there are no distinct breaks within this sequence the hornblendite is interpreted to be part of a multiphase or differentiated mafic intrusion that collectively forms unit 4. The massive sulfide mineralization is spatially associated with the hornblendite interval and, likely represents an accumulation of magmatic sulfides. The lithologies that host the massive sulphide interval are located on the north-dipping limb of a regional F2 fold. The hornblendite records an early foliation (S1) and both the massive sulphide and hornblendite intervals are folded by F2 and F3 folds (Figs. 22 and 24). This indicates that the hornblendite and the contained massive sulphide have seen all of the deformation events recognized in the Ferguson Lake area. Because the G1 and G2 events are tentatively correlated with the 2.62 Ga thrusting and 2.55 Ga folding and metamorphism recorded in the Yathkyed greenstone belt (Relf et al. 1999 and references therein), and assuming that the interpretation of unit 4 (host to mineralization) being intrusive in origin are correct, the mineralization is inferred to have formed from an Archean multiphase or differentiated mafic intrusion that was intruded into a supracrustal sequence.

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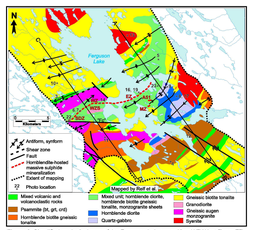
Digital data preparation and presentation by C. Gilbert and J. Taylor, Canada-Nunavut Geoscience Office (C-NGO)



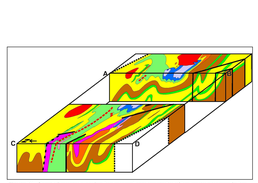
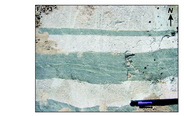
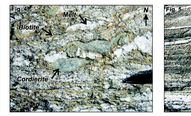
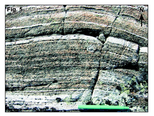


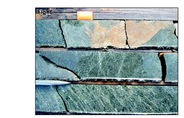
Figure 24. Block diagrams showing the present-day geometry of the rocks exposed in the Ferguson Lake area. Locations of cross-sections are shown in Figure 2.

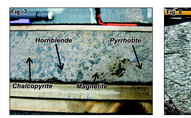
Figure 2. Simplified geological map of the Ferguson Lake area. Key: WZ-West Zone; EZ-east Zone; WZS-West Zone South; AS1-Anomalie S1; SDZ-South Discovery Zone; MZ-M Zone. Locations of photographs discussed in the text are indicated on the map.

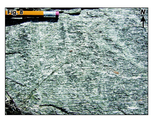


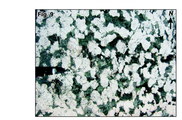


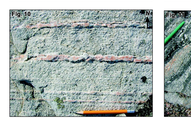


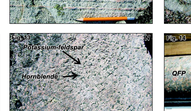


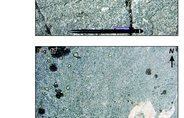


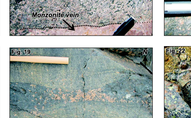


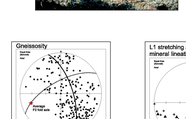


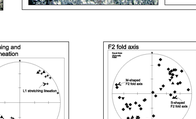


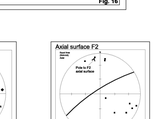


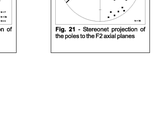












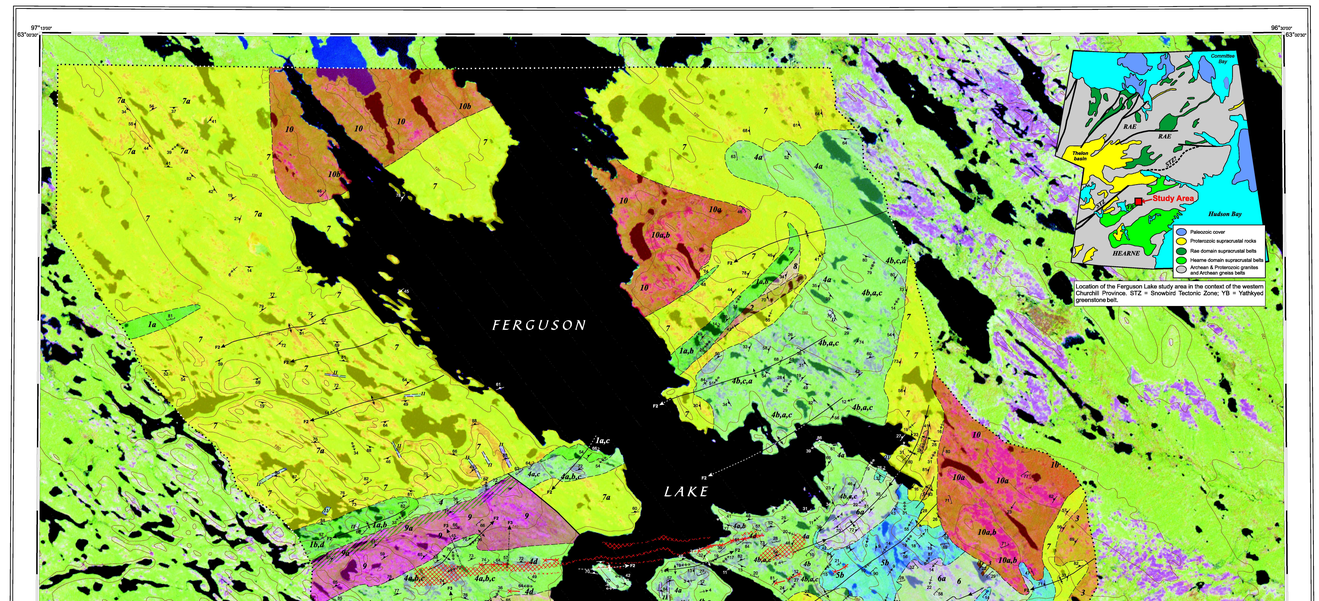


Fig. 1

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