GEOLOGY OF THE PROTEROZOIC IRON OXIDE-HOSTED, NICO COBALT-GOLD-BISMUTH, AND SUE-DIANNE COPPER-SILVER DEPOSITS, SOUTHERN GREAT BEAR MAGMATIC ZONE, NORTHWEST TERRITORIES, CANADA

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Abstract - The NICO cobalt-gold-bismuth and Sue-Dianne copper-silver deposits of the Mazenod Lake area, Northwest Territories, are currently being drill-delineated by Fortune Minerals Limited. They are the only known significant Canadian examples of the Proterozoic iron oxide-hosted polymetallic class, more commonly referred to as hydrothermal iron oxide copper-gold deposits. NICO and Sue-Dianne are located in the southern part of the Great Bear magmatic zone, the central tectonic subdivision of the Bear Structural Province. It is a post-collisional plutonic terrane with related continental volcanic rocks dating from 1867 Ma and culminating with the emplacement of A-type rapikivi granite plutons at approximately 1856 Ma. Iron oxide occurrences are widely distributed within the Great Bear magmatic zone, ranging from Salobo-type magnetite-rich schists and ironstones in receptive basement rocks to Kiruna-type magnetite-apatite-rich veins and Olympic Dam-type sulphidised magnetite-hematite breccias in overlying volcanic rocks. NICO is hosted in iron- and potassium-altered, brecciated basement sedimentary rocks at and beneath the volcanic unconformity, showing similarities to the Salobo-type. The host "black rock" amphibole-magnetite-biotite schists and ironstones are capped by potassium feldspar-magnetite "red rock" felsite. In contrast, Sue-Dianne shows the essential characteristics of Olympic Dam-type ores, with mineralisation hosted within a well-zoned diatreme breccia complex crosscutting a rotated ash flow tuff succession above the unconformity. At both NICO and Sue-Dianne, ongoing detailed paragenetic studies demonstrate that early, reduced, high-temperature mineral assemblages are overprinted by late, oxidative, low-temperature assemblages. These together with stratigraphic relationships, indicate fluid mixing at shallow crustal levels was important in deposit formation. Proximity of the NICO and Sue-Dianne deposits to subvolcanic porphyries, rapakivi granite and various other phases of the Marian River Batholith, together with geochronology and mineralogy studies, suggest they are all genetically related. The occurrence of diverse iron oxide deposit types within the Great Bear magmatic zone, makes this region favourable for exploration and for the study of the Proterozoic iron oxide class as a whole.

Introduction

The NICO cobalt-gold-bismuth and the Sue-Dianne copper-silver deposits are located in the southern part of the Great Bear magmatic zone, the central tectonic subdivision of the Proterozoic Bear Structural Province (Fig. 1). They occur in the Mazenod Lake area, approximately 160 km northwest of the City of Yellowknife, Northwest Territories (Fig. 2). NICO, the largest known deposit in the area, is owned by a joint venture between Fortune Minerals Limited (80%) and Maple Leaf Terminals Ltd. (20%). The Sue-Dianne mining lease is 20 km north of NICO and is a joint venture between Fortune (53%) and Noranda Mining and Exploration Inc. (47%). The current mineral resources of the NICO and Sue-Dianne deposits are presented in Table 1, prepared in accordance with proposed National Instrument 43-101 and

the guidelines established by the CIM Ad Hoc Committee Report (The Toronto Stock Exchange and Ontario Securities Commission, 1999; CIM, 1996; Thalenhorst, 2000; Mumin and Tufts, 1999). The NICO resources are currently being re-evaluated following a 34-hole drill program completed in August, 2000.

NICO and Sue-Dianne are the only known significant Canadian examples of the Proterozoic iron oxide-hosted polymetallic class, more commonly referred to as Proterozoic iron oxide copper-gold deposits because of the dominance of these metals. Worldwide, the type locality for this class is the "giant" Olympic Dam deposit in South Australia, which contains an inferred resource of 2 Gt, grading 1.6% Cu, 0.6 g/t Au, 3.5 g/t Ag, and 0.6 kg/t uranium oxide (Reeve *et al.*, 1990). Consequently, they are
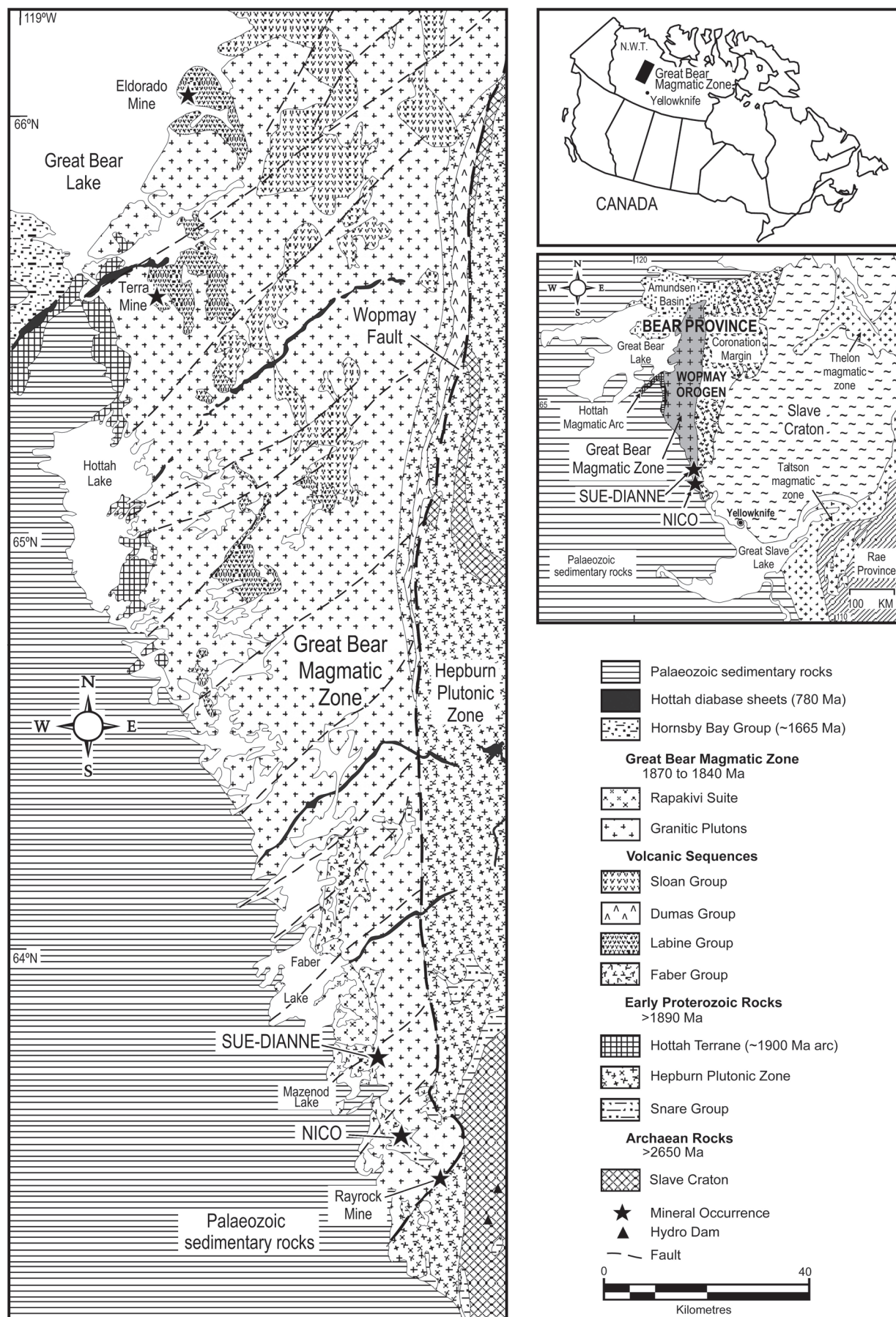
Figure 1: The location and regional geology of the Great Bear Magmatic Zone (modified from Gandhi *et al.,* 1996).

Table 1: Measured and indicated in-pit mineral resources for the NICO and Sue-Dianne deposits as of April, 2000. The figures quoted represent tonnages and grades for different cut-off grades, as quoted for Sue-Dianne. Those for NICO represent a range of options at different cobalt prices, between a low grade 0.06% Co cut-off to a high grade core.

Tonnage (Mt)	Cobalt (%)	Gold (g/t)	Bismuth (%)	Copper (%)	Silver (g/t)	Cut-off
NICO Deposit						
42.10	0.10	0.5	0.12	-	-	0.06% Co
35.20	0.11	0.6	0.13	-	-	
24.40	0.12	0.7	0.15	-	-	
5.00	0.20	0.7	0.30	-	-	H.G. core
Sue-Dianne Deposit						
17.30	-	-	-	0.72	2.7	0.25% Cu
10.60	-	-	-	0.96	3.3	0.5% Cu

also referred to as "Olympic Dam-type". Other significant global examples of this class include Ernest Henry, Kiruna/ Aitik, and Salobo in Australia, Sweden, and Brazil, respectively. Their typically large size and polymetallic ore assemblages make these deposits highly attractive exploration targets. Despite the abundance of favourable geological terrane, only a limited amount of exploration has been directed at these types of deposits in Canada.

Proterozoic iron oxide-hosted polymetallic deposits are characterised by a number of diagnostic, regional- and deposit-scale geological features, which were important attributes in developing a strategy for exploration in the southern Great Bear magmatic zone. Although Phanerozoic examples exist, the most important known deposits of this type are Palaeoproterozoic to Mesoproterozoic in age. They occur in an extensional cratonic setting characterised by A-type granite magmatism and associated continental style volcanism (Goad *et al.*, 1998, 2000). Deposits are commonly proximal and located preferentially in the roof zones of megacrystic granite to syenogranite intrusions, which may display unusual myrmekitic, granophyric, and rapakivi textures. Mineralisation is commonly situated on major structural lineaments related to rifting (Reeve *et al.*, 1990). Deposits also occur along active shear/ fault zones transecting the aureoles of granitic plutons. Proterozoic, iron oxide-hosted polymetallic deposits occur in diverse lithologies demonstrating that a specific rock type is not an important control for localising metal concentrations. Data from various deposits indicate that the chemistry of associated host rocks may play a role in contributing metals (Hitzman *et al.*, 1992). Lithology also influences the physical characteristics of the deposits and their behaviour during deformation. Alteration and metal zonation, trace-element geochemistry, and oxygen- and sulphur-isotope data indicate that fluid mixing in the near-surface environment has an important role in metal precipitation. Deposit formation occurs at redox boundaries as a result of the interaction between hot (up to 500°C), alkaline, moderately to strongly saline (5 to 45%), iron- and volatile-rich (CO_2, F ± Cl), sulphur-poor magmatic fluids, and cool, oxidising, meteoric water. Mechanisms causing precipitation of metals are thought to have been a combination of decreasing temperature and pressure,

boiling, changing pH or fO_2, and wall-rock reactions (Reeve *et al.*, 1990; Hitzman *et al.*, 1992; Williams and Blake, 1993; Davidson and Large, 1994; Haynes *et al.*, 1995; Adshead, 1995). A near-surface depositional setting is commonly indicated by proximity to an unconformity or palaeo-weathering surface between the host assemblage and either volcanic rocks related to granite plutonism or platformal sedimentary-cover sequences (Reeve *et al.*, 1990; Hitzman *et al.*, 1992; Goad *et al.*, 1998, 2000).

Numerous publications document the similar age, tectonic setting, and regional and local geological characteristics between the Great Bear magmatic zone and environments hosting Olympic Dam and its global analogues (Hildebrand, 1986; Hildebrand *et al.*, 1987; Gandhi and Bell, 1989, 1996; Gandhi, 1992, 1994; Hitzman *et al.*, 1992; Oreskes and Hitzman, 1993; Gandhi and Halliday, 1993; Williams and Blake, 1993; Adshead, 1995; Gandhi *et al.*, 1996; Goad *et al.* 1998, 2000; Sidor, 2000; Mumin and Camier, 2000; Camier *et al.*, 2000). Fortune Minerals employed the Olympic Dam model in its exploration of the Mazenod Lake area following earlier work by the Geological Survey of Canada (GSC) emphasising these similarities. Deposit- model development and application facilitated discovery of NICO in 1995 following a program of geological mapping and geophysical surveys. It also provided a better understanding of the controls of mineralisation in the previously known Sue-Dianne deposit, facilitating its expansion by the Company. This paper describes the geology of the NICO and Sue-Dianne, identifying them as prime Canadian members of the Proterozoic iron oxide- associated deposit family.

Regional Geology of the Southern Great Bear Magmatic Zone

The NICO and Sue-Dianne deposits are situated in the southern part of the Great Bear magmatic zone, a regional subdivision of the Proterozoic Bear Structural Province of the Canadian, Precambrian Shield. The Bear Province forms a triangular-shaped region on the western margin of the 2500 to 3960 Ma Archaean, Slave Craton, extending northward from Great Slave Lake to the Coronation Gulf on the Arctic Ocean (Hoffman, 1980; Fig. 1). The Bear
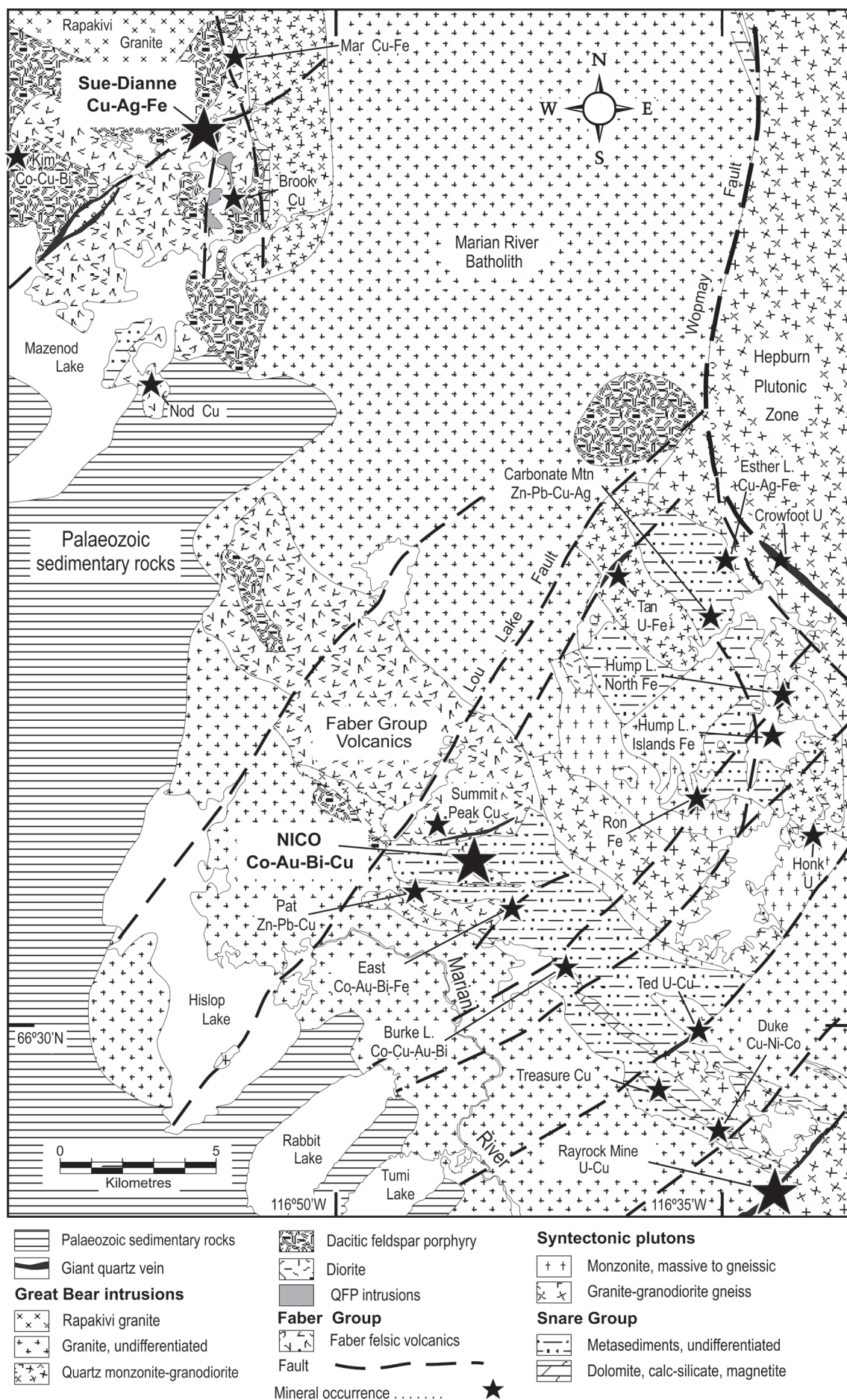
Figure 2: Geology and mineral occurrences of the southern Great Bear Magmatic Zone.

Province is subdivided into two major regional domains: the Wopmay Orogen and the Amundsen Basin. The 2100 to 1800 Ma Wopmay Orogen consists of plutonic, volcanic and sedimentary rocks deposited in three distinct tectonic zones: the Coronation margin to the east, the Hottah magmatic arc to the west, and the central Great Bear magmatic zone (Hoffman, 1980; Hildebrand and Bowring, 1984). The Hottah terrane is a continental calc-alkaline volcano-plutonic arc with associated sedimentary rocks that formed above a subducting plate along the western margin of the Slave Province (Hildebrand *et al.* 1987; Clowes 1997). Sedimentary rocks of the Coronation Supergroup form a depositional prism of continental margin shelf and slope sediments divided into the Epworth, Snare and Akaitcho Groups (Hoffman, 1973, 1980). They are comprised of arenite, dolomite, siltstone and shale, with shallow-water facies predominant in the southern and eastern parts, and deeper-water facies prevalent in the northern part of the basin (Fraser *et al.*, 1972; Hildebrand and Bowring, 1984). Eastward subduction resulted in arc-continent collision causing crustal thickening from folding and thrusting, and emplacement of the Hepburn suite of gabbro, diorite, tonalite and granite plutons within deformed shelf rocks between 1900 and 1880 Ma. The final stages of continental volcanism and related plutonic activity in the Wopmay Orogen created the 400 km long and up to 100 km wide Great Bear magmatic zone between 1876 and 1850 Ma (Fraser *et al.*, 1972; Hildebrand and Bowring, 1984; Hoffman and Bowring, 1984; Hoffman, 1973, 1980, 1988; Gandhi, 1988, 1989). It is separated from the Coronation margin by a major crustal suture, the mylonitic Wopmay Fault Zone. The Great Bear magmatic zone is comprised of low titanium/high aluminum calc-alkalic volcano-plutonic rocks emplaced between the Hottah arc and Hepburn plutonic suite (Hildebrand *et al.*, 1987; Hoffman, 1988). Subaerial volcanic rocks overlap both the Hottah arc and Coronation margin (Clowes, 1997) and are intruded by a suite of hornblende- and biotite-bearing plutonic rocks of similar age (Hoffman and Bowring, 1984; Hildebrand and Bowring, 1984).

The southern Great Bear magmatic zone is exposed in outcrop from Faber Lake in the north to its southern terminus against the Wopmay Fault, at the site of the former Rayrock uranium mine (Fig. 2). However, the Great Bear magmatic zone is known to extend further to the south and west beneath a thin veneer of Palaeozoic sedimentary cover rocks (Clowes, 1997). The exposed portion of the region is also referred to as the Mazenod Lake area and contains the NICO and Sue-Dianne deposits, occurring within a 40 km long and up to 10 km wide northwest-trending arcuate keel comprised of basement sedimentary and overlying volcanic rocks. A second similar, 15 km long belt of sedimentary and volcanic rocks to the east contains numerous iron oxide occurrences with or without minor sulphides. Both belts preserve the unconformity between sedimentary rocks of the Snare Group and younger (1867 to 1851 Ma) volcanic rocks of the Faber Group, and are the immediate host rocks for the known significant mineralisation (Gandhi *et al.*, 1996). The Snare Group are the oldest rocks in the area and are comprised of an upward coarsening, homoclinal sequence

of siltstone, carbonate, subarkosic wacke, and arenite. They are unconformably overlain by rhyodacite ash flow tuffs and associated flows, tuffs, breccias, volcaniclastic rocks and minor andesite flows (Gandhi, 1988, 1989; Goad *et al.*, 1998). Coeval domical granitoid intrusions are emplaced along the margins of the belts. They include the Marian River monzogranite to granodiorite batholith (1866 ± 3 Ma) emplaced between the two sedimentary-volcanic belts, and feldspar porphyritic quartz monzonite stocks (1867 ± 3 Ma) and undated granitic plutons to the south and west. The north end of the main western belt is intruded by the younger (1856±3 Ma) Faber Lake rapakivi granite pluton (Gandhi *et al.*, 1998). Similar rapakivi and syenitic phases have also been identified in late peripheral phases of the Marian River Batholith south of NICO and in the vicinities of Hump and Crowfoot Lakes near barren iron oxide occurrences. A series of late northeast-trending transverse faults transect all of the rocks in the Mazenod Lake area. They merge with the Wopmay Fault zone on the east boundary of the area and are considered related splays. Giant quartz veins up to 100 m wide are emplaced into some of these faults. Diabase dykes are the youngest rocks found in the area, and also typically trend northeasterly along right-lateral fault zones.

Geology of the NICO Property

The NICO claim group is located near the centre of the larger 40 km long, northwest-trending, arcuate basement discontinuity and its intersection with a major transverse fault through Lou Lake (Figs. 2 and 3). The deposit and other related zones of mineralisation are situated predominantly below the angular unconformity between Snare Group sedimentary rocks and younger volcanics of the Faber Group. Minor amounts of mineralisation extend into the overlying volcanic rocks and subvolcanic porphyry dykes. The Snare Group are the oldest rocks on the property and are exposed in a 3 to 5 km wide area extending southeast from Lou Lake. They are covered by volcanic rocks to the northwest but are locally exposed as inliers. Sedimentary rocks consist of an upward-coarsening regressive sequence of laminar siltstones overlain by thick-bedded to massive subarkosic wacke and arenite, which strike 120° and dip 40 to 70° to the north. Subarkosic wacke is intercalated with and grades laterally into calcareous wacke and dolomite a few kilometres southeast of the deposit. Subarkosic arenites are also volumetrically more important to the southeast and locally grade upward into cross-bedded quartz arenite. Snare Group sedimentary rocks are strongly hornfelsed marginal to Great Bear magmatic zone granitoid intrusions and contain assemblages of biotite, actinolite, hornblende, diopside, andradite, and grossular garnet, indicative of upper greenschist- to amphibolite-facies grades of metamorphism.

Above the unconformity, Faber Group volcanic rocks are exposed over an area up to 7 km wide extending northwest of Lou Lake, and also as erosion resistant outliers and upthrown fault blocks southeast of the Lake. They strike at 100 to 110° and dip 20 to 40° to the north and consist of thick-bedded rhyolite to rhyodacite tuffs, flows and

minor volcaniclastic rocks. In ascending order, they are comprised of heterolithic breccias containing altered Snare Group clasts and lapilli resulting from explosive pyroclastic activity during the onset of volcanism. Distribution of the breccias is localised, otherwise the basal volcanic unit consists of massive to flow-banded, potassium feldspar-altered rhyolite (felsite) with or without magnetite laminae (Fig. 4A). These rocks are overlain by thick-bedded, ash-flow tuffs with lesser amounts of porphyritic flows, lapilli tuff and volcaniclastics. The basal, potassium feldspar-altered rhyolite yields an imprecise age of 1851 +18/-16 Ma using uranium-lead isochrons from zircons (Gandhi *et al.*, 1996). Sedimentary rocks and felsite on the NICO property are intruded by early quartz-feldspar porphyritic dykes emplaced parallel to the strike of the Snare Group, and later feldspar ± amphibole ± quartz porphyritic dykes emplaced parallel to the strike of the Faber Group (Fig. 5H). Approximately 1 km to the east of the deposit, a larger feldspar-amphibole porphyry that is compositionally similar to the later dyke set is exposed over a 1 km wide area. Fine-grained felsic dykes are also encountered in drill core, which can be traced into compositionally similar volcanic flows (felsite) and are considered feeders to the overlying volcanic pile. Diapiric monzonite and syeno-granite of the Great Bear magmatic zone intrude sedimentary and volcanic rocks northeast and southwest of the deposit. They include a smaller quartz monzonite stock exposed on the south shore of Lou Lake, which yields a uranium-lead isochron age of 1867 ± 1.5 Ma (Gandhi *et al.*, 1996).

Late northeast-striking (040°) transverse faults, with predominantly vertical displacement, transect Snare and Faber Group rocks and adjacent granitoid intrusions forming horst and graben structures. Major regional faults striking 070° have also been recognised Giant quartz veins are emplaced locally along both fault directions, including a 50 m wide subvertical quartz vein system transecting the unconformity at Lou Lake. It can be traced for approximately 4 km, consists of quartz stockwork and breccia with marginal silicification, and is sporadically mineralised with hematite, pyrite, chalcopyrite, sphalerite and galena.
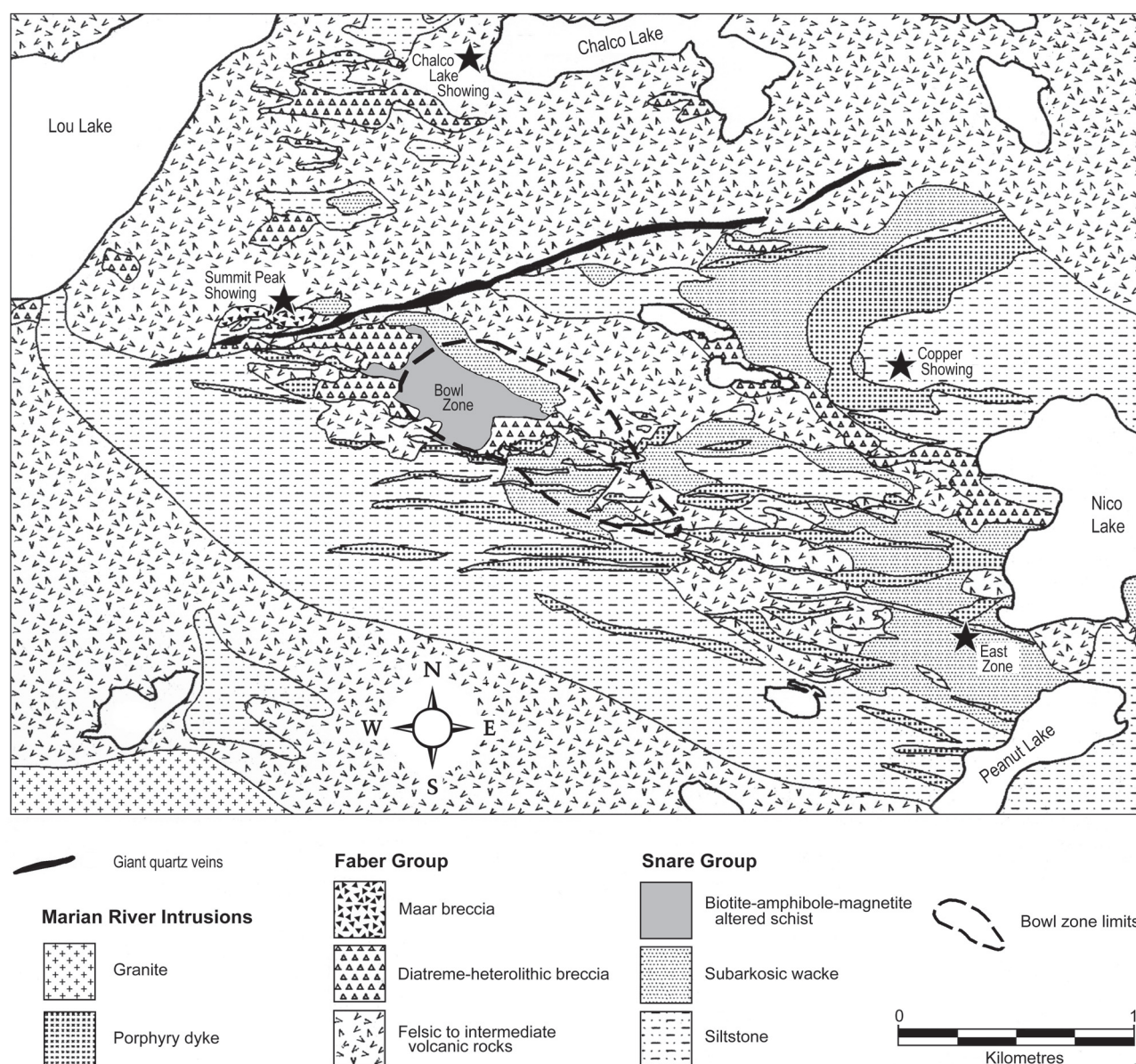

Figure 3: Geology of the central NICO claims and the Bowl Zone deposit.

A variety of hydrothermal diatreme breccias are common on the NICO property, particularly in the Snare Group immediately below the volcanic unconformity. Breccias are spatially related to zones of polymetallic sulphide mineralisation, and are typically capped by massive pink potassium feldspar-altered felsite along the unconformity. Most of the breccias consist of angular to rounded potassium feldspar-altered clasts of Snare Group wackes and siltstones with lesser felsite clasts (Fig. 4D). They are cemented by a matrix of biotite, amphibole, chlorite and potassium feldspar-altered rock flour and iron oxides. These breccias contain only minor sulphides and yield low metal concentrations, despite their proximity to sulphide-bearing mineralised lenses with similar hydrothermal alteration assemblages. Subtle crackle breccias are also common within the deposit, but are typically annealed by subsequent intense amphibole-biotite-magnetite alteration. Some breccias at the unconformity display low-angle bedding, graded bedding, and clast imbrication indicative of maar-facies deposition (Fig. 4C). The occurrence of maar-facies breccias at the volcanic unconformity suggests that volcanism was initiated by near surface diatreme-related activity. The proximity of breccias to mineralisation and the common presence of iron oxide- and potassium-dominated metasomatism suggest that formation of diatreme and maar breccia was broadly coeval with sulphide mineralisation. Brecciation also extends into the overlying volcanic rocks within a few tens of metres vertically above the unconformity, but are volumetrically less important than breccias in the Snare Group. They are comprised of angular and rounded clasts of felsite ± Snare Group sedimentary rocks in a matrix of iron oxides and altered rock flour.

NICO Cobalt-Gold-Bismuth Mineralisation

Intense potassium and iron metasomatism with associated sulphide mineralisation is recognised at and near the volcanic unconformity over a 7 km strike length on the NICO property, particularly between Burke and Lou Lakes (Figs. 2 and 3). The most important discovery to date is the multimillion-tonne cobalt-gold-bismuth deposit delineated in altered sedimentary rocks in the Bowl Zone. Similar mineralisation occurs in the East and Burke Lake zones 1.5 and 5 km to the southeast, respectively. Conversely, the Summit Peak and Chalco Lake copper occurrences, as well as other similar prospects, are hosted in felsite above the volcanic unconformity north and west of the Bowl Zone. All of the mineralisation discovered to date occurs within an intense zone of potassium and iron metasomatism centred around Lou Lake. This alteration produces a variety of coincident geophysical anomalies, which contributed to the discovery of the NICO deposit. They include an approximately 12 km^2 potassium anomaly with peak concentrations up to 8.39% and corresponding very low thorium/potassium ratio, indicative of a secondary hydrothermal source. This is the largest hydrothermal radiometric anomaly ever detected by the GSC in Canada (Hetu *et al.*, 1994; Charbonneau *et al.*, 1994; Gandhi *et al.*, 1996). Potassium enrichment coincides broadly with a 20 km^2 total field magnetic anomaly between 5000 and 20 000 nanotesslas above background, and is rimmed by a peripheral uranium anomaly. A 3 km^2, 3 milligal bouguer gravity anomaly and coincident low resistivity at the centre of the larger anomalies correlates with the Bowl Zone (Goad *et al.*, 1998, 2000).

The Bowl Zone is largely constrained to within subarkosic wacke with the footwall defined by less intensely altered and generally unmineralised laminar siltstone. The hangingwall grades upwards into less altered wacke or, is abruptly capped by the unconformity and overlying felsite or, terminated against porphyry dykes or diatreme breccia. The subarkosic wacke is medium- to coarse-grained, massive and relatively mechanically isotropic relative to siltstone. Consequently, mineralisation is considered to have been preferentially focused within this unit because of its greater porosity from brittle behaviour during deformation. Within the mineralised zone, host wackes are pervasively metasomatised to a "black rock" alteration assemblage of massive, banded and laminar amphibole-biotite-magnetite schist, ironstone and breccias, which has completely overprinted primary minerals and textures (Figs. 4E and 4F). This pervasive alteration grades into less altered horizons of biotite-amphibole-altered wacke preserved between mineralised lenses and gradationally less altered biotite-amphibole-altered wackes in the hangingwall. Volcanic rocks overlying the deposit are comprised of an alteration assemblage of massive and banded mosaic-textured microcline, adularia, quartz, magnetite ± hematite felsite with accessory biotite, amphibole, tourmaline, carbonate, arsenopyrite, pyrite, and chalcopyrite. The intensity of potassium metasomatism in felsite immediately overlying the deposit produces nearly monominerallic potassium feldspar assemblages with local magnetite banding (Figs. 4A and 4B). Similar alteration occurs in the earlier synvolcanic quartz-feldspar porphyritic dykes but is less intense in the later feldspar-amphibole porphyritic dykes intruding the deposit. Australian Proterozoic iron oxide-hosted deposits refer to similar assemblages as "red rock" alteration (Williams and Blake, 1993).

The Bowl Zone is delineated by approximately 225 drill holes at 25 to 50 m spacing along sections 50 m apart, with sections 100 m apart at the deposit ends. Mineralisation occurs in several closely stacked, stratabound, sulphide-bearing lenses of ironstone extending beneath the volcanic unconformity. Mineralised lenses can be traced continuously along a 1.9 km strike length trending approximately 110°, parallel to the strike of the host subarkosic wacke. Lenses vary in width between 250 and 700 m along the 30 to 50° north dip. Individual lenses are up to 70 m in thickness, the three principal referred to as the "Upper", "Middle", and "Lower" lenses. They are variably enriched in cobalt, gold, bismuth, copper and locally tungsten (Mumin, 1998) with metals occurring in concordant and discordant sulphide-rich fractures and disseminations typically comprising between 5 and 10% of the rock (Fig. 4G). Within the mineralised lenses, alteration mineralogy consists of an early prograde event of ferro-hornblende, biotite (annite), magnetite, potassium feldspar, minor clinopyroxene (diopside-hedenbergite), ± carbonate and accessory apatite

(Fig. 4E). This assemblage evolves into retrograde ferro-actinolite, secondary biotite (annite), chlorite and hematite with local tourmaline (Fig. 4F). Iron oxides are dominated by early emplacement of magnetite, which varies between 5% and massive veins up to 30 cm wide, but averages approximately 20% in the mineralised zones. Hematite is subordinate to magnetite, occurring predominantly within the retrograde phases and also commonly as rims around earlier grains of magnetite. Locally, magnetite and hematite exhibit successive rim textures. The association of iron and potassium metasomatism is reflected in the late precipitation of hematite along the cleavage planes of biotite (Fig. 4H). The sulphide and ore mineralogy also demonstrates an evolving system of prograde to retrograde assemblages. Early minerals are chalcopyrite, pyrite and pyrrhotite, evolving to gold, native bismuth and bismuth tellurides and sulphosalts, evolving to bismuthinite, cobaltite and loellingite, and then to bismuthinite, cobaltian arsenopyrite and scheelite and finally arsenopyrite (Walker, 1999). Mineral texture relationships reflect a generally retrograding fluid system with local thermal pulsing, possibly due to dyke emplacement. They also suggest that early stages of the mineralisation are controlled by restrained fluid flow within areas of peak metasomatism associated with the growth of relatively coarse ferro-hornblende. Under these conditions, bismuth, gold and copper predominate. Later stages are controlled by higher rates of fluid flow developing connected veins and fractures with cobalt dominating (Walker, 1999).

Cobalt is the most important economic metal in the NICO deposit. Petrographic and electron microprobe analyses demonstrate that it is essentially contained within a solid solution series between arsenopyrite and cobaltite (Fig. 5A), with minor cobaltian loellingite. Concentrations occur up to 2.4% over one-metre core samples, but average 0.1% within the deposit and 0.2% within a five million tonne, higher-grade core. Gold occurs as microscopic grains of native gold ranging from <1 to >100 microns in size (Fig. 5B) and as various gold-bismuth-antimony-tellurium alloys. Gold typically occurs attached to sulphide and telluride grain boundaries, particularly bismuth sulphides and tellurides, and less commonly as inclusions within sulphide minerals. Some native gold also occurs within silicate gangue, but typically remains associated with finely disseminated sulphide and/or telluride minerals. The distribution of gold within the deposit is bimodal with large areas barren and a discrete gold-rich zone within the central core, yielding grades up to 62 g/t in core samples. Drill hole intersections within this gold zone commonly yield grades of 3 to 10 g/t over 10 to 30 m widths. Bismuthinite is the dominant bismuth mineral with lesser amounts of native bismuth and bismuth tellurides and sulphosalts. Bismuth averages 0.12% within the deposit and locally grades up to 3.3% in core samples. Bismuth and cobalt have the closest association of any two metals in the deposit with a correlation coefficient of 0.3 (Sidor, 2000), although their enrichment envelopes are even more correlatable on the deposit scale. Copper was not evaluated in the most recent resource estimates but averages approximately 0.05% in the deposit with grades locally up to 1.15%. Tungsten, occurring as scheelite, averages approximately 200 ppm in the deposit and grades locally up to 2% in core samples. Trace element geochemistry and metallurgical testing reveals an average arsenic concentration of 0.75%, barium values between 1000 and 2000 ppm, and phosphorous between 100 and 800 ppm. Silver is rarely detected, although assays up to 40 g/t occur locally.

The near-surface, 40 to 50° north-dipping geometry of the Bowl Zone mineralised lenses facilitates open pit mining with a low stripping ratio. Flotation tests on composite core samples at Lakefield Research indicates that the economic minerals are contained within the 5 to 10%

Figure 4.

(A)   Microcline-enriched rhyolite (felsite) with thin bands of magnetite indicative of strong potassium and iron oxide alteration of Faber Group volcanic rocks. Length of white card is 9 cm.

(B)   Mineralized felsite in the hangingwall of the Bowl Zone exhibits a penetrative potassium feldspar alteration, which has migrated along fractures of the volcanic protolith with tourmaline (Tour) and chalcopyrite (Cpy).

(C)   Stratification and grading in Maar-facies breccia from the north rim of th Bowl deposit, NICO property. Diameter of drill core is 4.8 cm.

(D)   Matrix-supported hydrothermal breccia from the NICO deposit contains potassium feldspar-altered sedimentary fragments from th Snare Group set in a magnetite-amphibole-biotite-enriched matrix.

(E)   Photomicrograph in plan transmitted light of potassium feldspar (K-Fsp) intergrown with hornblende (Hbl). The large hornblende crystals include smaller subhedral (Apy). Sample is from the Bowl Zone. Field of view is 0.7 mm wide. Photo from Camier (1996).

(F)   Photomicrograph of semi-radiating sheaths of ferro-actinolite and biotite overprinting the primary prograde assemblage. Opaque bands are magnetite and bismuthinite. Sample is from the Bowl Zone NICO property. Field of view is 1.5 mm wide. Photo from Walker (1999).

(G)   Biotite-magnetite amphibole schist or ironstone containing numerous veins of cobaltian arsenopyrite, bismuthinite and chalcopyrite from the Bowl Zone, NICO property. Length of specimen is 17 cm.

(H)   Back scatter electron image of a mineralized sample from the Bowl Zone. Intergrown biotite (Bt) and hematite (Hem) demonstrate the intimate relationship between potassium and iron metasomatism.
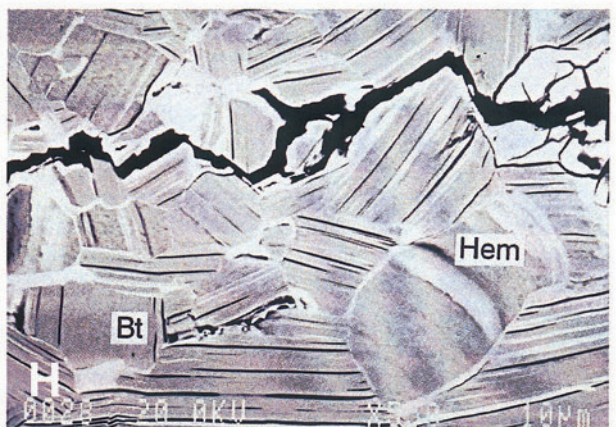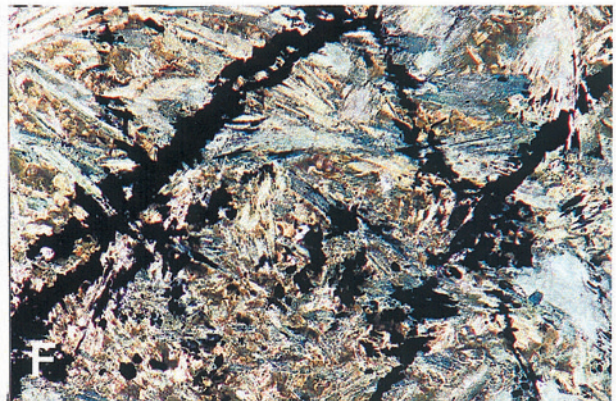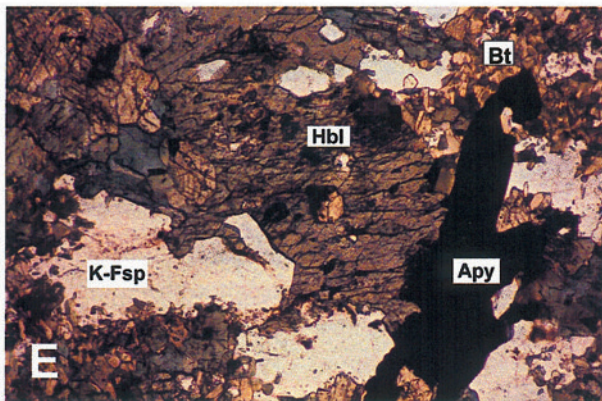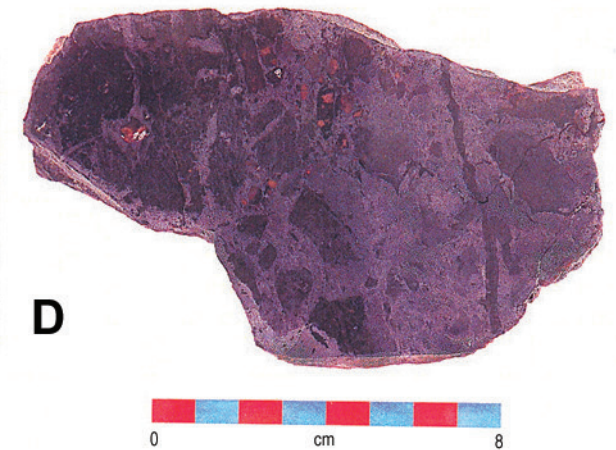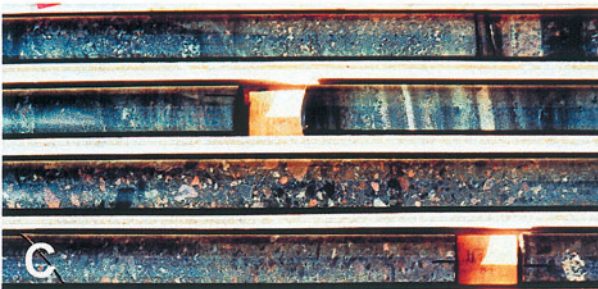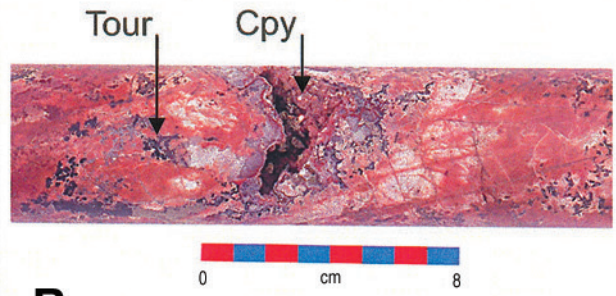
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sulphide fraction, which produces a bulk concentrate, grading between 4 and 5% cobalt. The gold grade of the concentrate is between 2 and 35 g/t, varying with production from different parts of the deposit. The concentrate can be sold, or the valuable minerals processed to pure metal and/ or intermediary carbonate, sulphate or hydroxide products at the site. Metallurgical testing indicates total recoveries of approximately 80% for cobalt and up to 75% for gold using low-temperature (180°C) acid pressure oxidation followed by cyanidation of the residue (Mezei *et al.*, to produce non-hazardous, stable ferric-arsenate waste. Selective flotation of the bulk concentrate can recover approximately 55% of the bismuth, which is followed by a ferric chloride leach and cementation onto iron (Ferron *et al.*, 2000).

Geology of the Sue-Dianne Property

The Sue-Dianne mining lease straddles the central portion of Dianne Lake at the north end of the main western belt of preserved Snare Group sedimentary rocks and overlying volcanic rocks of the Faber Group (Fig. 6). The deposit occurs within a diatreme breccia complex at the centre of the property and is hosted within altered ash flow tuff above the volcanic unconformity. Minor mineralisation also extends into underlying plagioclase and potassium feldspar porphyry. The diatreme breccia complex is situated at the intersection of the north-south-trending Mar Lake Fault, and the northeast-trending (070°) Dianne Lake Fault. The Dianne Lake Fault has displaced the Mar fault by right-lateral movement of approximately 500 m.

The dominant rock type on the Sue-Dianne property is a 5 km wide, well preserved sequence of west-striking and 40 to 65° north-dipping, unaltered ash flow tuffs yielding ages of 1862 +8.7/-1.3 to 1869 +1.3/-1.2 Ma using uranium-lead isochrons from zircon (Gandhi *et al.* 1998). They consist of multiple sheets of predominantly plagioclase porphyritic crystal tuff, welded tuff, with lesser lapilli and minor tuff breccia (Fig. 5C). North of the Dianne Lake Fault they are variably potassium feldspar- and hematite-altered, locally to felsite. Ash flow tuff on the east side of Dianne Lake is intruded by a feldspar porphyritic sill several tens of metres thick. Approximately 1 km northwest of the deposit, ash flow tuff is intruded by a one- and two-feldspar (potassium feldspar and plagioclase) porphyritic stock with local trachyitic phases (D'Oria, 1998). Potassium feldspar- and epidote-altered, plagioclase and potassium feldspar porphyry has also intruded the lower parts of the Sue-Dianne deposit (Fig. 5H). The Faber Lake rapakivi granite pluton intrudes these porphyritic rocks northwest of the deposit (Fig. 2), and mapping, mineralogy and chemistry suggest they are all related phases (D'Oria, 1998). Windows of Snare Group sedimentary rocks outcrop approximately 2 km north and south of the deposit and are comprised of subarkosic arenite and siltstone, respectively. Siltstones exposed on the south shore of Dianne Lake are locally brecciated, resembling breccias in the Snare Group beneath the volcanic unconformity on the NICO property. They are comprised of angular fragments of laminar siltstone in a locally derived biotite-chlorite-altered matrix with iron oxides. The proximity of the Sue-Dianne deposit to brecciated Snare Group sedimentary rocks indicates the volcanic-sedimentary unconformity is an important regional control over the mineralisation. Monzogranite to granodiorite of the Marian River Batholith intrudes the margin of the volcanic belt 2 km east of the deposit (Fig. 2). Strongly hornfelsed subarkosic arenites and banded calc-silicate rocks of the Snare Group are also locally preserved as trapped remnants between the volcanics and this intrusion.

Sue-Dianne Copper-Silver Mineralisation

The Sue-Dianne deposit is hosted within a fault-bounded, crudely elliptical, hydrothermal diatreme breccia complex, approximately 600 m long and 500 m wide, characterised by distinct structural and alteration zoning. Peripheral alteration is weak to moderate potassium feldspar and iron oxide alteration of plagioclase-phyric rhyodacite ash flow tuffs with well-preserved fiammé (Fig. 5C). They contain rounded lapilli clasts (occasionally rotated) in a fine-grained microcrystalline groundmass of quartz and feldspar. Brecciation within the complex is constrained by an outer margin of intense shearing and quartz veining that occurs within the peripheral potassium feldspar alteration zone. These rocks contain predominantly quartz, epidote and chlorite as veins, stockwork breccias, or pervasive silicification and/or epidote flooding. This outer zone grades inwards into moderately potassium- and iron oxide-(hematite) altered and fracture brecciated ignimbrite with seldom preserved relic textures (Fig. 5D) and numerous intermittent crosscutting quartz veins, stockworks and fractures. Fracture breccias are sparsely mineralised, but pervasively potassium feldspar-altered and fractures are typically filled with up to 15% iron oxides (hematite > magnetite; Fig. 5E). Minor pitchblende also occurs in near-surface fractures but is less common in core samples from within the deposit (Fig. 5F).

Sulphide mineralisation is concentrated within the inner core of the complex, defined by even more intense brecciation and potassium feldspar and iron oxide alteration. The deposit is continuously defined by 65 drill holes at 25 to 50 m centres along a northeast-plunging, inclined mushroom-shaped structure, measuring 450 m along strike, up to 350 m in width and 300 m deep. The transition to the mineralised zone in both the footwall and hangingwall, is commonly marked by potassium- and epidote-altered, silicified and annealed fault gouge. It is a mottled green to pink, fine-grained siliceous rock comprised of epidote, quartz, chlorite, potassium feldspar, and occasional reddish-brown rounded fragments of microcrystalline quartz and hematite. The inner core of the complex is dominated by matrix- and clast-supported breccias, typified by monolithic, angular to rounded, potassium feldspar- and iron oxide-altered ignimbrite clasts with localised feldspar porphyry fragments, generally less than 25 cm in diameter (Fig. 5G). The fragments are set in a matrix of hematite/magnetite, potassium feldspar, chlorite, epidote, andradite garnet, fluorite, and copper and iron sulphides. Zoned intergrowths of andradite and fluorite are locally developed.

Less common heterolithic breccias contain fragments of ignimbrite, porphyry and hydrothermal vein material with some clasts showing evidence of previous stages of fragmentation and polycyclic brecciation (Walden, 1998; Camier *et al.*, 2000). Microbreccias occur locally in deeper parts of the deposit and are comprised of fine-grained, reddish-brown, iron oxide- and potassium feldspar-altered, rock flour with minor copper and iron sulphides, locally displaying flow-like banding.

Iron oxides are the dominant alteration minerals in the Sue-Dianne deposit and comprise between 5 and 20% of the deposit. Hematite and lesser specular hematite predominates, however, there is a distinct transition to magnetite dominance at depth where massive veins up to 3 m occur, locally intergrown with chalcopyrite. Intense iron oxide and potassium feldspar alteration gives rise to distinctive geophysical signatures, which contributed to Noranda's discovery of the deposit in 1975. They include a 2 km^2 total field magnetic anomaly approximately 800 nanoteslas above background, coinciding with distinct high uranium and weaker potassium radiometric anomalies (Richardson *et al.*, 1974; Hetu *et al.*, 1974; Charbonneau, 1988). Sulphide minerals within the deposit also generate low resistivity and high chargeability induced polarisation anomalies (Goad *et al.* 1998, 2000).

Sue-Dianne is variously enriched in copper, silver, and locally gold with metals contained within disseminations, fracture filling and veins of sulphides comprising approximately 5 to 10% of the rock. Copper primarily occurs in chalcopyrite (Fig. 5I) within the breccia matrix and is also intergrown with or replaces iron-bearing silicates and oxides, particularly magnetite in deeper parts of the deposit. Oxidation of chalcopyrite to bornite, chalcocite and covellite increases with proximity to the hematite-rich periphery and upper parts of the deposit (Fig. 5J). Copper concentrations average 0.7% in the deposit, with grades of 1% in a 10 million tonne higher-grade core, and 2% within smaller areas. Bornite-rich parts of the deposit can contain up to 5% copper over a few metres. Minor glaucodot ($(Co,Fe)AsS$) and djurleite ($Cu_{31}S_{16}$) are occasionally present within the bornite zone (Walden, 1998; Mumin *et al.*, 1998; Mumin and Tufts, 1999; Camier *et al.*, 2000). Abundant secondary covellite and goethite in some near-surface rocks suggest either a palaeo-weathering surface or mixing of hydrothermal fluid with oxidised meteoric water close to the surface. Conversely, modern weathering is characterised by locally abundant malachite along near-surface fractures. Silver is the major by-product metal in the Sue-Dianne deposit and is associated with zones of abundant bornite. It has not been observed as a separate silver-bearing mineral. Silver averages 2.7 g/t but commonly grades between 5 and 30 g/t in bornite-rich parts of the deposit. Gold occurs locally within a distinct zone on the north periphery of the deposit where it grades 2 g/t over a few metres in some drill hole intersections. Otherwise gold is only locally detected. Other significant local metal enrichments are molybdenum, as microcrystalline molybdenite with grades of 0.01% over 315 m drill hole intersections at the centre of the deposit. Uranium occurs primarily in near-surface fractures as pitchblende, locally weathering to uraninite with grades up to 3060 ppm. Bismuth occurs as bismuthinite, and native bismuth up to 354 ppm, cobalt up to 304 ppm, barium commonly greater than 1000 ppm, and phosphorous between 150 and 610 ppm in randomly selected drill core samples. Rare earth element-bearing minerals have locally been

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Figure 5.

(A)   Back scatter electron image of euhedral cobaltite (Cob) intergrown and replaced by cobaltian arsenopyrite (Apy). Sample is from the Bowl Zone on the NICO claims.

(B)   Back scatter electron image of fracture filling chalcopyrite (Cpy), maldonite (Au_2Bi) and native gold (Au) in colbaltite. Field of view is 0.2 mm.

(C)   Least altered ignimbrite host from the Sue-Dianne deposit. Length of magnet is 12.2 cm.

(D)   Potassium-altered ignimbrite host rock of the Sue-Dianne deposit.

(E)   Hematite- and chlorite-altered (Hem, Chl) fracture breccia with chalcopyrite mineralization (Cpy) from the Sue-Dianne deposit.

(F) Outcrop of Sue-Dianne fracture breccia which exhibits uranium (pitchblende) and copper (malachite, Mal) mineralization. Length of pencil is 10 cm.

(G)   Matrix-supported diatreme breccia from Sue-Dianne deposit. Length of magnet is 12 cm.

(H)   Porphyry samples from Sue-Dianne (upper) and NICO (lower) deposits. Sue-Dianne: two feldspar + amphibole porphyry showing strong potassium alteration with late epidote fracture filling in the footwall of the deposit. NICO: contact between amphibole-biotite schist and feldspar-amphibole porphyry. Light grey portions of the schist represent relic wacke host rock, whereas the darker amphibole-biotite-enriched bands reflect metasomatic addition of iron and potassium (black rock alteration).

(I)   Photomicrograph of hematite (Hem), magnetite (Mag) and chalcopyrite mineralization (Cpy) in diatreme breccia at Sue-Dianne. Field of view is 1.1 mm wide.

(J)   Photomicrograph of hematitebornite-chalocite-glaucodot intergrowth in fracture breccia at Sue-Dianne. Field of view is 1.1 mm wide.
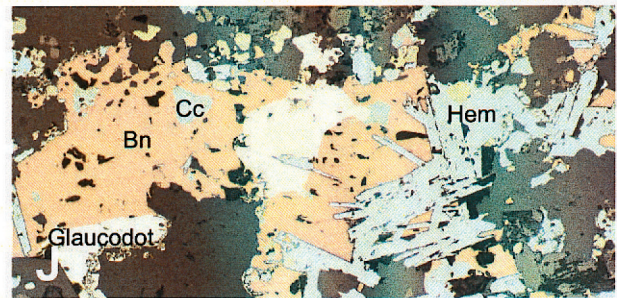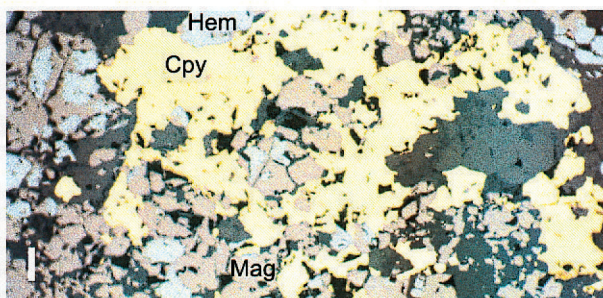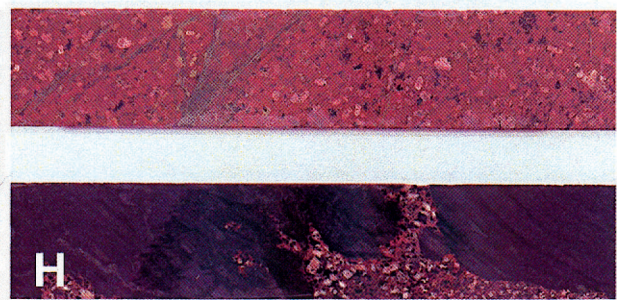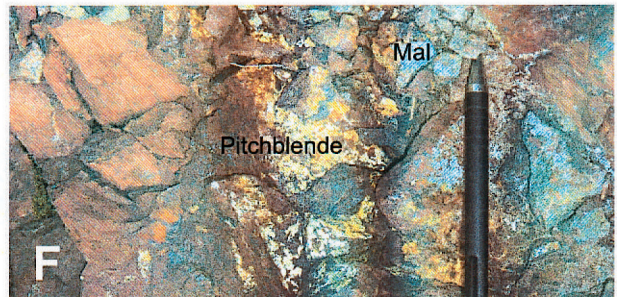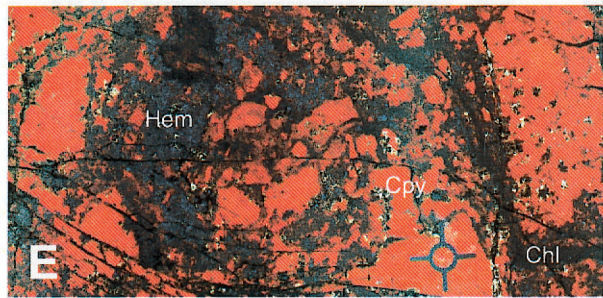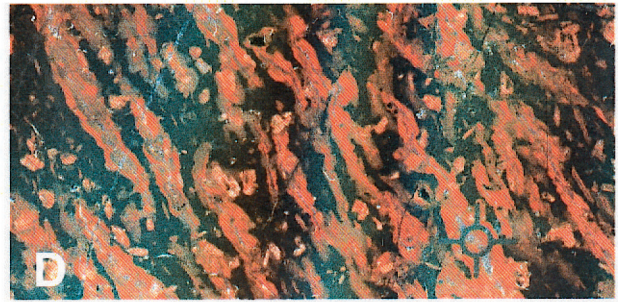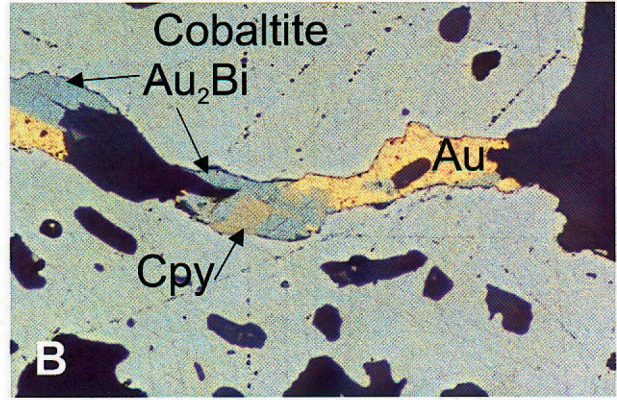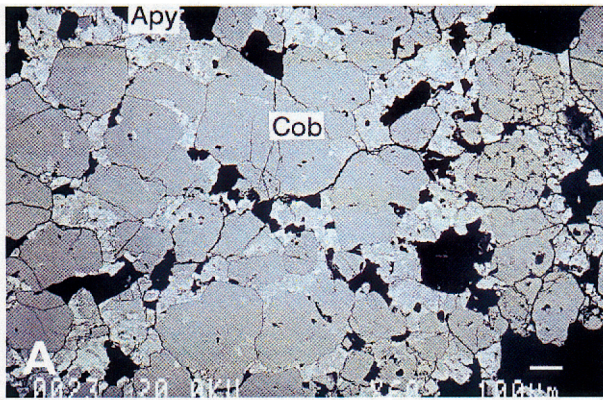
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observed within the matrix-supported breccias associated with subhedral allanite intergrown with epidote analysed for a suite of rare earth elements contained up to 324 ppm cerium and 331 ppm lanthanum.

The Sue-Dianne deposit is amenable to open pit mining with a low stripping ratio. Tests carried out at Lakefield Research on composite core samples achieved recoveries of 90 to 93% of the copper, 77% of the silver and 81% of the gold in a bulk flotation concentrate. Acid pressure oxidation at 180°C produced copper recoveries of between 96 and 99% from concentrate using the same conditions as the NICO test work. Gold recoveries were 96% from gold-rich concentrates within the deposit.

Discussion and Conclusions

Global mineral discoveries during the past twenty-five years have resulted in the recognition of a distinct class of polymetallic sulphide deposits hosted in iron oxides associated with A-type granite intrusions and continental-style volcanism. Their large size (eg. billion-plus tonne Olympic Dam and Salobo deposits) has stimulated additional research and exploration directed at the search for new deposits of this class. Until very recently, only minimal exploration was carried out in the Great Bear magmatic zone for iron oxide-hosted polymetallic deposits. This was due in part to limited access, but also to the general lack of appreciation for the potential for this deposit-type in Canadian Proterozoic terranes. Given the regional distribution of known iron oxide occurrences within the Great Bear magmatic zone, the potential for discovering further significant deposits must be considered high. Iron oxides, with or without polymetallic sulphide concentrations, are regionally distributed in the Great Bear magmatic zone, generally occurring near the base of remnant ash flow volcanic fields. Tectonic reconstruction of the Bear Province suggests a collisional orogenic event between 1900 and 1880 Ma, closely followed by the development of an extensive granite/rhyolite core at 1870 to 1865 Ma, and culminating in A-type rapakivi granite plutonism at 1856 to 1850 Ma. Given the diversity of iron oxide occurrences, including barren and polymetallic-enriched iron oxide in brecciated basement rocks and in
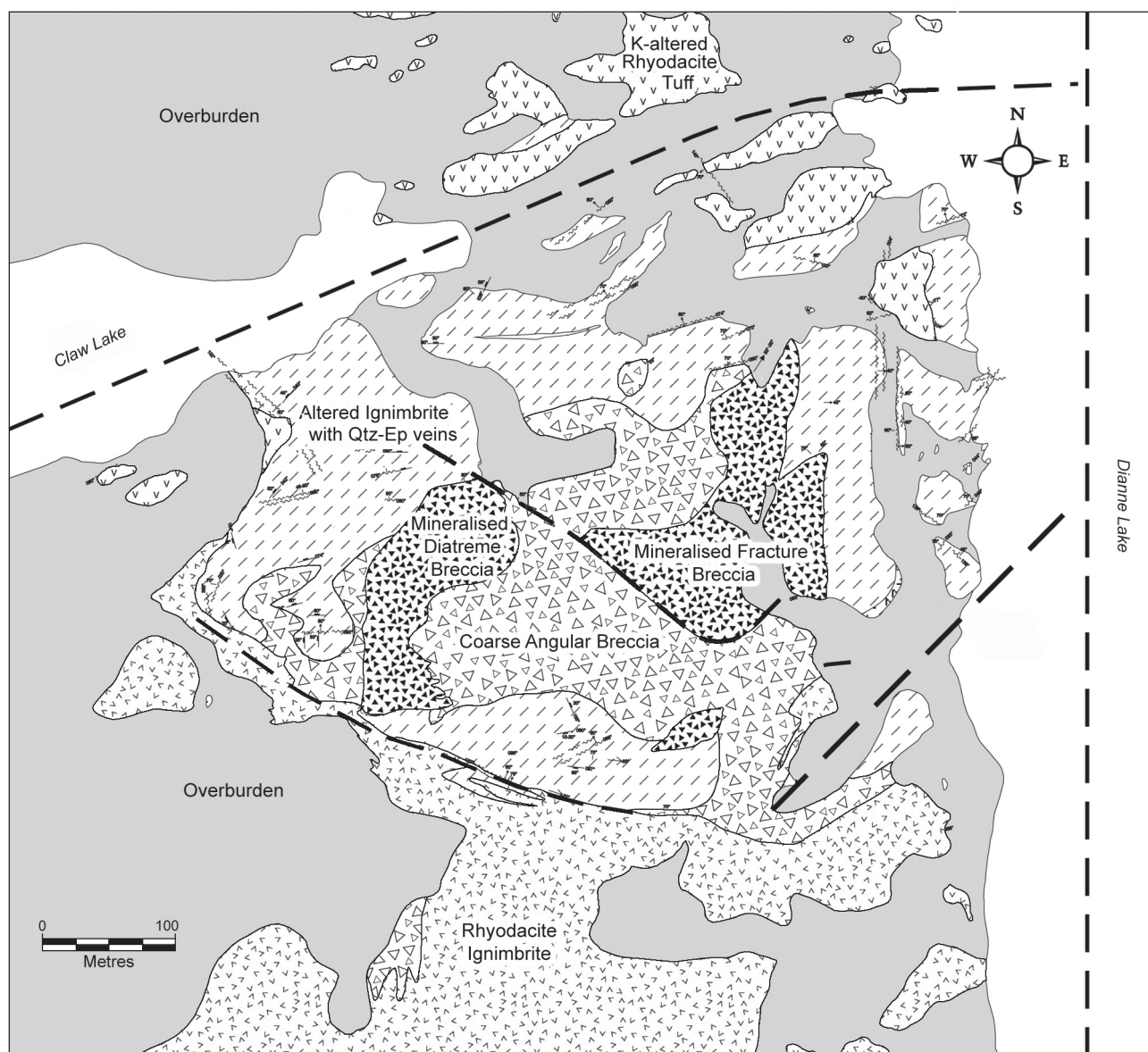

Figure 6: Geology of the Sue-Dianne copper-silver-gold iron oxide-rich breccia complex

felsite above the volcanic unconformity, there is mounting evidence that deposit formation continued from the initial stages of volcanism through to the time of rapakivi granite emplacement.

The ongoing drill delineation by Fortune Minerals of the NICO cobalt-gold-bismuth and Sue-Dianne copper-silver deposits makes these the most advanced exploration projects in the Bear Province. NICO is a replacement-style deposit hosted in iron oxide- and potassium-altered, brecciated basement sedimentary rocks capped by potassium-altered rhyolite (felsite). Despite its atypical metal assemblage, "black rock" amphibole-magnetite-biotite ironstones which host the NICO deposit are somewhat analogous to alteration assemblages at Salobo and Ernest Henry. Sue-Dianne, however, has the essential characteristics of Olympic Dam, with mineralisation hosted in a well-zoned diatreme complex that crosscuts a tilted marginal to nearby rapakivi granite. Both, NICO and Sue-Dianne formed proximal to the volcanic base, indicating the subvolcanic to lower volcanic environment is the preferred one for iron oxide enrichment. Detailed petrological studies of NICO (Mulligan, 1995; Walker, 1999; Sidor, 2000) and Sue-Dianne mineralisation (Walden, 1998; Camier, in preparation) are bringing to light increasing complexity in mineral paragenesis. Both deposits show early high temperature reduced mineral phases being overprinted by late low temperature oxidative assemblages. The overall paragenesis suggests mixing of reduced high temperature fluid from depth with an oxidative near-surface hydrologic regime. Work to date suggests early prograde magnetite formation with widespread potassium feldspar metasomatism, followed by retrograde sulphidation to more oxidised minerals at Sue-Dianne, and to sulpharsenide mineral phases at NICO. At present, we cannot conclusively identify a specific magmatic source for the early high temperature fluids. However, proximity to subvolcanic porphyries and various phases of the Marian River Batholith (including rapakivi granite), geochronology, and mineralogical evidence suggests that they are all genetically related.

The wide diversity of mineralisation styles, from barren Kiruna-type magnetite-apatite to Olympic Dam-type magnetite/hematite breccia ores to NICO-type replacements in this region identifies it as a key area not only for exploration but for continued research into the classification and genesis of the diverse ore-types occurring within the Proterozoic iron oxide class as a whole.

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