VARIATIONS IN SILICATE AND SULPHIDE MINERAL CHEMISTRY BETWEEN FREE-MILLING "METALLIC" AND REFRACTORY "INVISIBLE" GOLD ORES, CON MINE, YELLOWKNIFE, N.W.T.

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ABSTRACT

The Con Mine is an epigenetic mesothermal Archean lode gold deposit sited in deep seated crustal shear zones that transect 2.70-2.65 Ma volcanic rocks of the Yellowknife Greenstone Belt. The economic gold is concentrated within the greenschist facies rocks of the Con and Campbell Shear Systems that retrograde amphibolite facies metabasalts within the contact metamorphic aureole of the multiphase (2634-2604 Ma) Western Plutonic Complex. Shear deformation and fluid mobility commenced at peak metamorphic conditions. Protracted retrograde fluid evolution within the shear zones occurred in an environment of steep and inverted geothermal gradients.

The Con Mine hosts both free-milling "metallic" and refractory "invisible" gold mineralisation. There is no continuum between ore types: free-milling ores display heterogeneity in texture, mineralogy, and alteration both along strike and down dip reflecting prolonged, episodic vein evolution within a brittle ductile deformational regime. Free-milling ores are characterised by a muscovite-phengitic muscovite-chlorite-calcite-albite-pyrite-pyrrhotite-native gold assemblage associated with folded and boudinaged quartz carbonate veins. Temperatures calculated by the chlorite geothermometry, a subtle decrease in gold fineness with depth, and previously calculated fluid compositions indicate that free-milling ores formed at temperatures of less than 375°C, with Na/K <1, δ^{18} O of 6.8%c.

Refractory ores occur structurally higher and footwall to free-milling ores in productive shear strands. Refractory ores are characterised by a paragonitic muscovite-Al chlorite-Fe/Mg carbonate-arsenopyrite-pyrite assemblage associated with ductile deformation of pre-existing quartz-carbonate vein systems. The "invisible" refractory gold

is hosted in As-enriched rims of As/S zoned arsenopyrite (up to 1900 ppm Au), and locally within As-enriched domains of pyrite grains (up to 450 ppm Au). Calculated temperatures of mineralisation are 300-420°C, Na/K >1, and δ^{18} O and δ^{13} C fluid values of 9.1%c, and -2.27%c respectively.

The amphibolite facies environment, greenschist retrogression and presence of refractory gold ores makes the Con Mine a unique member among Archean lode gold deposits spanning the granulite to subgreenschist facies terranes. The refractory mineralisation at the Con Mine specifically relates to an environment that straddles structurally deeper amphibolite facies and structurally shallower greenschist facies gold depositional environments within the Archean gold continuum.

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CHAPTER 1

INTRODUCTION

1.1 General Statement and Purpose of Study

Over 4.5 million ounces of gold have been produced from the Con Mine since its discovery in 1936. Collectively, all deposits within the Yellowknife Greenstone Belt have produced in excess of 14 million ounces of gold from 1938 until present. The majority of gold production has been from auriferous quartz veins hosted within the Con and Campbell-Giant Shear Systems that transect the Yellowknife Greenstone Belt in the vicinity of the city of Yellowknife. Since the work of Boyle (1961) the gold-quartz vein deposits of Yellowknife have been recognised as type examples of shear hosted gold-quartz deposits. The subsequent work of Kerrich et al. (1977), Kerrich and Allison (1978), and Kerrich and Fyfe (1987, 1988) have presented the Yellowknife deposits as being typical of Archean shear hosted mesothermal gold mineralization in terms of fluid geochemistry and vein geometry. Although the geology of the Yellowknife Greenstone Belt and of gold deposits hosted within the belt have received a great deal of attention, the mineralogy of the ore bodies (Coleman, 1953; Coleman 1957; Boyle, 1961) and associated alteration (Boyle, 1961) have recently not been critically investigated.

Gross and subtle differences in alteration and vein mineralogy within mesothermal gold-quartz systems are attributed to the pressure and temperature of gold deposition (i.e. Mueller and Groves, 1991), lithological controls (Bohlke, 1989), and variability with depth relative to present day erosional surfaces (Robert and Brown, 1986; Albino, 1988; Hagemann and Brown, 1996). The range in conditions for formation of Archean lode

gold deposits has led to consideration of a crustal continuum for these large hydrothermal systems (Ridley et al., 1996; Hagemann and Brown, 1996). The physical site and mineralogical nature of gold deposition and the metallurgical behaviour of gold ores is seldom addressed in discussions of gold metallogeny, although considerable attention has been given to the nature of the depositional sites for refractory "invisible" gold in Fe-As sulphides (Cabri, 1992 and references therein). Known occurrences of refractory gold ores in mesothermal systems are found in the Red Lake Greenstone Belt (Andrews et al., 1986; Tarnocai, 1996). Barberton Greenstone belt (Anhaeusser, 1986; Cook and Chryssoulis, 1990; Cabri et al., 1989), and Cambrian - Ordovician gold deposits in the Central Massif, France (Boiron et al., 1989; Wu et al., 1990). Refractory ores are located in shears and replacement bodies that transect lithogically complex stratigraphic sequences.

The presence of refractory and free-milling gold ores at Yellowknife has been previously recognised (Campbell, 1949: Lord, 1951: Breakey, 1975: McMurdo, 1975: Nikic, 1974: Padgham and Brophy, 1985: Webb, 1992). Although the zonation from refractory ores near surface to free-milling ores with depth is mentioned it has not been addressed as a problem until recently (Armstrong, 1992; 1993). The Con and Campbell Shears both host refractory and free-milling ore bodies within shears that transect an essentially geochemically homogenous mafic volcanic stratigraphic sequence.

The purpose of this study is to detail the physical distribution and to characterise ore and gangue mineral assemblages associated with refractory and free-milling ores at the Con Mine. This thesis specifically documents the relationship of muscovite to freemilling and paragonitic muscovite to refractory gold ores. Determination of this previously unrecognised mineral chemical variability between ore types provides key indictor minerals for utilisation in regional exploration. These key differences in mineral paragenesis also provide an effective and rapid means by which the metallurgical properties of mineralised material may be determined. The Con Mine provides an unique opportunity to investigate two shear systems hosting distinctly different gold ores in terms of metallurgical behaviour and to elucidate the relative timing and evolution history of these ore types in an Archean mesothermal fluid regime.

1.2 Location. Access and Physiography

The Con Mine lease (114°25'W.62°25'N) is situated immediately south of the City of Yellowknife, within the city limits. Yellowknife, the capital of the Northwest Territories, with a population of 17 000 is located on the west shore of Yellowknife Bay on the North Arm of Great Slave Lake (Figure 1.1). The mine lease is easily accessed by all weather gravel roads from Yellowknife.

The topography of the area surrounding the mine is rugged with low swampy areas bounded by steep scarps with topography varying from 10 to 30 metres. Outcrop exposure is excellent and averages around 70-80%. Due to weathering and the gouging effects of glaciation, shear zones have recessive weathering features limiting exposure of shear zone material to trenched areas and thin wisps along the margins of linear depressions. Operation of roasters at the two gold mines eliminated lichen cover in the immediate mine site area with a gradual increase away from the mine sites. Outcrop exposures along the shores of Yellowknife Bay are well wave washed with minimal lichen cover.





1.3 Previous Geological Investigations

The Yellowknife Greenstone Belt has been prospected, mined, mapped, and debated for over 100 years and represents one of the best preserved slivers of Archean crust exposed on Earth. The <u>stratigraphy</u> has been addressed by: Jolliffe, (1938, 1942, 1946): Boyle, (1961): Henderson and Brown, (1966): Henderson, (1970, 1975, 1985), Helmstaedt et al., (1979): Helmstaedt et al., (1986): Helmstaedt and Padgham (1986a,b), Bullis et al., (1987): Padgham (1981, 1985, 1987): Bailey (1987): Relf (1988): Webb (1992).

The <u>structure</u> has been addressed by: Henderson and Jolliffe (1939): Jolliffe (1945): Campbell (1947a.b.c: 1948): Henderson and Brown (1950): Brown (1955): Boyle (1961): Henderson and Brown (1966): Drury (1977): Helmstaedt et al.. (1979): Hemlstaedt et al.. (1986): Helmstaedt and Padgham (1986a.b). Bullis et al.. (1987): Padgham (1981, 1985, 1987): Helmstaedt and Bailey (1987): Bailey (1987): Relf (1988): Webb (1992).

<u>Geochronology</u> of the intrusives, and basement rocks has been addressed by: Green and Baadsgaard (1971): Nikic et al. (1975, 1980): Bowring (in Padgham, 1985); Bowring and Padgham (1987): Isachsen and Bowring (1989); Henderson et al. (1987); Isachsen et al. (1991a,b,c); Faulk et al. (1991). Atkinson and van Bremman (1990); Atkinson and Fyfe (1991).

<u>Geochemistry</u> of volcanic flows and intrusions is discussed by: Baragar (1966); Jenner et al. (1981): Goodwin (1988): Cunningham and Lambert (1989); Webb (1992); Strand (1993).

Giant Yellowknife Gold Mine has been discussed by: Merrill (1947): Dadson and

Bateman (1948); Bateman (1952); Coleman (1957); Brown et al. (1958); Boyle (1961); Henderson and Brown (1966); Hodgson (1976); Brown (1989); Goucher (1991).

Con, Rycon. Negus gold mines have been discussed by: Breakey (1975, 1978); Campbell (1949); Lord (1951); Ridland (1941); Coulson (1950); Sproule (1952); Boyle (1955, 1959, 1961); Boyle et al., (1963); McMurdo (1975); Armstrong and Duke (1990, 1991); Armstrong (1991b, 1992, 1993); Strand and Duke (1990, 1991); Strand (1992, 1993); Webb (1992); McDonald et al. (1993); Duke and Nauman (1990); Duke et al. (1990). Bullis et al. (1987); Webb (1992) and within many unpublished internal mine documents.

General Yellowknife gold discussions have been presented by: Coleman (1953): Boyle, (1961); Boyle et al., (1963); Kerrich (1977); Kerrich et al. (1977); Kerrich and Allison (1978); Boyle (1961); McConnell (1964); Ames (1962); Lord (1951); Kerrich and Fyfe (1987, 1988); Wanless et al (1960); Relf (1988).

1.4 Field Work and Methodology

Field mapping, diamond drill core logging, underground mapping, sampling, petrography, and chemical analysis of rocks and minerals constitutes the database for this study. Core logging and field mapping were conducted on the Con Shear System through the winter and summer of 1990, and during the summer field seasons of 1991 and 1992. Underground examinations of the Con Shear were carried out during the summers of 1991 and 1992. Underground mapping of crosscuts and sampling of active stopes within the Campbell Shear were conducted during the 1992 summer field season. A total of 16 months were spent conducting field work and various geological tasks in the Yellowknife

area by the author.

Sample numbers and locations are listed in Appendix B. Several samples from the Negus portion of the Campbell Shear and the Fault Lake area were provided for use to the author by D. McDonald. Samples from Giant Yellowknife Mine were selected from the Suffel Collection at the University of Western Ontario. Sampling of mined out stopes within the Con Shear and the upper levels in the Campbell Shear was hampered by hazardous ground conditions and was restricted to areas around chutes and raises.

From this sample suite a total of 250 polished thin sections were prepared. A series of seven sulphide float concentrates were examined petrographically with the electron microprobe and by secondary ion mass spectrometry to determine the distribution and concentration of "invisible" gold in Fe-As sulphides.

Whole rock and trace element geochemical analyses were conducted on a total of 61 host, altered, and mineralised rock samples. Stable isotope geochemistry of carbonate minerals from host rocks, metasomatised zones and ore zones was conducted on samples from the Con Shear beneath Rat Lake.

1.5 Metallurgical Classification of Yellowknife Gold Ores

The recovery of gold from Yellowknife ores has proceeded by several metallurgical techniques during the past 55 years including cyanidation, amalgamation, roasting, and pressure oxidation (Campbell, 1949; Martin, 1990). For the purposes of this study a classification scheme for ore types will be applied to Yellowknife gold ores with particular reference to Con Mine, based on the metallurgical behaviour of the ores to traditional extraction techniques.

Cyanidation will dissolve native gold, electrum, and Au-Ag tellurides. The rate of dissolution for these minerals is dependant on particle size, degree of liberation, presence of surface coatings, exposure time to cyanide solutions, and presence of minerals that may consume cyanide (i.e. preg robbers such as aurostibite and other Sb minerals and carbonaceous material (Martin, 1990)).

The extraction of gold from gold bearing sulphides is entirely dependant on the style of gold crystallization: i) as inclusions in the sulphide; ii) along cleavage planes or fractures or iii) as solid solution "invisible gold". In all cases except the latter, the gold will be recoverable through cyanidation coupled with a fine grind. In the case of "invisible" gold the sulphide minerals must be oxidised either through roasting or pressure oxidation.

Floatation of sulphide minerals and free gold is used to generate a concentrate that may be roasted or subjected to pressure oxidation. Cyanidation of a float concentrate before roasting or pressure oxidation will recover free gold and any gold that may occur as inclusions within a sulphide: the remaining tails would contain all gold not recoverable by cyanidation and therefore refractory in nature.

The following classification scheme is followed throughout the present work and is based on a combination of cyanide recoveries, cyanide tails grade. floatation tails grade, and floatation recoveries:

i) FREE MILLING - cyanide recoveries of > 90%. cyanide tails grades of 0.01 to 0.06 ounces/ton Au and floatation tails grades of < 0.02 ounces/ton Au.

ii) REFRACTORY - cyanide recoveries of less than 50%, cyanide tails grade ranges from 0.01 to 0.26 ounces/ton Au, floatation tails grade 0.09 to 0.44 ounces/ton Au and

floatation recoveries of less than 35%. This classification also includes material with cyanide recoveries of less than 75% (17 - 75%), combined recoveries of > 73%, cyanide tails range from 0.142 to 0.23 ounces per ton Au, floatation tails grade 0.03 to 0.07 ounces/ton Au and floatation recoveries of > 55%.

Previous metallurgical studies of Con Mine ores indicate that an increase in fineness of the grind will not improve cyanide recoveries for refractory ores (Martin 1990; Chyrssouliss 1990) and there is no evidence for preg-robbing (Maltby, 1990).

CHAPTER 2

GENERAL GEOLOGY

2.1 Introduction

The Archean Slave Province occupies approximately 190 000 km² of the northwestern Canadian Shield. It is bordered to the south and east by the Proterozoic Churchill Province, to the west by the Proterozoic Bear Province, and to the southwest by Paleozoic rocks of the Interior Platform. Proterozoic sedimentary rocks of the Goulborn Group to the northeast and the Anthapuskow Group of the east Arm of Great Slave Lake to the south unconformably overlie Archean rocks. The Slave Province is comprised of 35-40% supracrustal and 60% granitic gneiss and granite. The volcanic and sedimentary supracrustal rocks are collectively termed the Yellowknife Supergroup with a lesser abundance of volcanic (20%) than sedimentary (80%) rocks (Henderson, 1970: Henderson, 1981: McGlynn and Henderson, 1972: Padgham, 1985). The abundance of sedimentary rocks within the Yellowknife Supergroup distinguishes the Slave Province from typical granite-greenstone belts that volumetrically contain more volcanic rocks than sedimentary rocks.

Pre-Yellowknife Supergroup sialic basement rocks have been identified at several localities. In the Point Lake - Itchen Lake area a granodiorite intercalated with heterogenous orthogneiss and migmatic gneiss yielded a U - Pb date of 3155 + /- 3 Ma (Krogh and Gibbins, 1978): the Acasta tonalite gneiss at the western border of the Slave Structural Province yielded a U - Pb date of 3.964 Ga +/- 3 Ma (Bowring et al., 1989): gneissic fragments included in a minette diatreme dyke located in the underground workings of the Con Mine at Yellowknife have y

of 3210 and 3300 - 3040 Ma (Nikic et al., 1975, 1980). Yellowknife Supergroup greywackes from the Point Lake - Itchen lake area yield a population of detrital zircons dating from 2800 to 3130 Ma (Sharer and Allegre, 1982). In the Dywer Lake area north of Yellowknife, fuchsite-bearing quartzo-feldspathic rocks occurring within a narrow band of felsic volcanic rocks and chert magnetite iron formation at the base of the Kam Group, first recognised by Helmstaedt and Padgham (1986a), yield detrital zircons exhibiting a U - Pb date of 3.0 Ga (Bowring, in Padgham, 1991) and U - Pb dates in excess of 2.9 Ga to greater than 3700 Ma (Isachsen et al., 1991a).

Slave volcanic rocks comprise a series of 26 narrow northerly-trending greenstone belts that have been separated into two general types: 1) Yellowknife-type with a thick lower unit of basalt variably capped by felsic volcanic rocks: and 2) Hackett River-type felsic dominated belts (Padgham, 1985). Greenstone belts occupy three discontinuous zones: mafic dominated belts occur in western and central zones while the felsic dominated belts occur in the eastern zone of the Slave Province (Padgham, 1985; Mortenson et al. 1988; Figure 2.1). Initial volcanism for both types of greenstone belt is believed to be felsic in composition (Helmstaedt and Padgham, 1986a,b). Basaltic komatilitic volcanic rock units have only recently been identified in the south-central and centrally located greenstone belts (Hrabi et al., 1992; Johnstone, 1992).

There is a distinctly bimodal distribution of ages for volcanism within the Slave Province. Early volcanism occurred between 2698 to 2687 Ma within the felsic volcanic dominated eastern zone and northern portions of the central zone (Mortenson et al., 1988). as well as within the mafic dominated portion of the Yellowknife greenstone belt (2716 to 2683 Ma; Isachsen et al., 1991b). After an hiatus of 15 - 20 Ma, mafic and



Figure 2.1 Generalised geology of the Slave Province. Modified from Padgham, 1985.

intermediate volcanism ranging from 2675 to 2663 Ma occurred across the central and western Slave Province (Mortenson et al., 1988). This later event broadly coincides with sedimentation within extensive turbidite basins (Padgham, 1985) and potentially coincided with the onset of late Archean granite plutonism (Helmstaedt and Padgham, 1986a,b).

It has been concluded on the basis of gravity survey results (Gibb and Thomas. 1980: McGrath et al., 1983) that the turbidite basins form a thin (5 km) veneer overlying granitic basement. This basement is comprised of older sialic gneisses and younger granites (Henderson, 1981: 1985). The granite domains exposed both peripheral to and internal to the supracrustal domains are comprised of mixed migmatites and granitic gneisses that may be derived from anatexis of the supracrustal sequences. The suite of 2.6 to 2.55 Ma granitic batholiths range in composition from granodiorite - quartz diorite - quartz monzonite to peraluminous granite. The emplacement of the granite suite occurred coeval with regional metamorphism. It is not apparent how extensive the volcanic rocks were prior to the formation of turbidite basins, deformation and the intrusion of late granites (Fyson and Helmstaedt, 1988).

Four main tectonic strategies have been presented to explain regional tectonostratigraphic relationships in the Slave Province. McGlynn and Henderson (1972) and Henderson (1981, 1985) suggest that the Yellowknife Supergroup was deposited on pre-existing sialic crust, infilling intracontinental rift basins. Yellowknife Group volcanism occurred along basin margin faults which later provided avenues for plutonism. Hoffman (1986) invokes a prograding arc-trench system (unspecified direction) comprised of arc volcanic and plutonic rocks, fore-arc basin deposits, and exotic blocks which may include seamounts, ophiolitic and sial fragments scrapped off subducting oceanic

lithosphere. Helmstaedt et al. (1986). Helmstaedt and Padgham (1986a), and Fyson and Helmstaedt (1988) suggest that some of the greenstone belts may have formed as the result of ocean floor spreading and represent preserved segments of obducted oceanic crust (ophiolites) formed within proto-oceanic or back-arc basins. Fyson and Helmstaedt (1988) suggest that closure of such basins during east-dipping subduction resulted in arc magmatism in the eastern Slave Province and eventual collision of an arc with the subduction complex. Kusky (1989, 1990, 1991) presents a more elaborate accretionary model, dividing the Slave province into four terranes: i) Hackett River terrane (magmatic island arc): ii) Contowyto terrane (accretionary prism): iii) Anton terrane (microcontinental fragment): and iv) Sleepy Dragon terrane (Anton terrane equivalent) and suggests collision of the Contowyto terrane with the older Anton microcontinent during east-dipping subduction.

Presently, there is no clear consensus as to which model best explains regional relationships (Padgham, 1991). The more recent recognition of a mature clastic succession that predates the Yellowknife Supergroup (Helmstaedt and Padgham, 1986a.b: Padgham, 1991) suggests that a stable platform existed prior to the onset of rifting, volcanism, and formation of turbidite basins. Lack of detailed geochronological work within most greenstone belts coupled with problems emerging between traditionally accepted stratigraphic correlations and recent age determinations within the Yellowknife greenstone belt (Isachsen et al., 1991b) make evaluation of any proposed geotectonic model premature.

2.2 Geology of the Yellowknife Greenstone Belt

The Yellowknife Greenstone Belt, located in the southwestern corner of the Slave Province, is 5 to 8 kilometres wide and about 50 kilometres long. It is bordered to the west by the composite Western Plutonic Complex, to the southeast by the Southeastern Plutonic Complex, and to the east by sedimentary rocks of the Burwash Basin (Figure 2.2). The stratigraphic scheme currently employed for the Yellowknife Greenstone Belt was introduced by Henderson (1970, 1975) and is largely based on re-interpretation of earlier stratigraphic work (Jolliffe, 1942, 1946; Henderson and Brown, 1950, 1966; Boyle, 1961). Helmstaedt and Padgham (1986a,b) presented a revised stratigraphic column that is broadly similar to the Henderson and Brown (1966) layer cake stratigraphic model for the Yellowknife area (Figure 2.3).

The Yellowknife Greenstone Belt forms a southeast younging and facing monoclinal succession, possibly occupying the western limb of a poorly defined synclinal fold that underlies Yellowknife Bay (Helmstaedt and Padgham, 1986a, 1986b). In the immediate Yellowknife area pre-Yellowknife Supergroup basement has only been identified in the form of gneissic fragments included in a diatreme dyke located in the underground workings of the Con Mine which have yielded discordant Pb - Pb minimum ages of 3210 and 3300 - 3040 Ma (Nikic et al., 1975, 1980). The Dywer Formation, a quartzite-rhyolite-banded iron formation assemblage structurally underling the northern portion of the belt yields, detrital zircons with Pb - Pb ages of 2.9 to greater than 3.7 Ga. Zircons from the overlying rhyolite unit have complex U - Pb systematics that suggest an age in excess of 2.8 Ga (Isachsen et al., 1991a).

Helmstaedt et al. (1979) and Helmstaedt and Padgham (1986a,b) identified



Figure 2.2 General geology of the Yellowknife Greenstone Belt. From Helmstaedt and Padgham, 1986a.





metamorphosed sedimentary rocks and volcanic rocks occurring structurally below Yellowknife Group volcanic rocks at the southern end of the Yellowknife Greenstone Belt. This assemblage, termed the Octopus Formation, is comprised of metamorphosed basic tuffs and flows lacking in primary depositional features overlain by metasedimentary rocks composed of greywackes, siltstones, and conglomerates. Pebbles in the Octopus conglomerate are dominated by metasedimentary rocks but include amphibolites, rhyolite porphyries and rare granitoids. Structural layering within the Octopus Formation is discordant to bedding-cleavage relationships in the overlying Kam and Banting Groups and the upper contact of the Octopus Formation forms an angular disconformity with the Kam Group. This evidence led Helmstaedt and Padgham (1986a.b) to suggest the Octopus predates Kam volcanism. The relationship between the Octopus and Dywer Formations is unclear but both may represent preserved slivers of a pre-Yellowknife Greenstone belt cycle deposited on old sialic crust.

As defined by Helmstaedt and Padgham (1986a.b). the Kam Group. previously referred to as the Kam Formation by Henderson (1970). and including most of the mafic volcanic rocks allocated to Division A by Jolliffe (1942. 1946) and Henderson and Brown (1950. 1966) forms a homoclinal sequence of southwest-trending and southeast younging basaltic flows with an aggregate thickness in excess of 10 kilometres. The Kam Group has been separated into four formations based on the occurrence of stratigraphic markers. variations in volcanic geochemistry. and presence of syn-volcanic intrusions (Helmstaedt and Padgham 1986a.b).

The formations from lower to upper that comprise the Kam Group include the Chan, Crestaurum. Townsite, and the Yellowknife Bay Formation. The Chan Formation is approximately 6 kilometres thick. However, the bottom portion has been intruded and assimilated by the Western Plutonic Complex so the original true thickness is unknown (Helmstaedt and Padgham 1986a,b). It is comprised of massive and pillowed basalts intruded by numerous gabbroic bodies (sills, irregular bodies, and dykes) that appear to be contemporaneous with the volcanic flows (Henderson and Brown 1966; Helmstaedt and Padgham, 1986a). Mafic dyke swarms within the Chan Formation have been compared to sheeted dyke complexes within ophiolites (Helmstaedt et al., 1986; Helmstaedt and Padgham, 1986a). The upper boundary of the basal Chan Formation is marked by the Ranney Chert that has yielded Pb - Pb dates of between 2.85 and 2.9 Ga (Isachsen et al., 1991a).

The overlying Crestaurum Formation is approximately 2 kilometres thick, and is primarily comprised of massive to pillowed mafic flows. It includes two laterally continuous variolitic pillowed units, the Stock and Fox Flows and two laterally continuous ash flow and cherty tuff units identified as the Cemetery Tuffs (Henderson and Brown, 1966). The Trapper Lake Tuff has been interpreted as correlative (Henderson and Brown, 1966). Geochronology of the Cemetery Tuff (U - Pb date: 2712 + /- 2Ma) and the Trapper Lake Tuff (U - Pb date: 2707 + /- 2Ma) by Isachsen et al., (1991b) generally supports the original correlation of Henderson and Brown (1966). The upper boundary of the Crestaurum Formation is located at the base of the Townsite Formation (Helmstaedt et al., 1986a).

The overlying Townsite Formation is comprised of interbedded rhyodacite breccias, tuffs, locally welded tuffs, and pillowed dacites (Helmstaedt and Padgham, 1986a; Henderson and Brown, 1966). The Townsite Formation has been separated into
the Niven Lake. Brock, and Vee Lake lenticles by faulting. Correlation of these separate lenticles based on stratigraphic arguments (Henderson and Brown, 1966; Helmstaedt and Padgham, 1986a) has not yet received full consensual agreement (Webb, 1992). Specific stratigraphic correlations are not borne out by available U - Pb dating. Henderson et al. (1987) report a U - Pb date of 2684 +16/-24Ma for the Niven Lake lenticle. Isachsen et al. (1991b) report U - Pb dates for the Niven Lake. Brock, and Vee Lake lenticles of 2683 ± 10^{-5} Ma, 2703 ± 10^{-2} Ma, and 2705 ± 10^{-3} Ma respectively.

The overlying Yellowknife Bay Formation is continuously exposed for 6.5 kilometres along the western shore of Yellowknife Bay from the Giant Mine section in the north to Kam Point in the south. Since the upper contact of the Yellowknife Bay Formation is truncated by a poorly exposed unconformity beneath the Jackson Lake Formation or occurs beneath the waters of Yellowknife Bay a true formational thickness is not known but is likely more than 5 kilometres (Helmstaedt and Padgham, 1986a). The Yellowknife Bay Formation is comprised of massive to pillowed flows with minor intercalated pillow breccia and two laterally continuous variolitic marker horizons, the Negus and Yellorex flows as well as numerous cherty tuff horizons that form laterally continuous marker horizons (Henderson and Brown, 1966; Campbell, 1948). The Bode Tuff that directly overlies the Yellorex flows yields a U - Pb zircon date of 2688 +/-3Ma (Isachsen et al., 1991b). Cherty tuff horizons become more prolific toward the top of the Yellowknife Bay Formation from Kam Point south. This section is infested with thick gabbro sills approaching an apparently conformable contact with the overlying Banting Group. A felsic unit at the top of the Yellowknife Bay Formation at Kam Point yielded a U - Pb zircon date of 2716 +/-9Ma interpreted by Isachsen et al. (1991b) to represent

its depositional age. This interpretation of this old date raises considerable questions regarding any simple layer cake stratigraphic model.

The tholeiitic Kam Group is variably tectonically juxtaposed. regionally unconformably, and locally conformably overlain by felsic to intermediate flows, tuffs, agglomerates and sedimentary rocks of the calc-alkaline Banting Group (Helmstaedt and Padgham, 1986a.b). The Banting Group is approximately 2 kilometres thick and has been separated into the Ingraham and Prosperous Members, that are bes: exposed north of Yellowknife Bay (Helmstaedt and Padgham, 1986a.b: Bailey, 1987). The Ingraham and Prosperous Members are conformably overlain by the Walsh Formation which interfinger with turbiditic sedimentary rocks of the Burwash Formation. Banting Group equivalents occur on Navigation Island. Latham Island. Jolliffe Island, Mosher Island, on the Sub Islands, and on the Mirage Islands in Great Slave Lake (Bailey, 1987; Relf, 1988). U - Pb zircon dating of Banting Group volcanic rocks has yielded dates of 2667 +4.1/-4.0Ma (Bowring, in Helmstaedt and Padgham, 1986b), 2670 +/- 14Ma (Henderson et al., 1987), and 2.66 to 2.68 Ga (Isachsen et al., 1991c).

The Kam and Banting Groups are intruded by several stages of mafic dykes and sills. In the northern basal portion of the belt the Chan Formation is intruded by anorthosite sills and crosscut by sheeted gabbro dykes. The irregular shaped gabbro bodies suggest an intimate relationship between intrusion of gabbro and formation of the volcanic pile. The presence of sheeted dykes within the Chan Formation may record an early spreading event (Helmstaedt et al., 1986: Helmstaedt and Padgham, 1986a,b). Other major gabbroic textured sills intrude the Townsite Formation and occur at the top of the Yellowknife Bay Formation (i.e. Kam Sills). The Yellowknife Bay Formation.

forming the southern portion of the belt is crosscut by numerous gabbro textured dykes locally comprising up to 50% of the rock volume (Henderson and Brown. 1966). These dykes trend NNW, are steeply west-dipping and increase in intensity and abundance with closer proximity to the Western Plutonic Complex contact. The dykes provide avenues for the injection of granite apophyses. Possibly the earliest appearance of granite is synchronous with the latest stages of dyking (Strand, 1993). Swarms of dykes also follow the granite contact to the north but are noticeably absent on the east side of the West Bay Fault in the vicinity of the Giant Yellowknife Mine.

The Jackson Lake Formation, a succession of cross-bedded sandstones and polymictic conglomerates that unconformably overlies and separates the Kam and Banting Groups (Helmstaedt and Padgham, 1986a,b). The Jackson Lake Formation represents the youngest known clastic sedimentary unit in the Slave Province (Mueller et al., 1993). The provenance of cobbles within conglomerates is dominated by mafic flow sources with lesser intermediate and felsic tuff and subordinate plutonic sources (Mueller et al., 1993). Other lithologies found in the conglomerate include vein quartz, ferruginous carbonate, argillite, green mica schist, and jasper (Henderson and Brown, 1966). The Jackson Lake Formation is interpreted to be deposited on an irregular erosional surface with topographic relief of up to 100 metres (Henderson and Brown, 1966) as terrigenous alluvial fans and/or fan deltas (Mueller et al., 1993) into fault controlled basins (Helmstaedt and Padgham, 1986a). Granitic cobbles at the base of the Jackson Lake Formation have been dated from several localities and yield dates of 2609 +/-8Ma (U -Pb zircon. Falck et al., 1991), 2609 +/-6Ma (U - Pb zircon, Isachsen and Bowring, 1989), 2605 +/- 7Ma (U - Pb zircon, Isachsen et al., 1991c), and of 2.554 and 2.534

Ga (Pb - Pb minimum ages) by Green and Baadsgaard (1971) and corrected by Easton (1984).

The Yellowknife Greenstone Belt is intruded both to the west and southeast by large composite batholiths. The Western Plutonic Complex forms the southern extent of a batholith that extends for over 600 kilometres along the western margin of the Slave Structural Province (Atkinson and Fyfe, 1991). Atkinson and van Breeman (1990) defined five separate phases of the Western Plutonic Complex (oldest to youngest): i) Anton Complex - a strongly deformed metaluminous tonalite - amphibolite - gneiss; ii) Defeat Suite (lower) - tonalite and granodiorite, layered hornblende gabbro and diorite along eastern margin of the Defeat phase are considered younger than a U - Pb zircon age of 2634 +/-5Ma (Atkinson and van Breeman, 1990); iii) Defeat Suite (upper) porphyritic biotite trondhjemite - granodiorite and granite plutons that locally intrude the Yellowknife Greenstone Belt vielding U - Pb zircon dates of 2618 +7/-20Ma, 2620 +/-8Ma (Henderson et al., 1987), 2621 +5/-8Ma (Atkinson, personal communication, 1993); iv) Awry Complex - peraluminous granite plus aplite-pegmatite-quartz veins, yielding U -Pb zircon dates of 2550-2530 Ma (Henderson et al., 1987), 2525 - 2585 Ma (Atkinson and Fyfe, 1991), and 2560 +/- 2Ma (Atkinson, personal communication, 1993); and v) Duckfish - Stagg Granite - alkali tonalite-amphibolite representing remobilised portions of the Anton Complex and equivalent to the Prosperous Lake suite of intrusions. U - Pb zircon dates for Stagg Granite are 2581 +29/-24Ma (Henderson et al., 1987) and 2589 +11/-9Ma (Atkinson and van Breeman, 1990; Atkinson and Fyfe, 1991), U - Pb zircon dates for the Duckfish Granite are $2585 \pm -4Ma$ (Atkinson and van Breeman, 1990; Atkinson and Fyfe, 1991).

The Southeastern pluton has yielded U - Pb zircon dates of 2618 + 7/-20Ma and is considered part of the upper Defeat Complex (Henderson et al., 1987). Relf (1988) inferred that part of a batholith lies east of the Mirage Islands under the waters of Great Slave Lake, thereby bracketing the Yellowknife Greenstone Belt to the south, east, and west by batholiths (Figure 2.4).

Several small stocks and plugs occur as satellite intrusions to the Western Plutonic Complex in the vicinity of the Con Mine (Strand, 1993). The Pud Stock is a trondhjemite quartz-feldspar plug yielding a U - Pb zircon date of 2634 +11/-10Ma (Strand, 1991); thus representative of the earliest phase of Defeat plutonism. A highly evolved trondhjemite exposed on the 950 Level of the mine workings, termed the Negus Porphyry hosts anomalous Au - Mo mineralization. The general attitude, shape and date have yet to be determined (Boyle, 1961: Henderson and Brown, 1966; Strand, 1993).

Three suites of diabase dykes intrude the Archean basement at Yellowknife. The older Dogrib dykes trend north-easterly and have a fixed Rb-Sr date of 2635 ± -80 Ma (Gates and Hurley, 1973; as reported in Easton, 1984). The Indin dyke swarm forms northwesterly and northeasterly trending sets dating at 2049 ± -80 Ma (Gates and Hurley, 1973; as reported in Easton, 1984) and these are offset by late brittle faults of Proterozoic age. The youngest Mackenzie swarm are rare in the Yellowknife region and these trend north-westerly and have K/Ar dates of 1200 ± -100 Ma (Leech, 1966).





2.3 Prograde Metamorphism

The rocks of the Yellowknife Greenstone Belt have been subjected to prograde contact metamorphism related to the intrusion of the bordering plutonic complexes. Metamorphic isograds generally parallel the granite-greenstone contacts. Boyle (1961) distinguished three metamorphic facies on the basis of mineralogy and field characteristics: amphibolite (dark black in outcrop. Ca-hornblende dominated with no groundmass epidote), epidote-amphibolite (light green in colour, actinolite dominated with groundmass epidote) and greenschist facies. More recently Duke and Nauman (1990) recognised the presence of slivers of garnet-amphibolite facies rocks along non-tectonised contacts of the Western Plutonic Complex. The metamorphic rank of the volcanic rocks rapidly decreases away from the granite-greenstone contact and within 2-3 kilometres the rocks are greenschist facies (Figure 2.5). In detail, isograds are transitional in nature and their spatial distribution is further complicated by both early ductile shearing and later brittle faulting.

Within the Yellowknife Bay Formation textural and mineral chemical relationships indicate the volcanic rocks have been subjected to only one period of prograde metamorphism. Intersecting metamorphic isograds within Burwash Formation turbidites in the vicinity of Jennejohn. Reid. and Buckham Lakes (Henderson, 1985) indicate that there has been two thermal metamorphic events: an older Defeat phase event (circa 2620Ma) followed by a younger Prosperous phase event (circa 2550Ma). Webb (1992) suggests that Prosperous age metamorphism overprints the Yellowknife Bay Formation in the vicinity of the Con Mine, however Prosperous Lake suite intrusions are well removed geographically (greater than 15 km to the northeast and 30 km to the west) from



Figure 2.5 Distribution of regional contact metamorphic isograds in the immediate vicinity of the Con Mine. From McDonald et al., 1993.

the mine site and no textural evidence has been presented to support multiple prograde events.

2.4 Retrograde Shear Systems

Within the Yellowknife Greenstone Belt shear zones have been divided into 2 different categories on the basis of their structural characteristics and relative age (Henderson and Brown, 1950; Boyle, 1961; Henderson and Brown, 1966); i) shear zones that parallel stratigraphy in strike and dip. and ii) shear zones that transect stratigraphy. Gold mineralization occurs in both types of shears although all economic gold is concentrated within shears that transect volcanic stratigraphy (Boyle, 1961).

Shear zones that parallel stratigraphy commonly are sited at flow contacts. within incompetent units such as cherty tuff horizons, or flow breccias. The Kam Point, Ranney, and A.E.S systems represent the three major bedding-parallel shears that have been described in any detail. All occur within felsic tuff horizons (Boyle, 1961: Henderson and Brown, 1966). Small pockets of high grade gold lenses discovered in the Kam Point System (Dean McDonald, pers comm., 1990) and the A.E.S System (Boyle, 1961) are hosted within narrow quartz veins (30 - 50 centimetres) associated with arsenopyrite, pyrite, and lesser sulphosalts. The parallel shear systems offset late gabbro dykes injected within the flows. In places these are in turn offset by shears that transect stratigraphy and are further offset by later brittle faults. Bedding parallel shears have not been traced into the granite intrusions (Boyle, 1961: Henderson and Brown, 1966).

Shear systems that transect volcanic stratigraphy host all known economic gold deposits in the Yellowknife camp. These shears transect stratigraphy at a relatively

oblique angle. The major crosscutting shear zone systems include the Con. Negus-Rycon. and Campbell west of the West Bay Fault. and the Giant. Bow Lake. and Crestaurum Systems east of the West Bay Fault. Henderson and Brown (1950, 1966) further subdivided these shears into two related subcategories: i) well defined quartz veins hosted in narrow shears (e.g. the Negus-Rycon veins) and ii) quartz veins hosted in large mineralized chlorite-carbonate-sericite schist domains (e.g. the Campbell, Giant). The Con and Campbell systems are subparallel, trending NNE with moderate to steep westerly dips within the Yellowknife Bay Formation. The Negus-Rycon Shears are a narrow NNW trending vein set with moderate to steep west dips commonly paralleling the contacts of late mafic dykes.

The Giant Shear System transects rocks of the Crestaurum. Townsite. and Yellowknife Bay Formations of the Yellowknife Greenstone Belt. Correlation of shear segments is complicated by the anastomosing nature of the shears and post-ore brittle faulting (section 2.6). The Giant Shear System has generally been interpreted as the fault offset continuation of the Campbell Shear System (Campbell 1947a.b.c, 1948, 1949; Henderson and Brown, 1950, 1966; Boyle, 1961). The fault offset of the Con Shear System is believed to outcrop approximately 300 metres northwest of the apparent hangingwall of the Giant System (Boyle, 1961). Although this has been contested (Webb, 1992) to date no convincing alternative models have been proposed.

The southern portion of the Giant Shear System is a northerly trending steeply west-dipping structure that subcrops beneath the waters of Fault Lake. The extreme footwall of the system lies under Back Bay coincident with the Kam Group-Banting Group contact. North of Fault Lake the southern extent of mining within the Giant Shear



Figure 2.6 Southern portion of the Yellowknife Greenstone Belt with location of major retrograde shears that transect stratigraphy and major brittle fault systems.

System is located within the west-dipping NNE trending Cameron. East. South. West, and Creek zones north of the AYE fault.

Other strands of the Giant System that have been exploited include the Bow Lake and Crestaurum systems. The Bow Lake Shear System occurs east of the Giant shear system and trends subparallel to the Giant System with a shallow 30° - 50° west dip. The Bow Lake System joins the A.S.D. zone at depth and to the north adjoins the Muir zone. Ore bodies are located at the junction of the Bow Lake and A.S.D. zones (Boyle, 1961; Henderson and Brown, 1966). The Crestaurum System within the Crestaurum Formation occurs in the northern portion of the Yellowknife Greenstone Belt. The shear zone trends northeasterly with a moderate 50° SE dip. ore bodies tend to have a northeasterly pitch. limited mining was conducted during 1945 and 1946 although no gold was produced (Lord, 1951).

The more recent recognition of major shear systems within the Banting Group indicates that shear zone development is not restricted to Kam Group mafic volcanic rocks. Exploration in the Banting Lake/Walsh Lake area has identified numerous gold bearing shears within felsic volcanic rocks (e.g. Sam Otto zone) and historic exploration also identified numerous gold bearing quartz veins in Walsh Formation turbidites (Lord, 1951). Examination of outcrop exposures of Banting felsic volcanic rocks and intercalated intermediate flows north of Yellowknife Bay and south of Walsh Lake located numerous previously identified and sampled iron carbonate altered shears with variable quartz veining and development of chrome mica. Diamond drilling conducted by NERCO in 1991 and 1992 encountered auriferous shears in the Banting Group both east and west of the West Bay Fault under Yellowknife Bay (Armstrong and McDonald, 1991). Known gold potential within shears transecting the Banting Group is hampered by the lack of any concerted exploration effort within this domain.

2.5 Brittle Fault Structures

The Yellowknife Greenstone Belt has been disrupted by at least two ages of postore and post-diabase brittle faulting. Details of offsets and relationships to gold mineralization have attracted the attention of most workers in the Yellowknife region (Jolliffe, 1942; Campbell, 1947a,b,c, 1948, 1949; White et al., 1949; Henderson and Brown, 1950, 1966; Brown, 1955; Boyle, 1961; Helmstaedt and Padgham 1986a, 1986b; Helmstaedt and Bailey, 1987; Webb, 1992). The West Bay - Indin Lake fault system is a network of north northwesterly-trending strike slip faults that extends for over 100 km from Yellowknife to the Indin Lake Area (Henderson and Brown, 1966). In the Yellowknife area the major north-northwesterly trending faults are the Kam, West Bay, and Hay Duck faults. Subsidiary cross over faults between the major faults are the Pud. Martin, AYE, Townsite, and Akaticho faults (Figure 2.6). Movement across vertically dipping subsidiary faults is dominantly horizontal with a left-hand sense of displacement (Brown, 1955). Henderson and Brown (1950, 1966) systematically determined the offset of key stratigraphic horizons. Offsets indicated by the strike displacement of stratigraphic horizons characteristically vary along the fault (Brown, 1955) as a result of additive movement due to subsidiary faults joining the dominant fault structures planes (Henderson and Brown, 1950, 1966; Brown, 1955).

Henderson and Brown (1966) describe four groups of late brittle faults, the dominant group is represented by the NNW trending faults. A set of complimentary NNE trending faults forms at right angles to the dominant NNW faults. In the southern part of the belt this complimentary set of faults parallels flow contacts, in the northern part of the belt where stratigraphy has a more northerly trend these faults crosscut flows. Movement across the subsidiary faults is dextral with moderate displacements of less than 30 metres, locally increasing toward their junctions with the major sinistral NNW trending faults (Henderson and Brown, 1966). A third set of faults occur as east-southeast trending dextral tension faults inclined at 45° to the principal fault direction. Displacement across these are in the order of 2 to 30 metres. The fourth set of faults trend northeast parallel to stratigraphy but have near vertical dips with a sinistral sense of displacement. The Negus Fault is the most important of these faults with its south side calculated to have moved 660 feet east and 100 down relative to the north side (Henderson and Brown, 1966; Brown, 1955). This fault set displaces ore bearing shears and dykes but is offset by the NNW set of late faults indicating long lived movement along brittle fault structures.

With the exception of the Negus Fault and the southeast trending tension faults traces of late brittle faults appear as distinct linear features on airphotos. The major West Bay fault is commonly defined by a gouge zone that may only be several inches wide although locally the fault is marked by a zone of intense quartz and hematite flooding within wide (100 metre) zones of fault breccia and cataclasite. Spectacular outcrops of this phenomena are exposed at Ranney Hill where there is a slight inflection in the strike of the West Bay Fault to a more NW trend south of the junction with the Akaitcho Fault. A similar fault breccia/cataclasite with quartz and hematite flooding was intersected in a diamond drill hole A-81 collared by NERCO at the south end of Back Bay. This brecciation occurs along a segment of the West Bay Fault transecting rocks of the Townsite Formation (Armstrong and McDonald, 1991). At this location the West Bay Fault zone is a 45 metre wide zone of brecciation with local 3 to 4 metre wide salmon red zones of cataclasis characterised by intense quartz and hematite flooding and minor disseminated pyrite (Armstrong and McDonald, 1991).

Lack of suitable marker horizons hampers the determination of vertical movement on the late brittle faults. Campbell (1947a.b.c: 1948) used several Indin diabase dykes as markers to calculate the vertical (525 metres) and horizontal (5380 metres) slip across the West Bay Fault. with the east side moving down and south relative to the west side of the fault. Brown (1955) used the Cemetery tuff horizon and an Indin diabase as suitable horizons to calculate a vertical slip of 300 metres and a horizontal slip of 5366 metres with the east side moving down and east relative to the west side of the West Bay Fault. Campbell (1947a.b.c: 1948) used the West Bay Fault resolution to predict the continuation of Giant Shear gold mineralization at depth on the Negus and Con/Rycon properties to the south. Diamond drilling confirmed Campbell's hypothesis. Since the successful fault resolution of Campbell (1947a.b.c: 1948) the Giant and Campbell shears have been considered offset portions of a once continuous shear system.

CHAPTER 3

CON MINE GEOLOGY

3.1 Introduction

The Con Mine is located at the southern outskirts of Yellowknife. Gold mineralisation is sited within ductile shears transecting the flows of the Yellowknife Bay Formation immediately overlying the Townsite Formation. The detailed geology of the mine site has recently been reviewed by Bullis et al. (1987). Webb (1992). and Strand, (1993). In the immediate area of the Con Mine the Yellowknife Bay Formation has been subdivided into several informal members. For the purpose of the present work emphasis is placed on defining prograde metamorphic and retrograde metasomatic alteration in host rocks to mineralisation.

3.2 Host Lithologies

3.2.1 Volcanic Flows

Geographic reference points and general geology are depicted on maps 3.1a,b in the back pocket. The volcanic units stratigraphically above the Townsite Formation are described from north to south. Descriptions are referenced to location with respect to the hangingwall and footwall of individual shear strands (Figure 3.1). The host flows have a uniform NE trend, striking 050°-060°, have a steep SE dip. and consistently young to the southeast.

Massive to pillowed flows form a series of thin (5-10 metre thick) laterally continuous units. These flows change in colour from buff apple green, dark green, to black approaching the Western Plutonic Complex. Pillowed and massive flow contacts



Figure 3.1 Distribution of regional contact metamorphic isograds and retrograde shear zones in the immediate vicinity of the Con Mine. From McDonald et al., 1993.

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

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are generally sharp. Massive flows occasionally have coarse to medium grained bases that fine upward into pillow sequences. The coarser grained flows are characterised by a meta-gabbroic texture with coarse interlocking sheafs of calcic amphibole, plagioclase and medium to fine-grained ilmenite. Pale green units with pillowed variolitic flow tops are well exposed on Tin Can Hill and persist into the hangingwall of the Campbell Shear. Pillow forms generally are well preserved but with localised flattening becoming more frequent toward the Western granodiorite. Selvages are rusty due to iron carbonatechlorite-epidote-pyrite alteration. Pillow flows are characterised by fine feathery calcic amphibole intergrown with plagioclase, and ilmenite. Drainage cavities are infilled with quartz-epidote-carbonate. In the vicinity of the C-1 Shaft exposures of flow breccia occur hangingwall to the Con Shear. Flow breccias may attain widths of several 10's of metres. Pillow breccias are comprised of angular to sub-angular basalt fragments in a biotitic matrix the pillow fragments range from 1 to 10 centimetres in size and may exhibit bleached reaction rims.

3.2.2 Gabbroic Intrusives

Variably textured synvolcanic gabbroic sills parallel the volcanic stratigraphy and exhibit textures similar to massive flows and are not described further. Coarse textured gabbroic sills are especially common within the underlying Townsite Formation and also near the top of the Yellowknife Bay Formation. Well defined sills are lacking within the immediate flow sequence at the mine. A peculiar gabbroic textured sill/dyke both subparallels and transects the Con Shear through the mine site and is referred to as the Arsenic Pond Gabbro. Numerous types of mafic dykes have injected the stratigraphic pile: these are described by Strand (1993) whose nomenclature has been adopted for the purpose of the following synopsis.

3.2.2.1 Arsenic Pond Gabbro

A leucocratic 10-15 metre wide, NNE to N trending, shallow west-dipping dioritic to gabbroic, light weathering dyke transects stratigraphy footwall to the Con Shear System from south of the Pud Fault to the north end of Rat Lake and has a total strike length of greater than 7 kilometres (Henderson and Brown, 1966). North of Rat Lake the dyke outcrops between the northernmost splays of the Con Shear and continues along a large outcrop hangingwall to the Campbell Shear. The dyke has a characteristic mottled greenish-grey weathered surface with 5-10% dispersed bone white plagioclase phenocrysts in a light green-grey groundmass of fine to medium grained feathery to equant amphibole. Major element geochemistry is similar to that of the sheeted calc-alkaline dykes although REE geochemistry profiles are similar to the tholeiitic flows.

3.2.2.2 Late Gabbro Dyke Suite

Normal tholeiitic to Fe-Ti tholeiitic dykes are the most abundant variety located on the mine site. They have been interpreted as feeders to volcanic flows by Henderson and Brown, (1966) and Helmstaedt and Padgham (1986). However recent work suggests that dyke injection post-dates rotation of volcanic rocks to near vertical yet pre-dates granite intrusion (Duke, 1990; Duke and Strand, 1990; Strand, 1993). Dykes trend 160°/50-60°W through the mine yard. There is an apparent increase in abundance toward the contact of the volcanic rocks and the Western Plutonic Complex where dykes may comprise greater than 50% of outcrop exposures but they do not penetrate into the granite and show the same prograde metamorphic overprint as the adjacent volcanic flows.

Individual dykes vary in width from 1 to 10 metres, many show internal chills and thin < 50 cm hornfelsed domains in bordering volcanic rocks. The identification of chill margins may be used to distinguish flows from dykes however hornfelsing of bordering volcanic rocks makes dyke margins difficult to distinguish. The fine-grained internal chills are black due to the abundance of amphibole. Normal tholeiitic dykes host plagioclase phenocryst trains parallel to contacts. Fe-Ti tholeiitic dykes weather a dark green to black. Compositionally the dykes are similar to medium and coarse grained massive flows.

Basaltic komatiite dykes are most restricted in their spatial distribution. They have been identified in a domain west of the Robertson Shaft and Pud Fault and south of Pud Lake (Strand, 1993). The basaltic komatiite dykes are characterised by deep green coarse grained rough weathered surfaces. They are irregular in width and discontinuous along strike, commonly occurring along the margins, crosscutting or occur as inclusions within Fe-Ti tholeiite dykes.

Sheeted calc-alkaline dykes are locally observed hangingwall to the Con Shear System and as fragments within the Negus Breccia Zone (Strand, 1993). At least 6 previously unrecognised outcrop exposures of this dyke type have been identified by Armstrong and Strand during 1990-1993. Based on surface exposures and drill core intersections the sheeted calc-alkaline dykes appear to subparallel the trend of the shears with strikes of 025°-040° and moderate west dips (45-60°W). The known distribution broadly follows that of the Arsenic Pond Gabbro dyke. The sheeted calc-alkaline dykes are also geochemically and mineralogically similar to the minette matrixed diatreme exposed hangingwall to and internal to the Campbell Shear System.

The sheeted calc-alkaline dykes display planar grain size variability ranging from coarse grained, dark brownish green with a rough weathered surface to finer grained lighter green layers. The dykes commonly have foliated biotitic upper contacts and consistently show internal chills with variable grain size and composition. Individual layers range from 10 to 15 centimetres in width. Underground mapping of the upper levels of the Con Shear System during the late 1930's and early 1940's identified a "sheared lamprophyre" that may represent the underground expression of this dyke. Footwall to the Con Shear System sheeted dykes occur near the security gates and as fragments within the Negus Breccia Zone (Strand, 1993).

Strand (1993) demonstrates that the sheeted dykes are geochemically identical to the diatreme dyke exposed in the hangingwall of Campbell Shear System. Nikic et al. (1975). Webb and Kerrich (1988) and Webb (1992) describe the diatreme matrix as shosonitic lamprophyre. It predates last movement along the shear and where deformed may host economic gold mineralization. The diatreme has now been identified sporadically for over 2.8 km along strike and 1.1 km down dip with an average strike and dip of 007/55W. Underground development on the 3100 Level and diamond drilling on 2300L in the immediate hangingwall of the Campbell Shear has added at least 600 metres to the known dip extent of the diatreme. This exposure demonstrates that the diatreme hosts a heterolithic assemblage of fragments and that there is a tremendous variation in fragment size ranging from boulder size to less that 5 cm (Plate 3.1). The variability in

Plate 3.1 Diatreme Dyke. (A)Diatreme dyke expose on 3100 Level exposure demonstrate variability of xenolith size and distribution. (B) Diatreme Dyke exposed on 3100 Level.R.L. Hauser examining large gneissic xenolith.



fragment size appears to be zonal. Since the dark green/black colour of the diatreme matrix is identical to the host volcanic rocks it is impossible to observe any basalt fragments. Where fragments are abundant the groundmass of the diatreme may contain 2-3% fine grained, rounded fragments of quartz and feldspar.

3.2.3 Granite Intrusions

A 100 metre wide sliver of the Western Plutonic Complex outcrops on the eastern side of the Kam Fault 1000 metres west of the C-1 headframe. At this location it is a pink homogenous medium grained biotite granodiorite. Between the granite and volcanic rocks there is a bleached whitish pink domain injected by numerous aplite dykes and amorphous greasy blue-grey 10 to 50 cm wide quartz veins. Similarly bleached contact domains occur immediately north-east of Stanton Yellowknife Hospital. along the shores of Long Lake in Fred Henne Park, and northeast of Grace Lake south of the - Yellowknife airport.

The Pud Lake Stock dated at 2634Ma (Strand, 1993) and the Negus plug are the major intrusive bodies in the immediate mine site. Intrusive breccia centres associated with the Pud and Negus stocks have been described in detail by Strand (1993). The strike of these intrusive centres and associated breccias, with an attendant perturbation of metamorphic isograds was termed by Strand as the Con Intrusive Corridor. The tonalitic Pud Lake stock is variably sheared and hydrothermally altered. Narrow 1-3 metre wide shears can be observed transecting the eastern contact of the Pud Stock on surface and a correlative sheared intrusive is exposed on the 1550L within the Con Shear workings. Notably a diamond drill hole from the 2300L of the Con Shear workings intersected an

auriferous shear developed interior to the Pud intrusive (R.L. Hauser pers. comm. 1991: Strand, 1993,). As observed by the writer albite is progressively altered to fine grained carbonate, chlorite and white mica as shear fabric intensifies (samples: 27596, 27547, 27548, 27549).

The Negus plug is exposed for 75 metres on the 950L in a crosscut connecting the workings of the Negus mine with the C1 shaft. The exact three dimensional distribution of the porphyry is still unknown but it is manifested as numerous apophyses within the Negus Breccias on surface (Strand, 1993). The Negus Porphyry has been classified by Strand as a highly evolved trondhjemite with granophyric textures. Minor to trace pyrite, pyrrhotite, chalcopyrite and molybdenite occur as fine disseminations throughout the apex of the porphyry and locally the sulphide content attains concentrations of up to 20 modal percent (Strand, 1993).

Granitic quartz feldspar porphyry dykes occur throughout the Negus Breccia centre and on surface quartz feldspar porphyry dykes persist east of the Negus-Rycon shears extending into the immediate hangingwall of the Campbell Shear System. These dykes range from 1 cm to 4 metres in width and are offset by shears. They are typically less altered than the Negus and Pud Lake intrusives (Strand, 1993).

3.3 Prograde Contact Metamorphism

The volcanic sequence has been contact metamorphosed by intrusion of the Western Plutonic Complex. The volcanic flows, gabbro sills and dykes were all subjected to the prograde metamorphic event. However, sheeted calc-alkaline dykes do not demonstrate textural evidence of any prograde overprint suggesting emplacement under

peak to post peak metamorphic conditions. The prograde overprint decreases away from the Western Plutonic Complex contact from garnet amphibolite to greenschist facies over a distance of 4 kilometres (Figure 3.2). Anomalous thermal conditions relating to the intrusive activity associated to satellite bodies within the Con Intrusive Corridor perturbate the metamorphic isograds that regionally subparallel the granite/greenstone contact.

The specific mineralogy and distribution of metamorphic facies and the relationship of isograds to shears is best examined with reference to the Con Shear System where excellent outcrop control can be established. Garnet amphibolite facies volcanic rocks exist in isolated, discontinuous bands immediately adjacent to the Western Plutonic Complex and the Pud Stock. Three to four millimetre idioblastic almandine garnet porphyroblasts are intergrown with olive green to dark green compositionally homogenous ferro-tschermakitic hornblende and clear unstrained quartz. Ilmenite occurs as 0.1 to 0.02 mm inclusions in amphibole. Fractures within almandine orientated at right angles to the rock fabric are infilled with chlorite and quartz. Millimetre scale crosscutting epidote lined fractures and veinlets are common.

Hornblende-amphibolite facies volcanic rocks outcrop immediately HW to the Con Shear. Weathered surfaces are dark green to black. Both pillowed and massive flows may contain up to 5% disseminated lath-shaped plagioclase microlites. Upper hornblende amphibolite facies volcanic rocks (27571) are characterised by homogenous recrystallised ferro-tschermakitic hornblende intergrown with groundmass and microlite labradoritebytownite. Epidote is stable within pillow selvages, amydules, drainage cavities, and along later joint surfaces.

Mid-amphibolite facies volcanic rocks (R209-138, R209-176, C1675-45) occur in



Figure 3.2 Distribution of regional contact metamorphic isograds and retrograde shear zones in the immediate vicinity of the Con Mine. From McDonald et al., 1993.

the immediate hangingwall to the Con Shear north of the C-1 Shaft Zone and contain zoned blue-green amphiboles with actinolitic-hornblende cores and Mg-hornblende to ferro-tschermatikic hornblende rims. Mid to lower hornblende amphibolite facies volanic rocks are characterised by ubiquitously zoned calcic amphiboles with actinolitic cores and hornblendic rims. Groundmass and microlite plagioclase compositions vary from An_m- An_{78} . Low amphibolite facies volcanic rocks occur hanging wall to the Con Shear north of Rat Lake and as pockets footwall to the Con Shear south and east of Rat Lake, and within the Con Intrusive Corridor. Amphibole core compositions are dominated by actinolite and rim compositions vary from Mg-Fe hornblende (27533, 27593) to ferrotschermakitic hornblende (27583, 27561, 27537). Plagioclase compositions vary from andesine to labradorite (An₄₈-An₇₀). The samples with ferro-tschermakitic rims are dominated by labradorite. Plagioclase microlite textures vary from sample to sample and two textural varieties are identifiable. Blocky, equant 2-5 mm subhedral, twinned grains are seen on weathered and fresh surfaces and commonly occur as glomerophyric clusters or disseminations. The second variety of microlite occur as groundmass bladed to acicular grains, 0.05 to 1mm in length and commonly demonstrate a preferred orientation akin to trachyte flow textures. The high anorthite content could indicate orientated growth during prograde metamorphism likely in response to local strain gradients. Epidote may occur as relict fine grained groundmass disseminations.

Epidote amphibolite facies volcanic rocks are divided into two separate sub-facies on the basis of physical and mineralogical characteristics. Upper epidote-amphibolite facies volcanic rocks occur footwall to the Con Shear and within the Con Intrusive Corridor. Amphiboles are ubiquitously zoned with actinolitic cores and Mg/Fehornblende rims intergrown with plagioclase that varies in composition from oligoclase to labradorite. Samples from this domain containing labradorite occur in close proximity to the Con Shear footwall and within the Con Intrusive Corridor (27609) or within a mottled domain where pillow cores are epidote stable and pillow rims are hornblende amphibolite (27565). An increase in metamorphic grade is manifested by a decrease in groundmass epidote and an associated increase in the thickness of prograde hornblende rims.

Samples containing oligoclase and andesine co-exist with abundant groundmass epidote and are located footwall to the Con Shear east of Rat Lake. Surface expression of lower epidote-amphibolite facies volcanic rocks outcrops along the shoreline of Yellowknife Bay, north of Con Camp, and are characterised by pale yellow-green coloured weathered surfaces. Epidote occurs as a fracture fill and is disseminated throughout the groundmass, commonly associated with plagioclase microlites and amydules. Feathery (0.05mm to 0.3mm) sheafs of actinolite are intergrown with fine grained mosaics of twinned albite, polygonal quartz, and minor epidote. Actinolite is compositionally homogenous with variable development of chlorite altered grain boundaries. Epidote occurs as a minor phase and is a stable within amydules, varioles and more rarely within the groundmass. Calcite fills amydules and varioles and is finely disseminated throughout the groundmass (< 1%). Opaque mineralogy is dominated by accessory isolated titanite. The lower epidote-amphibolite volcanic rocks present at depth footwall to the Campbell Shear exhibit compositionally homogenous actinolite intergrown with fine grained locally annealed, untwinned albite. Abundant groundmass and fracture filling Fe-epidote is present on 5900L. All samples proximal to the

Campbell Shear show pervasive chlorite retrogressed domains and chlorite as fracture fill.

The distribution of metamorphic facies and isograds hanging wall and footwall to the Campbell Shear underground is less well constrained than for the Con Shear (Figure 3.3). At surface volcanic rocks in the hangingwall of the Campbell Shear are epidote amphibolite grade and greenschist facies footwall Banting Group volcanic rocks have been identified in drill core and outcrop on islands in Yellowknife Bay. Greenschist facies rocks do not outcrop in the mine site area but sub-crop beneath Yellowknife Bay footwall Mineralogy is comprised of relict albite phenocrysts in a to the Campbell Shear. groundmass of recrystallised quartz and chlorite. McDonald and Hauser (1991) demonstrate that with depth along the Campbell Shear hangingwall pockets of hornblende amphibolite volcanic rocks exist. This study has identified epidote amphibolite facies volcanic rocks footwall to the shear at depth (5960 XCW, 5960M-7,8,9,10). The distribution and continuity of these pockets is limited by underground exposures and the surface expression is likely manifested by the presence of the Con Thermal Corridor pertubating local isograds.

3.4 Peak Metamorphic Schist and Vein Development

3.4.1 Amphibolite Schists

Amphibolitic schists proximal to the Western Plutonic Complex are comprised of compostionally homogenous 0.2 to 0.3 mm subhedral, interlocking, optically aligned magnesio-hornblende intergrown with clear unstrained, fine grained albite and potassium feldspar (Plate 3.2a). Such schists are commonly crosscut by later epidote veinlets. Footwall to the Con Shear massive volcanic rocks locally demonstrate a weak, spaced (1-



Figure 3.3 Vertical cross section through the Con and Campbell Shears on section 19500 with distribution of metamorphic facies in the hangingwall and footwall of the shear strands. Distribution of ore lenses is also shown for the Campbell Shear.

2mm), slightly anastomosing fabric defined by alignment of ilmenite and fine grained bladed to fibrous amphibole within recrystallised volcanic rocks lacking original igneous Porphyroblastic, euhedral, amphibolitic schists occur at the textures (Plate 3.2b). extreme north end of the Con Shear (1100L-27625, Plate 3.2c) with unstrained andesine and ilmenite rimmed by titanite. Considerable chlorite retrogression of amphibole occurs along grain boundaries. The most calcic plagioclase occurs as inclusions within compositionally homogenous magnesio to ferro-tschermakitic hornblende. Amphibole grains vary in length from 0.05 to 1.0 millimetres, and demonstrating optical continuity define the fabric for the rock (27625). Fine grained recrystallised, weakly foliated basalts occur at the extreme north end of the Con Shear System south of the Igloo Inn (27598, Plate 3.2d). Epidote replacement and chlorite retrogression of medium grained idioblastic amphibole (Plate 3.2e,f) occurs in the immediate hanging wall of the Campbell Shear on the 5900 level of the mine within the extreme south end of the mine workings (5960M-1). Porphyroblastic euhedral 0.5 to 1mm epidote overgrows chlorite schist altering relict amphibole. Blue green, homogenous acicular euhedral amphibole may be psuedomorphed or replaced by chlorite along cleavage planes. Relict andesine/labradorite are preserved as inclusions within amphibole or as a fine-grained groundmass partially altered to quartz and albite.

3.4.2 Quartz-Plagioclase-Amphibole Veins

Prograde epidote and hornblende amphibolite facies volcanic rocks are locally infested by Ca-amphibole-plagioclase-quartz veinlets. These are particularly common in sheeted joint systems developed within the Con Intrusive Corridor and in the hangingwall **Plate 3.2** Microscopic textures of amphibolitic schists. (A) Sample KL-1. Interlocking, optically aligned magnesio-hornblende schist adjacent to Western Granodiorite. PPL. Field of view 1.25mm. (B) Sample 27605. Weak, spaced anastomosing fabric defined by ilmenite and amphibole in footwall of Con Shear. PPL. Field of view 2.5mm. (C) Sample 27625, 1250L Con Shear. Large amphibole grains defining foliation within unsheared lithon between C4 and C34 Shears. PPL. Field of view 1.25mm. (D) Sample 27598, north end of Con Shear System. Moderate chlorite retrogressed amphibolitic schist within 2 metre wide shear zone. PPL. Field of view 1.25mm. (E) Sample 5960M-1. Immediate hangingwall of Campbell Shear, 5960M XCW. Chlorite retrogressed amphibolitic schist. PPL. Field of view 1.25mm. (F) as (E), intense chlorite retrogression and development of chlorite schist after amphibole. PPL. Field of view 1.25mm.


and footwall of the Con Shear. Veinlets are sharp-walled. vary in width from 0.5 mm to 1mm and commonly form brittle conjugate sets (27615. Plate 3.3a,b) with open space growth of amphibole. feldspar. and quartz. Although intra-vein variation is minimal with homogenous amphibole chemistry the inter-vein variation in amphibole composition is considerable.

Veinlets developed within mid-amphibolite facies volcanic rocks typically are 2 to 3 mm wide. These exhibit a mineralogy of Mg hornblende/Ferro-tschermakitic hornblende occurring as euhedral sheafs to columnar aggregates within a fine mosaic of clear untwinned labradorite and quartz (C1675-45). Footwall to the Con Shear epidote-amphibolite volcanic rocks are cut by narrow (1mm) quartz-plagioclase-Ca amphibole veinlets (27596, 27615, R18-411). Medium-grained sub-euhedral sheafs of amphibole occur as clusters or separate grains (Plate 3.3c.d) commonly associated with medium to fine grained subhedral pyrite. Patchy chlorite retrogression of amphibole occurs along vein walls and locally replaces amphibole along cleavage planes (27615, R18-411) or psuedomorphs amphibole (27596). Homogenous amphibole with acicular to fibrous habits occur with fine grained interlocking untwinned calcic plagioclase (labradorite) along 0.01 mm joint planes (CON 4. Plate 3.3e) crosscutting horses within the Con Shear.

3.5 Post-Peak Potassium Metasomatism

Potassium metasomatism is primarily manifested by wide spread development of biotite increasing in intensity in the immediate hangingwall of the Campbell Shear. Potassium feldspar veinlets occur within amphibolite schists and shear zone related alteration adjacent to the Con Shear System. Potassium feldspar occurs adjacent to the Plate 3.3 Microscopic textures of quartz-plagioclase-calcic amphibole veins. (A) Sample 27615. Sharp walled veinlet with sheafs of amphibole. Note textural variation between vein amphibole and that of fine grained wall rock amphibole. PPL. Field of view 5 mm. (B) same as (A). Increased magnification. Carbonate alteration associated with later crosscutting veinlet. PPL. Field of view 2.5mm. (C) Sample 27596. Footwall of Con Shear, sharp walled veinlets with sheafs of MG-hornblende. Note sharp walled nature of veinlet and disparity with fine grained bladed amphibole of host pillow basalt. PPL. Field of view 2.5mm. (E) Sample CON 4. Footwall to C4 shear in unsheared lithon between C4 and C34 shears. Narrow joint plane with acicular amphibole associated with Ca-plagioclase. PPL. Field of view 1.25mm.



Pud Stock in veinlets and along joint planes as fine grained murky coloured grains associated with quartz and carbonate (27533. Plate 3.4a). The weathered fracture surfaces are commonly reddish brown. Potassium feldspar lined joints increase in size and abundance with closer proximity to the Pud Stock. Samples with potassium feldspar joints lack groundmass biotite alteration. The known distribution of early potassic alteration is concentrated in the immediate footwall of the Con Shear north of the C1 Shaft and hangingwall to the Con Shear south of the C-1 shaft and coincides with major shear systems.

Biotite alteration increases in intensity with closer proximity to intrusive centres. Biotite development within host volcanic rocks adjacent to the Con Shear is manifested by fine grained disseminations (0.01-0.02 mm, Plate 3.4b), as replacement of amphibole along grain boundaries and cleavage planes, and as discrete columnar grains or aggregates of grains (0.2mm-0.35mm) associated with microlites and varioles (Plate 3.4c). Biotite may also demonstrate a spatial association with joints with a greater abundance of fine grained biotite adjacent to hairline fractures and 0.5-1.0mm joints (27588, 27584, NDH-488.S-765. 27611. 5700ND). The distribution of biotite in hangingwall regions of the Campbell Shear is less well constrained than the Con Shear occurring mainly in sheeted joints and alteration selvages to hairline and 1-2 mm wide calcite-quartz-epidote fractures. Hangingwall to the Campbell Shear biotite occurs within joint breccias and within discrete alteration selvages to 1-2 millimetre wide carbonate veinlets. No occurrences of biotite have been noted in basalts footwall to the Campbell Shear. Biotite rarely occurs within quartz-plagioclase-amphibole veinlets and where present replaces amphibole (CON-4, 27615, 27616).

Plate 3.4. Post-peak potassium metasomatism. (A) Sample 27533. Hornblende amphibolite facies massive basalt in hangingwall of Con Shear, within 30 metres of Pud Stock. Turbid. murky potassium feldspar joint (vertical joint in central portion of photo) cut by later quartz filled joint plane. PPL. Field of view 1.25mm. (B) Sample 27616. Fine grained disseminated biotite in pillow basalt; footwall of Con Shear. PPL. Field of view 1.25mm. (C) Sample D218-441; footwall of Con Shear. Fine grained biotite associated with plagioclase microlites within pillow basalt. PPL. Field of view 1.25mm.



Correlation of hangingwall sheeted joints domains with ore shoots within the Con Shear (Armstrong, 1990) and the Campbell Shear (Webb, 1987) is well documented. Numerous conjugate joint sets are rotated into parallelism with the hangingwall of major shears throughout the mine site. Based on observed crosscutting relationships early joints are characterised by an epidote +/- carbonate assemblage and locally contain relict amphibole or potassium feldspar. later joints are dominated by carbonate, chlorite. albite +/- epidote assemblage. Early epidote-carbonate joints lack alteration haloes and are comprised of fine-grained interlocking carbonate-epidote (ND5900L, ND6100L, 27574) with epidote lined walls (27575). Later crosscutting carbonate dominated joints and fractures are characterised by bleached margins that obliterate prograde metamorphic textures and mineralogy. Intensity of jointing and bleaching commonly increases toward the structural hangingwall of shears concomitant with increasing modal chlorite and intensity of the foliation fabric.

3.6 Post-Peak Retrograde Brittle/Ductile Shear Systems

Prograde metamorphic mineral assemblages of the host lithologies are overprinted by structurally controlled domains of post-peak retrograde metasomatism. The most significant and readily identifiable retrograde structural domains are the brittle/ductile shears zones transecting amphibolite facies volcanic host rocks and which may host significant gold mineralisation. Retrograde shears of the Con Mine host both "metallic" free-milling and refractory "invisible" gold ores. The two styles of gold crystallisation occupy discrete zones within the mine.

3.6.1 Metallurgy of Con Mine Ores

From 1939 until 1947 gold ore from the Negus Mine was free-milling with greater than 90% gold recovery by cyanidation, jigs, and blanket table processes. The remaining 10% of the gold was lost in the tailings and believed to be intimately associated with arsenopyrite (Lord, 1951; Bureau of Mines 1940d). Rycon Mine ore was treated at the Con Mine Mill and until early 1940's approximately 92% of the gold was recoverable through cyanidation, jigs and blanket tables (Lord, 1951; White et al., 1949). For both Negus and Rycon ores 30% of gold was recovered by jigs and blanket tables alone (Lord, 1951).

From 1939 - 1941 early milling operations for the Con Shear recovered 90% of the gold through a combination of jigs. blanket tables and conventional cyanidation (Lord. 1951: White et al., 1949). Early mining within the Con Shear focused on the Shaft Group of veins and narrow portions of the C4, C34, and C32 strands. Subsequent to 1941 more refractory ores were encountered within the Con Shear System and a roaster was installed to treat sulphide concentrates generated after conventional cyanidation in order to boost gold recoveries. Bottle roll testing in 1990 of C4 ore intersections beneath Rat Lake indicated that expected recoveries from cyanidation alone would be less than 50% (Maltby, 1990). Material from lenses dominated by quartz veining within narrow shear trends achieved the best recoveries with cyanidation while the zones with less abundant veining and a more laminated arsenopyrite rich character were more refractory.

The Campbell Shear System is host to both free-milling (metallic) and refractory ("invisible") gold ores. Approximately 55 bottle roll cyanidation tests have been conducted on different lenses within the Campbell Shear in order to determine tailings

grade, and gold recoveries and the results are represented on Figure 3.4. Based on the metallurgical testing refractory ore lenses are restricted to the 102 and 103 zones and can be inferred to exist within the Negus Zone since roasting was required to achieve adequate recoveries from the Negus portion of the Campbell Shear (Coulson, 1950; Lord, 1951). Arsenopyrite is the dominant host for the invisible gold and locally arsenian-pyrite hosts significant invisible gold.

A roaster was utilised at the Con Mill from the early 1940's until 1970 and treated a sulphide float generated subsequent to cyanidation (Martin. 1990) and a pressure oxidation autoclave was commissioned at the Con Mine in 1992 to treat calcine residue and refractory ore from the 103/102 zones within the Campbell Shear. Metallurgical testing of refractory ores hosted in the Campbell Shear indicate that finer ore grind and increased cyanide do not improve gold recoveries through cyanidation treatment and cyanide tailings gold values consistently fall in the range of 0.10 ounces per ton (Martin, 1990). Gold recovered through cyanidation ranges from 30 to 95%: although samples with high cyanide recoveries also had elevated cyanide tailing grades. The grade of cyanide tailings may be influenced by two factors i) incomplete dissolution of coarse gold, or ii) the presence of "invisible" gold hosted in sulphide minerals. Cyanidation treatment of floatation concentrates produced subsequent to cyanidation provides no significant increase in gold recovery while cyanidation of floatation concentrates produced prior to cyanidation recovered 35 to 90% of the gold.

During the period from 1970 until 1990 mining was restricted to the 100 and 101 free-milling regions of the Campbell Shear. Recoveries with cyanidation average greater than 93% and tailings grades for free-milling ores are on average less than 0.04 ounces





3.6.2 Negus-Rycon Shears

The auriferous Negus-Rycon veins have been classified by Boyle (1961) as quartz veins hosted in narrow shears that transect stratigraphy. These veins form a series of discontinuous ore bodies with a combined strike length of 1100 metres and a dip extent in excess of 1000 metres. Their geology has been described by Lord (1951), and Boyle (1961). The Rycon veins were staked in 1936, mining started in 1938 and ceased in the mid-1940's. The southern portion of the Negus-Rycon shears were exploited by Negus Mines Limited from 1939 until the summer of 1948 (Coulson, 1950). The Negus-Rycon veins occur approximately 700 metres ENE of the Robertson Shaft and form an anastomosing set of NNW-striking, moderate to steep west dipping veins that crosscut stratigraphy and locally follow gabbro dyke-volcanic flow contacts. Host volcanic rocks lie within the Con Intrusive Corridor and mineralised shears offset quartz-feldspar porphyry dykes. Productive portions of the Negus-Rycon System are bounded by the Negus Fault to the south and the Con Diabase to the north. The eastern portion of the Rycon system is defined by the R-51 and R-53 shears forming the N-15. N-9, and N-1 veins on the Negus property. The western portion of the Negus-Rycon System is defined by the R-57 and R-54 veins correlating with the N-3 (C-26) and N-2 veins respectively. Negus type veins are recognised at deeper levels within the mine on the 3100L, 3700L. and 3900L in the immediate hangingwall of the Campbell Shear.

Veins and shears are narrow with widths varying from 30 centimetres up to 9 metres and average 1.5 metres. Quartz vein-wallrock contacts are sharp with minor

chlorite schist development. Practically all gold is found in quartz associated with pyrite. arsenopyrite, sulphosalts, scheelite and carbonate (Lord, 1951; Boyle, 1961). The Negus-Rycon veins are typified by a wall rock alteration referred to as "Negus alteration" comprised of bleached buff green silicified, sulphide-rich wall rock that may or may not be auriferous. Examples of this alteration referred to by Boyle (1961; plate VII) are associated with narrow veins in the immediate hangingwall of the Campbell Shear on the 3100 and 3700 levels of the mine. Vein selvage alteration may be up to 50 centimetres wide. Mineralogy consists of fine grained albite, carbonate, muscovite, pyrite and euhedral arsenopyrite with trace sphalerite, electrum and gold. Alteration selvage pyrite may contain 1-2 micron blebs of electrum (3191-3, fineness = 683-692, n=3). Electrum also occurs in ankerite or quartz gangue (3191-10, fineness = 812-829, n=5) contrasting with electrum in quartz gangue from vein material (3191-4, fineness = 839, n=5). Negus veins are truncated and deformed by movement along the Campbell Shear (Plate 3.5).

3.6.3 Con Shear System

The Con Shear is the western most of the major ductile shear system and the second most important gold producer on the Con Mine property. Exploration by trenching and sporadic diamond drilling has been conducted along a strike length of over 10 kilometres from the City of Yellowknife south through Rat Lake, Keg Lake, Meg Lake and Octopus Lake and to a depth of 850 metres in the Con Mine. The Con Shear System is an anastomosing, north-northeast trending, west-dipping shear system and is comprised of several different shear strands and mineralised domains. Host rocks are dominated by mafic flows in the northern portion of the shear through the mine yard

Plate 3.5 Negus Vein (A) Negus vein on 3100 level. Looking east. Bone white quartz vein with thin wall rock septa on footwall portion of vein. Bleached buff green carbonatealbite-white mica alteration "Negus Alteration" along footwall of vein. (B). Negus vein on 3100 level. Looking northerly, photo of drift back. Negus vein truncated and sheared by hangingwall of main Campbell Shear.





although with depth the shear passes into and deforms the Pud Stock. The main components to the Con Shear System include the Shaft System (C10, C8, C1, C2, C17, and C18 shears) and the Con System (C32, C34, C36, C12, C4 shears). Historic gold production from the Con Shear System occurred from 1938 until the early 1950's and is restricted to a 1 kilometre portion of the system ranging from the north end of Rat Lake south to the Pud Fault and is accessed through the C-1 shaft.

The HW C4 and FW C34 shears trend N10-30E with moderate to steep westerly dips. The area between Rat Lake and the Pud Fault is a zone of anastomosing and bifurcating shears, in section and plan, interlaced with large elongate horses of unsheared volcanic rocks enclosed by the C4 and C34 shears (Figure 3.5). Cross-over structures (C36, C37, C38) may crosscut horses, strike more northerly to northwesterly than the C4 and C34, and host significant ore bodies. Crack seal open space veins occur within the unsheared horses (C39) forming small discontinuous ore lenses.

The C4 and C34 shears form narrow (1-10 metre) individual shears near surface separated by a large volcanic horse which with depth and along strike pinches out resulting in a thickened portion of the shear (30-40 metres) creating a loci for ore zone development. The plunge of individual ore shoots approximates the line created by the intersection of the shear with stratigraphy and the intersection of the 010 trending shear with the brittle cross structures.

3.6.3.1 Shaft System

The Shaft Group is a NNW striking, west dipping series of shears and veins occurring west of the C-1 Shaft. The mineralisation occurs within the hornfelsed aureole

Figure 3.5 Plan map of the 250, 450, 950, 1100, and 1250 levels of the Con Shear accessed by the C-1 Shaft. The major shear strands are labelled along with the distribution of mineralised zones along the strike of the productive portion of the Con Shear. Locations for samples discussed within the text are also shown.





to the Pud Stock. locally along the Pud Stock/volcanic contact, and may follow gabbro dyke/volcanic contacts. Initial exploration and mining was conducted within this series of veins with a decline shaft driven on the C-10 Shear in 1937. Important members of the Shaft Group include the C10, C8, C1, C2, C17, and C18 shears.

The eastern most shears (C17, C18) are narrow and moderately carbonated. Brittle sheeted joints hangingwall to these shears occur 30 to 50 metres from the granite contact. Mineralised domains consist of 15-30 cm ribboned, grey to white quartz veins with coarse free gold, arsenopyrite, and sulphosalts enveloped by narrow bands of chlorite schist. The footwall is dominated by shear parallel sheeted joints (300/60W) that fade into footwall volcanic rocks lacking shear parallel joints (100/40N).

The C10, C2, C8, and C1 shears form a series of NNW to NW trending. variably west-dipping shears adjacent to the C-1 Shaft and Con Mill buildings. The C-10 shear, mined from surface to the 650 Level, varied in width from 30 cm to 2.5 metres. The C10 shear trends N31W/81W, varies in width up to approximately 2 metres with a wider hangingwall alteration zone comprised of spaced sheeted joints. A conjugate set of hangingwall joints (300/90, 030-040/80E) with bleached carbonate-chlorite altered margins increase in frequency and alteration intensity with closer proximity to the shear contact. The joint sets do not offset pillow selvages of hangingwall flows. Narrow zones of moderately foliated chlorite schist envelope strongly foliated quartz-muscovite-ankerite schist hosting 10-15 cm quartz vein boudins. Quartz vein material is variably deformed on a thin section scale with domains of strong cataclasis associated with a secondary introduction of ankerite, sheridanite, muscovite, albite, and arsenopyrite (Plate 3.6a). Distribution of sulphide, carbonate, and recrystallised quartz define an anastomosing

cleavage through the macroscopically mottled quartz vein.

3.6.3.2 C32 Shear

The C32 Shear trends NNE with a steep to moderate west dip. has been traced by drilling and mining for approximately 500 metres. was exploited on the 150. 250 levels of the mine and occurs immediately east of the C-1 Shaft. At surface the immediate footwall of the C32 Shear is marked by a sheeted calc-alkaline dyke possibly correlating to a "sheared lamprophyre" noted on old map plans from the 250 level. Gold mineralization is associated with mottled, grey-white quartz veins enveloped by green white mica or chlorite schist: locally alteration associated with the C32 may attain thickness of 10 metres with 10-15% quartz stringers. Gold grade and widths of veining are variable with higher grade intersections associated with silicified, white mica selvages and a vein mineralogy of arsenopyrite. pyrite, chalcopyrite. Internal pressure solution selvages and wall rock septa are common, white mica alteration is commonly apple green in colour.

3.6.3.3 C4 Shear

The C4 forms the major hangingwall shear for the Con System and varies in width, dip, and nature of gold mineralization along its known strike and dip extent. Based on physical and mineralogical criteria two distinct styles of gold mineralization are hosted in the C4 shear: i) narrow quartz veins with free gold hosted in narrow shears, and ii) carbonated refractory schists hosted in wide shears.

Free-milling ore in narrow shears

The C-4 shear outcrops immediately behind the main mine office where it may be traced for 300 metres. The shear transects a package of intercalated pillowed and massive flows with individual flows averaging 5-10 metres in thickness. The shear ranges in width from 2.5 to 10 metres, trends 010 - 015 through massive flows, changes strike to 025 - 030 while transecting pillowed flows. Mineralised dilational zones occur within 025 - 030 trending portions of the shear. Narrow (15 centimetre to 3 metre wide) high grade quartz veins were exploited from surface to the 950 level along a strike length of 500 metres from the south end of Rat Lake to just north of the C-1 Shaft (Figure 3.6). The strike length of individual shoots decreases with depth. Average stope grades were high attesting to the abundant visible gold in the veins. A 400 metre portion of the C4 shear exposed on the 250L outlined 200 metres of ore contained within six different shoots ranging in strike length from 30 to 100 metres. in width from 20 centimetres to 5 metres, and in grade from 1 to 1.3 ounces per ton Au (Jolliffe, 1941). South toward the Pud Stock the C4 shear near surface remains a narrow 2-3 metre wide 010 steep west dipping structure along which no dilational zones have been identified to date by surface diamond drilling.

Brittle jointing hangingwall to the shear preferentially disrupts pillowed flows relative to massive flows, increasing in intensity within 1 to 2 metres of the hangingwall contact (Plate 3.6b,c,d). Joints are manifested by clean cleaved surfaces with narrow bleached haloes created by carbonation of amphibole and joint breccias develop in the immediate hangingwall of the shear (Plate 3.6e).

Barren chlorite - calcite altered portions of the shear transecting massive flows



Figure 3.6 Vertical cross section through a narrow portion of the C4 Shear immediately northeast of the C-1 Shaft. The C4 Shear is narrow, steeply dipping and hosts ore within dilatant zones developed at the intersection of the shear with pillowed flows. The C34 Shear has a shallower dip, is anastomosing and barren in this locality.

trend more northerly (010 - 015), have a steeper dip, and locally demonstrate a brecciated appearance. Dilational jogs occur at pillow/massive flow contacts, commonly have a pillowed hangingwall, and occur where a cross structure (070/65-75W) that subparallels contact between pillowed and massive flows intersects the 010 trending shear. Dilational jogs are characterised by an abrupt change in strike and dip (Plate 3.6f) and are comprised of 15 to 20 centimetre wide blue-grey to mottled white boudinaged quartz veins enveloped by a silicified paragonitic muscovite-ripidolite-arsenopyrite-pyrite schist with widths of 50 to 100 centimetres.

Selvages to veins vary in width from several centimetres up to 1 metre and are comprised of laminated fine grained ankerite. paragonite. paragonitic-muscovite. albite. ripidolite. euhedral pyrite and arsenopyrite assemblage. Thin anastomosing (0.5 to 1 cm) optically aligned bands of paragonitic-muscovite and ripdiolite transect fine grained cryptocrystalline quartz. albite. and ankerite with medium to coarse grained euhedral pyrite and arsenopyrite. Sulphide grains are associated with domains of polygonal quartz and demonstrate pressure shadow development. Wrapping of pargonitic-muscovite bands around sulphide grains and preservation of relict carbonate-sulphide patches suggests development of the anastomosing fabric post dates pyrite-carbonate alteration.

Quartz veins within dilational zones vary in colour from greasy grey to white and in width from 30 cm to greater than 1 metre. Texturally quartz veins appear brecciated with the quartz having undergone variable degrees of recrystallization with undulose extinction. sub-grain boundary development, sutured grain boundaries and domains of polygonal quartz indicating cataclastic deformation of pre-existing quartz vein material (C204-2, C4-1, Plate 3.7a-d). Secondary anastomosing cleavage is defined by a Plate 3.6 Wallrock and vein textures for narrow segments of the Con Shear. (A) Sample 27554, C10 Shear. Cataclastic quartz vein with subgrain boundary development and concentration of arsenopyrite along late foliation plane preferentially developed in carbonate rich portion of vein. PPL. Field of view 1.25mm. (B) Sheeted joint system in hangingwall of Con Shear, looking easterly toward C4 Shear. sheeted joints preferentially developed in pillow flow units. (C) Brittle jointing in pillow flow. Pillow outline is still preserved with most intense joint development along pillow selvages, within 10 metres of C4 Shear hangingwall contact. (D) Parallel sheeted joints in immediate hangingwall of Shear zone, chloritic joint breccia with calcite cement of intensely chloritised and carbonated wallrock. (F) C4 Shear looking southeasterly along 025 trending dilatant zone. At picket ore lens terminates and C4 Shear pinches to approximately 50 centimetres and trends more north-south.



muscovite, ripidolite, ankerite, arsenopyrite, +/- pyrite, sulphosalt, galena, and gold assemblage that defines a "matrix" to the brecciated quartz. Sheridanite is associated with ankerite alteration within a folded quartz vein in the immediate hangingwall of the C4 shear on the 250L (C204-2). Sulphides are restricted to the secondary cleavage domains (C4-1, C204-2, Plate 3.7a,c) as euhedral fine to medium grains or are associated with ankerite-muscovite domains within relatively undeformed whitish quartz veins.

Gold mineralization occurs both within the alteration selvages to quartz veins and in the veins. Within the schists gold occurs as isolated inclusions within arsenopyrite and pyrite hosts, along fractures in sulphide, or as discrete grains at sulphide grain boundaries. Gold inclusions hosted in pyrite and along fractures have a greater fineness (range 842 to 948; C404-4) relative to gold grains at pyrite grain boundaries (range 555 to 561; C404-4) and arsenopyrite grain boundaries (fineness 723-724; C404-5). Gold within quartz veins may occur as large 10-20 micron blebs (fineness range 904-906: C4-1) hosting arsenopyrite inclusions within an anastomosing cleavage, as isolated inclusions within arsenopyrite (fineness range 839-951; C404-2), and isolated grains at arsenopyrite grain boundaries in contact with polygonalised and annealed quartz (C404-2). Gold grains occurring at arsenopyrite grain boundaries may be zoned with respect to Au/Ag ratios with fineness varying from 754 to 520 (C404-2, Plate 3.7e,f) as discrete patches in one grain or gold grains may be homogenous (fineness of 518-539: C404-2). Arsenopyrite grains are zoned with low As cores, high As rims; pyrite in alteration selvages may contain elevated As toward rims. Veins host accessory galena, sphalerite, and a variety of sulphosalts including jamesonite, stibnite and boulangerite.

Plate 3.7 Narrow Con Shear quartz vein textures. (A) Sample C204-2, 250 level of Con Shear. Brecciated, polygonalised quartz vein material. White mica, carbonate and sulphide are associated foliation developed during vein deformation. PPL. Field of view 5mm. (B) same as (A). XN. (C) Sample C4-1, surface exposure of C4 Shear vein material. Polygonalised quartz vein material, sulphide and sheet silicates associated with secondary foliation. PPL. Field of view 5mm. (D) same as (C); XN. (E) Sample C404-2. Electron microprobe backscatter image of homogenous arsenopyrite grain hosting metallic gold as fracture fill, discrete inclusions, and at sulphide/silicate boundary. (F) Increased magnification on gold grain at sulphide/silicate interface. Mottled gold grain with Au-rich (bright) and Ag-rich (dark) domains.



8811 28.8KV X138 1888m

2009 20 0KU x3.500 12Mm

Refractory ore in wide shears

The Con Shear beneath Rat Lake, north of the surface exposure of the C4 Shear, is a thick 30 - 50 metre wide complex zone of interfingering strongly foliated, moderately to strongly laminated white mica-chlorite-carbonate schists (Figure 3.7). Two distinct lenses occur within this thicken portion of the shear: the C4 hangingwall shear and C34 footwall shear. The lenses are separated from each other by a 5-10 metre wide zone of weakly foliated chlorite schist and weakly sheared pillowed and massive flows. The down plunge extension of the Rat Lake C4 ore lens may be traced to the 1250 foot level of the Con System occurring as a thickened portion of the shear associated with intense carbonate alteration.

Jointing hangingwall to the thickened C4 Shear segment is more pronounced than hangingwall to narrow portions of the C4 Shear. Hairline joints with 0.05 mm with 1 mm wide bleached selvages comprised of calcite, chlorite, and epidote alteration of host amphibolite facies volcanic rocks exist 30 metres from the hangingwall contact of the shear. With closer proximity to the shear joints increase in abundance and thickness (1 to 1.5 mm. R209-150) with a concomitant increase in the width of the attendant alteration (4-5mm; R209-150). Joints are infilled by fine grained calcite, pycnochlorite, quartz, +/- albite and epidote and rarely muscovite (R209-150). Monomineralic calcite joints crosscut earlier generations of calcite-epidote filled joints.

Within 10 metres of the hangingwall contact sheeted jointing and pervasive carbonation obliterates prograde metamorphic textures of the host basalt. The alteration is readily distinguished by a buff grey green colouration and is comprised of fine grained calcite. chlorite, quartz +/- pyrite. Sheeted joints are infilled with calcite with minor



Figure 3.7 Vertical cross section through a wide portion of the Con Shear beneath Rat Lake. C4 Shear is characterised by mineralised carbonate-paragonite-chloritearsenopyrite assemblage. The C34 and C4 Shears are separated by variable thicknesses of chlorite-white mica schist. Hangingwall contact is characterised by intense carbonate flooding and associated bleaching.
quartz and locally medium grained euhedral pyrite. Sheeted jointing becomes progressively brecciated and foliated toward the shear contact and undergoes a sharp transition from a calcite to an ankerite dominated alteration assemblage. Buff alteration domains that lack well developed foliation are comprised of medium grained equant ankerite-pyrite alteration that are transected by 1-2 cm spaced chlorite-muscovitepotassium feldspar shear planes. Pyrite grains are rotated into the shear plane and where preserved within ankerite domains exhibit pressure shadow development (R09-192). Wispy tension gashes are infilled with ankerite. A planar fabric defined by a fine intergrowth of chlorite, ankerite, leucoxene, potassium feldspar, and albite may wrap around tension gashes (R218-321.5, R214-172) and create pressure shadow growth around disseminated pyrite grains. The hangingwall contact of the shear is defined by the presence of a moderately developed spaced (1 - 1.5 cm) cleavage marked by planar bands of chlorite, increasing in pyrite and white mica content.

Within 3-4 metres of the ore lenses ankerite-chlorite alteration increases in intensity, relict fine grained hydrothermal (0.1-0.3 mm) potassium feldspar, and equant twinned 0.2-0.3 mm albite grains lie across the foliation and are locally rotated into the fabric (R09-230.6; Plate 3.8a). Potassium feldspar and albite are progressively altered to muscovite, chlorite, and ankerite with increased development of fabric. Chlorite-muscovite shear bands increase in intensity toward the ore lenses.

The C4 ore lens under Rat Lake is characterised by a strongly laminated steely grey coloured carbonate flooded ankerite-paragonitic muscovite-ripidolite-arsenopyritepyrite schist with accessory tourmaline and titanite. Contacts with enveloping ripidolitemuscovite-ankerite-pyrite schists are sharp. Ore grade material is associated with intensely ankerite flooded domains which are transected by later spaced (1-2mm) thin (0.5-1.0 mm) cleavage planes comprised of paragonitic muscovite, ripidolite, quartz, arsenopyrite. +/- pyrite, albite, and tourmaline (R09-239, R09-255, 27621) imparting a banded to laminated texture to the rock (Plate 3.8c.e.f). Ankerite domains are characterised by subhedral to anhedral interlocking medium (0.4-0.8 mm) grained aggregates comprising up to 60-70 modal volume, with 1-2% disseminated arsenopyrite and pyrite. Arsenopyrite occurs as fine grained (0.01 to 0.4mm) acicular to prismatic euhedral grains or aggregates of grains along paragonitic-muscovite foliation planes and may comprise up to 10-20% modal percent. Pyrite is limited in its distribution to ankerite flooded domains and where present along foliation planes grains are fractured, abraded, and pulled apart into the foliation (Plate 3.8b.f). Locally pyrite cores appear corroded and replaced by paragonitic muscovite and chlorite.

More barren portions of the ore lens are comprised of extremely fine grained ankerite and less abundant mica-chlorite-arsenopyrite foliation planes. Locally quartzankerite-tourmaline lozenges are enveloped by anastomosing paragonitic muscovitechlorite planes (R09-255) and pressure shadow development around arsenopyrite aggregates occur adjacent to later crosscutting quartz ankerite stringers.

Quartz veins are present within the ore and consist of sub-vertical, thin 3-4 cm, mottled to laminated grey white veins and locally host arsenopyrite, sulphosalts and visible gold. The second variety of veins crosscut mineralization, are barren of gold and sulphide and are comprised of late vuggy quartz, pink carbonate, and pockets of medium grained pale green paragonitic-muscovite.

Gold is observed in three main sites of deposition: i) as free gold in sub-vertical

Plate 3.8 Alteration and mineralisation textures of Con Shear refractory schists. (A) R209-230.6. Albite (ab) replacing potassium feldspar (k) in chlorite-white mica schist in immediate hangingwall of auriferous zone. XN. Field of view 1.25mm. (B) R209-239. Pyrite (py) as abraded and fractured grains along thoroughgoing planar shear fabric. Arsenopyrite replaces pyrite and occurs as subhedral grains along foliation planes. Reflected light. Field of view 1.25mm. (C) R209-239. Late anastomosing paragonitic muscovite-chlorite-sulphide foliation plane transecting polygonalised carbonate alteration. XN. Field of view 2.5mm. (D) R209-255. Pyrite (py) with poikiolitic cores within preserved ankerite domain. Reflected light. Field of view 2.5mm. (E) R209-255 Planar paragonitic muscovite-arsenopyrite-chlorite foliation plane. XN. Field of view 2.5mm. (F) Same as (D). Pyrite associated with preserved vein carbonate. Euhedral arsenopyrite associated with late white mica foliation plane. XN. Field of view 2.5mm.



quartz veins, ii) as isolated inclusions within arsenopyrite grains, and iii) as solid solution within arsenopyrite grains. The abundance of free gold in veins is volumetrically restricted and where present have uniform fineness (fineness of 762-786, C4-20). Arsenopyrite grains are ubiquitously zoned with low As cores and high As rims. Isolated inclusions of gold (1-3 microns) hosted in arsenopyrite are associated with high As growth bands within the arsenopyrite and have a uniform fineness (896-905, R09-239). The high As growth bands also host the invisible gold within the arsenopyrite grains. Arsenianpyrite cores pyrite grains and is barren of invisible gold and free of gold inclusions. Tetrahedrite occurs within veins, as disseminations associated with arsenopyrite, or as inclusions within cores of individual arsenopyrite grains. Bournonite, jamesonite, and berthierite are associated with arsenopyrite within the schists (R09-239). Sphalerite and chalcopyrite are present in trace amounts.

3.6.3.4 C34 Shear

The C34 Shear defines the footwall of the Con Shear system and has been traced on surface and underground for a strike length of approximately 1500 metres. The shear does not outcrop and hosts a variety of ore lenses and unlike the C4 Shear the style of mineralization is more quartz vein dominated. The productive portion of C34 Shear has a strike length of approximately 250 to 300 metres. Near surface under Rat Lake the ore lenses lie north of the Con 4 Diabase, which bisects the lens at depth, and plunges moderately to steeply south down to the 1550L with a separate zone south of the C-1 shaft on the 1550L immediately north of the sheared Pud Stock. Milky white quartz veins in the footwall of the Con Shear at Rat Lake contain sphalerite, tetrahedrite, gold. disseminated arsenopyrite and pyrite. Enveloping ankerite-paragonitic muscoviteripidolite schists (R09-298) are similar to alteration within the C4 lens at Rat Lake.

South of Rat Lake ankerite-paragonitic muscovite-ripidolite schist selvage milky white quartz veins with internal septa of gold, tourmaline and carbonate. Selvages to veins are comprised of buff greenish brown intensely ankerite flooded domains transected by paragonitic muscovite-arsenopyrite foliation planes with extremely fine grained ankerite and quartz. Locally medium grained interlocking ankerite lozenges are preserved in the alteration and are wrapped by the fine grained ankerite-mica foliation (27614. Plate 3.9e): there is a significant reduction in ankerite grain size away from the preserved lozenges toward the shear planes (Plate 3.9a,b). Fine grained acicular arsenopyrite is confined to the shear planes whereas medium grained, subhedral, locally pulled apart pyrite may be associated with medium grained carbonate domains or within shear planes.

Quartz vein material is deformed with grain size variable from several millimetres to micron size. Undulose extinction. subgrain boundaries and pressure solution grain size reduction (sutured grain boundaries) along grain contacts are common textures. Internal vein septa are comprised of fine grained tourmaline ankerite, rutile and are the preferential site for gold, arsenopyrite, low Fe-sphalerite, galena. Ag-tetrahedrite, stibnite, and bournonite which are rarely found as isolated grains in quartz. Gold occurring as 0.1 to 0.15 mm diameter grains isolated in quartz gangue have a lower fineness (758-775) than gold grains associated with sulphide and sulphosalt minerals (916-939) within ankerite septa (C34-12L).

Material from the C34 ore lens (L15-1, L15-3) exposed on the 1550L is comprised of buff to tan brownish green ankerite-mica-chlorite arsenopyrite pyrite schist. Pressure shadows are developed around sub-euhedral medium grained pyrite and arsenopyrite within medium grained ankerite flooded domains. Anastomosing ankerite-muscovitechlorite foliation bands with fine grained acicular arsenopyrite transect the coarser grained ankerite-sulphide domains. Chalcopyrite is intimately associated with pyrite within the coarser grained portions of the alteration package. Significant quartz vein material is lacking at this location.

3.6.3.5 C36 Shear

The C36 shear forms an important NNW trending. cross-over shear between the C4 and C34 shears and may be traced from surface at the nose of the large greenstone horse along a southerly plunge to the 1500L. The strike length of ore lenses is variable. Ore was mined intermittently from quartz veins along the entire dip extent of the C36 shear. The lower portions of the C36 Shear on the 1400L and 1500L are characterised by an increase in carbonate alteration with an attendant decrease in sulphide content and a decrease in quartz veining (Sproule, 1952).

Laminated ankerite-paragonitic muscovite-chlorite-pyrite schists (27610a) containing relict potassium feldspar (Plate 3.9c) and albite envelop variably deformed and mylonitised quartz veins (27610, 27617a, 27617). The laminated texture of schist material selvaging veins results from variation in ankerite grain size associated with increased paragonitic mica and chlorite content adjacent to coarser grained ankerite pyrite bands. Locally pressure shadows are developed around pyrite grains and relict hydrothermal potassium feldspar grains are rotated in the plane of the foliation.

Plate 3.9 Vein texture of the C34, C36, and C39 Shears. (A) Sample 27614, C34 Shear. Polygonalised and boudinaged quartz vein fragments enveloped by anastomosing white mica-sulphide foliation bands. Vein fragments demonstrate intense polygonalisation. XN. Field of view 2.5mm. (B) 27614. Fine grained white mica-carbonate schist bordering lithon of relict quartz vein in lower left portion of photo. XN. Field of view 2.5mm. (C) Sample 27614. C36 Shear. Grain size reduction and brecciation of relict potassium feldspar grain in paragonitic muscovite chlorite schist. XN. Field of view 1.25mm. (D) 27610. C36 Shear. Grain size reduction of carbonate during progressive deformation of quartz carbonate vein. XN. Field of view 5mm. (E) 27614. Lozenge of moderately polygonalised carbonate with acicular arsenopyrite (opaque) enveloped by later micaceous foliation. XN. Field of view 2.5mm. (F) Sample 27612, C39 Shear. 1250 level, Con Shear. Moderately deformed crack-seal quartz carbonate vein. XN. Field of view 5mm.



Quartz vein material varies in width from 10's of cm up to metre scale and are variably deformed and boudinaged and host arsenopyrite, pyrite, gold, low Fe-sphalerite, and sulphosalts. Vein material may be brecciated (27610a) or boudinaged (27617.27617a) with significant grain size reduction. A secondary cleavage transecting quartz ankerite veining is defined by paragonitic muscovite and chlorite shear bands that envelop quartz ankerite domains characterised by undulose extinction and subgrain development. Arsenopyrite is restricted to the later crosscutting foliation bands that can be seen to pinch and swell through the quartz host. Ankerite grain size dramatically decreases as white mica content and foliation intensity increase (Plate 3.9d).

3.6.3.6 C39 Shear

The C39 shear is a WNW trending narrow. brittle. crack-seal quartz vein with weakly sheared chloritic selvages. It occurs within an unsheared volcanic horse internal to the Con System and was exploited on the 950 and 1250 levels. Sheridaniteclinochlore-muscovite-arsenopyrite foliation bands transect variably deformed and cataclastic quartz carbonate vein material (27613). Crack-seal vein filling textures are locally preserved with alternating bands of herring bone quartz and coarse grained ankerite-calcite (Plate 3.9e). Fine grained acicular arsenopyrite sheridanite aggregates occur along the contact between carbonate and quartz layers. Acicular arsenopyrite and euhedral sheafs of sheridanite may also occur disseminated in carbonate. Muscovite is intergrown with sheridanite along later crosscutting cleavage domains. Iron rich sphalerite, stibnite, boulangerite, and scheelite form important accessory minerals within the quartz veins.

3.6.4 Campbell Shear System

On surface the Campbell Shear System subparallels and lies 2500 metres SE of the Con Shear System and subcrops in Yellowknife Bay. Since discovered in 1945 the Campbell Shear has produced in excess of 5 million ounces of gold. The shear strikes N05E and dips 50 to the west steepening to 65-75 west below a flexure in the shear at the 5100 level of the mine. To the north the shear zone is truncated by the West Bay Fault at Negus Point. It has been traced by diamond drilling south for more than 10 kilometres to Kam Point and to depths of 1000 metres below surface. The productive portion of the Campbell shear lies within a block bounded by the Pud, Negus, and West Bay Faults and lies approximately 2500 metres to the footwall of the Con Shear. Ore has been produced from four main zones (Negus, 101, 102, and 103; Figure 3.8) over a strike length of approximately 2500 metres and to a depth of 1800 metres. Both freemilling and refractory ores occur within discrete zones within the Campbell Shear (Figure 3.9). This portion of the Campbell Shear is a complex of anastomosing, ramifying chlorite-carbonate, chlorite-white mica-carbonate schists bordering unsheared horses of host rock. The system has an aggregate thickness up to 200 metres. Gold ore is not evenly distributed over this strike length and is restricted to structurally controlled. deformed quartz veins and alteration selvages.

3.6.4.1 Negus Zone

The Negus Zone of the Campbell Shear lies between latitudes 18000-19000 and 3 lenses (40, 60 and 90) were exploited for a dip extent of approximately 300 metres. Stoping was conducted primarily north of the Negus Fault with the exception of one stope Figure 3.8 Vertical longsection of the productive portion of the Campbell Shear with bounding Proterozoic faults, mined out stopes, and active mining blocks. Levels are 200 vertical feet apart.







Figure 3.9 Vertical longsection of the Campbell Shear outlining the distribution of free-milling (101) and refractory (102, 103) ore zones.

located south of the fault on the Negus 13 level. The Campbell Shear in this area is comprised of two shear zones separated by a large unsheared to weakly deformed volcanic horse creating an aggregate shear thickness of between 100 to 200 metres. The shear strikes NNE and the hangingwall dips westerly at between 45-50. Ore shoots trend parallel to the hangingwall contact and have little or no discernable plunge (Boyle, 1961). Hangingwall contacts are sharp while footwall contacts are more gradational in nature. Individual shoots have strike lengths of 25 to 75 metres, are comprised of carbonate-mica schist ribboned with quartz (20-80% modal percent) and may be veined by later mottled grey quartz veins (Coulson, 1950). Chlorite-carbonate-mica schists are the primary host for mineralization. A quartz-feldspar porphyry dyke/sill hosts gold mineralization on the Negus 11 level at latitude 19150 (Coulson, 1950).

Moderately to strongly laminated ankerite-paragonitic muscovite-quartz-ripidolitealbite-pyrite-arsenopyrite schists form intensely carbonated alteration selvages to veins on the Negus 20 and 21 levels. Fine grained to cryptocrystalline ankerite and quartz (+/albite) intergrown with 1 to 2% disseminated 0.5 to 1mm subhedral pyrite with pressure shadows are transected by thin (1 to 2 mm) paragonitic muscovite ripidolite foliation planes (Negus-20L). With an increase in paragonitic muscovite and arsenopyrite content foliation planes become wider (2-3 mm) and carbonate grain size decreases dramatically

Acicular prismatic arsenopyrite (1-2 mm) may demonstrate pressure shadow development or appear abraded along grain boundaries (Negus-21). Ribboned quartz veins within the schist host pyrite, arsenopyrite, sulphosalts, sphalerite, galena and stibnite. Foliation parallel grey mottled quartz veins that locally crosscut the foliation tend to have a greater abundance of visible gold than the schist material (Coulson, 1950).

3.6.4.2 102 Zone

The 102 Zone lies between latitude 20000 to 18900, has been exploited from the 2300 to 3300 level and has a strike length of 250 metres with a steep southerly plunge. The zone occurs in the immediate footwall of the Campbell Shear hangingwall to a large horse (30-40 metres wide) that parallels the zone in strike and dip over the mined extent of the 102 zone. Developed within the 102 Zone are two main en echelon lenses lying approximately 30 metres apart from each other. On the upper levels the southern extent of the 102 Zone is defined by narrow shears anastomosing around a series of horses, with depth to the 3300 level the zone fades into a series of wispy shears that denote a poorly defined footwall to the Campbell Shear. In section the ore lenses within the 102 zone parallel the dip of the shear (Figure 3.10, 3.11), have a strike length on the order of 250 metres, range up to 10 metres wide, and strike 010°.

The horse hangingwall to the 102 zone on 3100 Level is intensely bleached and altered up to 30 metres from the ore zone. Peripheral alteration within the horse. 30 metres from the ore zone, is manifested by pervasive calcite and chlorite alteration creating a buff greenish grey colouration associated with pervasive apatite alteration. Amphibole is psuedomorphed by finer grained calcite and chlorite alteration and the groundmass consists of carbonate, chlorite and minor albite-andesine. Thin 1-2 millimetre wide pinch and swell paragonitic-muscovite quartz foliation bands crosscut the alteration (3191-18). Within 20 metres of the ore lenses metamorphic textures are obliterated by a pervasive but very weakly foliated chlorite carbonate epidote alteration associated with the growth of randomly oriented, blocky to equant, euhedral, medium grained (0.45 to 0.5 millimetre) sheafs of paragonitic-muscovite (Plate 3.10a). The

Figure 3.10 (page 100) Vertical cross section through upper portion of the Campbell Shear at latitude 19500. Refractory 102 Zone ores occur in the footwall of the Campbell Shear along the footwall of a large weakly deformed "horse" of massive yolcanic rocks. Free-milling ores occur in the hangingwall of the Campbell Shear on this section at this elevation and generally have a steeper dip than the encompassing schist.

Figure 3.10. Free-milling ores are abutting against the hangingwall of the Campbell Shear and refractory ores occupy Figure 3.11 (page 101) Vertical cross section through upper portion of Campbell Shear at latitude 19600, 100 feet north of the footwall of the shear zone.





paragonitic-muscovite sheafs are commonly associated with clear untwinned albiteandesine intergrowths (3191-17). Carbonate and mica alteration increase with foliation intensity as grain size decreases dramatically with closer proximity to the ore zone (3191-16. Plate 3.10b). Very fine grained paragonitic-muscovite (0.05 to 0.07 mm) is intergrown with chlorite, ankerite, calcite and trace albite creating a strongly foliated carbonate flooded bleached greenish grey alteration zone. Relict sheafs of paragoniticmuscovite are replaced by fine intergrown clots of more sodic paragonitic-muscovite (3191-16). In the immediate hangingwall wispy ankerite veinlets crosscut spaced (2-3mm) strongly foliated, laminated, and friable chlorite carbonate-paragonitic muscovitequartz schist with trace pyrite (3191-15, Plate 3.10c).

Immediately peripheral to ore lenses buff grey, interlocking, herring-bone textured, coarse grained ankerite and quartz flooded domains with intergrowths of medium grained, euhedral pyrite are transected by paragonitic-muscovite-chlorite foliation planes that deform and wrap around the quartz carbonate alteration (3136C, Plate 3.10d). Atoll textured pyrite grains within finer grained cataclasised domains have cores replaced by sheafs of mica and fine to medium interlocking carbonate creating a skeletal appearance (3136b, 3136D, Plate 3.10e,f). Intensely ankerite flooded domains are transected by a 1-2 millimetres spaced anastomosing foliation (Plate 3.12a) defined by paragonitic muscovite and euhedral fine-grained prismatic arsenopyrite, subhedral pyrite, minor rutile and apatite. Typically pyrite grains have inclusion riddled cores with carbonate, quartz, and mica inclusions. These cores are also enriched in arsenic. Rounded, annealed quartz balls are wrapped into the foliation (Plate 3.11a,b,e) and where elongate and less deformed host low Fe-sphalerite and locally sulphosalt minerals (Plate

Plate 3.10 102 Zone alteration and mineralisation. (A) Sample 3191-17. Sheafs of paragonitic muscovite in hangingwall alteration. XN. Field of view 2.5mm. (B) Sample 3191-16. Carbonate flooding in closer proximity to ore lens associated with decreased paragonitic muscovite grain size and development of penetrative fabric. XN. Field of view 1.25mm. (C) Sample 3191-15. Immediate hangingwall alteration. Carbonate-quartz flooding bordered by laminated white mica-chlorite carbonate schist. XN. Field of view 1.25mm. (D) Sample 3136D. Anastomosing white mica-chlorite foliation with euhedral arsenopyrite transecting polygonalised and brecciated quartz carbonate vein material. XN. Field of view 2.5mm. (E) Sample 3136D. Atol1 textured pyrite. Cores are replaced by white micas and chlorite, grains are rotated into, and pulled apart along white mica-chlorite defined foliation. PPL. Field of view 2.5mm. (F) as (E) XN.



Plate 3.11 102 Zone ore textures. (A) 3136E. Lithons of relict quartz vein material in polygonalised matrix of carbonate, white mica and carbonate. Smallest lithon demonstrate greatest degree of subgrain boundary development. XN. Field of view 5mm. (B) as (A), PPL. Field of view 5mm. (C) 3136F. Polygonalised lithon of quartz vein material enveloped by fine grained quartz and white mica schist. Opaque is Fe-sphalerite. XN. Field of view 5mm. (D) as (C). PPL. Fe-sphalerite preserved in lithon of quartz vein material. (E) 3136F. Anastomosing white mica-chlorite-sulphide foliation planes enveloping weakly deformed lithons of vein material and hosting sphalerite and sulphosalts. PPL. Field of view 5mm. (F) 3136E. Free gold (au) associated with sphalerite (sph) in relict quartz vein material. Reflected light. Field of view 1.25mm.



3.11c.d). The diameter of the quartz balls varies with the degree of deformation from 0.5-0.75 mm to 4-5mm (2750-102, 3136A, 3136B; Plate 3.12 b,c.d). Grey mottled quartz vein material is brecciated and re-annealed by anastomosing domains of fine grained carbonate, paragonitic-muscovite and arsenopyrite. Relict lithons of vein material are comprised of annealed to strongly strained quartz intergrown with euhedral, amber low Fe-sphalerite, arsenopyrite, stibnite, boulangerite, tetrahedrite and gold. Gold occurs as free grains associated with relict vein material hosted in a gangue of quartz, sphalerite and sulphosalts (Plate 3.11f). Grains are relatively silver rich (fineness of 770) and enriched in mercury (up to 1.5 wt% Hg; 3136E). The refractory or invisible gold within 102 Zone ores occurs within arsenopyrite (maximum values of 1900 ppm) and arsenian pyrite (up to 410 pp Au). Pyrrhotite was not encountered within the 102 Zone.

3.6.4.3 103 Zone

The 103 Zone. Iying between latitude 21700 to 22700 and the 2300 to 3100 levels. comprises the largest northern most stoping block within the Campbell Shear. In longsection the 103 Zone forms a flat topped and bottomed stoping block with a vertical to steep southerly plunge. The lower extension of the 103 Zone lies in the footwall of the Campbell Shear. hangingwall to a large horse on the 2900 Level. The zone thickens upward toward 2300 Level and in the thickest portions between 2750 and 2600 levels the 103 Zone is comprised of a series of en echelon vein/shear systems persistent from hangingwall through to the footwall of the Campbell Shear. The northern portion of the zone pinches and fades into interfingering, anastomosing shears and horses. The 103 zone are truncated by the West Bay

Fault between the 2750 and 2300 levels.

Ore zones are typified by strongly foliated and laminated carbonate-mica-chloritepyrite-arsenopyrite schists with mottled grey to white quartz veins. A wide spectrum of colour variation exists ranging from brown through apple green to buff grey and is manifested by a fine intergrowth of carbonate, mica and sulphide minerals and subtle variation in mica mineral chemistry. Ore lenses may be comprised of several parallel carbonate flooded sulphide rich laminated schists separated by 3-4 metres of chlorite-mica carbonate alteration schist. Hangingwall alteration is comprised of dark green chlorite calcite altered volcanic rocks, with incipient weakly paragonitic muscovite alteration as hatched intergrowths within chlorite rich foliation bands. Footwall alteration is comprised of anastomosing zones of 2-3 millimetre wide alternating bands of fine grained calcitedolomite and chlorite-paragonitic muscovite with minor tourmaline and 3-4% subrounded annealed quartz aggregates that appear rotated within the foliation. Pyrite is the dominant sulphide mineral with arsenic-rich cores (J92-79-2622Z).

Ore lenses are comprised of strongly carbonate flooded zones that have been brecciated and sheared (Plate 3.12e.f). An anastomosing cleavage comprised of paragonitic muscovite. chlorite. fine-grained crypotocrystalline ankerite and euhedral arsenopyrite transect domains of coarse grained, drusy, brownish, euhedral herring-bone textured carbonate quartz alteration. Quartz within relict domains is ragged with subgrain boundaries and extreme undulose extinction whereas recrystallised fine-grained quartz within foliation bands are clear and unstrained. Arsenopyrite and pyrite are restricted to later cleavage planes while moderately deformed carbonate quartz domains host low Fesphalerite intergrown with carbonate and local tetrahedrite. gold. and tourmaline (J92-82**Plate 3.12** 102 and 103 zone ore textures. (A) 3136C. Grain size reduction of ankerite rich portion of vein material toward planar white mica-chlorite domain (upper left portion of plate). XN. Field of view 5mm. (B) 2750Level-102 Zone. Fractured and moderately polygonalised lithon of quartz vein material enclosed in fine grained anastomosing white mica-carbonate-chlorite schist. XN. Field of view 5mm. (C) 2750Level-102 Zone. Polygonalised quartz vein fragment. XN. Field of view 5mm. (D) 2750Level-102 Zone. as (C), PPL. Field of view 5mm. (E) J92-82, 103 Zone. Anastomosing white mica-carbonate foliation planes enveloping annealed quartz domains. XN. Field of view 5mm. (F) J92-84, 103 Zone. Anastomosing white mica-carbonate foliation within polygonalised carbonate alteration. XN. Field of view 2.5mm.



2622Z, 27671-29218R). Scheelite, apatite, monazite, galena, occur as isolated trace minerals.

Tetrahedrite. chalcopyrite and sphalerite commonly occur as inclusions within poikiolitic cores of pyrite grains. Tetrahedrite within weakly deformed carbonate-quartz grains occurs as both a silver rich phase and an arsenic-antimony rich phase. Galena occurs as rare isolated inclusions within pyrite. Pyrrhotite was not identified within 103 Zone ores. Arsenopyrite grains demonstrate excellent zoning with low As cores and high As rims and form the significant host for invisible refractory gold (Chyrssoulis, 1990). Gold has been observed as isolated inclusions within an arsenopyrite host within carbonated shears, within milky white quartz veins as inclusions within pyrite (J92-85, fineness of 830). associated with low Fe-sphalerite in coarse grained carbonate-quartz veins (27671, 29218R, fineness of 918), and as liberated grains within flotation tails (B8027, 29219 stope, fineness of 927 to 919).

3.6.4.4 101 Zone

The 101 Zone forms the bulk of material mined from the Campbell Shear and hosts free-milling native gold ore. The 101 zone comprises a domain from latitude 20500 to 15500 and from 3100 level to the 6100 Level of the mine. The uppermost extent of free-milling 101 Zone ore abuts the hangingwall of the Campbell Shear at the 3100 Level of the mine within an area where the Campbell Shear is near its widest point and refractory ores lie in the footwall of the shear (Figure 3.12). In gross detail the hangingwall of the Campbell Shear is well defined with a 45 dip on the upper levels steepening to 75 below a flexure in the shear at the 5100 Level. At depth the southern

Figure 3.12 Plan view of the 2900, 3100, and 3300 levels of the Campbell Shear outlining the location of free-milling 101 Zone ore and refractory 102 and 103 Zone ore bodies. Both the 102 and 103 zones gradually feather out along the footwall of the shear below 3300 level.




portion of the shear is thickest with a NNE trend, northward the shear thins and strikes more northerly. Mineralised domains within the free-milling portion of the mine are not continuous but form a series of en echelon stoping trends with variable strike and dip extents ranging up to 300 metres. Plan maps of various levels outline the gross

extents ranging up to 300 metres. Plan maps of various levels outline the gross macroscopic geology of the shear zone and distribution of quartz lodes within the shear (Figure 3.13). Mineralization is primarily hosted within well defined quartz carbonate veins that have steeper dips than the enclosing schist. In gross detail individual stoping blocks tend to trend from the hangingwall to footwall of the shear. Quartz veins are boundinaged, folded and sheared disrupting original orientations. Attention will be placed on the uppermost free-milling ores and ore material from the northern and southern portions of the Campbell Shear at depth. The structure and geometry of the shear and its relationship to quartz vein distribution and relative timing between various vein sets have been addressed by other workers (Allison and Kerrich 1977; Webb 1992; Duke and Nauman, 1990; McDonald et al. 1993).

Macroscopically stoping trends (i.e. 60M, 68M trends) follow correlatable but discontinuous veins sets over vertical distances of up to several hundred metres. Individual stoping trends are characterised from each other by variations in quartz vein colour, thickness, abundance and degree of deformation combined with overall distribution within the mine. Each stoping trend is not discussed in detail given the size of the ore body as a whole, the complexity of the vein systems and the idiosyncrasy apparent within each stope on a day to day basis. Figure 3.13 Plan view of the 3100, 4500, and 5300 levels of the Campbell Shear outlining the general geology of the host rocks. morphology of the shear system with depth, and location of significant stoping trends discussed within the text.

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Shallow free-milling ores were examined on the 3100 and 3300 Levels and occur in a region where the lower extent of the 102 Zone ores occurs in the footwall of the shear. The uppermost extent of 101 Zone free-milling ore abuts the hangingwall of the Campbell Shear above the 3100 Level and occurs approximately 10 metres from the hangingwall of the shear. The lens has a strike length of approximately 70 metres and an overall width of approximately 20 metres. Exposure is restricted to a 20 metre long section of drift around chutes as open stopes crossing the level limit access. Milky white, sacchrodial annealed quartz veins with abundant visible gold occur within laminated chlorite-pyrite-ankerite-calcite-muscovite schist. Alteration adjacent to veins may be comprised of thin (6-10 centimetre) laminated to anastomosing muscovite-chlorite-pyrite schists bordered by chlorite rich schists (3100A, 3100D). Black to dark brown tourmaline-ankerite flooded zones are transected by muscovite-pyrite-arsenopyrite foliation planes and later narrow (1-4 mm) sharp walled quartz veinlets hosting gold and low Fe. moderately cadmium enriched sphalerite (3100C). Gold grains hosted within annealed quartz veins are associated with tourmaline carbonate chlorite septa with minor pyrite and galena and have uniform fineness (804 to 852; 3100D). Gold grains within crosscutting sharp walled veinlets occur isolated in quartz gangue with a fineness range of 851 to 893 (3100C).

The 101 Zone on 3300 Level has an aggregate strike length of approximately 430 metres and lies 30 metres from the hangingwall contact of the Campbell Shear. Mining is not continuous along this strike length and is separated into northern and southern domains by a large diabase dyke. The northern portion (33207 stope) has a strike length

of 50 metres while the southern portion (3312 stope) has a strike length of 330 metres. Ore lenses are comprised of milky white quartz veins hosted within strongly foliated chlorite-muscovite-ankerite-calcite-pyrite-arsenopyrite schists with pressure shadow development adjacent to sulphide grains (33207A: Plate 3.13a,b). Quartz vein selvages are variably deformed with laminated muscovite-chlorite schists enveloping lozenges of medium grained quartz aggregates with strong undulose extinction and polygonalised grain boundaries. Euhedral pyrite and arsenopyrite are restricted to the transecting cleavage domains (3300D, 3300B). Quartz vein material demonstrates little colour variation but microscopic textures have considerable variability within individual veins. Textures vary from medium to coarse grained ankerite and quartz with strong undulose extinction and pressure solution deformation along grain boundaries (3300D, 3300E, 33207B) to extremely fine grained, annealed, polygonal quartz with interstitial ankerite, muscovite, and chlorite (33207C, 3300DPlate 3.13 d,f). Accessory gangue minerals consist of scheelite, tourmaline, and apatite.

Sulphide and sulphosalt mineralogy is variable and complex. Sulphide and sulphosalt minerals are commonly associated with carbonate septa or appear to be seeded on carbonate domains interstitial to quartz grains. Pyrite grains commonly have poikiolitic cores which may have minor As enrichments, inclusions of gold (3300B) and sphalerite (3300C). Arsenopyrite grains are commonly euhedral, acicular with low As cores and high As rims, are associated with pyrite, tetrahedrite, sphalerite, and may host inclusions of gold (3300D). Lollingite was noted as 2 to 4 micron wide rims on arsenopyrite in one sample (33207B). Sphalerite occurs as low Fe-sphalerite containing up to 1 weight percent cadmium associated with coarse ankerite in relatively undeformed

Plate 3.13 101 Zone free-milling ore textures. (A) 33207a. 33207 Stope. Pressure shadow development adjacent to arsenopyrite in white mica-quartz-chlorite schist selvaging auriferous quartz veins. XN. Field of view 2.5mm. (B) as (A). (C) 33207C. Native gold associated with weakly brecciated pyrite (py). Reflected light. Field of view 1.25mm. (D) As (C). polygonalised quartz vein hosting py and native gold. PPL. Field of view 1.25mm. (E) 3300D. Pyrite and arsenopyrite occupying anastomosing foliation planes in annealed quartz vein. Native gold occurs as inclusions in pyrite in lower central portion of vein. Reflected light. Field of view 2.5mm. (F) 3300D Narrow white mica foliation plane in polygonalised recrystallised quartz vein. XN. Field of view 1.25mm.



quartz veins (3300B, 3300C, 33207B); iron enriched sphalerite occurs as inclusions within pyrite and adjacent to pyrite grains (3300C). Sulphosalt mineral assemblages are complex and may comprise up to 2-3% of metallic minerals. Bournonite rims silver enriched tetrahedrite (3300B), and variable Ag-As substitution occurs within tetrahedrite with As enriched tetrahedrite associated with gold and galena within polygonalised quartz veins (33207A,C). Galena forms an important accessory sulphide and locally rims sphalerite (33207C). Rare occurrences of pyrrhotite were noted as minute 5 micron blebs isolated within pyrite associated with arsenopyrite (3300C).

Gold occurs as inclusions within pyrite and arsenopyrite, as solid solution within arsenopyrite, hosted in quartz or carbonate gangue and as variable gold-silver solid solution (Plate 3.13 c.e). Arsenopyrite from the southern domain may host up to 300 ppm of gold as solid solution gold within the arsenopyrite structure, arsenian pyrite is rare and does not host significant invisible gold. Mineralogically gold from the upper freemilling ores ranges in composition from electrum to aurian silver. Isolated gold blebs within pyrite and arsenopyrite are mineralogically homogenous as are grains of gold in contact with quartz and carbonate gangue. Gold grains isolated in carbonate are associated with the more iron-rich ankerite within zoned ankerite grains. Large 50 to 60 micron gold grains in contact with tetrahedrite, pyrite and arsenopyrite within polygonalised quartz veins demonstrate complex Au-Ag zonation. Homogenous, porous low Ag cores are rimmed by and contain diffuse patches of aurian silver (33207C. 33207B. 3300B). Contacts between gold and aurian silver rims are sharp and the thickness of the rims ranges from 2 to 5 microns. Diffuse 10-15 micron wide silver enriched patches may occur as subtle zones that are in turn rimmed by zones of increased

silver content. Discrete, 2-3 micron wide slivers of aurian silver with sharp contacts occur along gold grain boundaries where gold is in contact with pyrite grains (3300B, 33207C) and associated with muscovite and chlorite. Aurian silver occurs within both strongly polygonalised quartz veins (33207B, 33207C) and coarse grained weakly deformed veins (3300B).

Deep free-milling ores

Deep free-milling ores are comprised of numerous quartz carbonate vein systems that define individual stoping trends. The area of the shear lies below the 3300 Level from latitude 15500 to 20500 to the 5900 Level of the mine. The central portion of the mine has been mined out and stopes were visited with production geologists in the upper and lower southern portion and the deep northern portion of the mine.

The degree of carbonate alteration, associated bleaching and white mica alteration is less well developed within the deep Campbell Shear and veins are hosted within chlorite-calcite-ankerite schists with localised development of strongly laminated white mica schist (53204 stope, 5760M stope). Vein-schist contacts are sharp and in many instances no visible change may be recognised in alteration mineralogy within the schist at vein-schist contacts (4372Z: Plate 3.14a). Quartz vein colour is variable from stoping trend to stoping trend, along the strike of veins, and across the width of veins (Plate 3.14 a,b,c). Pink to rose quartz veins are common in the upper south end of the mine (4163L, 4558R: Plate 3.14 e,f), milky white to grey veins dominate in the central and deep southern portion of the mine (60M, 68M, 5393M, 5557R, 5557M), dark grey to black quartz veins are common in the deep north (53204, 4792Z, 4997Z, 4799M). Basalts 10 to 15 metres from the hangingwall of the shear on 4500 level are pervasively chloritised and calcite altered with minor fine grained groundmass albite and numerous subparallel calcite quartz filled sheeted joints (Plate 3.14d). Laminated chlorite calcite schists hangingwall to veins locally preserve 2-3 millimetre lathes of idioblastic hydrothermal, twinned, euhedral albite as isolated grains that may be rotated into the foliation (Plate 3.15a,b: 4768Mc, 5360Ma) with minor pressure shadow development or as clusters to semi-massive albite chlorite intergrowths (4792Zi; Plate 3.15c,d). Albite porphyroblasts locally constitute 10 to 15 modal percent of the rock and are variably altered to calcite, chlorite and muscovite and appear to lie across and be rolled into the foliation planes defined by optically aligned chlorite with minor muscovite pyrite and chalcopyrite. Footwall laminated chlorite calcite schists also may contain preserved 0.5 to 0.25 millimetre laths of albite (5760Me) texturally similar to albite developed within hangingwall schists.

Visible alteration selvages to quartz veins are lacking in hangingwall stopes in the central portion of the mine (4372Z, 4997Z, 4799M, 4794Z; Plate 3.14a.b.c) where weakly to moderately foliated chlorite schist envelops smoky grey quartz veins up to 7 metres wide. As these veins narrow or are deformed and rolled, they tend toward lighter smoky to milky white in colour (4792Z, 4799M; Plate 3.14b.c). This hangingwall system of veins within the lower central portion of the mine share similar characteristics in vein colour and selvage mineralogy. Quartz veins vary from dark grey to milky white and colour variation appears independent of grain size. Quartz grain size varies from 0.50 to 0.75 mm polygonal unstrained aggregates (4792Za, 4792Zh) to domains of coarse grained strained dusty quartz with sweeping undulose extinction (4792Za, 4792Zh,

Plate 3.14 101 Zone quartz veins. (A) Hangingwall contact of 4372Z shrinkage stope. Dark grey to black auriferous quartz vein in sharp contact with chlorite-albite-calcite hangingwall alteration with boudinaged quartz stringers. Measuring stick is 30 cm. (B) 4372Z shrinkage stope. White quartz vein at edge of economic ore grade cut off contrasts to auriferous black quartz. Breast face looking south. HI stick is 45 cm. (C) 4799M sub. Hangingwall mottled white/grey quartz vein separated from black quartz (lower left portion of photo) vein material by chlorite-albite-calcite schist. Paint line approximately 4 cm wide. (D) 4500 Level Campbell Shear. Sheeted calcite veinlets as a portion of sheeted joint system. J. Heimbach for scale. (E) 4163L cut and fill stope. Looking north. Pink. laminated quartz carbonate vein along back and on breast face. (F) 4163L, close up of breast face looking north. Boudinaged pink quartz carbonate vein with tourmaline/chlorite septa. Hammer for scale.



Plate 3.15 Plagioclase alteration associated with free-milling ores. (A) 4768Z Stope. Rotated albite in chlorite-calcite alteration selvaging auriferous quartz veins. XN. Field of view 1.25mm. (B) 4768Z Stope. Albite grains with incipient white mica-calcite alteration. XN. Field of view 1.25mm. (C) 4792Z shrinkage stope. Cluster of albite with white mica, carbonate alteration in hangingwall of productive quartz vein system. XN. Field of view 1.25mm. (D) 4792Z shrinkage stope. Albite preserved along margin of calcite veinlet in immediate hangingwall of auriferous vein. (E) 5557M undercut. Hydrothermal albite with incipient muscovite alteration internal to productive quartz carbonate vein. XN. Field of view 5mm. (F) 5557M undercut. Hydrothermal albite internal to quartz carbonate vein. XN. Field of view 5mm.



4792Z. 4997Za. 4794Z). Styolitic grain boundaries are common within coarser grained portions of the veins. Ankerite occurs as fine grained interstitial grains or as isolated medium to coarse grains. Sulphide mineralogy is dominated by pyrite. Pyrrhotite, sphalerite, chalcopyrite, and galena vary in modal abundances and importance. Sulphides occur as coarse euhedral aggregates at quartz grain boundaries or interstitial with carbonate, chlorite, tourmaline, and apatite. Pyrrhotite and chalcopyrite are intimately associated, the pyrrhotite as fractured masses up to several millimetres in diameter. Sphalerite varies in colour from pale reddish brown to clear beer bottle brown colour with enriched cadmium (greater than 3 wt%, 4792Z, 4792Zh) near contacts with chalcopyrite and pyrrhotite. Cobaltite occurs as isolated grains with high Co rims associated with pyrite, chalcopyrite, pyrrhotite, and apatite (4794Z). Bismuth tellurides were also noted in contact with iron-cadmium rich sphalerite as 10-15 micron grains in quartz gangue (4792Z).

Chlorite schist envelopes boudinaged quartz veins in the south central portion of the mine (4372Z, 4163L, 5166L, 5361A, 5368M, 3975M; Plate 3, 14e, f) with little visible alteration adjacent to veins within the upper portions of the 60M trend (5360M) and the southern portion of the mine. Quartz vein widths vary dramatically from less than 30 centimetres to greater than 2 metres. Upper southern stopes are noted for pinkish quartz veins (5173R, 4163L, 4558R, R.L. Hauser pers comm. 1992) while most other veins in this region are characterised by a milky white to mottled grey colour. Quartz veins are massive with chlorite-tourmaline-sulphide septa and 1 to 2 % sulphide, laminated, or have preserved crack seal textures (4163L). Massive quartz veins with sharp unsheared contacts (5368M) have coarse clots of chalcopyrite and gold, medium grained unfoliated

chlorite and muscovite, minor pyrrhotite and pyrite. Coarse to medium grained euhedral pyrite occurs intergrown with medium to coarse grained quartz with strong undulose extinction and subgrain boundaries and ankerite (5168Ma). Quartz grain size reduction and polygonalisation is associated with anastomosing muscovite-chlorite-pyrite foliation planes transecting the quartz carbonate vein. Carbonate occurs as fine interstitial grains or coarse grains within coarser portions of the vein (5360M, 5168M, 3975M). Sulphide mineralogy consists primarily of pyrite with lesser pyrrhotite, galena. sphalerite and trace arsenopyrite and arsenian pyrite (arsenian pyrite restricted to 5173R, 5360M). Loellingite was noted in one sample as 1-2 micron rims on fine grained arsenopyrite (5360M). Gersdorfite occurs as isolated grains associated with galena. chalcopyrite, and pyrite grains isolated in quartz carbonate gangue adjacent to crosscutting cleavage planes (5168Ma). Bismuth-gold and Au-Ag tellurides occur as 1-2 micron isolated inclusions within arsenian pyrite domains (5360M stope).

In the south end of the mine (latitude 15500) vein sets occur (5557R, 5557M) immediately footwall to 10 to 20 metre wide horse, within 30 metres of the hangingwall contact of the shear. Mineralization consists of a 3 to 5 metre wide zone of laminated grey to white quartz veining with abundant visible gold, sphalerite, galena and pyrite. Arsenopyrite, chalcopyrite and pyrite are abundant within enveloping chlorite-muscovite schists. Vein walls are lined by pyrite, arsenopyrite and coarse grained, subhedral, interlocking albite, ankerite, and quartz. Albite grains have relict twinning and are variably altered to fine grained carbonate and muscovite (Plate 3.15 e,f). Styolitic septa of chlorite-tourmaline and carbonate host sulphide (pyrite, sphalerite, galena, pyrrhotite) tetrahedrite, and gold internal to the vein.

muscovite-quartz-ankerite-calcite-chlorite schists with pyrite. Laminated arsenopyrite, gold, accessory apatite, tourmaline and boudinaged quartz vein material preserving sphalerite, chalcopyrite, gold, and pyrrhotite selvage quartz veins in several locations (53204, 5760M, 5960XCW, 4558R, 3565M, 5168R, 4368M). The 53204 stope is characterised by a wide pale grey laminated muscovite-quartz-ankerite schist that envelops grey to jet black quartz veins. Ankerite occurs interstitially with the muscovite. tourmaline and chlorite and as discrete thin 1-2 mm bands. Black guartz veins are characterised by extremely fine grained, cataclastic textured, polygonal dusty quartz with interstitial ankerite, pyrrhotite, Fe-sphalerite, and gold. Laminated muscovite-quartz schists with variable carbonate and sulphide content form selvages to quartz veins (5168Mf, 5768, 5760Md), planar shear bands (3565M) and septa to sheared and laminated quartz veins (4558R, 4368M). Quartz is fine grained polygonal and is bisected by narrow 5-10 mm optically aligned muscovite and chlorite and by wispy interstitial connected mica planes. Sulphides are commonly associated with the muscovite foliation planes or locally within quartz lozenges. Medium grained weakly deformed ankeritequartz-chlorite alteration is locally transected by 3-5 mm wide penetrative foliation planes (5760Md).

Gold within the deep free-milling ores may occur in a variety of habits: i) free gold in quartz and/or carbonate gangue, ii) associated with chlorite-tourmaline septa, iii) as coatings on pyrite grains, iv) as isolated inclusions within pyrite grains, v) as inclusions associated with high As domains in pyrite, vi) along white mica slip planes "paint gold" and vii) as coarse clots intergrown with chlorite on vein margins. Gold fineness within deep free milling ores demonstrates little variation with only two exceptions noted to date.

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Free gold associated with Fe-sphalerite (with fine globules of pyrrhotite) rich brecciated quartz vein with disseminated galena. Fe-chlorite and tetrahedrite have a fineness of 600. A single grain of gold associated with medium grained pyrite and muscovite from the 5168M stope has a 1-2 micron lip of aurian silver in contact with muscovite. Elsewhere grains of gold have a homogenous chemistry on the scale of a single thin section.

CHAPTER 4

GEOCHEMISTRY

4.1 Bulk Rock Geochemistry

4.1.1 Introduction

Bulk rock geochemistry was determined on a series of samples representative of fresh host volcanic rocks, dykes and sheared domains enveloping productive lode gold systems. Sample traverses were carried out across visibly unaltered host rocks into shears for the Pud Stock on the 1550 level, and on both the 3100 and 5900 levels for the Campbell Shear. All analysed volcanic rocks are from the Yellowknife Bay Formation. Selected samples of the lamprophyric diatreme from the 3100 level and correlated sheeted calc-alkaline dykes from the HW of the Con Shear were included in the sample batch. Major oxide and trace element compositions were determined at the University of Western Ontario XRF Laboratory operated by C. Wu using a Philips PW 1450 Automatic Sequential Spectrometer.

4.1.2 Major Element Geochemistry

The selected samples of host basalt, gabbroic dykes and lamprophyric diatreme/sheeted calc-alkaline dykes were screened for alkali mobility due to metasomatism. Samples that fall within the metasomatic field of Huges (1973) demonstrate petrographic evidence for development of penetrative fabric (27604) or biotite/K-feldspar alteration (27533, 27561) associated with potassium metasomatism (section 3.5). The Yellowknife Bay Formation and Kam Group volcanic rocks have been the focus of numerous previous geochemical studies (Baragar, 1966; Green and

Baadsgaard. 1971: Condie and Baragar. 1974: Goodwin, 1988; and Cunningham and Lambert. 1989) and no attempt was made to replicate those efforts here but rather to analyze "fresh" volcanic rocks to establish a control in mass balance calculations. Those samples that demonstrate limited mobility were used for discrimination plots. Representative analyses for individual rock types are summarised on Table 4.1. When host basalts were plotted on an AFM diagram they demonstrate clear tholeiitic affinities with evident iron enrichment (Figure 4.1). On a total alkalis versus silica plot the volcanic rocks cluster entirely in the sub-alkaline field (Figure 4.2). A Jensen cation plot classifies host volcanic rocks and gabbro dykes as high iron tholeiites (Figure 4.3).

On an AFM diagram diatreme dykes and layered dykes from the mine workings are characterised by high MgO and bridge the tholeiitic/calc-alkaline discrimination line (Figure 4.4). These same dykes bridge alkaline and sub-alkaline fields as shown on a total alkalis versus silica plot (Figure 4.5). The Arsenic Pond Gabbro dyke plots as high-Mg tholeiites, diatreme and layered dykes demonstrate tholeiitic affinities and several samples plot as basaltic komatiites and a Jensen Cation plot (Figure 4.3b). Whole rock rare earth element profiles demonstrate clear variations between volcanic hosts and the various dykes. Volcanic flows and the Arsenic Pond Gabbro have flat REE distributions (Figure 4.6a), while layered calc-alkaline dykes and diatreme dykes have elevated LREE and moderately depleted HREE and high total REE's (Figure 4.6b). Extended elemental profiles demonstrate similar relationships between dyke types. Layered calc-alkaline dykes and diatreme dykes have distinct Th, U, La, Ce high with a distinct Nb low and over all greater abundances of the LREE relative to the Arsenic Pond Gabbro dyke.

Table 4.1 Representative Whole Rock Analyses for Dykes and Volcanic Flows

Sample	27604 APG	R218-232	CON-15 LCA	27535
\$102	46.10	43.12	44.52	51.99
Ti 02	0.50	0.49	0.45	0.73
A1203	16 07	9.77	10.47	14.65
A1203	0.02	7 93	8 75	11 03
Fezos	9.05		-	
reo	- 15	0 17	0 16	0 17
MnO	0.15	14 27	12 05	6 99
MgO	11.64	11.21	14.95	10 01
CaO	8.49	13.30	11.11	10.91
Na20	1.51	1.11	0.86	2.02
K20	1.37	2.60	0.80	0.50
P205	0.02	0.66	0.69	0.07
Total	95.63	93.48	94.06	99.11
LOI	4.18	5.75	4.78	1.09
Mg #	70.11	78.09	74.56	55.62
-				
Cr		-	-	
Ni	307	351	321	81
Co	-	-		-
Sc	30	-	34	
v	-	-	-	77
Cu	58	39	31	7
Pb	5	11	16	94
Zn	88	144	112	
				18.00
Ав	44.00	5.00	50.00	
				4649
ĸ	11373	21583	6641	14
Rb	60	90	22	-
Cs	1.69	-	0.59	135
Ba		-	-	14
Sr	133	702	1012	
Ga	15	12	13	4.0
90				79
Тэ	0 10	-	0.10	4376
ND	2.10	2 0	2 0	14
110 116	2.0 17	2.V -	3 39	
71L 7-	0.77	116	155	2 56
21 m:	1000	2020	2509	2.30
11	4338	2330	2050	
Y .	9	19	74 80	
Th	0.50	-	24.00	
σ	0.20	-	3.60	
La	1.77	-	174.00	
Ce	4.58	-	417.00	
Nd	3.80	-	193.00	
Sm	1.20	-	31.90	
Eu	0.48	-	7.44	
ть	0.25	-	1.54	
УĎ	0.96	-	1.29	
Lu	0.13	-	0.16	
Density	2.60	2.65	2.65	



Figure 4.1 AFM discrimination plot for mafic volcanic host rocks from Irvine and Baragar, 1971.



Figure 4.2 Total alkalis versus silica discrimination plot for host basalts from Irvine and Baragar, 1971.



Figure 4.3a Jensen cation plot for host basalts from Jensen, 1976.



Figure 4.3b Jensen cation plot for gabbro dykes. O layered calc-alkaline dykes; ● Arsenic Pond Gabbro (APG) dyke; □ Diatreme dyke 3100L; ■ #8 gabbro dyke



Figure 4.4 AFM discrimination plot for gabbro dykes from Irvine and Baragar, 1971. O layered calc-alkaline dykes: ● Arsenic Pond Gabbro (APG) dyke: □ Diatreme dyke 3100L: ■ #8 gabbro dyke.



Figure 4.5 Total alkalis versus silica discrimination plot for gabbro dykes from Irvine and Baragar. 1971. O layered calc-alkaline dykes: ● Arsenic Pond Gabbro (APG) dyke: □ Diatreme dyke 3100L: ■#8 gabbro dyke.



Figure 4.6a. Chondrite normalised REE spider diagram for gabbro dykes. The data are normalised to chondrite with normalising factors from Taylor and McLennan, 1985.



Figure 4.6b. Chondrite normalised spider diagram for gabbro dyke types. The data are normalised to chondritic values from Taylor and McLennan, 1985.

4.1.3 Bulk Chemical Fluxes

The net chemical changes for major and trace elements between unaltered and deformed/altered samples were determined utilising the isocon technique of Grant (1986) as a solution to Gresens' (1967) equations for metasomatic alteration. Relative gains and losses in weight percent of major oxides are plotted relative to distance from the mineralised vein as shown by Leitch et al., (1991). Appendix C.2 provides a table of volume factors and relative gains and losses for each traverse. Unless otherwise stated host rocks were assumed to be tholeiitic basalt. Least altered equivalents were chosen for each sample traverse on the basis of proximity to the ore zone, degree of alteration. and deformation. The bulk chemical changes are reported relative to alumina and titanium which are assumed to have remained immobile during metasomatism. Samples of laminated schist that host refractory ores were not included in the data sets since they are the sheared equivalent of pre-existing quartz carbonate veining. Bulk chemical changes were determined for alteration associated with refractory ores on the 3100L of the Campbell Shear, flux was also determined for a deformed portion of the Pud Stock. and a traverse through a free-milling ore body on the 5900L of the Campbell Shear.

4.1.3.1 Pud Stock

The onset of alteration and development of penetrative fabric within the Pud Stock produces a gradual volume gain associated with influx of SiO₂, K₂O, CaO, and LOI and losses in Fe₂O₃, MgO, Na₂O, P₂O₅ during breakdown of albite, hornblende and biotite to white mica, with increased carbonate alteration. Complete destruction of primary mineralogy during progressive deformation and development of a penetrative fabric resulting in formation of laminated quartz-white mica schists is reflected by a net volume loss (-30%) with further increases in SiO₂. K₂O, As, and a concomitant loss of all other major cations (Figure 4.7).

4.1.3.2 102 Zone

Samples collected across 150 metres of the Campbell Shear from HW through to refractory FW 102 Zone mineralisation are plotted on Figure 4.8. A domain of quartzcarbonate veining with low grade gold mineralisation is hosted within HW chlorite schist. Development of penetrative fabric and chloritisation results in minor losses of MnO, MgO, CaO, Na₂O, and K₂O. Shoulders on the narrow vein system demonstrate gains in Na₂O reflecting the albitisation common to free-milling ore zones. Within progressively bleached and carbonate-white mica altered basalts toward the HW of the refractory ore zone there are substantial gains in SiO₂. Fe₂O₃, MnO, CaO, K₂O, LOI, and losses in Na₂O, P₂O₅, TiO₂. Noticeable loss in MnO within immediate HW rocks is offset by gains of MnO within ore zones. A steady volume increase with progressive carbonate alteration is reflected in the increased gains in LOI and CO₂ assays (Figure 4.9). As paragonitic micas are located within zones of overall Na₂O loss suggests Na influx is not a requirement to stabilise paragonite.

4.1.3.3 101 Zone

The traverse from the HW crackle breccia/sheeted joints through the 60M ore trend into moderately foliated massive basalts on the 5900 Level demonstrates bulk chemical flux for free-milling ores (Figure 4.10). Silica shows steady enrichment toward



Figure 4.7 Modified Gresens' plot of weight percent loss or gain of major oxides, plotted against proximity to most intensely sheared portion of the Pud Stock. Volume factor is based on alumina and titania values of 27529, least altered Pud Stock.

Figure 4.8 Sample locations along 3100L traverse from the hangingwall of the Campbell Shear thru to hangingwall alteration associated with 102 Zone mineralisation.

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Figure 4.9 Modified Gresens' plot of weight percent loss or gain of major oxides, plotted against proximity to 102 ore zone on the 3100L. Volume factor is based on alumina and titania contents in sample R209-150. Samples 1 (3136A) and 2 (3136B) correspond to mineralised and sheared vein material. Most altered sample at x-y intercept.

Figure 4.10 Sample locations along 5960M XCW from crackle breccias and relict amphibolitic schist on the immediate hangingwall of the Campbell Shear thru to weakly altered footwall flows. Samples 4 and 6 and quartz stringers.





Figure 4.11 Modified Gresens' plot of weight percent loss or gain of major oxides, versus proximity to vein plotted along traverse from HW (sample 2, 5960M-2) through mineralised zone to weakly sheared footwall volcanic rocks (sample 10, 5960M-10). Volume factors based on alumina and titania content of 5960M-1. Samples 4 and 6 represent quartz stringer zones.

the ore zone but depletion immediately adjacent to the veins. Total Fe_2O_3 demonstrates losses throughout while K_2O along with variable Na_2O demonstrate gains immediately adjacent to veins. Volume increases with degree of foliation in FW flows but demonstrates minor losses immediately adjacent to vein material (Figure 4.11).

4.2 Mineral Chemistry

Electron microprobe analyses were performed on a JOEL 8600 Superprobe at the University of Western Ontario under the supervision and technical assistance of Robert Barnett and Dave Kingston. Operating conditions and standards are reported in Appendix A.1. The electron microprobe was utilised to document mineralogical variability within host rocks. alteration zones and auriferous domains. Minerals investigated include amphibole, feldspar, white mica, biotite, chlorite, pyrite, arsenopyrite, gold, sphalerite, sulphosalts, tetrahedrite, apatite, pyrrhotite and carbonates.

4.2.1 Amphibole

Compositional variation of calcic amphiboles relative to metamorphic grade has been documented in various basaltic sequences (Liou et al. 1974: Begin and Carmichael 1992: Terabayashi 1993: Apted and Liou, 1983). The Al and Ti contents of calcic amphibole in conjunction with the anorthite component of co-existing plagioclase have been used as pressure and temperature indicators for metamorphism (Spear 1981; Raase 1974: Hammarstrom and Zen, 1986). Amphiboles were investigated within prograded host basalts in conjunction with plagioclase to determine metamorphic grade transitions along and across shear zones. The composition of amphiboles within prograded basalts will be compared to that of amphibole within amphibolitic schists and fluidised joint systems. In total 219 amphibole analyses were carried out on 27 samples, representative analyses are provided in Table 4.2.

Structural formula for amphiboles were re-calculated from microprobe data utilising the PAPIKE program (Papike et al., 1974) to determine the ferrous/ferric iron split and site occupancies for amphibole classification. The Papike calculated Fe_2O_3 utilised for structural formula calculations is the midpoint value between all iron as FeO and all iron as Fe_2O_3O . As classified according to the scheme outlined by Leake (1978) the amphiboles are entirely calcic species. A generalised structural formula for calcic amphiboles proposed by Deer et al., (1969) is as follows:

$$A_{0-1}B_{2-3}Y_5Z_8O_{22}(OH)_2$$

where A = A-site, B = B-site, Y = the octahedral site, and Z = the tetrahedral site. Calcic amphiboles within prograded basalts, amphibolitic schists, and quartz-plagioclaseamphibole veinlets demonstrate significant variations in alumina content, alkali content and A-site occupancy. The principal substitutions controlling amphibole compositions within the data set are the tschermakitic:

$$(Al^{v_1}+Fe^{3-}+Ti+Cr), Al^{v_1} = (Fe^{2-}+Mg+Mn).Si$$

and the edenitic substitutions:

$$(Na + K)^{A}.Al^{n} = \sim^{A}.Si$$

where the box represents vacancies within the A-site (Laird and Albee. 1981).

The control of both the edenitic and tschermakitic substitutions on amphibole chemistry are illustrated in Figure 4.12. As a group amphibole compositions are Mg rich and lower Mg/Mg + Fe^{2+} ratios accompany decreased silica values. The silica content

TABLE 4.2

CON MINE AMPHIBOLE MICROPROBE ANALYSES

	1	2	3	4	5	6	7	8
SiO2	42.92	43.36	52,40	55.88	53.23	43.47	42.85	50.98
TiO2	.43	.36	. 04	.00	.04	.49	. 30	.30
A1203	12.40	14.55	3.12	1.44	2.75	13.82	12.45	4.74
Cr2O3	.05	.07	.01	.00	.00	.00	. 08	.00
MnO	.36	.30	. 23	. 20	. 20	.40	.47	.28
FeO	20.84	18.11	14.46	12.60	13.43	18.50	20.79	17.69
MgO	7.22	7.41	14.17	15.53	14.00	7.71	6.69	11.47
CaO	12.04	11.63	11.95	12.94	12.65	11.68	11.41	12.04
K2O	. 38	. 27	.12	.04	. 07	.27	. 26	.08
Na20	1.00	1.24	.33	. 02	. 32	1.43	1.07	.53
F	.16	.04	.00	.00	.00	.10	.20	.00
CL	.03	.04	. 02	.00	. 09	.08	.02	.02
SUM	97.83	97.38	96.85	98.65	96.78	97.95	96.59	98.13
O= F+CL	.07	.03	.00	,00	. 02	.06	. 09	.00
SUM	97.76	97.35	96.85	98.65	96.76	97.89	96.50	98.13

1 27571 UNIFORM AMPH GRN 2 27537 LT RIM 3 27537 DK CORE 4 27590B EQUANT HOMO AMPH

5 27597 MOTTLED AMPH DK ZONE 6 27597 LTR RIM ZONE SAME GRAIN 7 27625 LG FOLN PARALLEL 8 27615 VEIN AMPH

AMPHIBOLE STRUCTURAL FORMULA PAPIKE RE-CALCULATION

	TETRAHEDRAL				OCTAHEDRAL						M4	SITE		A-SITE			
SAMPLE	Si	A1	SUM	A1	Fe2+	Fe3	⊦ Mg	Mn	Тi	SUM	XOCT	* Ca	Na	SUN	1 Na	K	SUM
27571 UNIFORM AMPH GRN	6.47	1.53	8	0.68	2.19	0.44	1.62	0.05	0.05	5.03	0.03	1.95	0.03	2	0.26	0.07	0.34
27537 LT RIM	6.48	1.52	8	1.05	2,11	0.16	1.65	0.04	0.04	5.04	0.04	1.86	0.09	2	0.27	0.05	0.32
27537 DK CORE	7.66	0.34	8	0.19	1.64	0.13	3.09	0.03	0.00	5.08	0.08	1.87	0.05	2	0.04	0.02	0.06
27590B EQUANT HOMO AMPH	7.93	0.07	8	0.17	1.50	0.00	3.28	0.02	0.00	4.98	0.00	1.97	0.01	2	0.00	0.01	0.01
27597 MOTTLED AMPH DK ZONE	7.77	0.23	8	0.24	1.64	0.00	3.05	0.02	0.00	4.96	0.00	1.98	0.02	2	0.07	0.01	0.08
27597 LTR RIM ZONE SAME GRAIN	6.49	1.51	8	0.92	2.13	0.18	1.72	0.05	0.06	5.05	0.05	1.87	0.08	2	0.33	0.05	0.38
27625 LG FOLN PARALLEL	6.55	1.45	8	0.79	2.28	0.37	1.52	0.06	0.03	5.06	0.06	1.87	0.07	2	0.25	0.05	0.30
27615 VEIN AMPH	7.48	0.52	8	0.29	2.03	0.14	2.51	0.03	0.03	5.04	0.04	1.89	0.07	2	0.08	0.01	0.10

Fe_iO_i is calculated as mid-point between all iron as FeO and all iron as Fe_iO_i.

-**1** 5 of the amphibole reflects the degree of aluminum substitution in the tetrahedral site (tschermakitic substitution) and provides the most critical criteria for the classification of the various amphibole species. Due to intra-sample compositional variations individual analyses are plotted as opposed to averages for individual samples.

Compositional zoning is ubiquitous within prograde amphiboles. Core to rim variation in Al. Ti. Mg, and Na content are typical. Increased Na and the resultant increase in A-site occupancy associated with increased tetrahedral aluminum demonstrates the sharp compositional gaps between cores and rims reflecting increasing metamorphic grade and the importance of the edenitic substitution.

With increased metamorphic rank prograde hornblende rims increase in width at the expense of actinolitic cores concomitant with a decrease in modal groundmass epidote and increasing An content of co-existing plagioclase (Plate 4.1 a-d). A sharp compositional gap exists within each individual grain where cores are poikiolitic, with low Al, Ti, Fe, and Na, rims are enriched in Al, Ti, and Na, Fe with lower Si and Mg. Rim compositions may vary considerably within the sample suite from actinolitic hornblende, magnesio-hornblende through ferro-tschermakitic hornblende while core compositions are restricted to the actinolite and actinolitic-hornblende fields. Total A-site occupancy (Figure 4.13a - e) and variation in tetrahedral Al (Figure 4.14a - e) demonstrate core-rim chemical variation and increased metamorphic conditions as determined by amphibole rim compositions.

Variations in rim compositions are married to the An-content of co-existing plagioclase and the relative abundance of groundmass epidote. As rim compositions progress toward ferro-tschermakitic hornblende and as individual grains become texturally



Figure 4.12a Silica versus the ratio of magnesium to magnesium and iron in atomic formula units after the calcic amphibole classification scheme of Leake (1978).



Figure 4.12b Variation diagram of A-site occupancy (Na-A + K) versus tetrahedral aluminum. A line connecting X-Y intercept with upper left corner of diagram box represents ideal edenitic substitution.

Plate 4.1 Backscatter SEM images of metamorphic calcic amphibole. (A) 27593. Lower epidote amphibolite actinolite grain with very thin bright ferro tschermakitic rim. (B) 27597. Epidote amphibolite sample with progressively wider rim of a more TiO², FeO, aluminous amphibole species (brighter rim). (C) 27537. Hornblende amphibolite sample demonstrating progression of more TiO², FeO, CaO, aluminous rim composition as epidote is consumed. (D) 27597. Upper hornblende mphibolite, almost total replacement of actinolitic core by higher grade amphibole species. (E) R209-150. Large amphibole grain with inclusion of labradorite (p). Large amphiboles commonly host inclusion of Ca-rich plagioclase.





and compositionally homogeneous the An-content of plagioclase demonstrate an increase to labradorite-bytownite as groundmass epidote is consumed (Figure 4.15).

Garnet amphibolite facies volcanic rocks are characterised by homogeneous ferrotschermakite hornblende (Figure 4.14a) with lower $Mg/Mg + Fe^{2-}$ ratios and Ca content than ferro-tschermakite hornblende rim compositions within upper amphibolite samples. Plagioclase is not stable within garnet amphibolites with excess Ca from plagioclase and Mg from amphibole incorporated into almandine garnet.

Upper amphibolite facies amphiboles are homogeneous in composition and rim compositions lie toward the ferro-tschermakitic hornblende co-existing with labradorite-bytownite (Figure 4.14b). Homogeneous ferro-tschermakitic hornblende within garnet amphibolites facies volcanic rocks have similar Al(iv), Si, lower Mg/Mg+Fe²⁺ ratios, and are devoid of plagioclase in comparison to hornblende amphibolites.

Within upper epidote amphibolite and lower hornblende amphibolite facies rocks neither core or rim compositions are homogeneous. There is significant inter-sample variation but little intra-sample variation in the core and rim compositions (Figure 4.14c,d). The evident compositional variation is also married to a consistent increase in the An-content of co-existing plagioclase. Core compositions may cluster in. or trend from actinolite through actinolitic hornblende: rim compositions for all samples regardless of core composition demonstrate rim compositions overlapping the magnesio/ferrohornblende to ferro-tschermakitic fields. The co-existing plagioclase demonstrates an anorthite component increase, similar to that of the Al content of hornblende cores.

Lower epidote amphibolite facies volcanic rocks contain homogeneous actinolite and actinolitic hornblende (Figure 4.14e) associated with albite, groundmass epidote, and Figure 4.13 Variation diagrams of A-site occupancy (Na + K) versus tetrahedral aluminum for various metamorphic facies within basalts demonstrating core-rim compositional variability: (a) garnet amphibolite; (b) upper amphibolite facies; (c) upper epidote amphibolite; (d) epidote amphibolite; (e) lower epidote amphibolite.

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Figure 4.14 Variation diagrams of silica versus the ratio of magnesium to magnesium and iron after the calcic amphibole classification scheme of Leake (1978) for all prograde metamorphic facies in host basalts. Composition changes with increased metamorphic rank: (A) garnet amphibolite; (B) upper amphibolite facies; (C) upper epidote amphibolite; (D) epidote amphibolite; (E) lower epidote amphibolite.



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Formation basalts, quartz-plagioclase-amphibole veinlets, and amphibole schists. An content of plagioclase increases concomitantly with thickness of hornblende rims. Amphibole from veins and shears do demonstrate core rim variations in Al₂O₃ contents. Figure 4.15 Anorthite component of plagioclase plotted with range in AI,O, for co-existing amphibole from Yellowknife Bay



titanite. With increasing depth and footwall to the Campbell Shear actinolites are homogeneous but slightly enriched in Al, Ti. They co-exist with more abundant groundmass and fracture fill epidote relative to surface exposures. Within the hangingwall of the Campbell Shear on surface actinolite and actinolitic hornblende rims may be retrogressed to chlorite.

Foliated, aligned, and prismatic calcic amphibole within amphibolitic schists do not display the sharp zonation patterns observed within the thermally prograded basalt sequences (Figure 4.16a,b, Plate 4.2). Intra sample variation in chemistry define clusters that are distinguishable from the overall intersample chemical variation. Amphibolitic schists preserved within the hangingwall of the Campbell Shear (5960M-1) or within horses of the Con Shear (27625) are characterised by an amphibole population with lower Si and Mg/Mg + Fe²⁻ ratios than amphiboles internal to narrow schists zones detached from major shears (27598, KL-1). Thin ferro-actinolitic to actinolitic rims are locally developed (5960M-1, KL-1) reverse to zonation patterns observed within the prograded basaltic sequences. Foliation parallel ferro-tschermakitic hornblendes contain lower Mg/Mg + Fe²⁻ ratios than host rock hornblende.

Calcic amphibole preserved within veinlets are locally chaotically zoned with intra and inter sample variation lying across the spectrum of amphibole compositions (Figure 4.17). The variation in Mg/Mg+Fe²⁻ ratios range from 0.5 to 0.7. Notably these compositions are not similar to amphiboles within adjacent wall rock indicating that the vein amphiboles have not been stoped from adjacent vein walls.

Plate 4.2 Backscatter SEM images of amphibolitic schist. (A) 27625, 1250Level Con Shear. Homogeneous amphibole grains with minor groundmass chlorite alteration. (B) 27625, 1250Level Con Shear. Homogeneous amphibole compositions with more progressive chlorite alteration.







Figure 4.16a Foliated amphibole schist. Silica versus the ratio of magnesium to magnesium and iron in atomic formula units after the calcic amphibole classification scheme of Leake (1978).



Figure 4.16b Foliated amphibole schist. Variation diagram of A-site occupancy (Na-A + K) versus tetrahedral aluminum.



Figure 4.17a Veinlet amphibole. Silica versus the ratio of magnesium to magnesium and iron in atomic formula units after the calcic amphibole classification scheme of Leake (1978).



Figure 4.17b Veinlet amphibole. Variation diagram of A-site occupancy (Na-A + K) versus tetrahedral aluminum.

4.2.2 Feldspar

Plagioclase occurs within both prograded host basaltic sequences and retrogressed shear zones. Fine grained untwinned albite is associated with low grade greenschist facies and lower epidote amphibolite volcanic rocks. Much rarer potassium feldspar is restricted to isolated domains hangingwall to refractory ore bodies and along joint/fracture systems immediately adjacent to the Pud Stock.

The anorthite component of plagioclase within basalts systematically increases with metamorphic grade concomitant with the gradual loss of epidote and the associated increase in the rim width of prograde aluminous calcic-amphibole (Figure 4.15). Intra sample variation is generally on the order of 20 An units with no discernable zonation patterns, although aluminum rich domains within amphibole commonly contain isolated grains of plagioclase with higher An content (labradorite, Plate 4.1e). Plagioclase within amphibolite schists have a lower An content than prograded basalts with similar amphibole chemistry.

Albite is a common mineral phase within chlorite schists peripheral to mineralised vein systems within both the Con and Campbell Shear Systems. Grain size is variable ranging from fine grained untwinned masses to 2-3mm lathes with albite twinning. Preserved lathes are characteristically rotated into the planar foliation where they occur as lozenges wrapped by fine grained chlorite and carbonate. Albite may be associated with pressure shadow development in schists selvaging free-milling quartz veins. Although ubiquitous within vein selvages within quartz veins albite is very restricted occurring only in veins within the deep southern portion of the mine workings (5557R, 5557M stope).

Potassium feldspar is commonly located along joint surfaces within 100 metres of the Pud Stock and are manifested by rusty red weathered surfaces. It has been identified in isolated patches hangingwall to refractory ore bodies within the Con Shear. Grains are typically cloudy and similar to albite are rotated into foliation planes with limited pressure shadow development. Anhedral untwinned grains are variably altered to chlorite, quartz, and carbonate.

4.2.3 Biotite

Biotite associated with joints and as pervasive groundmass alteration demonstrates minor compositional variability (Figure 4.18). MgO contents range from 9 to 12 wt% and FeO contents fall in a range from 19 to 21 wt%. The biotite associated with joints and altered plagioclase microlites are typically less iron enriched. Biotites with greater iron contents tend to occur as groundmass disseminations and replacement of amphibole (R218-411). Titanium is consistent throughout the data set ranging in value from 1.3 to 1.8 wt%.

4.2.4 Chlorite

Chlorite mineral species are ubiquitous within the alteration envelopes and veins of the Con and Campbell shears. locally along retrograde joint surfaces, and replacing amphibole within amphibolitic schists. Four chlorite species are identified utilising the plot of Hey (1955). The dominant species is ripidolite. Pyncnochlorite is found as an alteration product within volcanic rocks, on joint surfaces and in amphibolitic schists. Clinochlore and sheridanite are only associated with narrow veins within the Con Shear



Figure 4.18 Variation diagram of FeO versus MgO in weight percent for biotite associated with joint and groundmass alteration within host basalts.

System (C10.C39 Shears).

Retrograded metavolcanic and joint chlorite chemistry is comprised of pycnochlorite with Al^w.Al^w contents of less than 2.8 pfu (Figure 4.19). Pycnochlorite with Al^w > Al^w are associated with grain boundary alteration of amphibole within amphibolitic schists. Within sheeted joints chlorite chemistry is dominated by ripidolite with Al^w > Al^w and increasing Fe/Fe+Mg ratio as chlorite develops a preferred orientation.

Narrow veins and shears within the Con Shear System contain chlorites with $AI^{n}, AI^{n} < 2.8$ pfu, Si > 5.25, and Fe/Fe+Mg ratios that range from 0.10 to 0.50 (Figure 4.20). Clinochlore occurs as matts and sheafs within narrow cataclastic quartz veins of the C10 vein. Sheridanite occurs as isolated tabular sheafs within crack seal veins of the C39 shear (27613). foliation parallel chlorite within selvages of narrow veins range in composition from sheridanite to ripidolite (27612). Wider portions of the C4 and C36 Shears are dominated by ripidolites with Fe/Fe+Mg ratios of 0.4 to 0.5, and Alⁿ > Alⁿ with the exception of chlorite associated with abundant tourmaline (29621, C4-1250Level) (Figure 4.21).

Ripidolite associated with alteration and mineralization within the Rat Lake region of the Con Shear demonstrate subtle variations across the mineralised zone. Hangingwall and footwall ripidolites associated with chlorite-iron carbonate schists have Fe/Fe+Mg ratios of greater than 0.5 and $AI^{vi} > AI^{iv}$ (Figure 4.22). Ripidolite associated with laminated auriferous schists have Fe/Fe+Mg ratios of less than 0.5 and variable $AI^{iv} > =$ AI^{vi} . Late wispy ripidolite most commonly have $AI^{iv} > AI^{vi}$.

Subtle increases in Fe/Fe+Mg ratios associated with decreasing Si occur as

Figure 4.19 - Figure 4.27 (A) Chlorite compositions according to classification scheme of Hey (1954). (B) Variation diagram of octahedral aluminum versus tetrahedral aluminum. Diagonal line represents 1:1 correlation.

Figure 4.19 (p. 173) Joint and retrograde amphibole schist chlorite.

Figure 4.20 (p. 174) Con Shear narrow vein and shear chlorite.

Figure 4.21 (p. 175) Wider portions of the C4 and C36 chlorite.

Figure 4.22 (p. 176) Rat Lake alteration and mineralisation chlorite.

Figure 4.23 (p. 177) 102 Zone chlorite.

Figure 4.24 (p. 178) 103 Zone chlorite.

Figure 4.25 (p. 179) Shallow 101 Zone chlorite.

Figure 4.26 (p. 180) Intermediate 101 Zone chlorite.

Figure 4.27 (p. 181) Deep 101 Zone chlorite.
















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alteration intensifies within the hangingwall of the 102 Zone on 3100 level of the Campbell Shear. Vein ripidolites have lower Fe/Fe+Mg ratios than ripidolites within refractory schists of the 102 Zone (Figure 4.23). Ripidolite from the refractory 103 Zone demonstrates little intra sample compositional variation with the exception of strongly foliated but weakly mineralised samples selvaging auriferous schists. Footwall ripidolites from the 103 Zone have Fe/Fe+Mg ratios < 0.45, (Figure 4.24) similar to auriferous schists of the 103 zone and auriferous veins of the 102 zone. Hangingwall ripidolites of the 103 Zone have Fe/Fe+Mg ratios of > 0.45.

The 101 zone samples examined all contain ripidolite with little intrasample variability but a wide range of intersample variability. In general 101 zone ripidolites contain $AI^{n} > AI^{n}$ and demonstrate a weak trend of increasing Fe/Fe+Mg and AI^{n} with depth (Figure 4.25.26.27).

4.2.5 White Mica

Dioctahedral phyllosilicates of the common mica group are an important mineral phase within mineralised domains of the Con and Campbell Shear Zone Systems. Structurally the common micas consist of a sheet of octahedrally co-ordinated cations (Y-site) between two identical sheets of tetrahedral co-ordinated (Si,Al)O₄ tetrahedra (Z-site). The idealised structural formula for the common micas is as follows:

 $X_2Y_{4.6}Z_8O_{20}(OH,F)_4$ X = K, Na, Ca (Ba, Rb, Cs) Y = Al, Mg, Fe, Mn, Cr, Ti, Li Z = Si, Al Four hydroxyl ions are replaced by apical oxygens of the tetrahedral layer and complete the octahedral co-ordination of the sheets. The composite layers comprised of the three sheets have a net negative charge which is balanced by planes of ions (X-site) with a twelve fold co-ordination.

Substitution of Si by Al within the tetrahedral site coupled with variable substitutions within the octahedral sheets and the interlayer position creates three major compositional fields of importance to the present study.

Si:Al=4:1
$$K(Al,Fe,Mn,Ti,Mg)_2[AlSi_3O_{10}](OH)_2$$
 muscovite

Si:Al>3:1
$$K(Al,Fe,Mn,Ti,Mg)_2[AlSi_3O_{10}](OH)_2$$
 phengite

Si:Al=3:1 Na(Al,Fe,Mn,Ti,Mg)₂[AlSi₃O₁₀](OH)₂ paragonite

Paragonite is the sodium end member of the common white micas where sodium replaces potassium within the interlayer position. The paragonite component is the ratio of sodium to total alkalis and is calculated as follows:

Experimental and field studies have established an immiscibility gap between muscovite and paragonite. Muscovite rarely contains between 30% and 75% paragonite component. Many analyses in this study fall within this gap and this is attributed to mixed layer intergrowth of sodium enriched and sodium depleted layers (Plate 4.3). For the purpose of this study paragonitic muscovite describes analyses with compositions of between pg12mu88 and pg35mu65, analyses falling between pg35mu65 and pg100mu0 are referred **Plate 4.3** Backscatter SEM images of white mica relationships. (A) and (B). Relationship of fine layered intergrowth of paragonite (p) with paragonitic muscovite (pm) with quartz (q). Paragonite is darker grey phase and the fine intergrowth of the two phases accounts for the infill of the immiscibility gap within the white mica data set.





to as paragonite.

Substitution of siderophile elements for aluminum within the octahedral site requires a coupled substitution of silica for aluminium within the tetrahedral site in order to maintain the charge balance. This is referred to as the phengitic substitution. The extent of the substitution of siderophile elements is defined as their sum, in atomic formula units (afu), referred to as the phengite component. A phengite requires at least one of four octahedral sites to be fully occupied by siderophile elements. For the purpose of this study phengitic muscovite refers to analyses in which the siderophile elements (Fe, Mg, Ti, Mn) occupy greater than one half of one site within the octahedral layer.

Within the data set a striking chemical variability exists between white micas associated with refractory gold ores from those associated with free milling gold ores (Table 4.3). Paragonitic muscovite and paragonite dominate in alteration haloes and ore zones of refractory ore lenses while alteration micas from free milling ore lenses are dominated by muscovite and phengitic muscovite. Ore types within the Con Shear are especially well distinguished on the basis of white mica compositions: narrow shear structures within the C4 Shear and Shaft group are characterised by muscovite while wider schist dominated. refractory bodies are defined by paragonite/paragonitic muscovite. Within the Campbell Shear each distinct ore zone (101, 102, 103, Negus) and its alteration halo contain specific white mica species.

4.2.5.1 Con Shear Mica

White mica mineral chemistry demonstrates distinct variability between various shear strands and thick versus narrow portions of individual shear segments. Narrow

	MINE
	CON
	ANALYSES,
-	MICA
ole 4.3	WHITE
Tal	REPRESENTATIVE

8	45.54	.35	33.98	00.	0.	1.57			00.	.16	10.60	16			17 66	00	93.41	6.205 *	1.795 8.000	3.662 *	• 036 •	• 000.	• 100.	* 179 *	.177 4.054	• 000.	* 600 .	1.842 *	.082 1.933	• 000.	• 500.	22.000 *	4.26	95.74	1.019	.505			
7	44.67	.25	32.85	.05	00.	4.40	34. 0		20.	.14	7.19	1 12			93.04	00	93.04	6.112 *	1.888 8.000	3.408 *	.026 +	• 005	• 000.	.503 *	.479 4.422	• 003	* 800.	1.255 *	.297 1.562	• 000.	• 000.	22.000 *	19.15	80.85	1.051	.512		•	
9	48.48	.05	37.30	.04	.01	. 55			.10	00.	6.13	2.13	00	00	94.94	00	94.94	6.281 *	1.719 8.000	3.975 *	• 005	• 004	• 100.	• 060	.029 4.074	.014 *	* 000.	1.013 +	.535 1.562	• 000·	* 000.	22.000 +	34.56	65.44	2.095	.677	0.3136A CP 2 MIC	TCA	
2	45.51	.11	37.99	.06	.01	.43	12	10	97.	.01	6.64	3.11	00	00	94.27	00	94.27	6.012 *	1.988 8.000	3.926 *	. 011 .	• 900.	• 100.	.048 *	.024 4.015	.040 .	• 100.	1.119 *	.797 1.956	• 000.	* 000.	22.000 *	41.59	58.41	2.058	.673	****102 20NE 19	192-3136A CR 2 M	
4	47.13	00.	40.67	00.	.02	.46	16		62.	00.	2.54	5.94	00	00	97.15	00.	97.15	5.944 *	2.056 8.000	3.988 *	• 000.	• 000.	.002 *	• 049	.030 4.069	• 031	• 000.	• 409	1.452 1.892	• 000.	• 000.	22.000 +	78.05	21.95	1.684	.627	Ľ		
9	46.11	.05	39.14	00.	.00	.40	UE		£0.	.01	5.74	3.87	00	00	95.71	.00	95.71	5.974 *	2.026 8.000	3.950 *	.005 *	• 000.	• 000.	.043 *	.058 4.056	.012 *	• 100.	* 646.	.972 1.934	* 000.	• 000.	22.000 *	50.61	49.39	.748	.428		ASPY AN	
7	46.40	.18	36.93	.01	00.	1.21	44		20.	.02	9.65	1.00	00	00.	95.86	00.	95.86	6.105 *	1.895 8.000	3.831 *	.018 *	• 100.	• 000.	.133 *	.086 4.069	• 003	• 100.	1.619 *	.255 1.878	• 000.	* 000.	22.000 +	13.61	86.39	1.543	.607	04-2 FOLN MTC	239 MIC NEXT TO	
1	47.56	.21	32.79	00.	00.	. 83	1 0 1		60.	00.	10.39	.25	.00	. 02	93.15	г00	93.15	6.435 *	1.565 8.000	3.663 *	.021 .	• 000.	• 000.	* 460.	.204 3.982	• 013	* 000.	1.793 •	.066 1.872	* 000.	.005 *	2.000 +	RA 3.53	ISC 96.47	M .461	FM .316	BOW C4 SHEAP 24	LAKE C4 R209	
	sio2	Ti02	A1203	Cr203	MnO	FeO	MaO			BaO	K20	Na2O	ĹĿ	cr	SUM	-0= F+C	MUS	IS	AL	AL	1T	CR	W	ЕE	MG	CA	BA	X	NA	(La	CF	0	PA	M	F/	F/	1 NAR	2 RAT	

northerly trending segments of the C-4 Shear. NNW trending shears and veins (C10. C39) are characterised by vein and schist white mica with low Fe/Fe + Mg ratios (< 0.4)(Figure 4.28a). Al^w of less than 2 afu (Figure 4.29a). Al^w < 3.8 afu. paragonite component less than or equal to 10Pg90Mu (Figure 4.30a) and phengitic substitution with greater than 0.25 octahedral sites occupied by transition elements (Figure 4.31a).

White micas associated with NNE trending 10-15 metre wide shear segments and within thickened (up to 30 metres) portions of the shear are separated into two data sets: one representing narrower segments (C4, C36, C34) and another representing wider zones with more intense alteration (C4/C34 - Rat Lake). White mica associated with schist and vein material from the narrow C4. C36, C34 Shears have Fe/Fe+Mg ratios < 0.4 (Figure 4.28b), paragonitic component > 10, Alⁿ < 2.2 > 1.6 afu (Figure 4.29b, 4.30b), an Alⁿ > 3.8 afu. Siderophile elements occupy less than 0.25 of an atomic formula unit thus lacking in significant phengitic substitution (Figure 4.31b). Tetrahedral and octahedral aluminum contents and Fe/Fe+Mg ratios increase with increasing sodium content and is reflected in increased paragonite content. Outliers from the data set include analyses from intensely carbonate altered schist selvaging veins that contain white micas with Fe/Fe+Mg ratios of < 0.40, although these values are still greater than Fe/Fe+Mg ratios associated with narrow shear segments.

The Rat Lake sample suite (C4/C34 Shears) shows similar trends although hangingwall and footwall samples demonstrate less intrasample variation with lower paragonite components and tend toward an increasing phengitic substitution trend. Overall all samples have a Fe/Fe+Mg of >0.4 (Figure 4.28c), Al^{iv} < 2.2 > 1.6, and Al^{vi} > 3.8 (Figures 2.29c, 4.30c, 4.31c). Sample R09-200 represents hangingwall

- Figure 4.28 a-c White mica variation diagram of paragonite component versus the ratio of iron to iron and magnesium.
 - (A) Northerly and NNW trending shears and veins of the Con Shear.



- Figure 4.29 a-c White mica variation diagram of octahedral aluminum versus tetrahedral aluminum.
 - (A) Northerly and NNW trending shears and veins of the Con Shear.



- Figure 4.30 a-c White mica variation diagram of paragonite component versus octahedral aluminum.
 - (A) Northerly and NNW trending shears and veins of the Con Shear.



- Figure 4.31 a-c White mica variation diagram the sum of siderophile elements in the octahedral layer (Ti+Fe+Mn+Mg) versus octahedral aluminum. Dashed line represents a half of an octahedral site occupied by siderophile elements and an increased phengitic component.
 - (A) Northerly and NNW trending shears and veins of the Con Shear.



alteration where white micas are associated with the breakdown of fine grained aggregates of potassium feldspar and these micas have the lowest paragonite component among the Rat Lake data set. The data set also demonstrates variability from HW to FW across the alteration and mineralised zones. Paragonite contents within the most auriferous schist (R09-239, R09-255) bridge the immiscibility gap and are shouldered by HW/FW schists with lower sodium contents, and increased transitional element substitution within the octahedral site.

4.2.5.2 Campbell Shear Mica

Gold mineralization within the Campbell Shear may be separated into three distinct zones on the basis of spatial and metallurgical relationships. For the purpose of this study these zones are outlined as the refractory 103 and 102/Negus and the free-milling 101/100 zones.

White micas are also ubiquitous both within the alteration halo and within auriferous samples from the refractory 102/Negus Zone. The Negus portion of the Campbell Shear is represented by two grab samples of buff altered carbonate-white mica-chlorite schist from the 20 and 21 levels of the Negus Mine. The rest of the data set is comprised of a sample traverse from hangingwall alteration into auriferous zones on the 3100 level of the mine and a representative grab sample from the 2750 level of the mine. All samples from the 102/Negus data set have a paragonite component of > 10 with an upper limit of 90. Al^{NI} ranges from 3.4 - 4.1, Al^{NI} ranges from 1.2 - 2.1, Fe/Fe+Mg ranges from 0.4 to 0.9. Traverse from hangingwall alteration toward selvages (hw3191-18, 3191-17, 3191-16, 3191-15fw) to ore lenses demonstrates decreasing Fe/Fe+Mg

ratios with associated decrease in paragonite content. Al^w, Al^w and increased phengitic substitution. Porphyroblastic micas become progressively sodium depleted as grain size decreases and as preferred orientation becomes more pronounced. Within auriferous samples and their immediate wallrocks white micas become significantly enriched in Na (3136A, 3136D, 3136F, Negus 21,20) with paragonite components of up to 90. Fe/Fe+Mg ratios stabilise at greater than 0.6, Al^w > 1.6, Al^w > 3.8, and less than 0.25 of one octahedral site are occupied by siderophile elements (Figure 4.32b, 4.33b, 4.34b, 4.35b).

White micas in the refractory 103 Zone demonstrate notable variability in sodium enrichment. Traverses from HW to FW generate maximum paragonite component values of 40 although all samples have paragonite components greater than 10: AI^{v_1} ranges from 3.4 - 4.0. Fe/Fe+Mg ratios range from 0.4 to 0.8 (Figure 4.32a, 4.33a, 4.34a, 4.35a). In general these samples show more scatter amongst data points than in the other data sets.

White micas from free-milling 101/100 Zone ore and alteration is comprised of 15 samples and 186 analyses divided into 3 separate data sets on the basis of vertical distribution within the shear zone. Both vein and alteration halos were sampled in individual stopes. The overall data set demonstrates little intrasample variation but taken as a whole there are striking contrasts to the refractory Con Shear and 103. 102/Negus Zone data sets. Relative to refractory ore lenses white micas from free-milling ores are almost entirely muscovite with paragonite component values of less than 15 and correspondingly lower Al^{vi}. Al^{vi} demonstrates similar data scatter as in refractory ores.

Figure 4.32 a-c White mica variation diagram of paragonite component versus the ratio of iron to iron and magnesium.

(A) 102 and Negus Zone.

(B) 103 Zone.



Figure 4.33 a-c White mica variation diagram of octahedral aluminum versus tetrahedral aluminum.

(A) 102 and Negus Zone.

(B) 103 Zone.



- Figure 4.34 a-c White mica variation diagram of paragonite component versus octahedral aluminum.
 - (A) 102 and Negus Zone.

(B) 103 Zone.



- Figure 4.35 a-c White mica variation diagram the sum of siderophile elements in the octahedral layer (Ti+Fe+Mn+Mg) versus octahedral aluminum. Dashed line represents a half of an octahedral site occupied by siderophile elements and an increased phengitic component.
 - (A) 102 and Negus Zone.

(B) 103 Zone.



AI'' > 3.8 are associated with albite alteration (Figure 4.32c, 4.33c, 4.34c, 4.35c).

4.2.6 Carbonate

Carbonate mineralogy was investigated on a total of 20 samples from various zones within the Con Mine. Carbonate minerals are ubiquitous within both alteration envelopes and ore zones of the Con and Campbell Shear Systems. Carbonate mineralogy includes calcite. dolomite, and ankerite species. (Figure 4.36). Calcite is the dominant carbonate species within chlorite alteration peripheral to refractory ore zones and within chlorite-albite schists immediately adjacent to free-milling quartz veins. Calcite may occur sporadically as a gangue mineral within auriferous veins within refractory ores. Dolomite and ankerite species dominate refractory schists and internal to auriferous free-milling quartz veins.

4.2.7 Sulphide

Within the Con and Campbell Shears gold mineralization is intimately associated with sulphide and sulphosalt mineral species. Sulphide mineral chemistry was investigated both in individual samples of mineralised material and on metallurgical composites from various ore blocks. No attempt was made to quantify the sulphide content of the various ore types, however empirically it appears that the free-milling or refractory nature of an ore is for the most part independent of sulphide content. Refractory ores may have a greater abundance of arsenopyrite versus pyrite but overall sulphide content and sulphide mineralogy within all ore types varies erratically throughout the mine. Figure 4.36 Ternary plot of carbonate mineral chemical analyses in mol% for refractory alteration and mineralisation within both the Con and Campbell shears. Ca - calcite: Mg - magnesite: Fe - siderite.

Figure 4.37 Ternary plot of carbonate mineral chemical analyses in mol% for free-milling alteration and mineralisation within the Campbell shears. Ca - calcite: Mg - magnesite: Fe - siderite.





4.2.7.1 Pyrite

Pyrite is the most ubiquitous Fe-sulphide associated with free-milling and refractory gold ores of the Con and Campbell Shears. Pyrite occurs as disseminated grains within peripheral chlorite-calcite schists, within white mica-carbonate schist vein selvages, internal to quartz-carbonate veins and as a specific host for gold. Grain size varies from fine to medium, occurring as isolated dustings, as heterogenous disseminations, to semi-massive patches. Pyrite is associated with arsenopyrite, pyrrhotite, chalcopyrite, galena, and sulphosalts and may host inclusions of galena, tetrahedrite, pyrrhotite, chalcopyrite, tellurides, and gold. Pyrite chemistry was determined on a series of samples collected from various zones including both refractory and free-milling varieties of gold ore. Variations in Fe. S. Ni. Co. As, and Au were investigated and the 2:1 metal: ligand ratio was satisfied for the data set. Where present arsenian pyrites from all ore types maintain the 2:1 metal: ligand ratio as required by the ideal stoichiometry of pyrite and demonstrate a strong negative correlation of arsenic to sulphur. No significant variation was noted in Co and Ni contents of pyrites from refractory or free-milling ore zones. Representative pyrite analyses are listed in Table 4.4.

All ore zones contain As-zoning in pyrite. The As content of pyrite ranges from below detection limits to a maximum of 5.49 wt% As. Pyrite from vein dominated portions of the Con Shear System may host metallic inclusions of gold and do not demonstrate appreciable enrichments in As. Abraded, fractured, brecciated, corroded pyrites occur as relict grains in laminated refractory schists (C4 Shear, 102 and 103

			2	PITE MIN		JEANCTR	Ş						
~	/EIGHT%		-				∢	TOMIC%					
SAMPLE	FE	S	z	CO	AS	AU	1	Ц Ц	S	ž	СО	AS	AU
B-8030	46.58	53.65	0.00	0.00	0.01	0.00	100.24	33.26	66.73	0.00	0.00	0.00	0.00
B-8030 PT2	46.98	53.07	0.01	0.11	0.00	0,00	100.17	33.67	66.25	0.01	0.07	0.00	0.00
B-8030 PT3	45.48	50.71	0.01	0.05	3.53	0.04	99.81	33.32	64.71	0.01	0.03	1.93	0.01
B-8030 PT4	45.19	52.71	0.02	0.01	0.88	0.06	98.87	32.82	66.67	0.01	0.01	0.47	0.01
B-8030 PT5	45.91	49.60	0.01	0.03	3.48	0.00	99.03	34.03	64.02	0.01	0.02	1.92	00.00
B-8030	45.20	48.99	0.00	00.00	5.49	0.01	99.70	33.58	63.38	0.00	0.00	3.04	0.00
B-8030	46.13	50.27	0.01	00.00	3.22	0.03	99.65	33.89	64.33	0.00	0.00	1.77	0.01
B-8030	45.71	50.26	00.0	00.0	2.89	0.14	99.00	33.75	64.63	0.00	0.00	1,59	0.03
B-8030 DK RIM PY	46.17	51.97	0.01	0.34	0.13	0.01	98,63	33.67	66.02	0.00	0.23	0.07	00.00
B-8030 SLLY LTR	46.06	51.80	0.00	0.00	1.65	0.03	99.54	33.49	65.61	0.00	0.00	0.90	0.01
3312XC BRT DOMAIN	44.83	51.68	0.02	00.0	1.25	0.05	97.83	33.01	66.28	0.01	0.00	0.69	0.01
3312XC BRT DOMAIN	45.22	53.71	0.07	00.0	0.14	0.00	99.13	32.55	67.33	0.05	0.00	0.07	0.00
3312XC HOMO PY	45.52	54.13	0.01	0.05	0.14	0.04	99,90	32.52	67.35	0.01	0.03	0.08	0.01
3312XC HOMO PY	45.75	53.96	0.02	0.00	0.21	0.02	99,96	32.70	67.18	0.01	0.00	0.11	00.00
STP 2 CR 7	45.64	51.95	0.01	0.04	1.21	0.07	98.92	33.29	66.00	0.01	0.02	0.66	0.01
STP2 CR7	46.05	53.34	0.01	0.06	0.13	0.00	99.59	33.10	66.79	0.01	0.04	0.07	0.00
STP2 CR8 BRT	44.89	51.15	0.01	00'0	2.40	0.00	98.45	33.06	65.61	0.01	00.00	1.32	0.00
STP2 SIMS PT 12	46.22	53.99	0.04	0.00	0.20	0.03	100.48	32.91	66.95	0.03	00.00	0.10	0.01
STP2 SIMS PT 1	46.01	53.37	0.01	0.00	1.17	0.03	100.59	32.90	66.47	0.00	0.00	0.62	0.01
STP2 SIMS PT 2	46.37	54.23	0.01	0.03	0,09	00.0	100.73	32.90	67.02	0.00	0.02	0.05	0.00
STP2 SIMS PT 4	46.10	53.06	0.00	0.00	1.86	0.07	101.08	32.95	66.05	0.00	0.00	0.99	0.01
STP 2 SIMS PT 4 DK	46.34	54.62	0.00	0.00	0.02	0.11	101.09	32.74	67.23	0.00	00.00	0.01	0.02
STP2 SIMS PT 6	46.55	53.86	0.00	0.09	0.58	0.00	101.08	33.04	66.59	0.00	0.06	0.31	0.00
B8176 NL	45.93	53.72	0.11	0.00	0.00	0.00	99.76	32.90	67.03	0.07	0.00	0.00	0.00
8176 AS ZONE	44.90	51.44	0.02	0.01	3.32	0.00	99.70	32.77	65.40	0.01	0.01	1.81	0.00
POIK CENTRE	46.56	54.65	0.10	0.12	0.08	0.00	101.51	32.79	67.03	0.07	0.08	0.04	0.00
B8176NL AS-PY	44.56	49.83	0.00	0.11	4.39	0.04	98,94	33.07	64.41	0.00	0.08	2.43	0.01
B8176NL AS-PY	45.68	52.10	0.00	0.00	1.03	0.11	98.93	33.29	66.13	0.00	0.00	0.56	0.02
5371R LT PY W AU	46.13	52.62	0.00	0.14	0.00	٩N	98.89	33.45	66.45	0.00	0.10	0.00	AN
5371R LT PY W AU	46.18	52.75	0.00	0.08	1.45	AN	100.46	33.17	66.00	0.00	0.05	0.78	AN
5371R LT PY W AU	46.26	52.85	0.00	0.06	1.39	AN	100.56	33.19	66.03	0.00	0.04	0.74	AN
DARK DOMAIN	46.50	53.78	0.00	0.10	0.00	AN	100.38	33.15	66.78	0.00	0.07	0.00	AN

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zones) and are characterised by As-enriched cores (Plate 4.4a) and poikiolitic cores (Plate 4.4d). The As-domains are generally restricted to the cores of pyrite grains in thin, 10 - 20 micron wide laminae symmetrical to crystal faces (Plate 4.4c), as broad domains, or complex As-zonation patterns within large poikiolitic grains with As-enriched rims (Plate 4.4b). Arsenic contents for enriched domains range from 1.18 to 3.69 wt% As, sulphur contents range from 53 to 50 wt% S.

Pyrite from shallow free-milling ores of the Campbell shear 101 Zone (B8030.3312XC.33207.STP2.B8176NL) demonstrate variable As-zoning with low As poikiolitic cores, high As core zones, and low As rims. Arsenic contents for the high As domains range from 0.74-5.49 wt%, sulphur contents range from 49 to 53.8 wt% S. Pyrite from deep free-milling 101 Zone ores (5360M, 5173R) tend to have high As-domains associated with micro-fractures and inclusion trains of gold and Au-Ag-Bi tellurides (Plate 4.4e). The As content of these domains range from below detection limits to 3.37 wt% As with accompanying low end sulphur contents of 51.74 wt% S.

A total of sixty-nine SIMS analyses for gold were conducted on pyrite grains from refractory and free-milling ore zones. Results are summarised in Table 4.5 and where possible electron microprobe values (As, Au) for the same grain are listed with the SIMS results. Abraded pyrite grains from the Con Shear with As-enriched core zones (R209-139) and similar textured grains from B8176 and located above the 2750 Level north of the 102 Zone have Au contents of between 0.30 ppm and 26 ppm Au (7 determinations). Although individual grains have spot analyses of up to 1.5wt% As no appreciable Au enrichment was noted.

Arsenian pyrites from the 102 Zone demonstrate a variety of As zonation patterns

Plate 4.4 Backscatter SEM images of arsenian pyrite. (A) R209-239, C4 Shear, Con Shear. Atoll textured pyrite grain with arsenic enriched core zone (bright domain). Typical pyrite texture within refractory schists, low solid solution gold values with SIMS. (B) B8030, 102 Zone. Low As polkiolitic core with broad As enriched zones symmetrical to grain boundaries, maximum As content of 5 wt % As, As zones do not display gold enrichment. (C) B8040, 102 Zone. Broad As enriched zone in central portion of grain. Circle represent positions of SIMS analysis. Point 11 returns gold values of 230 ppm Au with an As content of 3.63 wt%. Point 12 returns a gold content of 31 ppm Au and As content of 1.68 wt%. Gold is associated with domain of elevated As. (D) STP2, 101 zone free-milling ore, 3300 Level. Poikiolitic As-enriched core zone, with zonation symmetrical to crystal faces. No gold enrichment is associated with As-enriched core. (E) 5360M Stope. Deep free-milling stope. Complex As-enriched zones associated with microfractures. Fractures are associated with As-enrichment host numerous inclusions of native gold and Bi tellurides.





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		1	TABLE 4.5		
		PYRITE "II	NVISIBLE" GOLD CONTEN	T BY SIMS	
SAMPLE	*PROBE-As WT%	Au SIMS	SAMPLE	•PROBE-As WT%	Au SIMS
B8030 CR1-1 CR1-2 CR1-3 CR1-4 MAX MIN AVG	5.49 1.83	18.00 14.00 5.00 7.00 18.00 5.00 11.00	3312XC CR3-4 CR1-6 CR1-7 CR1-8 CR6-9 CR6-12 CR9-13 CR6-16		0.66 0.15 0.08 0.33 0.13 0.93 0.28 1.30
STOP2 CR7-1 CR7-2 CR7-3 STOP2 CR8-4	1.17 0.09 0.12 1.86 0.02	0.50 0.60 0.30 0.35	MAX MIN AVG		1.30 0.08 0.48
STOP2 CR1-6 STOP2 CR5-12 MAX MIN AVG	0.58 0.20	0.25 1.00 1.00 0.25 0.50	B8084 CR4-1 CR4-2 CR4-3 CR4-4 CR4-5 CR4-5	1.33 3.73	18.00 21.00 385.00 5.90 15.00
B8085 CR5-1 CR5-2 CR5-3 CR5-4 CR5-6 CR5-6 CR5-7 CR7-7		0.60 0.67 0.70 1.70 1.70 0.93 2.00 1.90	CR4-5 CR4-7 CR4-8 CR4-9 B8084 CR4-10 CR4-11 CR4-11	3.31 2.17 3.44 0.00 3.53 3.41 3.63 1.68	240.00 4.00 160.00 180.00 68.00 230.00 31.00
B8085-CR4-1 CR4-2 CR4-3 CR4-3 CR4-4 CR4-5 CR4-5	1.83	0.50 0.50 2.50 0.60 0.60	CR4-13 CR4-14 CR7-17 CR7-18 B8084 CR5-19 CP5 20	1.76 2.52 1.77	24.00 8.00 10.50 57.00 39.00 2.00
CR7-3 CR7-4 CR7-5 CR7-5 CR7-7 CR7-8 MAX	2.68	35.00 3.50 6.00 1.90 1.90 35 0.50	CR5-21 CR5-22 CR5-23 MAX MIN AVG	1.60 1.59 1.20	26.00 11.00 28.00 385.00 2.00 74.45
AVG 88090 CR7-17 CR7-19 CR7-20	2.56	3.43 410.00 0.59 0.15 3.00	RO9-239 CR2-1 CR2-2 CR2-3 MAX MIN AVG	0.03 1.48 0.03	0.25 0.30 0.27 0.30 0.25 0.27
• if available		3.00 410.00 0.15 103.44	B8176 CR4-1 CR4-2 CR6-3 CR3-5 MAX MIN AVG		1.50 0.40 26.00 0.30 26.00 0.30 6.98
and have Au concentrations ranging from 0.15 to 410 ppm Au (44 determinations). The enhanced Au contents from these grains demonstrate a positive correlation with As content and are restricted to specific growth domains within pyrite grains (Plate 4.5). Arsenian pyrite domains from shallow 101 Zone free-milling ores (STP2. 3312XC) contain low Au concentrations ranging from 0.48 to 1.3 ppm Au (15 determinations), pyrites from free-milling lenses above 3100 level (B8030) have slightly elevated gold concentrations ranging from 5 to 18 ppm Au (4 determinations). Although As contents ranged up to 5.5 wt% As in individual grains no positive correlation with Au content was observed.

4.2.7.2 Arsenopyrite

Arsenopyrite is an accessory sulphide mineral in free-milling ores and forms the dominant sulphide mineral within refractory ores of the Con and Campbell Shear Systems. Arsenopyrite occurs as euhedral to subhedral blocky grains internal to quartz carbonate veins within the Con Shear System and as fine-grained euhedral kite shaped grains along late anastomosing cleavage domains within laminated white mica schists within refractory ore bodies of both the Con and Campbell Shears. Within free-milling ores arsenopyrite is mainly associated with white mica schists selvaging veins and less frequently as an accessory sulphide internal to quartz veins. Arsenopyrite grains may host inclusions of gold, tetrahedrite, and galena.

Arsenopyrite grains were analyzed with the electron microprobe and secondary ion mass spectrometer to determine zonation characteristics and gold concentrations. Variations in Fe, S, Ni, Co, As, and Au were investigated and the 2:1 metal:ligand ratio **Plate 4.5** Backscatter SEM images of Au-enriched arsenian pyrite. (A), (B) B8084. 102 Zone. Low As poikiolitic core with broad As-enriched rim domains. Points 8,9, and 10 and associated craters represent SIMS analytical points. Beam position was adjusted to try and determine Au content in low As and high As domains, some overlap was realised due to large beam size. Point 8 returned gold values of 160 ppm with electron microprobe As value of 3.44 wt^o6; point 9 returned a gold value of 180 ppm Au; point 10 returned a gold value of 68 ppm and an electron microprobe As content of 3.41 wt%. Good correlation exists between gold content and elevated As content of the pyrite grain.





Arsenopyrite grains hosted in quartz veins from the Con Shear lack consistent zonation patterns. Grains demonstrate little intrasample variation and are enriched in Co and Ni up to 0.5 at%. Zoned grains contain cores with low As (29.75 - 31.21 at% As) and high S (38.66 - 35.75 at% S). Rims are enriched in As (32.14 - 33.54 at% As) with correspondingly lower S (34.96 - 33.67 at% S) (Figure 4.38). Grains with high-As rims are brecciated and associated with galena and may host inclusions of gold (samples C404-2.C4-1). Grains with subtle core-rim variations in As and S contents (C204-2) demonstrate As variations on the order of less than 1 at% As. Arsenopyrite grains hosted in quartz veins from the Con Shear did not demonstrate gold enrichment by of electron microprobe analyses and were not tested by the secondary ion mass spectrometer.

Arsenopyrite hosted in Fe-carbonate, chlorite, paragonitic muscovite schists selvaging narrow quartz veins within the Con Shear demonstrate minor variations in As and S contents. Arsenic content varies from 30.53 to 32.49 at%, sulphur varies from 36.28 to 35.55 at%. Gold may occur at arsenopyrite grain boundaries within these schists, no gold enrichment was noted with electron microprobe analyses and grains from these domains were not analyzed with the secondary ion mass spectrometer.

Euhedral to subhedral arsenopyrites that occupy anastomosing foliation planes within auriferous schist of the Con Shear typically demonstrate core-rim variations in As, S and Au content. Zonation patterns consist of core domains with low-As/high-S bounded by broader As-enriched rim zones, oscillatory growth laminae are not prevalent. Arsenopyrite cores may be poikiolitic and host inclusions of tetrahedrite (Plate 4.6a).

		Т	ABLE 4.6	6									
	4	RSENOP	YRITE M	INERAL	CHEMIS'	TRY							ł
SAMPLE	WEIGHT	%				-	/	ATOMICS	% 				
	AS	FE	<u> </u>	<u>NI</u>	AU	5	101AL	AS	FE	<u> </u>	NI	AU	5
3312XC ACIC ASPY	45.11	34.51	0.15	0.17	0.07	21.68	101.68	31.66	32.49	0.13	0.16	0.02	35.56
3312XC RIM	43.97	33.53	0.00	0.05	0.03	21.23	98.80	31.72	32.45	0.00	0.04	0.01	35.79
3312XC	44.90	34.03	0.16	0.25	0.00	21.08	100.42	31.99	32.54	0.14	0.23	0.00	35.10
3312XC	45.09	33.41	0.38	0.66	0.00	21.86	101.40	31.69	31.50	0.34	0.59	0.00	35.89
33207 LG ASPY GRAIN	44.62	34.79	0.00	0.00	0.03	21.73	101.17	31.41	32.85	0.00	0.00	0.01	35.73
33207 LG ASPY	44.05	34.83	0.11	0.03	0.07	22.00	101.09	30.93	32.82	0.10	0.02	0.02	36.10
33207 LG ASPY	45.26	34.81	0.08	0.01	0.00	21.00	101.15	32.07	33.09	0.07	0.00	0.00	34.77
33207 LG ASPY	44.50	34.63	0.05	0.08	0.00	21.25	100.50	31.61	33.00	0.04	0.07	0.00	35.27
33207 HOMO ASPY	43.44	34.71	0.00	0.00	0.00	22.30	100.45	30.57	32.76	0.00	0.00	0.00	36.67
33207 SIMS PT 1 AT RIM	42.31	34.88	0.00	0.02	0.00	22.22	99.42	30.00	33.17	0.00	0.01	0.00	36.81
33207 SIMS PT 4 AT RIM	42.93	34.53	0.02	0.01	0.00	22.03	99.52	30.50	32.91	0.02	0.01	0.00	36.56
33207 SIMS PT 2	44.57	34.33	0.02	0.01	0.04	20.77	99.73	32.01	33.08	0.02	0.01	0.01	34.87
33207 SIMS PT 3 AT RIM	43.79	35.13	0.04	0.05	0.02	21.77	100.81	30.86	33.21	0.03	0.05	0.01	35.84
STP2 DK ZONE IN ASPY	38.37	35.95	0.00	0.02	0.04	24.67	99.06	26.59	33.43	0.00	0.02	0.01	39.94
SAME GRAIN SLLY LTR	43.77	34.55	0.04	0.20	0.02	20.54	99.13	31.62	33.48	0.04	0.19	0.00	34.67
STP 2 CR 4 BRT DOMAIN IN ASP	` 44.45	33.64	0.46	0.46	0.00	20.10	99.11	32.28	32.77	0.42	0.43	0.00	34.10
STP2 SIMS PT 10	41.97	34.36	0.00	0.02	0.05	23.13	99.52	29.52	32.43	0.00	0.01	0.01	38.02
STP2 SIMS PT 11	40.65	35.65	0.00	0.04	0.05	24.92	101.31	27.70	32.58	0.00	0.04	0.01	39.67
SIMS PT 11 BRT RIM	45.16	33.80	0.04	0.30	0.00	21.37	100.67	32.06	32.19	0.04	0.27	0.00	35.45
STP2 SIMS PT 5 ASPY DK CORE	43.15	35.22	0.13	0.02	0.04	22.04	100.60	30.36	33.25	0.12	0.01	0.01	36.24
STP2 SIMS PT 7 ASPY	42.83	34.72	0.00	0.01	0.13	23.02	100.70	29.90	32.51	0.00	0.01	0.03	37.55
STP2 SIMS PT 8 ASPY	45.16	34.20	0.08	0.08	0.00	20.82	100.34	32.28	32.80	0.08	0.08	0.00	34.77
B8090	43.83	34.92	0.05	0.02	0.00	21.55	100.38	31.06	33.19	0.05	0.02	0.00	35.68
B8085-FL DK ZONE	40.90	35.73	0.02	0.00	0.00	23.84	100.48	28.29	33.16	0.01	0.00	0.00	38.54
SLLY LTR	42.43	35.46	0.02	0.08	0.08	23.23	101.29	29.37	32.93	0.01	0.07	0.02	37.58
	45.95	34.76	0.04	0.06	0.01	19.52	100.33	33.22	33.71	0.03	0.05	0.00	32.98
B8085 SIMS PT 2	44.37	33.37	0.05	0.03	0.08	19.83	97.72	32.72	33.02	0.04	0.03	0.02	34.17
88085 SIMS PT 9	44.92	33.79	0.00	0.00	0.04	20.02	98.78	32.78	33.08	0.00	0.00	0.01	34.13
88085 SIMS PT 6	44 39	33.68	0.06	0.08	0.00	20.33	98 54	32 34	32 92	0.06	0.08	0.00	34 60
88085	44.38	34.06	0.00	0.07	0.05	19.84	98.40	32 50	33.46	0.00	0.06	0.01	33.95
BO9-239 LT CENTRE OF ASPY	44.66	33 59	0.01	0.07	0.00	20.23	99.75	32.50	32.81	0.01	0.00	0.01	34 42
SULY DKER TOWARD RIM	44.00	34 16	0.00	0.07	0.72	20.20	100 11	32.51	33.01	0.00	0.00	0.20	34 60
BO9-239 BRT APY WALLING	45.52	33 17	0.00	0.02	0.98	19.33	99 08	33 55	32.81	0.01	0.02	0.28	33.29
DK INTERIOR	42.92	34 67	0.00	0.03	0.00	21 44	99 11	30.75	33.32	0.00	0.03	0.01	35 89
BRT RIM	45.97	32.08	0.00	0.03	0.53	19.96	98 57	33.83	31.67	0.00	0.03	0.15	34 32
I T ASPY BIM	46 11	33 73	0.00	0.00	0.59	19.26	99.76	33 74	33 11	0.00	0.03	0.16	32.93
	10.11		<u></u>	0.01	0.00	10.20	00.70	30.14	00.11	0.04	0.00	0.10	32.00



Figure 4.38 Con Shear Narrow veins. Ternary plot of arsenopyrite chemical compositions. Box outlines field of arsenopyrite solid solution.



Figure 4.39 Rat Lake - Con Shear. Ternary plot of arsenopyrite chemical compositions. Box outlines field of arsenopyrite solid solution.

Arsenic core contents are low relative to rims and some analyses fall outside of the accepted solid solution field for naturally occurring arsenopyrite.

Arsenopyrites from the C34 Shear on 15level contain As and S values for cores that range from 27.91 to 30.67 at% As, 39.83 to 36.88 at% S. Rims on arsenopyrite grains contain As and S values that range from 32.00 to 33.37 at% As, 35.58 to 34.15 at% S. Individual grains have As variations on the order of 4 at% As.

Arsenopyrite from auriferous schists (R09-239) from the C4 Shear under Rat Lake demonstrate similar zonation patterns as noted above. Values for As and S in cores range from 25.65 to 31.14 at% As, 41.65 to 35.11 at% S (Figure 4.39). Cores are not enriched in Au as revealed by microprobe and SIMS analyses. Rims are As enriched and these As rich zones may host metallic inclusions of gold (Plate 4.6b). Microprobe analyses of As enriched rims indicates ranges in As. S. and Au of 33.83 to 31.67 at% As, with the majority of As values falling around 33 at% As: 34.32 to 33.83 at% S: and 0.12 to 0.28 at% Au. Secondary ion mass spectrometry was conducted on selected grains from R09-239 and reported Au contents range from 70 to 1500 ppm Au (11 determinations). Twinning of SIMS analytical points with electron microprobe analysis indicates a positive correlation of As and Au for arsenopyrite rims (Table 4.7: Plate 4.6c,d).

Arsenopyrite grains from Campbell Shear refractory 102 and 103 Zone ores demonstrate similar zonation patterns as those found in the auriferous schists of the C34 and C4 Shear segments of the Con Shear. Cores have As and S values ranging from 27.89 to 30.82 at% As; 38.90 to 36.10 at% S. Rims on the same grains range in As from 33.22 to 31.89 at% As and 32.89 to 34.99 at% S (Figure 4.40). As determined

Plate 4.6 Backscatter SEM images of arsenopyrite. (A) R209-239, C4 Shear, Con Shear. Low As, high S core zone with inclusions of tetrahedrite rimmed by variably As-enriched, S depleted, Au enriched rim zones. (B) R209-239. Bright inclusions of high fineness native gold within As.Au-enriched domains, polkiolitic core zones are As-depleted and Srich. (C) R209-239 Zoned arsenopyrite grain with point 7 and point 8 representing SIMS analytical points. Point 7 returned a gold value of 450 ppm from an analysis that overlaps As-enriched and As-depleted portions of the grain. Point 8 returned a gold value of 850 ppm from the rim zone. Corresponding gold and arsenic values as determined by electron microprobe are: 32.68 at%As, 0.75 wt% Au (rim) and 30.71 wt As and 0.11 wt% Au (core). (D) R209-239. Zoned arsenopyrite crystal. Points 9,10, and 11 represent SIMS analytical points. Corresponding SIMS gold values and electron microprobe gold and As values are: Point 9 400 ppm Au, 27.89 at% As, 0.00 wt% As (core), 31.34 at% As, 0.45 wt% Au (rim); Point 10, 800 ppm Au, 0.45 wt% Au, 31.34 at% As; Point 11, 105 ppm Au, 0.00 wt% Au, 30.41 at% As. (E) STP 2, Shallow 101 Zone free-milling ore, 3300 Level. Zoned arsenopyrite with low-As core (dk grey) and high As rims (bright). (F) Sample 27650, deep free-milling 101 Zone ore. Low As core (dk grey) with multiple high As low S laminae toward rim of grain. Maximum As content of 35.82 at% is greater than that of refractory schists.







		TABLE 4.7			
ARSENC		SIBLE" GOLD	CONTENT BY SIMS		
SAMPLE	Au SIMS (ppm)	•Au PROBE WT%	SAMPLE	Au SIMS (ppm)	*Au PROBE WT%
3312XC CR3-1 CR3-2 CR3-3	33.00 15.00 11.00	NA NA NA	88085 CR5-8 CR5-9 CR5-9	150.0 78.0 7.0	NA NA NA
CR6-10 CR6-11 CR9-14 CR9-15	1.30 2.00 4.50 2.30	NA NA NA	88085 CR7-2 CR7-6 CR7-9 MAX	1500.0 20.0 1900.0 1900.00	0.08 ND 0.04
MAX MIN AVG	33.00 1.30 9.87		MIN AVG B8090 CR7-22	7.00 609.17 3.50	NA
STOP2 CR8-5 STOP2 CR1-7 CR1-8 STOP2 CR5-10 CR5-11	31.0 370.0 68.0 300.0 45.0	0.04 0.13 ND 0.05 0.05	CR7-23 CR7-24 MAX MIN AVG	85.00 4.00 85.00 3.50 30.83	NA NA
MAX MIN AVG	370.00 31.00 162.80	0.00	R09-239 CR1-4 CR1-5 CR1-6 R09-239 CR7-7	550.0 70.0 1500.0 450.0	0.97 0.04 0.04 C 0.11
S33207 CR3-2 CR3-3 CR8-4 CR5-5	4.5 2.0 5.0 2.0	0.04 0.02 ND ND	CR7-8 R90-239 CR4-9	850.0 400.0	R 0.75 0.76 C 0.00 R 0.45
MAX MIN AVG	5.00 2.00 3.38		CR4-10 CR4-11 MAX MIN AVG	800.0 105.0 1500.00 70.00 590.63	0.45 ND
• if available	<u>C = Core</u>	R = Rim	ND = Not detected		



Figure 4.40 103 and 102 Mineralisation. Ternary plot of arsenopyrite chemical compositions. Box outlines field of arsenopyrite solid solution.



Figure 4.41 101 Zone mineralisation. Ternary plot of arsenopyrite chemical compositions. Box outlines field of arsenopyrite solid solution.

by secondary ion mass spectrometry gold content of As-enriched domains for 102 Zone arsenopyrite grains range from 3.5 to 1900 ppm Au (9 determinations).

Shallow free-milling ores of the Campbell Shear also contain arsenopyrite as an important accessory sulphide. Homogeneous grains demonstrate little variation in As and S content. 30.86 to 32.07 at % As and 34.77 35.89 at % S. Grains that are zoned (Plate 4.6e) have a similar zonation patterns as arsenopyrite from refractory ores with As ranging from 26.59 to 32.28 at % As and sulphur varies from 34.10 to 39.67 at % S (Figure 4.41a). Enhanced Au concentrations ranging from 31 to 370 ppm Au (SIMS analysis, sample stp 2, 6 determinations) are associated with such As/S zoned arsenopyrite grains.

Deep free-milling ores hosted within the Campbell shear contain arsenopyrite as an important accessory sulphide. Arsenopyrites may either be homogeneous in composition or have complex oscillatory variation in As and S contents. As contents range from 29.61 to 29.89 at% As for low As domains to 32.45 to 33.19 at% As for As rich domains (5760M stope). Oscillatory growth zonation creates variation of As contents ranging from 28.67 at% As to 35.82 at% As within individual grains (Plate 4.6f. Figure 4.41b).

4.2.7.3 Accessory Sulphides and Sulphosalts

Sphalerite is present as an accessory sulphide phase in all ore types examined. A total of 20 individual samples were examined for variations in Zn, Fe, Cd, and Cu contents for a total of 59 analyses which are reported in Appendix. Sphalerite colouration varies within each ore zone and ore type and does not delineate any clear discernible

zonation pattern. Iron contents range from 14.2 mol% FeS to less than 0.3 mol% FeS. maximum CdS and CuS contents are 3.22 mol% and 0.96 mol% respectively. Intersample variations in composition are wide spread while there is little intra-sample compositional variation. Cadmium-rich (2.18 - 3.22 mol% CdS) and iron-rich sphalerite in smokey grey to black quartz veins from the deep north free-milling ores are associated with Fe-Ni sulphides, chalcopyrite and pyrrhotite (Figure 4.42). Cd-enhanced sphalerite (> 0.5 mol% CdS) may occur in samples containing gold grains with sharp compositional variations in Au and Ag (upper 101 Zone free-milling ores) and/or Hg enhanced gold grains (102 Zone refractory ores: Figure 4.43). Within shallow free-milling ores honey coloured low-Fe sphalerite associated with Pb-Sb sulphosalts also demonstrate moderate Cd enrichment (0.38 to 0.5 mol%CdS). Overall sphalerite demonstrates a general increase in Fe content with depth within free-milling ores. Free-milling and refractory ores contain both Fe- poor and Fe-rich sphalerite grains.

Pyrrhotite is restricted in distribution to free-milling ore within the 101/100 Zones of the Campbell Shear. Pyrrhotite occurs as medium to fine grained disseminations and as coarse grained brecciated aggregates associated with galena. chalcopyrite, and sphalerite internal to quartz veins. The presence of pyrrhotite was not noted in refractory Con Shear, 103, 102 or Negus ore zones.

Accessory sulphosalt minerals occur in all ore types with the greatest abundance and occurrence within refractory ore bodies and upper free-milling zones. Boulangerite was analysed in a sample from the 102 Zone (3136E) where it occurs as large feathery grains in relict quartz carbonate domains. Boulangerite was also noted with other sulphosalt minerals. Jamesonite was analysed in three samples of Con Shear ores where



Figure 4.42 Variation diagram of ZnS mol% versus CdS mol% for sphalerite in Con and Campbell Shears.



Figure 4.43 Variation diagram of ZnS mol% versus FeS mol% for sphalerite in Con and Campbell Shears.

it occurred as an inclusion in arsenopyrite (R09-239), as rims on Ag-tetrahedrite (C34-12L), or as large bladed grains associated with dark red Fe-sphalerite (C27612 - C39 shear). Only minor variations in Fe content were noted between analyses. Bournonite occurs as inclusions in pyrite (3300B), rims Ag-tetrahedrite (3300b), associated with arsenopyrite (R09-239), or as discrete grains in gangue (C4-1, 3136A).

Tetrahedrite is a particularly common accessory mineral within refractory ore bodies and upper free-milling ore lenses but less commonly so in deeper free-milling ores. Tetrahedrite occurs as inclusions within pyrite and arsenopyrite grains and as isolated grains in gangue. It is occasionally overgrown by bournonite. Tetrahedrite grains on occasion do demonstrate zonation from more Ag and As rich zones internal to grains. The data set does demonstrate coupled variations in Ag/Cu and As/Sb. The more As-rich and Ag-poor grains usually are associated with samples with fairly homogeneous gold grains. and tetrahedrite that occurs as inclusions within sulphides have low Ag contents.

4.2.8 Native Gold

The mineral chemistry of gold grains was examined by electron microprobe for Au. Ag. and Hg contents for each ore type. A total of 35 samples were examined. The native gold hosted in the Con and Campbell Shears is an amalgam of gold, silver, and mercury in varying proportions and will be referred to as Au-Ag amalgam. Gold and silver form a continuous solid solution spectrum with electrum occupying a compositional field from 20 to 40 wt% Ag. Representative analyses are provided in Table 4.8. Visible and microscopic gold grains occur in varying habits common to all ore types. Au-Ag amalgam may occur as free grains in quartz or carbonate, as inclusions within a sulphide

		TABLE 4	12		
	GOLD MI	NERAL CH	IEMISTR	Y	
SAMPLE	Au	Ag	Hg		FINENESS
C404-4 AU IN PY	94.64	5.16	0.73	100.53	948.30
C404-4 AU AT PY EDGE DK ZONE	54.14	42.41	0.25	96.80	560.75
C404-4 LT ZONE IN AU	70.08	26.14	0.10	96.32	728.33
C404-4 AU IN PY	84.23	14.90	0.44	99.57	849.69
C4-20 IN FG CATA QTZ W MICA	77.51	22.11	0.25	99.86	778.06
C4-20 IN FG CATA QTZ W MICA	77.69	21.65	0.20	99.54	782.06
C4-20 IN FG CATA QTZ W MICA	78.43	21.81	0.15	100.38	782.42
3136E 20X20 MICRON GRAIN	73.79	22.22	1.40	97.41	768.57
3136E 20X20 MICRON GRAIN	75.15	22.46	1.62	99.23	769.90
3136E 20X20 MICRON GRAIN	74.97	22.59	1.59	99.15	768.45
3191-4 NEGUS VN AUIN QTZ	84.60	16.51	0.15	101.26	836.71
3191-4 FREE GRN IN QTZ	84.02	13.61	0.18	97.81	860.60
AU ALONG SLIP 3191-4	80.42	17.83	0.00	98.25	818.52
FR AU IN QTZ 3191-4	83.98	16.13	0.21	100.32	838.88
FR AU IN QTZ 3191-4	84.50	16.19	0.00	100.69	839.21
3191-10 VN ALTN W QTZ CARB	80.95	18.14	0.00	99.09	816.93
3191-10 VN ALTN W QTZ CARB	81.49	18.44	0.00	99.93	815.47
3191-10 FG AU IN CARB	81.47	16.82	0.00	98.29	828.87
3191-10 FG AU IN CARB	80.11	18.58	0.00	98.69	811.73
3191-10 FG AU IN CARB	80.65	18.25	0.00	98.90	815.47
3191-3 NEG VN AU IN PY	67.28	30.01	0.00	97.29	691.54
3191-3 ALTN SEL TO NEG VN AU IN PY	66.68	30.76	0.00	97.44	684.32
3191-3 AU AT EDGE OF PY W ASPY GR	66.73	30.99	0.00	97.72	682.87
3100C FG AU IN QTZ VNLT	84.21	14.74	0.20	99.15	851.04
3100D CR 1 AU ALON SLIP	80.07	19.54	0.00	99.61	803.83
33207C HOMO GOLD	85.80	14.03	0.19	100.03	859.46
3300B CR 1 AU VAG ZONE	45.36	51.82	0.78	97.97	466.76
3300B SLLY LTR	62.39	35.46	0.34	98.20	637.61
3300B DK RIMMED BY AU > > AG W LOW A	49.59	47.91	0.53	98.03	508.62
3300B HIGH AG IN CT W PY	52.01	47.36	0.70	100.08	523.40
3300B HIGH AG IN CT W PY	43.39	54.63	0.49	98.51	442.66
33207C CR 3 AU AG RICH ZONE	21.75	75.18	0.00	96.93	224.39
3975M AU IN SLIP	91.54	7.71	0.10	99.35	922.32
3975M AU IN SLIP	91.80	7.38	0.16	99.34	925.59
4368M AU ENCAP IN PY	89.70	9.78	0.09	99.57	901.69
4368M AU ENCAP IN PY	89.70	9.78	0.09	99.57	901.69
4792ZH AU IN QTZ	89.13	11. 9 9	0.18	101.30	881.43
4997ZA AU IN QTZ 30 MIC GRN	90.97	8.70	0.05	99.73	922.32
5168A AU AT PY GRB EDGE	84.16	15.43	0.00	99.59	845.06
5168A CR 1 AU IN PY	85.19	15.81	0.00	101.00	843.47
5173ST AU ASSOC W FRAC	92.30	7.88	0.17	100.36	921.34
5360MC1 CR 1 AU AT MARGIN OF PY	85.76	13.40	0.00	99.16	864.86
5360MC1 CR 1 AU AT MARGIN OF PY	83.75	14.38	0.00	98.14	853.46
27660 53204	86.30	13.16	0.02	99.48	867.69
5557A1 AU IN QTZ	83.83	16.72	0.00	100.55	833.71
5557A1 AU IN QTZ	82.13	17.04	0.00	99.18	828.17
5760M LG AU ASSOC W GN	66.87	32.00	0.26	99.14	676.34
5760M LG AU GRAIN	67.18	31.62	0.30	99.10	679.96

host, at sulphide grain boundaries, or along fractures within sulphides. All grains examined contain Ag, the maximum Ag content determined is 76.4 wt% Ag, and the minimum is 6.18 wt% Ag. Minor enrichments of mercury were determined in individual analyses with a maximum Hg content of 3 wt% from a refractory ore lens. Low totals were achieved for certain analyses due to the small grain size, porosity, and with grains occurring as inclusions in a sulphide host or along fractures.

4.2.8.1 Con Shear Gold

Discrete grains of gold hosted in pyrite (C404-4) and arsenopyrite (R209-239. C404-2) within the Con Shear have a higher fineness than grains sited along fractures, sulphide grain boundaries, or in a silicate/carbonate host. Gold grains occurring in brecciated, polygonalised quartz veins with advanced grain size reduction (C4-20, C404-5,-2,-4) have a lower fineness and lower Hg content than grains in moderately to weakly deformed quartz carbonate veins (C4-1, C34-12L). Intrasample and intragrain variation is minor although intersample variation is well developed (Figure 4.44a). Ag-enriched grains (>35 wt% Ag) occur at sulphide grain boundaries as discrete grains in contact with other gold grains within sulphidic quartz carbonate veins that are moderately brecciated and polygonalised.

4.2.8.2 Negus Veins

Native gold grains occur both within the alteration selvages and internal to the Negus veins. Examination of gold grains from an exposure on 3100L outlines a trend of gold enrichment. Ag-depletion moving from selvage toward the central portion of the vein

Figure 4.46 Variation diagram of gold compositions for Au versus Ag in weight percent.

(A) (p. 235) Con Shear System

(B) (p. 235) 102 Zone and Negus vein on 3100 Level

(C) (p. 236) Shallow 101 Zone

(D) (p. 236) Deep 101 Zone





(Figure 4.44b). Grains of gold encapsulated in pyrite grains or associated with a quartz carbonate gangue within the alteration selvage have a lower fineness than gold grains hosted within the quartz vein proper.

4.2.8.3 Campbell Shear Gold

A sample from the refractory 102 Zone containing gold grains associated with stibnite and Cd-enriched Fe-sphalerite within a lithon of vein material. Gold encapsulated within less deformed quartz lozenges and lithons have a lower fineness and elevated Hg contents in comparison to free gold grains in moderately deformed veins of the refractory 103 Zone.

Within Campbell Shear free-milling ores intra-sample variation in Au/Ag is limited with only several outliers. Intersample variation is well developed throughout the freemilling zones and is dependant on individual stoping trends and broad zonation throughout the mine (Figure 4.44c.d). Intra-sample variations in Au/Ag content with sharp compositional boundaries exist within three samples (33207,3300b, 5168M). Silver rich domains rim low-Ag homogeneous core zones in 33207B,C. Ag-rich zones are mantled by homogeneous Au-rich rims in 3300B. slivers of Ag-rich material are interleaved into homogeneous domains within 5168M sample. The Ag-rich domains typically are enriched in mercury.

Smoky grey, black, and pink coloured quartz carbonate veins tend to host gold grains with a higher fineness than white quartz vein systems. With increasing depth there is an overall trend to lower fineness in individual samples and stoping trends (Figure 4.45).



Figure 4.45 Variation diagram for fineness versus approximate depth for deep free- milling ores of the 101 Zone. Stope name (i.e. 3975M) represents approximate vertical position within Campbell Shear.

4.3 Geothermometers

Several geothermometers based on mineral chemistry of individual minerals and co-existing mineral phases were utilised to determine approximate temperatures of gold deposition for refractory and free-milling ores types as well as to show whether vertical variations in temperatures existed within the deposit.

4.3.1 Arsenopyrite Geothermometry

Kretschmar and Scott (1976) demonstrate that the As concentration within arsenopyrites is temperature dependant. Based on correspondence of natural arsenopyrites compositions and experimentally determined limits a sliding scale geothermometer was constructed based on the atomic % As and the sulphur activity during ore formation. This geothermometer has been applied by other workers and has yielded anomalous results in comparison to other forms of temperature estimation. Sharp et al. (1985) conclude that application of the geothermometer appears valid for deposits metamorphosed to greenschist and lower amphibolite facies but yield low temperatures for deposits metamorphosed to upper amphibolite and granulite facies, and is inconsistent for lowtemperature epithermal hydrothermal systems.

For refractory ores the sulphur activity is established by a pyrite-arsenopyrite assemblage and for free-milling ores by an arsenopyrite-pyrite-pyrrhotite assemblage. Arsenopyrite from variably deformed quartz carbonate veins of the Con Shear may be zoned with respect to As and S and have a range in temperature of crystallization from less than 300°C to 487°C (Figure 4.46a). Arsenopyrite that contain invisible gold concentrations as determined by electron microprobe and secondary ion mass

Figure 4.46a Arsenopyrite geothermometer from Sharp et al., (1985). Given the range in As at% content of individual crystal due to zoning average temperatures are plotted for individual samples. A C204-2: narrow Con Shear quartz vein; B C404-5; intermediate width C4 Shear; C C4-1:narrow Con Shear quartz vein rims; D-D': Rat Lake range in rim compositions; E 27612: C39 Shear. Figure 4.46b Arsenopyrite geothermometer from Sharp et al., (1985). Given the range in As at% content of individual crystal due to zoning average temperatures are plotted for individual samples. A: upper 101 Zone free-milling, 33207 Stope; B lower 101 Zone freemilling, 5760M Stope.



spectrometry from refractory Con and Campbell Shear ores have core As contents that correspond to crystallization temperatures of less than 300°C and rims that correspond to a range of crystallization temperatures from 412 to 494°C (Figure 4.46b). Arsenopyrite from free-milling ores of the Campbell Shear correspond to crystallization temperatures ranging from less than 300°C to 450°C (Figure 4.46b). Application of arsenopyrite geothermometry suggests that refractory auriferous arsenopyrites crystallised at slightly higher temperatures than arsenopyrite within free-milling ores.

4.3.2 Chlorite Geothermometry

Cathelineau and Nieva (1985) used the Al^w content of chlorites and measured temperatures from drill holes in the Los Azufres geothermal field to construct a chlorite geothermometer based on increased Al^w content with increasing temperature. Kranidiotis and Maclean (1987) modified the geothermometer to correct for changes in Fe/Fe+Mg ratios and Jowett (1991) further corrected for Fe and Mg influences on Al^w contents. Representative chlorite crystallization temperatures calculated from the geothermometers of Kraniditis and Maclean (1985) and Jowett (1991) are shown in Table 4.9. Calculated chlorite temperatures from free-milling veins of the Con Shear. 101 Zone of the Campbell Shear, and alteration peripheral to refractory ore zones are generally lower than temperatures associated with refractory schists of the Con and Campbell Shears. Chlorites within mineralised refractory lenses indicate higher temperatures than alteration envelopes.

Temperatures calculated utilising the geothermometer of Jowett (1991) most closely correspond to temperatures calculated by the arsenopyrite geothermometer.

				TABLE 4.9				
		REPRESE	NTATIVE C	HLORITE G	EOTHERM	OMETRY		
SAMPLE	SI	TETAL	OCTAL	AL/AL+AL	F/M	F/FM	JOWETT	K&M1987
102 - 3136	4.988	3.012	2.988	0.502	1.063	0.515	428	375
102 - 3136	4.937	3.063	3.065	0.500	1. 149	0.535	437	382
102 - 3136	5.043	2.957	2.920	0.503	1.123	0.529	420	371
103-J92-79	5.100	2.900	3.062	0.486	0.819	0.450	408	359
103-J92-79	5.051	2.949	3.039	0.492	0.841	0.457	416	365
103- J9 2-81	5.014	2.986	3.044	0.495	1.083	0.520	424	373
103-J92-81	5.141	2.859	3.026	0.486	0.952	0.488	403	357
103-J92-82	5.054	2.946	3.038	0.492	0.784	0.439	415	363
103-192-82	5.088	2.912	2.977	0.494	0.772	0.436	409	359
C4-R09-230	5.309	2.691	3.042	0.469	0.985	0.496	376	340
C4-R09-230	5.285	2.715	3.017	0.474	0.999	0.500	380	343
C4-RO9-239	5.106	2.894	2.767	0.511	0.858	0.462	407	359
C4RO9-239	5.057	2.943	2.982	0.497	0.895	0.472	415	365
C4-R09-255	5.095	2.905	2.862	0.504	0.735	0.424	408	357
C4-R09-255	5.119	2.881	3.037	0.487	0.729	0.421	404	355
C4-1250L	5.084	2.916	2.867	0.504	1.138	0.532	413	367
C4-1250L	5.042	2.958	2.877	0.507	1.133	0.531	420	371
C4-C404-5	5.280	2.720	2.839	0.489	0.756	0.431	379	338
C4-C404-5	5.172	2.828	2.970	0.488	0.791	0.442	396	351
C10 SHEAR	5.660	2.340	2.391	0.495	0.246	0.197	311	281
C10 SHEAR	5.722	2.27B	2.258	0.502	0.153	0.133	299	269
C4 NARROW	5.629	2.371	2.553	0.482	0.756	0.430	323	301
C4 NARROW	5.563	2.437	2.565	0.487	0.792	0.442	334	309
C39 SHEAR	5.570	2.430	2.242	0.520	0.424	0.298	328	298
C39 SHEAR	5.488	2.512	2.393	0.512	0.298	0.230	339	301
33207A	5.191	2.809	2.892	0.493	0.812	0.448	393	349
33207A	5.139	2.861	2.861	0.500	0.784	0.439	401	354
5173R	5.271	2.729	2.571	0.515	0.774	0.436	380	340
5173H	5.208	2.792	2.551	0.523	0.797	0.443	390	34/
53204 STOPE	5.228	2.772	2.791	0.498	0.581	0.367	380	339
53204 STOPE	5.205	2.735	2.831	0.491	0.628	0.360	360	337
5557H	5.203	2.797	2.932	0.488	0.801	0.440	391	340
555/H	5.218	2.782	2.852	0.494	0.816	0.449	369	340
5960M	5.331	2.669	2.669	0.500	0.582	0.368	300	328
DSOUVI	5.318	2.082	2,555	0.512	0.070	0.407	314	337
NUOEC	5.279	2.721	2.541	0.517	0.932	0.462	360	342
JOWETT TEMP=3	19(Aliv*)—69; WHE	ERE Aliv*=	Aiv+0.1(Fe	/Fe+Mg); F	F/FM <0 .6		
K&M(1987) TEMP=	=106(Ali	v*)+18; W	HERE Aliv	*=Aliv+0.7(Fe/Fe+Mg)			

- - -

Temperatures calculated utilising the geothermometer of Jowett (1991) most closely correspond to temperatures calculated by the arsenopyrite geothermometer. Temperatures of crystallization for arsenopyrite and chlorite as determined by their respective geothermometers both indicate that the refractory ore lenses formed at slightly greater temperatures than free-milling quartz veins (Figure 4.47). Within free-milling Campbell Shear ores temperature variations are heterogeneously distributed with respect to depth likely due to the heterogenous distribution of quartz veining and associated gold mineralisation.

4.4 Stable Isotope Geochemistry

Samples of calcite and Fe-Mg carbonates from alteration and auriferous zones of the Con Shear were extracted to examine variations in carbon and oxygen isotopes within refractory ore systems and to compare them with published data for free-milling ores from the Campbell Shear. The ratios of ¹³C to ¹²C and ¹⁸O to ¹⁶O within carbonate minerals are known to vary systematically and to be sensitive to temperature, fluid composition, mineral-fluid fractionation, pH, and various other processes such as oxidation state, phase separation and pressure, all of which will impact on fluid composition.

A total of 29 determinations were conducted on 23 samples. Carbonates were extracted from alteration and ore lenses of refractory ore zones associated with the C4 Shear. In particular, samples of calcite and ankerite were separated across a rapid transition from buff green chlorite-calcite to buff grey green-ankerite alteration on the hangingwall of the C4 Shear.



Figure 4.47 Variation diagram for the range and average temperatures for various freemilling and refractory zones as calculated by the arsenopyrite and chlorite geothermometers. Line connects chlorite and arsenopyrite average temperatures.

Selected veinlet and alteration carbonate species were extracted from diamond drill core and thin section slabs using a high speed, precision drill equipped with either a burr or diamond-tipped bit. The bit size (1-2mm) was appropriate to obtain the carbonate minerals without significant contamination from wallrocks and other gangue mineralogy. Samples were checked for mineralogical purity by powder X-ray diffraction using a Rigaku RTP 300 RC rotating anode X-ray diffractometer. All sample preparation and isotopic analyses were conducted at the Laboratory for Stable Isotope Studies at the University of Western Ontario by the author under the supervision of P. Middlestead and F.J. Longstaffe.

For isotopic analysis 10 to 15 mg samples were reacted with 100% orthophosphoric acid. Calcite samples were reacted at 25°C for twelve hours in evacuated tubes (McCrea, 1950), ankerite samples were reacted at 50°C for 18-24 hours in evacuated tubes. The evolved CO₂ was purified using cold traps at the appropriate temperatures to eliminate possible contamination from H₂O and SO₂. Carbon and oxygen isotope data were obtained δ using a DAAC-upgraded VG Micromass 602C mass spectrometer, and are reported in the usual \neg -notation relative to V-PDB (carbon) and V-SMOW (oxygen) in parts per thousand (1). Standards of the carbonate species as well as a calcite standard were analysed with each batch of samples run. The standards utilised were WS 1 for calcite and DOLO 368 for ankerite. Maximum deviation from the average for standards is +/- 0.05‰ δ^{13} C and +/- 0.07‰ δ^{18} O for WS 1 and +/- 0.15‰ δ^{18} O and +/- 0.18‰ δ^{13} C for DOLO 368. Dulpicates were run for both calcite and ankerite species, maximum deviation from the average of duplicates is =/- 0.5‰ δ^{18} O and +/- 0.3‰ δ^{13} C for ankerite and +/- 0.2‰

4.4.1 Results

The stable isotope results for calcite and ankerite are listed in Table 4.10 and illustrated in Figure 4.48. Calcite from amydules in lower epidote amphibolite facies volcanic rocks FW to the Con Shear and within hairline weakly bleached joints HW to the Con Shear have δ^{18} O values of 9.3‰ and 9.4‰, and δ^{13} C values of -2.4‰ and -3.6‰ respectively. Calcite occurring as cement in bleached HW joint breccias have δ^{18} O values of 9.8‰ and 9.4‰ and δ^{13} C values of -1.6‰ and -1.8‰ Calcite from weakly foliated chloritic schists HW to bleached zones and intensely bleached buff grey-green pervasively chlorite calcite altered domains in the immediate HW of the mineralised system have δ^{18} O values of 9.3‰ to 10.0‰ and δ^{13} C values of -3.8‰ to -1.5‰. Calcite from FW chlorite carbonate schists have δ^{18} O values of 9.6 t‰ 0 10.0‰ and δ^{13} C values of -2.5 to -1.9.‰

Ankerite from intensely bleached buff grey-green pervasively ankerite-chlorite altered domains within 30 centimetres of calcite dominated alteration have δ^{18} O values of 25.9‰ to 28.3‰ and δ^{13} C values of -4.1 ‰ to -1.8‰. Ankerite from foliated ankeritechlorite-white mica schists that may be gold enriched and selvage auriferous zones have δ^{18} O values of 12.9‰ to 24.6 ‰ and δ^{13} C values of -4.1‰ to -2.7‰. Ankerite from vein material within refractory auriferous quartz-carbonate-white mica schists have δ^{18} O values of 11.8‰ and 15.5‰ and δ^{13} C values of -5.2‰ and -3.3.‰.

The isotopic composition of the fluids were calculated utilising temperatures derived from the chlorite and arsenopyrite geothermometers. Where possible, temperatures are

Sample	Species	Description	δ ^{1×} 0%ω	δ ¹³ C‰
27590b	сс	in amydule	9.3	-2.4
C404-16	cc	cement in joint bx	9.4	-1.8
C404-16	cc	cement in joint bx	9.8	-1.6
C404-10	ank dolo	qtz-cb vn	15.5	-3.3
R209-150	cc	lining joint w thin bleached selvage	9.4	-3.6
R209-212	cc	chl-cc schist	9.3	-3.8
R209-212	cc	chl-cc schist	9.2	-3.5
R209-230	ank/dolo	cb-chl-mica schist	16.4	-3.9
R209-234	ank dolo	cb-chl-mica schist	19.6	-4.1
R209-245	ank dolo	minz cb-chl-mica	20.6	-4.0
R209-255	ank dolo	qtz-cb vn	11.8	-5.2
R209-258	ank dolo	cb-chl-mica schist I	2.9	-4.7
R209-268	ank/dolo	cb-chl-mica schist	24.6	-2.7
R209-287	ank/dolo	cb-chl-mica schist	23.6	-3.5
R209-318	cc	chl-cc schist	10.1	-2.5
R214-170	cc	bleached pervasive chl-ec altn	9.9	-1.5
R214-170	cc	as above	9.9	-1.9
R214-172	ank dolo	bleached pervasive chl-ankerite altn	28.3	-2.0
R214-300	cc	chl-cc schist	10.0	-2.3
R215-168	ank dolo	chl-cb schist	26.8	-2.4
R215-168	ank dolo	as above	25.9	-2.1
R215-168	ank dolo	as above	26.2	-1.8
R216-298	cc	chl-cc schist	9.7	-4.3
R216-300	ank dolo	chl-cb schist	26.6	-4.1
R216-412	cc	chl-cc schist	9.6	-1.9
R218-319	сс	bleached pervasive chl-cc alteration	9.5	-3.2
R218-319	cc	as above	9.7	-3.6
R218-321	ank dolo	bleached pervasive chl-cb alteration	28.1	-3.3
R218-321	ank dolo	as above	26.4	-3.0

Table 4.10 Carbon and Oxygen Isotope Compositions of Calcite and Ankerite



Figure 4.48 Carbon and oxygen isotope compositions of calcite and ankerite from alteration and mineralised domains of the Con Shear.

matched directly for samples with both isotopic and mineral chemistry data. For those sample without chlorite geothermometer data, averages were calculated from samples in the immediate vicinity. Fluid δ^{18} O and δ^{13} C compositions calculations are in the form of $1000 \ln \alpha = AT^2 + B$ where $1000 \ln \alpha$ is equivalent to δ mineral - δ fluid (Longstaffe, 1989): A and B are constants whose values have been taken from existing literature. For the purpose of this study the $\alpha_{min-fluid}$ was calculated for $\alpha_{min}-\alpha_{fluid}$ which takes the form:

$$\alpha_{a-b} = (1000 + \delta_a)/(1000 + \delta_b)$$

Fluid δ^{18} O and δ^{13} C compositions for calcite were calculated using the formulae derived by Friedman and O'Neil (1977) and Deines et al., (1974). Fluid δ^{18} O values were calculated for dolomite using the formulae of Land (1983) after Sheppard and Schwarcz (1970) and for ankerite utilising formula of Dutton and Land (1985). Fluid δ^{13} C values calculated from ankerite and dolomite were calculated according to Deines et al., (1974) due to a lack of suitable formula in the literature. Utilisation of a formula presented by Mumin (1994) and Mumin et al., (1996) for calculation of fluid δ^{13} C values for ankerite in equilibrium with siderite generates fluid δ^{13} C values approximately 1‰ lighter than calculations from Deines et al., (1974). Fluid compositions are listed in Table 4.11 and shown on Figure 4.49. Average fluid δ^{18} O and δ^{13} C values for HW calcite alteration are 5.7 ‰ and -2.4‰ respectively: FW calcite-bearing schists have fluid compositions of δ^{18} O and δ^{13} C values of 6.1^{\omega} and -1.4^{\omega} respectively. A sharp compositional gap occurs between bleached pervasively altered ankerite bearing schists and weakly foliated chloritecalcite altered HW basalts. Average calculated fluid δ^{18} O and δ^{13} C values are 20.0% and -2.0‰. During progressive development of shear fabric, the fluid δ^{18} O and δ^{13} C values

			(`alculated 1	lluid ð ^{is} O an	d δ ¹³ C for Carbo	nate	
Sample	Location	Phase	ن، ^۱ ۶	۶ _{۱۱} ۲.	Temp ^u C .	δ ¹⁸ Ο _{θ120}	۵ ¹¹ C رون
AVG HW	HW Schist	ર	9.6	-3.1	368	5.7	
schist							i
AVGFW	FW Schist	ວວ	10.0	- <u>-</u> -	368	6.1	4 . -
schist							
WH DVA	Pervasive	ank	26.9	-2.8	378	20.0	-2.0
	Bleached Zon	2					
R2()9-23()	schist	ank	16.4	9.6-	378	4.6	-3.1
R209-234	schist	ank	19.6	- . +	378	12.6	-3.2
R209-245	schist	ank	20.6	-4.0	398	14.0	-3.0
R209-258	schist	ank	12.9	-4.7	101	6.4	-3.7
R209-268	schist	ank	24.6	-2.6	372	17.5	6'I-
R209-287	schist	ank	23.6	-3.5	372	16.5	-2.7
AVG Mineral	ised Schist	ank	19.6	-3.8	386	12.8	-2.9
C404-10	vein	ank	15.5	-3.3	405	9.1	-2.3
					·414	9.2	-2.2 2.2
R209-255	vein	ank	8.11	-5.2	405	5.4	4 1
				14	5.6	-4,1	
+ temperature	estimate by chlori	te geothermomet	ег				
* temperature	estimate by arsend	pyrite geotherm	ometer				
8""O ₁₁₂₀ cc 10	$00\ln\alpha = 2.78(10^{-1})$	T ^{-'})-2.89 (Friedn	an and O'Neil, 197	(7			
8 ¹³ C ₁₀₂ cc 10	001na = 1.194(10 ⁵	⁶ /T ²)-3.63 (Deine	s et al., 1974)				
δ ¹⁸ O ₁₁₂₀ ank 1	$000 \ln \alpha = 2.7 \% 10$	$^{n}T^{2}$)+0.32 (Dutte	on and Land, 1985)				
$\delta^{13}C_{thud}$ use δ^{1}	¹ C calculation of I	Deines et al., 197	-				


Figure 4.49 Calculated carbon and oxygen isotope values for fluids associated with alteration and mineralisation.

CHAPTER 5

DISCUSSION

5.1 Introduction

The Con Mine is an Archean lode gold deposit sited on shear zones that transect 2712-2680 Ma greenstone assemblages bordering on 2634-2604 Ma plutonic complexes. Deformation on the host shears was initiated at peak amphibolite facies metamorphic conditions and continued until greenschist conditions prevailed within the mineralising system. The two distinct styles of gold mineralisation (i.e. free-milling and refractory ores) occupy distinct spatial environments within the shear systems. The nature of gold precipitation within refractory "invisible gold" ore bodies and the textural and mineralogical disparities between free metallic gold and invisible gold is discussed within the metamorphic framework of the Yellowknife Greenstone Belt. Subsequently, the Yellowknife setting is compared to that of other lode gold systems to demonstrate that it is an intermediate member in the Archean lode gold continuum.

5.2 Prograde Metamorphism and Retrograde Shearing

No specific absolute age may be attributed to the onset of deformation and retrograde alteration along the Campbell and Con Shear Systems. However qualitative age constraints may be applied to bracket the timing of deformation. Contact prograde metamorphism overprints the host Yellowknife Greenstone Belt assemblages at the immediate mine site. Amphibolite facies conditions prevail in the hangingwall of the Con Shear and epidote amphibolite conditions prevail in the shallow hangingwall of the Campbell Shear.

All volcanic hosts were subjected to prograde metamorphism during Defeat suite plutonism. Shear deformation of the Pud Stock (2634 Ma, lower Defeat suite) and marginal phases of the Western Plutonic Complex (2618-2621 Ma, upper Defeat suite) and lack of shear deformation within the Stagg/Prosperous plutonic suite brackets deformation and gold mineralisation as less than 2634 Ma and older than 2560 Ma. The presence of quartz-plagioclase-calcic amphibole veinlets within hangingwall and footwall metavolcanic rocks of the Con Shear indicate fluid mobility at peak metamorphic conditions. Preservation of calcic-amphibole schists within, along strike, and subparallel to retrogressed auriferous deformation zones indicates high strain ductile deformation was initiated at near peak metamorphic conditions; prior to lamprophyric dyke injections.

Sheeted calc-alkaline lamprophyric dykes have preserved magmatic amphibole assemblages that were not subject to prograde metamorphism (Webb and Kerrich, 1988: Webb, 1992; Strand, 1993). The injection of sheeted lamprophyric dykes and of a persistent lamprophyric diatreme along the outer margin of the Defeat thermal aureole may have played a critical role in creating zones of weakness for the Con and Campbell Shears. Lamprophyric dykes tap deep structural levels including pre-Yellowknife Greenstone Belt basement (Nikic et al., 1977). As witnessed by sheared diatreme dyke material on the 2300 level of the Campbell Shear and occurrence of auriferous veins in deformed diatreme (Con Mine Staff personal communication, 1994) lamprophyre magmatism preceded retrogression of deformation and mineralisation. The association of lamprophyre dyking and gold deposits has long been recognised and utilised as an exploration tool (Boyle, 1979), however the relationship of lamprophyre magmatism to the development of Auenriched fluidisation fronts still remains enigmatic (Rock and Groves, 1988; Kerrich and Wyman, 1990; Barron, 1996).

The Con and Campbell Shears of the Con Mine are hosted within the contact metamorphic aureole to the Western Plutonic Complex. The Yellowknife Greenstone Belt is approximately 20 kilometres wide at the point where the gold endowment of the Con and Giant Systems is greatest and the deposits are sited within 2 kilometres of the granitegreenstone contact. A perturbation of the regional distribution of isograds is created by a corridor of anomalous plutonic activity that separates the Con and Campbell Shears. Metamorphic grade of immediate host rocks ranges from hornblende amphibolite to greenschist facies. The deformation zones subparallel metamorphic isograds and mineralisation generally occurs at the transition from amphibolite to epidote amphibolite and greenschist rocks. Reverse movement along shear strands creates an inverted distribution of metamorphic isograds. However, metamorphic grade increases with depth in both the HW and FW of shears to amphibolite grade below 5500 Level.

5.3 Stable Isotope Geochemistry

Kerrich (1987). Kerrich and Fyfe (1987). Webb and Kerrich (1988). Kerrich (1989). Kyser and Kerrich (1990). and Webb (1992) report ranges for δ^{18} O and δ^{13} C values for alteration and vein calcite and ankerite for the Con, Campbell, and Giant shears. No comprehensive data tables are supplied for the carbonate isotope data with these publications. Webb and Kerrich (1988) provide average δ^{18} O values of 8.9‰ and 10.2‰ for ankerite and calcite respectively with a range of 7.1‰ to 16.0‰; the δ^{13} C values

range from 0% to -6%. Ankerite and calcite δ^{18} O values from shallow portions of the Con and Campbell shears that are greater than 16% are discounted as having been isotopically shifted due to interaction with surface waters or post-Archean brines (Kerrich. 1989: Kerrich. 1990). The present study documents isotopic shifts of up to 18% in δ^{18} O between calcite and ankerite across distances of 30 to 60 centimetres. That only ankerite would be isotopically shifted relative to calcite seems implausible. It is more reasonable to accept that the δ^{18} O values are representative of fluid variability during alteration and mineralisation.

The large shift in δ^{18} O values for calcite and ankerite across narrow intervals of visually similar alteration cannot be explained by a fluid of similar compositions since this would require an temperature change of greater than 300°C. This temperature change is unrealistic based on mineralogy and temperatures obtained by chlorite geothermometry. The sharp mineralogical boundary between calcite and ankerite represents a CO₂ metasomatic front within peripheral alteration of HW and FW volcanic rocks with ankerite becoming stable with attendant increase in PCO₂. Carbon isotope values for calcite alteration within wallrocks with low water-rock ratios are enriched relative to pervasive ankerite-chlorite altered zones and ankerite dominant sheared and mineralised zones. The overall trend to lower δ^{13} C values may occur as a response to Rayleigh fractionation within the fluid phase as CO₂ is consumed a residual fluid is generated that precipitates progressively more depleted carbonate. The observed sharp boundary from calcite to ankerite dominated alteration and presence of calcite within peripheral alteration zones is indicative of a progressive consumption of CO₂ (Smith et al., 1984; Kerrich, 1989; Mumin

et al., 1996). Further lowering of the δ^{13} C values for more intensely mineralised zones and veins may reflect CO₂ immiscibility within these zones creating a fluid with still lower ¹³C values. Oxygen values also decrease with increased water rock ratios and as deformation and mineralisation increase in intensity. Removal of CO₂ through Rayleigh distillation will generate a residual fluid depleted with respect to ¹⁸O and ¹³C (Bowers, 1991. Mumin et al., 1996). During progressive deformation and re-equilibration with the residual fluid focused along conduits at slightly higher temperatures, the δ^{18} O and δ^{13} C values of carbonates become lower. This change reflects a mixing or re-equilibration between a fluid associated with early vein development and alteration and a subsequent depleted fluid generated during progressive ductile shearing of a previous vein event. This shift in isotopic signature of the fluid matches the observed progressive development of shear fabric and grain size reduction within pre-existing quartz-carbonate vein material and the late introduction of auriferous arsenopyrite.

Fluid compositions for Campbell Shear mineralisation have been reported by Kerrich (1987a) at $\delta^{18}O = +6.8\% + -1.0$ at temperatures ranging from 270 to 380°C. Data presented by Kerrich and Fyfe (1987) report an average $\delta^{18}O$ value for fluids associated with Con Shear ore and refractory ore of the 102 Zone on 2300 Level of $\delta^{18}O = 8\% + -0.2$ at a temperature of 466 + -30% C. Average $\delta^{18}O$ fluid compositions for carbonate data calculated for refractory ores from the current study range from +20% c at temperatures of approximately 378% C for HW alteration to auriferous zones. Average calculated $\delta^{18}O$ fluid compositions are +12.8% c for mineralised schists and +9% c for quartz vein material at temperatures ranging from 385 to 410% C.

Carbonate isotopes and calculated fluid compositions for refractory Con Shear ores are slightly isotopically heavier than values reported for other Archean lode gold systems but are similar to values reported for lode gold systems within the Motherlode District of California (Figure 5.1). Fluids associated with free-milling gold deposition were lower in temperature and have ¹⁸O values lower than ore fluids associated with refractory ore lenses.

5.4 White Mica Chemistry

Geochemical trends in white mica chemistry best reflect the variations in the metallurgical properties of different ore zones within the Con and Campbell shears. Destruction of plagioclase during deformation adjacent to refractory ore lenses liberated Na to the fluid. Depletion of Na by the fluid flux is indicated by mass balance calculations. However complete loss of Na to the fluid does not occur as Na is preserved within paragonitic muscovites. That bulk Na addition is not required to stabilise paragonitic micas has been documented for the Hope Brook (Stewart, 1994) and San Antonio (Ames et al., 1991) deposits.

In all refractory ores examined, paragonitic mica defines a secondary micaceous foliation within shears associated with significant grain size reduction including cataclasis of auriferous quartz veins. These zones are characterised by increased carbonate content and significant CO_2 metasomatism of aluminous assemblages. Ames et al. (1991) suggest that paragonite is formed within aluminous rocks with progressive CO_2 metasomatism. Stabilisation of paragonite requires a slightly greater activity of sodium than potassium in the fluid. The restriction of paragonite to refractory ore lenses and their alteration envelopes is a manifestation of the progressive ductile deformation of a pre-existing



Figure 5.1 Carbon and oxygen isotope values for carbonates associated with gold mineralisation in the Motherlode District of California, the Timmins camp of Canada (T), the Hollinger Mine (H), and the Kalgoorlie district of Australia (K). From Taylor, 1987. Field of horizontal dashed lines represent calcite alteration from the hangingwall and footwall of the Con Shear, light stippled pattern represents hangingwall ankerite and ankerite from mineralised schists, dense stipple pattern represents ankerite from veins within the Con Shear. feldspar-bearing alteration assemblage. The resultant increase in activity of Na relative to K in the fluid preferentially stabilises paragonite over muscovite in the aluminous host. Freemilling ores are characterised by a lesser degree of ductile deformation, veins are generally folded and boundinaged as opposed to shear laminated. Alteration adjacent to free-milling lenses is albite-bearing and albite is also present within the vein mineralogy. The activity of Na in the fluid phase does not surpass that of K and as a result muscovite and albite are the stable aluminosilicate mineral phases rather than paragonite.

The occurrence of paragonitic micas in the Yellowknife gold camp is not just restricted to the productive refractory portions of the Campbell and Con Shears. Refractory ores are mined within the Giant System and auriferous zones have been identified south of the Con Mine within shallow portions of the Campbell Shear at Yellorex. Samples from the Giant System and the southern strike extent of the Cameron zone beneath Fault Lake share textural characteristics with refractory ores at the Con Mine. White micas that define a micaceous foliation within auriferous samples from Giant and Fault Lake are paragonitic-rnuscovites (Figure 5.2a). Samples from the Yellorex portion of the Campbell Shear are also paragonitic (Figure 5.2b) suggesting that ores from this region will be refractory in nature and that a potential exists for free-milling ores to occur at depth within this portion of the Campbell Shear.

Documentation of white mica mineral chemistry data for Archean refractory ore bodies and the specific connection between paragonite and refractory lenses is limited within the literature. However this relationship is likely more common than has been recognised. For instance the Campbell Mine and the Cochenour-Willans Mine in the Red Lake Greenstone belt of Northwestern Ontario both host refractory arsenopyrite-rich gold ores Figure 5.2 White mica variation diagram of paragonite component versus octahedral aluminum.

(a) white micas associated with gold mineralisation at the Giant Mine, Yellowknife, and immediately south of Giant Mine.

(b) white micas associated with alteration and gold mineralisation at Yellorex.

(c) white micas associated with alteration and gold mineralisation at the Cochenour-Willans Gold Mine, Red Lake, Ontario. Data from Armstrong, 1989.



5.5 Paragenesis of Refractory Gold Ores

Refractory ore lenses of the Con Mine form planar zones that parallel the HW and FW of the encompassing shear zone. Free-milling ore zones have steeper dips than the encompassing shear zone, are typically boudinaged and folded and have not been subjected to a through-going planar deformation event. With respect to the degree of deformation, the gross distribution, variations in quartz vein colouration, degree of selvage development, and vein mineralogy indicate episodic vein formation and heterogenous deformation within free-milling zones of the Campbell Shear. Timing relationships between free-milling and refractory zones are difficult to discern due to lack of crosscutting relationships and of a continuum between ore zones.

Free-milling veins record a history of episodic brittle vein formation and ductile deformation that is heterogeneously distributed along dip and strike within the reverse shear zone. Fluids associated with veins and attendant alteration have Na/K < 1 and greater sulphur activity as indicated by the ubiquitous association with pyrrhotite. Multiple vein forming events is compatible with a high fluid pressure regime and repeated fluid transport via seismic pumping (Sibson et al., 1988). Gold occurs in its native state within sulphide, silicate, and carbonate gangue. A slight decrease in gold fineness occurs with depth.

Sulphide-rich refractory ores are dominated by arsenopyrite. The auriferous arsenopyrite occurs as fine, euhedral acicular to kite shaped grains concentrated along

continuous to semi-continuous foliation laminae. Pre-existing auriferous quartz-carbonate veins are brecciated through progressive cataclasis resulting from ductile deformation. Anastomosing micaceous laminae provide nucleation sites for auriferous arsenopyrite (Plate 5.1a). Carbonate rich portions of veins are preferentially deformed (Plate 5.1b). Lithons of relatively undeformed pre-existing quartz-carbonate vein material host sulphides (pyrite, arsenian pyrite, sphalerite), sulphosalts, and metallic gold (Plate 5.1c). Arsenian pyrite grains are brecciated, fractured, and abraded suggesting growth during vein formation prior to late ductile deformation. Arsenian pyrite grains have corroded cores that are manifested by atoll-like textures (Fleet et al., 1988; this study) that are infilled with carbonate and sheet silicates.

Both macroscopic (Plate 5.1d) and microscopic textures demonstrate that the refractory gold component was introduced during deformation of a pre-existing auriferous quartz-carbonate vein event. During progressive vein deformation Au, As, and S are remobilised and/or introduced into the mineralising system (Figure 5.3).

Both pyrite and arsenopyrite are members of the disulphide group. The presence of anion pairs sets this group apart from other sulphide minerals. The pyrite crystal structure is cubic with octahedrally coordinated metal atoms (Fe,Ni,Co) at the corners and face centers of the cube unit cell (Vaughan and Craig, 1978). The pyrite structure is described as AX_2 with a dianion of $[S_2]^{-2}$ translating into a pyrite formula of $[Fe]^{2+}[S_2]^{2-}$. The arsenopyrite structure is described as AXY with a dianion of $[Fe]^{3+}[AsS]^{3-}$. The negative charges on the nonmetal dianions require that the metal ion have an equal positive charge to eliminate charge imbalance (Wood and Strens, 1979).

Plate 5.1 (A) Anastomosing paragonitic mica domain with arsenopyrite crystals. C4
Shear, R209-245, XN, FOV 1.25mm. (B) Carbonate rich portions of veins are preferentially deformed during ductile shearing. C4 Shear, Rat Lake, R209-255, XN, FOV, 1.25mm. (C) relict lithons of pre-existing vein material commonly host sulphide/sulphosalts, and locally gold. 102 Zone, 3136F, PPL, FOV 5mm. (D) Anastomosing laminae of fine grained arsenopyrite/white mica crosscutting light grey quartz vein material in footwall of ore zone, 2851 Stope, Campbell Mine, Red Lake, Ontario.







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Substitution of arsenic into the pyrite structure will generate a charge imbalance as some of the dianions will take the form $[AsS]^{3}$. The incorporation of As into the pyrite structure results from a substitution of As for S (Fleet et al., 1989; MacLean 1991; Fleet et al., 1993) indicated by the inverse relationship between As and S creating a metastable phase Fe(S.As)₂. Incorporation of gold into the pyrite structure is associated with domains of arsenic enrichment but the relationship is not universal (MacLean, 1990; Griffin et al., 1991; this study).

Several substitution schemes have been devised for the incorporation of Au into arsenian pyrite grains. However the lack of universal positive correlation between As and Au suggests that these schemes fail to properly identify the criteria for Au incorporation. Boyle (1979) suggested that gold may be incorporated into pyrite and arsenopyrite structures through solid solution and substitution for arsenic. That gold does not occur as colloidal inclusions has been demonstrated by high resolution transmission electron microscopy studies and Mossbauer studies (Wagner et al., 1986; Cabri et al., 1990; Marion et al., 1991). MacLean (1991) suggests that the substitution of As for S in the pyrite structural will distort the octahedral ligand field and potentially allow incorporation of the Au atom into the structure. Cook and Chryssoulis (1990) suggest that the substitution of As into the structure will create a charge imbalance with the metal ion. This charge imbalance may be countered by the substitution of a trivalent cation such as As^{3+} , or Au^{3+} in place of the divalent iron cation. Fleet et al., (1993) suggest that Au may occur as monoatomic ions or ionised clusters at sites of As-enrichment. This mode of gold enrichment does not require a coupled or combined double substitution of As for Fe and Au for Fe on the Fe site or a direct substitution of Au for Fe. Both electron microprobe data and secondary ion mass

spectrometry of arsenian pyrite grains of the Con Mine reveal that high Au contents always occur with high As and the reverse is not true. Similar relationships have been identified for pyrite from the Fairview Mine (Fleet et al., 1993). A positive correlation between As and Fe does not exist for pyrite grains at the Con Mine (Figure 5.4).

Arsenopyrite grains demonstrate a negative correlation of As and S from refractory and free-milling ores. Auriferous arsenopyrite grains from refractory ores demonstrate a positive correlation of As and Au. Cabri et al. (1989) suggest that there is not a positive correlation of Au and As for arsenopyrites analysed from the Sheba Mine but do not report core-rim relationships from individual grains. Arsenopyrite grains from pyrite buffered refractory ores generally have maximum As contents of 33 at %; free-milling quartz veins and pyrrhotite buffered free-milling ores have maximum As contents of greater than 33 at % As. This indicates that incorporation of Au into the arsenopyrite structure is attainable at As contents of 33 at % As within pyrite buffered systems. Similar As contents are reported for auriferous arsenopyrite grains from Bogosu and Prestea mines (Mumin, 1994); Villeranges deposit (Marcoux et al., 1989); Le Bourneix deposit (Touray et al., 1989); and Campbell Mine. Red Lake Ontario (Tarnocai, 1996). Based on hydrothermal synthesis of goldbearing arsenopyrite Wu and Delbove (1989) suggest that Au substitutes for Fe in the arsenopyrite structure at As contents of greater than 33 at% As from solutions with increased chloride activity.

Several workers suggest that Au^{3+} will substitute for Fe^{3+} within the arsenopyrite structure (Wu and Delbove, 1989; Johan et al., 1989; Cook and Chryssoulis, 1990). Comparison of electron microprobe and secondary ion mass spectrometry data from individual crystals of arsenopyrite from the refractory 102, 103 and C4 zones demonstrate a



Figure 5.4 Variation diagram for iron at% versus arsenic at% for pyrite from the con and Campbell Shears.

positive correlation of Au with As (Figure 5.5), however this does not hold for grains with greater than 33 at% As from pyrrhotite buffered mineralised zones. There is a subtle enrichement of Au in arsenopyrites less than 33 at% Fe (Figure 5.6), however, there is no linear correlation for Fe and As in arsenopyrite (Figure 5.7). Indications for colloidal gold within arsenopyrite crystals was not evident during secondary ion mass spectrometry analytical runs. The presence of high fineness metallic gold inclusions within As-enriched domains of auriferous arsenopyrite lends support to the presence of ionised clusters of gold at sites of As-enrichment (i.e. Fleet et al., 1993).

5.6 Archean Refractory Gold Ores

The presence and mineralogical description of refractory "invisible" gold ores occurring in Archean lode gold systems has been documented (Boyle, 1979). More recent studies have investigated the crystallographic site of invisible gold within host sulphide grains with little attention awarded to the metamorphic setting of individual deposits (Fleet et al., 1988: Cabri et al., 1989: MacLean, 1990: Cook and Chryssoulis. 1990: Fleet et al., 1993; Tarnocai 1996). Although more recent publications have recognised variances in refractory ore types relative to metamorphic environments (Neumayr et al., 1993) most publications document refractory ores without complete characterisation of both sulphide and gangue mineralogy (Salmita Mine, Ransom and Robb, 1985; Sheba Mine, Wagener and Wiegand, 1985; The New Consort Gold Mine, Voges, 1985; Fairview Mine, Wiggett et al., 1985). The presence of refractory gold ores and associated sulphides within post-Archean deposits have been documented in Proterozoic greenstone belts of western Africa (Mumin, 1993; Mumin et al., 1994); Paleozoic lode gold deposits (Boiron, 1988;

Figure 5.5 Variation diagram of arsenic wt% versus gold wt% for arsenopyrites from the Con and Campbell Shears.

Figure 5.6 Variation diagram of iron at% versus gold at% for arsenopyrites from the Con and Campbell Shears.

Figure 5.7 Variation diagram of iron at% versus arsenic at% for arsenopyrites from the Con and Campbell Shears.



Cathelineau et al., 1988; Boiron et al., 1989; Cathelineau et al., 1989; Touray et al., 1989; Wu et al., 1990; Griffin et al., 1991): and within Paleozoic sediment hosted Tertiary-aged gold deposits (i.e. Carlin type: Arehart et al., 1993). The above sited references describe solid solution gold in both arsenopyrite and arsenian pyrite mineral phases: which also host the refractory gold at the Con Mine.

The Campbell Mine sited in the Red Lake Greenstone Belt of the Superior Province provides a close analogy to the Con Mine in Yellowknife. Exposed supracrustal rocks of the greenstone belt within the prolific gold producing region is approximately 25 kilometres in width perpendicular to bordering batholiths (Figure 5.8). Supracrustal evolution of the belt was prolonged (2992 to 2733 Ma) and is comprised of a mixed sequence of komatilites. tholeiitic basalts with minor intercalated felsic pyroclastics. Plutonic activity initiated shortly after volcanism with intrusion of batholiths in the northern portion of the belt (2731 - 2717 Ma) followed by intrusion of intra-belt stocks and plugs (2720-2718 Ma) culminated with intrusion of large batholiths to the southeast and west (2700 Ma; Andrews et al., 1986). The Campbell Mine is located within the thermal contact metamorphic aureole of the Trout Lake Batholith and within seven kilometres of the granite-greenstone contact. The garnet isograd, considered as the transition from greenschist to amphibolite facies conditions, passes subhorizontally through the mine workings (Andrews et al., 1986: Biotite-chlorite-Fe carbonate-plagioclase retrogression associated with Tarnocai, 1996). quartz carbonate veins in amphibolite facies ultramafic/mafic volcanic host rocks is common. Sheared, laminated, and brecciated quartz carbonate veins and replacement zones with high concentrations of arsenopyrite contrast to relatively sulphide poor. narrow. (brittle) gold-bearing veins. Arsenopyrite grains within refractory ores may contain up to



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- Mafic & ultramafic intrusives
- Figure 5.8 General geology of the Red Lake Greenstone Belt. Note scale and width of greenstone belt. From Andrews et al., 1986.

5600 ppm Au within As-rich portions of grains. Pyrite may also demonstrate gold enrichment of up to 168 ppm Au (Tarnocai, 1996).

Refractory gold ores occur within gold deposits situated in the 3.5 Ga Barberton Greenstone Belt of southern Africa. The Fairview, New Consort, and Sheba mines have produced approximately 66% of the greater than 7 million ounces produced from the Barberton Greenstone Belt (Figure 5.9). These significant gold deposits are all located within six kilometres of the granite-greenstone contact (Anhaeusser, 1986). At the Fairview Mine refractory arsenopyrite and pyritic ore zones form concordant and discordant fracture systems within metagreywackes and shales. Quartz carbonate veins occur within conformably underlying talc-carbonate schists (Wiggett et al., 1986). At the Sheba mine refractory arsenopyrite rich zones occur within intensely altered mafic and ultramafic units and are preferentially associated with quartz sericite schists where sulphides impregnate brecciated mineralised veins (Wagener and Wiegand, 1986). Fleet et al. (1993) report gold contents for arsenian pyrites ranging from 0.3 to 1000 ppm from mineralisation at the Fairview Mine. Cabri et al., (1989) report gold contents ranging from 440 to 1900 ppm for complex and chaotically As/S zoned arsenopyrites from the Sheba Mine. Other refractory ore bodies within the Barberton Greenstone Belt southeast of the Sheba and Fairview mines have been described by Anhaeusser (1986) and de Ronde et al. (1988). Although detailed descriptions of pre-metasomatic metamorphic conditions and mineral assemblages are lacking for the Barberton deposits the close <6 kilometre proximity of deposits suggests a regional contact thermal metamorphic environment for these deposits.

Figure 5.9 (A) General geology of the Barberton Greenstone Belt. Box inset on Figure A represents more detailed sketch shown in (B) location of Sheba, New Consort, and Fairview mines. Note scale and proximity of deposits to intrusive batholiths.

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5.7 Summary

The Con Mine represents a prime example of an Archean shear zone hosted lode gold quartz vein system. Onset of plutonism and heat generated by early Defeat phase plutonism (circa 2634 Ma) initiated prograde regional contact metamorphism. Evidence for fluid mobility during initial shear development is preserved as brittle, sharp walled quartzplagioclase-amphibole veinlets within amphibolite facies volcanic rocks in the hangingwall and footwall of the Con Shear. Activation of regional shear systems occurred at near peak conditions and lamprophyric dyke injection utilised these zones near the outer limits of the Defeat thermal aureole. Continued intrusive activity (2620-2600 Ma) generated voluminous fluid by devolatilisation within the thermal aureole.

Refractory arsenopyrite bearing ores of the Con and Campbell Shears are characterised by ductile shearing of pre-existing auriferous quartz carbonate vein systems: thus indicating early brittle, late ductile evolution of these zones. Geochemical signatures of alteration and ore mineral assemblages indicate refractory mineralisation occurred during fluid flux with high CO₂ partial pressures. Breakdown of early albite resulted in fluids with a sodium activity greater than potassium activity resulting in stabilisation of paragonite. Native gold occurs in sulphide and silicate gangue and solid solution gold occurs in Asenriched zones of arsenopyrite and more locally within broad As-enriched domains of pyrite. Refractory systems thus have a lower sulphur activity than free-milling ores as shown by the lack pyrrhotite. A schematic diagram (Figure 5.10) summaries the relationship between free-milling and refractory ores within the Con Mine gold system and the relative physical and mineralogical variances between ore types. Refractory and free-



Figure 5.10 Schematic diagram of the Campbell Shear Zone. Drawing outlines physical separation of the free-milling and refractory ore bodies and their relationship to the main deformation zone.

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milling ores occur within different structural settings of the long-lived deformation zones: protracted retrograde fluid evolution occurred within the environs of an inverted geothermal gradient.

CHAPTER 6

CONCLUSIONS

6.1 The Archean Gold Continuum

Recognition of a range in conditions for formation of Archean lode gold deposits at different crustal levels from fluids with similar characteristics has led to the proposal of a crustal continuum for these large hydrothermal systems (Mueller and Groves, 1991; Groves et al., 1992; Groves, 1993; Ridley et al., 1996; Hagemann and Brown, 1996). This continuum is here modified to incorporate the occurrence of refractory ores, which to date have been by and large ignored within Archean metallogeny. The proposed continuum is subdivided into 3 broad categories: 1) amphibolite gold in an upper amphibolite to lower granulite facies host, 2) greenschist gold in amphibolite facies host, and 3) greenschist gold in greenschist to sub-greenschist facies environments. A schematic cartoon (Figure 6.1) outlines the crustal scale variations in Archean lode gold systems and the various host rock and depth relationships. A summary of deposits that span the continuum is provided in Table 6.1.

Considerable debate exists regarding the timing of mineralisation relative to metamorphism for gold deposits located in upper amphibolite to lower granulite facies host rocks. Early pre-metamorphic gold deposition with subsequent metamorphism (Kuhn et al., 1986: Johnson, 1996), synmetamorphic gold deposition (Couture and Guha, 1990: Barnicoat et al., 1991; Neumayr et al., 1993; and Neumayr et al., 1995), and post-peak metamorphic gold deposition (Pan and Fleet, 1992).

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	DEPOSIT	Oz	HOST ROCK	INTRUSIVES	METAMORPHISM	ALTERATION
G R	SIGMA Val'Dor Quebec Abitibi GSB Superior Province	>4 m	Upper Malartic pillowed/massive porphyritic diorite	feldspar porphyry porphyritic diorite	greenschist Regional	chl-cb-wht mica cb-wht mica cb-albite
E N S C H	DOME Timmins ON .1bitibi GSB Superior Province	>13 m	south limb Porcupine Syncline, mafic & ultramafic flows metasediments,qfp	qfp porphyries	greenschist Regional	chl-cb-Cr mica cb-py-sio2
I S T	KERR- ADDISON Virginiatown ON <i>Abitibi GSB</i> Superior Province	> 10	mafic volcanics ultramafic volcanics	?	greenschist Regional	talc-carbonate chl-carbonate musc-albite
	CON MINE Yellowknife NWT Yellowknife GSB Slave Province	> 6 m	tholeiitic basalts (flows and sills)	isolated qfp plugs w anomalous Au-Mo lamprophyre dykes	greenschist epidote-amph amphibolite	chl-cb-wht mica chl-cb-albite
A M P					Connact	
H I B	CAMPBELL MINE Red Lake ON <i>Red Lake GSB</i>	> 9m	tholeiitic basalts ultra mafic flows/intru. felsic volc	qtz-feld porphyry lamprophyre dykes	greenschist amphibolite	chl-cb-biotite chl-cb-albite wht mica
0 L I	Superior Province		BIF, dioritic intru.		Contact	garnet, cpx, epidote
T E	ULU DEPOSIT High Lake GSB NWT	~1 m?	? tholeiitic basalts co-genetic gabbro sills metasediments	qfp dykes	amphibolite	biotite-tour-epidote plag-act-hb diopside, homblende
	Slave Province				Contact/Regional	
	MT YORK DISTRICT Zankanaka Prospect	??	amphibolites ultramafics		amphibolite	qtz-calc silicate vns qtz-diop-kspar-plag
G R ♪	Pilbara Craton NW Australia				Contact/Regional	amph vns
N U L	GRIFFIN'S FIND Southern Cross Province <i>Yilgarn Craton</i>	<u>??</u>	mafic volcanics meta sediments		amphibolite lower granulite	cpx, Ca-amph, plag, biotite, garnet Mn-grossular
T E	S» Austrana				Contact/Regional	

ref: Robert and Kelly 1986a,b, Kishida and Kerrich, 1987, Carpenter, R.L., 1994; Neumayr et al., 1993, 1995, Mueller and Groves, 1991; Montz and Crocke
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TABLE 6.1 ARCHEAN GOLD CONTINUUM

PHISM	ALTERATION	MINERALISATION	Au HABIT	Au MINERALS	COMMENT
chist onal	chl-cb-wht mica cb-wht mica cb-albite	sub-vert qtz vns in ductile shears sub horz tension vn	native Au fracture fill in sulphide/silicates incl in py	native Au tellurides	po, tourmaline, biotite increase with depth metamorphic grade increases with depth/ degree of retrogression decreases with depth
chist	chl-cb-Cr mica	foliation parallel vns	assoc w po/cpy native Au	native Au	broad alteration zone
onal	cb-py-sio2	en echelon tension vns stockwork vns in metasediments	fracture fill	tellurides?	
ichist onal	talc-carbonate chl-carbonate musc-albite	qtz-cb vns in Cr-mica qtz cb altn vnlts in disseminated "flow ore"	native Au in vns bkgd enrichment native Au assoc w pyrite		broad alteration zone
schist -amph bolite	chl-cb-wht mica chl-cb-albite	foln parallel qtz cb vns laminated schists	native Au Au as inclusions fracture fill in sulphides	native Au tellurides aspy As-pyrite	all vns/auriferous schists retrogressed to grnsch refractory ores in FW of shear above 3500L, free milling ores in HW of shear 2300L > 5900L No continuum between ore types
laci			in aspy/ As-py		shear zone and alteration telescopes with depth
schist bolite	chl-cb-biotite chl-cb-albite wht mica	crack-seal qtz-cb veins replacement/mineralised domains	native Au Au incl in sulphide host	native Au tellurides aspv	refractory ores sited at rheological boundaries Ductile ultramafics/brittle mafics
tact	garnet, cpx, epidote	sheared veins	solid solution Au in aspy/ As-py	As-pyrite	refractory ores share textural similarities to Con refractory ores
bolite	biotite-tour-epidote plag-act-hb	qtz veins qtz-aspy-kspar bx's	native Au Au incl in lollingite	native Au	new style of Au mineralisation recorded in in Slave Prov.
Region al	diopside, hornblende		Au at lollingite/aspy grain boundaries		Bi associated with native Au at aspy/lo grain boundaries
bolite	qtz-cale silicate vns	qtz-calc silicate vns	assoc w po/py	native Au	aspy rims on lo cores
Region al	amph vns		шиог азру	3010 301 AU 11 10	no solid sol'n Au in aspy, aspy formed under slightly retrograde conditions
ibolite ranulite	epx. Ca-amph, plag, biotite, garnet Mn-grossular	vns in ductile shears	assoc w po,lo,aspy solid sol'n Au in lo Au at lo/aspy	native Au solid sol'n Au in lo	aspy rims on lo cores Au at aspy/lo grain boundaries no solid sol'n Au in aspy, aspy formed under
Regional	Erossanar		grain boundaries		slightly retrograde conditions

ler and Groves, 1991, Moritz and Crocket, 1991

TABLE 6.1 EAN GOLD CONTINUUM

MINERALISATION Au HABIT Au MINERALS		COMMENT	COMMENT		
sub-vert qtz vns in ductile shears sub horz tension vn	native Au fracture fill in sulphide/silicates incl in py assoc w po/cpy	native Au tellurides	po, tourmaline, biotite increase with depth metamorphic grade increases with depth/ degree of retrogression decreases with depth	B R O	
foliation parallel vns en echelon tension vns stockwork vns in metasediments	native Au fracture fill	native Au tellurides?	broad alteration zone	A D	
qtz-cb vns in Cr-mica qtz cb altn vnlts in disseminated "flow ore"	native Au in vns bkgd enrichment native Au assoc w pyrite		broad alteration zone		
foln parallel qtz cb vns laminated schists	native Au Au as inclusions fracture fill in sulphides solid solution Au in aspy/ As-py	native Au tellurides aspy As-pyrite	all vns/auriferous schists retrogressed to grnsch refractory ores in FW of shear above 3500L, free milling ores in HW of shear 2300L > 5900L No continuum between ore types all vns sheared and/or folded shear zone and alteration telescopes with depth		
crack-seal qtz-cb veins replacement/mineralised domains sheared veins	native Au Au incl in sulphide host solid solution Au in aspy/ As-py	native Au tellurides aspy As-pyrite	refractory ores sited at rheological boundaries Ductile ultramafics/brittle mafics refractory ores share textural similarities to Con refractory ores	T E L E	
qtz veins qtz-aspy-kspar bx's	native Au Au incl in lollingite Au at lollingite/aspy grain boundaries	native Au	new style of Au mineralisation recorded in in Slave Prov. Bi associated with native Au at aspy/lo grain boundaries	S C O P E D	
qtz-calc silicate vns	assoc w po/py minor aspy	native Au solid sol'n Au in Io	aspy rims on lo cores Au at aspy/lo grain boundaries no solid sol'n Au in aspy, aspy formed under slightly retrograde conditions		
vns in ductile shears	assoc w po,lo.aspy solid sol'n Au in lo Au at lo/aspy grain boundaries	native Au solid sol'n Au in lo	aspy rims on lo cores Au at aspy/lo grain boundaries no solid sol'n Au in aspy, aspy formed under slightly retrograde conditions		

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Figure 6.1 Schematic cartoon of the Archean crustal gold continuum.

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Such deposits are situated in narrow highly metamorphosed and attenuated greenstone belts. Examples of these deposits include the Ulu Deposit. High Lake Greenstone Belt, Slave Province, Canada (Carpenter, 1994), Mt. York District, Pilbara Craton and Griffin's Find, Yilgarn Craton (Barnicoat et al., 1991; Neumayr et al., 1993; Neumayr et al., 1995; Mueller and Groves, 1991). Mineralisation associated with these deposits does not display significant wallrock retrogression and is dominated by an arsenopyrite-lollingite sulphide mineral assemblage. Mineralisation occurs at peak metamorphic conditions, lacks carbonate alteration and is associated with biotite-amphibole, quartz-calc silicate alteration. Arsenopyrite rims and replaces lollingite, arguing against metamorphism of a pre-existing mineral assemblage which would have led to desulphidation reactions and lollingite rimming arsenopyrite (Barnicoat et al., 1991, Neumayr et al., 1993; Carpenter, 1994). Lollingite is the host to any significant refractory "invisible gold" component (Neumayr et al., 1993). Metallic gold is preferentially located at lollingite-arsenopyrite grain boundaries and the arsenopyrite is interpreted to form under slightly retrograde conditions (< 500°C) but at temperatures too great to allow incorporation of Au into the arsenopyrite structure (Neumayr et al., 1993; Carpenter, 1994). Recognition of this style of mineralisation and exploration for these deposits within higher metamorphic rank greenstone terranes is well advanced in Australia, but limited within Canada. Gold mineralisation is suggested to have occurred concurrently with widespread thermal reworking of the lower crust at upper amphibolite to granulite facies metamorphism (Witt, 1991: Kent et al., 1996).

Greenschist facies gold deposits within amphibolite host rocks occur within deformation zones that transect contact thermal metamorphic aureoles of large plutonic

complexes. These deposits typically occur within 25-35 kilometre wide greenstone belts. The Con Mine, Slave Province; Campbell Mine, Superior Province; and mines of the Barberton Greenstone Belt all share the same metamorphic environment. Free-milling metallic gold occurs within brittle-ductile quartz-carbonate veins with a pyrite-pyrrhotitearsenopyrite assemblage. Refractory arsenopyrite-rich ores are characterised by a more aluminous alteration assemblage and are distinguished by continued deformation of preexisting quartz carbonate vein systems. The degree of wallrock retrogression and greenschist facies mineral assemblages contrast to the higher metamorphic grade of host rocks. indicating a history of prolonged retrograde fluid flux during deformation. Textural and geochemical differences of refractory ores indicates a deformation and fluid evolution history that contrasts with free-milling ores hosted within the same deformation zones. The metamorphic grade of host rocks, degree of retrogression, nature of gold deposition, and structural style of mineralisation sets refractory gold ore bodies apart from refractory/free milling amphibolite facies and free milling greenschist facies deposits.

Greenschist gold hosted in greenschist to subgreenschist host rocks form a large group of deposits well documented within Canadian gold literature and include the most prodigious gold camps of Canada (Timmins, Kirkland Lake, and Val'dor camps, Abitibi Greenstone Belt). Deposits are situated in aerially large greenstone belts with low grade regional metamorphism and are characterised by extensive alteration haloes, readily observable adjacent to veins (Fyon and Crocket, 1982; Robert and Brown, 1986; Kishida and Kerrich, 1987; Moritz and Crocket, 1991). These deposits are characterised by the universality of free-milling metallic gold ores hosted within brittle quartz carbonate vein systems and alteration zones with pyrite as the dominant Fe-sulphide mineral phase. Gold mineralisation within greenschist terranes with lower geothermal gradients allows for fluid evolution and retrogression at ambient metamorphic conditions.

Hagemann and Brown (1996) compiled geobarometric data from available fluid inclusion studies for Archean lode gold deposits. This compilation indicates that inferred crustal depths of mineralisation display a depth continuum that is compatible with observed ore, alteration, and metamorphic mineral assemblages. Pressure estimates for the Con Mine (200 to 250 MPa; Kerrich and Fyfe, 1987) and the Campbell Mine (300 Mpa, Tarnocai, 1996) place refractory gold systems as mesozonal deposits at a position that straddles shallow epizonal free-milling systems from structurally deeper mesozonal deposits.

6.2 Recommendations

Determination of the metamorphic grade of host rocks and degree of retrogression within the deformation zones provides information regarding anticipated styles of deformation. alteration haloes. quartz vein development, gold mineralisation type, and variations in sulphide content and assemblages. Although high grade metamorphic greenstone terranes are candidates to host gold mineralisation Canadian exploration efforts have traditionally avoided these environments. High geothermal conditions within these deep amphibolite/granulite facies metamorphic environments generates a focused fluid flow with minimal wallrock retrogression. Prolonged re-activation of deformation systems within contact metamorphic environments results in formation of complex retrograde auriferous sulph-arsenide assemblages. Refractory ores within these environments are characterised by a paragonitic muscovite sheet silicate assemblage. Lower geothermal conditions in greenschist to subgreenschist environments allows for widespread wallrock alteration and fluid evolution at ambient metamorphic conditions. Recognition of the continuum in deposits type and their associated variations in metamorphic grade and degree of retrogression provides a useful unifying exploration model.

The association of paragonitic micas with refractory ores in the Yellowknife camp is an association that has neither been recognised nor documented within other gold camps. Utilisation of white mica mineral chemistry in the Yellowknife camp provides immediate information regarding the metallurgical properties of the ore and may provide indications of where within the shear zone more free-milling ores may be sought. Documentation of white mica variability within other refractory systems would not only provide support for the paragonite-refractory gold association in Archean deposits documented herein but also refine an application that may assist in exploration for gold in mesothermal contact metamorphic environments.

Further research is warranted on several key areas of Con Mine geology. The timing of calc-alkaline lamprophyre dyking relative to Defeat phase plutonism and ore mineralisation is an outstanding problem. Absolute age dating of these dykes and a fuller understanding of their regional extent and relationship to gold is a prime topic for further study. Examination of fluid inclusions from various free-milling stoping trends combined with careful study of fluid inclusion data from refractory veins would shed further light on the chemistry of the fluid systems involved.

6.3 Conclusions

The important conclusions which have been reached in this study are:

(1) The gold mineralisation is concentrated within the thermal aureole to Defeat phase plutonism (2634-2604 Ma). Inverted isograds marginal to the intrusion were structurally activated at near peak metamorphic conditions.

(2) The outer margins of the thermal aureole was injected by lamprophyre dykes whose relationship to fluid evolution still remains enigmatic.

(3) The Con and Campbell Shears both host free-milling and refractory gold ores.

(4) There is no physical continuum between free-milling and refractory ores.

(5) Free-milling ores are characterised by a muscovite-chlorite-calcite-albite-pyritepyrrhotite-native gold assemblage associated with folded and boudinaged quartz veins. Gold-bearing veins formed at temperatures of less than 375°C, from fluids with Na/K <1. δ^{18} O of approximately 6.8‰.

(6) Refractory ore zones are characterised by a paragonitic muscovite-Al chlorite-Fe/Mg carbonate-arsenopyrite-pyrite assemblage associated with progressive planar deformation of pre-existing quartz-carbonate veins. Refractory "invisible" gold occurs as structurally bound gold in As-enriched rims of As/S zoned arsenopyrite and locally within As-enriched domains of pyrite. Calculated temperatures of quartz vein mineralisation are $300-420^{\circ}$ C, and fluids are characterised by Na/K > 1, and δ^{18} O and δ^{13} C values of 9.1‰. and -2.27‰.

(7) In comparison to other Archean lode gold deposits the Con Mine represents an upper-intermediate member of a crustal continuum that includes deep-seated granulite/amphibolite, retrograde amphibolite, and shallow greenschist hosted deposits.

Refractory gold mineralisation is typified by greenschist mineral assemblages within deformation zones transecting amphibolite facies supracrustal assemblages.

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APPENDIX A

ANALYTICAL TECHNIQUES

Electron Microprobe

Electron microprobe analyses were done on a JEOL JXA-8600 electron microprobe equipped with four wavelength spectrometers and electron backscatter capabilities housed in the Department of Earth Sciences, University of Western Ontario. R.L. Barnett and D. Kingston of the Electron Microprobe Laboratory conducted the calibration, schedule set-up, and standard selection. Following calibration, the author analysed silicates and carbonates from the various samples. Sulphides were probed both by the author and the technical support staff.

Quantitative corrections for atomic number, absorption, and fluorescence effects were performed with a Tracor Northern ZAF correction program.

Silicate measurements were conducted at 15 kV with a beam current (cup reading) of 10 nanoamperes using natural mineral standards calibrated on kaersutite. Sulphide analyses were conducted at 20 kV with a beam current (cup reading) of 20 nA using the following standards: for arsenopyrite Fe, As, and S were calibrated on ASP 200 a natural homogeneous arsenopyrite from the Lucie pit of the Helen siderite mine near Wawa. Ontario; for pyrite Fe and S were calibrated on a natural homogeneous pyrite; Ni was calibrated on synthetic NiS. Co was calibrated on pure Co. Au was calibrated on a pure gold standard. Trace element analyses (Co, Ni, Au) were done with a beam current of 20 nA and a counting time of 40 seconds with the backgrounds on, gold analyses were determined utilising the Au*L* line for pyrite and arsenopyrite.

A CAMECA IMS-3f ion microprobe housed at Surface Science Western was used to quantitatively determine the gold concentration of arsenopyrite and pyrite. The measurements were made with a cesium beam of 30–40 nA while monitoring negative secondary ions. Selected grains were analyzed with a primary beam diameter of approximately 25-30 microns; minimum detection limits for arsenopyrite and pyrite are approximately 0.1 ppm, analysis time ranged from 3 to 5 minutes. Details concerning operating conditions and standardization techniques are outlined below and in Chryssoulis et al., (1987), Chryssoulis et al., (1989), and Cook and Chryssoulis, (1990). Analyses were conducted by Chris Weisner and Gary Mount of Science Western in the presence of the author.

Primar	y Beam	Secondary Beam			
	beam	Cs			
polarity	positive	polarity negativ		/e	
high voltage	10 KV	high voltage		4300V	
raster	0	offset voltage		200V	
current	30-40 nA	transfer optics 150nm			
	Contrast aperture		ure	4 (largest)	
		energy window open		130eV)	
		detector		EM	

Gold was quantified using external standardization utilising Au ion implanted pyrite and arsenopyrite with doses of 5×10^{13} at/cm², implanted at 600 KeV. The area under the intensity versus depth curve was calculated and a sensitivity factor (SF) was found so that the concentration versus depth area would produce a dose of 5×10^{13} at/cm². A relative sensitivity factor (RSF) was found by referencing the sensitivity factor to a matrix intensity (mass 34, S; Wilson et al., 1989).

Individual ion microprobe spot analyses were labelled on electron microprobe backscatter photographs to provide documentation of probed domains. Ion microprobed spots were further checked with an optical microscope and some were examined in SEM and backscatter mode on the electron microprobe to ensure that the proper domains (i.e. As-rich, As-poor) had been analyzed and to collect further data on As and Au zonation patterns. The SIMS beam (25-30 microns) was larger than some domains of As enrichment within arsenopyrite and pyrite grains and therefore the gold values reported reflect regions of variable As/Au enrichment.






IMAGE EVALUATION TEST TARGET (QA-3)









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