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THE UNIVERSITY OF ALBERTA

Structure, Mineralogy, and Stable Isotopes - Bullmoose Lake Gold Deposit, N.W.T.

by

Stephen P. Swatton

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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OF Master of Science

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Sometimes a scream is better than a thesis

Ralph Waldo Emerson (1803 - 1882)

Aaaeeeeyaaaayaaayaaayaa.....

Johnny Weismuller (1908 - 1984)

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Structure, Mineralogy, and Stable Isotopes - Bullmoose Lake Gold Deposit, N.W.T. submitted by Stephen P. Swatton in partial fulfilment of the requirements for the degree of Master of Science.

....

Supervisor

R. E. Johnston ....

R. J. Rampant ....

....

Date 6 May 87 ....

Dedication

To my parents Pat and Peter and my sister Elaine.

Abstract

The Bullmoose Lake gold deposit is located in Archean metasediments of the Burwash Formation, Yellowknife Supergroup. The majority of the gold was recovered from en échelon blue-grey quartz veins hosted by a relatively narrow zone of silicified metapelites and graded metagreywackes. The auriferous quartz veins were emplaced at sites of dilation that were generated during left-lateral shear. Schistosity and two phases of folding were produced during one [illegible] metamorphic event which showed an increase in its intensity towards the end of metamorphism.

Isotopic, fluid inclusion, and mineralogical data are consistent with emplacement of gold after peak metamorphism. Available physical and chemical constraints on gold mineralization in volcanic shear zone deposits and their similarity to metasediment-hosted gold deposits, in some respects, makes it likely that the auriferous fluids were derived by metamorphic processes. In this model the ore fluid and the ore components were derived by devolatilization of the Slave supracrustal rocks during low-and medium grade-metamorphism. The gold was transported by 'single pass' flow mechanisms as a reduced sulphur complex in reduced near neutral fluids of varying CO_2, salinity and CH_4 content. The fluids were focussed locally into horizons and beds which had fractured, due to their relatively low tensile strength.

The mineralogy shows two slightly different paragenetic stages during which gold emplacement occurred. An early stage ('main-phase') in which gold is mainly associated with Fe-sulphides and a later cross-cutting stage ('late-phase') in which gold is more often associated with galena, sphalerite and chalcopyrite. The temperatures of deposition of the of 'main-phase' mineralization are unclear; however, the 'late-phase' minerals were deposited between 140° and 300°C.

Deposition of gold took place due to: (1)a fluid-temperature reduction, (2)reduction of the fluid by interaction with graphitic horizons and/or (3)by sulphidation of Fe-rich host-rocks.

This deposit, and many similar metasediment-hosted gold deposits worldwide, is characterised by very narrow, patchy wall-rock alteration, inferring low water to rock ratios. This alteration style and the varied sulphide mineralogy associated with gold mineralization at Bullmoose Lake indicates rapid precipitation of gold from several pulses of fluid.

Acknowledgements

I would like to express my gratitude to a large number of people who have provided advice, encouragement and assistance throughout the duration of this project.

Roger Morton initiated the study and provided much needed guidance throughout. I am also very grateful to Amarendra Changkakoti for his valuble advice and assistance during the latter stages of the study. Phillippe Erdmer is acknowledged for his help with some of the structural interpretations and microscopy.

I appreciate the co-operation of various project heads for allowing me access to their laboratories. Dr. J. Gray (Dept. of Physics) provided free use of his sulphur isotope line, Dr. K. Meuhlenbachs (Dept. of Geology) allowed access to his oxygen isotope line, and I am particularly grateful to Dr. R. Krouse (Dept. of Physics, University of Calgary) for the use of his mass spectrometer and for sharing with me some of his knowledge of stable isotopes. Pierre Maheux kindly performed the oxygen isotope analyses.

I kindly acknowledge the the financial and logistic assistance of Terra Mines Ltd., Edmonton. All office staff and field geologists at Terra Mines Ltd., are thanked for their support and friendship, but I extend particular thanks to Hank Sanche, Chief geologist, for allowing me a free rein throughout the course of this study.

John Brophy (INAC, N.W.T) first introduced me to the the geology of the Slave Province and I extend warm thanks to him for many stimulating discussions and for imparting some of his enthusiasm for field-geology. By the same token I would like to express my gratitude to Dr. Bill Fyson (University of Ottawa) who very kindly visited some of the properties and provided invaluble help with the interpretion of many (seemingly) unusual structual configuations encountered in the field.

I would like to acknowledge an INAC Charles Camsell bursary which enabled me to travel to Yellowknife and give a presentation (1986).

I appreciate the support of fellow students, particularly Paul Lhotka for imparting some of his knowledge of Northern geology, Lori Walton for demonstrating the 'mechanics' of fluid inclusion analysis, "J.D" Fournier for his help in transferring the structural data onto disk and Mike Dufresne for help with the many formatting problems encountered.

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Finally, the list of acknowledgements would not be complete without thanking Mike Ryan (dept. of geology, Portsmouth Polytechnic) for his guidance during my geological apprenticeship and for suggesting that I should study at the University of Alberta!.

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Abbreviations used

andal - andalusite
ab - albite
ank - ankerite
apat - apatite (fluorapatite)
Au - gold
asp - arsenopyrite
act - actinolite
BiTe - Bismuth Telluride mineral
bi - biotite
cpy - chalcopyrite
chl - chlorite
cord - cordierite
epi - epidote
graph - graphite
gn - galena
ged - gedrite
gw - greywacke
ilm - ilmenite
musc - muscovite
mt - magnetite
olig - oligoclase
po - pyrrhotite
pn - pentlandite
plag - plagioclase
py - pyrite
ppl - plane polarized light
qtz - quartz
rut - rutile
sph - sphalerite
sch - scheelite
sill - sillimanite
ser - sericite
tour - tourmaline
tet - tetradymite
xpl - cross polarized light

I. Introduction

A. General statement

The Bullmoose Lake gold deposit is located 77 km south-east of Yellowknife, Northwest Territories, Canada (62° 20'N / 112° 45'W, Fig. 1). The ore occurs in several narrow veins which are hosted by Archean (2700 Ma), amphibolite-grade metasedimentary rocks of the Burwash Formation, a member of the Yellowknife Supergroup. The total possible ore reserves of the property were calculated at 183,863 tonnes at a grade of 10.3 g/tonne Au (Sanche, 1986).

The topography of the area is relatively flat (maximum elevation of 300m); the climate is mild in the summer (-5 to 20°C) and cold in the winter (-10 to -50°C), and the vegetation is of sub-tundra type (small trees and shrubs). The clarity of the rock exposure is relatively poor in the local area around the minesite, due to extensive lichen cover and to extensive areas of muskeg in and around the lakes.

B. Purpose of study

The objectives of this thesis were three fold, namely:

1. To undertake a field orientated, structural study of a typical metasediment-hosted vein gold deposit.
2. To produce a document collating information about metasedimentary-hosted gold deposits in the Slave Province and presenting it in a manner that would be useful to persons both in industry and academia.
3. To integrate the field data with laboratory investigations of :
   a. The petrology of the veins, wallrock and country rock.
   b. Stable isotopes (O, D/H, S).
   c. The fluid inclusions of the vein materials.

Ramsay (1973a) and English (1981) studied various aspects of the metamorphism and fluid inclusions respectively, from a number of different gold deposits. This study constitutes

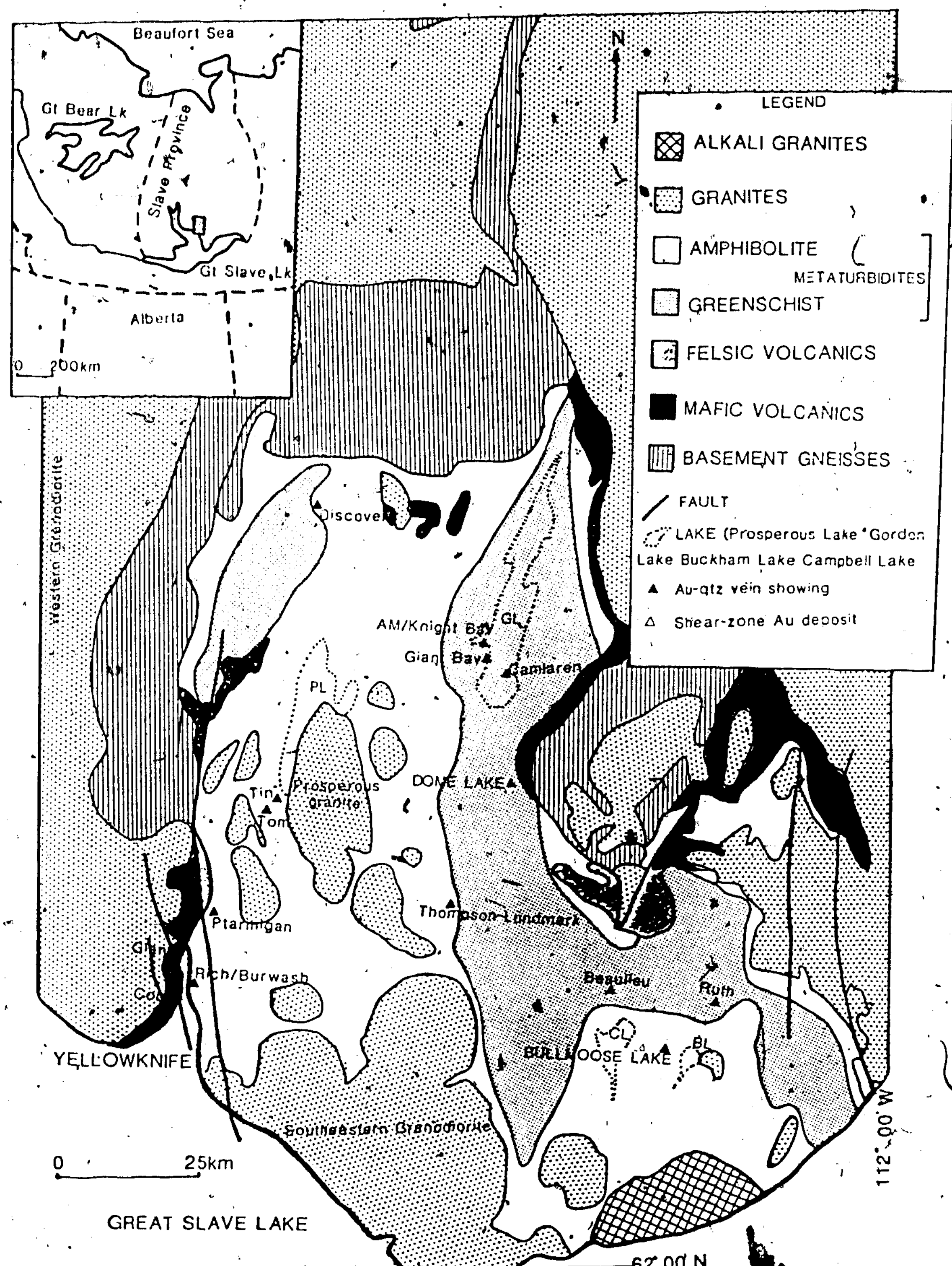


Figure 1. The geology of the Southern Slave Structural Province

an update of their work and concentrates upon information obtained from one operating mine, rather than upon information of a regional character. The emphasis of this study was therefore to integrate all of the available regional reports, both academic and non academic, with the plethora of information that has been gained from studying the Bullmoose Lake auriferous veins in a three dimensional perspective. The study was particularly concerned with a better understanding of the relationship between structure and emplacement of auriferous veins.

Geological reports are available on other turbidite-hosted deposits in the area, for example; Ptarmigan, (Boyle, 1961, 1979); Camlaren, (Wiwchar, 1957); Thompson-Lundmark (Lord, 1951). These previous reports were primarily based upon field descriptions and constitute very useful primary sources of information, but as expressed by Padgham (1985a)...... 'surprisingly little modern research has been done on the Northwest Territory turbidite-hosted gold deposits'.

C. Methodology

Surface and underground mapping of the Bullmoose Lake auriferous veins was carried out in the summer of 1985. Detailed structural mapping and collection of over 500 rock samples from a 10 km² area of the property complimented more detailed work carried out in the immediate vicinity of the mine site.

Reflected-light and transmitted-light thin section investigations were carried out on the auriferous veins and wallrocks, and on selected rocks from locations away from the minesite. The mineralogy, texture, fabric and deformational characteristics of each were studied in detail.

Stable isotope studies on the sulphide minerals were performed in order to try and establish the temperature, or temperatures, of sulphide deposition. This information was integrated with a few D/H and O isotope analyses of vein quartz. Fluid inclusion investigations of the ore-bearing veins were performed for comparison with earlier studies of nearby deposits (Ramsay, 1973a; English, 1981), and to augment the isotope study.

Minor sulphide phases were qualitatively investigated using the scanning electron microscope (S.E.M) and N.I.S.O.M.I.[1], in order to determine their composition with respect to other phases that were determined by normal optical methods.

During the summer of 1986 the property was revisited in order to follow up some of the initial findings. More samples were taken and the remainder of the summer was spent studying similar showings in the Burwash Formation of the Yellowknife Supergroup. Rocks were taken from the Dome Lake property (53 km north-east of Yellowknife), which contains a similar deposit to Bullmoose Lake, but in this case hosted by rocks metamorphosed in the greenschist facies, rather than amphibolite facies rocks. A detailed structural investigation was carried out on the basis of the strong similarity to the Bullmoose Lake property and because of good exposure. Stable isotope analyses were performed on the sulphide minerals to compare them with the Bullmoose Lake isotope results. The purpose of this phase of the study was the investigation of the effect of metamorphism upon the fractionation of the isotopes and also the documentation of the isotopic signature of equilibrium pairs from a set of veins with a slightly different mineralogy.

D. History of the Bullmoose Lake Operation

The original TA claims were staked by C.S. McDonald and U.J. Arsenault in 1939. Between 1940 and 1941 Cominco Ltd., trenched the #3 and #4 veins and sunk a small shaft on the #4 vein. Some ore from the #1 vein was also hand-sorted and assayed 600 g/tonne gold. Seventeen diamond drill holes were drilled during this period, but the results were obviously disappointing, for between 1942 and 1968 no further appreciable amount of work was done on the property. In 1968 a floating open-market system for the selling of gold was introduced which resulted in a rise in gold prices and renewed interest in these high-grade gold properties. Between 1968 and 1976 Duke Mining Ltd., carried out extensive drilling on the #1, #2, #3, #4 and #7 veins. In 1976 Terra Mines Ltd., took 50% title of the property and began a program of underground drilling and extension of underground workings on the #1,

[1]Nottingham Interactive System for Opaque Mineral Identification - method of analysing the spectral reflectance of minerals

#2 and #4 veins. In 1981 Terra Mines Ltd., obtained the remaining 50% ownership by a takeover of Duke Mining Ltd. Between 1981 and 1986 the decline into the main mine workings (the core vein area) was extended to a vertical depth of 230m.

E. Mining methods and reserve estimates

The majority of the ore in the Bullmoose Lake mine is hosted by many narrow (often less than 1m) quartz veins which dip 70° eastwards and are arranged en échelon at about 5-10m intervals. The gold ores are mined by shrinkage stoping, but high-grade ore shoots which pitch steeply within the plane of the vein are exploited by raise-mining.

Ore reserve estimates and systematic, long-term mine planning are hampered by highly erratic grades along the strike and within the plane of the vein. Total proven and probable reserves, as of September 1986, were estimated at 42,526 tonnes with a grade of 12.7 g/tonne (Sanche, 1986) and total possible reserves stand at 183,863 tonnes with a grade of 10.3 g/tonne gold.

Gold and minor silver are the only commodities recovered from the doré metal.

A portable mill (maximum capacity approximately 66 tonnes a day) was brought on to the site in 1986 and in the first six months of operation 26,927 tonnes of ore were processed and 203.3 kg of gold recovered (millhead grade of 7.5 g/tonne (Cloutier, 1986)).

II. Regional Geology

A. Tectonics, stratigraphy and implications for the evolution of the Slave Structural Province

The Slave Structural Province, is a domain of essentially metasedimentary and metavolcanic rocks that spans a distance of 710 km between the Coronation Gulf to the north and Great Slave Lake in the south. The Province covers an area of some 180,000 km² and the rocks are for the most part Archean in age. The most noticeable features of the province are large granitic masses separated by sinuous, keel-like synforms of variably metamorphosed metasediments and metavolcanic rocks (Drury, 1977). To the northwest, southeast and northeast, the Archean rocks are conformably overlain by Aphebian metasediments.

Sedimentary and volcanic rocks (or their metamorphic equivalents) cover an area of less than 30% of the total Slave Province. The remainder of the Province is composed of extensive granitic batholiths (McGlynn and Henderson, 1970). Gravity measurements carried out near Yellowknife indicate that the supracrustal rocks represent but a very thin veneer above a granitoid basement and according to a model by Gibb and Thomas (1980) both the metavolcanics and the metasediments have a present vertical thickness (not a stratigraphic measurement) of generally no more than 1-3 km, with a maximum of 7 km of metavolcanics at the head of Yellowknife Bay (Fyson, 1981). One feature that distinguishes the Slave Province from other Archean provinces is the preponderance of metasedimentary units within the stratified sequence. The 5:1 ratio of metasedimentary to metavolcanic rock is in contrast to other provinces such as the Superior Province, where metavolcanic rocks dominate by the same amount.

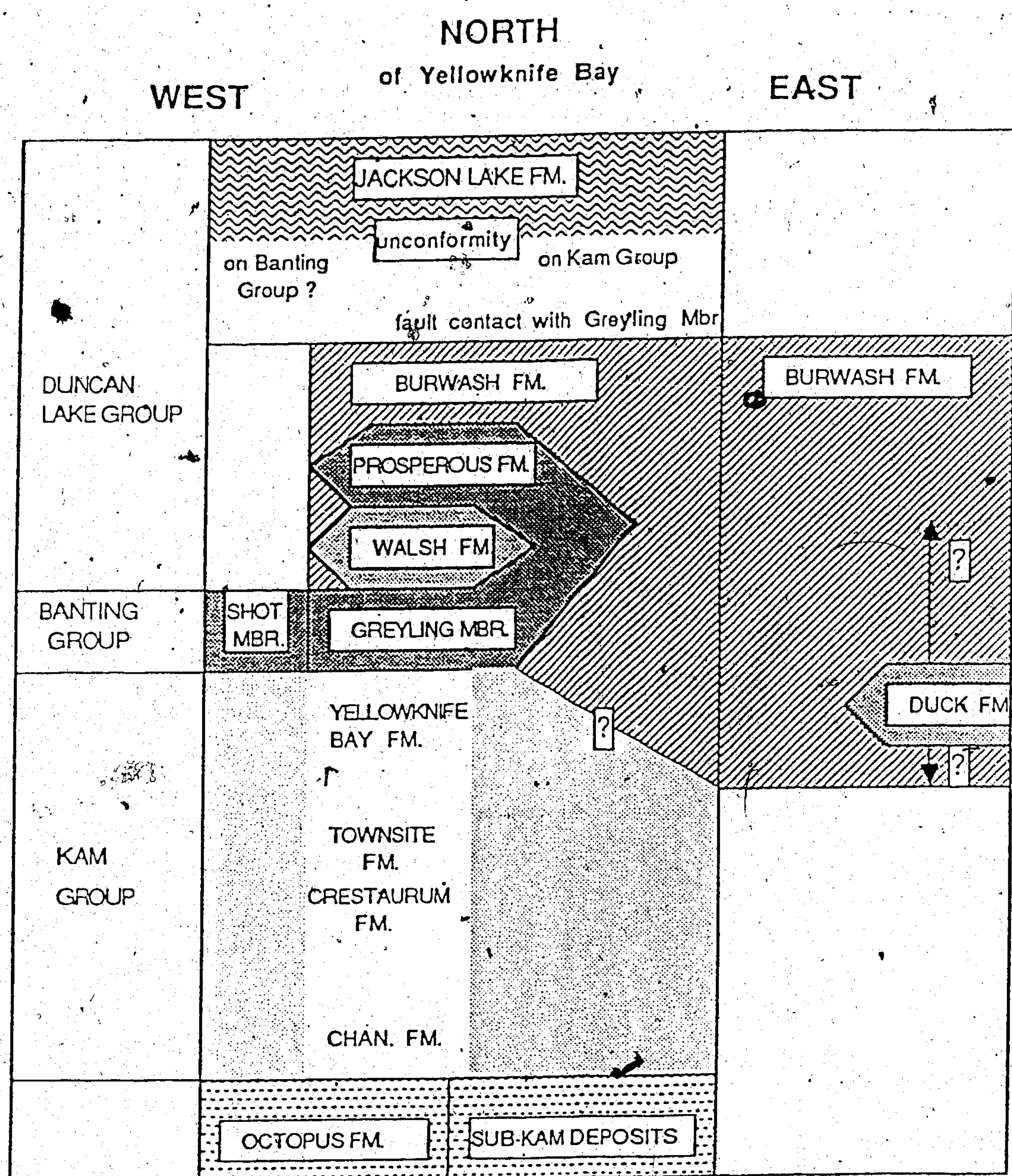
All the supracrustal rocks of Archean age in the Slave Province are part of the Yellowknife Supergroup (Henderson, 1970). The stratigraphic column presented by Henderson (see Fig. 3, Henderson, 1970) is a reinterpretation and update of the work by Jolliffe (1942, 1946), Boyle (1961) and Henderson and Brown (1966). The current ideas of some workers concerned with the stratigraphy are summarised in a paper by Helmstaedt and Padgham (1986). In this contribution they essentially modify the lithostratigraphic units established by

Henderson (1970) by adding a new unit, the Octopus Formation, and elevating the stati of the Kam and Banting Formations to Groups (table 1). In general, the supracrustal successions represent thick sequences of early metavolcanics and later immature metasediments. The transition between the two rock types is conformable, the former consisting of thick sequences of massive and pillowed subaqueous flows, of predominantly basaltic to andesitic composition (McGlynn and Henderson, 1970) and the latter of interbedded greywackes and mudstones that show many of the features characteristic of turbidites (Henderson, 1972).

It was quite widely accepted by several authors (McGlynn and Henderson, 1972; Fyson, 1975; Drury, 1977; Henderson, 1985; Padgham, 1985; Helmstaedt and Padgham, 1986) that the Yellowknife Supergroup accumulated within rifted basins developed on a basement of granitoid composition older than 3,000 Ma. The mafic metavolcanics were probably extruded along linear fractures between the uplifted and depressed areas (McGlynn and Henderson, 1970). The metasediments were derived both from the developing basic metavolcanic pile and from basement granitoids.

The tectonic scenario responsible for the emplacement of the mafic metavolcanics is still under debate (for example see Cunningham, 1984; Goodwin 1977, 1981; Helmstaedt and Padgham, 1986; Henderson 1981, 1985; Lambert, 1976; Park, 1981; Windley, 1977). Work based upon field observations (especially Henderson, 1981, and Helmstaedt and Padgham, 1986) has lead to interpretations suggesting the possibility of an analogy with proto-oceanic basins, similar in size to the present day Red Sea. This conclusion was drawn mainly from the occurrence of linear tongues of basic metavolcanics sited along extensive block faults. Helmstaedt and Padgham (1986), in a different setting, also note some similarities between the Yellowknife Basin rocks and the late Mesozoic Rocas Verdes, of Chile which represents a back-arc basinal type of environment. They envisage the possibility of the Banting calc-alkaline metavolcanics representing part of a series of rocks derived by oceanic plate subduction, and the Kam Group and Octopus Formations the proto-oceanic and basement-transition rocks respectively. This model is similar to an earlier concept proposed by Drury (1977), although his model also involved the partial melting of mantle material to

Table 1. Stratigraphic column of the Yellowknife Supergroup (after Helmstaedt and Padgham, 1986).



produce the Kam Group.

In contrast to these ideas, studies of a more geochemical nature (Lambert, 1976; Cunningham, 1984) have concluded that the.... 'Slave craton was rifted by a mantle hot spot resulting in extrusion of tholeiitic basalts and basaltic andesites, derived from partial melting of mantle material. Partial melting of pre-existing hydrous basaltic crust material produced intermediate to felsic metavolcanics of calc-alkaline affinity, with some mafic volcanism. Partial melting of pre-existing sialic crustal material resulted in extrusion of calc-alkaline felsic metavolcanic rocks'. This hypothesis is similar to the example put forward by Easton (1985), where he cited the Basin and Range Province of the U.S.A as a close analogy to the S[illegible]e Province, based upon Henderson's 1981 model of graben and half graben development [illegible]tended sialic crust.

As a final statement to this section it is of importance to point out that before a region such as the Slave Province is studied in terms of its basinal characterisics, the fundamental criteria used to define a basin must be recognized. Although this may seem an obvious point to make, it appears as if some of the structural conclusions and ambiguous sedimentological interpretations have had more of an influence in defining separate basins and provinces than more rigorous sedimentological data (see Walker, 1978 for discussion).

B. Metavolcanic rocks

Metavolcanic rocks constitute 20% by volume of the Yellowknife Supergroup by volume and consist of a range from mafic to felsic composition (Helmstaedt and Padgham, 1986). The metavolcanic belts generally trend north-south and are typically in the order of 100 km length by 20 km width. A characteristic feature of the metavolcanics in the Slave province is the dominance of mafic rocks in the west and felsic rocks in the east (Helmstaedt and Padgham, 1986, Henderson, 1970). In the 18 to 19 volcanic belts that exist, metabasalt and metaandesite (3:1 ratio) predominate, but the distribution of felsic metavolcanics, although recessive, is neither restricted to the base nor the top of the units (Padgham, 1985b).

The metavolcanic sequence consists of both contemporaneous extrusive flows and of intrusive dykes and sills of similar composition, with relatively minor amounts of metavolcaniclastic material throughout the sequence (Henderson, 1985).

Metamorphic grades within the metavolcanics vary according to the proximity to the granite/granodiorite intrusives, and in general amphibolite and greenschist grade rocks are the most common. It is noticeable that at all metamorphic grades, primary structures such as pillows, flows and flow breccias are commonly preserved.

C. Yellowknife metasedimentary rocks

The metasedimentary units are generally conformable with the mafic metavolcanic sequences and in some cases are interlayered (Henderson, 1981).

Metagreywacke and metapelites/metasemipelites account for the majority of the rocks in the metasedimentary terrane. Individual units vary in thickness from several tens of metres to less than a centimetre. Very commonly the lower grade metasedimentary rocks display an array of palimpsest structures such as graded bedding (in the form of partial Bouma sequences), flame structures, cross-bedding, mud-cracks, load structures, convolute bedding and ripple marks. In the higher metamorphic grade rocks, particularly those of amphibolite grade, primary structures are not as common, although partial Bouma sequences can often be recognised by the superimposed metamorphic mineral assemblage. Reconstruction of paleocurrent data suggests that the metasediments were derived from the area now occupied by the Yellowknife townsite and Yellowknife Bay (Henderson 1972, 1975). Petrographic data (Henderson, 1981) show the precursor sediments to have been derived from both a granitic source (sialic basement and felsic Banting Group) and from a volcanic source (Kam Group and Octopus Formation).

The Burwash Formation

The Burwash Formation is host to the Bullmoose Lake gold deposit and is by far the most dominant lithologic unit east of Yellowknife Bay in the Slave province. The metamorphic grade of this unit varies from lower greenschist to upper amphibolite (Thompson, 1978). Much of the early work (Henderson, 1970) was concentrated along the shore of Yellowknife Bay, where sub biotite grade metamorphism has preserved almost all of the primary metasedimentary structures.

The Formation is essentially a metasedimentary unit with minor tuffaceous horizons (mainly in the Duck Lake area). From field and petrographic evidence and chemical data (Ramsay and Kamineni, 1977) 4 types of metasediment have been recognized, ranging from matrix-free metaarkoses, through the predominant metagreywackes with abundant matrix, to sand-free pelites. The most common palimpsest structure is graded bedding, which is often the only feature preserved at the higher metamorphic grades. The interbedded metagreywackes and slates, which constitute over 90% of the metasedimentary material, exhibit all the features of turbidites. The individual metagreywacke beds are laterally continuous and often display some of the characteristics of a Bouma cycle (Bouma, 1962). The proportion of metaarenite to metapelite in each graded unit is variable, but generally the metaarenite greatly exceeds the pelite by a factor of 10:1.

A comprehensive description of all of the palimpsest metasedimentary features seen in this Formation was given by Henderson (1972, 1975). In chapter VIII the importance of lithological variation with respect to the location of quartz veins is discussed, but it is not the intent of this thesis to describe all of the many primary features seen in the Burwash Formation.

The Walsh Formation

The Walsh Formation has many of the characteristics of the typical Burwash metaturbidites, but differs in that it contains more argillite (Henderson, 1975). The metagreywacke and argillite portions of the beds are generally much thinner and finer-grained.

The Jackson Lake Formation

By reference to the stratigraphic column (Helmstaedt and Padgham, 1986) the Jackson Lake Formation is the youngest formation of the Yellowknife Supergroup and consists of a locally distributed basal conglomerate, overlain by cross-bedded sandstone and thin conglomerate layers. The basal conglomeratic unit lies unconformably on the Kam metavolcanic rocks, but its relationship to the Banting and Burwash Formations is not as clear (Henderson 1981, 1985; Helmstaedt and Padgham, 1986). The latest published information suggests that the Jackson Lake Formation is not a lateral equivalent of the Burwash Formation (for example see Henderson, 1981) and therefore it may be necessary to exclude the Jackson Lake Formation from the Duncan Lake Group.

D. Intrusives

The supracrustal succession has been affected by 3 large intrusive bodies (Fig. 1), ely,:

1. The Western Granodiorite (2555 Ma) - A large granitic batholith of dioritic to syenitic composition (Green and Baadsgaard, 1971).
2. The Southeastern Granodiorite (2520 Ma) - Comprising a dioritic and a granodioritic phase (Jolliffe, 1942; Easton, 1985).
3. The Prosperous Lake Granite (2520 Ma) - A post-orogenic 2 mica pegmatite (Henderson, 1976).

E. Metamorphism

Early work (Denton, 1940; Folinsbee, 1942; Jolliffe, 1942, 1946; Henderson, 1943) recognized the fundamentals of the metamorphic progression of the Slave craton and concluded that 3 phases of metamorphism had taken place, namely:

1. Regional metamorphism under confining pressure.
2. Superimposed aureoles of a more thermal nature.
3. Late phase of localized hydrothermal retrogression.

This general model has been substantiated by more recent work. (Boyle, 1961; Heywood and Davidson, 1969; Kretz, 1968, 1973; Ramsay and Kamineni, 1977) but the opinion of these later authors was that the 3 'phases' were actually part of a single metamorphic epoch rather than 3 distinct, temporal episodes.

Geochronologic studies in the Yellowknife area by Green and Baadsgaard (1971) concluded that the Slave tectonic event began with volcanism at 2700-2600 Ma ago and ended with the intrusion of the Prosperous Lake granitiod at about 2520 Ma ago (recalculated by Cunningham, 1984). The metamorphism is believed to have reached its peak at about 2600 Ma ago, corresponding to the Kenoran orogeny. Thompson (1978) classifies the metamorphism as low (greenschist), medium (amphibolite), and high grade (upper amphibolite). The first appearance of cordierite (knotted schist) marks the transition between low and medium-grade and the transition from a cordierite schist to a gneiss or migmatite marks the transition from medium-to high-grade metamorphism.

Independent detailed studies by Ramsay (1973) and Kamineni (1973) in the Prosperous Lake area (fig. 1) and the Sparrow Lake area respectively support this type of zonation and conclude that the metamorphic characteristics vary according to a fluctuating heat source (granitoid bodies) and structural regime (Ramsay and Kamineni, 1977). Early (M2) pressures and temperatures were estimated at 3 kb - 4.5 kb and 500°C and peak metamorphism (M3) at about 2.5 - 3.5 kb and a wide range of temperatures from 300-700°C, according to the distance from the pluton. Figure 2 represents a schematic diagram showing the metamorphic mineralogy and the zones that have been recognized on the basis of mineralogy.

Thompson (1978) plotted the compositions of the metamorphic assemblages characteristic of the Yellowknife Supergroup on a series of AFM diagrams. He came to the same conclusion as Henderson (1975), namely, that the metametasediments are somewhat iron-rich and more aluminous than Pettijohn's (1957) average Archean greywacke. In general the Fe content was not high enough to form garnet and staurolite, although evidence for abundant Al is shown, (where metamorphic conditions permit), by the extensive growth of

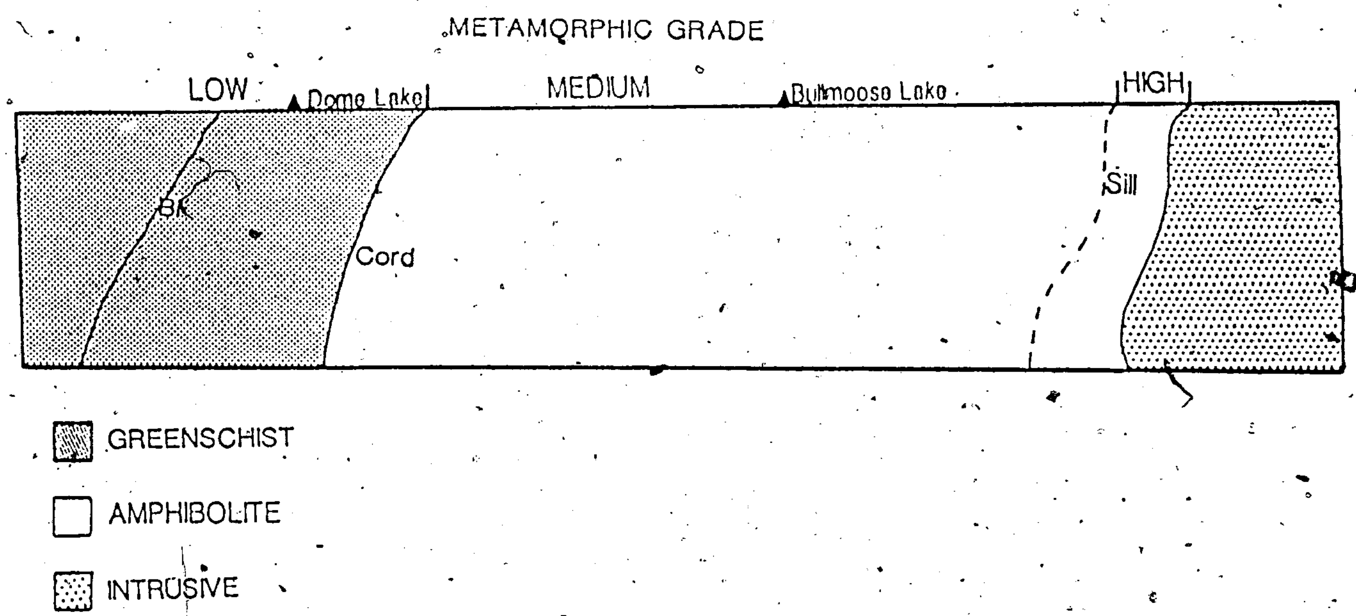


Figure 2. Schematic metamorphic zoning of rocks in the Southern Slave Structural Province (modified after Ramsay and Kamineni, 1977 and Thompson, 1978)

cordierite, Al-rich phyllosilicates, gedrite, sillimanite and andalusite.

E. Regional structure of the Slave Province

Attempts have been made to relate the metamorphism to tectonic episodes in the Slave Province (Drury, 1977; Fyson, 1975, 1978, 1982; Kamineni *et al.* 1979; Ramsay and Kamineni 1977). These authors concluded that, although the deformation was short-lived (100-180 Ma, based on the data of Green and Baadsgaard, 1971), it was not a tectonically simple period. Three main phases of deformation have been recorded, D1, D2 and D3 (Fyson, 1975), but Fyson (1978) and Kamineni (1979) recognized a later phase D4. Figure 3 correlates the deformational episodes (D), folding (F), metamorphism (M), and schistosity (S), evident at Bullmoose Lake to the data presented by Fyson (1975, 1978, 1982, 1984), Drury (1977), Ramsay and Kamineni (1977), and Kamineni (1979). The data are somewhat difficult to compile, due to a lack of uniformity in correlating the various episodes from different areas and the recognition of events not documented in earlier reports.

The general scenario records several periods of cleavage development and metamorphism that, in part, reflect progressively changing regional tectonics and diapirism. The pattern of north-northwesterly striking ellipsoidal granitoid bodies, metavolcanic 'rafts' and pervasive cleavage has been produced by regional tectonics (σ_1 is east-west to northeast-southwest). Local diapiric intrusions have caused deflections of earier fabrics and the resultant outcrop patterns (Fig. 1) reflect an interplay between the uprise of granitic bodies and sub-horizontal forces (Fyson, 1982).

[illegible]nt workers, concerned with reconstructing the Precambrian tectonic history of the Slave Province (e.g. Ramsay and Kamineni, 1977; Drury, 1977; Fyson, 1975, 1984) suggest that [illegible] the siting of plutons, and the horizontal compression, were controlled by movements along a system of deep-seated (pre-Kenoran) fractures. Evidence for this is possibly the linear arrangement of narrow metavolcanic belts that discontinuously follow the angular outlines of granitoid bodies, including basement rocks. Trend lines of F1 folds also tend to be very regularly aligned in a northwest-southeast or a northeast-southwest direction, some trend

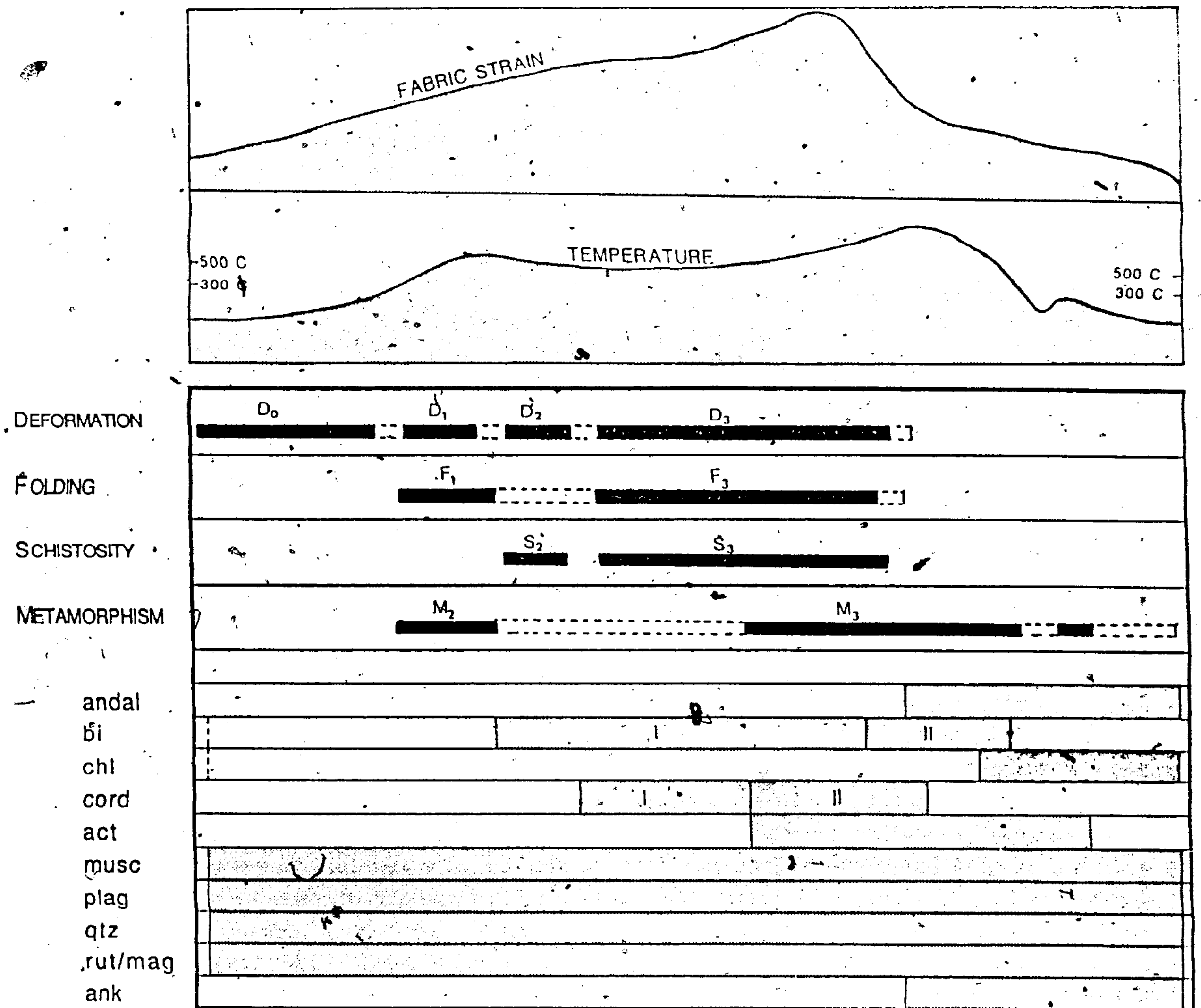


Figure 3. Mineralogy, predicted relative strain, and metamorphism of the Bullmoose Lake rocks (some data modified after Fyson, 1978 and King, 1981)

parallel to F0 homoclines and to elongate granitic plutons (Fyson, 1984). The adjacent sets of F1 folds (northwest-southeast and northeast-southwest) are well displayed at Gordon Lake. They show no evidence of rotation and it is possible that where the two fold directions intercept marks the site of a structural front (Fyson, 1984). A late S3 cleavage also undergoes a marked transformation at the proposed structural front. Two S3 cleavages merge at almost the same location as the hinge trace defined by the mergence of F1 folds (Fyson, 1984). The interpretation of such features has been either that:

1. the basement fractures acted as stress-modifiers during regional deformation. The supracrustal rocks above were subject to different orientations (and probably amounts) of stress either side of the fracture whilst compression continued.
2. the generation of shear folds in the supracrustal rocks was a result of strike-slip movement by basement blocks. The folds form en échelon along the shear zones and continued propogation may infact have produced late cleavage sets (i.e S3A and S3B).
3. the formation of an open, upright, north-south trending regional refold that deforms the isoclines and regional NW cleavage, resulting in a NE-trending crenulation cleavage (Stokes *et al.* 1987).

For further discussion concerning these models see Fyson (1984) and Stokes *et al.* (1987).

III. Gold Mineralization in the Metaturbidite Sequence of the Burwash Formation and Comparisons With Other Similar Deposits Worldwide

Padgham (1985a) classified the gold deposits of the Northwest Territories into several categories (see table 1, Padgham, 1985a). The metaturbidite-hosted deposits of the Burwash Formation (and equivalent) were classed in the second category (type 2 deposits) under the general heading 'Quartz veins in shear zones and fractures, insignificant wall-rock alteration'. The type 2 rocks were further subdivided into 5 classes, based upon host-rock lithology and proximity to lithological boundaries :

- 2a - deposits 'at or near (the) volcanic-sediment contact'.
- 2b - 'narrow veins in turbidites far from volcanic rocks'.
- 2c - 'quartz stockworks in turbidite'.
- 2d - deposits hosted by granitoids
- 2e - deposits hosted by dykes.

The Bullmoose Lake veins are therefore a type 2b deposit in Padgham's classification, and about 170 other showings in the Northwest Territories are listed in this class (Padgham, 1985a).

Since the discovery of gold in the Yellowknife district during the mid 1930's, approximately 300,000 kg of gold have been gained from shear-hosted deposits (e.g. Con and Giant), 37,000 kg of gold from metavolcanic-hosted deposits (e.g. Discovery and Salmita), 13,000 kg from metamorphosed Banded Iron Formations (e.g. Lupin and Cullaton Lake), and 4,000 kg from metaturbidite-hosted quartz veins (see Padgham, 1985a table 2 and list below). When productions from all types of deposit in the Slave Province are included in the total production of gold, turbidite-hosted quartz veins only account for 1.1% of the total production of the Northwest Territories, modified from the kg totals of Padgham (1985).

The turbidite-hosted deposits are traditionally divided into 4 types based on the work of Henderson and Jolliffe (1939), Lord (1951), Boyle (1961,1979):-

1. Quartz veins in contorted schist zones and faults that transect the metasedimentary stratification (Fig. 4, (e.g. Ptarmigan mine, Tom claims, Burwash mine, Rich group)).

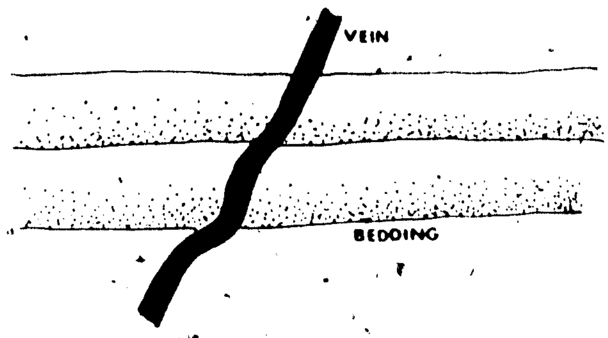


Figure 4. Quartz veins cross-cutting bedding, Southern Slave Structural Province

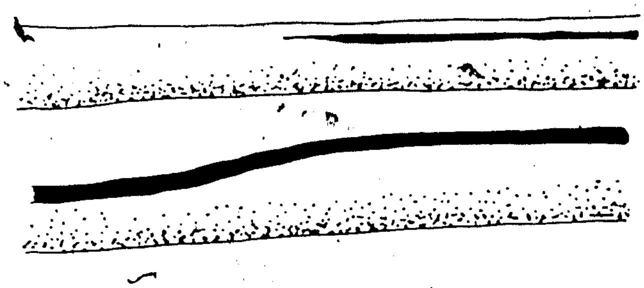


Figure 5. Bedding-parallel quartz veins, Southern Slave Structural Province

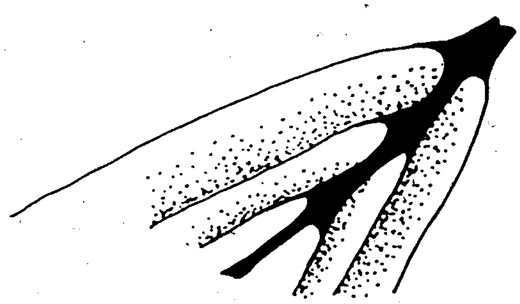


Figure 6. Quartz veins located at the axes of folds, Southern Slave Structural Province

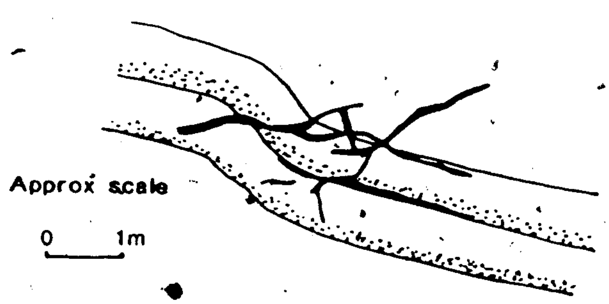


Figure 7. Irregular quartz veins, Southern Slave Structural Province

2. Quartz veins in schist zones and fractures which parallel the metasedimentary strata (Fig. 5, (e.g. Tin claims, Thompson-Lundmark mine, Camlaren mine, Bullmoose Lake Core-zone)).
3. Ruptured and sheared axes of isoclinal folds (Fig. 6 (e.g. 11 zone of the Bullmoose Lake mine)).
4. Quartz veins and stringer zones in irregular fractures (Fig. 7, (e.g. Knight claims, Gordon Lake?)).

Most of the deposits in the Slave Province are of the second type listed above, but from the author's experience and the descriptions of other metaturbidite-hosted vein deposits in the literature, (for example the Reefton gold deposits, New Zealand, Williams, 1965; the Otago schist deposits, New Zealand, Henley *et al.* 1976; the Bendigo deposits, Victoria, Australia, McAndrew, 1965; Beaconsfield, Tasmania, Noldart and Thatcher 1965; Cochrane Hill deposit, Nova Scotia, Canada, Smith, 1983, 1984; Connemara schists, Ireland, Yardley, 1983, 1986) the divisions of the 4 classifications are not as rigid. Although an individual vein may be found preferentially located in one of the situations described, many subsidary veins in the local area of the major vein or veins may be found in a combination of the situations listed.

The mineralogy of the veins is likewise varied. The principle component, quartz, often comprises 95-97% of the vein, but the remaining 3-5% is made up principally of sulphides in varying abundances, most commonly Fe, Cu and As sulphides. Feldspar, typically oligoclase and albite, and other minerals, such as tourmaline, muscovite, biotite, actinolite, sericite, chlorite and scheelite are also often present. The blue-grey colour of many auriferous veins has been attributed to the presence of graphite. Wall-rock fragments are abundant in some veins, for example the 7 vein at Bullmoose Lake (Swatton, 1985), AM veins at Gordon Lake (English, 1981), and the Treasure vein at the Thompson-Lundmark property (Lord, 1951). The occurrence of gold in the veins is erratic but is commonly associated with sulphide-rich pockets. Table 2 lists some of the auriferous vein deposits in the Slave metasedimentary rocks and their structural and mineralogical characterisics. The wallrock mineralogy is, of course,

Table 2. Structural and mineralogical characteristics of some auriferous vein deposits in the Slave metasedimentary rocks

LOCATION	WALLROCK HOST	STRUCTURAL CHARACTERISTICS FOR VEIN	OTHER
BULLMOOSE English, 1981; Swallon, 1985	BIOTITE SCHIST/ KNOTTED SCHIST	BEDDING PARALLEL PARALLEL TO S3 IN SHEAR	SHEARING ALONG VEIN MARGIN qtz, sph, cpy, gn, Bi Te, py, po, asp, ank, sch, act, bi, musc, lm VEIN STRIKE 347 - 354°
DOME Faulkner, Swallon, 1986	BIOTITE CHLORITE PELITE BET ARENITE + AT PELITE/ARENITE CONTACT	HINGE LIMB OF F1 FOLD PARALLEL TO S3	qtz, sph, cpy, gn, asp, native cu (po,py) MINOR SHEARING (18 Vein) VEIN STRIKE 340-350°
PTARMIGAN (& TOM) Boyle 1961,1979; English 1981	KNOTTED SCHIST	MAIN VEIN CUTS ACROSS BEDDING AT 115°	BEDDING 170°/E OVERTURNED EN ECHELON VEINS qtz, Au, tour, py, sph, gn WALLROCK ALTERATION bi, py, po
THOMPSON - LUNDMARK Lord 1951; Boyle 1979	NODULAR BIOTITE SCHIST	PARALLEL TO BEDDING ROCK FRACTURED AT CONTACT ONE VEIN CUTS BEDDING AND THEN PARALLELS IT - LORD, 1951	qtz, Au, tour, Fspar, py, asp, po, cpy, gn, sph ORE PITCH IN VEIN 65°N (KIM VEIN ZONE) Cvge NW/GRANITE BODIES IN AREA. S3 CLEAVAGE - NW GRANITE BODIES IN AREA
CAMLAREN Lord 1951; Boyle 1979	SLATY BEDS BETWEEN MORE MASSIVE GW	SADDLE REEFS AND LEGS ON THE NOSE OF A PITCHING ANTICLINE (HUMP VEIN) PARALLEL TO BEDDING	qtz, ank, native au (py, cpy, gn, sph)) 020 - 045° - FOLD AXIS STRIKE - 020 - 045°
GIAQUE LAKE (DISCOVERY MINE) TYPE 2a Wiwchar 1957, Boyle 1979	THIN BEDDED GW BETWEEN NODULAR SCHIST HORIZONS	NOSE OF FOLD	qtz, olig, po, py, musc, ser, act, chl, sch, sphl, gn, cpy, andal
RUTH English, 1981	SLATE HORIZON	SUBPARALLEL TO BEDDING	VEINS 000 - 020° FINE GRAINED qtz, biotite inclusions Scheelite
KNIGHT BAY Caelles J.C. 1985 Mahe, Ad, Pol, Bear, Lynk Claims	BLACK CARBONACEOUS SILTSTONES	SUBPARALLEL TO BEDDING	EVIDENCE OF DRAG FOLDING
AM (KNIGHT BAY) English, 1981	SLATES, GW + GRAPHITIC HORIZONS	SUBPARALLEL TO BEDDING NR. NOSE OF PLUNGING FOLD SOME SHEARING IN GRAPHITIC HORIZONS	BEDDING STRIKE 110 - 130° Minor py, gn and visible Au
JOON English, 1981	NARROW GRAPHITIC/SLATE HORIZON	SUBPARALLEL TO BEDDING MINOR SHEARING IN GRAPHITIC HORIZON	VEINS 140 - 150°/E STRIKE b/g qtz + py

varied to an extent due to local sedimentary differences, but in the Northwest Territories' Camlaren, Bullmoose Lake, Dome Lake, Discovery, Ruth, AR and AM at Knight Bay, Beaulieu, and possibly the Thompson-Lundmark, Ptarmigan, Tom and Burwash deposits, there is a strong correlation between the general composition of the wallrock and the location of the auriferous quartz veins.

In all of these examples the vein is located within a fine-grained, metapelite or meta-semipelite, which is often adjacent to coarser-grained greywackes. Padgham (1985) indicated the possibility of some lithological control on the siting of quartz veins, but concluded that insufficient data were available to make a firm decision on this issue. One conclusion of this study is that there *is* clearly sufficient evidence from published and open-file geological reports on the Slave Province metaturbidite-hosted gold deposits (Lord, 1951; Boyle, 1961, 1979) and from studies by the author on the Bullmoose Lake, Dome Lake and Pensive Lake trenches (on the TT claims) to indicate that host-rock composition does indeed excert a strong lithological control on the location of quartz veins in metaturbidite-hosted lode gold deposits (see appendix for Dome and Pensive Lake properties).

In support of this hypothesis, reports on other metaturbidite-hosted deposits worldwide also provide compelling evidence for the common occurrence of auriferous (and barren) quartz veins in the metapelitic components of metasedimentary sequences. In the Meguma sequence rocks, of Nova Scotia, Smith (1984) documented quartz veins within specific metapelitic horizons which had a unique lithogeochemical signature and carried enhanced gold values. In the Golden Blocks goldfield, South Island, New Zealand (Williams, 1965) ore is located within carbonaceous argillite, between quartzite and argillite units. A similar situation has been documented from the Ballarat West goldfield, Victoria, Australia (Baragwanath, 1953) in which lodes are confined to 20-35m thick, carbonaceous, black slate horizons.

It is apparent that almost all metaturbidite hosted lode-gold deposits have a lithological or a structural control, but more commonly, high-grade gold deposits are found where a combination of the two controls exists, or a strong structural controls exist (e.g.

Bendigo, Australia, McAndrews, 1965).

The minimal wallrock alteration, or the lack thereof, is also one of the fundamental characteristics of these deposits. If alteration is present at all, the halo is often only in the order of a few cm to a metre wide. Boyle (1961) documents some variation in alteration style between low- and medium-grade rocks as follows:

1. Low grade - A thin, bleached zone containing quartz, albite, chlorite, sericite, pyrite, arsenopyrite, occasional pyrrhotite and biotite.
2. Medium grade - Quartz, albite, oligoclase, biotite, muscovite, chlorite and some pyrrhotite and arsenopyrite.

Boyle (1979) analysed the low-grade rocks around the Ptarmigan deposit and concluded that some alteration had occurred, but that it was very localized. In summary the net changes *towards* the vein were as follows:

- Increase - Al_2O_3, total Fe, CaO, MgO, K_2O, H_2O, TiO_2, P_2O_5, CO_2 and S.
- Decrease - SiO_2 and Na_2O

Almost all the elements analysed (Boyle, 1979) showed an increase towards the veins. Marked increases were noted for Cs, Cu, Ag, B, Ga, Sc, As, V, Te, Co, Ni, Zn, Cd, Sn, Pb, W and F.

It is apparent that relatively few world-wide occurrences of metaturbidite-hosted lode-gold deposits have been carefully studied in terms of their alteration. Of those for which data exist (e.g. Caribou, Nova Sotia, Bell, 1948 *in* Boyle, 1979; Reefton, New Zealand, Gage, 1948 *in* Boyle, 1979) the results are similar to the Ptarmigan deposit. One interesting example is the Muruntau deposit, Uzbek, S.S.R (Baimukhamedov, 1975) in which skarn-type mineralization has occurred in calcareous siltstones. The metasiltstones are said to be banded, due to 'metamorphic segregation' of brown, biotite-rich, green actinolite-rich and grey quartz-rich layers. The cause of the skarn-type alteration is interpreted as being related to an assumed granitoid intrusive body concealed at some depth.

The data presented by Boyle (1979) for a number of shear-zone deposits worldwide are consistent with a general depletion in quartz and increased K_2O/Na_2O and Au/Ag ratios, and also with noticeable increases in K, As, S, Al, Fe, and Mg in the wall-rock mineralogy towards the vein. The CO_2 content fluctuates widely within the alteration zone, causing erratic SiO_2/CO_2 ratios, but in general the level of CO_2 increases towards the veins. Boyle (1961) argued that the depletion of silica towards the veins in the Yellowknife shear-zone belt (type 1a and 1b classification, Padgham, 1985) indicated migration of silica from the altered walls, towards the centre lines of the shears. Boyle (1979) in an extensive review of the literature, concludes that there is not enough information on the transport of gold to present a convincing hypothesis concerning the origin of this metal in shear zone and metaturbidite hosted gold deposits. However, he does infer that lateral secretion is the most likely process, as that is how some of the quartz was derived and gold is very commonly seen associated with quartz.

In summary the bulk element changes in the alteration zone noted by Boyle (1979) for the shear-zone type deposits are also applicable, albeit to a lesser extent, for the metasediment-hosted deposits. As a generalisation those changes which occur towards the mineralized veins are represented by:

1. an increase in K_2O/Na_2O, Au/Ag
2. a decrease in SiO_2/CO_2, SiO_2/volatiles

Boyle (1979) states that these features may be useful guides in the prediction of a local auriferous ore body.

IV. Geology of the Bullmoose Lake Gold Deposit

A. Introduction

The mineralization at the Bullmoose Lake gold deposit occurs within narrow, en échelon veins that are hosted by the Burwash metasediments of the Yellowknife Supergroup. Cordierite and biotite are the most extensively developed prograde metamorphic minerals, the former mineral being indicative of amphibolite grade metamorphism. A noticeable variation in the lithology of the metasedimentary rocks occurs throughout the property ranging from metaquartzwacke to metapelite (Fig. 8). The ore-bearing quartz veins are hosted by metagreywacke units, which are stratigraphically bound by older metaquartzwackes, and by younger metapelites and metasemipelites. Palimpsest megascopic textures are locally preserved in the metagreywackes and metapelites/metasemipelites (e.g graded-bedding, flame-structures and cross-bedding) but in general, metamorphic overgrowths and structural anisotropies have obliterated the primary fabrics. Regional mapping of bedding contacts has shown that the mineralized veins are hosted by metaBouma (graded unit) sequences of fairly constant width (1-2 metres). These veins are not strictly stratiform, as they tend to anastomose throughout the graded units; but, in general, they are preferentially located within the finer-grained, upper portions of each metaBouma sequence (the 'interturbidite' layer, Bouma, 1962).

Bouma (1962) provides a complete documentation of the characteristics of 'Bouma sequences', and further sedimentological interpretations are summarized in Middleton and Hampton (1976) and Reading (1978). The terminology adopted herein is in keeping with that of Bouma (1962).

The only other rock types recorded from the area are mafic dykes. These rocks probably belong to the younger Proterozoic dyke suite which generally trends north-west (McGlynn and Henderson, 1970) and has been dated at about 2000-2100 Ma (Leech, 1966). The dykes are not related to the gold mineralization at Bullmoose Lake.

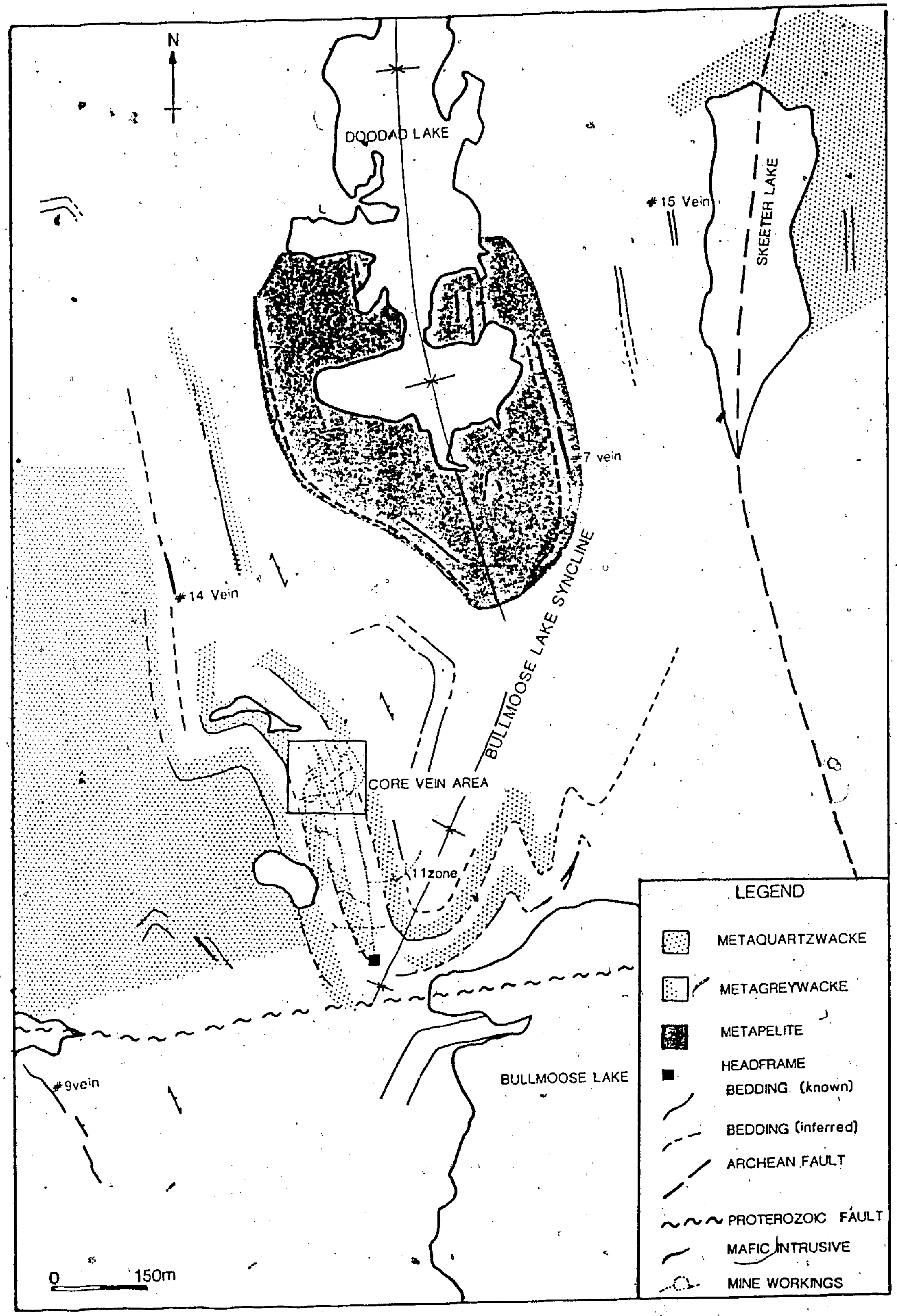


Figure 8. The geology of the Bullmoose Lake gold deposit

B. Petrology of the different rock units at Bullmoose Lake

Metaquartzwacke

- qtz, bi, chl, pl, py, ilmen, lithic frags, seric

This unit occupies approximately 70% of the rock-outcrop at the surface. The stratigraphic thickness of individual beds is unknown, due to the indistinctive boundaries between each bed. The buff-brown to grey metaquartzwackes are quite distinct in colour from the darker feldspathic metagreywackes, metapelites and metasemipelites. Sometimes, horizons of darker more pelitic material, occur within the otherwise uniform, undifferentiated metaquartzwacke and they are useful indicators of the strike of the bedding.

The rock has a heterogranular, granoblastic texture and is composed of 80-90% quartz, 10-15% biotite and the remainder is made up of minor chlorite, plagioclase, pyrite, lithic fragments, sericite and ilmenite. There is no matrix due to its recrystallization into biotite during metamorphism. The quartz grain-size is bimodal, 70% of the grains are small (<0.2mm) anhedral, rounded grains and these are intergrown with larger (>0.5mm) subrounded grains. Both grain populations display undulose extinction and some grains show pressure-solution shadows. The rock is cemented by secondary quartz, derived from the partial solution of the quartz-grains during regional deformation. Biotite and chlorite laths are randomly oriented, but it is apparent that the chlorite is more commonly associated with local biotite clusters and often cross-cuts and replaces the biotite. Anhedral plagioclase grains (An_{0-8}) are partially to almost totally recrystallized and often display albite twins. In some thin-sections plagioclase contributes up to 20% of the mode; it is therefore evident that a compositional range from metaquartzwacke to metaarkosicwacke (Dott, 1964, *in* Greensmith, 1978) is apparent in these rocks. Lithic fragments are rarely seen in this unit although occasionally, small clasts of other metasedimentary rock are seen quasi-parallel to bedding in outcrop.

Metagreywacke

- Base of beds: qtz, bi, chl, pl, py, asp, seric, musc, lithic frags, ilmen, graph
- Top of beds: qtz, bi, chl, cord, pl, ilmen, mt, seric, graph, ank, andal, py, po, asp, rut, lithic frags, (act, apat, epid)
- sulphide minerals and gold (mainly in the vein material)

The metagreywackes are not as uniform in composition as the metaquartzwackes. These units usually have a well defined base and top and on average the beds are 1-2 m wide, although the range of size is considerable. The most conspicuous feature of some of these beds is their palimpsest graded bedding (meta Bouma sequences, plate 1 and 2). The buff-coloured, quartz-rich base of each turbidite unit grades into finer-grained, darker metapelitic material at the top. Although graded units are easily recognized in good outcrop, they are not typical; more common is a unit of either metaquartzwacke with some interbedded metapelitic/metasemipelitic, material, or a metapelite/metasemipelite with minor horizons of metaquartzwacke. In these beds there is a distinct lack of palimpsest grading visible in outcrop, although in thin section a slight mineralogical gradation can be detected. In the zone defined by the 'metagreywackes', some 30% of the rocks are visibly graded whilst the remainder are relatively homogeneous, with a composition in the range of the two end members.

Massive graded units

The base of the graded beds ('the massive graded' units, Bouma, 1962) are typified by coarse-grained, recrystallized, sub-rounded quartz and feldspar, set in a matrix of quartz and biotite, with minor chlorite, muscovite and partially recrystallized feldspar. The rocks display a granoblastic, coarse-grained, heterogranular texture with grains varying in size from 0.05 mm - 1 cm. These rocks are mineralogically, chemically, and texturally immature, as shown by evidence of a primary matrix abundant in unstable rock fragments and feldspar. The high quartz content of the massive graded units (85-98%), is attributed to two factors:

1. the primary rock composition, and more significantly;
2. the recrystallization of the of the rock during metamorphism.

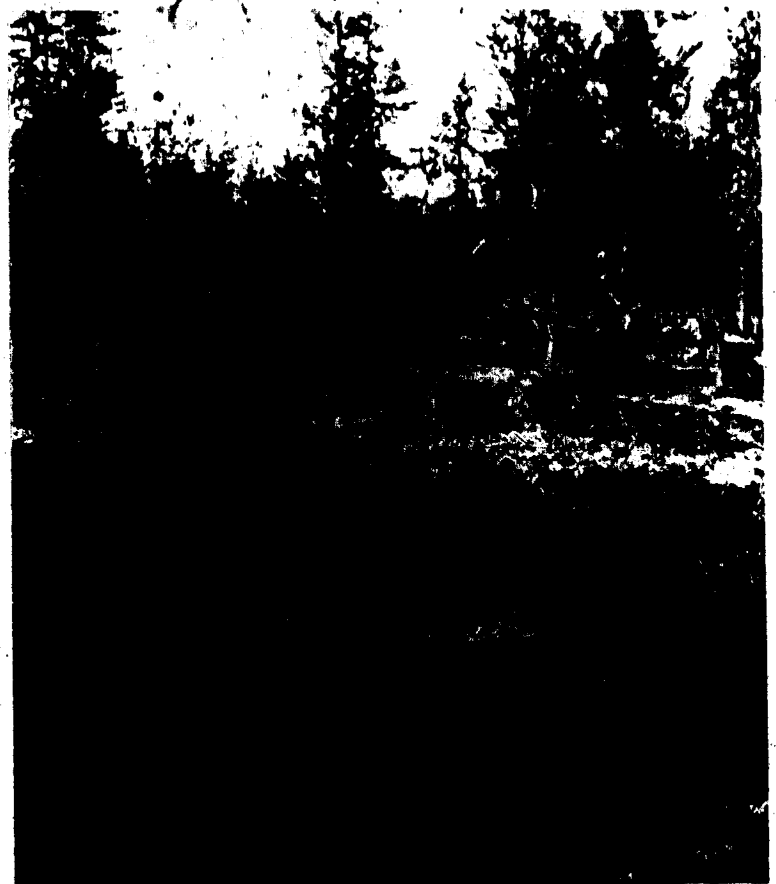


Plate 1. Regular bedding of metagreywackes, Core-vein area, Bullmoose Lake

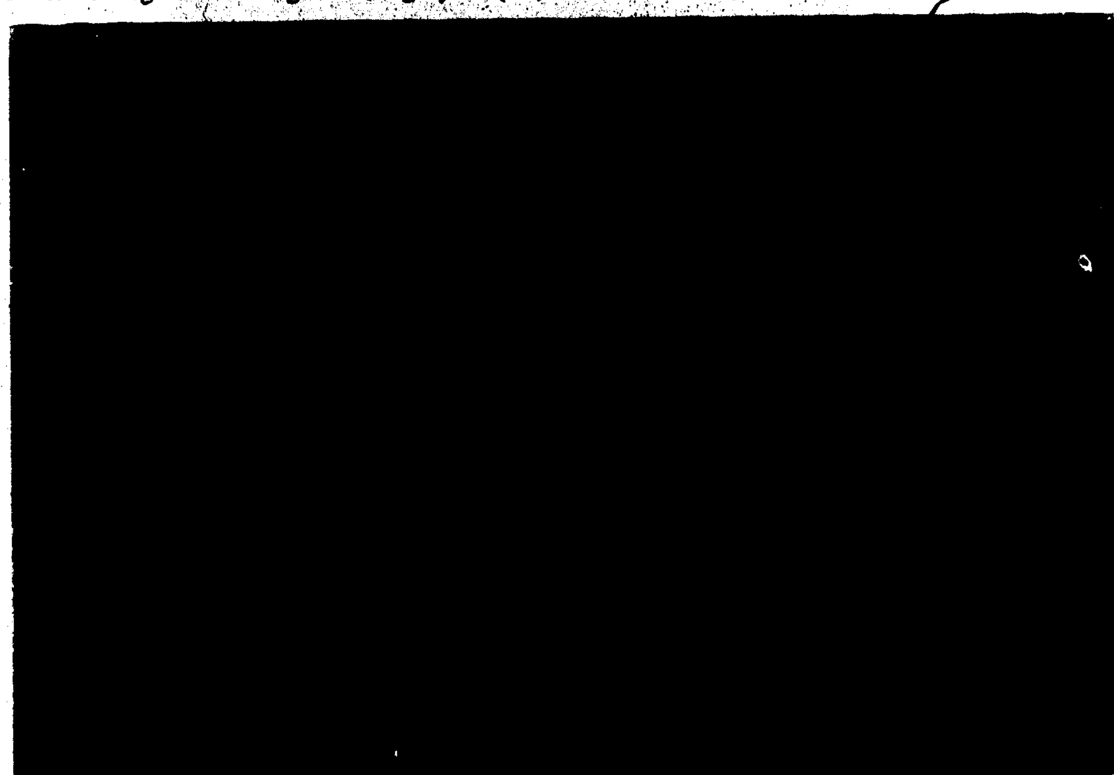


Plate 2. Graded bedding and deflection of a stratabound vein, Core-vein area, ("way-up" is indicated by the pencil), Bullmoose Lake

Biotite laths, and to a lesser extent, quartz, are quasi-parallel to the pervasive late cleavage (S3). The biotites are noticeably bimodal; one population having the lath-shaped form and constituting some 70% of the biotite popultion, and a second, later biotite being more equidimensional and often appearing to be larger in the plane of most of the thin sections, which have been cut in the a-b plane perpendicular to σ_1 (of S3, the pervasive cleavage).

Interturbidite units

The finer-grained upper horizons of the metaturbidite units ('interturbidite' units, Bouma, 1962 (Plate 2), have a more varied mineralogy, typically consisting of 25-40% biotite, cordierite (<25%), recrystallized quartz and feldspar, and minor amounts of ilmenite, pyrrhotite, pyrite, chlorite and sericite. The cordierite is poikiloblastic and contains numerous helictic quartz, sericite and ilmenite inclusions. The quartz inclusions are randomly oriented but the 'felted' phyllosilicate inclusions have a definite orientation in some of the cordierite crystals. A notable feature of the quartz inclusions is that they are smaller than the surrounding matrix. There is evidence of two generations of cordierite (discussed in chapter V), and the earlier porphyroblasts are often replaced by ankerite, sericite, chlorite and occasionally by later cordierite. The cordierites range in size from <0.5 mm to about 5 cm length. The proportion of each mineral in the rock can vary to an extent both in the same section and between different beds, this being probably the result of local variations in the bulk-rock chemistry of the primary rock (also see Ramsay, 1973c for discussion). Two biotites are present in the rock, both are lath-shaped, and an interesting feature of the later biotite generation is the abundance of pleochroic haloes (Plate 3). In the sections studied some 90% of the pleochroic haloes occurred in late-stage biotites. The ilmenite, magnetite and lithic fragments are sporadically distributed throughout the rock. The lithic fragments are often replaced by ankerite. Plagioclase feldspar (An_{0-8}) is typically associated with coarse-grained quartz. The most characteristic petrographic feature of the interturbidite horizons is the strong foliation defined by the alignment of phyllosilicate minerals, ilmenite, and by the long axes of most cordierite porphyroblasts.

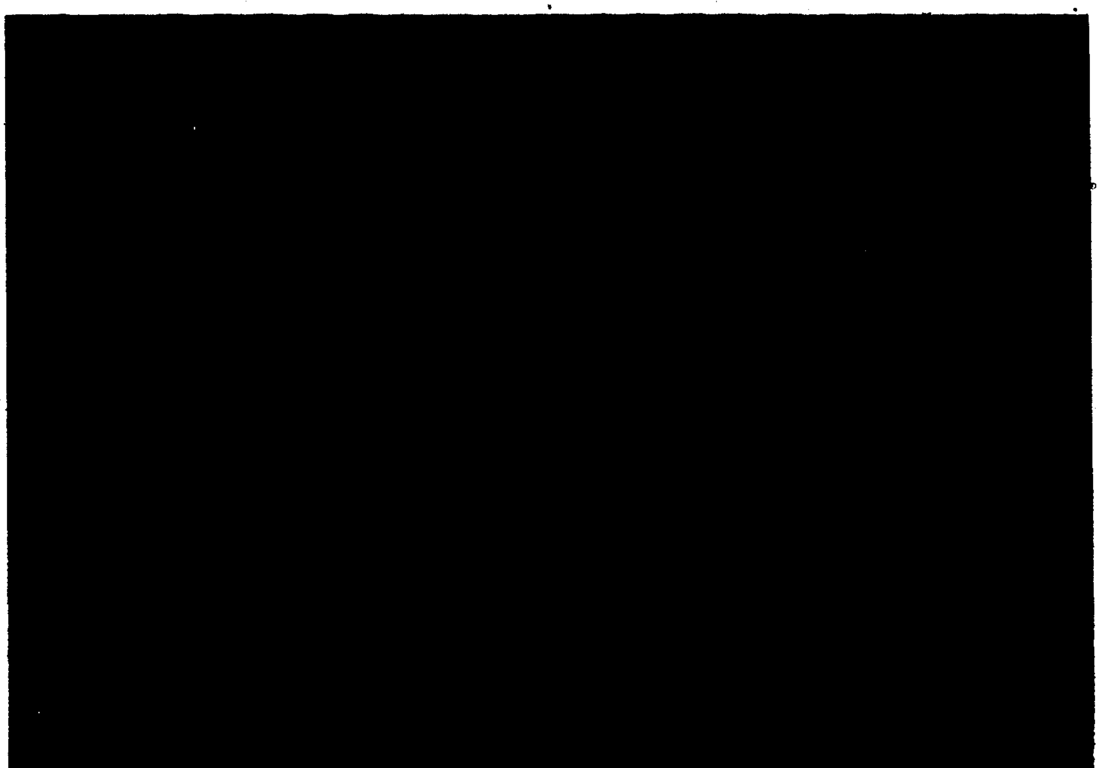


Plate 3. Late biotite laths displaying pleochroic haloes in the metaturbidite units, Bullmoose Lake

Banding

Banding, or mineralogical layering, within the metaturbidite rocks adjacent to quartz veins is a common phenomenon, and has been recorded from other type 2a and 2b deposits (see page 18, and Padgham, 1985), e.g the Discovery deposit N.W.T (Lord, 1951) This mineral segregation gives the rock a grano-lepidoblastic texture (Bard, 1986), consisting of biotite (and secondary chlorite) aligned parallel to the pervasive cleavage, and interlayered with poorly-aligned quartz and plagioclase.

The biotite layers are often cut by high-angle late fractures, infilled with chlorite, opaques and occasionally ankerite. The width of these bands varies (0.5 mm - 2 cm) and they are generally laterally continuous with the margin of the veins.

The intermittent quartz bands are epigranular and have a constant composition of 97-100% quartz and minor plagioclase. The grains are interlocked and triple junctions are a common feature. Locally, stylolites and fine-grained epigranular ribbon quartz are developed parallel to the banding. The larger quartz grains on either side of the ribbon-quartz are partially to completely recrystallized and yet still display undulose extinction signifying post-recrystallization deformation. Some of the partially recrystallized quartz grains exhibit a relict fabric, which has a common orientation parallel to the banding (Plate 4).

A large graphitic component (up to 30% modal) is seen in some of the interturbidite horizons (e.g the 4B and 4L veins). The graphite occurs either as isolated grains (<0.05mm) or as wisp-like sheets oriented quasi-parallel to bedding. Rarely, large euhedral, pink andalusite crytsals are found in extremely graphite-rich horizons (e.g DDH BM84-22 and #4B vein wallrock. The graphite content is depleted in the more quartz-rich beds, but the mineral is ubiquitous in all of the rocks studied at Bullmoose Lake.

Calcium metasomatism

In some beds adjacent to quartz veins the mineralogy is influenced by localised calcium metasomatism. Actinolite is seen replacing biotite and more rarely, cordierite. Isolated euhedral hexagonal, green fluorapatite crystals are sometimes present in the quartz veins (e.g the #14 zone, Bullmoose Lake and the Beaulieu deposit, Lord, 1951). Adjacent to some

Plate 4. Relict fabric in quartz grains?, (ppl), #4B vein, Bullmoose Lake

veins, particularly in the 'Core-vein' area minor quantities of scheelite have been detected.

In the 'Core-vein' area, rocks which have been subject to intense metasomatism are often mineralogically banded and intensely silicified, and the most characteristic petrologic feature is the development of two kinds of actinolite (e.g #4F vein at the 90m level). The bands have similar dimensions to those described above, but are green rather than brown/black due to the different mineralogy. The actinolite rich bands are the equivalent of the biotite, quartz and plagioclase bands in the previous section, but are conspicuously devoid of biotite. Some sericite growth is evident but the only other minerals of significance in these layers are quartz, chlorite, ilmenite, minor apatite and epidote. Occasionally, cross-cutting ankerite veins occur, particularly in the vicinity of and adjacent to, vein-sulphide minerals. The actinolite occurs in two forms, as xenomorphic, radiating, acicular aggregates, and a mass of idiomorphic lath-shaped crystals. Plate 5 shows a basal section of idiomorphic actinolite displaying the familiar 56-124° cleavage. The needle-like actinolite is most often hosted by quartz or plagioclase in the presence of chlorite (replacing biotite) at the margins of the bands, where as the idiomorphic crystals are more commonly seen directly replacing biotite in the interior of the bands.

Metapelite/metasemipelite

- qtz, bi, pl, chl, cord, graph, py, po, asp, ilmen, mt, seric

The metapelite/metasemipelite beds are local in extent and are best developed in the #7 vein area and on the east shore of Doodad Lake (Fig. 8). The maximum combined thickness of these beds (not stratigraphic) is about 40 m. The beds have a uniform composition and tend to be well-cleaved, giving the rock a 'ropey' appearance in outcrop, in contrast to the smooth metaquartzwackes. Veins hosted in these rocks occasionally display alteration. The #7 and Max veins both exhibit a bleached, propylitic alteration extending up to 3 cm away from the vein. Some of the horizons in the metapelites are graphite-rich. These rocks have been categorized as a separate unit from the metagreywacke, due to their apparent thickness. However, it is possible that they represent extensive metainterturbidite units, which are

Plate 5. Euhedral actinolite surrounded by quartz grains, #4 vein (ppl) (note primary liquid inclusions in the quartz), Bullmoose Lake

unusually thick or structurally stacked.

Mafic dykes/sills.

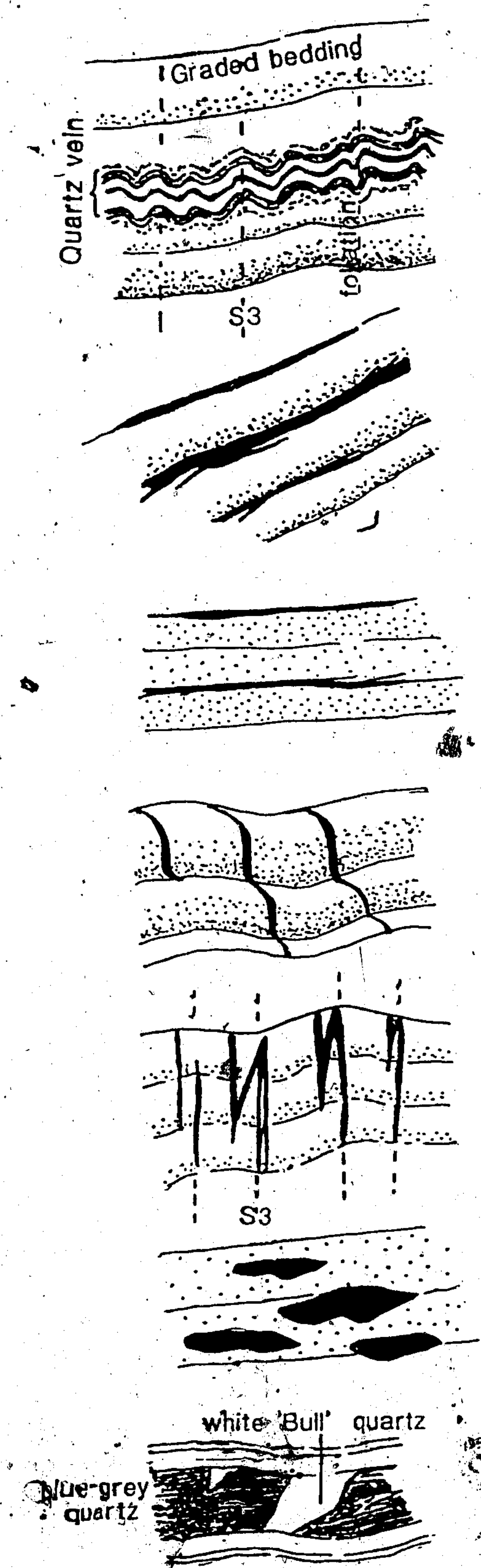
pl, pyx, mt, ilmen.

The dykes and sills constitute less than 1% of the rocks present on the property and have rarely been intercepted in the mine workings. These intrusives both cross-cut and parallel the bedding, and are discontinuous along strike. On the northwest tip of Bullmoose Lake the dykes are noticeably flat-lying and perpendicular to the dip of the bedding. The intrusions have been assigned to the Mackenzie dyke swarm on a purely geographical basis, (Henderson, 1985) and on the basis of their common northwesterly strike. The intrusions have a basaltic composition and porphyritic texture with euhedral plagioclase and clinopyroxene set in a medium-grained plagioclase matrix. The rocks display chilled margins which are enriched in opaque iron oxides.

C. Introduction to the quartz-veining at Bullmoose Lake

The quartz veins have been subdivided into several different categories based upon their configuration (figure 9).

The mineralized veins at Bullmoose Lake are predominantly blue-grey en échelon (Bpé) bedding-parallel veins. The Bpé 'Core-veins' (fig. 9) at Bullmoose Lake extend for a length of approximately 90-100 m and are less than a metre wide (typically less than 12 cm). They are grey or bluish-grey, coloured by spots of amorphous carbon or graphite (similar to the Ptarmigan veins, Boyle, 1979). In thin section, the quartz veins are composed of sub-rounded, heterogranular, interlocking grains which display undulose extinction and triple boundaries. These quartz veins are host to a variety of sulphide minerals and gold (chapter VI and table 3). Minor amounts of plagioclase, sericite and wisp-like inclusions of chlorite also occur in the veins. The sulphide minerals are often rimmed by ankerite, which was apparently introduced into the vein after the crystallization of quartz.



	TIME RELATIONS
Bpb veins Bedding veins (parallel to bedding). These veins occur throughout the property and are particularly well developed in well bedded areas. Often banded. Location: West Zone Core Veins and throughout property	Syn F_1
Bpe veins Blue-grey veins parallel to bedding and quasi-parallel to schistosity. Not banded. Location: Throughout property, particularly in core vein area, 7 vein and 9 vein.	Syn F_1 to post S_3
Displacement shear veins. Veins parallel to bedding and quasi-parallel to schistosity. Not banded, blue-grey or white quartz. Location: Throughout property, particularly in "core-vein" area and also #7, #14, #9 and #15 veins.	Syn. F_1 to post S_3
Stratabound veins. Lie within but oblique to beds. Deflection of the vein due to the competency contrast of the matrix within individual units defines the way up of the beds. Location: South of Cominco shaft and next to assay lab.	Syn S_3
Foliation veins. Parallel or subparallel to foliation. Location: Localised throughout property- West zone core vein area, 7 vein?, 9 vein.	Syn S_3
Quartz segregations. Irregular shaped bodies (blue-grey to bull white quartz). Location: Throughout property particularly in metapsammitic units.	Syn deformation
"Bull" white quartz veins. Often cut earlier, blue-grey quartz (Bpe veins). Location: Throughout mineralized and unmineralized areas particularly noticable in 7 vein.	Post blue-grey Qz.

Figure 9. The habit of quartz veins at Bullmoose Lake

A sucrosic variety of quartz has been observed adjacent to, and intergrown with, the blue-grey quartz. This type of quartz is generally a milky-white or brick-red colour and occasionally has distinct banding of chlorite in the vein. In thin section the quartz-grains have a polygonal, mosaic texture. Rarely are any other minerals, except sericite, seen in this variety of quartz. The sucrosic appearance of the rocks is attributed to its partially broken down intergranular cement, which renders it rather friable. The brick-red colour, occasionally seen in outcrop (and never in the mine workings), is caused by the incursion of Fe-oxide rich surface waters into the quartz-grains adjacent to intergranular spaces.

A banded variety of quartz vein (Bpb) is very noticeable in outcrop and is always parallel to bedding (plate 8). The quartz is usually white to translucent, and based upon the mineralogy and timing of emplacement, these veins are not related to the Bpé veins.

Late white quartz, (often referred to as 'Bull-quartz'), is commonly seen cross-cutting all types of veins and country-rock [illegible] the property. These quartz veins are very erratic in outcrop and are often on[illegible]ntimetres thick. In thin section, the quartz is medium-grained, has a polygonal [illegible] texture and exhibits sharp extinction. The quartz is almost totally devoid of graphite which probably explains why it is characteristically light in colour, or transparent. Assays registered ≤ 0.1 g/tonne Au for all samples collected from these quartz veins.

V. Deformation and Metamorphism of the Bullmoose Lake Rocks

Introduction

Several authors have published papers concerning the relationship between the regional structure and metamorphism in the Slave Structural Province (see pages 12 and 13, this thesis). In this present study the author was concerned with the analysis of the local structure at Bullmoose Lake to ascertain the variations in the local structural style and strain, and their effects on the locations of auriferous quartz veins.

Mapping of way-up palimpsest sedimentary features (e.g. graded bedding, and occasional crossed-bedded surfaces) on a 1:1200 scale revealed two major structural features of the Bullmoose Lake property, these being:

1. a major overturned isoclinal syncline with an axial plane trace striking north to north-east (356 - 015°) and dipping 70° east with a fold axis trending east (089°) and plunging 66°E (the Bullmoose Lake syncline).
2. a flexure on the western limb of the Bullmoose Lake syncline which is host to the gold deposits. Field-and underground-mapping indicate a left-lateral sense of shear for the flexure and petrographic studies of the syn-tectonic cordierite porphyroblasts, fractured grains and recrystallized grains are all consistent with this sense of shear.

A. Folding

Two main phases of folding are seen in the rocks:

F1 - The Bullmoose syncline and associated folds of relatively large magnitude (>10m) are the earliest folds seen on the property. The folds are generally tight to isoclinal and have a steep easterly dipping axial plane (50-70°E) with an axial plane trace that intersects the surface trending in a north or north-westerly direction. The Bullmoose Lake syncline is the largest of the F1 folds is overturned on its eastern limb (Fig. 8).

F3 - These are small-scale folds (< 10cm wavelength) axial planar to S3 (350°-010°). Bedding-parallel veins (Bpb, fig. 9) are folded by F3 (plate 8), and often irregular, narrow, late quartz veins are distorted into ptygmatic folds by this folding event.

B. Schistosity

Two phases of schistosity are evident in the rocks:

S2 - The earliest phase of schistosity recognized in the Bullmoose Lake rocks is preserved as a relict fabric that was developed between F1 and F3 and is recorded in some rotated cordierite porphyroblasts. There is no schistosity associated with F1 (Fyson, 1975, 1984, 1985) and it is probable that the inclusion fabric seen, is analagous to an S2 fabric that has been recognized elsewhere in the province (Fyson, 1982, 1984a). Fyson (1982) recorded S2 quartz inclusion trails in biotite porphyroblasts that probably correspond to a phase of deformation which transgressed the major NNW-SSE fabric in an east-west direction (see fig. 6, Fyson, 1982). At Bullmoose Lake the fabric is preserved by 'felted' phyllosilicate minerals (plate 11) that are orientated roughly perpendicular to the long axis of the cordierites. This tentative S2 fabric was only detected in about 30% of the specimens and the wide scatter in the fabric direction is attributed to the post-S2/syn-S3 rotation of the porphyroblasts. At Bullmoose Lake, no such inclusion trails were detected in biotite or in any other minerals, for it is probable that most of the phyllosilicates were completely recrystallized during subsequent metamorphic events. Most of Fyson's work (1975, 1981, 1982, 1984a, 1984b) records porphyroblasts in greenschist grade rocks.

S3 - The S3 schistosity is a regional fabric which probably developed during a major phase of compression towards the end of the deformational sequence. The schistosity extends throughout the whole Slave Province and varies from 320 to 010° strike (Henderson, 1985). At Bullmoose Lake the S3 varies from 330-354° and dips 50-75° east. The S3 is, as mentioned earlier, axial planar to F3 but is also parallel or quasi-parallel to F1. The schistosity is defined in thin section by the alignment of phyllosilicates, in particular biotite and sericite, and also by recrystallized quartz and plagioclase.

C. Faults, shears and tensional features

Introduction

Many surface structural features have an orientation and relative location that suggests minor faulting accompanied local left-lateral shear movement during progressive deformation of the metasedimentary rocks at Bullmoose Lake. The structures have been infilled with quartz, and a complete description of the mechanisms of quartz emplacement in shear and tensional regimes is given by Secor (1969), Yardley (1986) and Kerrich and Allison (1978a). Ideally, in a purely isotropic medium, fractures should form perpendicular to σ_1 (a situation that may have occurred for the massive metabasalt hosted veins at Lex Lake, N.W.T). The rocks at Bullmoose Lake are strongly anisotropic as indicated by primary lithological variations; most of the veins are located more or less parallel to schistosity and bedding which is probably as a direct result of the σ_1 shear stresses operating at an oblique angle to the fabric in the rock. Purely tensile structures can only be formed in an homogeneous lithology which is oriented in the correct sense to the principle stresses, and when the fluid pressure (P_f) exceeds the lithostatic pressure (P_l). At Bullmoose Lake P_f may not have exceeded P_l because there is abundant evidence that shear or oblique stresses (Beach, 1980) were more influential than tensile stresses, particularly during the late Kenoran.

Genesis of the quartz veins in the Core-vein area

The Core-veins (Fig. 10), sometimes also referred to as the west-zone or the 4-veins, are the focus of mining activity at Bullmoose Lake, with over 95% of the ore being recovered from these veins. There are approximately ten major, and twenty minor, veins in this en échelon array. The veins pinch and swell along their length and often split-up into a number of stringers along strike. The stringers can persist into the wall-rock for lengths of up to 2 m and they often bend in an anticlockwise direction away from the main vein (Fig. 12). The main veins within the Core-zone (e.g. #4, #4I, #4L, #4B) vary in length from about 90-100 m and generally strike 342-347° and dip from between 65-70°E. Some veins have been intercepted at depths of 270 m by deep-drilling (Cloutier, 1986), although it is unknown

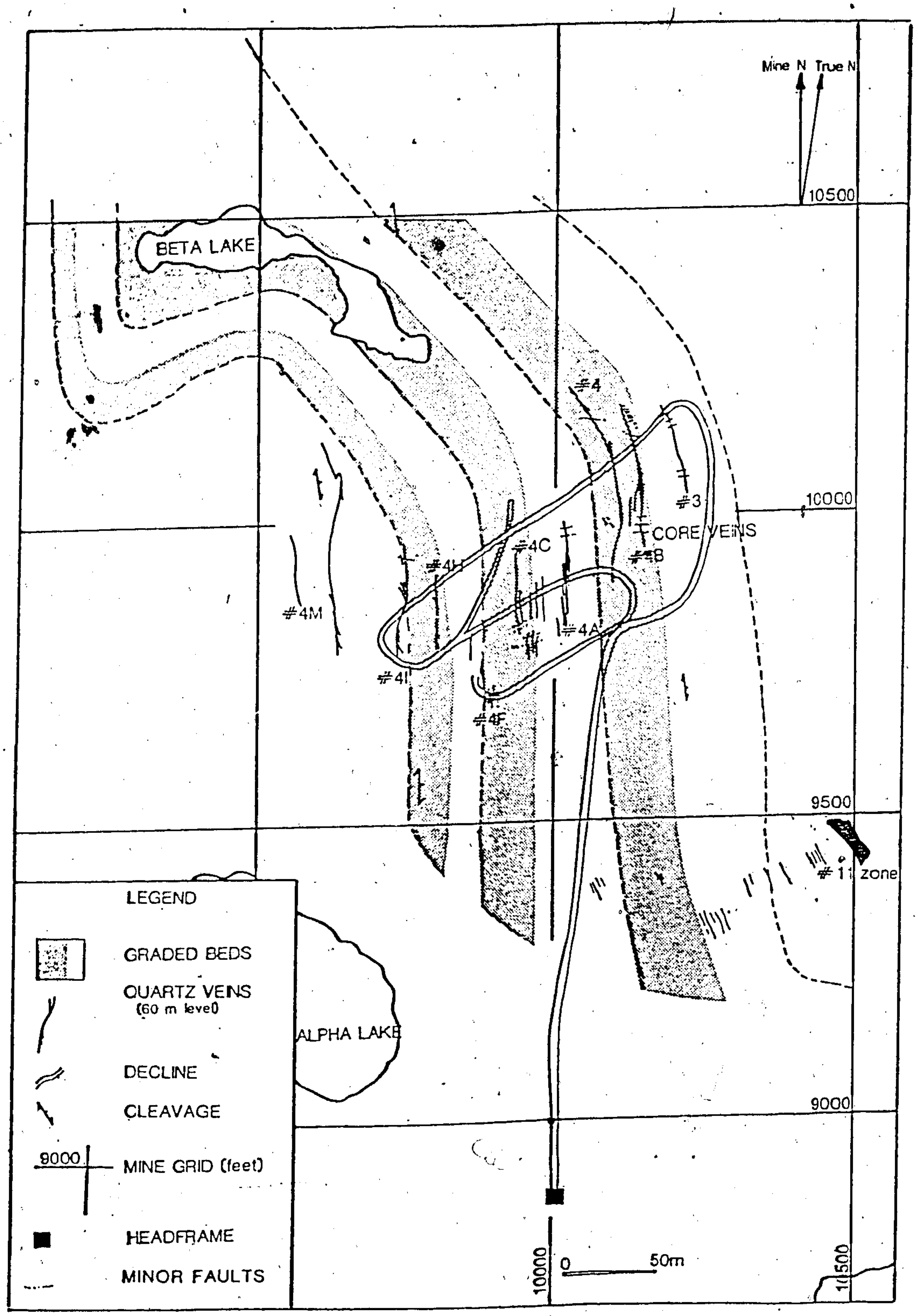


Figure 10. Detailed geology of the Core-veins area, Bullmoose Lake

whether the veins being exploited in the mine-workings are the up-dip extensions of the deeper veins, or represent a seperate set altogether. In places 'cross-veins' can be recognized in the mine-workings; these veins transgress the wall-rock at an oblique angle and join two adjacent main veins. The textural relations and orientation of these veins suggests that they were emplaced at the same time, or same period of time, as the main veins.

The orientation of the en échelon veins, parallel to bedding within the F1 folds, suggests that the veins were emplaced coeval with the deformational event. The Core-veins were emplaced when the orientation and magnitude of the deviatoric stresses caused a shear component to induce fracture parallel to bedding and schistosity (although it is possible that the S3 fabric developed during and/or after the period of shear).

The expression $P_f > P_l + T$ (Henley *et al.* 1976) where T = the tensional strength of the rock perpendicular to P_l, applies to the development of tensional fractures, but as mentioned, P_f does not neccessarily exceed P_l if a large deviatoric stress component is involved. T is therefore of fundamental importance, and at Bullmoose Lake the metapelites have a lower tensile strength than the metaquartzwackes and are therefore more susceptible to hydraulic fracture. Studies performed on the variation between different rock strengths in shear zones throughout the world (Phillips and Groves, 1983; Groves *et al.* 1985; Foster, 1985; Wood *et al.* 1986; Henley *et al.* 1976; Graves and Zentilli, 1982) are consistent with the general idea that most mineral vein deposits are emplaced in host-rocks with low tensile strengths. Although the Bullmoose Lake deposit is not of the 'shear-zone' type, the mechanisms of hydraulic fracturing in metasediment-hosted deposit are the same.

In the metasediments of the Slave Province, it has been noted (J. Brophy, pers comm 1986) that the occurrence of veins is often restricted to graded metagreywackes. Areas of massive metaquartzwacke are not as conducive to hydrofracture, for the variation between the deviatoric stresses was not great enough to induce brittle failure. This therefore suggests that if fluid loss occurred, as is possibly indicated by petrogaphic evidence of recrystallization during metamorphism and pressure solution features, it equalled production by pervasive flow mechanisms (i.e. no fracture, Wood and Walther, 1986). At Bullmoose Lake, minor white quartz-veins and quartz-segregations (see Fig. 9) are seen in the metaquartzite but they are probably related to a later event, probably even later than F3.

Evidence of hydraulic fracture in the core-vein rocks is not only shown by the quartz-filled shear fractures, but also by the development of zones of stockwork micro-fractures (plates 6 and 7). These were apparent at the surface, and particularly noticeable at the termination of the main quartz veins. They probably represent a situation where the P_f is not maintained and the shear stress is dissipated at the tips of the fractures (Nicholas, 1987).

Beach (1980) states that *extensive* growth of hydraulic shear-fractures is most likely to occur under conditions of low deviatoric stress, and short shear-fractures will form when the stress difference is relatively higher. In the core-vein area at Bullmoose Lake, and elsewhere on the property, the fractures are short and it is therefore presumed that large deviatoric stresses have operated to form these fractures.

There is some evidence to suggest that there has been a fluctuating, but noticeable increase in the intensity of strain during the Kenoran (Fyson, 1978; King, 1981). The vein morphology may in fact be directly related to this strain increase. Fyson (1984) cites the possibility of late horizontal tectonics causing refolds (of F1) and late cleavage sets (S3A and S3B) elsewhere in the Slave Province. This implies that σ_1/σ_3 may have generally increased during progressive metamorphism from early Kenoran tectonism (F1) to late Kenoran (F3/S3). It is therefore worthy of speculation to consider whether during the early Kenoran, conditions were more conducive to tensional vein growth, but with continued σ_1 influence shear veins were more commonly produced during the later stages of the Kenoran.

Banded bedding-parallel veins (Bpb, plate 8) veins were therefore probably produced during regional $P_f > P_l$. Although $P_f > P_l$ produced the initial *fracture*, the *quartz-veins* were probably produced by the influx and precipitation of fluid along the dilatent fracture and also by quartz migration from the immediate wall-rock (the 'crack-seal' method, Ramsay, 1980). Under amphibolite grade conditions, fluids are transported by 'single-pass' flow (Wood and Walther, 1986), and by this flow mechanism it is typical to get a reversal of stress conditions

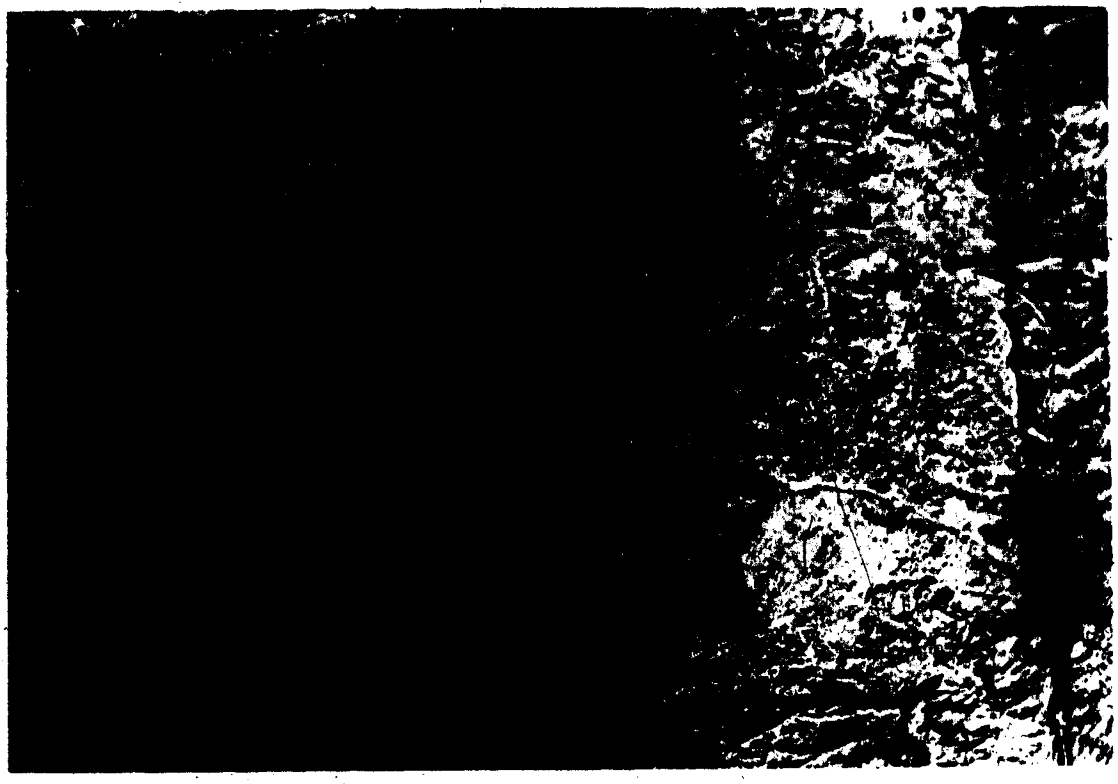


Plate 6. Stockwork hydrofractures in metagreywackes, #15 vein, Bullmoose Lake

Plate 7. Stockwork hydrofractures in metagreywackes, #11 zone, Bullmoose Lake

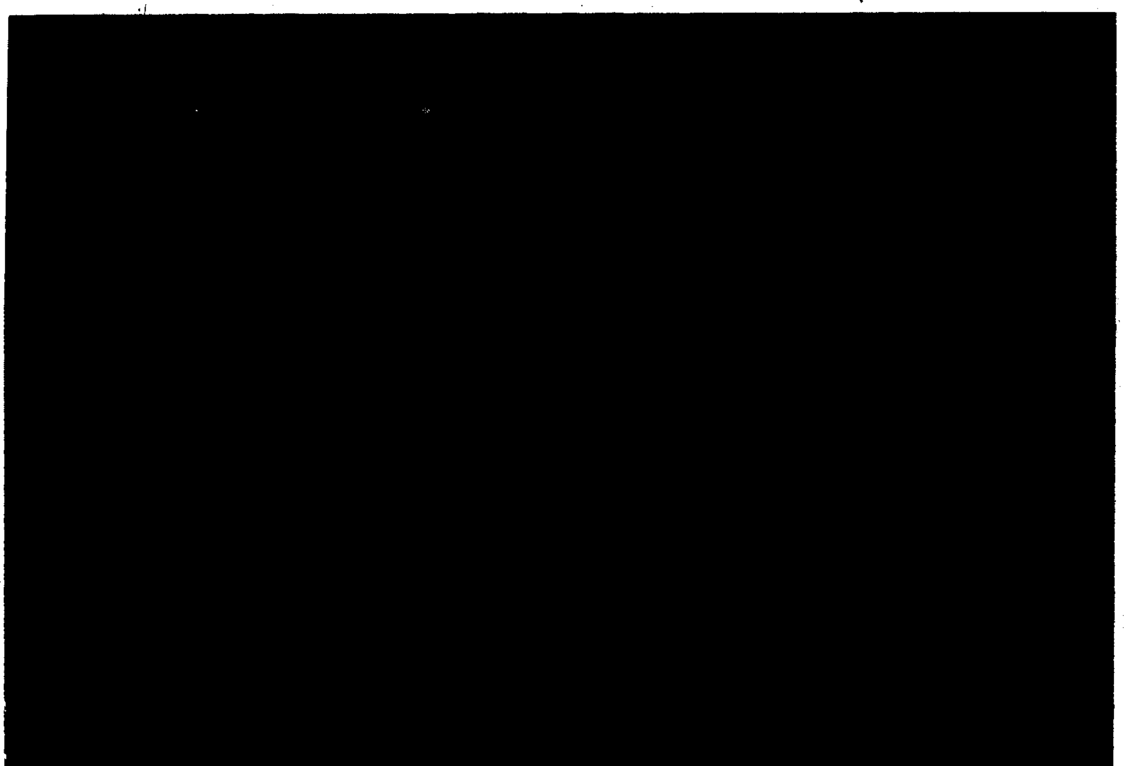


Plate 8. Bedding-parallel (Bpb) quartz vein, and minor zone of alteration around the vein, folded by F3 (parallel to pencil), Core-vein area, Bullmoose Lake

at the tail of the fracture (i.e. $P_f < P_l$). The net result of this process is the migration of fluids into the crack immediately behind the hydrofracture tip. Wall-rock inclusion bands (Ramsay, 1980) which parallel the vein margins, divide quartz-layers of the Bpb veins at Bullmoose Lake (plate 8) and are good evidence for antitaxial growth of these veins by pressure-solution (i.e. growth of the veins from a central location towards the wall-rocks). Repeated fracturing and sealing occurred along the same crack in response to P_f build-up, release and subsequent elastic-type recovery by wall-rock quartz migration to produce the characteristic banding in these veins. The relatively consistent strike of the veins parallel to bedding and their extensive lengths may also be additional evidence in support of a tensional regime (Yardley, 1986). There is also a lack of evidence for shear along the margins of the veins, in outcrop and in thin-section.

Boyle (1979) and several other authors discovered minor silica depletion around 'bedding-parallel' veins but it is not known whether the distinction was made between bedding-parallel veins (Bpb, this thesis) and auriferous veins that are also parallel to bedding but morphologically very different (Bpé, this thesis). The Bpb veins throughout the Bullmoose Lake property carry values of less than 0.1 g/tonne Au, which may be further evidence of migration of elements from a local, rather than a regional source (see discussion, chapter VIII).

Analysis of the sense of shear in the Core-vein area

The sense of shear in the Core-vein area was determined by several methods:

1. Field and underground mapping - Field-mapping on a 1:1200 scale and underground mapping on 1:240 and 1:120 scales delineated several en échelon veins with a distinctive form. The main Core-veins at surface, generally have a relatively constant strike (347°-354°) until an area just south of Beta Lake at the surface (Fig. 10), corresponding to a grid position at 10,110(foot) N in the mine. All veins at about this latitude bend towards the west on a bearing of 300°; correspondingly, some of the veins seen in the south stopes of the mine (approximately 9800N) tail-off in an easterly direction on a

bearing of 145°. The explanation of this quasi-sigmoidal shape is the deformation of rock by left-lateral shear. Further evidence in support of this sense of shear is the observation of splay-stringers which are bent in an anticlockwise direction (Fig. 12).

2. Petrographic evidence - This, of course, was used secondary to field data, but the study revealed the possibility of using certain thin-section criteria to deduce the sense of shear. These criteria are:

a. Pre/syn deformational porphyroblasts - There is evidence of 2 possible phases of cordierite growth in the rocks. The later cordierite sometimes has a relict inclusion fabric (S_i) of phyllosilicate material, which may represent an earlier schistosity obliterated during subsequent F3/S3 deformation. These cordierites are rotated and S_i often lies at a variable angle to the external fabric (S_e). Using the criteria of Zwart (1962), Vernon (1978), Olsen (1978) and Simpson and Schmid (1983), and Brunel (1986), strain shadows produced during the rotation of the cordierite appear to support a left lateral sense of movement (post S2 and syn/post S3), although it is probable that simple-shear was accompanied by some flattening. The S_e fabric tends to bend around some of the porphyroblasts in a manner that suggests the metamorphic environ was subject to more than one direction of stress, which is quite typical of sheared environments (Kerrich and Allison, 1978a; Ramsay, 1980a).

b. Obliquity of strained quartz within veins that parallel foliation. In one thin-section (#4B-6), a marked banding of extinction in recrystallized quartz grains at an angle to foliation gave evidence of left-lateral shear, similar to the example given in Simpson and Schmid (1983, page 1285). Simpson and Schmid (1983) attested that the obliquity of the grains to foliation indicated shear occurred up until the last stages of deformation. Care must be asserted when using this analysis because subdomains of quartz, may indicate the influence of a heterogenic stress regime.

c. Displaced broken grains. Occasionally broken grains provide an indication of the sense of shear (plate 9). Unfortunately this method was not very reliable in the Bullmoose Lake rocks, probably on account of the heterogeneity of the local stress

Plate 9. Broken porphyroblast(now replaced by ankerite) showing possible sense of shear, (ppl), #4B vein, Bullmoose Lake.

regimes, and due to the dislocation of grains during ductile deformation.

Determination of strain

The Rf/ϕ method (Dunnet, 1969) of strain determination was applied to the Core-vein and west-limb metaquartzites. Analyses were performed in order to determine whether it was possible to document a strain signature in the Core-veins and wallrocks, as compared with the surrounding country rocks. Many analyses of strain using this method have been described in the literature, for example Dunnet (1969), Lisle (1977, 1985), Ramsay and Huber (1983), and Onash (1984). The assumptions upon which the method are based are:

1. The deformation was homogenous.
2. The initial distribution of marker long axes was random.
3. There was no competency contrast between particle and matrix during deformation.

The ratio of the long and short axis of each deformed grain (Rf) was plotted against the long axis orientation (ϕ) measured from a line normal to the shortening direction. The Rs (the axial ratio of the strain ellipse) was determined by comparing the pattern of points on the Rf/ϕ plot with published curves (Lisle, 1985). The initial shape of the deformed markers can also be estimated by reference to the shape of the final plot curves.

Due to the size of the deformed grains, photomicrographs were used for these analyses. 10 plots were performed using a minimum of 40 points per plot (c.f. Dunnet, 1969 for discussion). Quartz and plagioclase were the only 2 types of grains used for the analyses, for it is probable that most of the phyllosilicates are completely recrystallized during late metamorphism and also they are unsuitable for this type of analysis, due to their inability to record strain as well as other deformed grains, notably quartz.

Several problems are inherent in applying this method to amphibolite grade rocks of this type. Firstly, the deformation cannot be considered homogeneous when there is evidence of:

1. pressure solution;
2. a primary matrix which would have caused the applied stress to be redirected in a

heterogeneous manner throughout the rock body.

3. a primary fabric, S2, which may have already caused the realignment of grains prior to the latest deformational event.

Secondly, it is doubtful whether the initial distribution of markers was random due to the sedimentary layering in the turbidites.

Despite these constraints, the results (Figs. 11a and 11b) do indeed reveal a possible difference in the amount of strain recorded in the Core-vein rocks, as compared with the surrounding metaquartzwackes. The influence of pressure solution causes wider fluctuations than would normally be expected (c.f Onash, 1984). By calculating the percentage shortening ([1-(1/Rs)] · 100) from the estimated Rs value, a difference of about 40% shortening is recorded between the less-deformed metaquartzwackes of the west limb of the Bullmoose syncline and the metapelites of the Core-vein area. Onash (1984) studied the effect of pressure solution and concluded that the Rf/ϕ data are applicable to this type of deformation, providing the grains are spaced at intervals that do not exceed the marker width. In all of the sections studied, the amount of matrix still preserved is negligible, due to its recrystallization into phyllosilicate material during early prograde metamorphism. It is therefore probable that the amount of strain recorded in the rock corresponds to late-stage deformation when the grains were closely-packed, as a result of ductile deformation and pressure solution at greenschist and amphibolite grade temperatures and pressures.

The interpretation is obviously subject to controversy, but this type of study may lead to a better understanding of the deformation, especially in suitable lower-grade metamorphic terranes.

The relationship of quartz veins on the Bullmoose Lake property with respect to principal stresses

The habit and strike of the quartz veins *outside* of the Core-vein area suggests that they were also formed during the same phase of left-lateral movement (Fig. 12). The largest of these veins are the #7, #9, #15, Skeeter fault vein (intersected by DDH BM85-22), Max

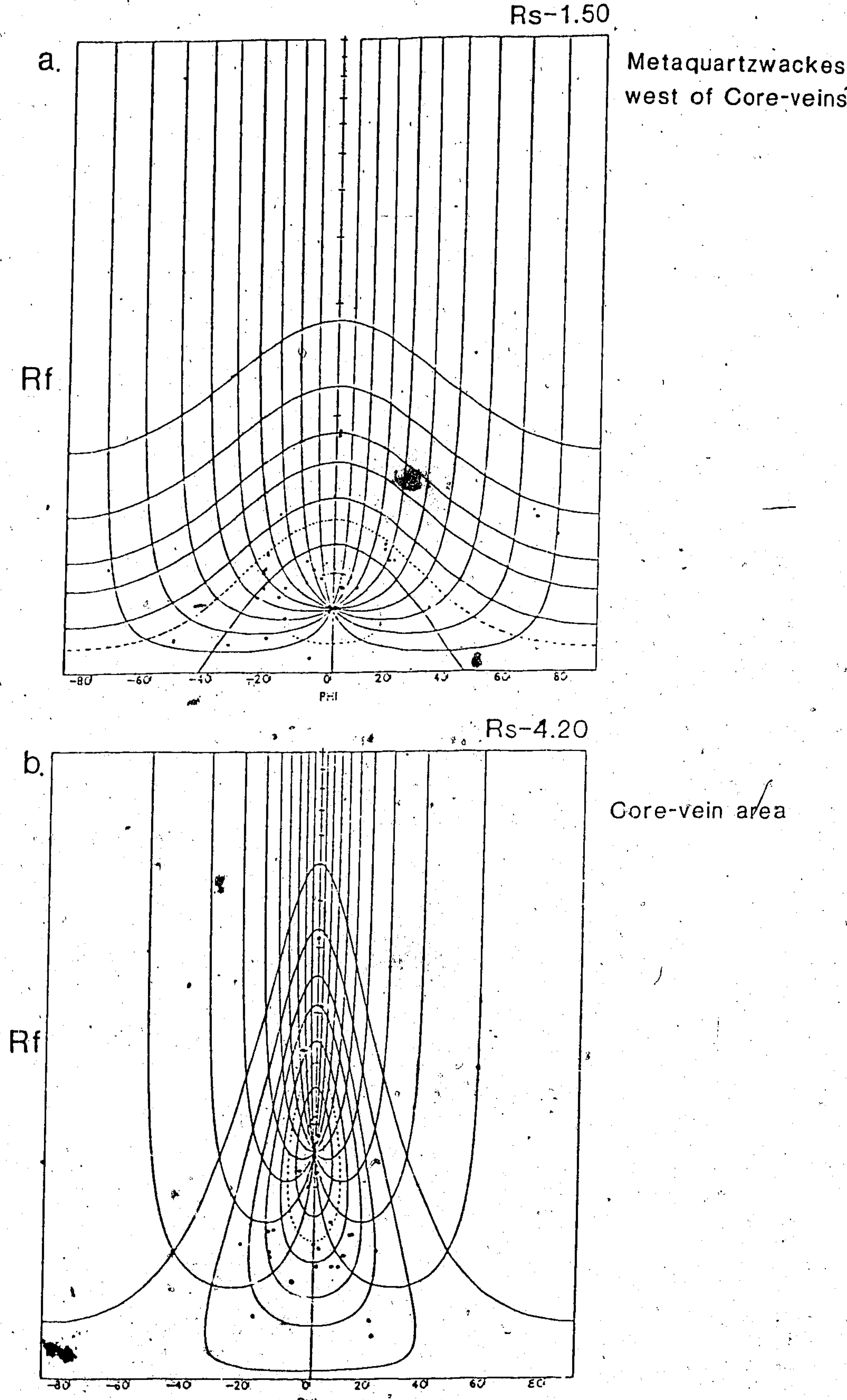


Figure 11. Rf/ϕ plots of the Core-vein area rocks and west limb metaquartzwackes of the Bullmoose lake Syncline

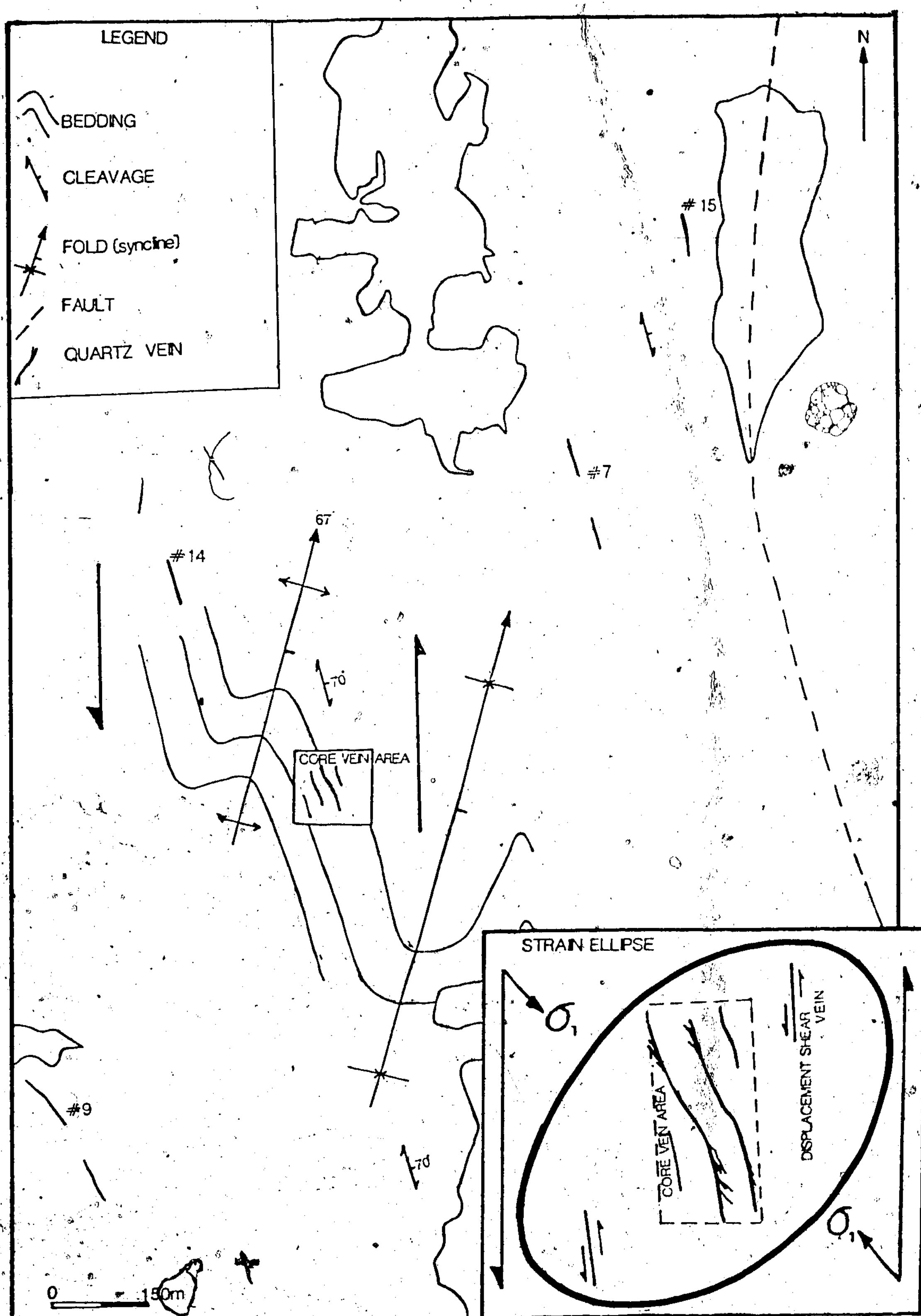


Figure 12. Relationship of the veins with respect to principal stresses, Bullmoose Lake

vein,[2] and the #14 vein. The veins strike approximately northwest-southeast, quasi-parallel to the S3 schistosity, and they vary in length and width. Gold values in these veins are anomalous (generally greater than 1 g/tonne for some of their strike) and exploitation of one vein, the #7 vein was started in October 1986.

The orientation of these veins with respect to the Core-vein area (Fig. 12) suggests that they represent synthetic displacement fractures (Ramos, 1977; Wilson, 1982). These are fractures which form oblique to σ_1 and characteristically display the same sense of movement as the major shear. The #7, #15, #14 veins show evidence of possible shear by the occurrence of wallrock in the veins, believed to be derived by splay during left-lateral shear. The incorporation of wallrock clasts in veins of the Southern Slave Structural Province is not uncommon and has been noticed in other nearby deposits, e.g. A.M veins, English (1981) and Thompson-Lundmark, Lord (1951).

Some east-west fractures that are noticeable in the mine (fig. 10) are probably local relaxation features produced by anisotropies in the host-rock. The high angle that these features make with the veins (80-90°) precludes the possibility that they are normal Reidel features (Bartlett *et al.* 1981).

D. Proterozoic(?) faulting

The Bullmoose Lake fault (Fig. 8) is the only significant fault on the property that is probably Proterozoic in age. The fault trends east-west for a distance of 30km and passes through the north end of Bullmoose Lake, and south of the Core-veins. Early geological reports (Mitchel, 1976) sought to integrate this fault with observed mineralization, but it is now clear from drill and underground data that this fault is not related to the auriferous event. The fault cross-cuts all Archean structures and is characteristically more pronounced than the Archean faults, showing up well on the aerial photographs of the area. Diamond drilling in 1984 intersected the fault, but no significant veining or mineralization was observed (Cloutier, pers. comm, 1985).

[2] Located 1000m north east of the #15 vein (fig. 12)

E. Interpretation of graphic plots of the structural data (surface and underground)

Structural data ~~for~~ bedding, cleavage, surface and underground veins have been plotted using the FORTRAN program ORIENT, written at University of Alberta.

The data show the dominant north-west trend of the structural features seen at Bullmoose Lake. It is probable that the latest major deformational event (D3) has rotated the earlier structures such that they now lie parallel or quasi-parallel to S3.

The plots were useful in the determination of precise fold characteristics when analysed in conjunction with conventional graphic plots on an equal area Wolf net. The salient points of interest are listed below:

1. The S3 cleavage points show a tight cluster and are therefore indicative of a consistent strike and dip (330-335° - 70° east).
2. The Core-vein area fold, on the west limb of the Bullmoose Lake syncline, has a fold axis trending 013° and plunging 67° north.
3. The Bullmoose Lake syncline is an overturned, tight to isoclinal (F1) fold. The axial plane of the fold strikes north-south and dips 70° eastwards with a fold axis that trends 089° and plunges 66° eastwards. The axial plane trace, which by definition must lie within the axial plane and fold axis, trends 013° as confirmed by surface data.
4. The trend of the main veins outside the 'Core-vein' area are quasi-parallel to the S3 fabric.
5. The main 'Core-veins' are oriented between 347-354° and dip 70° north-eastwards.
6. The stringers which splay off the main veins have a strike of 330-333° and dip 70° north-east.

The F1 folding is therefore *not* related to the S3/F3 event, as is shown by the different structural orientation from the two events. It is possible that the western limb of the Bullmoose Lake fold has been rotated into the plane of S3 as is shown by the anticlockwise orientation of the quartz stringers and by their sigmoidal shape. The stringers splay off the main veins at an average angle of 17 - 20°, which is consistent with a general stress direction σ_1 oriented NW-SE.

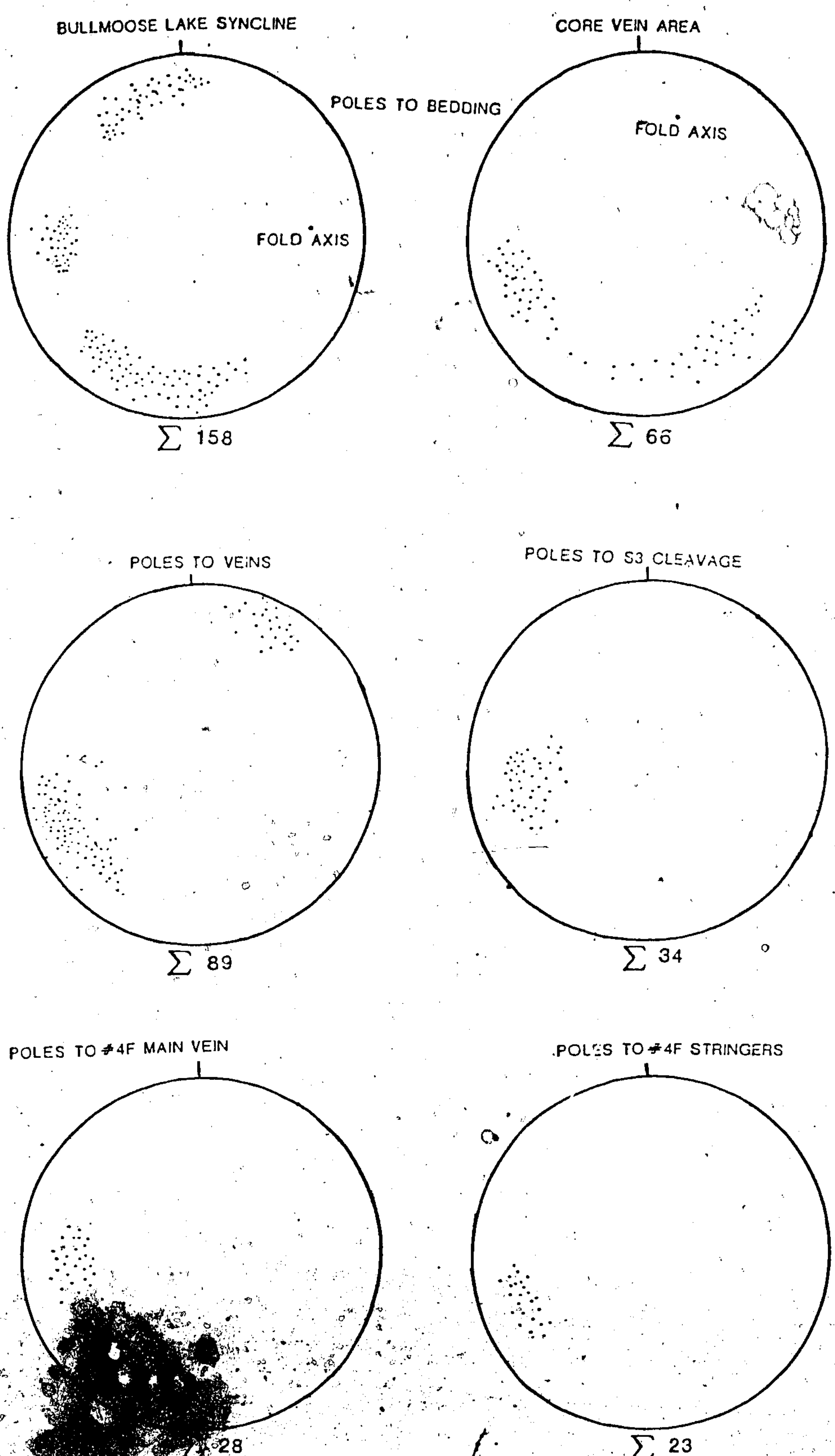


Figure 13. Equal area stereograms of structural data from Bullmoose Lake

F. Temporal relationship between the (Archean) structure, metamorphism and the development of metamorphic minerals at Bullmoose Lake

The metamorphic mineralogy of the Southern Slave Structural Province has been discussed by several authors, for example Ramsay (1973a,b,c, 1974), Ramsay and Kamineni (1977), Kamineni and Diva (1973), Kamineni *et al.* (1979), Fyson (1975,1982), Thompson (1978). The rocks at Bullmoose Lake contain cordierite in their metapelitic fractions, indicating that at some time during the evolution of these rocks, temperatures were in excess of 550°C (Ramsay, 1974; Ramsay and Kamenini, 1977; Thompson, 1978; Winkler, 1979) and pressures were less than 5 kb (Thompson, 1978; Ramsay and Kamenini, 1977; Winkler 1979). Ramsay and Kamineni (1977) studied an area between Yellowknife city and Ross Lake, N.W.T., 40 km North-east of Bullmoose Lake. Using staurolite and aluminium silicate stability data as geobarometers and sillimanite and other geothermometric indicators, (such as proximity to plutons), Ramsay and Kamineni (1977) concluded that 2 stages of a single metamorphic cycle were recorded in the rock. An early phase (M2 of Ramsay and Kamineni, 1977) has an assemblage suggesting conditions of 3-4.5 kb and 500°C (Buchan-type facies) and a later phase suggesting pressures of 2.5 - 3.5 kb and temperatures of 550°C, 700°C where sillimanite was developed (Abukuma-type facies).

At Bullmoose Lake zoning of metamorphic assemblages does not occur on the property. The nearest isograd lies 7 km to the north and it marks the transition to greenschist facies to the north. The nearest outcrop of a major igneous intrusion to the property is the Buckham Lake pluton of the Prosperous Lake granitic suite (Henderson, 1985) which lies 7.5 km to the east. This pluton is very small in comparison to the size of other Archean plutons in the Southern Slave Structural Province. Occurrences of other smaller pegmatites in the local area between Buckham Lake and Campbell Lake (west of Bullmoose Lake) were indicated by a gamma-ray spectrometer survey (Newton and Slaney, 1978). At Bullmoose Lake a spodumene-bearing pegmatite outcrops on the south end of the property, and is not related to the structures hosting the gold mineralization. The cordierite isograd to the north transgresses the regional north-west to south-east fabric, and this together the widespread occurrence of pegmatite veins in the area suggests the possibility of a buried granitoid pluton at depth. This observation is important in light of the following discussion, which draws upon some similarities to the results of work undertaken around the Prosperous Lake and Sparrow Lake plutons.

Early Kenoran metamorphism

The earliest phase of metamorphism recorded in the rocks at Bullmoose Lake is the F1 folding (D2 deformation of Fyson, 1978). The folding was probably related to the initial rise of granitic plutons in the Bullmoose Lake district. It is proposed that during the gradual rise of plutons in the early Kenoran, tensile forces were exerted in the supracrustal rocks above. Tensile fracture of the Bullmoose Lake rocks and minor fluctuations in the deviatoric stresses, and/or the geothermal gradient, produced the bedding-parallel Bpb veins. Petrographic evidence of pressures and temperatures using mineral geobarometers and geothermometers is sparse, due to recrystallization of early Kenoran metamorphic minerals during later regional events. Ramsay and Kamineni (1977) documented an early phase of metamorphism by recognition of relict garnet and staurolite, but at Bullmoose Lake a very altered cordierite (Cord1, plate 10) is probably the only remnant of this early metamorphic stage. The porphyroblasts are totally altered to ankerite and rimmed by later cordierite (Cord2) and by phyllosilicates. Cord2 sometimes preserves an S2 (S_1) fabric (plate 11), which therefore places a relative time constraint of pre-S2 on the age of formation of Cord1. Amphibolite grade conditions were therefore attained during an early phase of metamorphism that probably corresponds to the F1 folding. The M2 phase of Ramsay and Kamineni (1977) probably corresponds to this phase, although their rocks were probably slightly more Fe-rich to produce staurolite and garnet. It is possible that during the latter stages of F1 metamorphism stresses became slightly more deviatoric terminating the development of Bpb veins.

The next event recorded in the rocks at Bullmoose Lake is an internal fabric preserved in the Cord2 cordierite. This fabric, defined by fine-grained phyllosilicates (plate 11), is probably analagous to the S2 fabric recognized in biotite (Fyson, 1975, 1982, 1984) and garnet

Plate 10. Early cordierite (cord1, dark brown), now replaced by ankerite, a later cordierite (cord2, yellow), phyllosilicates, and quartz (ppl), #4 vein

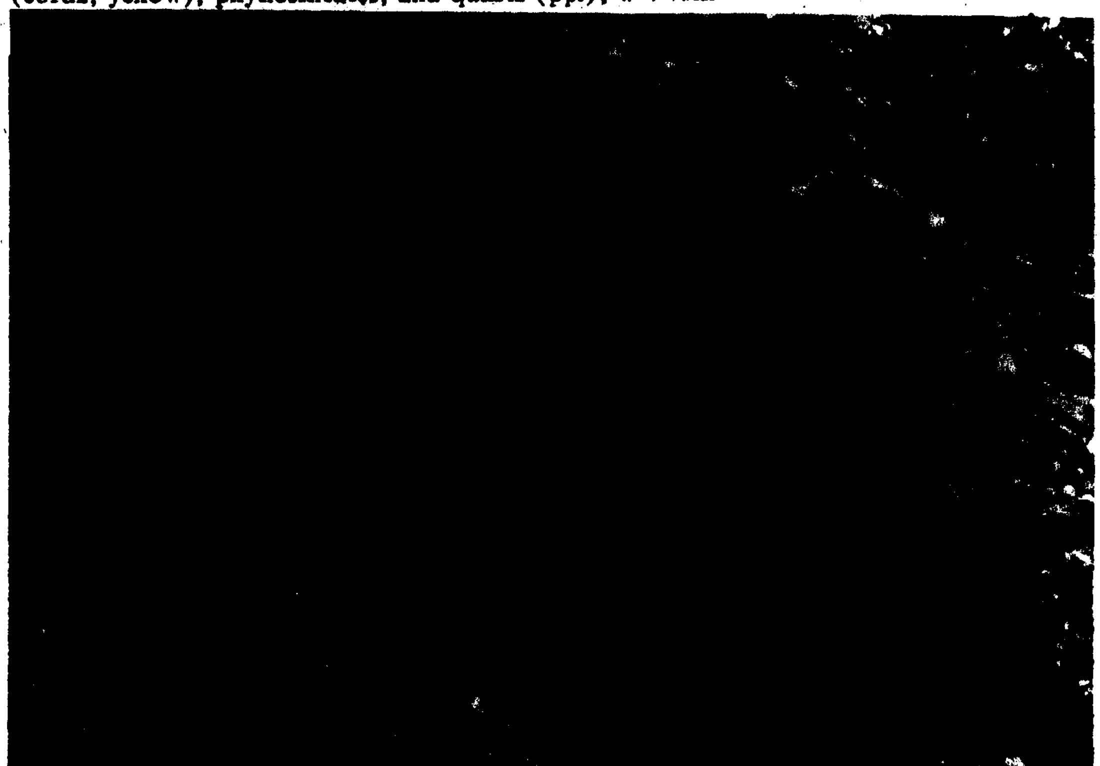


Plate 11. Late cordierite (cord2) with an internal fabric (Si) composed of "felted phyllosilicates" (ppl), #4 vein

(Kamineni *et al.* 1979) from elsewhere in the Southern Slave Structural Province. This fabric may represent waning of the rising pluton, although no direct evidence is published in support of such a hypothesis. It is possible that a general increase in horizontal stress σ_1/σ_3 produced the S2 fabric, the first recorded fabric in the rocks (Fyson, 1975).

Late Kenoran metamorphism

As the metamorphism progressed into the late Kenoran, a penetrative regional fabric, oriented NW-SE, was superimposed on to these earlier features. Elsewhere in the Southern Slave Structural Province it is apparent that this fabric, S3, is cross-cut by thermal aureoles which are associated with the rise of granitic plutons (Henderson, 1985 map-sheet 1601A).

At Bullmoose Lake evidence for temperatures in excess of 500°C is shown by the growth of Cord2. This cordierite is often aligned with its long axis parallel to S3, although occasionally equant crystals are seen that have grown across the cleavage and, are apparently, unaffected by it. The cordierite porphyroblasts are typically 0.5 - 3 cm in length and 0.5 - 1.5 cm in diameter. In thin section, some cordierite crystals are rotated in the S3 fabric and others are seen superimposed upon the S3. The cordierite, therefore, clearly grew post S2, as shown by some Cord2 crystals containing an internal S2 fabric, but their time-span of growth cannot be constrained during the late Kenoran by evidence of both syn-tectonic and syn-thermal metamorphic crystals developed in the same rock-specimens. Temperatures in excess of 500°C are therefore indicated for the late Kenoran phase at Bullmoose Lake and the amount of strain is also regarded as probably being the highest that was recorded during the Kenoran at Bullmoose Lake, as shown by the development of the penetrative fabric. Ramsay and Kamineni (1977) determined that pressures during the late Kenoran were probably lower, as recorded by the mineralogy. However, the confining pressures recorded by mineral geobarometers need not neccessarily reflect the strain of the rock, which is more dependent upon the magnitude of deviatoric stress and host rock composition in most cases, especially where a large shear component is involved.

The S3 fabric is defined by the recrystallized biotite (and minor muscovite) and is probably produced, together with the cordierite by the reaction:

$$chl + musc + biot(1) + qtz + ab + ilmen \rightarrow cord + biot(2) + water$$

(Ramsay and Kamineni, 1977)

One noticeable feature of the phyllosilicates at Bullmoose Lake is the development of two different biotite micas in the cordierite rich rocks. The later, cross-cutting variety may in fact be related to the thermal overprint, and hence their equant habit in sections cut normal to S3 is due to flattening by the influence of the thermal gradient affecting the rocks perpendicular and horizontal to S3 (Fig. 14). Kamineni and Carrara (1973) also recorded the occurrence of two biotites in the Sparrow Lake area. They concluded that they were developed during different stages of a continual metamorphic process, as for the above, but were produced by stress variation prior to granite emplacement, rather than by a thermal overprint.

Fyson (1984, 1985) studied the stress conditions during S3/F3, and during his extensive fieldwork he recognized refolding and additional cleavage sets, possibly associated with late Kenoran horizontal movement. In Fyson (1975) he cites pure-shear as a mechanism to produce the consitent strike of S2 quartz trails in S3 biotite, but later, (Fyson, 1984a) he postulates horizontal block-faulting (simple-shear) as a mechanism for the development of refolds and cleavage sets. Clearly pure-shear could not have operated (in the absence of simple-shear) to produce the rotated cordierite crystals at Bullmoose Lake, and garnet at Sparrow Lake (Kamineni *et al.* 1979).

The evidence therefore supports the hypothesis of increased influence of σ_1 by horizontal simple-shear. The Core-veins were therefore probably emplaced during a fluctuating metamorphic scenario, probably as early as F1, right up to, and postdating, the S3/F3/M3 events. Evidence put forward in chapter VII will show that the auriferous mineralization occurred during the waning stages of the metamorphism, and therefore the pathways for fluid migration had remained dilatent up to this time.

A late-stage retrogressive event (M4) has been documented elsewhere in the Southern Slave Structural Province (e.g.. M4, Ramsay and Kamineni, 1977), and at Bullmoose Lake

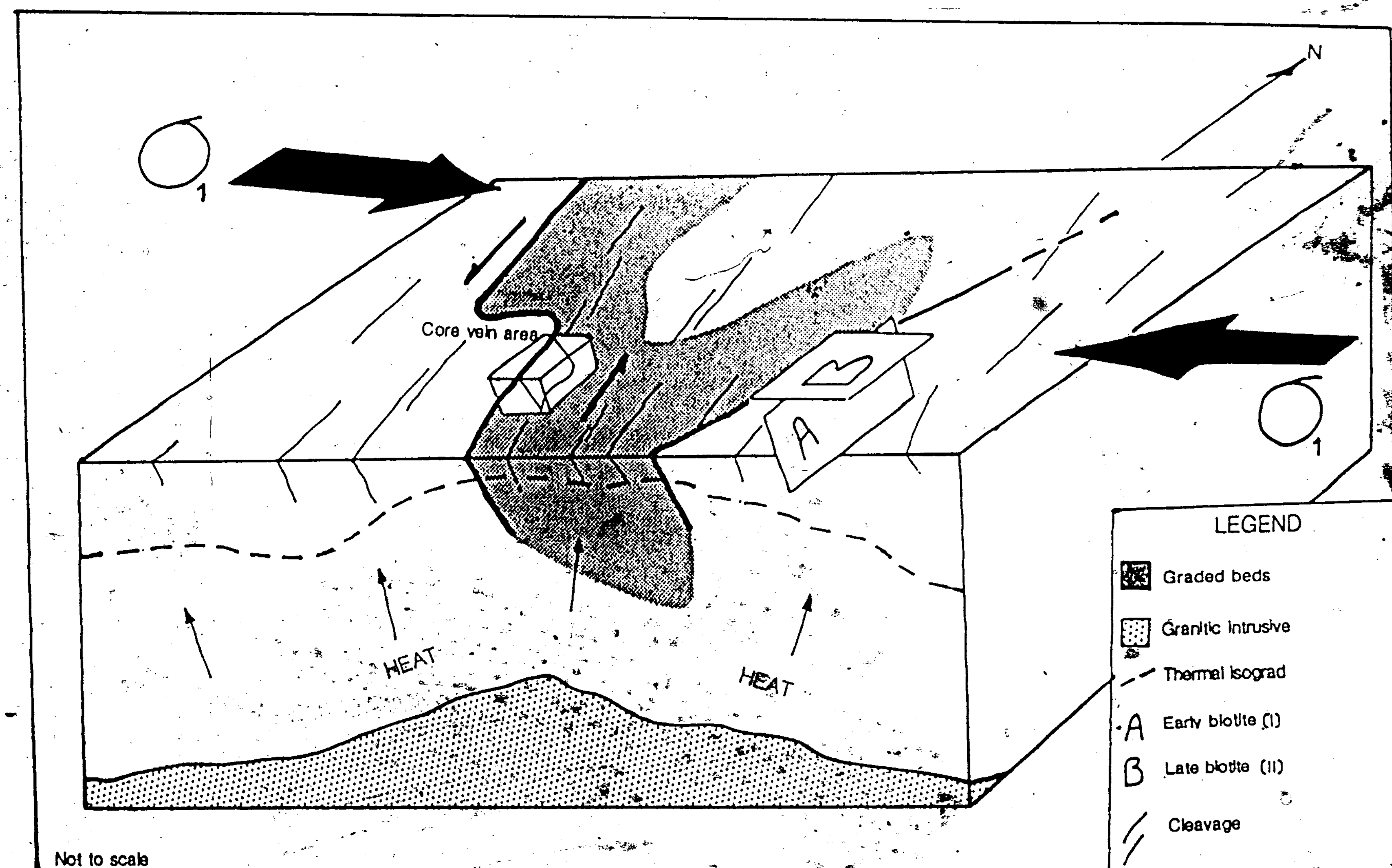


Figure 14. Diagram showing the mode of development of early biotite related to S3 and a later biotite related to M3, Bullmoose Lake

this is recorded by the noticeable direct replacement of biotite and cordierite by chlorite. Late stage euhedral andalusite is also associated with this phase, suggesting that temperatures and pressures were lower than for M3. The most significant feature of the chlorite from a paragenetic viewpoint, is its cross-cutting relationship to the minerals associated with main phase auriferous mineralization. A time, and a tentative temperature/pressure constraint, can therefore be placed upon the mineralization. Estimated temperatures and pressures of the M4 phase (Ramsay and Kamineni, 1977) are less than 500°C and 3kb respectively (also see Thompson, 1978 for discussion).

VI. Gold Mineralization and Mineralogy at Bullmoose Lake

The gold mineralization is hosted in blue-grey quartz veins which contain an abundance of sulphide minerals (up to 8%) and graphite. Occasionally gold is also found in a sucrosic variety of quartz (see page 38) and within 'quartz blebs' located in the metapelitic wall-rocks (plate 12).

Table 3 lists, in order of abundance, the sulphide minerals found in association with gold at Bullmoose Lake. Routine petrographic studies were accompanied by other analytical techniques such as mineral reflectance (N.I.S.O.M.I.)[3], S.E.M. and microprobe studies in order to determine the composition of the sulphides. The sulphide mineralogy is fairly typical of type 2b (see page 18) vein deposits (Padgham, 1985; Lord, 1951; Wiwchar, 1957), except that the BiTe mineral, tentatively identified as tetradymite, has not been recorded elsewhere in metasedimentary-hosted veins of the Slave Province to the author's knowledge.

Polished thin sections were prepared to investigate the relationship between the opaque and transparent minerals. The most abundant gangue mineral, quartz, is accompanied by albite, chlorite, biotite, sericite, ilmenite, magnetite, ankerite, fluorapatite, scheelite, graphite and minor actinolite (at the vein margins).

Sulphide minerals

The sulphide minerals and gold, are often located near the vein margins or within the silicified bands of the metapelitic units adjacent to the quartz veins. The sulphide phase assemblage (table 3) was introduced into the rock after the formation of most of the quartz, and noticeably cuts across the strained quartz (plates 13 and 14) or is interstitial to quartz grains (plates 15 and 16). The mineralizing fluids were clearly introduced after peak metamorphism, as deduced from their relationship with deformed quartz. The sulphide minerals are usually found either as amalgamations ('blebs') of different sulphide minerals (particularly Fe-sulphides) or as 'late-phase' cross-cutting veinlets. The veinlets commonly cut across the foliation (defined by gangue minerals) at a high angle and are often rimmed by

[3]Method of analysing the spectral wavelength reflectance of minerals (Atkin and Harvey, 1982)

Table 3. Sulphide minerals found in association with gold, Bullmoose Lake

NAME	FORMULA	PARAGENETIC STAGE	QUANTITY	HABIT AND OTHER CHARACTERISTICS
Pyrrhotite	$Fe_{1-x}S$	EARLY	COMMON	Closely associated with py / locally replaced by gn, +sph occasionally replaced by pn
Pyrite	FeS_2	EARLY TO LATE	COMMON	Coexists with po - sometimes associated with Au euhedral - anhedral
Galena	PbS	EARLY TO LATE	COMMON IN LOCAL PATCHES	Associated with BiTe mineral Anhedral; blue in colour
Arsenopyrite	FeAsS	EARLY	COMMON IN LOCAL PATCHES	Usually euhedral, isolated
Chalcopyrite	$CuFeS_2$	EARLY TO LATE	UNCOMMON except in (#7 VEIN)	Associated with py and often present late cross cutting veinlets
Bi Telluride Min (Tetradymite)	Bi, TeS (Bi_2Te_2S)	LATE	UNCOMMON / RARE	Predominantly late in the paragenesis. Asssociated with galena
Pentlandite	$(Fe,Ni)_9S_8$	EARLY TO LATE	UNCOMMON / RARE	Replaces po in local patches
Sphalerite	ZnS	EARLY TO LATE	UNCOMMON / RARE	Some Fe and Cd substituted into lattice, usually late but also found with Au early in paragenesis
Native Gold	Au	EARLY TO LATE	COMMON LOCALLY	Minor Ag (< 10%). Gold found in veinlets and in sulphide blebs

Plate 12. Quartz "bleb" containing gold in silicified metapelitic wallrock, #4 vein, Bullmoose Lake.

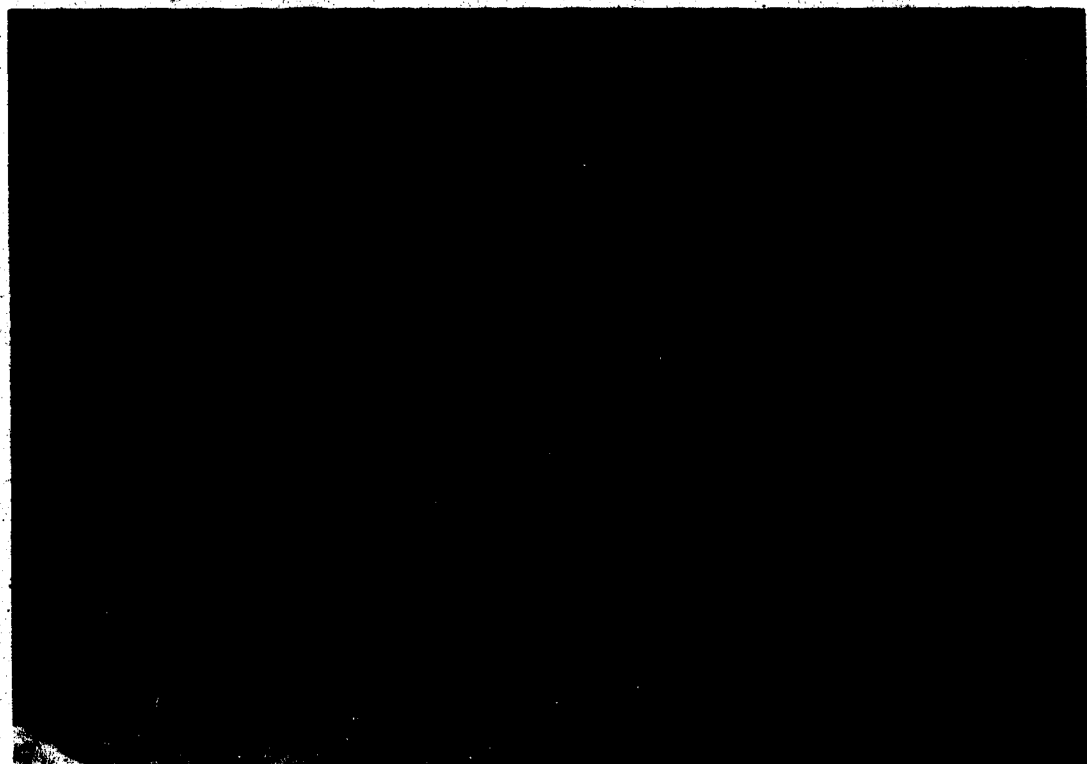


Plate 13. Secondary fluid inclusions and gold (ppl), #14 vein, Bullmoose Lake

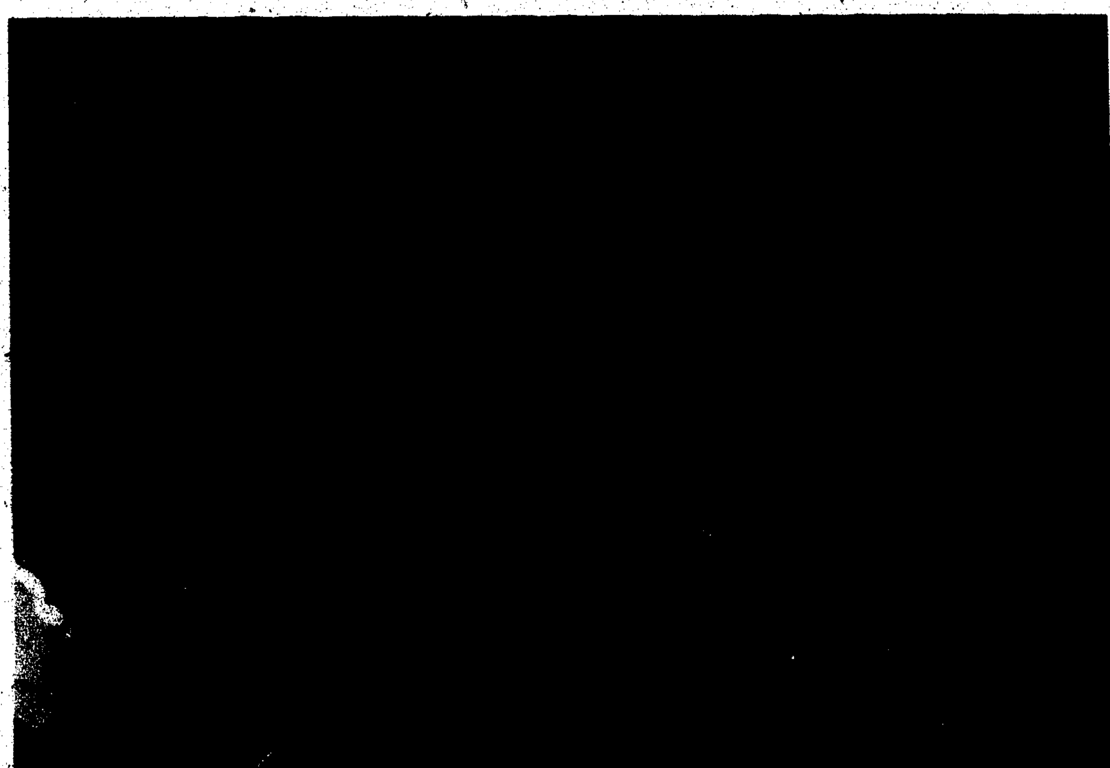


Plate 14. Secondary fluid inclusions and gold (note some fluid inclusions crossing quartz grain boundaries, at top of photograph) (xpl)

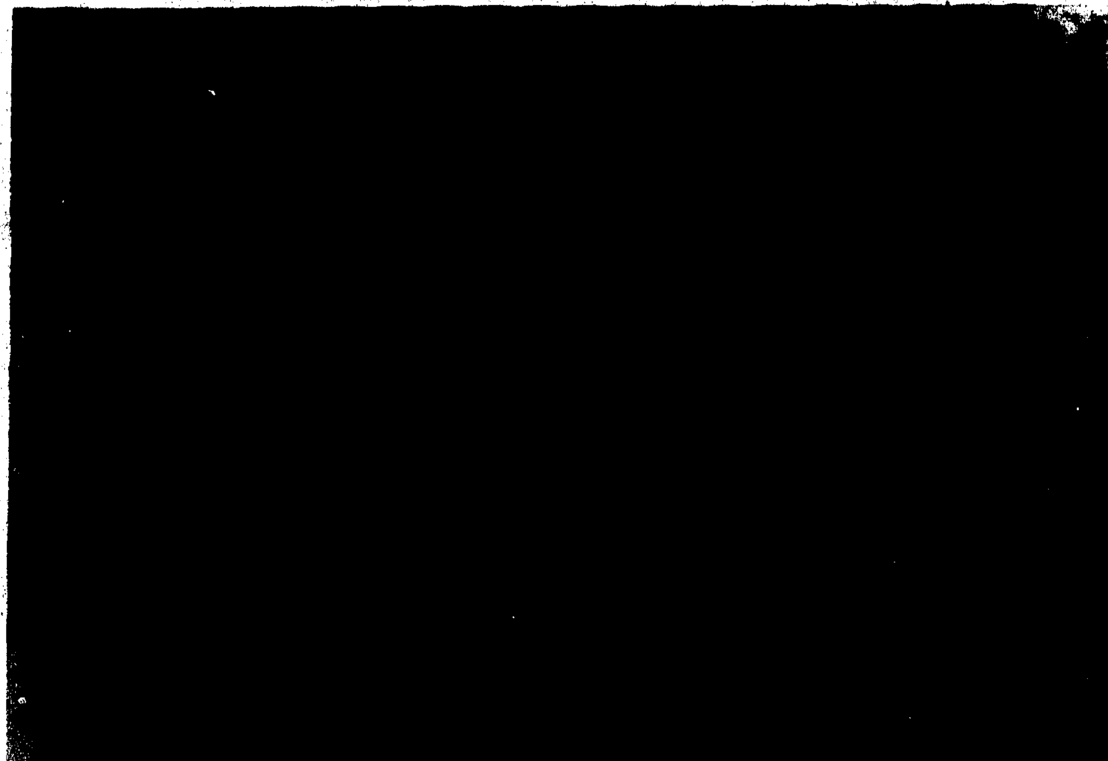


Plate 15. Pyrrhotite and gold forming interstitial to quartz, [illegible] #4L vein

Plate 16. Sulphide minerals (galena, BismuthTelluride mineral, pyrrhotite) and gold surrounded by quartz (xpl), #4L vein

chlorite, and occasionally ankerite. The veinlets sometimes follow the path of stylolites and it is very common for them to follow the penetrative fabric for some of their length. The sulphide veinlets and 'blebs' are not deformed (Volkes, 1969) providing further evidence of post-peak metamorphism mineralization.

The most common sulphide minerals, pyrrhotite and pyrite, are occasionally found coexisting within the same sulphide bleb. The grains are usually subhedral to euhedral and vary in size from 2-3 microns to several millimetres in length. Subidioblastic to idioblastic pyrite and pyrrhotite grains are also found in the metapelitic wallrock, surrounding quartz veins associated with idioblastic arsenopyrite. There is no evidence for replacement of pyrite by pyrrhotite or vice-versa. Pyrrhotite is by far the dominant sulphide found in the auriferous quartz veins. The pyrite most commonly seen in the mine workings is not associated with the auriferous mineralization. This coarse and often euhedral variety of pyrite is often present on cleavage and fracture planes and was probably formed much later than the gold mineralizing event.

Galena is a relatively rare mineral at Bullmoose Lake and is confined to the blue-grey quartz veins. It has often been mistaken for molybdenite, due to its blue colour and malleable nature. In thin section it does not show the characteristic triangular pitted cleavage but it has been conclusively identified as galena by S.E.M[4]. investigations. Galena is often a good indicator of high-grade ore, suggesting a common paragenetic link between the two minerals.

Arsenopyrite, BiTe, pentlandite, chalcopyrite and sphalerite are relatively rare phases in the veins (except for arsenopyrite), and they have generally co-precipitated late in the paragenesis. These sulphides are often found in fractures that contain, or are parallel to, secondary inclusions. Several fracture sets commonly intersect and there is no general preferred fracture orientation.

Figure 15 illustrates the observed paragenesis of the sulphide minerals. Although Fe sulphides are the most common minerals, petrographic evidence has shown that there is no clear sulphide paragenetic sequence, or paragenetic sequence between the sulphide minerals

[4] The S.E.M was fitted with an energy dispersive analyser

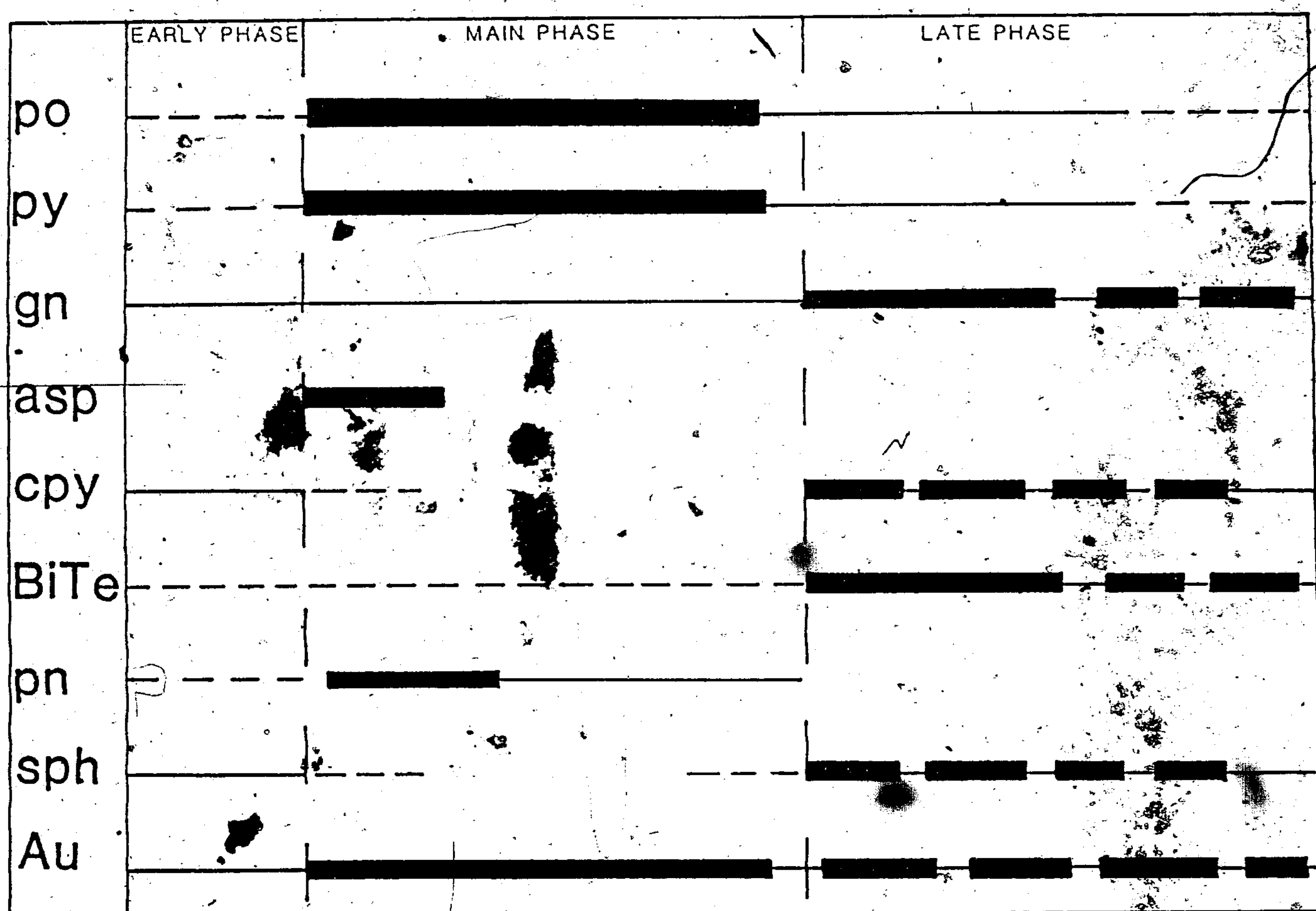


Figure 15. Paragenesis of the sulphide minerals and gold at Bullmoose La

and gold.

Mineralogy of the gold

The gold is fine-to coarse-grained (0.3 - 20 mm) and found in three forms:

1. Large blebs associated with any of the sulphide minerals listed above. The blebs range from about 0.3 mm to several cm in length. Very rarely the gold has been found exhibiting a cubic habit. Often two or three various sulphide grains will combine with a grain of gold and the assemblage will appear isolated in quartz (plate 16).
2. Late veinlets often contain quartz, chlorite, ankerite and various sulphide minerals, typically Fe-poor sulphides. In some cases gold is the only mineral in the veinlet besides quartz and/or ankerite. Ankerite is fairly common in the veinlets. The gold that occurs in veinlets, like the blebs, can be found in association with any of the listed sulphides, although there is a preference for galena, sphalerite and chalcopyrite over Fe-sulphides. In some cases a variety of different sulphides are precipitated along the length of one veinlet.
3. Interstitial to laths of biotite formed during metamorphism of the metapelites (plate 18). The gold also occasionally forms within the biotite flakes along the cleavage.

X-ray spectral investigations shows the gold to contain less than 10% Ag (plate 19), which is consistent with the findings of Boyle (1979) and Brophy (pers. comm., 1986).

Gold grades

The gold grade of individual veins varies considerably, a situation which is not uncommon to vein-gold deposits. Grades can range from 2358 g/tonne (over 1.2 m, Northern Miner, August 1985) to less than 1 g/tonne in the space of a few metres. The best grades were recovered from the quartz veins, very little gold being ~~found in the~~ wallrocks. The average grade in the mine was 7.5 - 9.0 g/tonne (Cloutier, 1986), but enhanced values of up to 12 g/tonne were recovered from:

1. ore-shoots that dipped 65 - 70°N within the plane of the vein

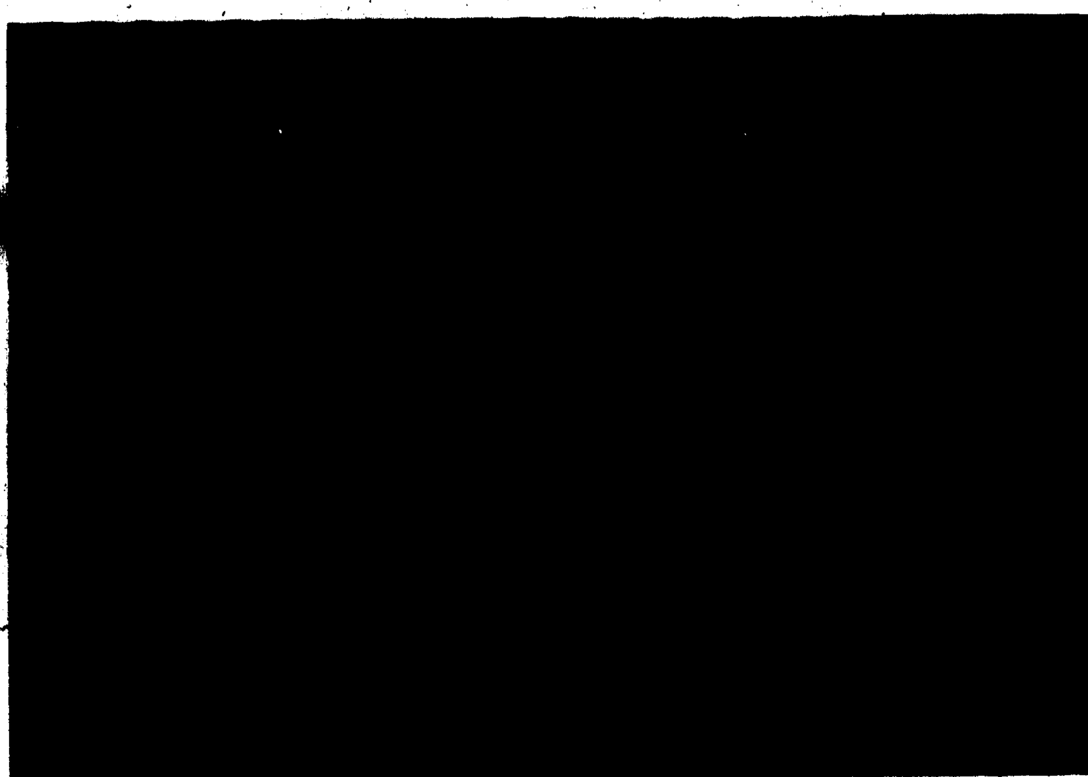


Plate 17. Gold replacing pyrrhotite, (pyrite top-right of photograph), #14 vein Bullmoose Lake

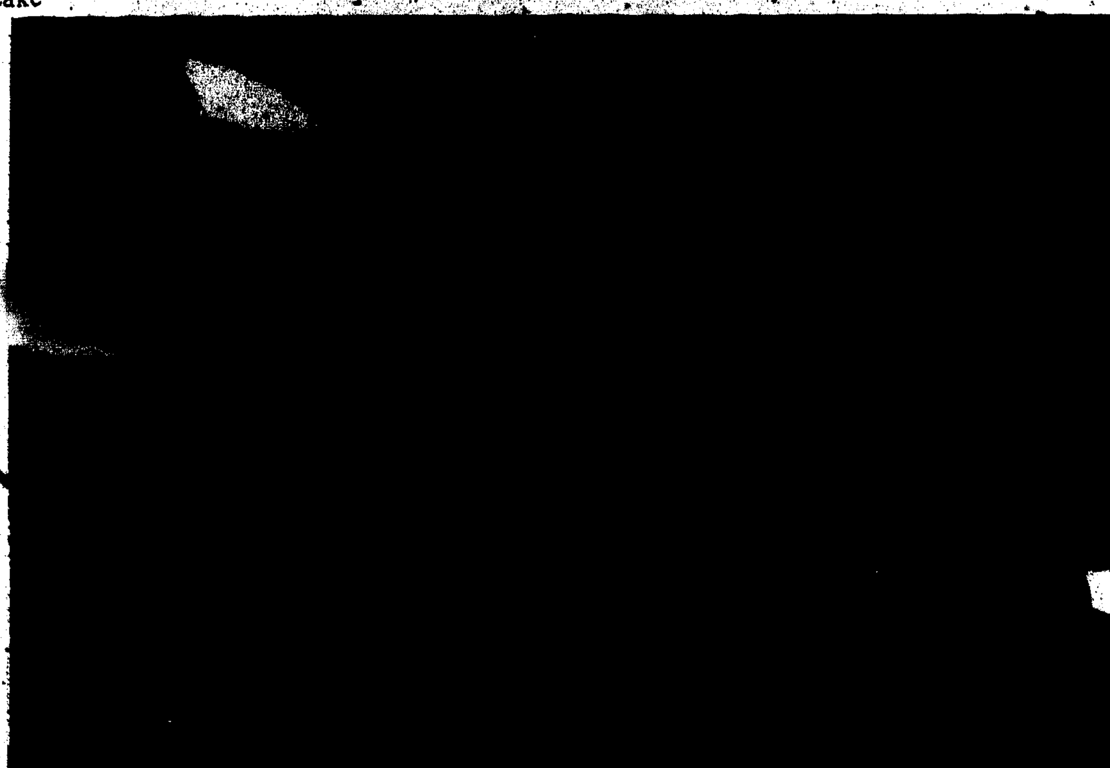


Plate 18. Gold forming interstitial between laths of biotite, (ppl), #14 Vein, Bullmoose Lake

Plate 19. X-ray spectrum histogram of a typical gold grain, Bullmoose Lake

2. stringers which splayed off the main veins (stope assay plans, 60m and 90m level).

The nugget effect caused gold grades between successive 'lifts' to be inconsistent, making mine planning a very difficult task.

Certain veins in the Core-vein area were more productive than others. The most productive veins to date (March, 1987) were the #4, #4F, #4I, #4I_2, and #4L veins.

Deep drilling has intersected auriferous veins at 270m, but it is doubtful whether exploitation to these depths would be profitable at the present time.

The left-lateral shear reported in the rocks down to the 90m level has not been recorded in the rocks of the 150m level. The structural environment strongly influences the location of auriferous sectors and therefore it is doubtful whether the conditions are conducive to extensive quartz vein emplacement at depths below 90m.

Summary

1. 'Main-phase' sulphides are characterised by a predominance of Fe-sulphide minerals, particularly pyrrhotite, which often form isolated blebs surrounded by quartz.
2. 'Late-phase' sulphides are those found in cross-cutting veinlets. Base metal sulphides and chalcopyrite are the most common sulphide minerals in these veinlets.
3. Gold is found in equal quantities in both 'main-phase' assemblages and 'late-stage veinlets'.
4. Gold grades were very erratic in the veins, however, better grades were exploited from ore-shoots and stringers.

VII. Fluid Inclusion and Stable Isotope (O,H,S) Investigations

A. Fluid inclusions

Previous studies on fluid inclusions from metasediment-hosted gold deposits in the Southern Slave Structural Province

Temperatures of homogenization (T_h) and estimates of fluid inclusion salinities from various auriferous and barren veins in the Southern Slave Structural Province were presented by Ramsay (1973a) and in more detail by English (1981). Their studies concluded that there were two compositionally different fluids involved on the formation of auriferous and barren quartz veins, namely:

1. an early fluid (primary inclusions) - Mean T_h; 250°C in greenschist grade rocks and 280°C in amphibolite grade rocks (range 150°-330°C).
   Mean salinity, 5.5 wt% NaCl equiv. (range 1-8%).
2. a later fluid (secondary inclusions) - Mean T_h, 140°C, in both greenschist and amphibolite grade rocks (range 100-200°C).
   Mean salinity, 11 wt% NaCl equiv. (range 6-22%).

CO_2 and CH_4 in the fluid inclusions

Crushing studies performed by English (1981) showed that a significant quantity of CO_2 was present, but he was unable to detect a carbon-dioxide clathrate ($CO_2.5.75H_2O$) during routine fluid inclusion freezing. CH_4 was not recorded directly from the crushing experiments (English, 1981), but its presence could be inferred by the observation of an hydrocarbon [illegible] CO_2 [illegible]ated kerosene in about 40% of the measurements, and by the observed presence of methane in nearby vein-gold deposits (e.g. the Con and Discovery mines at Yellowknife). CH_4 would be expected in the presence of CO_2 and H_2O, if the fluids were trapped during metamorphism, for the presence of graphite in the metapelitic wallro[illegible] would cause CH_4 to be an important species in the metamorphic fluid (Rye and Rye[illegible]

The fo[illegible] reactions could account for the presence of CH_4 (Morton[1] pers. comm 1985; French [illegible]:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$^{2}6FeSiO_3 + C + 2H_2 \rightarrow 6SiO_2 + 2Fe_3O_2 + CH_4$$

$$^{2}6FeO + C + 2H_2O \rightarrow 2Fe_3O_4 + CH_4$$

Smith *et al.* (1985) and Wood *et al.* 1986, identified CH_4 in fluid inclusions in quartz at the Hollinger mine, Quebec, where veins intersect carbonaceous horizons. Many other examples of CH_4 occurring in metamorphic rocks (e.g. Guha *et al.* 1982; Rye and Rye, 1974) are clear evidence that the presence of hydrocarbons is not in any way unusual in the Yellowknife metasedimentary rocks. CH_4 is not only important as a factor which may increase apparent fluid salinity, but also possibly an influential factor in the precipitation of some minerals by the process of reduction. The Camlaren and Con gold mines in the Slave Province have both recorded high quantities of CH_4 in the wallrocks of the mine, and in October 1973 an explosion occurred in the Con mine which was caused by the accidental combustion of CH_4.

Fluid inclusion study of the Bullmoose Lake quartz veins

English (1981) determined the temperature of homogenization (T_h) and salinities of 5 primary and 5 secondary inclusions from Bullmoose Lake (#4 vein, T.A. claims appendix #3, English, 1981). His study found that the inclusions had a mean primary and secondary T_h of 280°C and 140°C respectively. The inclusions also had estimated salinities of 5.5 wt% NaCl equiv. for primaries and 11 wt% NaCl equiv. for secondaries, both analyses corresponding well with the overall T_h and salinities for all of the veins that he studied in the Slave Province.

Freezing measurements were not performed in this present study.

During this investigation T_h experiments (in the liquid phase) were performed on 42 fluid inclusions from the Core-veins (#4, #4B, #4F, #4I, #4I₂, and #4L), 11 zone, #9 vein and airport veins using a U.S.G.S. fluid inclusion stage. The rocks were collected from the 60m level in the mine (#4, #4B, #4F), the 180m level (#4L, #4I vein), and the surface (#9 and Airport veins) Samples were carefully selected so that both visible gold and fluid inclusions could be observed. Sections were cut to about 0.5mm thickness and they were polished on both sides. It became apparent that several of the sections cut were not suitable for fluid inclusion analysis because of the scarcity of inclusions, probably as a result of deformation after fluid entrapment.

Primary, secondary and pseudosecondary inclusions were identified, using the criteria outlined in Roedder (1984). The types of inclusion found were, as expected, similar to those found by English (1981, Fig. 4) and most of the inclusions (over 80%) were therefore of the secondary liquid-rich H_2O-vapour variety (type 1a, English, 1981). Primary inclusions (type 1b, English, 1981) were much rarer, and these often contained more vapour than the secondary inclusions and occasionally contained liquid CO_2.

Homogenization temperatures for 18 primary inclusions and 24 secondary inclusions are shown in figure 16. The average T_h of primary inclusions is 272°C and of secondary inclusions 200°C. The results of the primary inclusion homogenization temperatures are therefore comparable with the amphibolite grade inclusions studied by English (1981), but the secondary inclusions are, on average, 50-60°C higher than his results. The limit of error in the procedure was ± 1.5°C.

Critical review of the data on fluid inclusions from the Bullmoose Lake deposit

Although the data collected during this study of fluid inclusions are limited, it is pertinent to review the results of English (1981) in the light of recent advances in fluid inclusion geothermometry and geobarometry.

The salinity data of English (1981) are difficult to compare with other similar data worldwide, due to the fact that very few of these types of deposit have been studied in terms

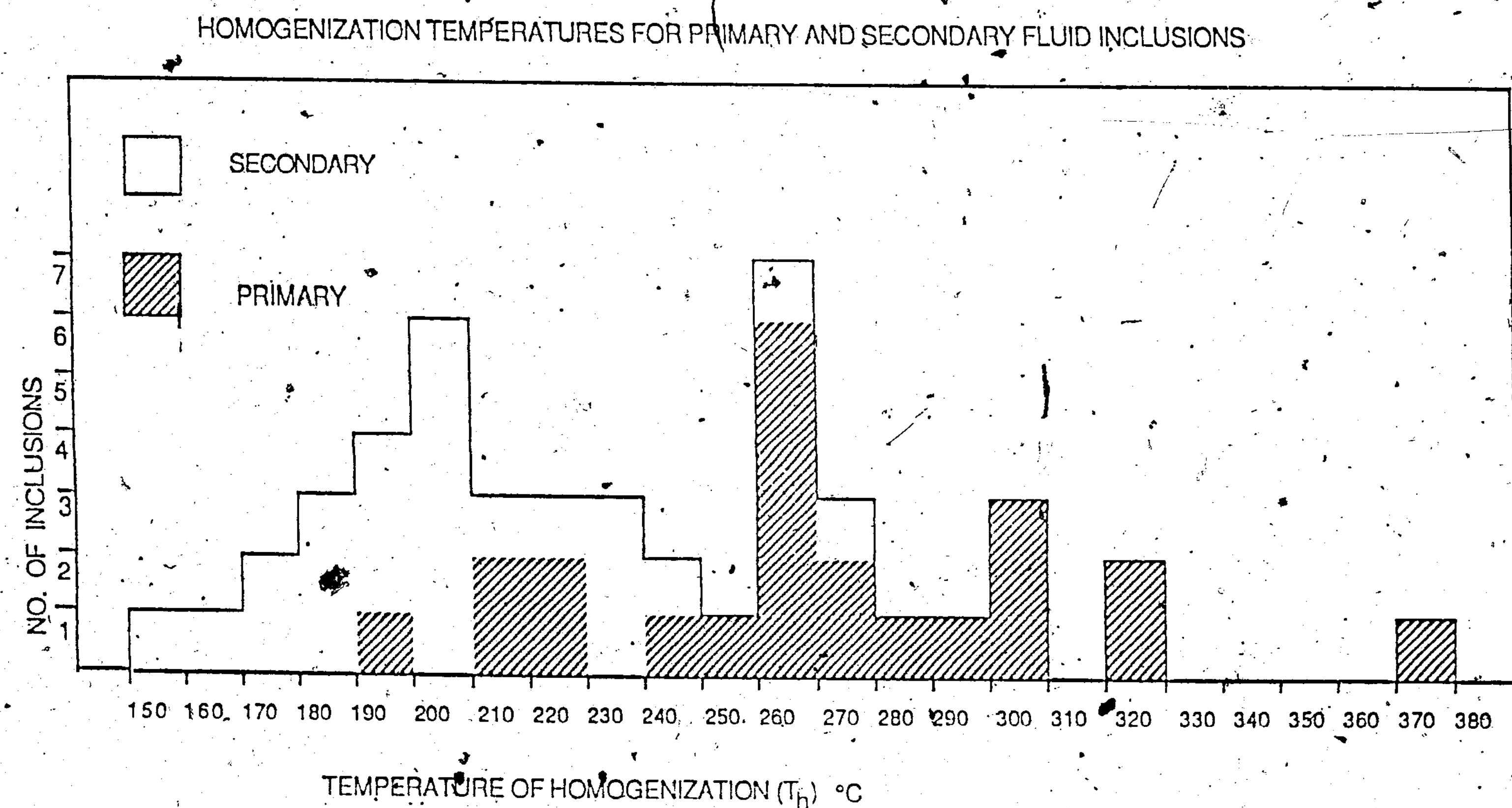


Figure 16. Fluid inclusion homogenization temperatures for primary and secondary inclusions, Bullmoose Lake

of their fluid characteristics. Yonover (1984) and Smith *et al.* (1983) Graves and Zentilli (1982) studied fluid inclusions from the Meguma district in Nova Scotia, but apart from these authors there has been no such study documented from metasediment-hosted gold deposits. Fluid inclusion studies in the more familiar 'shear-zone' hosted gold deposits, which are probably the closest analogy to metasediment-hosted gold deposits based on structure and genesis, typically have salinities that are less than 5 wt% NaCl equiv. with a mean of 2-3 wt% NaCl equiv.

The importance of establishing the correct fluid salinity is apparent when a pressure correction is applied to the T_h, in order to determine the temperature of trapping (T_t). Errors generated by estimation of the wrong NaCl (equiv.) content may lead to a temperature correction difference of 5° - 20°C for a body of rock experiencing the same amount of pressure (Potter *et al.* 1978). It is also important to document the fluid precisely so that its characteristics may be accurately compared with other deposits. English (1981) did not report having seen a clathrate, although a considerable amount of CO_2 was detected during his crushing experiments. The small size of the inclusions and difficulty in recognizing the clathrate precluded the recognition of CO_2, but as suggested by Higgins (1980), *dissolved* CO_2 in the aqueous phase can depress the melting point of ice by 3.2°C. If CO_2 is present, but remains undetected, the inclusions will therefore record an apparent salinity that is higher than the actual salinity of the fluid.

In summary, it is possible that the Bullmoose Lake and other similar vein fluid compositions may be slightly less saline than was previously considered (i.e. closer to the composition of fluids observed in 'shear-zone' type deposits). The salinity adjustments neccessary to account for CO_2 (in wt% NaCl) are therefore obviously greater for the primary inclusions than for the CO_2 poor inclusions of secondary origin.

Having outlined the influence of CO_2, it is also worthy of mention that methane is very soluble in sodium chloride brines (Collins, 1979) and, if left undetected, will cause an apparent increase in the salinity of the fluid. CH_4 is probably present in the inclusions at Bullmoose Lake and other metasedimentary deposits, thus its detection is critical if a precise salinity estimation is to be attempted.

Pressure correction of fluid inclusion data

Pressure estimates for the metamorphism of the Southern Slave Structural Province were presented by Thompson (1978) and Ramsay and Kamineni (1977) based upon the stability, and age relations, of successive metamorphic assemblages. The T_h of the fluid inclusions gives an estimate of the *minimum* temperature of formation, but by knowing the approximate pressure during mineralization a temperature correction may be applied to give an estimation of the temperature of entrapment. The mineralization was post-peak metamorphism, thus an upper limit on the pressure of entrapment can be placed at the pressures which are required to form cordierite (approximately 2.5 kb, Winkler 1979). If the mechanism of vein emplacement is then considered to be a function of the mechanical properties of the rock under the influence of P_f (Groves *et al.* 1985; Henley *et al.* 1976; Norris and Henley, 1976; Yardley, 1986) an approximate P_l can be assumed for the locii of emplacement.

Some authors (e.g. Phillips and Groves, 1983, Fyfe and Kerrich, 1984) cite the greenschist - amphibolite boundary as a significant site for hydrofracturing, due to the transition from ductile to brittle/ductile rheological conditions, and a site for the expulsion of fluids by devolatisation. The pressure at this depth within the supracrustal sequence has been reconstructed from the calculations of Thompson (1978) and corresponds to a figure of 2 - 2.5 kb. A pressure correction was therefore applied to the T_h fluid inclusion results of English (1981) and of this study, to predict the temperature of entrapment of the mineralizing fluids, providing it is assumed that these fluids actually introduced the gold.

It is impossible to estimate the limit of error incorporated in this approach, but it is safe to assume that the fluids were not connected to surface at the pressures and temperatures predicted for entrapment, therefore a pressure correction is warranted. English (1981) did not apply a correction because he wrongly assumed that CO_2 - H_2O phase separation ('boiling') had occurred in the rocks. The different filling ratios that English observed were partly produced by deformation of the inclusions during late tectonism and were possibly in part a simple function of errors of observation of irregular inclusions.

A conservative pressure correction of 2 kb has therefore been applied to the T_h for the the salinities measured by English (1981), using the curves of Potter (1978). Primary inclusions are therefore predicted to have a *maximum* T_t of 440°C (5 wt% NaCl equiv.) and secondary inclusions 302°C (11 wt% NaCl equiv.). The precise T_t is difficult to predict, but the estimated T_t is calculated as 360°C for primary inclusions and 220°C for secondary inclusions based upon the criteria cited above.

The significance of applying a pressure correction is therefore to show that the deposits were probably emplaced at temperatures higher than previously considered, but more data are needed to constrict the temperatures and pressures of fluid emplacement. An estimated salinity correction was not applied to the data, as freezing studies were not performed in this study. However, it is probable that the primary fluids are 2-3 wt% NaCl (equiv.) less saline than previously considered, on account of CO_2 (and possible CH_4), and the secondary fluids 1-2 wt% NaCl (equiv.) less saline, depending upon the amount of CH_4 present.

The apparent difference between the T_h results of English (1981) and this study for secondary inclusions is unclear.

Summary of results - fluid inclusion study

Primary inclusions - T_h ~ 280°C, T_t ~ 360°C, salinity ~ 3 wt% NaCl equiv.

Secondary inclusions - T_h ~ 140°C, T_t ~ 220°C, salinity 8-10 wt% NaCl equiv.

B. Oxygen and Hydrogen isotope study

Five samples of quartz were selected for oxygen and hydrogen/deuterium isotope analysis. Three samples were collected from blue-grey quartz veins (#4 vein, Lambert vein, #9 vein and the Airport vein) and the other sample was taken from a late white quartz vein (11 zone).

The oxygen isotope ratios of quartz were measured using the BrF_5 method (Clayton and Mayeda, 1963). Quartz was treated with BrF_5 for 24 hours at 650°C to liberate oxygen which reacted with carbon to form carbon dioxide. The CO_2 was analysed on a 602D MM mass spectrometer.

The D/H analyses were performed by extracting water from fluid inclusions in quartz. About 10-15 g of quartz were cleaned and heated in nickel tubes at about 150°C for 2-3 hours to remove adsorbed water. The fluid inclusion study clearly demonstrated a temperature of homogenization (T_h) difference between the primary and secondary inclusions, therefore water was collected at different temperatures in order to try and obtain the isotopic characteristics of each fluid. Fluid collected between 150°C and 350°C (by decrepitation) was considered to be representative of secondary origin and the fluids collected from above this temperature, primary. After extraction, the water samples were reacted with uranium metal at 750° to liberate hydrogen. The samples were then analysed for D/H ratios using a 602C MM mass spectrometer. The oxygen and hydrogen isotope ratios were expressed as:

$$\delta = (R_1/R_2 - 1) \cdot 10^3$$

δ is expressed as per mil (‰), and R_1 and R_2 are $^{18}O/^{16}O$ or D/H ratios of the sample and standard respectively.

Analytical error is estimated as ±0.1‰ for oxygen and ±3‰ for hydrogen.

The oxygen and hydrogen isotope ratios were recorded as a del value (δ) relative to Vienna Standard Mean Ocean Water (V-SMOW, Gonfiantini, 1978).

Results

The analytical results, together with other values recorded from similar veins are presented in table 4. The $\delta^{18}O$ values of the quartz samples ranged from 12.2 to 13.9‰ for the Bullmoose Lake fluids and the single Dome Lake value was 14.9‰.

The δD values (table 4) show a significant range of -84 to -129‰ for the Bullmoose Lake rocks. The primary fluids show a δD range of -84 to -95‰ and the secondary fluids which were collected from 150-300°C are significantly lighter (-119 to -129‰).

LOCATION	VEIN	METAMORPHIC GRADE OF COUNTRY ROCKS	$\delta^{18}O_{QUARTZ}$ SMOW	$\Delta^{18}O_{QUARTZ\ MINERAL}$	TEMPERATURE OF ENTRAPMENT (°C) (PRESSURE CORRECTED) FLUID INCLUSIONS	TEMPERATURE OF ENTRAPMENT (°C) (PRESSURE CORRECTED) Δ QZ-MINERAL	$\delta^{18}O$ FLUID H_2O	δD FLUID ‰ PRIMARY FLUID	δD FLUID ‰ SECONDARY FLUID
BULLMOOSE LAKE	#4 VEIN	MEDIUM	13.9	----	280 - 440	-----	+5.4 - +7.4	-91	-119
BULLMOOSE LAKE	#11 ZONE	MEDIUM	13.3	----	280 - 440	-----	+3.8 - +6.8		-129
BULLMOOSE LAKE	#9 VEIN	MEDIUM	12.2	----	280 - 440	-----	+3.8 - +5.7	-84	-126
DOME LAKE	LAMBERT	LOW	14.9	----	250 - 400	-----	+4.9 - +6.8	----	-----
BULLMOOSE LAKE	AIRPORT	MEDIUM	-----	----	280 - 440	-----	---------	-95	-----
CAMLAREN [1]	------	LOW	13.4	----	250 - 400	-----	+4.5 - +9.3 [4]	----	-----
McMEEKAN BAY [1]	------	LOW	13.3	----	250 - 400	-----	+4.4 - +9.2 [4]	----	-----
TOM [1]	------	MEDIUM	12.3	----	280 - 440	-----	+4.7 - +9 [4]	----	-----
PTARMIGAN [1]	------	MEDIUM	12.3	----	280 - 440	-----	+4.7 - +9 [4]	----	-----
McMEEKAN BAY [2]	------	MEDIUM	12.5	----	280 - 440	-----	+4.9 - +9.2 [4]	----	-----
PTARMIGAN [2]	------	MEDIUM	12.6	5.9 [5]	280 - 440	360	+5 - +9.3	----	-----
CON MINE [2]	VEINS IN SHEAR ZONE		11.5 - 12.5	3.5 - 3.8 [6]	-----	325 - 360	+5 - +7.5	----	-----

FOOTNOTES

1 DATA FROM ENGLISH, 1981
2 DATA FROM KERRICH, 1981
3 EQUATION FROM MATSUHISA et al., 1979
4 $\delta^{18}O$ FLUID RECALCULATED USING $\Delta^{18}O$ QUARTZ - H_2O EQUATION OF MATSUHISA et al., 1979
5 $\Delta^{18}O$ QUARTZ-CHLORITE
6 $\Delta^{18}O$ QUARTZ-MUSCOVITE

The oxygen isotope compositions of the original mineralizing fluids were calculated using the quartz-water fractionation equation of Matsuhisa *et al.* (1979). The temperatures used in the calculations were those determined from the estimated temperature of entrapment from fluid inclusions, and have therefore been corrected for pressure effects.

Discussion

The $\delta^{18}O$ values of the four samples are slightly higher than those determined by English (1981) and Kerrich (1980), who present results for similar veins. The results show the Lambert vein (Dome Lake) hosted in lower grade rocks, to be 1‰ heavier than the Bullmoose Lake rocks. Although only one such value is available, the relative enrichment is consistent with the findings of English (1981) and Rye and Rye (1974) where quartz veins are 1-3‰ heavier in greenschist grade rocks relative to amphibolite grade. Fleck and Criss (1985) attribute this type of trend to syn-metamorphic amphibolite grade fluids driven by heat from a crystallizing batholith. There is evidence therefore that the isotopic signature of the veins may be partly attributed to thermal metamorphism. Stokes *et al.* (1987) document evidence for vertical movement during M3/F3 in a similar vein deposit at Gordon Lake. It is possible that this movement was caused by the diapirism of a granitic body.

Recalculation of the mineral pair $\Delta_{quartz-chlorite}$ (using the equation of Wenner and Taylor, 1971) from veins of the Ptarmigan deposit (Kerrich, 1979) gives temperatures of 360°C for the temperature of entrapment of the fluid. This figure is consistent with the T_t of primary fluid inclusions of this study.

Five major types of water have been distinguished on the basis of isotopic analysis; meteoric water, ocean water, connate water, metamorphic water and primary magmatic water (Taylor, 1979). The ore could have been precipitated from any of these fluids, however the isotopic characteristics and field relations restrict the possibilities to metamorphic, meteoric or primary magmatic.

Evidence for some vertical movement caused by diapirism and the $\delta^{18}O_{fluid}$ values cannot completely preclude the possibility of the influence of magmatic fluids at Bullmoose

Lake, providing Archean fluids are presumed to have similar isotopic characteristics to Phanerozoic fluids. It is possible that some fluid may have been derived from a plutonic body and some by metamorphic devolatilisation. Isotopic readjustments may have occurred during waning from peak metamorphism. However, the veins are not connected to any visible magmatic feeder system and the fluids do not match the typical tight δD cluster of a primary magmatic fluid. It is improbable that if primary magmatic fluids were derived from a post-metamorphic [illegible]otopic variation would be recorded between the veins from greenschist rocks and those of amphibolite [illegible]liths in the area, of the Prosperous Lake granitic suite, are also slightly enriched in $\delta^{18}O$ (Kerrich *et al.* 1984) indicating the probability of a separate source.

The δD variation of the primary and secondary inclusions indicates the possibility of a different source for the two fluids. There is substantial evidence from the fluid inclusion study and the time relations of quartz emplacement that the primary fluids were of a high temperature origin. The primary fluid results are depleted in δD relative to a typical metamorphic fluid, however the field relations suggest a metamorphic origin is more likely than a high temperature meteoric origin.

The secondary fluids are strongly depleted in δD (-119 to -129‰). At first glance the results may indicate fluids that are strictly meteoric in origin, but in essence 3 plausible explanations are presented:

1. Although fluids were derived at different temperatures, it should be pointed out that significant mixing of these different fluid inclusion populations during decrepitation can not be be ruled out.
2. Metamorphic and meteoric waters may have mixed (in nature) to produce the results. Metamorphic waters have a $\delta^{18}O$ range of +3 to +20‰ and δD of 0 to -70‰ (Ohmoto, 1986) and meteoric fluids range from 0 to -25‰ and 0 to -200‰ for $\delta^{18}O$ and δD respectively (Taylor, 1979). Therefore the results for the secondary inclusions fall mid-way between the two end member fluids.
3. The presence of CH_4 in fluids causes δD values to be depleted (Rye and Rye, 1974). It is

important to note that methane is very soluble in sodium chloride brines (Price, 1979), particularly at high pressures (Haas, 1978). Rye and Rye (1974) documented significantly decreased δD values in graphitic host-rocks (of the Precambrian, Homestake gold deposit) and attributed them to the influence of CH_4. Crushing studies performed by English (1981) indicated that the fluids were trapped at high pressures and contained hydrocarbons. It is therefore probable that these results, together with the recognition of graphite in the metapelites and blue-grey quartz veins, make it highly likely that CH_4 was an influential component in the fluid.

In summary therefore, the evidence is inconclusive with regard to the source of the fluids. However, the results suggest that there was generation of a heavy δD and $\delta^{18}O$ fluid (of probable metamorphic origin) during metamorphic devolatilisation, followed by a mixed meteoric/metamorphic fluid of depleted δD and $\delta^{18}O$ values. The process envisaged is similar to that described by Kerrich *et al.* 1984, where they claim metamorphic and meteroric fluids were generated during separate episodes.

C. Sulphur isotope study

Forty-seven sulphide minerals from the Bullmoose Lake and Dome Lake properties were carefully picked out for isotopic analysis. The separates were representative of the sulphide assemblages emplaced with gold.

The petrographic study indicated the probability of mineral disequilibrium, however the common association of pyrite and pyrrhotite which may have been deposited during a separate episode from the other sulphides, justified a more detailed investigation. A second reason for performing these analyses was to initiate a sulphur isotopic investigation into metasediment-hosted gold deposits to compliment other isotopic and fluid inclusion data.

In the Yellowknife district, no sulphur isotopic study has been carried out on metasediment-hosted gold deposits, although such studies have been performed on the typical shear-zone hosted deposits (Chary, 1971; Wanless *et al.* 1960).

The sulphide samples were converted to SO_2 using the technique of Ueda and Krouse (1986). Four mg of sulphide were mixed with 80 mg of V_2O_5 + SiO_2 and then heated at 1000° for 30 minutes. The evolved SO_3 gas was then converted to SO_2 by reaction with metallic Cu. The gas was purified by freezing and then the SO_2 was analysed for its isotopic ratios on a mass spectrometer.

The ratio was expressed as:

$$\delta = (R_1/R_2) - 1 \ . \ 10^3$$

δ is expressed as per mil (‰) and R_1 and R_2 are $^{34}S/^{32}S$ ratios of the sample and standard respectively.

Analytical error is estimated as 0.2‰. The ratios are recorded relative to the troilite suphur phase of the Cañon Diablo meteorite (C.D.T., Ault and Jensen, 1962)

All analyses were performed at Dr. Grays' laboratory at the University of Alberta and were analysed for their $^{34}S/^{32}S$ ratios on the mass spectrometer in Dr. Krouses' laboratory, University of Calgary.

Results and discussion

Introduction

The results of the study are presented in figures 17 and 18 and are discussed below. The samples were selected from known 'main-phase' and 'late-phase' assemblages (fig. 15).

Pyrite, pyrrhotite, and arsenopyrite were collected from 'main phase' mineralization at Bullmoose Lake and sphalerite, chalcopyrite, and galena representative of 'late-stage' mineralization were collected from Dome Lake. Other sulphides identified from petrographic studies could not be isolated in quantities necessary for analysis. Fe sulphides were present in minor amounts at Dome Lake, therefore direct comparisons of $\delta^{34}S$ values of identical minerals from Bullmoose Lake (amphibolite grade) and Dome Lake (greenschist grade) were not possible except in the case of arsenopyrite.

The samples were checked for purity using a low-power binocular microscope, however higher-power petrographic studies showed that the sulphide minerals are almost

$\delta^{34}S$‰ (CDT)

SAMPLE #	LOCATION	py	po	asp	sph	cpy	gn
BM-604I-[illegible]-74	CORE VEIN BULLMOOSE LK		0.8				
BM-604I-1-75	"		1.4				
BM-304I2-108	"		1.1				
BM-304I2-109	"		0.7				
BM-304I2-126	"		0.1				
BM-4L-1-73	"					1.7	
BM-604L2-2-77	"					1.7	
BM-604L2-2-78	"					2.3	
BM-604L2-1-80	"		4.0				
BM-604L2-3-81	"		3.4				
BM-604L2-3-82	"		2.2				
BM-604L2-4-83	"	16					
BM-604L2-4-84	"	1.8					
BM-85-1-85	SKEETER LAKE			0.0			
BM-85-1-86	"			1.0			
BM-GS416-1-87	CORE VEIN AREA			5.5			
BM-GS416-1-88	"			4.8			
MAX1 89	MAX VEIN (BM)		1.7				
MAX1 97	"		2.8				
MAX2 98	"	1.7					
MAX2 99	"	1.9					
BMGS-1 100	CORE VEIN AREA		0.1				
BMGS-1 101	"		3.7				
BM4B-1 102	"	2.0					
BM4B-1 103	"	1.6					
BM4B-3 118	"		1.2				
BM4B-3 119	"	1.6					
BM4B-3 120	"	3.1					
BM7V-1 116	# 7 VEIN	1.2					
BM7V-1 117	"	0.9					
BM-15-1 105	# 15 VEIN	3.0					
BM-15-2 110	"	2.4					
BM-15-2 111	"	1.8					
BM4V-1 104	# 4 VEIN		1.2				
BM-GS-100	CORE VEIN AREA	0.3					
BM-GS-100		0.2					
DO-14-1 127	DOME LAKE #14 VEIN						-12.6
DO-14-2 128	" "				5.4		
DO-14-3 136	" "			4.9			
DO-14-6 137	" "						3.1
DO-14-6 138	" "			5.7			
DO-14-6 139	" "						1.8
DO-L-A(1)140	DOME LK. LAMBERT VEIN.						1.4
DO-L-B(1)141	" "				1.9		
DO-L-A(2)142	" "				2.5		
DO-L-B(2)143	" "						1.6
DO-L-2 144	" "					1.5	

Figure 17. $\delta^{34}S$‰ isotope values for sulphide minerals from Bullmoose Lake and Dome Lake

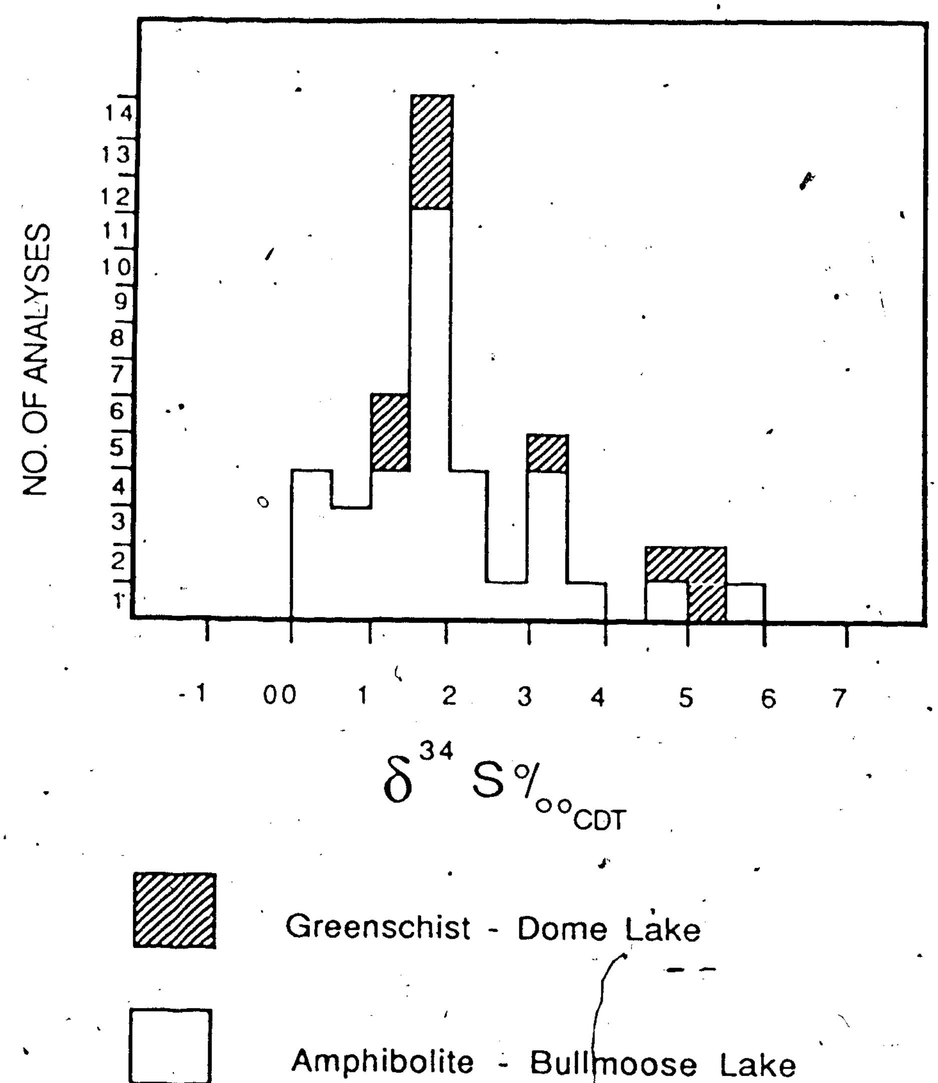


Figure 18. Range of Sulphur isotopes values from Bullmoose Lake and Dome Lake (δ^{34}S CDT‰)

always intergrown (particularly po and py). It is therefore possible that some sample contamination may have occurred.

$\delta^{34}S$ isotope characteristics of the different sulphide minerals

Fe sulphides

Fe sulphides from the Bullmoose Lake property have a $\delta^{34}S_{pyrite}$ range of +0.2 to +3.1 ‰ (15 values), and a $\delta^{34}S_{pyrrhotite}$ range of 0 to +4.0 ‰ (14 values). The fractionation factor for the py-po pair has been determined experimentally by Kajiwara and Krouse (1971) and Ohmoto and Rye (1979) over the temperature range 250 - 600°C. Current data indicate that pyrite should be enriched in ^{34}S relative to pyrrhotite under equilibrium exchange conditions (Bachinski, 1969), but, the results show incomplete seperation between the two minerals. Estimates of the temperature of deposition using the fractionation between Δ_{py-po} (Kajiwara and Krouse, 1971) therefore, gave a very wide range of temperatures (79° - 700°C) which were not consistent with fluid inclusion data. However, the relatively tight cluster of $\delta^{34}S$ values from the pyrite and pyrrhotite could indicate that the sulphides were originally precipitated in equilibrium with the mineralizing fluid. Subsequent metamorphism (which is inferred from petrographic study by the growth of late chlorite [M4, fig. 3] and $\delta^{18}O$ results) possibly adjusted the original isotopic ratios. Since pyrite undergoes sulphur isotopic re-equilibration sluggishly (Bachinski, 1977), the $\delta^{34}S_{pyrite}$ probably reflects original isotopic ratios.

Arsenopyrite

Six arsenopyrite samples were measured for their $\delta^{34}S$ values from the Bullmoose Lake and Dome Lake properties. The results show a wide $\delta^{34}S$ range from 0.0‰ to +5.7‰ and there is no significant variation in the values recorded from the two properties. However if the two samples from Skeeter Lake are considered anomalous, the $\delta^{34}S$ range is fairly tight (+4.8‰ to +5.7‰) and may reflect original $\delta^{34}S$ values. The samples taken from Skeeter Lake were taken adjacent to a fault-zone. Therefore the likelihood of disrupting the original $\delta^{34}S$ ratios under the influence of a later fluid and/or mechanical processes are far greater than for the other locations. Arsenopyrite was the easiest mineral to separate out from the other minerals due to its large idioblastic form in some specimens. Fractionation curves for arsenopyrite are not available at the present time (Krouse, pers. comm., March, 1987).

Chalcopyrite

Four chalcopyrite specimens were analysed for their $\delta^{34}S$ values, 3 from Bullmoose Lake and 1 from Dome Lake. The results show a relatively restricted range of $\delta^{34}S$, possibly reflecting their resistance to isotopic exchange during metamorphism.

Galena

Galena was obtained from 5 samples collected from the Dome Lake, #14 and Lambert veins. The galena analysed was coarse-grained (>5mm), idioblastic, and apart from some possible contamination by bismuth (as shown by petrographic work) was considered to be relatively pure. The results show a very wide range of values from -12‰ to +3.1‰ but is is probable that the one negative value was produced by an analytical error. Disregarding this value the range of $\delta^{34}S$ is +1.5‰, with a mean of +2.0‰. The samples of galena analysed were obtained from specimens which were co-existing with sphalerite. The predicted $\delta^{34}S$ enrichment of sphalerite > galena in equilibrium (Bachinski, 1969) was found in the co-existing sp-gn mineral pairs measured. Geothermometry based on the use of Δ mineral pairs may be therefore be possible in greenschist grade rocks in the Southern Slave Structural Province. Temperatures for the #14 vein were calculated using the Δ_{sp-gn} (Ohmoto and Rye, 1979) and give results of between 170° - 280°C. This temperature range corresponds with the temperature of entrapment determined for the secondary inclusions at Bullmoose Lake (140 - 300°C, English, 1981, and this thesis).

Sphalerite

Three sphalerite samples were collected from the Dome Lake property and ranged from 1.9‰ to 5.4‰ ^{34}S. The sphalerite as mentioned, co-exists with galena and therefore in the absence of idioblastic crystals the variation in $\delta^{34}S$ values may in part be due to contamination by galena.

$\delta^{34}S$ comparisons with other lode gold deposits

The $\delta^{34}S_{pyrite}$ range for the Bullmoose Lake samples (0 to +3‰) is similar to Archean metabasalt and metadolerite hosted lode-gold deposits from around the world (Lambert *et al.* 1984; Phillips *et al.* 1986) which typically have values from -4‰ to +4‰ (Lambert *et al.* 1984; Golding and Wilson, 1983; Phillips *et al.* 1986). At low oxygen fugacities, pyrite has a $\delta^{34}S$ value similar to near-neutral fluids from which it is being precipitated, and these circumstances explain the low positive $\delta^{34}S$ values for Fe-sulphides from many Archean deposits (Phillips *et al.* 1986). Deposits that show evidence of extensive alteration (e.g. Golden Mile deposit at Kalgoorlie, Australia) display depleted $\delta^{34}S$ values of -1 to -7 ‰ as a result of *local* fluid oxidation (Lambert *et al.* 1984; Phillips *et al.* 1986). The range of $\delta^{34}S_{pyrite}$ from Bullmoose Lake are consistent with expected low water-rock ratios, and therefore contain similar $\delta^{34}S$ to the Australian deposits with low water-rock ratios. However, they are slightly enriched (1-2‰) relative to the moderately altered Yellowknife deposits (Kerrich, 1979), and heavily enriched compared with extensively altered deposits such as Golden Mile, Australia (Phillips *et al.* 1986).

The $\delta^{34}S$ of the hydrothermal fluid was not calculated because an *accurate* measurement of the pH and fO_2 was not possible due to evidence for 'disequilibrium;' consequently the limit of error straddles the H_2S/HS^- boundary. The $\delta^{34}S_{pyrite}$ and the sulphide assemblage make it possible to restrict the fO_2 but not the pH of the fluid associated with 'main-phase' mineralization. Consequently any calculations of the $\delta^{34}S_{fluid}$ would be suspect, especially in light of the difficulty in interpreting S-isotopes from vein deposits (Ohmoto, 1986) and the age of the veins (i.e. they may have undergone post - Archean isotopic readjustments).

Summary of sulphur isotope data

1. The $\delta^{34}S$ values of all the sulphide minerals from Bullmoose Lake and Dome Lake ranged from -12‰ (one sample) to +5.7‰, however the main range is from +1 to +4‰.
2. the predicted enrichment of the $\delta^{34}S$ in different sulphide minerals (Bachinski, 1969)

indicates that disequilibrium has occurred in amphibolite grade rocks, probably due to late-stage metamorphism, however, in greenschist grade rocks equilibrium may have been maintained.

3. $\delta^{34}S_{pyrite}$ results from Bullmoose Lake and Dome Lake are typical for the $\delta^{34}S$ range of all Archean lode-gold deposits with low water-rock ratios (1-4‰).

4. there is no significant variation between the $\delta^{34}S$ from the same minerals in amphibolite grade rocks (Bullmoose Lake) and greenschist grade rocks (Dome Lake) based upon the two deposits studied.

5. geothermometry based on Δ mineral pairs is not possible in veins hosted by amphibolite grade rocks at Bullmoose Lake, but at Dome Lake, where the veins are hosted in greenschist grade rocks, Δ_{gn-sph} give temperatures of 170° - 280°C which are consistent with fluid inclusion data from secondary inclusions from Bullmoose Lake.

D. Composition and characteristics of the mineralizing fluids at Bullmoose Lake and Dome Lake

Several observations have to be taken into consideration when reconstructing the nature of the paleo-mineralizing fluid at Bullmoose Lake and Dome Lake:

1. the gold was precipitated with both 'main-phase' and 'late-phase' sulphide assemblages at Bullmoose Lake.

2. the predominant sulphides deposited in the ore-bearing veins were pyrrhotite at Bullmoose Lake and arsenopyrite and galena at Dome Lake.

3. secondary fluids were more saline than primary fluids (by up to 8 wt% NaCl equiv.)

4. the primary fluids were probably metamorphic in origin and their relationship to 'main-phase' and 'late-phase' mineralization is unclear.

5. the secondary fluid inclusions were probably of a metamorphic/meteoric origin and are

definitely related to the 'late-phase' mineralizing event.

The composition and nature of the mineralizing fluids is based on fluid inclusions and isotope data. Several points must be borne in mind concerning the collection of data. All of the fluid inclusion measurements were taken from the Bullmoose Lake property. The O/D isotope ratios were all measured from the Bullmoose Lake property (except for one oxygen number), but of the 47 $\delta^{34}S$ measurements, 11 were obtained from the Dome Lake property. 'Main-phase' and 'late-phase' mineralization was observed at both Dome Lake and Bullmoose Lake. Unfortunately due to the difficulty in separating out sulphide minerals from the different phases, only the the 'main-phase' minerals could be separated out at Bullmoose Lake and 'late-phase' minerals at Dome Lake.

The fundamental assumption that the following interpretation is based upon is, therefore, that the *'late-phase' mineral assemblage analysed from Dome Lake (cpy, sph, gn) is directly comparable to the 'late-phase' assemblage at Bullmoose Lake.* The structure, alteration assemblages, and type of quartz vein are very similar for the two properties, although the $\delta^{18}O_{quartz}$ suggest some isotopic variation (1-2‰) possibly due to metamorphism. However, mineralization is post-peak metamorphism and the $\delta^{34}S_{pyrite}$ ratios are presumed to have been essentially maintained in the Bullmoose Lake samples and the Dome Lake $\delta^{34}S_{sphalerite\text{-}galena}$ samples, despite some evidence for disequilibrium. Therefore this information which appears to suggest that: (1)the metamorphism has not affected the isotopic ratios to any major extent, (2)together with structural similarities, (3)locii of deposition (within pelites), (4)alteration and (5)paragenesis of sulphides, is in support of the validity of using the 'main-phase' minerals from Bullmoose Lake and the 'late-phase' minerals from Dome Lake in an interpretation of the fluid characteristics of both properties.

There are obviously inherent problems in adopting this line of approach, but in view of the fact that Dome Lake is unusually abundant in base metals relative to ferrous metals (J.Brophy, pers. comm., 1986) it is unlikely that quantities of both 'main' and 'late' stage minerals will be found in sufficient quantities for S-isotope analysis in a single metasediment-hosted gold vein in the Slave Province. The most obvious problem in adopting this approach is that, because the two properties are abundant in different metals (Bullmoose Lake - po>py> base metals; Dome Lake - asp>gn>sph>cpy>po>py) this alone suggests a different genesis for the two properties.

In summary therefore, this geological type of approach is not without problems, however the following interpretation of the modes of Au transport and deposition are considered the most reasonable under the circumstances.

Several analogies can be drawn between the metavolcanic lode gold deposits of Western Australia and Yellowknife, and the Bullmoose Lake deposit, based upon their structural style, fluid inclusion composition, wall-rock alteration , δO and δD_{fluid}, and $\delta^{34}S$ isotope values. Lambert *et al.* (1984) contest that the average $\delta^{34}S_{pyrite}$ values of +1‰ to +4‰ in Archean lode-gold deposits are produced by reduced fluids driven out of host greenstone rocks during metamorphism. They cite the conversion of pyrite to pyrrhotite and slightly elevated $\delta^{34}S$ values (approximately 1‰ higher) in the mineralized greenstones, relative to unmineralized greenstones, as evidence for devolatilisation and fluid reduction at elevated metamorphic conditions.

At Bullmoose Lake pyrrhotite and pyrite coexist, but, the overwhelming dominance of pyrrhotite is evidence of more reduced and higher temperature conditions than those necessary for pyrite stability. The S-isotope database in the Slave Province is too small to make any comparisons between mineralized and unmineralized areas at this time.

The $\delta^{34}S_{pyrite}$ results from Bullmoose Lake were plotted on an fO_2 vs pH diagram (fig. 19) and compared with the $\delta^{34}S_{pyrite}$ from gold deposits of Western Australia and Zimbabwe [(fig. 20, and Lambert *et al.* 1984; Phillips *et al.* 1986) and Yellowknife (Chary, 1971)]. The temperature of deposition for the Australian and Yellowknife deposits is approximately 290° - 360°C, 100°C higher than the temperature of secondary inclusion entrapment at Bullmoose Lake (based on fluid inclusion studies, Ho *et al.* 1985; Chary, 1971; English, 1981, respectively). The $\delta^{34}S_{pyrite}$ from Bullmoose Lake were therefore plotted at 250°C. Recent work on the stability of arsenopyrite (Heinrich and Eadington, 1986) shows that the pH/fO_2 of the Bullmoose Lake mineralizing fluid can be further constrained with

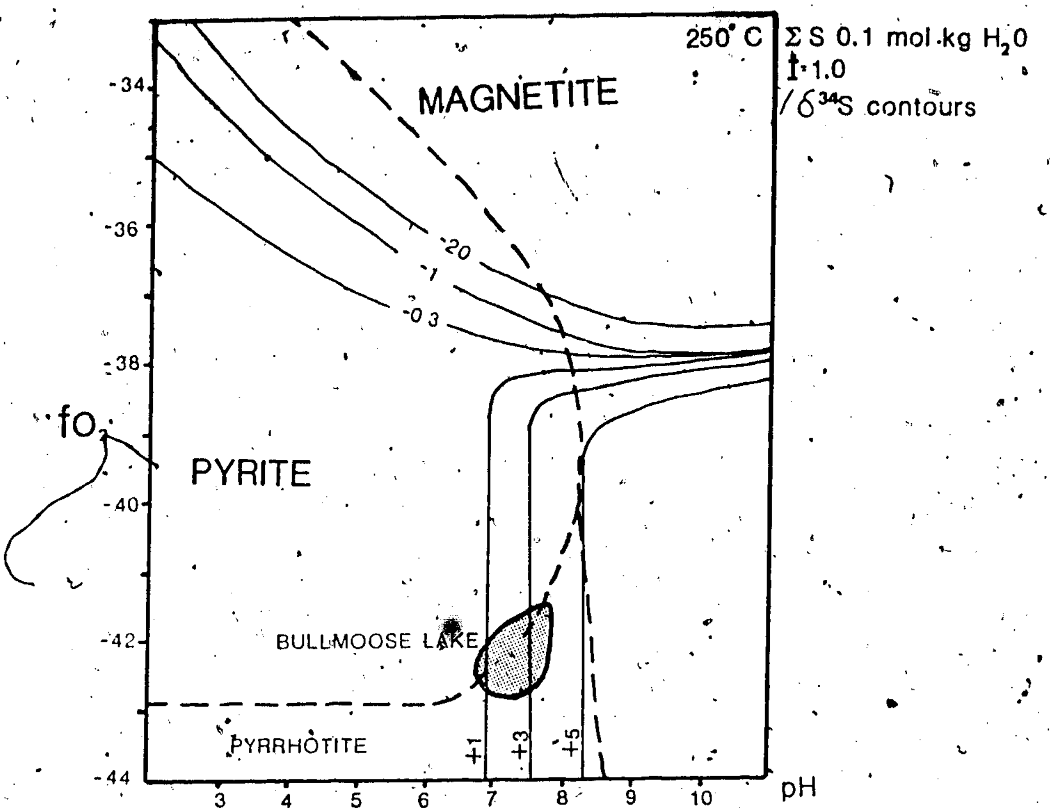


Figure 19. FO_2 vs. pH plot of the $\delta^{34}S$ contours within the stability field Fe-S-O at 250° and the inferred conditions at Bullmoose Lake (some data modified after Ohmoto, 1972)

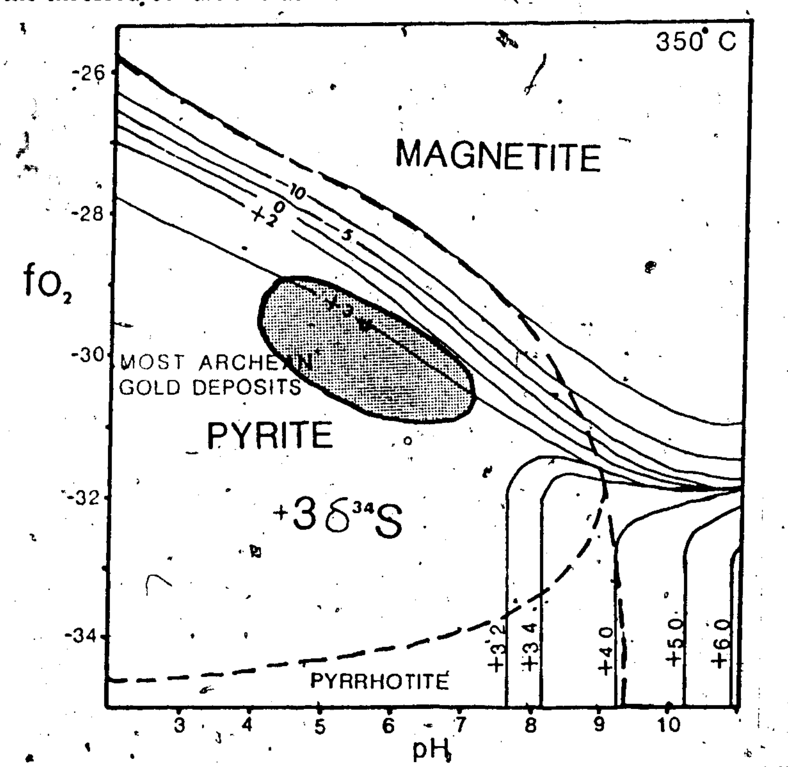


Figure 20. FO_2 vs. pH plot of the $\delta^{34}S$ contours within the stability field Fe-S-O at 350° and the inferred conditions for most Archean lode-gold deposits, (modified after Phillips *et al.* 1986)

some degree of assurance by plotting the stability of both Fe and As phases at 250°. This is especially useful in view of the absence of well defined alteration assemblages. The co-existance therefore of pyrrhotite, pyrite and arsenopyrite in the 'main phase' of mineralization shows that the fluid had an fO_2 of approximately -42 bars and a pH of 6-8 in a system that is sulphur-rich ($\Sigma S = 0.1 - 1$mole). A sulphur-rich mineralizing fluid is indicated by the abundance of sulphides particulaly Fe-sulphides within and around the quartz-veins, relative to the country rock.

The dominant sulphur species in the fluid as determined by approximating the pH and fO_2 were, H_2S and HS^-.

In deposits with large water-rock ratios, tighter Eh-pH constraints can be put on the fluid by charactersic alteration assemblages. However at Bullmoose Lake only local biotite (and propylitic-style assemblages), and minor actinolite alteration are evident and therefore the $\delta^{34}S$ of sulphide minerals present in the 'sulphide-phase' assemblage and lack of oxides are the only useful guides to the Eh-pH of the fluid.

The lowest realistic concentrations at which As, S, and Fe can be transported, occur between 200° and 300°C (Heinrich and Eadington, 1986). Therefore a change in the physico-chemical conditions of the fluids at or below these temperatures may bring about precipitation of sulphide minerals. The $\delta^{34}S_{pyrite}$ and the dominance of pyrrhotite over pyrite in the Bullmoose Lake deposit indicate a more reduced, mineralized fluid than typical higher temperature metavolcanic deposits (e.g. Kambalda, Australia and Yellowknife).

Parameters influencing the precipitation of sulphide minerals and gold from solution at Bullmoose Lake

The observed sulphide mineral and gold paragenesis (fig. 15) can be explained by reference to the relative solubility of metals in an evolved, reduced fluid and the effect of solubility and fluid-rock interactions on the stabilization of various element complexes (fig. 21).

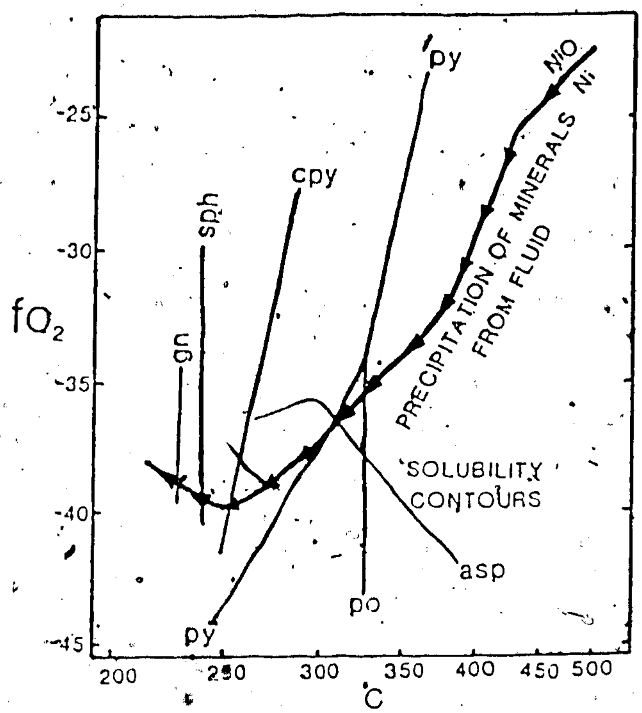


Figure 21. The solubility of the predominant sulphides present in the Au bearing fluids plotted with respect to temperature and fO_2 in a reducing environment, (modified after Heinrich and Eadington, 1986)

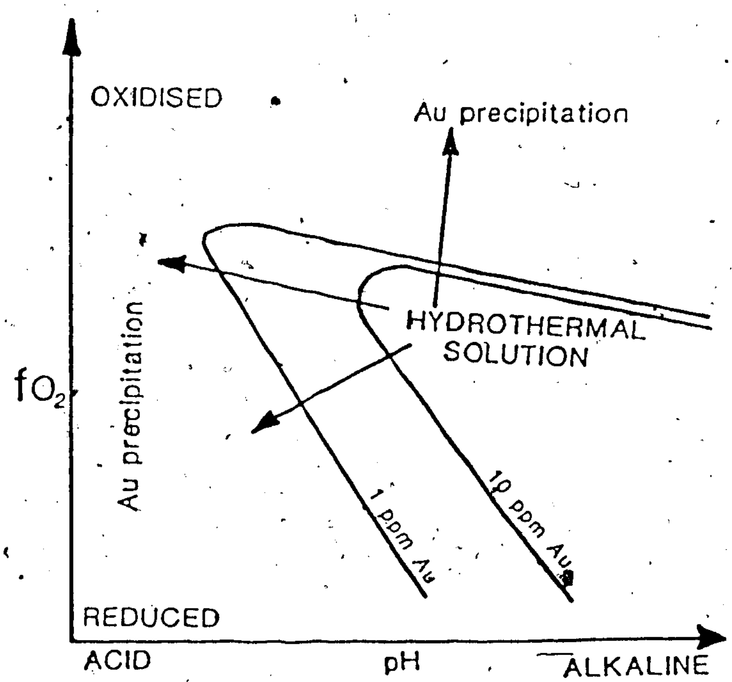


Figure 22. Schematic pH - Eh diagram showing some possible changes in fluid parameters that may have occurred at the site of deposition to cause precipitation of the Au from $Au(HS)_2^-$. No precise values are given. (Modified after Phillips and Groves, 1983; Seward, 1984).

Available thermodynamic data indicate that thio-complexing of gold is more important than chloro-complexing in near neutral solutions at temperatures below 350° (Barnes, 1979; Seward, 1984). If gold is transported as thio-complexes, changes in fluid temperature, pH, fO_2, or activity of reduced sulphur will cause precipitation (fig. 22, and Seward, 1984). The dominant species of sulphur in the fluid at Bullmoose Lake are HS^- and H_2S, therefore the dominant thio-complex transporting the gold is probably $Au(HS)_2^-$ (Seward, 1984).

Oxygen and hydrogen isotope studies, together with field relations suggest that primary and secondary fluids were derived by metamorphism, although the latter may have been influenced by meteoric water. At temperatures of approximately 500°C gold is readily transported as either a chloride or bi-sulphide complex (Fyfe and Kerrich, 1984). The generation of significant quantities of fluid by metamorphic processes are also evident at these temperatures (Fyfe and Kerrich, 1984). The rocks at Bullmoose Lake reached amphibolite grades, therefore the transport of gold and metals in fluids derived by metamorphism was most probable at temperatures above 300°C, especially as there is little evidence for fluids of magmatic origin.

The 'main-phase' sulphide assemblage at Bullmoose Lake is dominated by iron and arsenic sulphides, which are the first minerals to precipitate out in Fe-As-Cu-Pb-Zn-S rich fluids characterised by low fugacities (in the H_2S field, Heinrich and Eadington, 1986). For the predicted sequence of sulphide mineral precipitation (from pyrrhotite to galena) to occur by a redution in temperature, according to the solubility of metals dissolved in H_2S, the fluid would have to have been buffered by fluid-rock interactions over a relatively long time span. At Bullmoose Lake the patchy alteration around the quartz veins and relatively non-sequential precipitation of sulphide minerals and gold, are evidence for relatively rapid precipitation from sulphur-rich fluids source that were not of constant composition through time. The cross-cutting nature of the secondary fluids, and the variety of sulphide minerals carried in the fluids, are both evidence for sporadic mineral and fluid precipitation.

The most likely reaction that occurred to precipitate the observed quantities of pyrrhotite (and pyrite) is sulphidation of Fe-rich metapelitic wall-rocks, possibly by the reaction:

$$FeO\ (\text{in silicate}) + HAu^{1+}(HS^-) = Au^0 + FeS + H_2O$$

The oxygen fugacity of the fluid may have been partially buffered by ilmenite, magnetite and biotite in the wallrock during the onset of fluid migration into favourable sites. However, the relatively small area over which the the ore was deposited, lack of significant alteration, and amount of carbon probably already in the fluid indicates that the fluid was possibly already reduced. Limited changes in the redox state of the fluid brought about by wall-rock interaction, (and buffering of fluid by devolatilization equilibria), and/or fall in temperature significantly altered the solubility of the metals in the fluid. The removal of reduced sulphur from the fluid (to form pyrrhotite), effectively de-stabilizes any S-complexes that may be present in the fluid. Sulphidation is therefore one method of precipitating gold. Sulphidation does not neccessarily have to alter the oxidation state of Fe or Au, but in the reactions which are most likely to occur to form pyrrhotite or pyrite, reduction of both Fe and Au is evident (see above).

Kerrich *et al.* 1977 in a study of the reduction of iron around quartz veins in the Yellowknife district, concluded that to produce the anomanously reduced $Fe^{2+}/\Sigma Fe$ ratios observed around quartz veins, the fluids must have been ascending, already reduced and travelling over a steep P-T gradient. In the system po-py-mt-H_2O they showed that H_2 (derived from the interaction of ascending fluid with wall-rock) would be a more important reducing agent than sulphur species.

A reaction such as:

$$FeS_2 + CH_4 + 2H_2O \rightarrow FeS + H_2S + 3H_2 + CO_2$$

may be responsible for such reduction haloes. The observations of Kerrich *et al.* (1977) probably apply to the Bullmoose Lake and Dome Lake properties and to metasediment-hosted gold deposits in general.

Reduction may also occur if the fluid composition is buffered by a devolatilisation equilibrium (e.g. muscovite and quartz, Ohmoto and Kerrick, 1977). A pyrite + magnetite equilibrium assemblage would be reduced to pyrrhotite + magnetite by such a buffering assemblage (fig. 14, Ohmoto and Kerrick, 1977). Reduction by buffered silicate devolatilization equilibria may partially explain the reduction of Fe^{3+}/Fe^{2+} in the metagreywackes/metapelites wallrocks at Bullmoose Lake.

Reduction of the fluid by interaction with graphitic horizons (plate 20), is another method that may cause gold precipitation. The reaction of a gold-bearing fluid with graphite and iron oxides in the wallrock may occur as follows:

$$Fe_3O_4 + 3HAu^{1+}(HS^-) + 4CO_2 + 5H_2O = 3Au^0 + 3FeS + 4CH_4 + 6.5O_2$$

High temperature (400°C????) Lower Temperature (400 - 280°C????)

Under amphibolite and greenschist grade P-T conditions CO_2, H_2O and CH_4 are the main constituents of a fluid in equilibrium with graphite + pyrite + pyrrhotite (Ohmoto and Kerrick, 1977). French (1966) observed that CO_2 is preferentially concentrated in higher temperature, more oxidised conditions than CH_4. The lack of CO_2 and increased CH_4 in the secondary inclusions relative to primary fluids can therefore be explained in terms of temperature and fO_2. The lack of carbonation of the wallrock at Bullmoose Lake, as compared with Yellowknife-type and Australian shear-zone deposits, is therefore probably partly due to the reduced, lower temperature state of the fluid (i.e. 360°C for shear zone deposits vs. 220°C for metasediment hosted Au-quartz veins).

The relatively high NaCl content of the secondary fluids makes it likely that the base metals present in 'late-phase' veinlets were carried as a chloride complex. The reduction in temperature as the fluid interacts with cooler host-rocks would cause the chloride complexes to become unstable and precipitate galena and sphalerite. This reaction would effectively remove sulphur from the system and therefore any sulphur complexes such as $Au(HS^-)$ are destabilised causing the precipitation of chalcopyrite and gold in association with the base metals. The general observation of gn-sph-cpy-Au in the veinlets synchronous with secondary inclusions is evidence that in some cases the fluids may have had time to evolve in equilibrium with reducing conditions, like some epithermal Ag-Au and Au veins (Walton, 1987; Reed and Spycher, 1985). As a rule, the common occurence of Au with all sulphide minerals at Bullmoose Lake, suggests that although some fluid evolution may have occurred, the

Plate 20. Bands of coarse-grained pyrite and arsenopyrite parallel to bedding, in graphitic wall-rock, #4 vein, Bullmoose Lake

precipitation of sulphides and gold was so sporadic and strongly affected by rapid local Fe-sulphidation and C-reduction that progressional evolution of a single fluid would be improbable.

It is not known whether the primary fluids were in fact responsible for any mineralization, but data concerned with the solubility of metals show that, po and asp should be precipitated at significantly higher temperatures than the base metals in solution (fig. 21). If the primary inclusions are therefore indicative of temperatures of arsenopyrite and pyrrhotite mineralization, very steep temperature gradients may have caused the precipitation of heterogeneous sulphide assemblages.

The secondary fluids have $\delta^{18}O$ and δD ratios that may have been derived by mixing of meteoric and metamorphic fluids. This mixing may have also been an influential factor causing precipitation of sulphides by oxidation processes, although $\delta^{34}S$ values suggest that mineralization was largely confined to reduced conditions.

The interaction of sulphidation and reduction processes, combined with a steep temperature gradient therefore probably caused rapid precipitation of sulphides and gold, which may have favoured the deposition of local high-grade ores.

The genesis of the Dome Lake veins is considered to be similar to the Bullmoose Lake auriferous veins. The reason why the Dome Lake veins are rich in base metals, when almost every other known Au-qtz vein in the Hearne Lake area contains substantially lower quantities of these metals, is a mystery. The only explanation put forward to explain this anomaly is possibly that the mineralizing fluids were more NaCl-rich than at Bullmoose Lake and therefore they preferentially concentrated metals transported by Cl^- complexes. It is speculative, but maybe the origin of the fluids was a 'saline pocket' (see Fritz and Frape, 1982; Frape and Fritz, 1984, for discussion). Large quantities of arsenopyrite precipitated prior to the base metals may have acted as reduction traps (Heinrich and Eadington, 1986) and precipitation of gold may have been predominantly influenced by the abundance of arsenopyrite. At Dome Lake the spatial association between arsenopyrite and Au is particularly noticeable and was used as a prospecting tool. The paragenesis of sulphide minerals at this property may be more akin to some mesothermal veins (see Walton pp. 95-100 for discussion) although not enough information is available at present to draw any direct comparisons.

VIII. Conclusions

A. Model for the emplacement of Au-quartz veins at Bullmoose Lake and implications for the genesis of similar deposits in the Slave Province

Introduction

The Bullmoose Lake Au-quartz veins have been investigated by analysis of their structure, mineralogy, fluid inclusions and stable isotopes (O, H, S). The results are integrated with regional fluid inclusion and metamorphic data (English, 1981; Ramsay, 1973a). The thesis has endeavoured to describe all possible factors influencing the emplacement of all quartz veins at Bullmoose Lake, but at the same time it has broader implications which concern the emplacement of Au-quartz veins in such host-rocks throughout the Southern Slave Structural Province.

Structure and deformation

At Bullmoose Lake there were two distinct folding events which are also recorded elsewhere in the Slave Province. The earlier F1 event folded the rocks at Bullmoose Lake into an overturned isoclinal syncline. During and subsequent to this event, a parasitic shear developed on the western limb of the fold, due to the rheological anisotropy in the country rocks. The left-lateral shear is host to an en échelon set of blue-grey quartz veins that have developed parallel to bedding. The blue-grey quartz veins are located in Fe-rich and graphitic metapelites/metagreywackes and derive their colour from fragments incorporated from the graphitic host. Outside of this shear-zone veins are developed quasi-parallel to the shear (displacement fractures) but are not often blue-grey in colour, and are predominantly located in poorly-graded or ungraded metagreywackes.

Early Kenoran metamorphism

It is possible that during the compressional F1 event, fluids derived from recrystallization of metamorphic rocks frequently exceeded lithostatic pressures, producing banded, bedding-parallel (Bpb) veins. Bpb veins are located at the boundary between two beds, or between two distinctly different units within a bed. They form in a wide variety of lithological compositions ranging from metaquartzwackes to metapelites. These veins were probably emplaced by 'fluid recirculation' mechanisms under relatively low permeabilities at relatively low temperatures. Au values in these veins are characteristically less than 0.5 g/tonne and this factor together with their morphology, timing, and lack of evidence for shear indicate that they are not related to the ore-bearing veins.

The S2 is defined by a relict fabric in cordierite porphyroblasts, and probably indicates that continued horizontal tectonism induced a fracture into the rock after F1.

Late Kenoran metamorphism

During the later stages of deformation, a regional NW-SE fabric was developed (S3) in all of the lithologies at Bullmoose Lake. It is possible that the metapelites which host the auriferous quartz veins were rotated parallel to S3 during this episode. Strike-slip shear induced brittle failure in the relatively thin metapelites and interturbidite layers of metagreywackes, relative to more massive metaarenaceous units.

The progressive horizontal and associated strike-slip deformation style, which was initiated during F1 and continued up until and after F3/M3, suggests a gradual increase in horizontal tectonism during this time period. Vertical movement during F3/M3 has been documented from nearby deposits (Stokes *et al.* 1987) and has been attributed to the rise of granitic bodies at depth.

Rf/ϕ determinations were not particularly indicative of the strain variation between auriferous and non auriferous rocks. The strain variation between sheared and unsheared rock was more easily seen in outcrop.

Quartz veining

Several quartz vein types occur at Bullmoose Lake and each was classified according to its structural configuration, host rock, morphology or relative age. The seven major types of vein are:

1. Bpé - en échelon blue-grey quartz veins located within metapelites/metagreywackes in a left-lateral shear on the west limb of the Bullmoose Lake syncline. They occur quasi-parallel to bedding and schistosity. These are the ore-bearing veins on the property. Size - 2cm to 2m width, ~ up to 100m length. ('Core-veins')
2. Displacement shear veins - blue-grey or white quartz. Located quasi-parallel to bedding and cleavage. Very erratic mineralogy and ore-grades (<1 g/tonne to >30 g/tonne over ~1m). Size - 2cm to 2m width, ~ up to 50m length (#9, #14, #15 and Max veins)
3. Bpb - banded, bedding-parallel; found in all lithologies. Au grades typically < 1g tonne. Size - 2cm to 10cm width. (located throughout whole property)
4. Stratabound veins - Lie within, but oblique to, beds. Produced by rotation of beds by shear. Au grades - unknown, but unlikely to contain significant quantities of gold due to variable host and variable vein lengths. Size - 2cm to 1m width, often less than 3m length. (sporadic outcrop, particularly noticeable in Core-vein area)
5. Foliation veins - Parallel or sub parallel to foliation (schistosity). Au grades - variable <1g tonne - 30g/tonne, but often merge into Bpé veins. Size - 2cm to 10cm width. (Core-vein area and throughout property)
6. Quartz segregations - irregular quartz bodies, located paticularly within metaquartzwackes parallel to S3. (occur throughout the property)
7. "Bull white" quartz veins - Often cut blue-grey quartz veins. Au grades - variable <1g tonne to 30g/tonne (#11 zone only). Size - variable, #11 zone = approx. 100m³ quartz in nose of Bullmoose syncline to < 2cm in veinlets cross-cutting Core-veins.

Origin of mineralizing fluids, fluid transport mechanisms, and the precipitation of gold

Origin of fluids

Fluid inclusion studies show that the quartz veins were emplaced at temperatures of approximately 280°C to 440°C presenting evidence for emplacement of quartz veins at significantly lower temperatures than peak metamorphic grade.

O/H stable isotope studies and field relations show that it is probable that mineralizing fluids were derived by metamorphic processes. It is unlikely that the fluids were primary magmatic in origin, based upon the range of δD and field relations (most metasediment-hosted gold quartz veins in the Southern Slave Structural Province are not directly related to any visible magmatic sources). However, a magmatic/metamorphic mixture would be impossible to distinguish isotopically from an evolved metamorphic fluid. It is possible that heat induced into the rock from a granitic body of the Prosperous Lake suite was responsible for thermally driving the fluids towards the surface.

Transport of fluids

It is therefore likely that the fl[illegible] were generated at temperatures above 500°C (amphibolite grade), and to produce the quantity of quartz seen at Bullmoose Lake (~1% of the property), the fluids probably transported by 'one-way' fluid flow towards the surface (Yardley, 1986). It is possible that carbon isotopes may help in the investigation for the origin of fluid, although the criteria used (see Burrows *et al.* 1986) for recognition of different Archean fluids by this method, are not well established at the present time.

As fluids rose through the rock pile towards the surface they picked up H^+ ions, S and Au, and transported them as bi-sulphide complexes. The large increase in permeability developed in the metapelites and metagreywackes at the brittle/ductile rheological boundary would focus the ascending fluid into the fracture network from the surrounding rocks (Brace, 1980).

In outcrop, silicified banded rock is occasionally seen adjacent and parallel to quartz veins in metapelites/metagreywackes. It is probable that the influx of hot fluids into the country rock caused the segregation of minerals in the country rock. Local silicification, Ca metasomatism (e.g. actinolite and ankerite) and chloritisation are the most noticeable mineralogical changes around the veins, caused by this process. This is in contrast to the findings of Boyle (1961) where he documents a depletion of quartz around veins. A depletion of silica would be expected by 'one-way' fluid flow, if at the tail of the hydrofracture, Pf < Pl causes some fluid to be drawn back into the fracture to form a quartz vein. This style of fluid flow in a shear zone may therefore may explain why:

1. the metapelites/greywackes around Bpé quartz veins are banded and silicified and yet contain relatively less silica than the country rock.
2. the Bpé quartz veins contain wallrock fragments and graphite (although it is likely that some graphite will already be present in the mineralizing fluid).

Fluid composition and precipitation of gold

The $\delta^{34}S$ of the sulphide minerals deposited in association with gold show evidence for disequilibrium. However, the narrow range of $\delta^{34}S$ values and the predicted sluggish re-equilibration characteristics of py (Bachinski, 1977) enable some meaningful interpretations of the values. The $\delta^{34}S_{py}$ results and the known oxygen fugacities of mt-py-po were plotted on a pH/fO_2 diagram at the temperatures of entrapment for primary and secondary fluid inclusions. The fO_2 and pH of the mineralizing fluid was therefore estimated at -42 bars and 6-8, respectively.

Temperature estimates of sulphide precipitation using Δ mineral pairs in amphibolite grade rocks were not consistant with fluid inclusion data. However, in greenshist grade rocks at Dome Lake Δ_{sph-gn} from coexisting pairs correspond well with fluid inclusion temperatures for secondary inclusions (170°C - 280°C and 140° - 300°C, respectively).

The close analogy between Fe-rich and carbonaceous metapelites and the location of ore-bearing Au-quartz veins is evidence for an association between tensile strength of the rock and the precipitating mechanisms responsible for precipitation of gold. The fluid was focussed into the Core-vein area and the process of sulphidation and reduction associated with a drop in temperature caused the precipitation of gold .

The gold ranges in size from 0.3 - 20 mm and is generally found in two modes:

1. associated with po, py and other sulphides in 'blebs', surrounded by silicates, commonly quartz.
2. in late veinlets which commonly precipitate gn, sph and cpy in preference to Fe-sulphides.

The temperatures at which primary fluids were deposited are between 280° and 440°C. It is not known whether the sulphide 'blebs' were deposited at these temperatures, however by reference to the solubility of a reduced Fe-Zn-Pb-Cu-S fluid, Fe-sulphides would be expected to be deposited at higher temperatures than base metals (Heinrich and Eadington, 1986). The wide range of sulphide minerals precipitated with the gold indicates the possiblity of:

1. a succession of fluids with different compositions precipitating out different minerals.
2. several fluids of generally the same composition, however different cooling and equilibration rates of these fluids would tend to precipitate out a wide range of minerals especially if precipitation mechanisms were efficient.

The latter is favoured because at temperatures above 300° and at pressures of between 2-4kb the local fluid source (i.e. circulation within supracrustal rocks) would probably be fairly homogeneous.

The lack of extensive alteration zones indicates low water-rock ratios. The deposition of local 'high-grade' ore (>30 g/tonne Au) indicates that the fluid-rock interaction must have been an efficient mechanism of gold precipitation.

The primary fluids have an estimated salinity of 3 wt% NaCl equiv., (taking evidence of the presence of CO_2 and CH_4 into consideration). The salinities of primary fluids and temperatures of entrapment are similar to other Archean lode-gold deposits. Secondary fluids are more saline than primary fluids (approximately 8-10 wt% NaCl equiv., corrected for CH_4) and were trapped at temperatures of about 140° - 300°C.

The variation in fluid composition of primary and secondary inclusions suggests the possibility of:

1. the evolution of single metamorphic fluid of constant composition which interacted with

a Ca, Na and Cl rich source at lower temperatures.

2. the evolution of several metamorphic fluids of similar composition which cooled at different rates and therefore precipitated different suites of minerals. Interaction of these fluids with cooler meteoric/metamorphic fluids or rocks of sedimentary affinities would produce the observed primary and secondary fluid differences.

The last example is favoured, based upon (1)δD values, (2)water-rock ratios, (3)fluid inclusion CO_2 vs, CH_4 and NaCl compositions, (4)observed variation of sulphide assemblages, and (5)theoretical fluid reservoir transport and compositional characteristics at elevated temperatures in homogenous rock source regions.

Gold precipitation took place during both 'main-phase' and 'late-phase' mineralization. In the main phase of mineralization gold is *principally*, but not exclusively, associated with Fe-sulphides, notably pyrrhotite. In 'late-phase' mineralization, gold is more often associated with base metals. The dominance of pyrrhotite over pyrite indicates that fluids were more reduced than typical Archean lode-gold deposit fluids.

Indicators of high-grade ore (>10 g/tonne Au over 1m)

At the surface the occurrence of blue-grey quartz veins (hosted by metapelites/metagreywackes) was the best indicator of higher Au grades.

In the mine, stringers which splay off the main veins and 'ore-shoots' located within the veins dipping 70°N were the most productive Au producing areas of the shear structure. It is not known why these locii carry more gold, except it is possible that these locations are where most fluid-rock interaction has occurred. The presence of galena in the quartz veins was always an indicator of high-grade ore. The inconstancy of gold grades between successive 'lifts' within the mine are to be expected in these types of deposits because fluid-rock interaction is low and sporadic.

Summary of factors affecting the location of gold ore

In summary, the mechanisms governing the location of Au-quartz veins in metasediments are similar to those governing the location of gold in the Yellowknife-type and the volcanic-hosted gold vein deposits in the Slave Province. In all of these examples, structural preparation of the host-rock and an efficient method of gold precipitation, are the two most important factors to be aware of in the search for vein-type gold deposits. At Bullmoose Lake auriferous veins (with grades >30 g/tonne) were hosted in a narrow zone (~ 130m width at Bullmoose Lake) of sheared, silicified, metapelites and metagreywackes.

Auriferous veins outside of the shear-zone (displacement shear veins) carry sporadic values of gold (<3 g/tonne to >10 g/tonne over 1m). These veins are hosted by a variety of lithologies, therefore Au grades are expected to be sporadic due to the inconsistancy of the precipitating mechanism.

The #11 zone is different from the two types of vein described above. This zone is basically a large mass of white quartz that occupies the nose, and part of the west-limb hinge area, of an F1 fold.

B. Model for the emplacement and precipitation of Au in the Bullmoose Lake auriferous ("Core") veins

1. Fluids were generated by metamorphic processes at temperatures above 500°C and depths of 10-20km.
2. A buried heat source (e.g. Prosperous Lake granite suite - Buckham Lake pluton at depth ???) drove the fluids towards the surface. Fluids moved by intergranular 'one-way flow' under ductile conditions.
3. The metamorphic fluids picked up Au, H^+ and S ions from the supracrustal rocks. It is probable that at temperatures below 350°C, Au was transported at low fO_2 and near-neutral pH as a bisulphide complex such as $HAu(HS^-)$.
4. Under brittle-ductile conditions, hydrofracturing was developed in the rocks with the least tensile strength (metapelites and interturbidite horizons of metagreywackes). As the fluids ascended into cooler rocks they were therefore preferentially focussed into these areas of reduced pressure. At Bullmoose Lake the hydrofracturing occurred at the site of shearing, under conditions of $P_f < P_l$.
5. Gold precipitation occurred over steep temperature gradients, at low water-rock ratios, due to one or more of the following:
   a. temperature reduction
   b. sulphidation due to the precipitation of Fe-sulphides
   c. reduction of the fluids due to the interaction with carbon (in the form of graphite) or iron oxides/sulphides in the wallrock.
6. Gold precipitation occurred with both Fe-rich, 'main-phase' mineralization and base-metal rich, 'late-phase' mineralization.
7. The rocks then appear to have remained largely unchanged until erosion and exposure of the deposit.

Future work

The importance of understanding the structure of these deposits cannot be overemphasised. A better understanding of the mechanisms of quartz vein emplacement at other metasediment hosted gold deposits (such as the current one by T. Stokes) will help to more closely define the relative timing of mineralization. The classification of the veins into bedding-parallel, fold axes, etc., does not contribute to the overall understanding of the relative timing of Au-mineralization, because as is evident from this study, several different structural environments and methods of precipitation are possible in one deposit.

Fluorapatite was found in a few of the veins at Bullmoose Lake. This mineral could be dated by U/Pb methods and an absolute date for the emplacement of quartz veins may be useful to compare with the dates of granite emplacement. No method is currently available which will conclusively show whether the fluids are influenced by magmatic processes but a date for the fluorapatite may show if the veins were emplaced prior to, during, after granite emplacement.

Geobarometry of sphalerite (Scott, 1976) and arsenopyrite (Kretschmar and Scott, 1976) may be useful in conjunction with standard Al_2SiO_5 and other mineral geobarometers to reconstruct the pressures or pressure gradients operative during mineralization.

The possible influence of scheelite as an indicator of gold mineralization and its effect on ore-bearing fluids has not been discussed in this thesis. The mineral is present in several metasediment-hosted gold deposits (Lord, 1951), including Bullmoose Lake.

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IX. Appendix

A. Dome Lake property

Location: 62° 45'N, 113° 15'W

TT claims - # 14 vein, #18 vein, Lambert vein, Massif trenches

TAT 1 - South vein

TAT 2 - Pen and Pensive trenches

FRED1 - Fred vein

The Dome Lake quartz veins are hosted in well exposed greenschist grade rocks. The most significant veins (#14, #18, Lambert and South veins), trend N.W - S.E (320 - 350°), dip 60 - 80° E and cross-cut the (F1) bedding (fig. 23). The veins are located in metapelitic and metagreywacke beds, however, it has been noted that the most continuous veins are preferentially occur within metapelites at the boundary between metapelites and metagreywackes (#14 vein), or at the axial surface fold trace outcrop of metapelite (Lambert vein). Veins hosted in metagreywackes and metaquartzwackes (#18 vein, South vein, Pen vein, Pensive veins, Fred vein) are not very continuous and often completely pinch-out along strike.

Veins hosted by metapelites are blue-grey in colour (similar to the Bpé veins at Bullmoose Lake), where as veins hosted in metagreywackes and metaquartzwackes are typically white or slightly tarnished by Fe-oxides.

Sulphide mineralogy

The paragenesis is similar to Bullmoose Lake:

Early - po, py, asp

Late - gn, sph, asp, cpy

The most unusual mineralogical aspect of this property was the abundance of gn, sph and asp, relative to Fe-sulphides. At one locality (East trench), the whole vein mineralogy consisted of galena, quartz, sericite and gold (detected in assays). Native gold and electrum

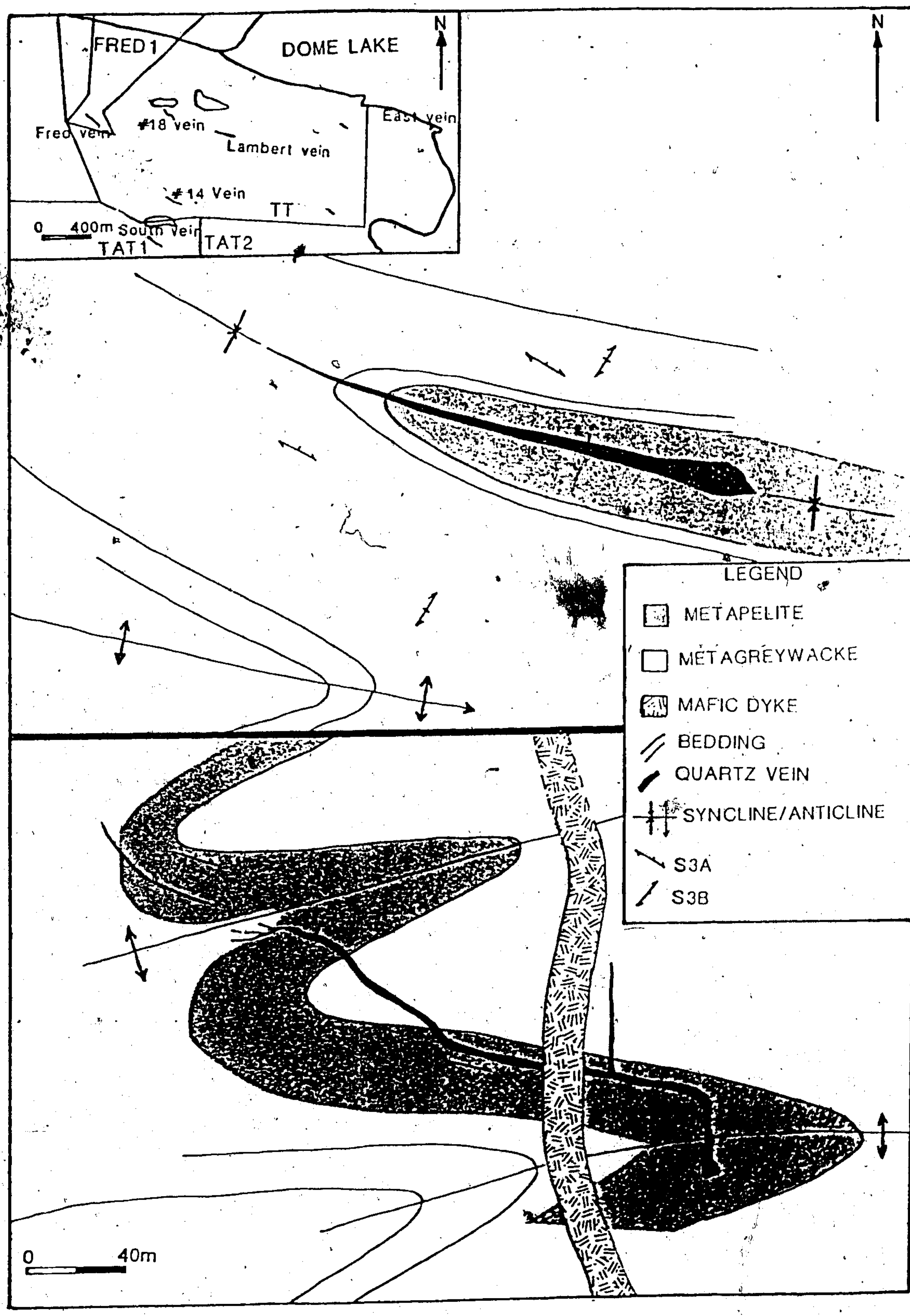

Figure 23. The geology of the Lambert and #14 vein, Dome Lake, Slave Province, N.W.T

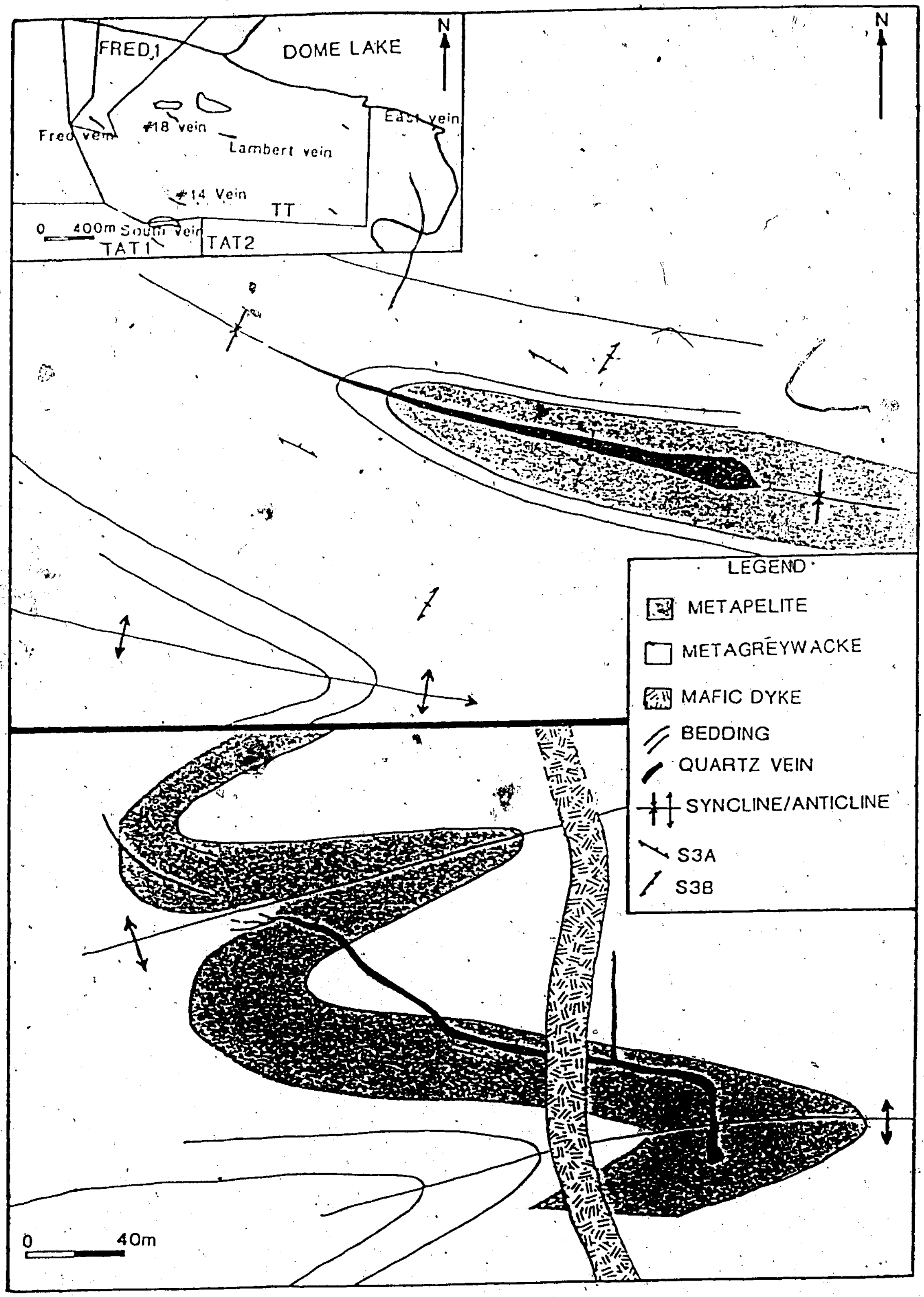

Figure 23. The geology of the Lambert and # 14 vein, Dome Lake, Slave Province, N.W.T

were found in the Lambert and #14 veins. The co-existance of (early) arsenopyrite and (late) galena was used as an indicator to finding gold.

Gold grades

Gold grades were highest in the metapelitic hosted veins (similar values to Bpé veins, Bullmoose Lake) but the exploitation of the Au is not profitable at the present time, partly due to the distance between the veins (Lambert and #14 veins are 500m apart).

Comparison of Dome Lake to Bullmoose Lake

Many of the features seen at Dome Lake are similar to those seen at Bullmoose Lake. The range of vein types recorded from Bullmoose Lake were also noticed at Dome Lake, but the most significant comparisons between the two properties are the siting and composition of the higher grade auriferous veins (>10 g/tonne Au) relative to lower grade veins (< 10 g/tonne).

The #14 vein (Dome Lake) is an excellent example of a blue-grey vein that is located due to the rheological variation of the host rocks. The #14 vein actually transects the boundary between into the metagreywackes in one area (fig. 23), and in this short interval the gold values are significantly lower relative to the Au values in the metapelite-hosted area on either side (compilation of assay results and maps, Faulkner and Swatton, company reports, August 1986). This information supports two of the fundamental conclusions drawn from the results of the Bullmoose Lake property, namely:

1. Metapelitic rocks are a more suitable rheological host to quartz veins.
2. The precipitation of Au is inherently related to wall-rock composition.

In many ways the Dome Lake property, by way of its lower grade and better exposure, shows more clearly the mechanisms of Au emplacement concluded for the Bullmoose Lake property. However, by careful observation of the lower grade rocks and using them as a guide for comparison to higher grades, interpretation of the Bullmoose Lake rocks was made a great deal easier.