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A REVIEW OF ARCHEAN OROGENIC GOLD DEPOSITS IN

GREENSTONE BELTS AND THE SLAVE PROVINCE:

EXPLORATION IN THE YELLOWKNIFE DOMAIN, NWT, CANADA

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Dedicated to those who love the romance of exploring.

"These days there seems to be nowhere left to explore, at least on the land area of the Earth. Victims of their very success, the explorers now pretty much stay home."

Carl Sagan

Pale Blue Dot: A Vision of the Human Future in Space

"Kids should be allowed to break stuff more often. That's a consequence of exploration. Exploration is what you do when you don't know what you are doing."

Neil deGrasse Tyson

"Part of the urge to explore is a desire to become lost."

Tracy Johnston

Shooting the Boh: A Woman's Voyage Down the Wildest River in Borneo

"I may say that this is the greatest factor: the way in which the expedition is equipped, the way in which every difficulty is foreseen, and precautions taken for meeting or avoiding it. Victory awaits him who has everything in order, luck, people call it. Defeat is certain for him who has neglected to take the necessary precautions in time, this is called bad luck."

Roald Amundsen

ABSTRACT

Keywords: Greenstone Belts, Orogenic Gold, Slave Province, Yellowknife, Beaulieu River, Cameron River, Exploration.

A review of Archean granite-greenstone terranes, orogenic gold deposits, the Slave Province and modern exploration tools, techniques and methods was conducted to identify prospective areas in the Yellowknife domain for hosting orogenic gold deposits and illustrate the best exploration methods for delineating this deposit type. This study identifies Archean granite-greenstone terranes as economically important hosts to quartz-carbonate vein-hosted orogenic gold deposits. These deposits occur at convergent plate margins, but can also be related to local extensional tectonics within a convergent setting. Heat generated from tectonic processes can trigger hydrothermal fluid movement along first-order faults and shear zones. Precipitation of gold-bearing quartz-carbonate veins from the hydrothermal fluids occurs in second- and third-order faults and shear zones related to the first-order structures.

This study also identifies the Archean Slave Province in northern Canada as a well-endowed craton with numerous orogenic gold deposits, diamondiferous kimberlites, VMS deposits and several other mineralization styles. In particular, three greenstone belts (Yellowknife, Cameron River and Beaulieu River) associated with likely first-order structures are comprised of prospective rocks for hosting orogenic gold and VMS mineralization. The Yellowknife greenstone belt hosts the past-producing and former world-class Con and Giant orogenic gold deposits, but has been little-explored with modern exploration techniques. The Cameron River and Beaulieu River greenstone belts host numerous base and precious metal VMS and BIF-hosted orogenic gold prospects and deposits, indicating mineralization is present. There is considerable potential for significant discoveries to be made using modern exploration techniques in the greenstone belts; however, exploration in the region has been hindered over the past decade by ongoing political negotiations.

Once the political negotiations are finalized, application of modern exploration methods and techniques in the prospective greenstone belts should be carried out. Regional scale methodologies should be applied to generate targets using predictive modelling, implicit 3D modelling, 3D geochemistry and exploration targeting so decisions defining a businesses strategy for ground acquisition of high priority targets are made using quantitative analysis. Once ground is acquired, field-based exploration for orogenic gold and VMS deposits should include geological mapping with a focus on structural geology, geochemical sampling and airborne magnetic, radiometric and EM geophysical surveys. Prior to reconnaissance drilling, integration of all data layers and interpretation within a common 3D earth model should be conducted. Following successful reconnaissance drilling, definition drilling along strike and down dip of intersected mineralization, combined with borehole geophysics, should be carried out to delineate the extent of mineralization.

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CHAPTER 1   **INTRODUCTION**

The Slave Province is a ~500 by 700 km Archean craton in the North Slave region of Northwest Territories and Kitikmeot region of Nunavut in northern Canada (Figure 1). It is comprised principally of metasedimentary basins and granite-gneiss terranes, separated by a total of 27 elongate enclaves of volcanic rocks known as greenstone belts (Figure 2). Globally, these granite-greenstone terranes are host to significant accumulations of gold mineralization, most commonly in the form of orogenic-style quartz-carbonate vein deposits (Figure 3) (Groves, 1993; Groves et al., 1998; Goldfarb et al., 2001; Goldfarb et al., 2005; Dubé and Gosselin, 2007) with fourteen of these deposits hosting >10 Moz (>280 tonnes) gold (Robert et al., 2007).

Figure 1. Location of the Slave Province (blue shading) in northern Canada. Star indicates study area (from ENR, 2001).
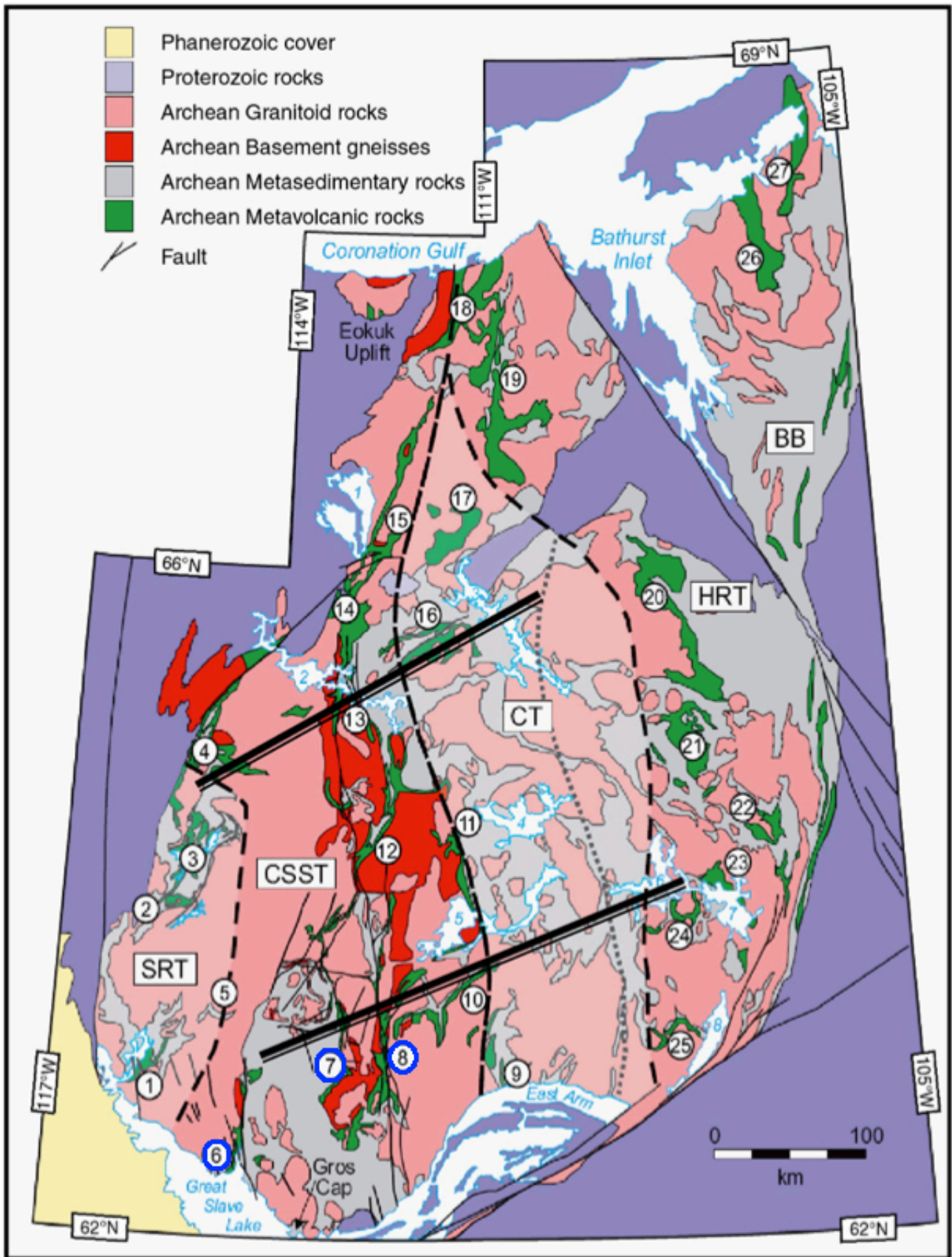
Figure 2. Terrane map of the Slave Province (caption continued on next page).

Demarcated by heavy dashed lines are divisions of Slave Province derived by Helmstaedt (2009): Snare River Terrane (SRT), Central Slave superterrane (CSST), Contwoyto terrane (CT), Hackett River terrane (HRT) and Bathurst Block (BB). CSST and CT boundary represents Thorpe, et al (1992) Pb isotope boundary. Dotted line represents Davis and Hegner (1992) Nd isotopic boundary. Two northeast trending double lines are lithospheric domain boundaries. Numbers indicate greenstone belts 1-Russel-Slemon lakes; 2-Kwejinne Lake; 3-Indin Lake; 4-Grenville Lake; 5-Wheeler Lake; **6-Yellowknife; 7-Cameroon River; 8-Beaulieu River**; 9-Benjamine (Brisbane) Lake; 10-Camsell Lake; 11-Courageous Lake; 12-Winter Lake; 13-Point Lake; 14-Northern Point Lake; 15-Napaktulik Lake; 16-Central Volcanic Belt; 17-Willingham Lake; 18-Anialik River; 19-High Lake; 20-Hackett River; 21-Back River; 22-Healey Lake; 23-Clinton-Golden Lake; 24-Aylmer Lake; 25-Cook Lake; 26-Hope Bay; 27-Elu (modified from Helmstaedt, 2009).

This study focuses on the greenstone belts of the southwestern Slave Province, particularly the Yellowknife (YGB), Cameron River and Beaulieu River (CBGB) greenstone belts. Along with the Yellowknife basin, which separates the YGB from the CBGB, the area will be collectively referred to as the Yellowknife domain. The well-studied YGB is host to the world-class Con and Giant gold deposits that were first mined in 1938 (Government of Northwest Territories, 2007).

Together, these two mines produced >14 Moz (435 tonnes) gold until they closed in 2003 and 2004, respectively. Although the CBGB host volcanogenic massive sulphide deposits and numerous prospects, there are no major quartz-carbonate vein-hosted gold prospects found to date. Nevertheless, the belts are favourably located proximal to the Beaulieu River Fault Zone, a deep-seated crustal structure cutting through the Beaulieu greenstone belt, and are comprised of prospective volcanic host-rock types in a relatively underexplored region.
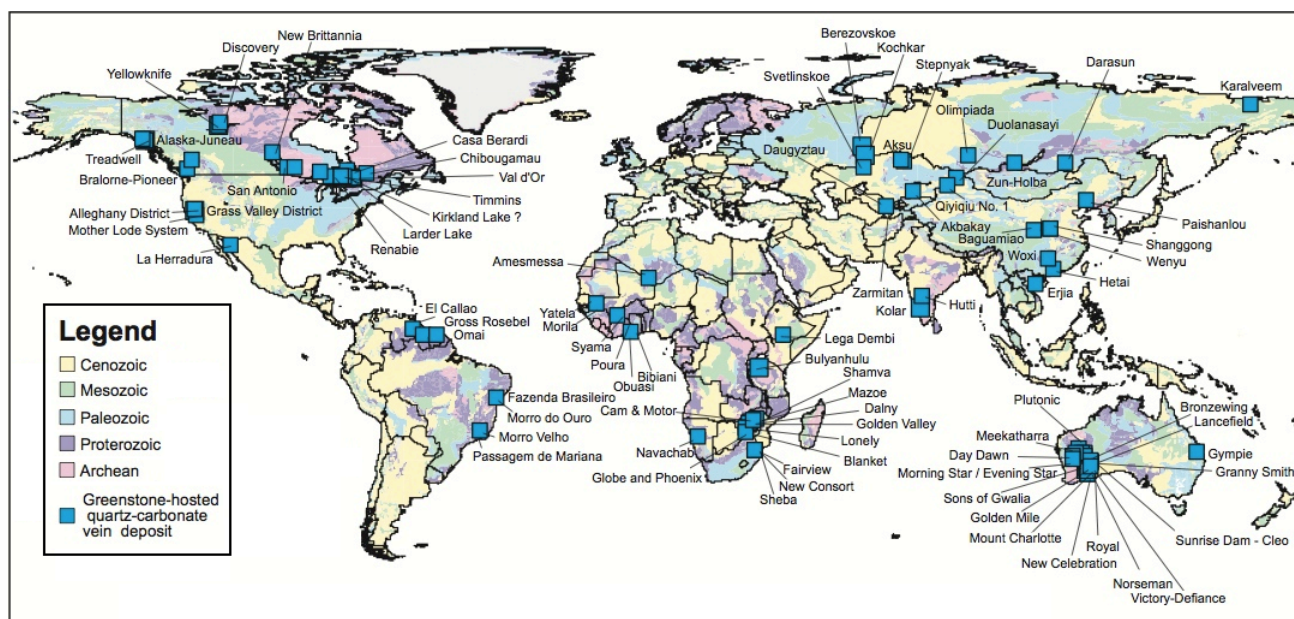
Figure 3. World distribution of greenstone-hosted quartz-carbonate vein deposits containing >1 Moz (>30t) of Au (modified from Dubé and Gosselin, 2007).

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The chief goal of this thesis is to review the latest exploration tools, techniques and methods being applied to orogenic gold deposits and provide an approach for delineating gold deposits, particularly in the greenstone belts of the Yellowknife domain in the Slave Province and other similar greenstone belt terranes.

To begin, the exploration environment of the Yellowknife domain is described (CHAPTER 2) followed by a general review of Archean greenstone belts (CHAPTER 3) and associated orogenic quartz-carbonate vein-hosted gold deposits (CHAPTER 4). To provide context for further discussing the local geology of the Yellowknife domain greenstone belts, the regional geology of the Slave Province is discussed (CHAPTER 5), followed by the lithological and structural frameworks, along with known mineralization of the Yellowknife domain greenstone belts (CHAPTER 6CHAPTER 7). Next, exploration tools and techniques followed by methodologies for regional-scale and property-scale exploration are outlined with a focus on orogenic gold deposits (CHAPTER 8). Lastly, exploration opportunities and threats in the Yellowknife domain are discussed and highlighted with a SWOT analysis (CHAPTER 9).

Although this area has been the focus of considerable exploration in the past (Atkinson, 1991; Padgham, 1992; Bianchi, 1999; Government of Northwest Territories, 2007; Falck and Gochnauer, 2013), it has not benefitted from the application of recent advances in knowledge. Rethinking the geology of this area and applying the latest exploration methods and geological models may yield exciting new discoveries in the Northwest Territories and provide new opportunities for development in Canada's northern region.

CHAPTER 2   YELLOWKNIFE DOMAIN EXPLORATION ENVIRONMENT

2.1   INTRODUCTION

Located in northern Canada, the Slave Province is split between the Northern Slave region of the Northwest Territories (NWT) and Kitikmeot region of western Nunavut (Figure 1). The study area, referred to as the Yellowknife domain, is found in south-central NWT and has a long history of mining beginning in 1938 with the opening of the Con Mine. Mining and exploration is a significant contributor to the local NWT economy, with $2.15 billion of mine production coming from four producing mines in 2008 and $770 million per annum in mining and development-related spending, while employing more than 3000 people (NWT and Nunavut Chamber of Mines, 2008; DITI, 2011). The capital city of Yellowknife is home to approximately 17,000-20,000 people, while NWT is home to around 43,000 (AANDC, 2010).

2.2   ACCESSIBILITY

In November 2012, the Deh Cho Bridge across the Mackenzie River was completed, allowing traffic and supplies to flow all year to the capital along government-maintained roads extending south to British Columbia and Alberta. Yellowknife has daily flights from Edmonton and Calgary, Alberta.

Accessibility in the Yellowknife domain is generally good, particularly in the Yellowknife greenstone belt, as the eponymous capital city is located at the southern end of the belt. An unmaintained winter road extends north to Nicholas Lake and parallels the northern margin of the greenstone belt. Depending on weather conditions, helicopter and ski- or float-equipped aircraft can be used to access the region.

For the Cameron River and Beaulieu River greenstone belts, access is more difficult, although it is considerably better than for most of the Slave Province, due to their proximity to Yellowknife (75-120 km to the northeast). Also, the presence of the government-maintained all-weather road, known as the Ingraham Trail, terminates within 30-50 km of the belts. Furthermore, a maintained winter road leading to the past-producing Lupin mine on Contwoyto Lake in Nunavut and the diamond mines in the Northern Slave region of NWT crosses the Northern Beaulieu greenstone belt and passes within 5-40 km of the southern belts. A right of way extension of the Ingraham Trail has been surveyed and cut to within 8 km of Sunrise Lake in the Beaulieu River greenstone belt and a separate winter road extends to the Sunrise deposit via Victory, Detour, and Turnback Lakes (Roscoe and Wallis, 2003).

2.3 CLIMATE

Northern Canada and the area of interest are characterised by long cold winters with short cool summers. Precipitation is light and typically falls in the summer months, with up to 450 mm annual accumulation, including roughly 150 cm of annual snowfall. Mean annual temperatures in the region are between -1 and -5 C°, with average temperatures ranging between -18 C° in the winter and 16 C° in the summer, though there is considerable seasonal, annual and decadal variability (NRCAN, 2009a). In addition to the colder temperatures and snow cover, the amount of daylight received per day is much less in the wintertime and can affect ground exploration efforts, aside from drilling and some geophysical surveys, although the presence of winter roads allows for improved access and potentially reduced mobilization costs if work is conducted in the winter.

2.4 INFRASTRUCTURE

Yellowknife is the biggest population centre as well as the major source of supplies and personnel in the territory. The local economy is generally dependent on government services, although mining and exploration activities throughout the NWT and Nunavut are also key components of the territories' economies. Mining in the territory began in 1933 with the opening of the Eldorado Uranium Mine on Great Bear Lake and has, until recently, been focused on base and precious metal mining. The biggest drivers of the economy and development were the past-producing Con, Giant, Tundra, Salmita, Colomac and Discovery gold mines, however now the focus has shifted to diamonds, with three producing mines (Ekati, Diavik and Snap Lake) in the territory and one more in final stages of approval (Gahcho Kué). As mentioned above, the Ingraham Trail extends towards the CBGB, with a maintained winter road that extends to the north along Gordon Lake and continues to the diamond mines.

2.5 FIRST NATIONS

Half of the approximately 43,000 residents of the Northwest Territories are aboriginal, with several Nations having land claims in the territory, including the Akaitcho, Dehcho, Gwich'in, Inuvialut, NWT Métis, Sahtu and Tłıcho Nations. The only nation represented in the Yellowknife domain and the study area is the Akaitcho Dene First Nations, which consists of people indigenous to and living in Dettah, N'Dilo, Łutselk'e and Deninu K'ue. In 2000, the Government of the Northwest Territories (GNWT), Akaitcho Dene First Nations (ADFN) and the Government of Canada began negotiating a Land, Resources and Self-Governance agreement, which has resulted in an agreement for the interim land withdrawal of 62,000 km^2 of Federal Crown land within the ADFN's asserted traditional territory on November 1, 2007 (DAAIR, 2013). The Interim Land Withdrawal protects certain areas from mineral staking (Figure 4) while the Akaitcho Agreement is being negotiated, though it does not

alter the current mineral rights of landholders. In spring 2013, a memorandum of understanding was reached between the parties and they will move forward in order to reach an Agreement in Principle. Other First Nations in the territory have negotiated settlement claims that either leave open mineral rights staking to external companies or completely restrict the right to stake mineral claims in their negotiated areas so the result of the eventual ADFN agreement is impossible to predict.
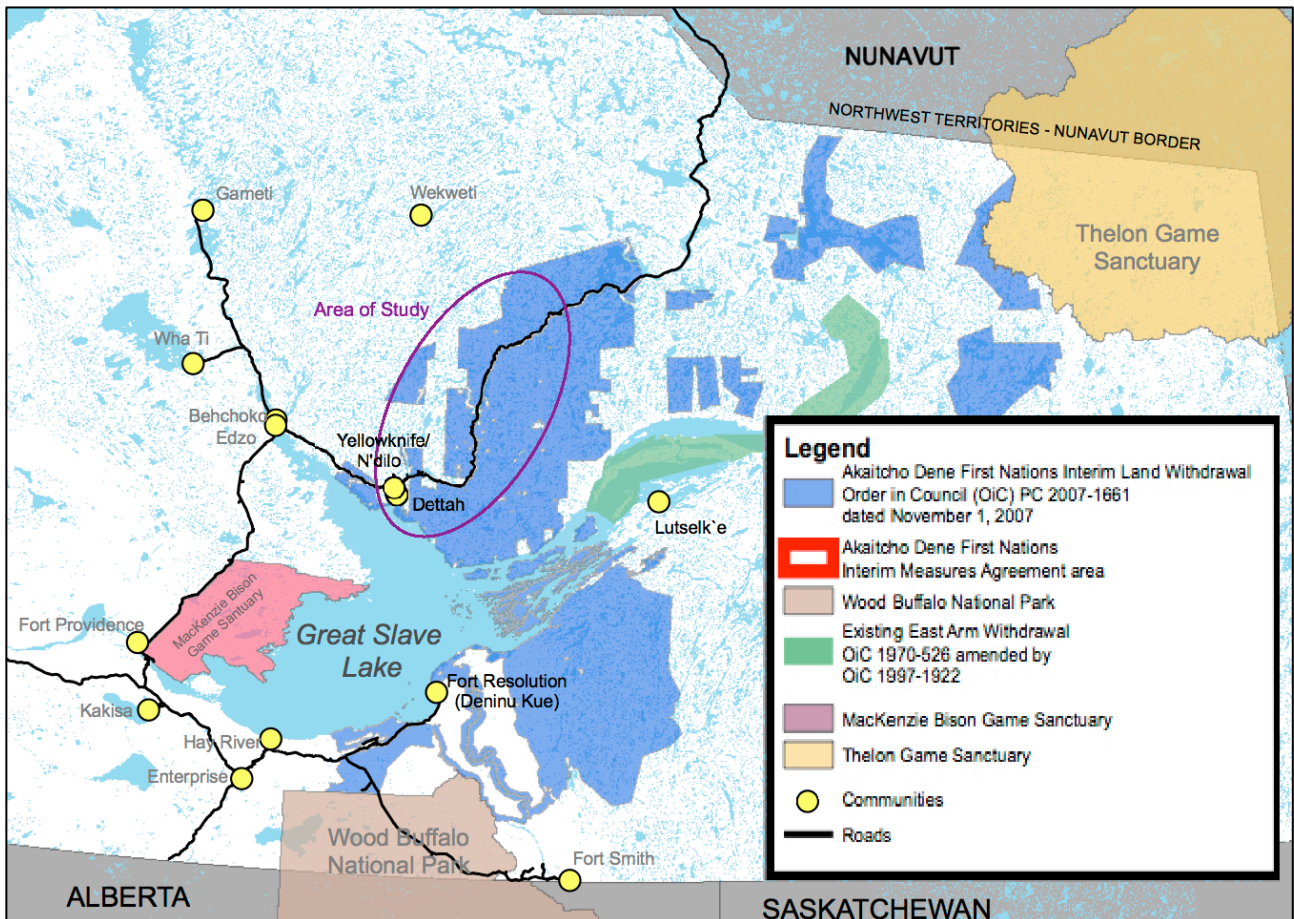
Figure 4. Akaitcho Dene First Nations Interim Land Withdrawal (modified from DAAIR, 2013).

2.6 PHYSIOGRAPHY

The Yellowknife domain is located in the Canadian Subarctic Lands and falls into the Taiga Plains ecozone, which forms part of the Canadian Shield physiographic region with macroscale land features largely controlled by the geological structure and lithology of the underlying rocks (French, 2012). The treeline boundary (Figure 5), which separates barren tundra from forested areas and approximates the zone of continuous permafrost (ground remaining below 0 C° for >2 years), runs through the Northern Slave region of the NWT with the Yellowknife domain straddling the transition.
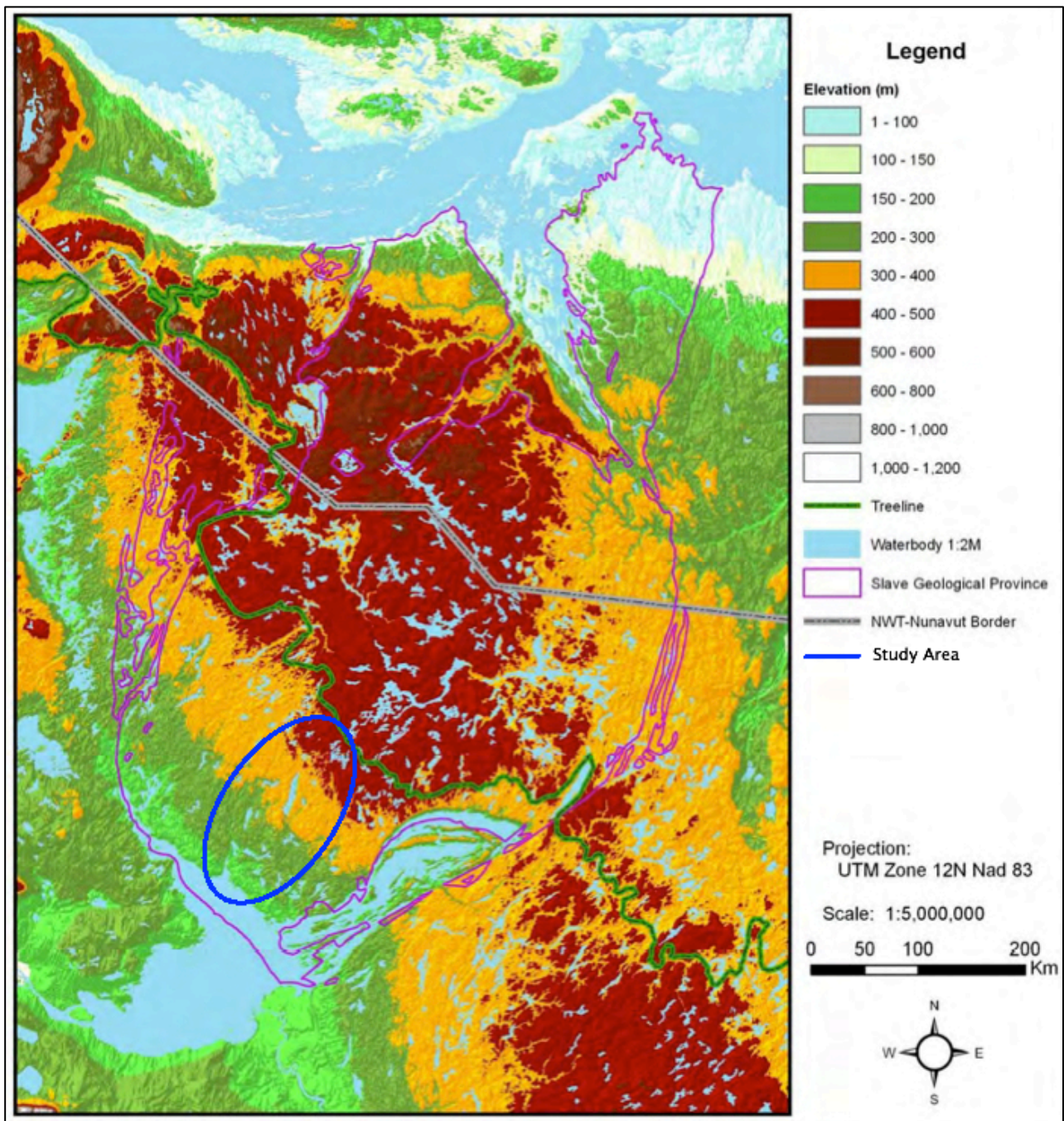
Figure 5. Elevation and waterbodies of the Slave Province (from Senes Consultants Ltd., 2008).

Higher elevations consist of structurally-controlled bedrock outcrops, whereas upland surfaces and upper valley slopes are covered by angular rock-rubble accumulations. Frost jacking of bedrock widens joints and fissures, leading to the separation of bedrock into angular and subangular blocks. Poorly lithified and unconsolidated sediments, commonly the remnants of glaciations, form more undulating, poorly-drained lowland terrain, which leave numerous thaw lakes along the landscape (French, 2012).

2.7   EXPLORATION ACTIVITIES

Aside from the diamond exploration in the North Slave region of the NWT, there are a number of gold projects being actively explored, along with the Providence copper-nickel-cobalt project, Indian Mountain copper-lead-zinc project, Moose lithium and Nechalacho rare-earth element projects (Figure 6).
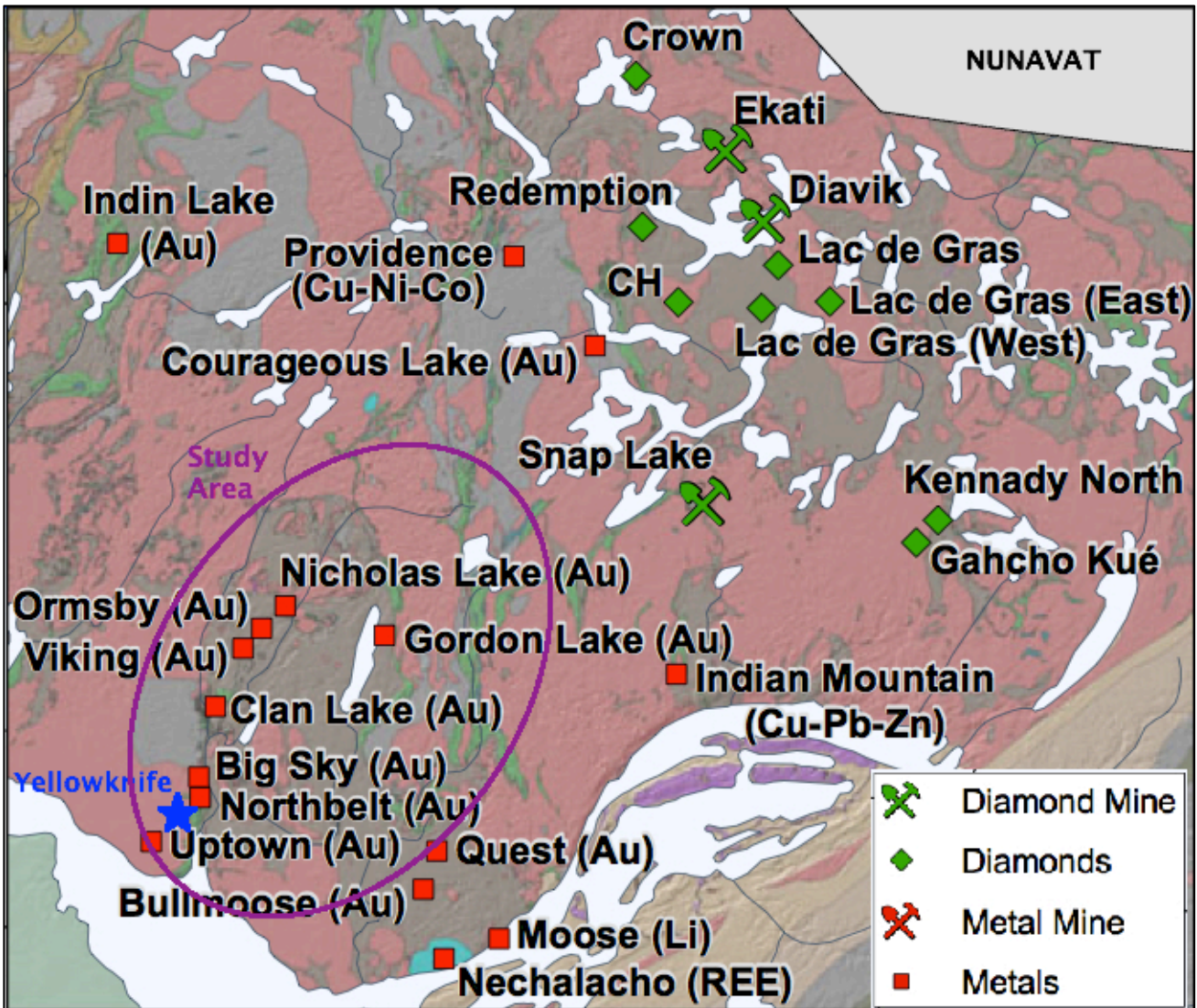
Figure 6. Locations of active mines and exploration projects in the Northern Slave region of NWT during 2012 (modified from Falck and Gochnauer, 2013).

As of 2012, the number of claims, leases and permits in the Yellowknife domain is rather small, as illustrated in Figure 7. As discussed above, since 2007, the Interim Land Withdrawal has precluded staking of new claims in the Yellowknife domain, but has allowed the existing licenses to remain in effect.
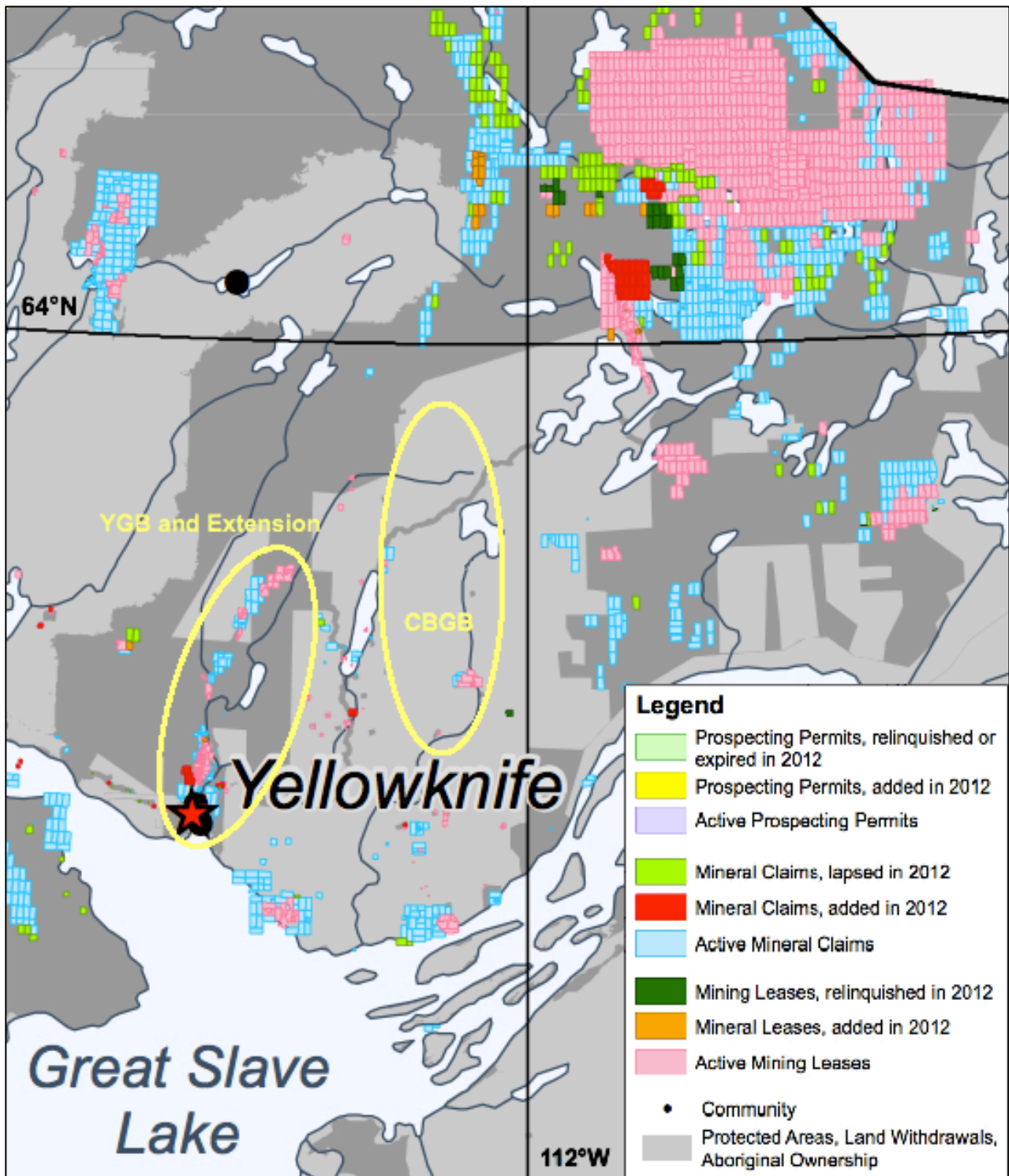
Figure 7. Location and areal coverage of claims, leases and permits for 2012 in Northern Slave region of Northwest Territories. YGB=Yellowknife greenstone belt; CBGB= Cameron River and Beaulieu River greenstone belts (modified from Falck and Gochnauer, 2013).

The most recent exploration activities on the Yellowknife domain greenstone belts have occurred at the Uptown Gold project (Manson Creek Resources, Inc.) adjacent to the past-producing Giant Mine, at Northbelt (TerraX Minerals Inc.), which includes the Crestaurum Mine, at Big Sky (Williams

Creek Gold Ltd. and Tyhee Gold Corp.) and at the Yellowknife Gold project (Tyhee Gold Corp.), which includes the Clan Lake, Ormsby and Nicolas Lake projects (Figure 6) (Falck and Gochnauer, 2013). The annual Exploration Overviews from the NWT Geoscience office (http://gateway.nwtgeoscience.ca/) for the past 10+ years indicates there has been no exploration activities carried out on the Cameron River or Beaulieu River greenstone belts in the past decade.

CHAPTER 3   ARCHEAN GRANITE-GREENSTONE TERRANES

3.1   INTRODUCTION

Most Archean cratons expose elongate belts of intrusive rocks, typically with aspect ratios of ~1:10, comprised of enclaves of ultramafic to felsic volcanic rocks metamorphosed mainly to greenschist and sub-greenschist metamorphic grades within areas of older tonalitic gneisses/plutons and younger granitoid plutons (Gorman et al., 1978; Isachsen and Bowring, 1994). These so-called granite-greenstone terranes are best preserved in the Archean rock record and reflect the formation of stable shield areas (cratons) throughout Archean time (de Wit, 1998). Models proposed for the evolution of the Slave craton are comparable to the inherently complex evolution of other granite-greenstone terranes, such as the Kaapvaal and Zimbabwe cratons of southern Africa and the Superior Province in eastern Canada (Isachsen and Bowring, 1994).

Globally, granite-greenstone terranes are an important host for gold deposits, with nearly 20% of the world's >10 Moz deposits associated with greenstone belts (Robert et al., 2007). Table 1 lists the world's 10 largest greenstone belt hosted gold deposits. The main type of gold mineralization associated with greenstone belts is quartz-carbonate vein-hosted orogenic gold (CHAPTER 4). Orogenic gold mineralization can also be hosted in turbidite and banded-iron formations associated with greenstone belts (Figure 8; Sections 7.2.2 and 7.2.3, respectively). Another style of gold mineralization associated with greenstone belts is known as atypical greenstone gold (Section 7.2.1), but this deposit type does not fit the standard orogenic model.

Table 1. World's 10 largest Archean greenstone belt deposits by contained gold (selected from Goldfarb et al., 2005).

Deposit Name	Country	Craton	Au (t)	Grade (g/t)	Tonnage (Mt)
Golden Mile	Australia	Yilgarn	1984	1.98	1002
Kolar	India	Dharwar	838	14.47	57.9
Campbell-Red Lake	Canada	Superior	799	21.28	37.5
Kirkland Lake*	Canada	Superior	797	14.97	53.2
Geita**	Tanzania	Tanzanian	788	4.01	196.5
Morro Velho**	Brazil	San Francisco	654	9.51	68.8
Bulyanhulu	Tanzania	Tanzanian	543	14.50	37.4
Sigma-Lamaque	Canada	Superior	444	4.48	99.1
Kerr Addison	Canada	Superior	327	9.10	35.9
Cuiaba	Brazil	San Francisco	318	7.42	42.9

*Atypical; **BIF-hosted

Greenstone terranes are attractive exploration targets, particularly beneath cover and in areas with limited or shallow historic drilling where hidden, sub-horizontal dipping greenstones may host new blind ore deposits that form as sub-vertically oriented shears (de Wit and Ashwal, 1995)
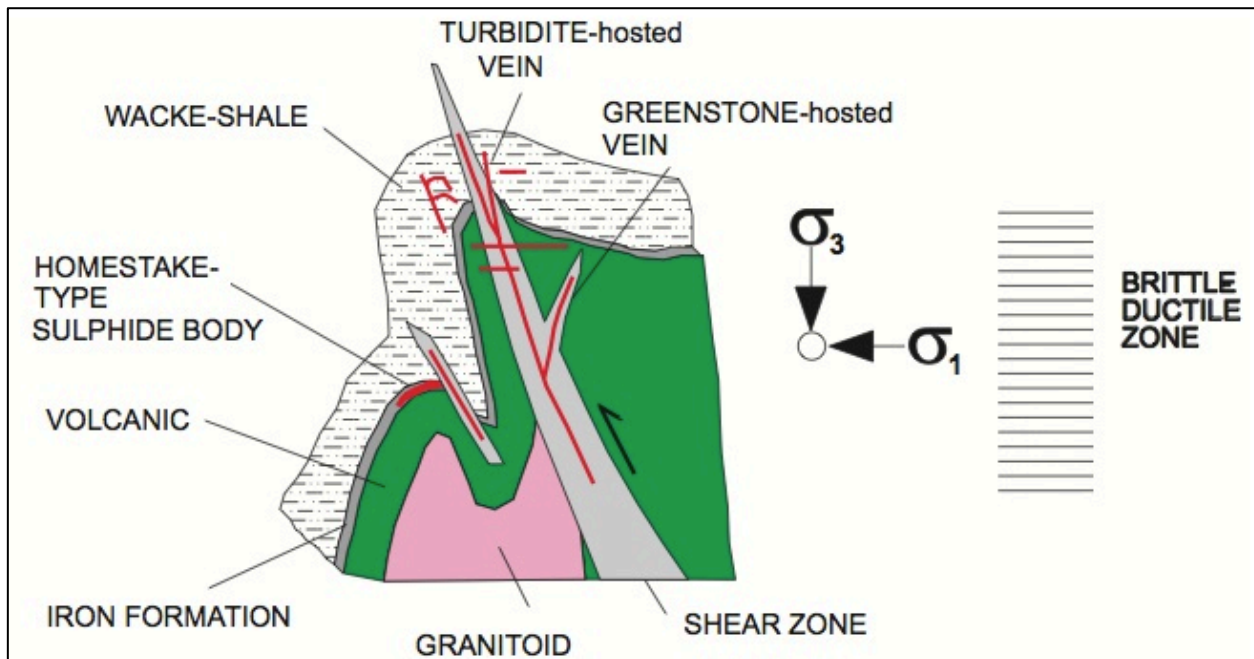
Figure 8. Schematic diagram illustrating the setting of greenstone hosted quartz-carbonate vein deposits (after Poulsen et al., 2000; from Dubé and Gosselin, 2007).

3.2 TECTONIC SETTING

A number of tectonic environments have been proposed for the setting of greenstone belts, such as the remnants of oceanic crust along suture zones of accreted terranes, collapsed back-arc basins, remnants of island arcs, intracontinental rifts, accreted arcs and bathymetric highs (Isachsen and Bowring, 1994). Most models assume individual greenstone belts developed within a single tectonic environment over 30-50 million year (m.y.) periods (Isachsen and Bowring, 1994), however de Wit and Ashwal (1995) describe greenstone belts as representing polyphase tectonic domains with a mixture of components from more than one tectonic environment and recording crustal evolutionary histories varying in age by more than an order of magnitude ranging from at least 50 to 500 m.y. periods. Furthermore, de Wit (1998) notes there is considerable lack of agreement regarding the early Earth tectonics, particularly during the first 2000 m.y. of Earth's history, making correlations between tectonics events in the early Earth challenging. Nevertheless, the well-studied Superior Province in Canada was used by de Wit (1998) to describe Late Archean cratonic tectonism. The Superior Province was chosen as an example because a number of Late Archean sequences from around the globe share similar tectonic interpretations.

The Superior Province is suggested to have undergone progressive north to south (present configuration) convergent plate-boundary tectonics ending with crustal stacking during the final convergence phase between two continental masses, comparable to the still evolving Indonesian Archipelago sandwiched between the continental masses of Australia and the Asian mainland (de Wit, 1998). Remnants of juxtaposed accreted island arcs, oceanic plateaux, marginal-basin crust, forearc-prisms and juvenile mircocontinental blocks have all been identified within the Superior Province and mark complex facies changes. A simplified model for crustal growth in the Superior Province is represented by the formation and accretion of a series of arcs, oceanic terranes and accretionary prisms along evolving plate boundaries and likely originated next to older continental margins. These accreted terranes indicate the Superior Province was subjected to a wide range of orogenic processes including extrusional tectonics and late extensional collapse (de Wit, 1998). Additionally, geophysical evidence suggestive of a suture zone and accretionary tectonics indicates the low-metamorphic-grade Abitibi belt in the Superior Province was subducted (de Wit, 1998).

Using geochemistry, all volcano-tectonic environments have been inferred from the extrusive mafic rocks of greenstone belts (de Wit and Ashwal, 1995). The range of volcanism found in greenstone belts suggests not all belts formed in a common tectonic setting. Also, individual greenstone belts have been recognized with several volcano-tectonic fields (de Wit and Ashwal, 1995). Further evidence for subduction-related tectonics in greenstone belts is the presence of a number of volcanogenic massive sulphide deposits in calc-alkaline basalt sequences, as well as the occurrence of many early Archean porphyry copper-like systems, both of which typically form in convergent margin settings (de Wit and Ashwal, 1995). Using experimental and modern analogs, it has been suggested that subducted oceanic slabs in the Archean were shallowly subducted, compared to modern steeply subducting slabs, resulting in the predominance of bi-modal dacite-basalt volcanicity in the Archean, versus Phanerozoic andesitic volcanicity; however, steeply dipping slabs and andesitic volcanicity have both been identified in the Archean (de Wit, 1998).

Additionally, the mineralogy, chemical composition and trace element geochemistry of greenstone belts suggest the origin of the Late Archean tonalite-trondhjemite-granodiorite (TTG) series of gneisses representing the deformed and metamorphosed granitic portion of the terranes are commonly related to subduction processes. Models propose that partial melting of mafic oceanic crust in subduction zones could produce TTG rocks (de Wit and Ashwal, 1995). Other models suggest direct melting of LILE (large-ion lithophile elements; K, Rb, Sr, Cs, Ba, Li, Na, Be, Mg, Pb, Eu^{2+})-enriched mantle peridotite or hydrous melting of basalt underplated at subduction zones could have generated a subset of TTG rocks (de Wit and Ashwal, 1995). Kusky (1993) describes the volumetrically significant late-stage to post-kinematic granitoid intrusions in Archean granite-

greenstone terranes as possibly being spatially and temporally related to late orogenic upper crustal extensional collapse and extensional structures whereby anatectic melting resulted in the emplacement of the late-stage plutons.

3.3 GEOLOGICAL CHARACTERISTICS

Since the mid-1800s, geologists have known that mafic-ultramafic rocks of greenstone belts comprise a variety of green secondary minerals typically associated with low-grade metamorphism. Commonly constituting >80% of the rocks, the green secondary minerals forming in greenstone belts include: serpentine, chlorite, epidote, actinolite and hornblende (de Wit and Ashwal, 1995). Metamorphic grade ranges from prehnite-pumpellyite, greenschist and amphibolite to granulite facies, though sub-greenschist to greenschist facies are most widespread. Characteristic geothermal gradients for granite-greenstone terranes are low-pressure, high temperature (andalusite-sillimanite type) and less commonly medium-pressure, high temperature (kyanite-sillimanite) metamorphism. The production of vertical or lateral transitions from low- to high-grade metamorphism in greenstone belts may have occurred in magmatic arcs or collision zones, respectively (de Wit and Ashwal, 1995).

As noted above, greenstone belts exhibit strong tectonism. It is typical for greenstones belts to be involved in some type of fold-and-thrust and/or listric extension tectonics during their evolution (de Wit and Ashwal, 1995). Geophysical models have shown that most greenstone belts are <10 km thick, with some <1 km thick (de Wit and Ashwal, 1995). It has been suggested that extensive structural duplication (stacking) and/or structural elimination of original stratigraphy has occurred in many greenstone belts, but typically this is not well quantified (de Wit and Ashwal, 1995). Gravity and seismic investigations can help assess if stratigraphic repetition and thickening or extension has occurred by comparing the mean mapped and geophysically modeled stratigraphic thicknesses (de Wit and Ashwal, 1995). Comparisons of greenstone belts globally using this method indicate the processes are rarely simple, with true stratigraphic thicknesses likely overestimated regularly as a result of the inability to confidently evaluate bulk strain, tectonic discontinuities and sequence stratigraphy in most belts (de Wit and Ashwal, 1995). Another significant factor limiting comparisons is the effect of erosion (de Wit and Ashwal, 1995).

Lithostratigraphy of greenstone belts is complicated, with correlations between different lithofacies nearly impossible due to a lack of depth indicators, which present challenges in defining either a shallow- or deep-water depositional environment of sequences (de Wit and Ashwal, 1995). Contacts between greenstone belts and the surrounding gneisses are typically separated by later granitoid intrusions and major structural breaks commonly unconformably overlain by clastic sedimentary

rocks (Gorman et al., 1978). The original sizes and shapes of basins where sedimentary rocks and greenstone belt volcanic rocks were deposited is commonly unknown, although a relatively constant ratio of 1:1.5 is noted for stratigraphic to geophysical thickness over a wide range of structural duplications and ages, which suggests there may be limited secular changes in the initial shapes of some greenstone basins and the angle of sediment progradation (de Wit and Ashwal, 1995).

A major component of most greenstone belts are sedimentary rocks, which usually comprise between 10 and 50% of the rocks within a belt, with some Archean examples having a minimum of 2% sedimentary rocks while a significant number contain 60-90% sedimentary rocks (de Wit and Ashwal, 1995). Preservation of more than one type of basin in a single greenstone belt is common with a wide variety of sedimentary environments and basins noted, although whether distinct sedimentary sequences are conformable or separated by either unconformities or tectonic discontinuities is generally poorly constrained (de Wit and Ashwal, 1995).

Mafic volcanic rocks with varying volcano-tectonic settings predominate the igneous rocks of greenstone belts, with a substantial portion forming as pillow lavas (de Wit and Ashwal, 1995). Like the sedimentary sequences, uncertainty is common when describing the original relationships between different volcano-tectonic rock packages. Typically, Archean basalts are enriched in Ni and related transition metals, regardless of volcanic assemblage when compared to post-Archean basalts (de Wit and Ashwal, 1995). Komatiites are a somewhat common (<5%) extrusive rock associated with greenstone belts, however not all greenstone belts contain them (de Wit and Ashwal, 1995).

Rhyolite and dacites, commonly subaqueous, constitute 50% or more of some greenstone belts, whereas andesites are commonly either entirely absent or volumetrically subordinate to basalts (de Wit and Ashwal, 1995). The inadequate representation of andesites in the greenstone belt rock record is possibly due to the high susceptibility to erosion and non-preservation of subaerial andesite stratovolcanoes (de Wit and Ashwal, 1995). The preserved volcanic rocks in greenstone belts suggest that mafic rocks with island-arc-like geochemical affinities and bimodal volcanic terranes dominate Archean greenstone belts compared to younger belts that are dominated by calc-alkaline affinities and intermediate (andesitic) volcanic rocks (de Wit and Ashwal, 1995).

Other significant components of most greenstone belts are felsic, intermediate and mafic-ultramafic hypabyssal-plutonic rocks, ranging from thin sills and dykes to individual plutons that merge with the surrounding large, composite batholiths and/or granitoid gneisses of the granite-greenstone terranes.

Typically, metasomatic processes have affected the geochemistry of rocks in most greenstone belts with the formation of secondary chert resulting from silica precipitation and removal of Mg, Ca, Fe and other elements by moderately low temperature (75-150°C) hydrothermal fluids, whereas metasomatic processes in banded iron formations result in complementary precipitation of Mg in mafic-ultramafic rocks at high temperatures and Fe at lower fluid temperatures (de Wit and Ashwal, 1995). A range of metasomatic processes dominated by H_2O and CO_2 have been recognized and typically individual greenstone belts experience different metasomatic activity at different times during their evolution (de Wit and Ashwal, 1995). The considerable fluid activity in greenstone belts are responsible for the formation of ore bodies, particularly shear zone hosted orogenic gold deposits, briefly introduced in the following section and further discussed in CHAPTER 4.

3.4   ECONOMIC MINERALIZATION

As highlighted in Table 1 and Figure 3, granite-greenstone terranes are host to the economically important greenstone-hosted Archean quartz-carbonate vein, or orogenic gold deposits, which are discussed in greater detail in CHAPTER 4. The presence of major duplexes and extensive stacking of thin-skinned tectono-stratigraphic slivers of greenstone belt stratigraphy suggests that the majority of lower contacts of the belts are likely to be shear zones, rather than intrusive contacts (de Wit and Ashwal, 1995). Commonly the shear zones are host rock-independent, forming indiscriminately in sheared volcanic and plutonic rocks. Shear zones known to have experienced large fluid flow associated with orogenic gold mineralization are thought to form relatively rapidly and late in the greenstone belt's history (de Wit and Ashwal, 1995). Complex, epigenetic orogenic deposits consist of simple to complex networks of gold-bearing, laminated quartz-carbonate fault-fill veins hosted in moderately to steeply dipping shear zones and faults, locally associated with extensional veins and hydrothermal breccias (Dubé and Gosselin, 2007). Additionally, volcanogenic massive sulphide deposits are an important economic mineralization style associated with granite-greenstone belts with several Au-rich examples noted in the prolific Abitibi Belt of the Superior Province (Dubé et al., 2007)

Worldwide production and reserve figures for greenstone-hosted quartz-carbonate vein deposits total 562 Moz (15,920 t) of gold (13% of world production) and is second in worldwide productivity after the giant paleoplacer Witwatersrand in South Africa (Dubé and Gosselin, 2007). Canada is an important producer of gold with total global production and reserves calculated at 327 Moz (9,280 t) of gold (7% of world production). Greenstone-hosted quartz-carbonate vein deposits account for approximately 35% of global production and reserves (194 Moz; 5,510 t gold) and 59% of Canadian gold production, primarily in the rich Abitibi Belt, which hosts 81% of the total Canadian gold, totaling 158 Moz (4,470 t) (Dubé and Gosselin, 2007). Figure 9 shows the tonnage versus grade of

greenstone-hosted gold deposits in Canada as well as global examples with >1 Moz (>30 t) contained gold.
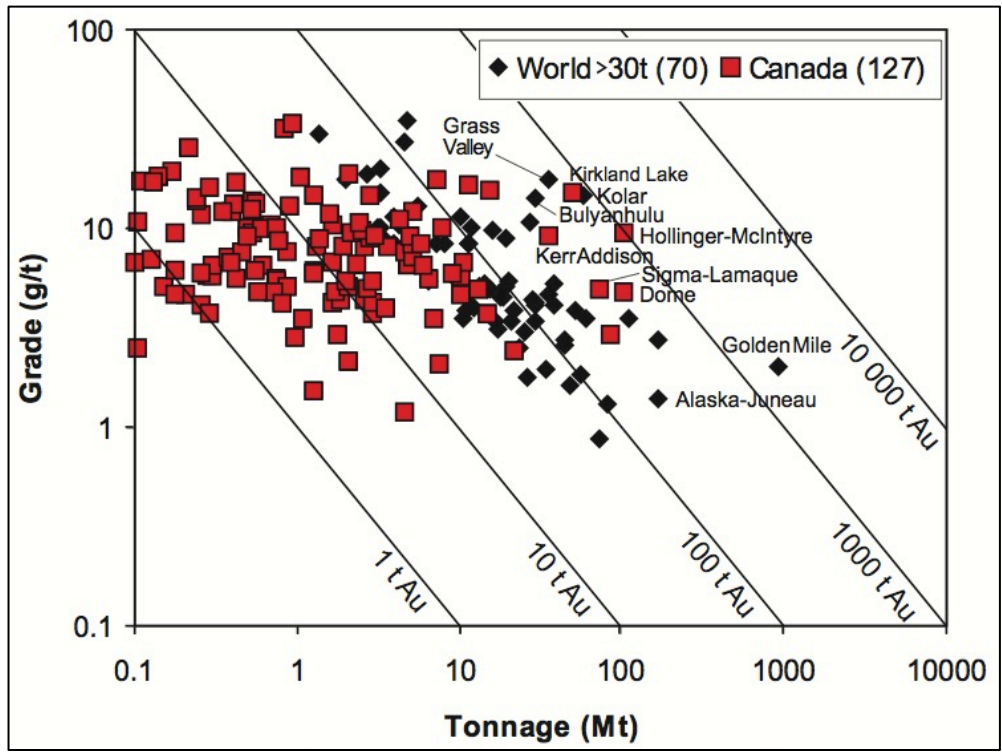
Figure 9. Tonnage vs. grade plot of Canadian greenstone-hosted gold and worldwide greenstone-hosted gold deposits containing at least 1 Moz (30 t) of Au in combined production and reserves (modified from Dubé and Gosselin, 2007).

CHAPTER 4   ARCHEAN OROGENIC GOLD MINERALIZATION

4.1   INTRODUCTION

The term orogenic gold deposits was first introduced by Groves et al. (1998) to describe and replace the class of epigenetic precious metal vein deposit terms commonly referred to in older literature as "lode gold," "Archean gold", "greenstone gold" or "mesothermal gold" since orogenic gold better reflects the processes leading to gold deposition over a wide range of depths and ages in metamorphic terranes. Orogenic gold deposits encompass a range of deposit styles with important examples found in a variety of Proterozoic and Phanerozoic settings, but of interest here are those associated with Archean granite-greenstone terranes. As the name implies, orogenic gold deposits are temporally and spatially associated with orogenies and are invariably associated with zones of high strain, regardless of lithology or crustal depth (Groves et al., 1998). The synchroneity with major accretionary and collisional orogenic episodes and the production of metamorphic fluids, less commonly magmatic, that precipitate metals at various crustal levels along deep-seated shear and fracture zones are the dominant and characteristic genetic features of all orogenic gold deposits (Robb, 2005).

Important global examples of orogenic gold deposits hosted in granite-greenstone terranes are found in the Superior Province of Eastern Canada, the Yilgarn Craton of Western Australia, and the Zimbabwe Craton. Orogenic gold deposits typically occur in second- or third-order structures associated with crustal-scale deformation zones, but as also evidenced in the Superior Province, they can be associated with swarms of lamprophyres and felsic porphyries derived from mantle and lower crustal depths, respectively (Groves, 1993). Kerrich (1993) summarized the similar characteristics of lode gold deposits, later incorporated by Groves et al. (1998) into the orogenic gold model, as being epigenetic, structurally hosted in lithologically and structurally complex metamorphic terranes, having undergone hydrothermal alteration with limited vertical zonation under varying P-T-t regimes, and having similar alteration (enrichment in CO_2, S, K and other LILE), ore metals (pyrite, pyrrhotite, chalcopyrite and arsenopyrite), geochemistry (Au, Ag, As, Bi, B, Hg, Sb, Se, Te and W) and ore fluid sources.

4.2   TECTONIC SETTING

Generally reflecting the compressional to transpressional tectonic settings where they form (Figure 10 and Figure 11), orogenic gold deposits are hosted within metamorphic terranes having undergone orogenesis and are typically related to crustal shortening, however, as highlighted in
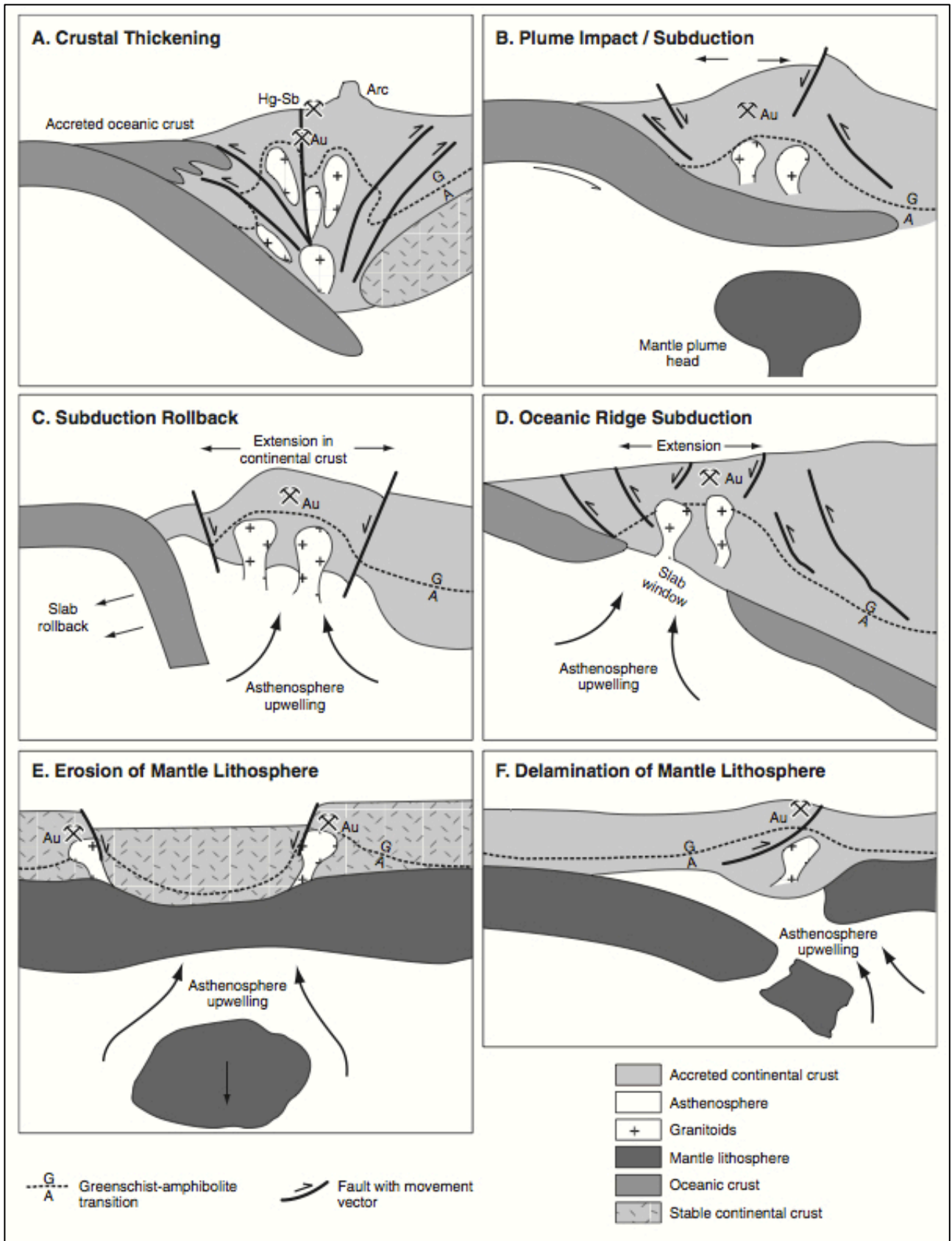
Figure 10. Various tectonic events that can provide the heat to mobilize gold-forming fluids in metamorphic terranes. Includes A) crustal thickening, (B) plume impact, (C) slab rollback, (D) ridge subduction, (E) erosion of pieces of mantle lithosphere, and (F) delamination of the lithosphere (after Goldfarb et al., 2001; from Goldfarb et al., 2005).

Figure 10, extensional tectonics within a convergent setting can provide the heat to mobilize gold-bearing fluids in metamorphic terranes.

These deposits consistently develop in the latter stages of ongoing regional deformation in the host metamorphic terranes and are characterised by high temperature/low pressure metamorphic assemblages (Groves et al., 1998).
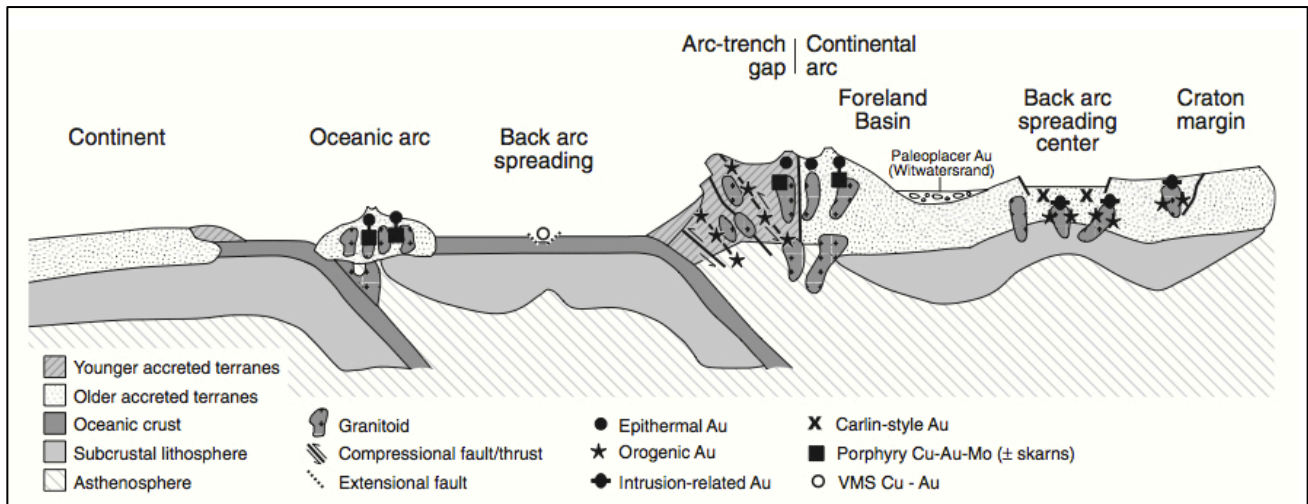
Figure 11. Schematic diagram showing the tectonic setting of various gold deposit types. Orogenic gold deposits develop in the forearc region of convergent continental margin over a wide range of crustal depths and may also develop in deformed back–arc sedimentary sequences on the craton margin (from Goldfarb et al., 2005).

According to the unified model for gold mineralization in accretionary orogens, presented by Hronsky et al. (2012), the major tectono-magmatic setting of orogenic gold deposits is at the inversions of retro-arc pericontinental rifts, typically located adjacent to continental margins or margins of continental crust fragments where primitive sedimentary and/or volcanic rock sequences are deposited. The favourable geodynamic setting is at the terminal stage of collisional inversion and minor post-orogenic extension where mantle-derived components are significantly dominated by crustal magmatic contribution (Hronsky et al., 2012).

4.3   MINERALIZATION CONTROLS

Orogenic gold deposits in greenstone belts are linked to lengthy (tens to several hundreds of kilometres), narrow (a few hundred metres wide) first-order crustal faults and shear zones extending to considerable depths in the crust and acting as conduits for focusing auriferous fluids (Groves, et al, 1998; Goldfarb et al., 2005). However, the first-order faults and shear zones, though proximal to deposits, do not directly host the ore bodies. Rather, the host faults and shear zones trapping the fluids and acting as sites of gold deposition are second- and third-order faults and shear zones, particularly along dilational jogs or changes in strike along the first-order structures. Commonly

associated with shortening and high-angle reverse motion, faults hosting orogenic gold deposits have long-lived and complex structural histories (Goldfarb et al., 2005). Groves et al. (1998) note controlling structures are highly variable in type, though are typically ductile to brittle in nature. In addition to forming in high-angle reverse brittle faults and ductile shear zones, controlling structures can be fracture arrays, stockwork networks and breccias in competent (volcanic, granitoid, BIF) rocks, or foliated zones and fold hinges in ductile turbidite sequences, as shown in Figure 8 (Groves, et al, 1998; Goldfarb et al., 2005).

Figure 12, from Hronsky et al. (2012), highlights three key elements for the formation of gold deposits:
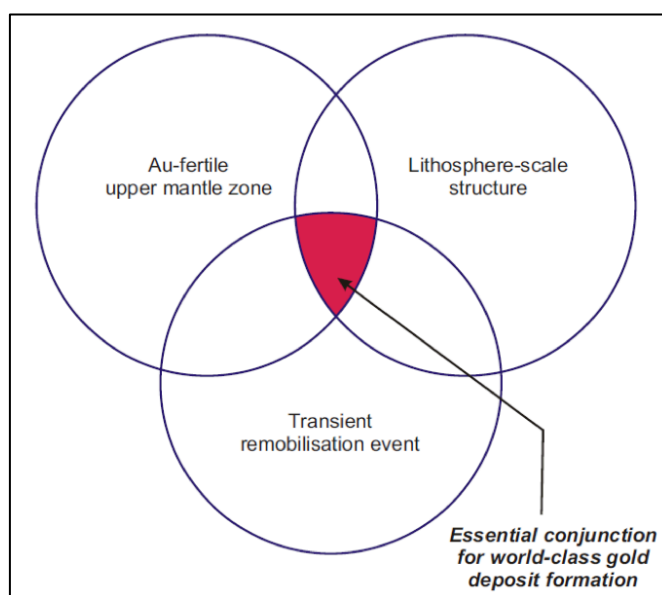
Figure 12. Schematic illustration of the conjunction of three independent parameters required to form a world-class gold deposit (of any deposit type) within an accretionary orogen (Hronsky et al., 2012).

1) the presence of a gold-enriched fertile upper mantle region produced by low-percentages of partial-degree melts of asthenospheric mantle (where gold behaves as an incompatible element) from the convecting mantle wedge up to the non-convecting upper lithospheric mantle, which allows gold to concentrate over time,

2) a favourable transient remobilization event that remobilizes gold-rich magmas and/or fluids from the upper mantle through selective re-melting of enriched domains with minimal dilution by other mantle melts, and

3) favourable lithospheric-scale structures, which are vital for allowing the focused transport of fertile magmas/fluids to the upper crust

4.4   DEPOSIT MINERALOGY

As described by Groves et al. (1998), orogenic gold deposits are characterized by quartz-carbonate dominated vein systems with ≤3-5% mainly Fe sulphide minerals and ≤5-15% carbonate minerals. Common gangue minerals are albite, white mica, fuchsite, chlorite, scheelite and tourmaline, whereas the main ore minerals are native gold along with pyrite, pyrrhotite and chalcopyrite in decreasing amounts (Dubé and Gosselin, 2007). Little change in mineralogy or gold grades is noted in these continuous vein systems that extend vertically from 1 to 2.5 km depth, though vertical mineral zoning does occur in some deposits (Dubé and Gosselin, 2007). Gold to silver ratios range from 1:1 to 10:1, with higher gold to silver ratios more common (Groves et al., 1998). Relatively high historic gold grades have been in the 5-30 g/t range, though recently, lower grades have been extracted with bulk mining methods (Dubé and Gosselin, 2007). Ore can be hosted in the veins or in sulphidized wallrock, with sulphide mineralogy reflecting the host rock lithogeochemistry, such as common arsenopyrite in metasedimentary country rocks or amphibolite facies rocks and pyrite or pyrrhotite more typical in meta-igneous host rocks (Dubé and Gosselin, 2007). Also present in some deposits are trace amounts of molybdenite and tellurides (Dubé and Gosselin, 2007). Variable enrichments in As, B, Bi, Hg, Sb, Te and W are noted in gold-bearing veins, whereas slightly elevated Cu, Pb and Zn values are typical (Groves et al., 1998).

The textures exhibited in quartz-carbonate veins of orogenic gold deposits vary according to the nature of the host structure, whether extensional or compressional (Dubé and Gosselin, 2007). Extensional veins typically exhibit multiple stages of mineral growth, with quartz and carbonate fibres developing at high angles to vein walls. Laminated veins are composed of massive, fine-grained quartz, and when present, fibres are sub-parallel to vein walls. Individual veins can vary in thickness from a few centimetres up to 5 m, with lengths ranging from 10-1000 m (Dubé and Gosselin, 2007).

Characteristic lateral alteration in orogenic deposits is on the scale of centimetres to tens of metres, whereas subtle vertical zonation is on the scale of hundreds of metres, except in sub-greenschist facies ore environments where "telescoped" alteration may be present (Groves, 1993). While widths and mineralogy of alteration zones vary with wallrock type and crustal level (Groves et al., 1998), proximal wallrock-alteration assemblages in ore zones of mafic-ultramafic deposits vary systematically with metamorphic grade of the enclosing rocks (Groves, 1993). Carbonates (ankerite, dolomite or calcite), sulphides (pyrite, pyrrhotite, arsenopyrite) and alkali metasomatism (sericitization, with less common fuchsite, biotite or K-feldspar and albitization) are most common wallrock alteration products, along with chloritization of mafic minerals. In greenschist facies rocks,

wallrock alteration involves the addition of significant amounts of CO_2, S, K, H_2O, SiO_2 ± Na and LILE (Groves et al., 1998).

At a regional scale, sites of mineralization can exhibit zones of intense carbonatization and chloritization extending for hundreds of meters from the mineralizing conduits (Robb, 2005). Associated intense wall-rock alteration and sulphidation also play a major role in metal precipitation as well as the phase separation of H_2O-CO_2, which may explain the siting of rich accumulations of gold in quartz-carbonate veins and the common association with the brittle-ductile transition due to the coinciding relevant P-T conditions of the H_2O-CO_2 solidus, as shown in Figure 13 (Robb, 2005).

4.5 GENETIC MODELS

Figure 13 illustrates the principal features of Archean orogenic gold deposits. As shown in Figure 11 and Figure 13, the main megascale features of orogenic gold deposits are convergent plate margins. Associated metamorphism partially results in the production of fluids that focus along major structural discontinuities, such as major shear zones within or along the margins of the metamorphosed greenstone belts. The shear zones represent district-scale hosts that are accompanied by broad zones of intense alteration with ore deposition occurring along second- and third-order structures, resulting from fluid rock interactions and H_2O-CO_2 phase separations (Robb, 2005).
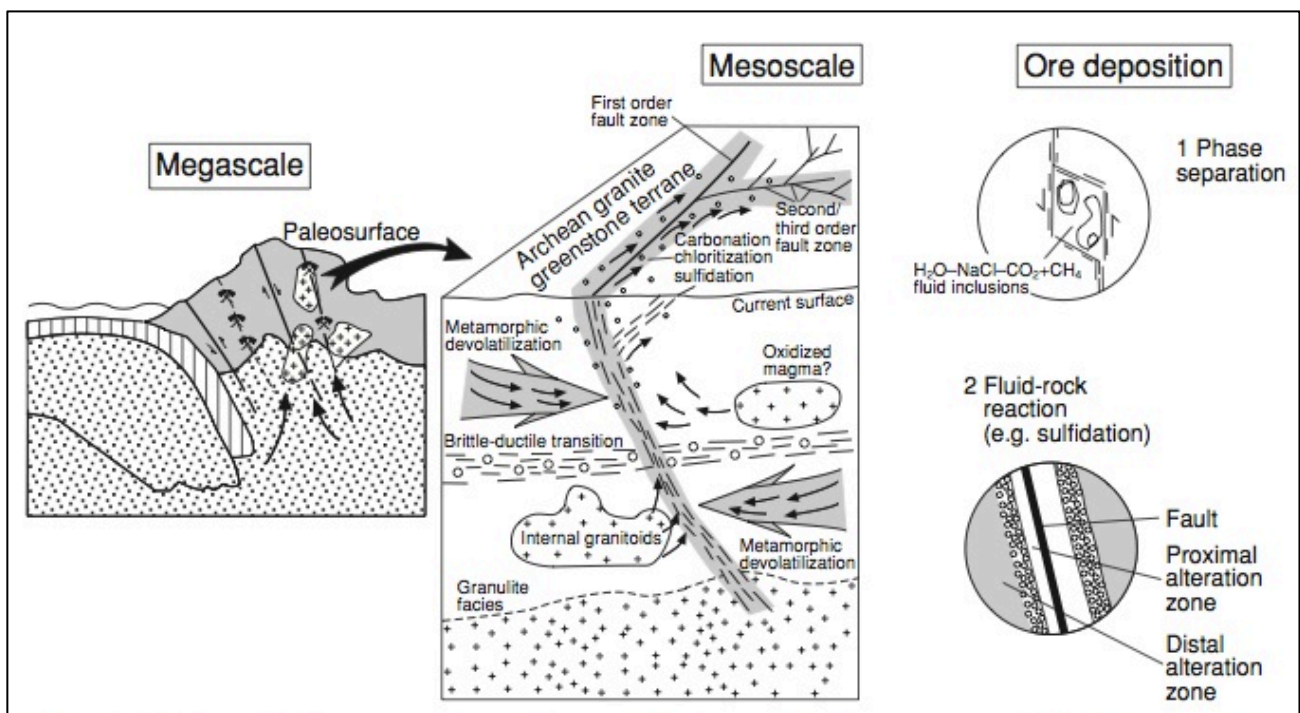
Figure 13. Schematic illustrations showing the principal features of Archean orogenic gold deposits (from Robb, 2005).

Figure 14 illustrates the crustal environments for hydrothermal gold deposits, which are widely recognized as forming a crustal continuum with a range of P-T conditions (180°C at <1 kb to 700°C at 5 kb) over a >15 km (<5 km to >20 km) crustal profile and occur in granulite to greenschist facies host environments with ductile to brittle structural regimes (Groves, 1993). Archean orogenic gold deposits are emplaced at around 300°C and form quartz-vein or fracture dominated ore systems (Groves, 1993). Timing of mineralization in orogenic gold systems is during syn- to post-peak regional metamorphism, implicating hydrothermal systems with large and deep sources of primary ore fluids (Groves, 1993). The hydrothermal systems have a number of possible deep fluid and solute reservoirs that include 1) basal segments of greenstone belts, 2) deep level, intrusive granitoids, 3) mid- to lower crustal granitoid-gneisses, 4) mantle lithosphere, 5) subducted oceanic lithosphere or 6) underthrusted terranes (Groves, 1993; Goldfarb et al., 2005). Isotopic evidence indicates fluid evolution and pathways are complex, being derived from, or in equilibrium with, a number of these reservoirs en route to depositional sites (Groves, 1993).

Common to all orogenic gold deposits is a low-salinity, H_2O-CO_2-CH_4 composition fluid with varying H_2O:CO_2:CH_4 ratios for different deposit locations (Groves, 1993). The origin of these fluids and their focused flow upwards into the crust is derived from the complex interplay of crustal thickening, deformation, metamorphism and synorogenic magmatism (Groves, 1993). Relatively reduced fluids created during regional prograde metamorphic dehydration have been implicated as playing a major role in the formation of orogenic gold deposits as they preferentially transport gold as a gold-hydrogen sulphide anion complex (Robb, 2005). Gold mineralization is broadly synchronous with peak regional metamorphism, though the peak may not be in the upper crust where mineralization is occurring, but rather in the lower crust, therefore mineralization can be syn- to epigenetic (Robb, 2005). Where there is a spatial link between mineralization and granitic intrusions, mineralizing fluids can be also be derived from the oxidized granitic magmas (Robb, 2005).

A common spatial association between base-metal-rich VMS deposits, oceanic volcanic rocks and vein-type gold deposits within a given gold province, noted in Goldfarb et al. (2005), led to the idea that gold was highly concentrated into massive sulphide ores during seafloor exhalative events and was later remobilized from the massive sulphide ores into veins and other epigenetic ore styles during subsequent deformation and/or metamorphism. A close spatial association does not exist in many greenstone belts hosting both deposit types; therefore it is an unlikely source of gold, sulphur and other components in epigenetic gold systems. However, many metamorphic, magmatic or mantle fluid source models suggest gold ore fluids were leached from syngenetic to diagenetic sulphide minerals (e.g. pyrite) in the metavolcanic and/or sedimentary pile and may have originally entered the oceanic strata through seafloor processes before subsequent concentration in epigenetic mineralization (Goldfarb et al., 2005).
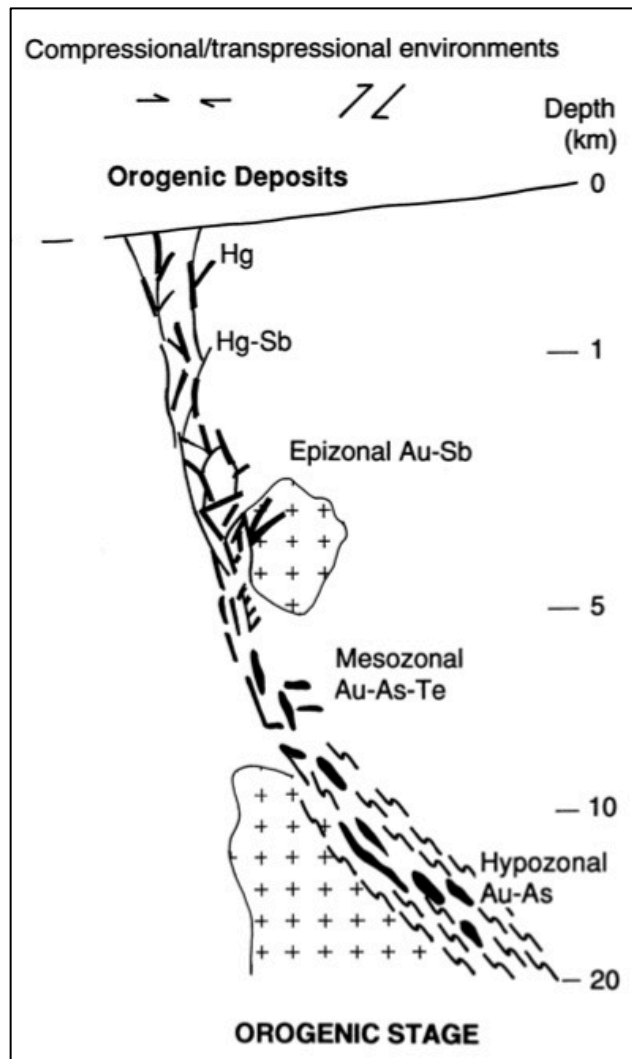
Figure 14. Schematic representation of crustal environments of hydrothermal gold deposits in terms of depth of formation and structural setting within a convergent plate margin. Not all deposit types or depths of formation will be represented in a single ore system (from Groves et al., 1998; after Groves, 1993; Gebre-Mariam et al., 1995; and Poulsen, 1996).

Generally, the metamorphic models form part of a continuum for ore genesis (Figure 14) and require a broad source region for ore fluid and metal formation (Goldfarb et al., 2005). Ultimately, the most commonly suggested association of gold transport and concentration is through metamorphic processes, mainly indicated by the volatile compositions of hydrothermal fluids, the progressive decrease of gold with metamorphic grade, the increase of enriched element concentrations associated with gold deposits and the common association of medium-grade metamorphic environments with ore deposits (Goldfarb et al., 2005). Metamorphic devolatization is a critical process for concentration of many volatile and metal species within orogenic gold deposits hosted in greenstone belts and turbidite sequences where ore fluid migration is controlled by the fault valve mechanism (Sibson et al., 1988) or low permeability caps during transport from the deep crust (Goldfarb et al., 2005). Fault-driven fluid flow, or the fault-valve model of Sibson et al. (1988)

describes the incremental deposition along fault veins hosting gold mineralization in greenstone belts, which commonly have extensive down-plunge continuity (100's to 1000's of metres).

Metamorphic models suggest that gold is removed from high-grade metamorphic rocks and concentrated in low-grade metamorphic rocks during regional metamorphism with auriferous fluids being continually released during prograde metamorphism along with increases in temperatures and pore pressures during uplift, followed by the release of fluids during subsequent hydraulic fracturing (Goldfarb et al., 2005). As mentioned above, rocks at depth with anomalous background gold values, such as metavolcanic rocks with interbedded pyritic shales, have been suggested as the source of gold in these models with subsequent mobilization of the syngenetic auriferous pyrite into epigenetic lodes during later metamorphic events. Tectonically driven changes in far-field stresses may be very important in driving fluid release during devolatization and may cause the release of fluids trapped within pores of low permeability zones prior to tectonic-induced changes (Goldfarb et al., 2005). An alternative metamorphic model suggests a subducting slab could introduce volatiles (H_2O and CO_2) during slab devolatilization, though this model contributes more to magmatic and mantle models for the formation of orogenic gold deposits.

Magmatic models have long been suggested as an origin for orogenic-type deposits largely due to the spatial and temporal association between the deposits and igneous rock (Goldfarb et al., 2005). Common relationships between intrusions and orogenic gold deposits exist with tonalite-trondhjemite-granodiorite (TTG) intrusions, oxidized felsic magmas, S-Type and I-Type granitoids. However, in some instances there are indications that gold ores are much younger than the spatially associated intrusions and the association of the two is structurally coincidental (Goldfarb et al., 2005). Also, lithophile element ratios in many alteration assemblages surrounding Archean orogenic gold deposits are inconsistent with magmatic sources and other elements, such as W, Bi and Te, are mobile in many types of crustal fluids, thereby they do not necessarily indicate proximity to a magmatic fluid source (Goldfarb et al., 2005). Moreover, the thermal aureole gold (TAG) model stresses a local, versus regional, heat source in deriving ore fluids allowing for either magmatic, metamorphic or meteoric systems to dominate in orogenic deposits (Goldfarb et al., 2005).

A secretion model related to metamorphism is a concept that focuses on providing a source of the mineralizing fluids rather than the processes of fluid formation and describing pathways for ore formation (Goldfarb et al., 2005). It has been described in literature for Barberton, Kirkland Lake and Ashanti orogenic gold deposits (Goldfarb et al., 2005). The model suggests relatively local "depyritization" of pyrite hosted within metamorphic rocks will release gold and sulphur into hydrothermal fluids along fluid flow pathways, or, alternatively, devolatilization of the host rocks can contribute fluids, sulphur and gold into the hydrothermal systems (Goldfarb et al., 2005).

Mantle-related models have suggested lamprophyres are an important component of the ore forming process. As alkali magmatic systems have an affinity for gold, lamprophyres are inherently rich in CO_2, S and Au, and they are consistently spatially associated with orogenic gold deposits (Goldfarb et al., 2005). However, there are a number of arguments against this model, which include, 1) inconsistent gold enrichment, 2) a lack of other elements associated with gold deposits in lamprophyres, 3) the broad range of lamprophyre tectonic settings, 4) the distinct differences between ore and lamprophyric isotopic signatures and 5) the quick loss of gold as a lamprophyre interacts with the continental crust during emplacement (Goldfarb et al., 2005). Asthenospheric upwelling and mantle plumes have also been suggested as possible sources for fluids through devolatilization or granulization of lower crust that produce auriferous fluids mobilized within lower crustal melts (Goldfarb et al., 2005).

CHAPTER 5   **SLAVE PROVINCE**

5.1   **INTRODUCTION**

The Slave Province is a large (~500 by 700 km) Archean crustal block or craton comprised of basement gneiss complexes, known as the Central Slave Basement Complex, unconformably overlain by the Yellowknife Supergroup, which consists of the thin (<200 m) discontinuous (par) autochthonous Central Slave Cover Group (2835-2734 Ma) continental shelf assemblage with overlying late Neoarchean (2730-2660 Ma) greenstone belts of thick tholeiitic to calc-alkaline volcanic sequences typically conformably lying at the margins of coeval to slightly younger (2680-2660 Ma) metaturbidite basins (Ketchum et al., 2004). Several pulses of granitoid plutonism across the Slave Province were emplaced during volcanism (ca. 2700 Ma) and continued during the widespread metaturbidite sedimentation with the emplacement of 2630-2605 Ma tonalite-trondhjemite-granodiorite (TTG) and 2600-2580 Ma granites (Davis et al., 1994). More or less coinciding with the late plutonism was a pan-Slave orogenic and deformation event between 2650-2580 Ma (van der Velden and Cook, 2002; Bleeker et al., 2004). In a global context, the Slave Province is comparable to the Dharwar, Zimbabwe and Wyoming cratons with respect to tectonic history. Although the Slave Province has a long history of gold production (e.g. Con, Giant and Lupin mines), current mining in the Slave Province is limited to three producing diamond mines (Ekati, Diavik and Snap Lake) and a fourth diamond mine (Gahcho Kué) was recently approved.

5.2   **TECTONIC SETTING**

The Slave Province (Figure 15) comprises an ovoid block of Archean rocks bordered by the Paleoproterozoic Thelon-Taltson and Wopmay orogens to the east and west, respectively, with the Great Slave Lake shear zone linking magmatic zones of Thelon-Taltson orogen (Helmstaedt, 2009). In the northern part of the province, remnants of relatively little deformed Paleoproterozoic cover rocks (Goulburn and Coronation supergroups) are preserved (Helmstaedt, 2009). Paleozoic rocks of the western Interior Platform overlap the southwestern part of the Province. To the northeast, the Neoarchean Bathurst Block is separated from the western terranes by the Bathurst Fault Zone and Proterozoic cover rocks of the Goulburn Supergroup (Helmstaedt, 2009).

Traditionally, the Slave Province has been divided into western and eastern domains (Figure 16) based on isotopic studies by Davis and Henger (1992) and Thorpe et al. (1992) that indicated older rocks, such as the Central Slave Basement Complex (Section 5.3.1) are only found in the western portion of the craton. Additionally, the isotopic division also considered that greenstone belts in the west are primarily composed of mafic and intermediate volcanic rocks, whereas volcanic rocks in

the east are more typically intermediate to felsic (Helmstaedt, 2009). Recently, the Slave Province has been viewed as a tectonic collage consisting of Mesoarchean micro-continental nucleus enlarged by the accretion of additional Neoarchean juvenile terranes with Helmstaedt (2009) proposing to subdivide the Slave craton into five distinct terranes (Figure 2) with at least four that can be viewed as separate tectonic domains (Central Slave superterrane, Contwoyto, Snare River and Hackett River terranes plus the Bathurst Block). The divisions are based on past interpretations made by Kusky (1989; 1990) and Bleeker et al. (1999a).
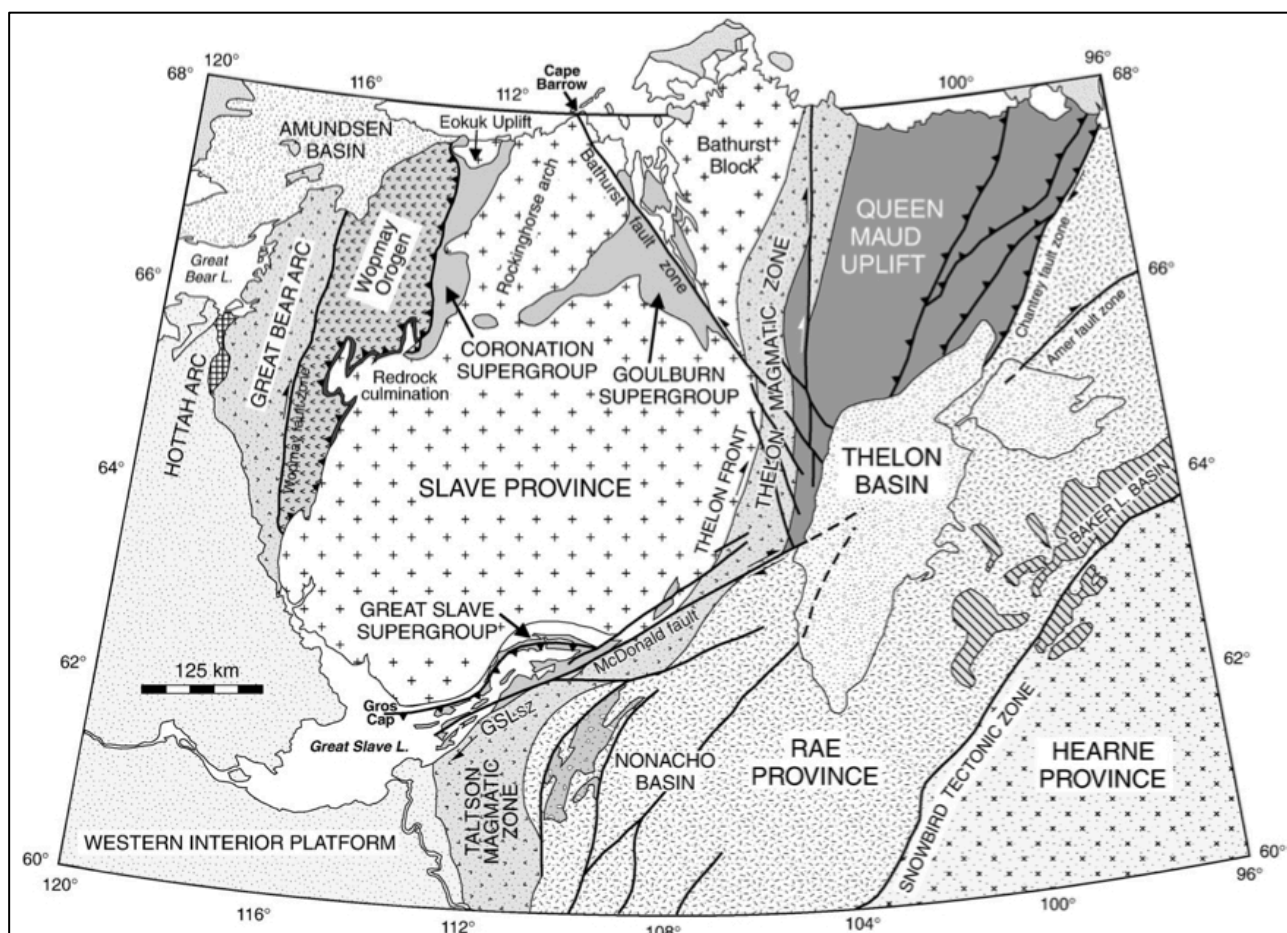
Figure 15. Tectonic setting of the Slave Province within the northwestern part of the Canadian Shield Archean rocks = crosses. GLSsz – Great Slave Lake shear zone (from Helmstaedt, 2009).

The Central Slave superterrane (CSST), which hosts the Yellowknife, Cameron River and Beaulieu River greenstone belts in the south, is described as a composite tectonic terrane that evolved between 4.0 and 2.85 Ga, before breaking up at the end of the Mesoarchean (Helmstaedt, 2009). It is bounded by the juvenile ca. 2.67-2.58 Ga Snare River terrane to the southwest and Contwoyto terrane to the east, whereas in the north, the CSST is in structural contact with the ca. 2708-2670 Ma Hackett River terrane (Helmstaedt, 2009). The Neoarchean Snare River terrane, located in the southwestern Slave Province and comprised of bimodal volcanic sequences, turbidite successions and synvolcanic plutons, is inferred to have collided with the CSST between 2.63 and 2.62 Ga while

30

in the northeast, accretion of the juvenile, felsic-dominated Hackett River terrane is inferred to have begun at 2650 Ma (Corcoran, 2012). Separating the Hackett River and CSST in the central and southern portion of the Slave Province are the intervening turbidites and minor volcanic rocks of the Contwoyto terrane, which structurally overlies the CSST and represents a forearc accretionary complex associated with the eastern arc system of the Hackett River terrane (Kusky, 1990).
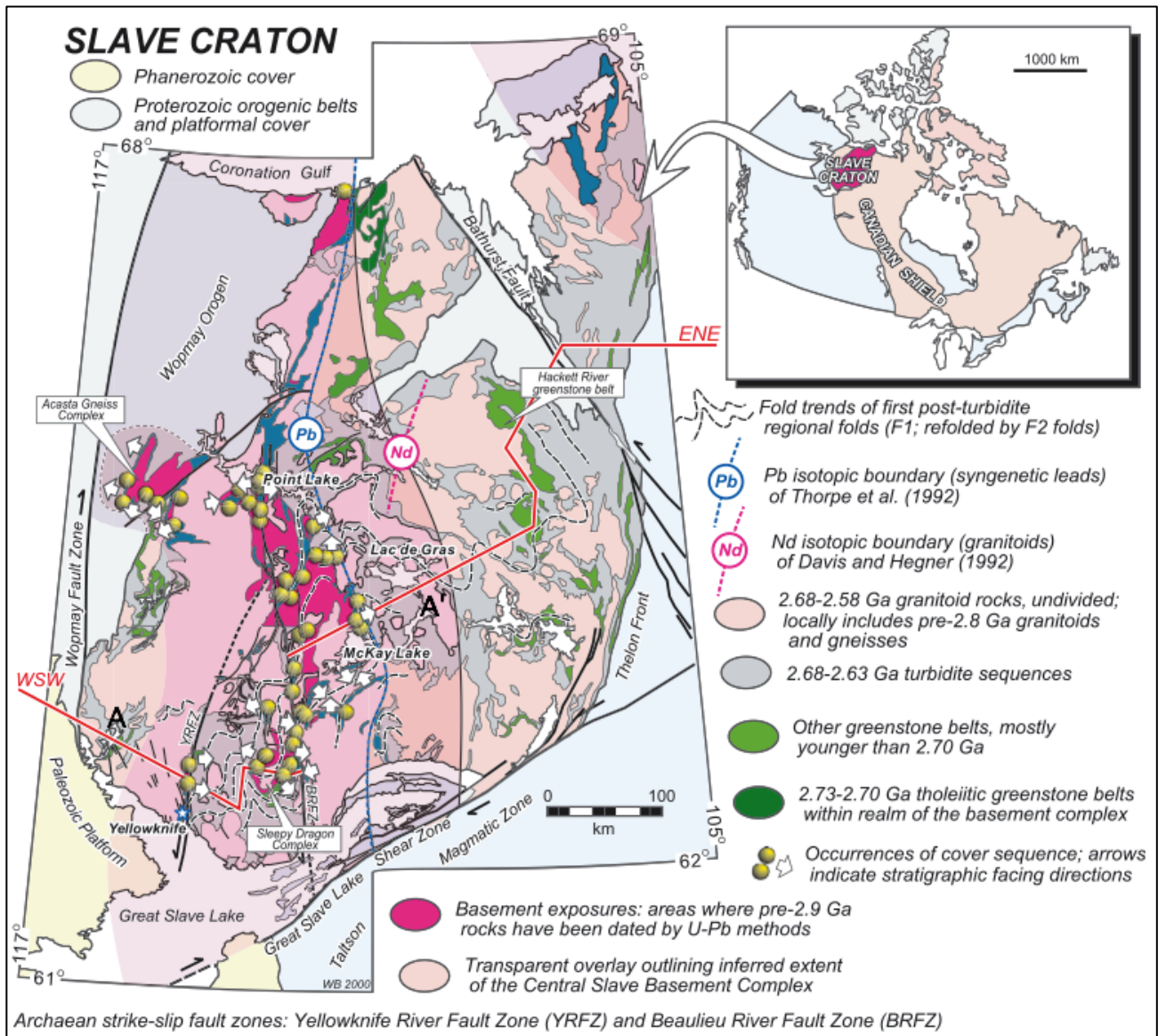
Figure 16. Geological map of the Slave craton. Inset shows location of the Slave craton in the Canadian Shield. Pb isotopic boundary of Thorpe et al. (1992), Nd isotopic boundary of Davis and Hegner (1992). YRFZ=Yellowknife River Fault Zone; BRFZ=Beaulieu River Fault Zone. A-A' defines cross-section in Figure 30 (modified after Bleeker, 2003).

5.3 TECTONOSTRATIGRAPHY

In the Central Slave superterrane, unconformably overlying the Central Slave Basement Complex (CSBC) are quartz-dominated arenite deposits of the Central Slave Cover Group (CSCG), which form the basal unit of Yellowknife Supergroup (Corcoran, 2012). Also, volcanic rocks of the pan-

Slave Yellowknife Supergroup sequence unconformably the CSCG (Henderson, 1985). Excluding the CSCG, the Yellowknife Supergroup sequence can be divided into basal rift volcanic rocks and overlying turbiditic successions of continental arc-marginal basin sequences (Figure 17). The Kam Group in the YGB and the mafic volcanic rocks of the CBGB represent the basal volcanic rocks of tholeiitic basalts to andesites, which become more felsic with andesites and rhyolites up-section. Neoarchean greenstone belt sequences occur province-wide, but show significant regional differences in composition and age ranges (Helmstaedt, 2009). Conformably overlying and interstratified with the volcanic stratigraphy are turbidite sequences (Corcoran, 2012). Locally, post-Yellowknife Supergroup and late-kinematic polymictic conglomerates and sandstones unconformably overlie the volcanic and turbidite sequences (Figure 17). Of the divisions proposed by Helmstaedt (2009), the Central Slave superterrane is the only terrane identified to host representations of all lithostratigraphic units of the Slave Province, as well as four unconformity-bounded sequences with significantly different age ranges and tectono-sedimentary environments.
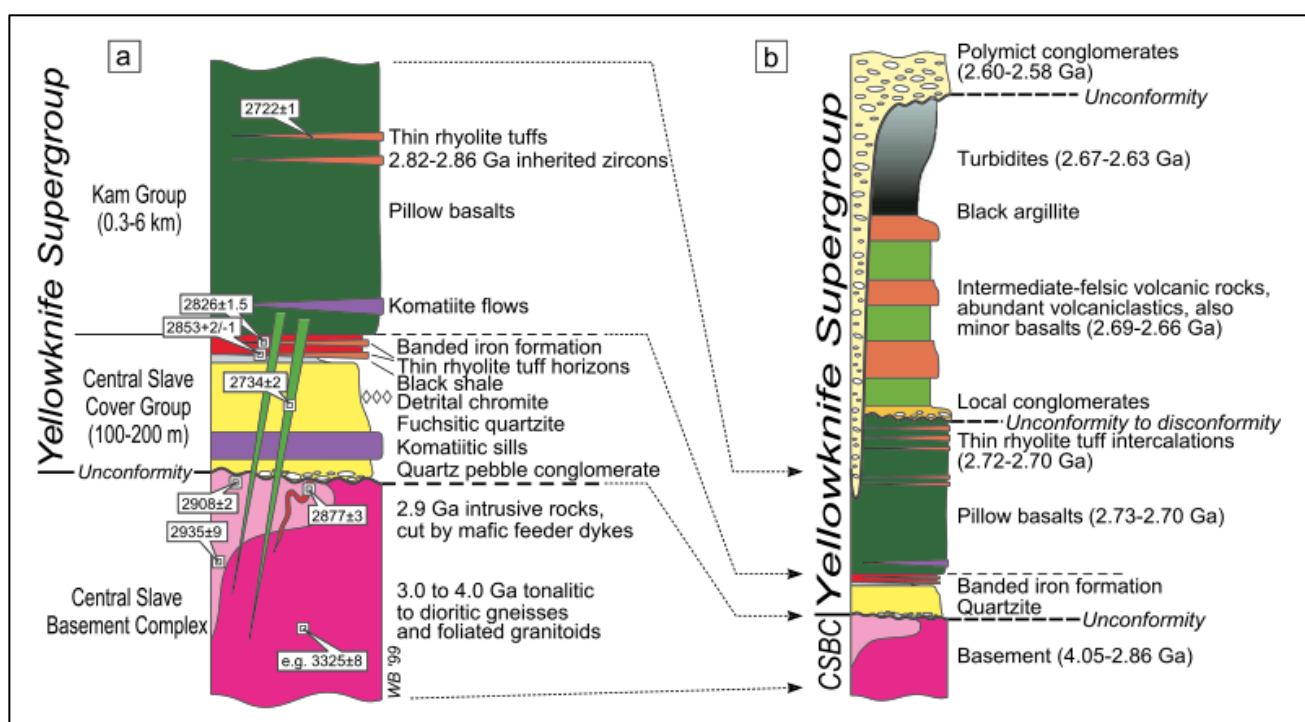
Figure 17. Generalized stratigraphy of the Slave craton (a) Typical stratigraphy of the Central Slave Basement Complex and its overlying sedimentary and volcanic cover. (b) Entire stratigraphy; ca. 2.69–2.66 Ga volcanic rocks and overlying turbidites occur across the craton, their distribution overlapping isotopic boundaries (Bleeker, 2001). Late-stage polymict conglomerates occur in small, restricted basins (from Bleeker, 2003).

5.3.1 CENTRAL SLAVE BASEMENT COMPLEX

The Hadean to Mesoarchean Central Slave Basement Complex (CSBC) gneiss-migmatite rocks and foliated granitoid plutons, dated between 4.0 and 2.8 Ga (Isachsen and Bowring, 1994; Ketchum et al., 2004) of the western and central Slave Province extend 180 km east of Yellowknife

and 340 km north of Great Slave Lake (Goodwin et al., 2006). A tectonic model for the CSBC suggests all basement blocks were united at ca. 2.9 Ga (Ketchum et al., 2004). As mentioned in Section 5.2, the eastern Slave basement is undefined and isotopically juvenile (Thorpe et al., 1992; Davis and Hegner, 1992) with no known instances of basement older than 2.8 Ga. Examples of basement in the CSST consist of >3.0 Ga gneiss beneath the YGB, 2.9 Ga granodiorite gneiss from the Sleepy Dragon Complex (Section 5.4.1.1) and 3.15 Ga tonalite from Beniah Lake (Isachsen and Bowring, 1994).

5.3.2   CENTRAL SLAVE COVER GROUP

The CSBC is unconformably overlain by the discontinuous, autochthonous to parautochthonous, dominantly quartz-rich siliciclastic Central Slave Cover Group (CSCG) sequence, which forms the lowest stratigraphic unit of the Yellowknife Supergroup (Figure 17) and the western Slave greenstone belts (Ketchum et al., 2004). Also, it is one of two pre-Yellowknife Supergroup supracrustal sequences, both of which are confined to the CSST (Helmstaedt, 2009). The widespread occurrence of the typically thin, 100-200 m CSCG marks the regional extent of the CSBC in the western Slave, but the minimum extent of the CSBC across the Slave Province is inferred as much larger (Ketchum et al., 2004). Representing a continental shelf assemblage, the CSCG is comprised of fuchsitic quartzites, thin rhyolitic tuff horizons, abundant detrital chromite, komatiitic sills and highly sheared, basal quartzite-conglomerate banded iron formation with local mafic-ultramafic volcanic units collectively dated at 2835-2734 Ma (Bleeker, 2003; Ketchum et al., 2004; Goodwin et al., 2006). The CSCG surrounding the Sleepy Dragon Complex was given formation names by Bleeker et al. (1999a), based on regional occurrences, for instance Brown Lake, Patterson Lake and Amacher Lake. Similar formations are noted in the Yellowknife (Dwyer Group), Beniah Lake, Winter Lake and Point Lake greenstone belts (Isachsen and Bowring, 1994).

5.3.3   GREENSTONE BELTS

As discussed in 0, greenstone belts represent greenschist to amphibolite grade metamorphism of volcanic rocks. As shown in Figure 2, the Slave craton has approximately 27 relatively small late Neoarchean, narrow, linear, steeply inclined, northerly trending greenstone belts separated by extensive sedimentary and plutonic rocks (Isachsen and Bowring, 1994; Fyson, 1998; Goodwin et al., 2006). Figure 18 shows the volcanic belts are broadly restricted to four, 50-200 km wide, northerly trending domains, namely the western, west-central, eastern and northeastern domains, with the Yellowknife, Cameron River and Beaulieu River greenstone belts lying within the southern portion of the west-central volcanic domain (Fyson, 2000).
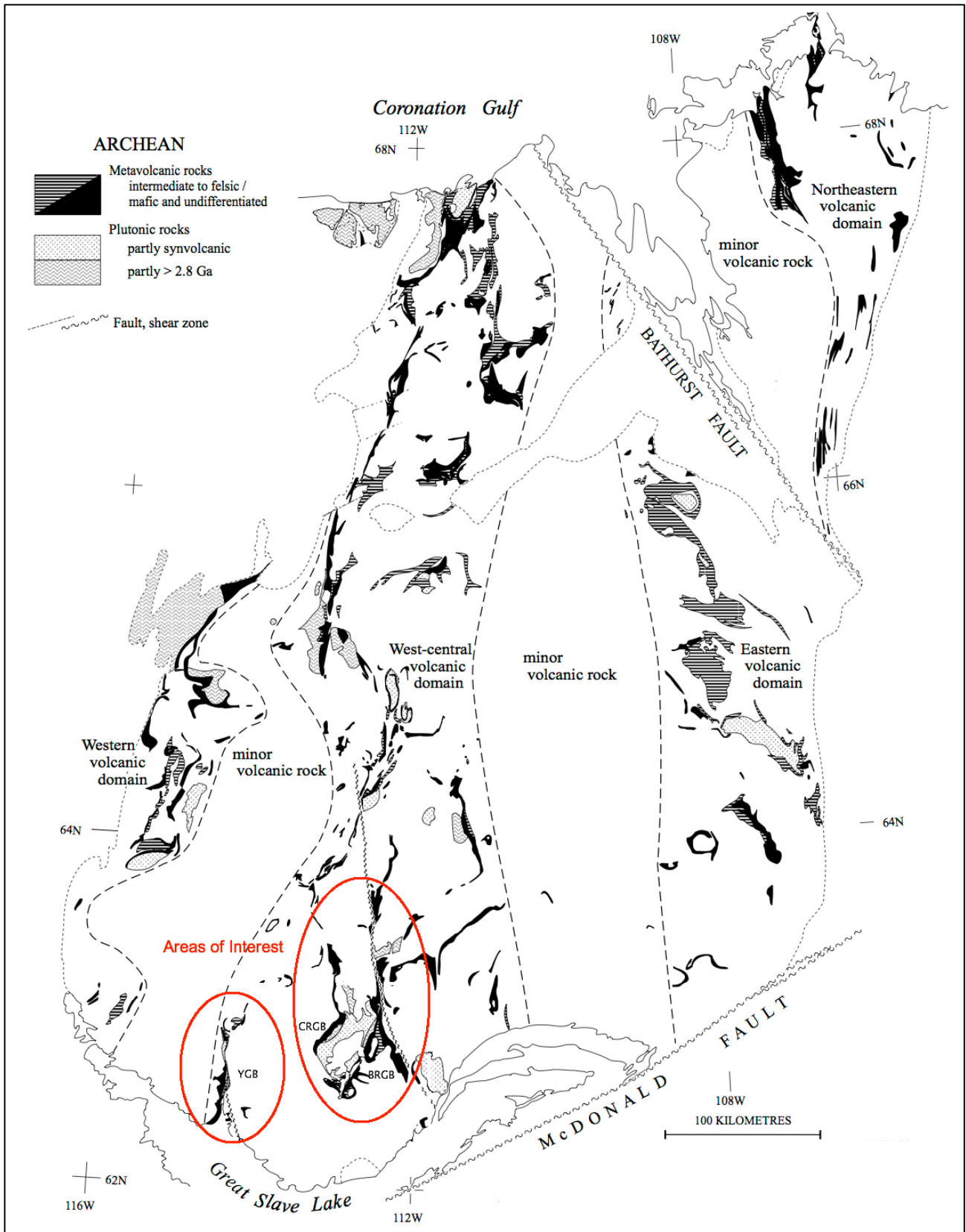
Figure 18. Domainal distribution of volcanic, synvolcanic and older rocks of the Slave Province. YGB=Yellowknife greenstone belt; CRGB=Cameron River greenstone belt; BRGB=Beaulieu River greenstone belt (modified from Fyson, 2000).

The majority of the volcanic rocks comprising the Slave Province greenstone belts erupted between 2.66 and 2.73 Ga and make up a large part of the Yellowknife Supergroup (Isachsen and Bowring, 1994; Fyson, 1998; Bleeker, 2003; Ketchum et al., 2004; Bleeker et al., 2004; Goodwin et al., 2006).

Volcanic rocks are locally conformably to disconformably overlying the basement granitic gneisses or the CSCG and contacts typically exhibit high strain zones with minor displacement (Fyson, 2000). Two major phases of volcanism in the Slave Province are noted; older tholeiitic volcanism (ca. 2.73-2.70 Ga) and younger typically calc-alkaline volcanism (ca. 2.69-2.66 Ga) with the best known examples being the Kam Group and Banting Group in the YGB, respectively (Fyson, 2000).

Older volcanic rocks are comprised of thick (1-6 km) and extensive tholeiitic basalts with minor komatiite and rhyolite tuff intercalations that everywhere overlie the CSCG (Bleeker et al., 2004). The lavas are thought to have erupted across the CSBC in a subaqueous environment and accompanied rifting of the basement complex, a process which was possibly assisted by mantle plume activity (Bleeker et al., 2004). Alternatively, Kusky (1989) describes the tholeiitic rocks, commonly referred to as Yellowknife-type, as being obducted slivers of oceanic crust (ophiolites). The younger volcanic calc-alkaline sequences, also referred to as Hackett River-type, are typically more felsic in composition and represent a transitional phase from intermediate to felsic (bimodal) volcanism, typically consisting of dacite-rhyolite complexes (Bleeker, 2003). Commonly associated with the younger volcanism are widespread tonalite-trondhjemite-granodiorite (TTG) sub-volcanic plutons (Bleeker, 2003).

5.3.4 CONGLOMERATES

Commonly sitting unconformably above regional volcanic piles and below turbidite units in the Slave Province are conglomeratic units that act as marker horizons of broad regional significance (Bleeker, 2001). These conglomerates give an indication as to the nature of the unconformities they overlie; however, depositional relationships at unconformable contacts can be wholly erased by intense deformation and metamorphism (Bleeker, 2001). In the Sleepy Dragon area, the discontinuous 2680 Ma Raquette Lake Formation comprising heterogeneous assemblages of sandstone, conglomerate and carbonate is exposed along the eastern shores of Upper Ross Lake for about 5 km, approximately 70 km east-northeast from Yellowknife, and has been used to develop the concept of craton-wide stratigraphy (Bleeker, 2001).
The correlative Detour Lake Formation, located further to the southeast of the Raquette Lake Formation, and the Raquette Lake Formation together form the Ross Lake Group (Bleeker, 2001). Originally, the conglomerates were thought to be a basal clastic succession of the Yellowknife Supergroup due to commonly faulted, unconformable contacts with the Ross Lake and Detour Lake

Granodiorites, though it was found to overlie an intravolcanic unconformity of the Cameron River Basalts Formation in the Yellowknife Supergroup stratigraphy (Bleeker, 2001). Overlying the conglomerates are turbiditic units, such as the Burwash Formation (Bleeker, 2001).

Additionally, late ca. 2.6 Ga conglomerate-dominated successions representing fluvial, alluvial fan and shallow water depositional settings in strike-slip basins unconformably overlie CSBC, CSGG, volcanic sequences and turbidite successions that developed after the accretion of the Hackett River and Contwoyto terranes with the CSST (Corcoran, 2012). Two examples are the Beaulieu Rapids Formation in the Beaulieu River greenstone belt and the Jackson Lake Formation in the YGB (Corcoran, 2012).

5.3.5 **METASEDIMENTARY ROCKS**

An unusually high proportion of preserved metasedimentary rocks, apart from the conglomerate units, distinguish the Slave Province from most other known Archean cratons (Isachsen and Bowring, 1994). Three large areas of metaturbidite sequences are preserved in the Slave Province, namely the Burwash Formation separating the CBGB and YGB in the Yellowknife domain, as well as the Contwoyto and Itchen Formations in the central Slave and the Beechey Lake Group in the northeast (Isachsen and Bowring, 1994). As volcanism began to wane (ca. 2.66 Ga), turbidites were deposited during the initiation of basins in rifted arc environment of the Slave Province and progressively buried the volcanic substrate during transgression of sea level (Ferguson et al., 2005). As the tectonic setting continued to change, two distinct age ranges of turbidite sequences were deposited; a ca. 2683-2647 Ma turbidite-dominated succession that developed as submarine fans in a fore-arc or intra-arc basin and a ca. 2637-2607 Ma turbidite succession representing deep water deposition in a back-arc basin (Ootes et al., 2009; Corcoran, 2012). The Burwash and Itchen Formations best represent the early turbidites, whereas the late successions are best represented by Contwoyto Formation and Emile River turbidites. The interval between the two ages of turbidites is marked by the closure of the Burwash Basin and the formation of a northeast-southwest D_1 structural grain of mostly upright, fold trains, along with the intrusion of ca. 2630 Ma magmatic arc plutons, represented by Defeat Suite granitic rocks (Section 5.4.2.1) (Bleeker et al., 2004; Ootes et al., 2009; Corcoran, 2012).

The turbidite-dominated successions are extensive, with thicknesses up to 5 km that conformably overlie or are interstratified with arc-related volcanic rocks of the Yellowknife Supergroup (Corcoran, 2012). The local transition from shallow water, coarse clastic deposits into deeper water shale and siltstone is suggestive of a transgression over a subsiding basin (Ferguson et al., 2005; Corcoran, 2012).

The largest and best-known example of metaturbidites in the Slave Province is the Burwash Formation, which infills the Yellowknife Supracrustal Basin separating the YGB and CBGB (Ferguson et al., 2005; Corcoran, 2012). It is bounded to the west by the YGB and the Anton Basement Complex (Section 5.4.1.2), to the east by the Sleepy Dragon Complex (SDC; Section 5.4.1.1) and Meander Lake Plutonic Suite (Section 5.4.2.2) and to the north by the Nardin Metamorphic Complex, whereas the southern margin is obscured by Great Slave Lake (Ferguson et al., 2005). The base of the Burwash Formation rests with apparent conformable contacts on diverse volcanic and sedimentary successions along the basin margins and turbidites are commonly interbedded with felsic volcanic tuff layers (Ferguson et al., 2005). Adjacent to the SDC, the Raquette Lake Formation at the southern margin of the Cameron River greenstone belt and the Detour Lake Formation to the south underlie the Burwash Formation (Bleeker, 2001). The Burwash Formation can be correlated over large areas due to bedding continuity and tuff-dominated intervals that provide recognizable stratigraphic markers (Ferguson et al., 2005).

In both the Tumpline and Sunset subareas (Sections 6.3.1.2 and 6.3.1.3, respectively) of the CBGB, up to 85 m thick, lensoid, non-bedded carbonate units are found in the volcano-sedimentary successions, mainly at the tops of rhyolite units and overlain by Burwash Formation sedimentary rocks (Lambert, 1988). Carbonates were deposited during the late stages of volcanism and form the matrix of rhyolite breccias and rhyolite dome-associated conglomerates (Lambert, 1988).

5.4 MAGMATISM

Granitic to gneissic basement with long complex intrusive and deformational histories are preserved in the Slave Province and are commonly overlain or in contact with volcanic and sedimentary rocks, as well as having later been intruded by granitic plutons and gabbroic sills and dykes (Henderson, 1985). Varied granitic rocks, ranging from massive to weakly foliated concordant plutonic complexes to massive, sharply discordant intrusive bodies, have intruded the supracrustal and basement rocks of the Slave Province at different times, but mainly in the Archean and under a range of different conditions (Henderson, 1985). Compositions range from granodiorite to potassic granite, though a few smaller plutons of gabbro to diorite and granodiorite complexes have been noted (Henderson, 1985). Additionally, extensive, thick contemporaneous gabbroic sills and dykes have locally intruded sedimentary and volcanic rocks (Henderson, 1985).

5.4.1 GRANITIC AND GNEISSIC COMPLEXES

5.4.1.1 Sleepy Dragon Complex

A distinct granite-gneiss domain of the south-central Slave Province is the Sleepy Dragon Complex (SDC), which is bordered by the CBGB of the Yellowknife Supergroup. As shown in Figure 19, the

SDC is roughly rectangular over a 25 km wide by 45 km long area trending NE-SW. It is bound by the northern segment of the Cameron River and Turnback Lake between Upper Ross Lake and Victory Lake (Henderson, 1985).
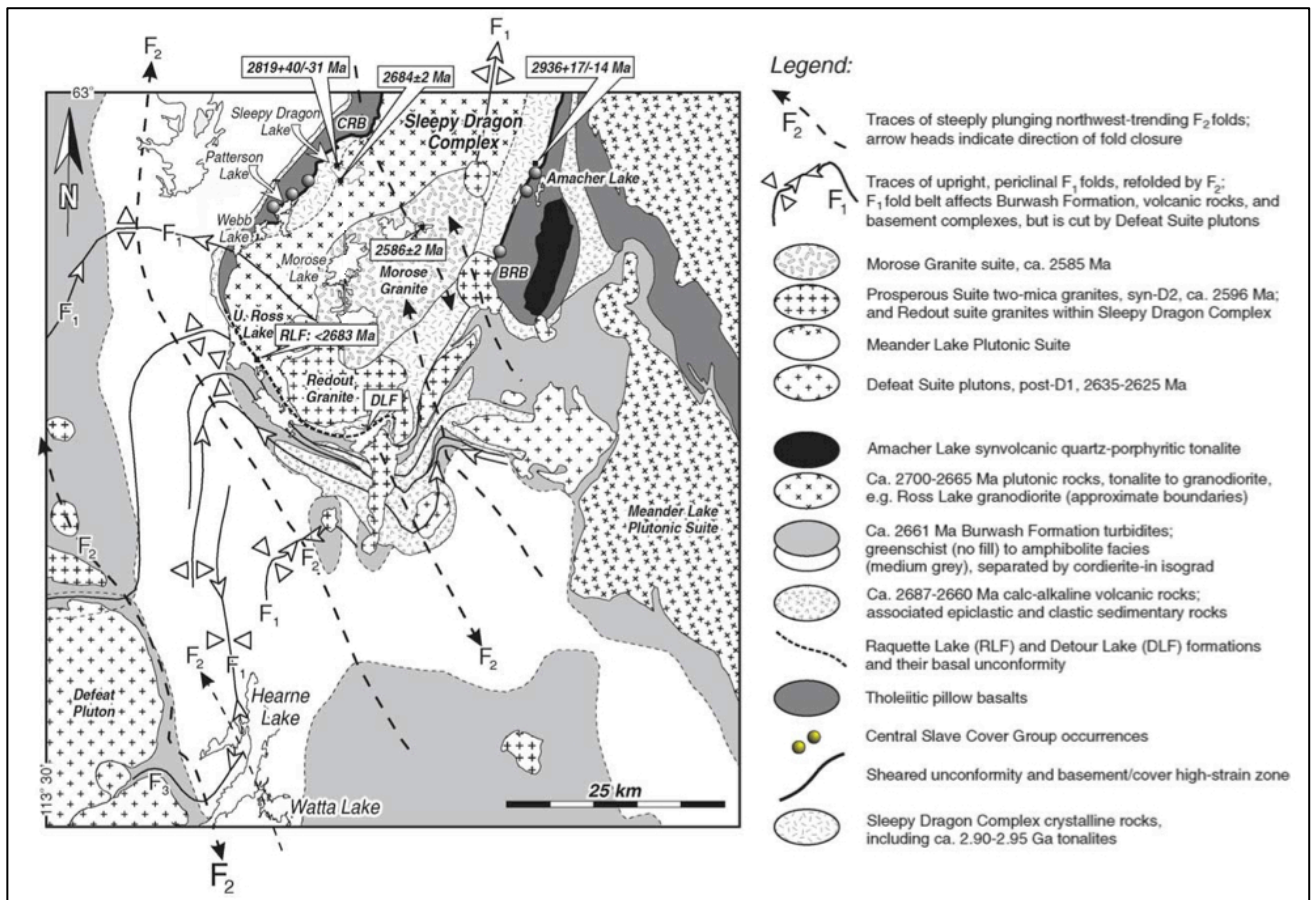
Figure 19. Regional geological of the Sleepy Dragon area showing the numerous pluton rocks in the area. CRB=Cameron River greenstone belt; BRB=Beaulieu River greenstone belt; RLF=Raquette Lake Formation; DLF=Detour Lake Formation (modified from Ketchum et al., 2004).

Comparable to other granite-gneiss terranes of the west-central Slave such as the Anton Complex (discussed below) and the Beniah Complex, the SDC is comprised of three main components (i) >2.9 Ga gneissic and foliated basement rocks of the CSBC; (ii) foliated, mainly synvolcanic granitoid plutons emplaced between ca. 2.73 and 2.66 Ga; and (iii) foliated to massive, ca. 2.64-2.58 Ga granitoid plutons (Henderson, 1985).

Basement rocks within the SDC comprise a heterogeneous assemblage of foliated to migmatitic, upper amphibolite facies tonalite, diorite, granodiorite, granite and gabbro that were deformed and metamorphosed before the deposition of the flanking volcanics and the emplacement of the synvolcanic granitic plutons (Lambert, 1988; Bleeker et al., 1999a; Bleeker et al., 1999b; Ketchum et al., 2004). It has been suggested that the Sleepy Dragon Complex is a large-scale mushroom interference pattern resulting from the regional F_1 and F_2 fold structures (Bleeker and Beaumont-

Smith, 1995). Commonly intruding through the SDC, particularly in the southwest, are metadiabase dykes representing feeders to overlying mafic volcanics (Henderson, 1985; Lambert, 1988; Ketchum et al., 2004).

5.4.1.2 **Anton Complex**

The roughly rectangular 30 km long and 15 km wide Anton Basement Complex is similar in many respects to the Sleepy Dragon complex (discussed above) and is located west of the Yellowknife River and north of Duckfish Lake (Henderson, 1985). The Anton Complex is comprised of metamorphosed granodiorite to quartz diorite to gneiss with intrusive phases of granodiorite and granite adjacent to metamorphosed Yellowknife supracrustal rocks (Henderson, 1985). The steeply dipping (though locally irregular), northerly to northeasterly trending, weakly to moderately foliated somewhat mafic orthogneiss is texturally and compositionally varied, ranging from units with cm- to m-scale compositional and texturally different layering to massive homogeneous units (Henderson, 1985). Dykes and small massive intrusions of leucocratic granite, likely related to adjacent intrusive granitic units, intrude the orthogneiss (Henderson, 1985).

5.4.2 **GRANITOIDS**

Emplacement of extensive Neoarchean granitoid plutons spanned a time ranging from ca. 2700-2580 Ma, with pulses at ca. 2700, 2670, 2635 to 2620, and 2610-2602 Ma ending with a final bloom from 2600 to 2580 Ma (Ootes et al., 2011). These latter plutons are ubiquitous throughout the southern Slave (Ootes et al., 2011). The abundant older tonalite-granodiorite±diorite plutons are diachronous across the craton from southeast to northwest and may have locally contributed to the emergence of volcanic piles above sea level, while the post-volcanic terminal tonalite-trondhjemite-granodiorites (TTG) with evolved K-feldspar megacrystic granites emplaced across the craton are typically two-mica granites that intruded areas of down-folded turbidites during coeval craton-scale deformation resulting in refolding of F_1 by north-northwest trending F_2 folds (Bleeker, 2003).

5.4.2.1 **Defeat Suite**

The unmetamorphosed, arc-like, ca. 2630-2620 Ma Defeat Suite is the most extensive plutonic unit in the southern Slave Province and forms a northeast-trending belt that cuts across most terrane boundaries (Henderson, 1985; Helmstaedt, 2009). Inferred trends of pre- to syn-Defeat Suite are roughly parallel to S_1 cleavage-related folds in metaturbidites of the Yellowknife domain, suggesting an arc environment for Defeat-suite magmatism during NW-SE convergence (Helmstaedt, 2009) Rocks within the various plutons range in composition from granite to tonalite occurring as scattered isolated individual plutons with diameters up to 20 km, ranging from circular to irregularly shaped bodies and having associated smaller satellite intrusions (Figure 20) (Henderson, 1985).
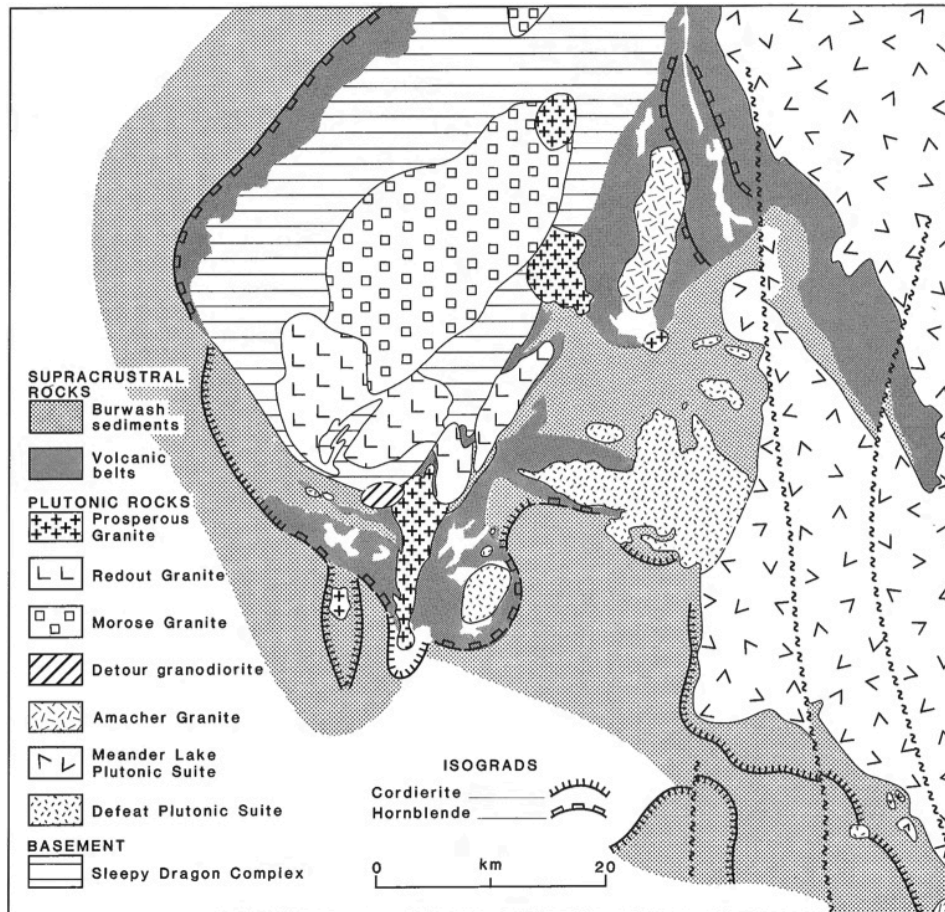
Figure 20. Granitoids of the Sleepy Dragon Complex area, with related cordierite and hornblende isograds (from Lambert, 1988).

5.4.2.2 Meander Lake Suite

The compositionally heterogeneous Meander Lake Suite consists of massive medium-grained, pink, equigranular to weakly porphyritic granitic rocks and intrudes the supracrustal Yellowknife Supergroup rocks within a 60 km long by 20 km wide area (Figure 19 and Figure 20). It is offset by a series of northerly striking sinistral faults and is transected by a major north-northeasterly striking cataclastic to mylonitic zone. Included in the Meander Lake Suite are a number of satellite plutons, the largest of which occurs in the metasedimentary rocks south of Sunset Lake, while smaller bodies occur near the main complex in the Burwash Formation (Henderson, 1985).

5.4.2.3 Amacher Granite

The 14 km by 3 km metamorphosed single northerly trending Amacher Granite pluton (Figure 19 and Figure 20), found to the east of the Sleepy Dragon Complex and west of Sunset Lake surrounded by Sunset Lake Basalts, is considered to be contemporaneous with Yellowknife Supergroup volcanism and may represent a comagmatic subvolcanic pluton (Henderson, 1985).

5.4.2.4   Detour Granodiorite

The small, 3 km by 2 km elliptical, metamorphosed Detour Granodiorite is found south of the Sleepy Dragon Complex at the southwest end of Detour Lake (Figure 20). The dominantly porphyritic intrusion ranges in composition from tonalite in the core to granodiorite at the margins; granodiorite dykes intrude the Burwash Formation sedimentary rocks (Henderson, 1985).

5.4.2.5   Redout Granite

Intruding into both the SDC and Yellowknife Supergroup, the Redout Granite (Figure 19 and Figure 20) is a massive to irregularly foliated, fine- to medium grained, equigranular, heterogeneous, two-mica granite with common pegmatite associations, occurring in the southern part of the SDC between Redout Lake and Turnback Lake as five closely spaced, commonly irregularly shaped, plutonic bodies (Henderson, 1985).

5.4.2.6   Prosperous Granite Suite

The ca. 2592 Ma S-type Prosperous Suite plutons were derived from the melting of sedimentary rocks at much deeper levels in the crust during crustal anatexis coinciding with the second stage of deformation in the Slave Province after accretion or collision to the south. These plutons are spatially and temporally related to turbidite-hosted gold mineralization, as well as shear zone-hosted gold mineralization, both of which formed during a second-generation foliation (Ootes et al., 2011). The suite is comprised of two-mica granite with common pegmatite associations and plutonic bodies are typically sharply discordant to the Yellowknife sedimentary rocks they intrude (Figure 19 and Figure 20) (Henderson, 1985).

5.4.2.7   Morose Granite Suite

Kusky (1993) describes the Morose Granite Suite (2583±1 Ma) as intruding the SDC shortly after the peak of contractional deformation and crustal thickening. The late- to post-kinematic Morose Suite and Prosperous Suite correspond to the TTG suite, or regional "granite bloom" emplaced ca. 2600-2580 Ma during the re-establishment of E-W convergence of the pan-Slave regional D_2 event which resulted in E-W shortening, crustal thickening, and regional low-pressure, high-temperature metamorphism (Ketchum et al., 2004; Bleeker and Hall, 2007; Helmstaedt, 2009). Its extents are shown in Figure 19 and Figure 20.

5.4.3   DYKES

Major swarms of mafic intrusions commonly referred to as amphibolite dykes (diabasic to gabbroic dykes and sills metamorphosed to amphibolite grade) and minor felsic intrusions intrude the volcanic belts and adjacent granitoids (Henderson, 1985). Three ages of Archean mafic intrusive

rocks are found in the south-central Slave Province, including pre-, syn- and post-Yellowknife Supergroup ages (Henderson, 1985).

The oldest mafic bodies occur as highly deformed amphibolite layers and lenses paralleling the foliation of the host granitic to tonalitic gneisses of the SDC, east of Cameron River (Henderson, 1985). Syn-volcanic mafic intrusive bodies occurring with the volcanic and sedimentary rocks of the Yellowknife Supergroup are likely genetically related to the volcanics (Henderson, 1985). These sills are compositionally uniform but texturally variable (Henderson, 1985). They are most commonly massive, but can be layered, with local shearing parallel to layering, while original mineralogy and textures have been altered by metamorphism (Henderson, 1985). The post-Yellowknife Supergroup mafic intrusions are primarily found in the Defeat Suite west of Yellowknife, occurring as metamorphosed mafic rocks ranging from narrow zones of amphibolite inclusions to well preserved dykes varying from massive, homogeneous, medium grained amphibolite to laminated or weakly compositionally layered amphibolite (Henderson, 1985).

Late (2.2-2.0 Ga) mafic dyke swarms intrude the Province and are thought to correlate with the breakup of the supercontinent Sclavia (Bleeker, 2003). These diabasic and gabbroic dyke swarms are typically undeformed and non-metamorphosed, cutting across volcanic, sedimentary and granitoid rocks (Lambert, 1988).

5.5 STRUCTURE

Multiple deformation structures are shown in all supracrustal rocks of the Yellowknife Supergroup, which record the episodes of regional compression, along with local deformation related to pluton emplacement (Helmstaedt, 2009). Post-collisional structures dominate the structural styles and trends, as recognition of syn-collision structures is difficult; however, it has been inferred that accretion of Neoarchean juvenile terranes to the CSST took place in a convergent environment roughly in an E-W direction, using present coordinates (Helmstaedt, 2009). Crustal thickening during Slave Province orogenesis is represented by the burial of supracrustal rocks of the Snare River terrane in the west to mid-crustal depths (Helmstaedt, 2009). As shown in Figure 16, several major late, north-south striking strike-slip faults occur in the Slave Province, such as the Yellowknife River and Beaulieu River (Beniah Lake in some literature) faults, which lie on the eastern flank of the Anton and Sleepy Dragon basement complexes, respectively (van der Velden and Cook, 2002). These strike-slip faults also preserve the last increments of Archean tectonics in the Slave with the formation of ca. 2.6 Ga strike-slip basins (Mueller et al., 2005). Supported by the Pb-isotopic boundary of Thorpe et al. (1992) and Davis and Henger (1992) mentioned earlier, the Beaulieu

River Fault is the most significant of these faults and generally separates the basement-controlled western Slave from juvenile arc-dominated eastern Slave.

The southern Slave Province has two major folding events, F_1 and F_2, that took place between 2645-2635 Ma and 2605-2590 Ma, respectively. As shown in Figure 19, F_1 folds developed a northeast-southwest trend in the Burwash Formation, followed by a refold of F_1 by north-northwest trending F_2 folds (Bleeker, 2003). Dextral transpression (D_2) during emplacement of both the Defeat Suite and Prosperous Suite granitoids, led to F_2 folding. Following F_2 folding, D_2 became localized in discrete dextral shear zones that record retrograde metamorphism (Bleeker and Beaumont-Smith, 1995). Figure 21 shows the generalized structure of Yellowknife domain.

As mentioned in Section 5.3.4, variably deformed conglomerates containing granitoid clasts commonly overlie significant unconformities. These conglomerates are tectonically significant as they suggest there was considerable uplift in order to exhume and erode granitic rocks, dated between >3.0 and 2.6 Ga (Fyson, 1993). Examples are found in the Yellowknife (Jackson Lake Formation) and Beaulieu River (Beaulieu Rapids Formation) belts.

Structurally, deformational events are most clearly expressed in the Yellowknife supracrustal rocks, particularly the thick units of mafic and felsic volcanics that behaved in a relatively competent manner compared to the interbedded greywacke-mudstones that exhibit highly complex fold patterns (Henderson, 1985). Mafic volcanics of the Kam Group at Yellowknife and Cameron River greenstone belts occur in thick steeply dipping to vertical, locally overturned, homoclinal successions, bounded by basement blocks or granitoid plutons on one side and metasedimentary rocks on the other in a generally northeasterly trend (Henderson, 1985). Conversely, the major thick volcanic sequences in the Tumpline Lake subarea (Section 6.3.1.2) to the southeast of the Cameron River belt and subarea (Section 6.3.1.1), do not occur in homoclinal successions, rather in a series of northeasterly and northwesterly striking structures bounded by metasedimentary rocks, truncated by, and mantling, the Prosperous and Defeat granitoid intrusions, respectively (Henderson, 1985). The dominant element of the complexly folded, primarily mafic volcanic complex of the Sunset Lake subarea (Section 6.3.1.3) in the northeast is a northerly trending synclinal structure through Sunset Lake. The western limb has a core of an elongate anticlinal dome, complicated by the Amacher Granite, whereas the southeasterly trending limb consists mainly of steeply dipping amphibolite grade, volcaniclastic sedimentary rocks (Henderson, 1985).
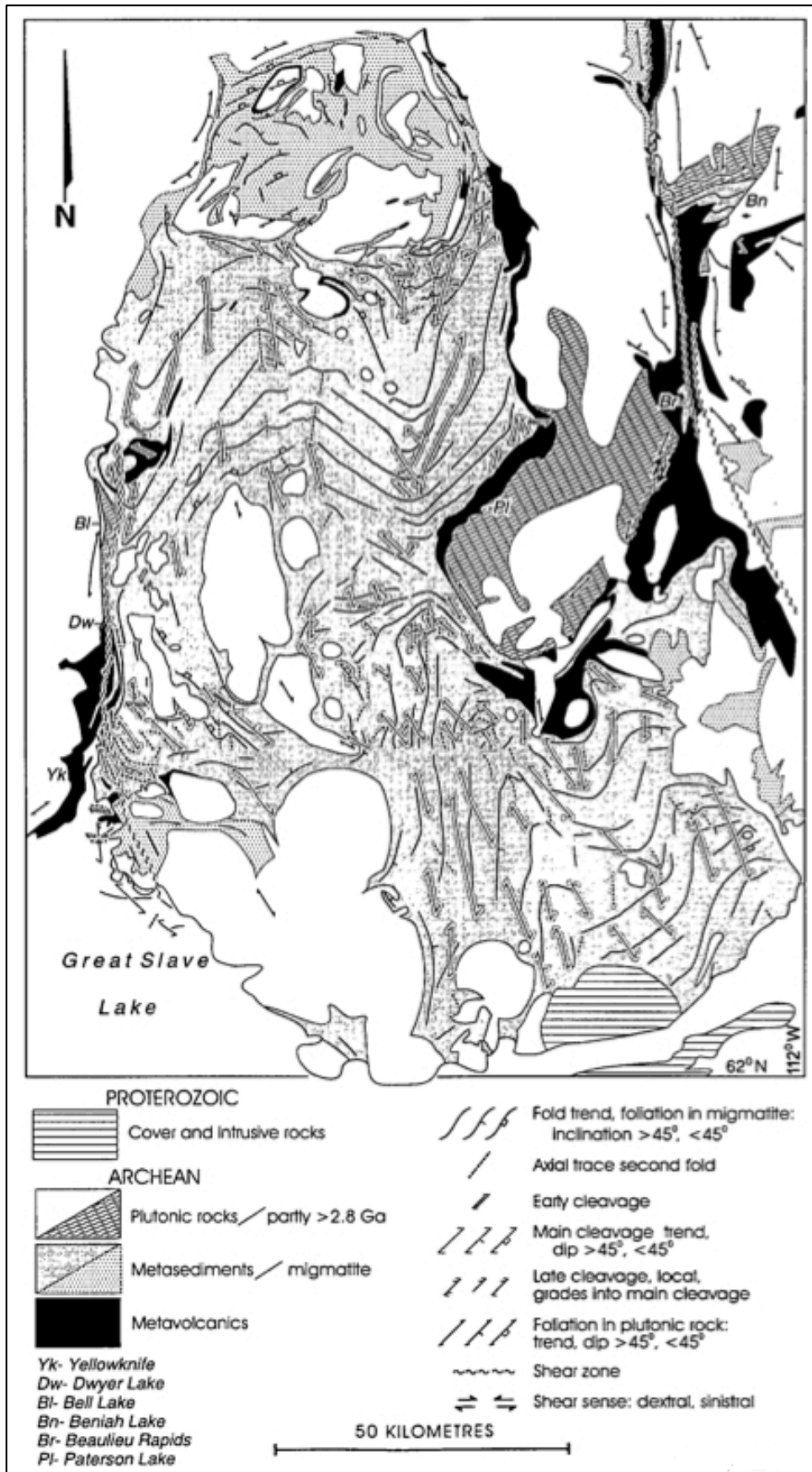
Figure 21. Lithological and structural map of the Yellowknife domain showing generalized trends, inclinations and locally defined generations of structures (from Fyson, 1996).

Many of the major rock units demonstrate a dominantly northeasterly structural trend (Figure 2 and Figure 18), for example, the major granitic units in the Yellowknife area, including the weakly foliated Defeat Plutonic Suite (Section 5.4.2.1) and the strongly foliated Anton Complex (Section 5.4.1.2) (Henderson, 1985). To the east, the Sleepy Dragon Complex (Section 5.4.1.1) also has a northeasterly trend; although the complex's internal structure is complicated (Henderson, 1985). The volcanic sequence at Yellowknife has an apparent northerly trend, though this is due to left lateral, north-northwesterly striking faults, which have offset the distinctly northeasterly trending flows (Henderson, 1985). To the east, volcanic rocks of the CBGB generally have a north to northeasterly trend, however volcanic rocks south of Payne Lake and Victory Lake have a southeasterly trend (Henderson, 1985). The Burwash Formation metasedimentary rocks have a much more complex structure than the volcanic rocks, mainly due to the less competent nature of the sedimentary rocks (Henderson, 1985). Structural relationships between adjacent volcanic and sedimentary rocks are everywhere concordant, while contacts with granitic intrusions are concordant with the Defeat Plutonic Suite and discordant with the Prosperous Granite and smaller intrusive bodies (Henderson, 1985). Local fold patterns in the Burwash Formation are highly varied, but generally consist of upright isoclinal folds with sub horizontal axes that locally plunge gently (<25°) and have wavelengths of 10's of metres up to 10 km (Henderson, 1985).

5.6 METAMORPHISM

The Neoarchean supracrustal rocks in most of the province have metamorphic grades from greenschist to upper amphibolite facies with metamorphic isograds spatially associated with granitoid plutons and migmatitic domains, suggesting a causative link between the two (Henderson, 1985). Following a classic P-T-t path, peak metamorphic pressures reached >6 kbar, as recorded in the granulite-facies of the Snare domain and structural culminations of the Contwoyto and Hackett River terranes where greatest crustal thickening occurred during terrane accretion (Helmstaedt, 2009). As shown in Figure 20, cordierite isograds commonly outline the thermal aureoles of intrusions in Burwash Formation sedimentary rocks surrounding the Sleepy Dragon Complex as well as the Anton Complex (Henderson, 1985).

5.7 EVOLUTION OF THE SLAVE CRATON

As mentioned in Section 5.2, the core of the Slave Province is comprised of the Central Slave superterrane (CSST), a composite tectonic terrane, which evolved between ca. 4.0 and 2.85 Ga and features scattered occurrences of the CSBC (Helmstaedt, 2009). According to Helmstaedt (2009) and partly based on Kusky (1990), >2.7 Ga rifting of the proto-CSST and deposition of break-up sequences on both sides of the Mesoarchean CSST proto-craton resulted in the deposition of the

CSCG on top of the CSBC (Figure 22a). From the LITHOPROBE seismic survey data, van der Velden and Cook (2002) interpreted the CSBC was delaminated during collision, such that the upper plate, along with the CSBC and supracrustal rocks were carried eastward and overrode the juvenile eastern Slave Province and accretionary wedge (Figure 23).
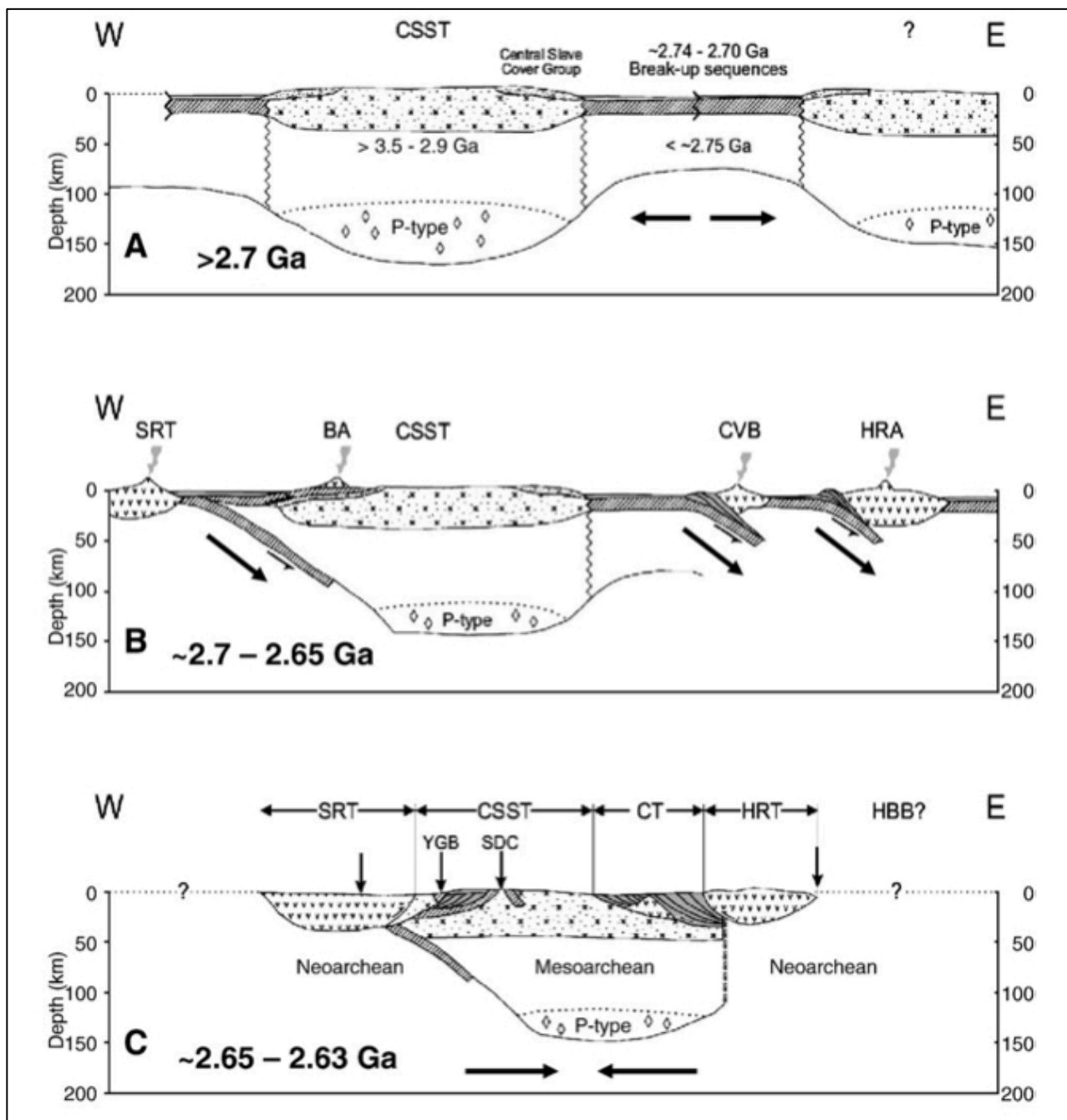
Figure 22. Schematic model for Neoarchean evolution of the Slave Province from >2.7 Ga to 2.63 Ga. Sections are drawn for the latitude of the northern end of the Yellowknife supracrustal domain. Grey represents imbricated metaturbidites. Vertical arrow in SRT is approximate position of western Paleoproterozoic rifted margin of Slave Province. See text for details (from Helmstaedt, 2009).

Regardless, Kam Group volcanism was initiated during continental rifting between 2730 and 2700 Ma with post-Kam Group volcanism (ca. 2.7– 2.65 Ga) marking the start of Hackett River arc (HRA)

formation (Helmstaedt, 2009). The Neoarchean Bathurst Block is thought to represent a back-arc-basin setting with respect to the Hackett River arc, suggested by the juvenile and bimodal character of the well-preserved volcanic belts in the north of the block (Helmstaedt, 2009). Structural emplacement of Kam Group volcanics on Mesoarchean basement preceded the beginning of Banting volcanism on the western margin of CSST (Helmstaedt, 2009). Following the generation of the HRA, Banting-age calc-alkaline centers in Snare River terrane (SRT), referred to as the Banting arc (BA), formed on basement by subduction of juvenile Neoarchean sea floor as the Central Volcanic belt (CVB) began to form (Figure 22b).
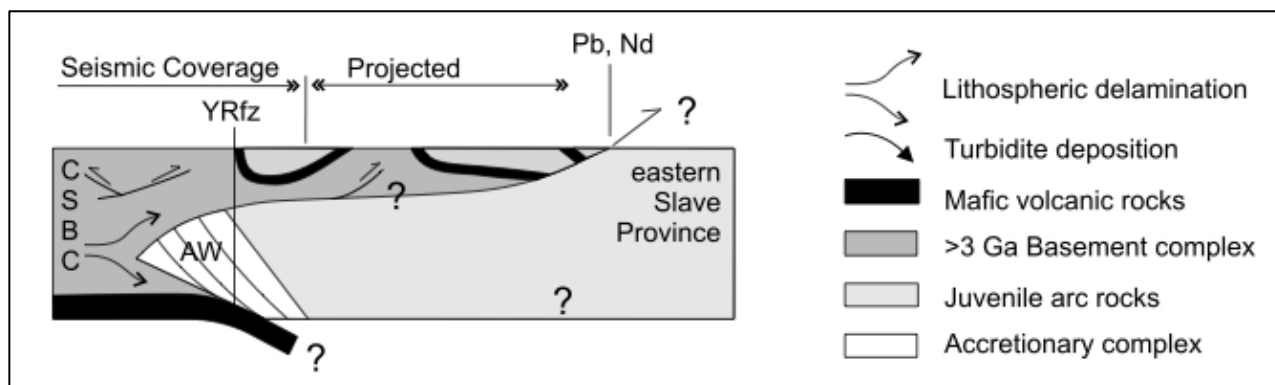
Figure 23. Alternative model for evolution of the western and eastern domains of the Slave craton. Seismic coverage from LITHOPROBE. Pb and Nd from Thorpe et al. (1992) and Davis and Hegner (1992), respectively. YRfz = Yellowknife River Fault Zone; CSBC = Central Slave Basement Complex; AW = Accretionary Wedge (from van der Velden and Cook, 2002).

Bleeker and Hall (2007) note that between ca. 2690 and 2660 Ma, the entire Slave Province was situated in a supra-subduction zone setting, coinciding with the formation of the HRA across rifted basement and evolved into large back-arc basins (Figure 24). Beginning in the east (ca. 2.65–2.63 Ga), accretion of adjacent juvenile terranes to the CSST started with the obduction of the Contwoyto terrane (CT) onto Mesoarchean basement and was followed by the docking of the Hackett River terrane (HRT; Figure 22c). Subsequent, roughly east-northeast deformation and plutonism (Defeat Suite) restricted to the southern part of the newly amalgamated Slave craton followed between 2630 and 2620 Ma (Davis and Bleeker, 1999).

Following the Defeat Suite plutonism and D_1 deformation, more evolved granites were developed in areas of down folded turbidites along with coeval craton scale D_2 deformation and crustal anatexis that led to the S-type plutonism and terminal granite blooms between 2600-2580 Ma, which developed across the Province and resulted in cratonization (Bleeker, 2003; Ootes et al., 2011). Late kinematic conglomerate sequences and large scale strike-slip faulting coincided with the terminal granite blooms (Bleeker, 2003). Ootes et al. (2011) give a concise timeline of events for the Slave craton summarizing the tectonics, gold mineralization, metamorphism, sedimentation and plutonism/volcanism between 2700 and 2550 Ma (Figure 25).
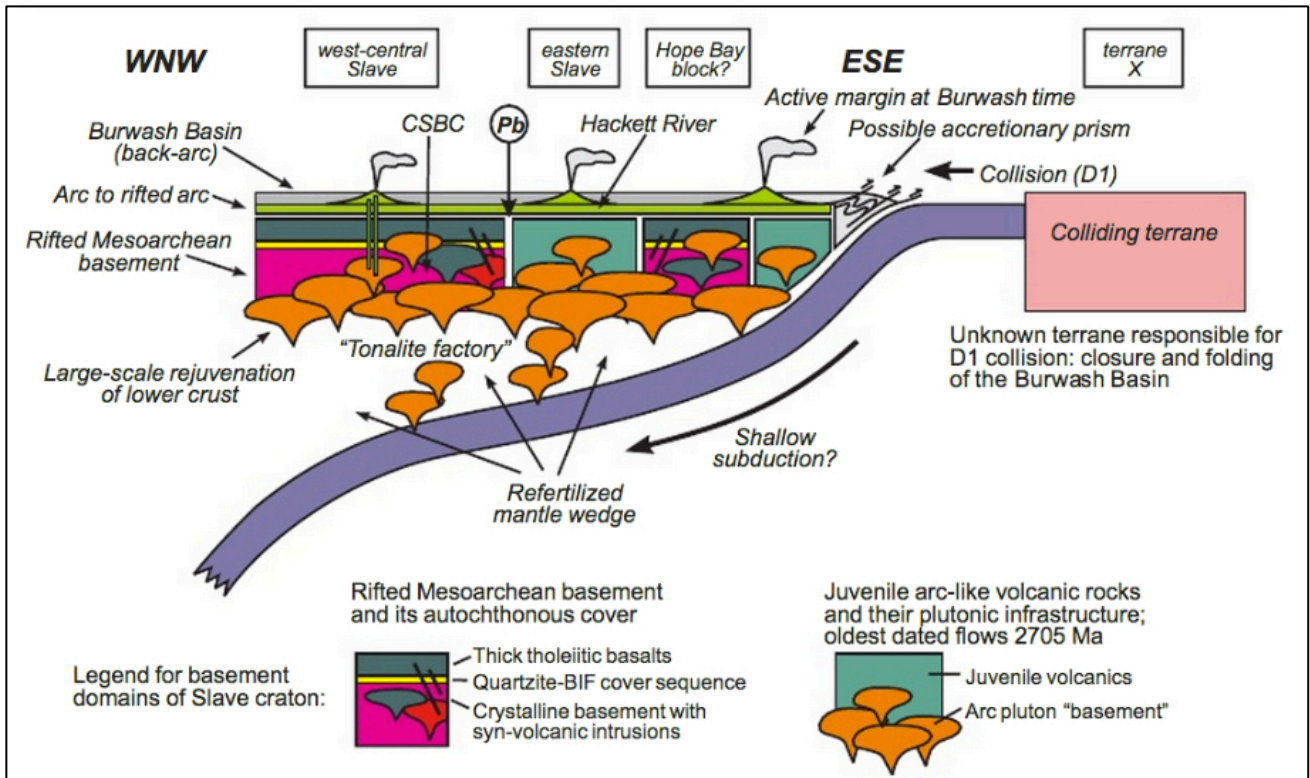
Figure 24. Tectonic model for the general setting of the Slave craton between ca. 2690 and 2660 Ma (from Bleeker and Hall, 2007).

Figure 15 illustrates that the Slave craton is bounded by three, possibly four, Paleoproterozoic-aged rifted margins; the Wopmay Orogen and Fault Zone to the west, the Great Slave Lake Shear Zone (also noted as the Macdonald Fault) to the south and the Bathurst Fault to the northeast (Bleeker, 2003). Following cratonization of the Slave, the current rifted margins are thought to have originated from the break-up of the much larger late Archean supercraton Sclavia along with a number of "nearest neighbour" cratons between 2.2 and 2.0 Ga. Discussed in Section 5.9, these nearest neighbours, namely the Zimbabwe, Dharwar and Wyoming cratons, share similar first-order characteristics to the Slave craton, (Bleeker, 2003). Post-Sclavia rifting, the Slave craton is thought to have drifted independently for ca. 200 m.y. prior to amalgamating with the Rae craton and initiating the growth of Laurentia (present day North America) and part of the supercontinent Nuna from 2.1-1.8 Ga (Bleeker, 2003).
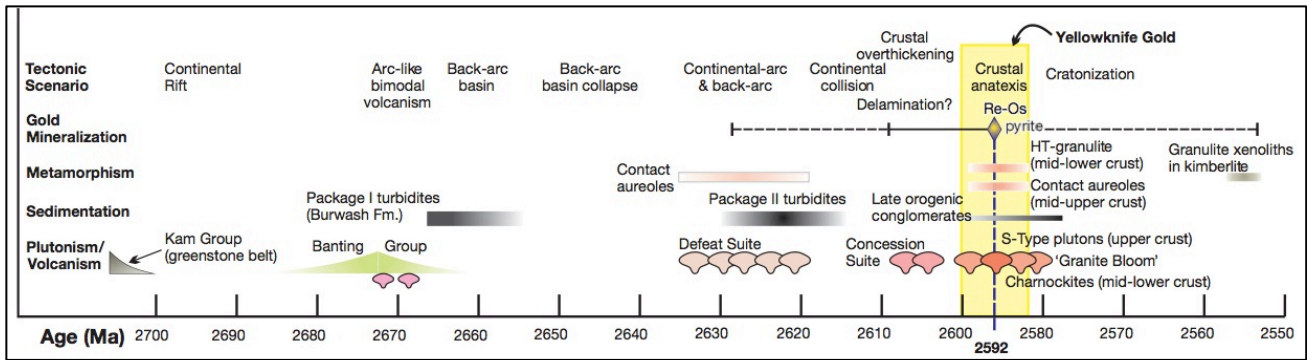
Figure 25. Timeline of events for the Slave craton (modified from Davis and Bleeker, 1999; from Ootes et al, 2009) Bar on Re-Os age indicates age uncertainty, dashed line is analytical uncertainty, solid line highlights geologically constrained maximum age, minimum age is constrained by analytical error. ? = uncertainty, HT = high temperature (Ootes et al., 2011).

5.8 MINERAL RESOURCES

The Slave Province has a long history of mining activity that began in 1938 with the opening of the Con Mine and was followed by the Giant Mine in 1948; however, gold production ceased at both operations in 2003 and 2004, respectively. Exploration is ongoing proximal to the past-producers, but no production is currently planned. In 1998, the Slave Province's first of four diamond mines, Ekati, was put into operation. Diavik followed in 2002, while Jericho was in operation between 2006 and 2008, Snap Lake went into production in 2007. In October 2013, the Canadian Government, despite stakeholder concerns not being met, approved the Gahcho Kué Diamond Mine. Diamond production in the Slave Province reached 12.6 million carats (Mct) in 2006, dropping to 11.8 Mct in 2010, making Canada the third largest diamond producer by value in the world, following Botswana and Russia. On a value basis, Canada's diamond production currently accounts for approximately 19.2% of world production, estimated in 2010 at 133.1 Mct and valued at US$12.0 billion (Government of Northwest Territories, 2007; NRCAN, 2010; AANDC Mineral Division, 2011). In addition to the gold and diamond deposits, there are several base metal and rare earth deposits and properties found in the Slave craton (Figure 26).
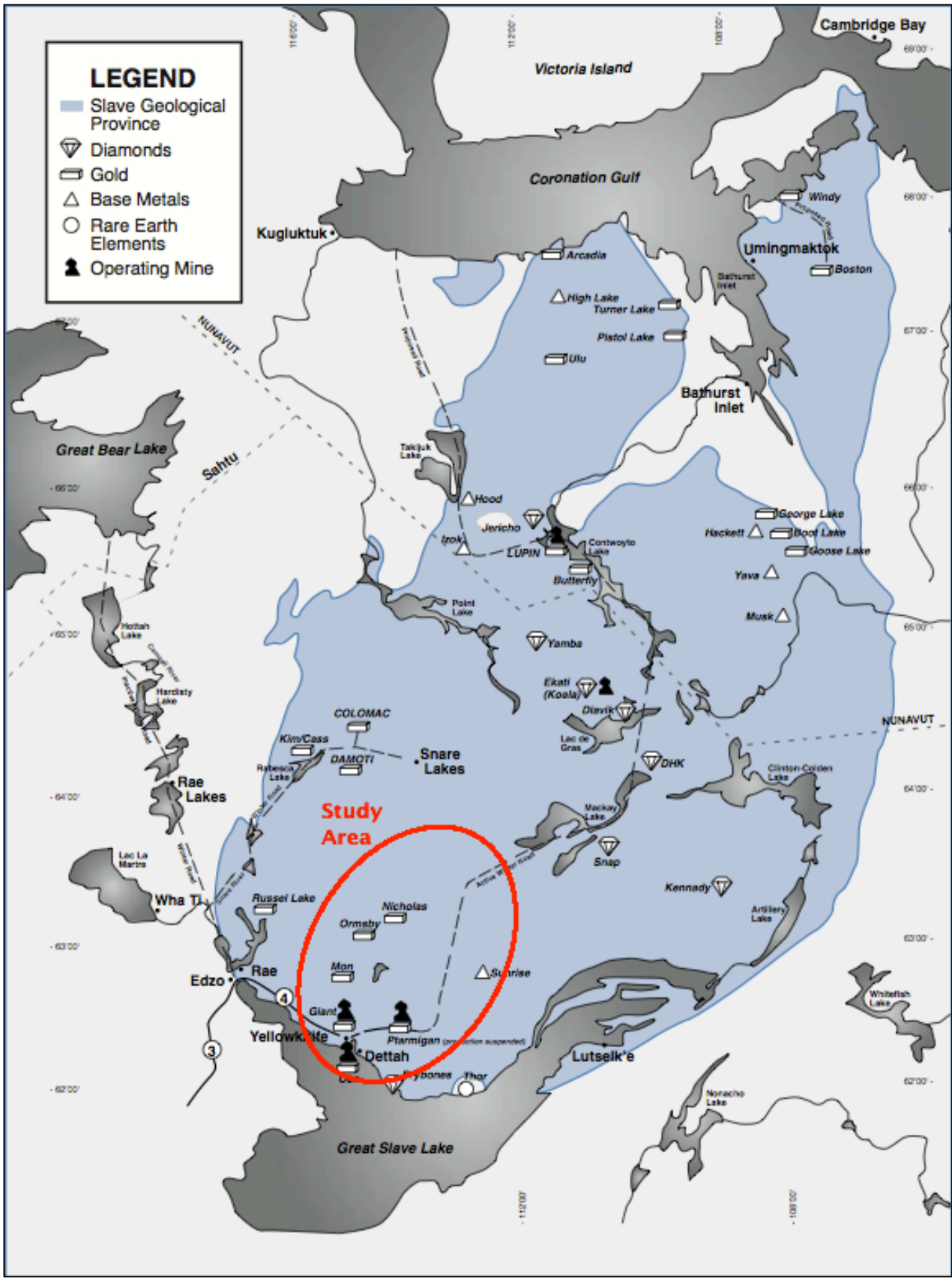
Figure 26. Mineral deposits of the Slave Province (from ENR, 2001).

5.8.1   **GOLD**

Gold deposits of the Slave Province can be divided into three major groups 1) auriferous quartz vein hosted 2) shear zone hosted and 3) iron formation hosted (Padgham, 1992). Numerous occurrences of turbidite-hosted quartz veins are found in the Burwash Formation, several of which have been mined at a small scale in the past, including the Ptarmigan, Thompson-Lundmark and Discovery mines (Government of Northwest Territories, 2007). Shear zones with associated quartz-carbonate veining, as discussed in CHAPTER 4, commonly intersect metasedimentary rocks and metavolcanic rock, such as found at the Con and Giant mines. Folded, Archean iron formation can also host crosscutting auriferous quartz veins, as at the Back River Project, owned by Sabina Gold and Silver Corporation and the former producing Lupin Mine in Nunavut, currently being explored by Elgin Mining Inc. Another example of gold deposit present in the Slave Province is auriferous quartz-sulphide veins hosted in a granodiorite plug intruding metasedimentary rocks as noted at Nicholas Lake, which forms part of the Yellowknife Gold Project. The Yellowknife Gold project, owned and operated by Tyhee Development Corporation, also includes the past-producing Discovery Mine, along with the Ormsby and Clan Lake deposits (Figure 26 and Figure 27).
 Other gold deposits in the Slave Province, as shown in Figure 26, include Arcadia, Ulu, Russell Lake, Boston, Windy, Damoti, Turner Lake, Pistol Lake, Kim/Cass, Goose Lake, George Lake and Boot Lake.

Table 2 highlights the major gold resources and reserves of the Slave Province, while Figure 27 shows the locations of NWT gold properties in 2007. Other gold deposits in the Slave Province, as shown in Figure 26, include Arcadia, Ulu, Russell Lake, Boston, Windy, Damoti, Turner Lake, Pistol Lake, Kim/Cass, Goose Lake, George Lake and Boot Lake.

Table 2. Significant Gold Resource and Reserves of the Slave Province.

Project	Classification	Cut-off (g/t)	Tonnage (Mt)	Grade (g/t)
Con and Giant[1]	Exhausted	-	11.466	15.6
Courageous Lake[2]	Resource	0.83	107.3	2.31
Yellowknife Gold[3]	Resource	-	27.1	1.97
Yellowknife Gold[3]	Reserve	-	20.4	2.03
Lupin[4]	Produced	-	11.8	9.3
Lupin[4]	Inferred	5.0	1.1	11.32
Back River[5]	Resource	1.0 (OP),	14.649	5.0
Back River[5]	Resource	4.0 (UG)	9.546	7.5
Hope Bay	Resource		36.014	4.5

[1](Government of Northwest Territories, 2007), [2](Seabridge Gold, 2013), [3](Tyhee Gold, 2012), [4](Harron, 2012), [5](AMC Mining Consultants (Canada) Ltd, 2013), [6](TMAC Resources, 2013); UG=underground, OP=open pit

Figure 27. Gold Properties of the Northwest Territories and southern Slave craton (Government of Northwest Territories, 2007).

5.8.2 DIAMONDS

Diamonds were first discovered in the Northwest Territories in 1970 when kimberlite was mapped on Somerset Island, which led to the discovery of numerous kimberlite pipes on the island and other areas in the Slave Province (Government of Northwest Territories, 2007). Exploration dramatically expanded in 1991 when diamonds were discovered in till samples at Lac De Gras, leading to the discovery of over 300 kimberlite bodies, with >70 reported as diamond bearing. In Northwest Territories, there are three operating diamond mines: 1) Ekati Diamond Mine, formerly owned and operated by BHP Billiton Diamonds Inc. and as of 2012 owned by Dominion Diamond Corporation (formerly Harry Winston Diamond Corporation); 2) Diavik Diamond Mine, owned and operated by

Diavik Diamond Mines Inc. and Dominion Diamond Corporation; and 3) Snap Lake Mine, operated by De Beers Canada Inc. (Government of Northwest Territories, 2007), while Nunavut is home to the past-producing Jericho Mine (Tahera Project), which was opened by Tahera Diamond between 2006 and 2008. It has recently handed over to the Canadian government (CBC News, 2013). Table 3 provides a breakdown of the resources and reserves of the Slave Province diamond mines while Figure 28 shows the location of known kimberlites in the Slave Province as of 1999. As shown in Figure 26, other diamond properties in the Slave Province include Drybones and Yamba.

Table 3. Resources and Reserves of the Slave Province Diamond Mines.

Project	Classification	Tonnage (Mt)	Carats (Mct)	Grade (cpht)	Year
Ekati[1]	Reserves	38.5	18.3	47.6	2009
Diavik[2]	Reserves	18.9	58.9	310	2011
Diavik[2]	Resources	7.4	19.5	264	2011
Snap Lake[3]	Resource	18.3	26.7	146	2010
Jericho[3]	Resource	5.5	4.675	85	2010
Gahcho Kue (Kennedy)[4]	Indicated	15.7	20.8	132	2013

[1](NRCAN, 2009b), [2](Yip, 2008), [3](NRCAN, 2010), [4](Nowicki and Makarenko, 2013)
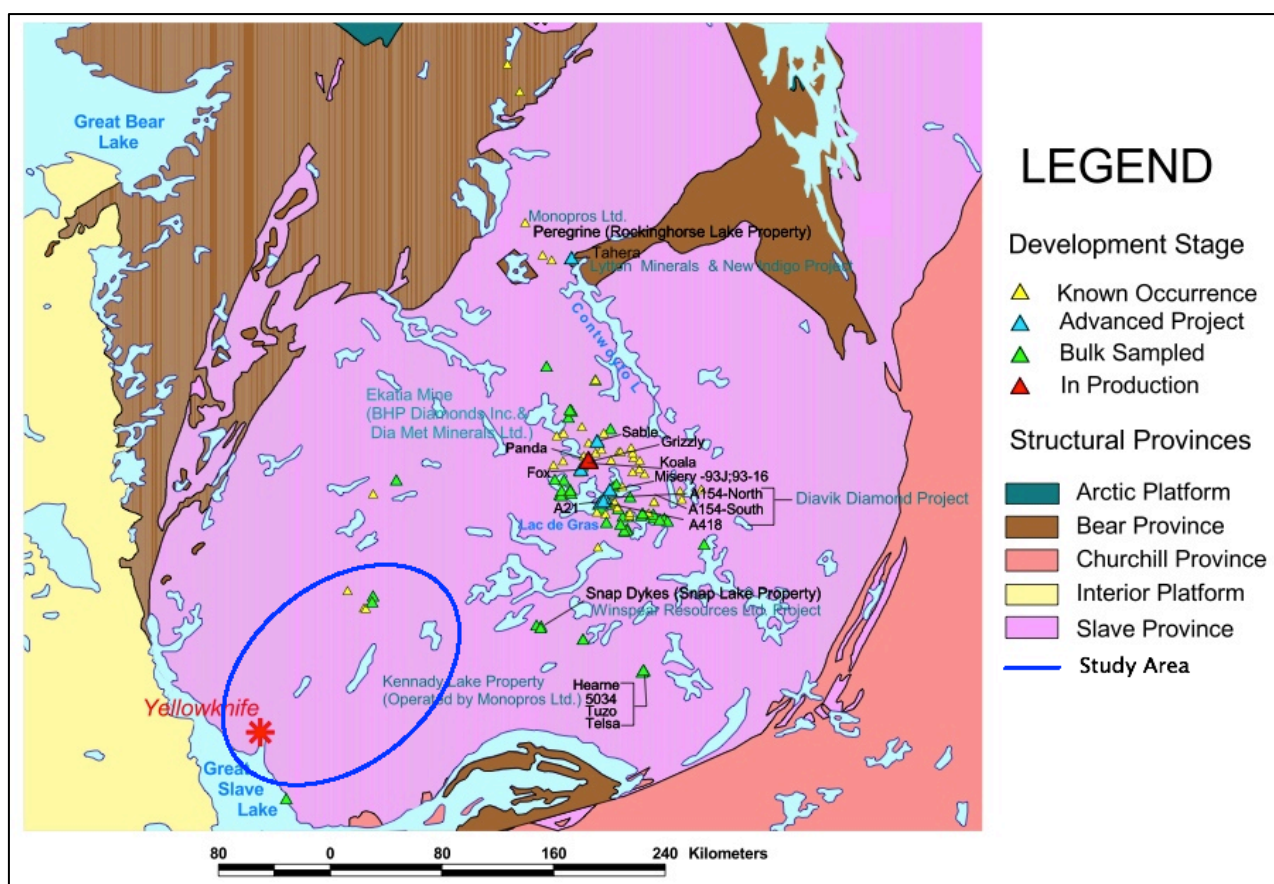
Figure 28. Slave Craton kimberlite occurrences as of 1999 (from Bianchi, 1999)

5.8.3 SILVER AND BASE METALS

Currently, there are no producing silver or base metal mines in the Slave Province, though there are a number of areas that host significant accumulations of base metals, including Hackett River, Izok Lake and High Lake in Nunavut, along with the Sunrise and Bear deposits in Northwest Territories (Figure 26; As shown in Figure 26, other base metal deposits in the Slave include Hood, Yava and Musk.

Table 4). These base metal and silver (± gold) deposits are primarily volcanogenic massive sulphides hosted in Hackett River-type volcanic belts or calc-alkaline felsic components of the Yellowknife-type belts (Padgham, 1992). Of note, the Beaulieu River greenstone belt hosts the Sunrise and Bear VMS deposits, as well as the Turnback XL VMS deposit. Metal ratios suggest three end-member VMS types in the Slave: 1) copper-rich with minor gold; 2) lead-zinc-silver-rich with minor copper and trace gold; and 3) zinc-silver-rich with minor copper or lead (Padgham, 1992). As shown in Figure 26, other base metal deposits in the Slave include Hood, Yava and Musk.

Table 4. Significant Silver and Base Metal Deposits in the Slave Province

Project	Classification	Tonnage (Mt)	Zn (%)	Pb (%)	Cu (%)	Ag (g/t)	Au (g/t)
Hackett River[1]	Resource	25	4.2	0.6	0.5	130	0.3
Sunrise[2]	Resource	1.359	-	-	-	280	-
Bear[3]	Resource	1.14	5.1	2.2	-	336	0.6
DEB[3]	Resource	1.02	2.96	-	0.83	21.9	-
Kennedy Lake[3]	Resource	0.88	9.5	0.7	-	116.5	-
Izok Lake[4]	Resource	14.8	12.8	-	2.5	-	-
High Lake[4]	Resource	17.2	3.4	-	2.3	-	-

[1](Glencore Xstrata, 2013), [2](Silver Standard, 2003), [3](Government of Northwest Territories, 2007), [4](MMG, 2013)

5.8.4 RARE EARTH ELEMENTS

Currently, there are no operating rare earth mines in the Slave Province, though there are a number of rare earth properties and showings in the region, including the past-producing Peg Tantalum Mine in the Sleepy Dragon Complex, the Murphy showing northeast of Yellowknife, and the Nechalacho deposit at Thor Lake on the northeastern shores of Great Slave Lake in the Proterozoic Blatchford Lake Intrusive Complex, which intrudes the southern margin of the Archean rocks of the Slave Province, as well as several showings in the Burwash Formation, such as the Freda and Jake showings. Potentially economic concentrations of niobium, tantalum, zirconium, gallium, beryllium,

yttrium, thorium, and uranium have been identified in areas of altered, brecciated, syenitic cores of the plutonic complex proximal to Thor Lake (Nechalacho; Table 5). The increasing demand for rare earth elements in the high tech industry may increase the price of these metals to a level that will encourage exploration for these deposits in the near future.

Table 5. Significant Rare Earth Resources of the Slave Province

Project	Classification	Tonnage (Mt)	Li_2O (%)	Ta_2O_5 (%)	Nb_2O_5 (%)	TREO (%)	ZrO_2 (%)
Murphy[1]	Resource	7.155	1.47	-	-	-	-
Nechalacho [2]	Resource	121.44	-	0.30	0.343	1.50	2.52

[1](Government of Northwest Territories, 2007), [2](Avalon Rare Metals Inc., 2012)

5.9 GLOBALLY COMPARABLE CRATONS

Based on similar, correlative first-order characteristics, three cratons were noted by Bleeker (2003) to be "nearest neighbors" to the Slave craton in the 2.6 Ga Sclavia supercraton; the Dharwar craton in southern India, the Zimbabwe craton and the Wyoming craton in USA, which were classified by Bleeker into the "Slave-clan" of cratons (Figure 29). These first order characteristics include extensive Early Archean basement complexes overlain by remarkably similar lithostratigraphic Meso- to Neoarchean successions comprised of quartz pebble conglomerate and fuchsitic quartzites on heterogeneous basement including abundant ca. 2.9 Ga tonalites. Overlying the basal quartzitic rocks are thin, banded iron formations or ferruginous cherts, stratigraphically below 2.73-2.70 Ga flood basalts, younger calc-alkaline volcanic rocks and turbidites, capped by late-kinematic conglomerates. Similar progressions of Late Archean granitoid suites culminating at around 2.6 Ga are also noted in all four cratons. These similarities could suggest similar mineralization histories of the four cratons and allow for comparisons to be made in future research and exploration.
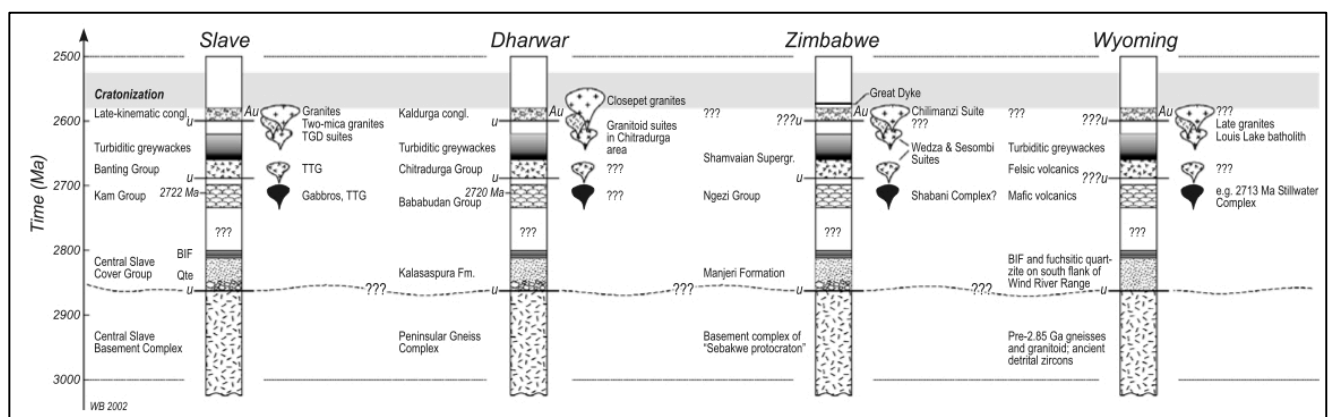
Figure 29. Comparison of key stratigraphic elements and granitoid suites between cratons of the "Slave clan": Slave, Dharwar, Zimbabwe, and Wyoming with possible correlative features identified. Features that have not (yet?) been identified are marked with question marks (e.g., ca. 2.60 – 2.58 Ga late-kinematic conglomerates in the Zimbabwe craton?) (from Bleeker, 2003).

CHAPTER 6   YELLOWKNIFE DOMAIN GREENSTONE BELTS

6.1   INTRODUCTION

There are three greenstone belts in the Yellowknife domain: the Yellowknife, Cameron River and Beaulieu River greenstone belts. The YGB is separated from the CBGB by the supracrustal Yellowknife basin and the folded metasedimentary rocks of the Burwash Formation. Figure 30 shows a cross section through the Yellowknife domain, as delineated in Figure 16. This chapter provides the lithological and structural frameworks as well as details on the mineralization for all three greenstone belts.
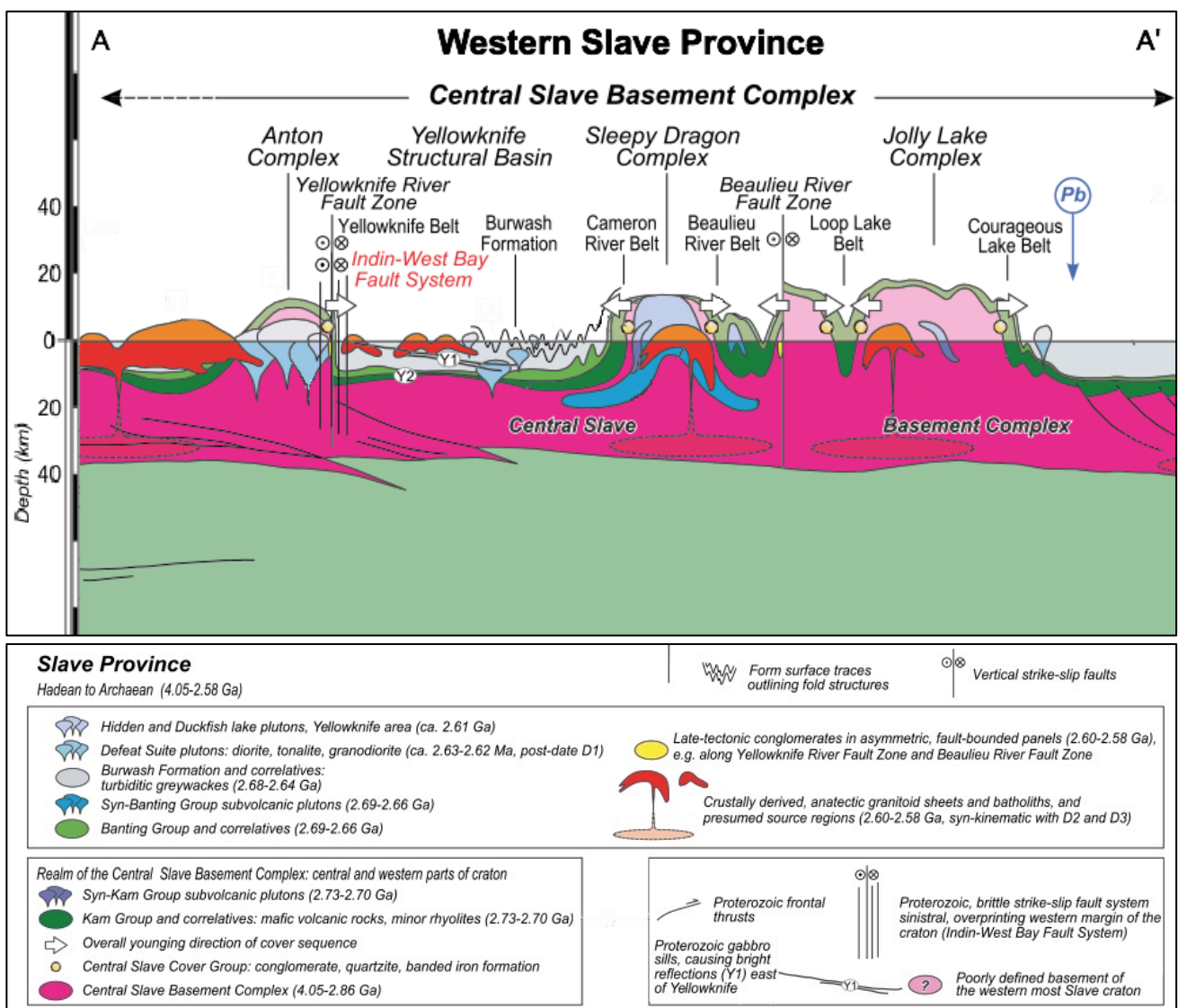
Figure 30. Cross section of the Western Slave Province. A-A' defined on Figure 16 (modified after Bleeker, 2003).

6.2 YELLOWKNIFE GREENSTONE BELT

The Yellowknife greenstone belt is extremely well preserved with well-exposed contact relationships and exhibits low-grade greenschist metamorphism, though metamorphic grade increases proximal to younger intrusions (Cousens, 2000). The metavolcanic supracrustal package comprising the belt forms a steeply dipping homocline with a southeast facing stratigraphic "way-up". Subsequent northerly Proterozoic faulting dismembered the belt into four major structural blocks (Cousens, 2000). Figure 31 shows a simplified geological map of the belt, along with the stratigraphy and major structures of the belt, discussed below.

6.2.1 LITHOLOGICAL FRAMEWORK

Originally termed the Dwyer Group, the basement of the YGB is comprised of >2.9 Ga gneissic granodioritic to tonalitic plutonic rocks along the eastern margin of the Anton Complex and the >2.8 Ga overlying fuchsitic quartzites, silicic volcaniclastics and chert-magnetite banded iron formation of the Bell Lake Group (Cousens et al., 2002), respectively comprising parts of the Central Slave Basement Complex (CSBC) and Central Slave Cover Group (CSCG) described in Section 5.3. Overlying the CSCG is the ≥2.72 to 2.70 Ga Kam Group, a steeply dipping, ~10 km thick, northeast trending, dominantly mafic tholeiitic to intermediate metavolcanic sequence, which comprises most of the greenstone belt (Isachsen and Bowring, 1994). Contacts are obscured by syn- to late-volcanic gabbroic sills, pervasive shearing and limited outcrop, although where noted, the lowermost exposures are characterised by <10 cm of phyllite abruptly grading into significantly less deformed amphibolitic pillowed flows (Isachsen and Bowring, 1994). Unconformably overlying the Kam Group are ca. 2.66 Ga, north-trending Banting Group calc-alkaline intermediate to felsic-dominated pyroclastic volcanic and sedimentary rocks, interpreted as a volcanic arc sequence (Cousens et al., 2002). Banting Group rocks grade upwards into the Walsh and Burwash sedimentary rocks, comprised primarily of YGB detritus. The Duck Formation is a mafic volcanic pile found only on the east side of Yellowknife Bay with probable Banting Group age (Cousens et al., 2002). The youngest supracrustal rocks in the belt are the 2605 Ma Jackson Lake Formation conglomerates and lithic quartz arenites, which infilled paleotopographic lows during deposition and unconformably overlie the Kam Group (Isachsen and Bowring, 1994; Cousens et al., 2002).

The Kam Group is composed of dominantly tholeiitic mafic pillowed and massive flows with thin cherty volcaniclastic to quartz feldspathic sandstone interbeds and is divided into four conformable formations, which are, oldest to youngest, the Chan, Crestaurum, Townsite and Yellowknife Bay Formations (Cousens et al., 2002). All formations, except the Townsite Formation are composed of mainly tholeiitic mafic volcanics.
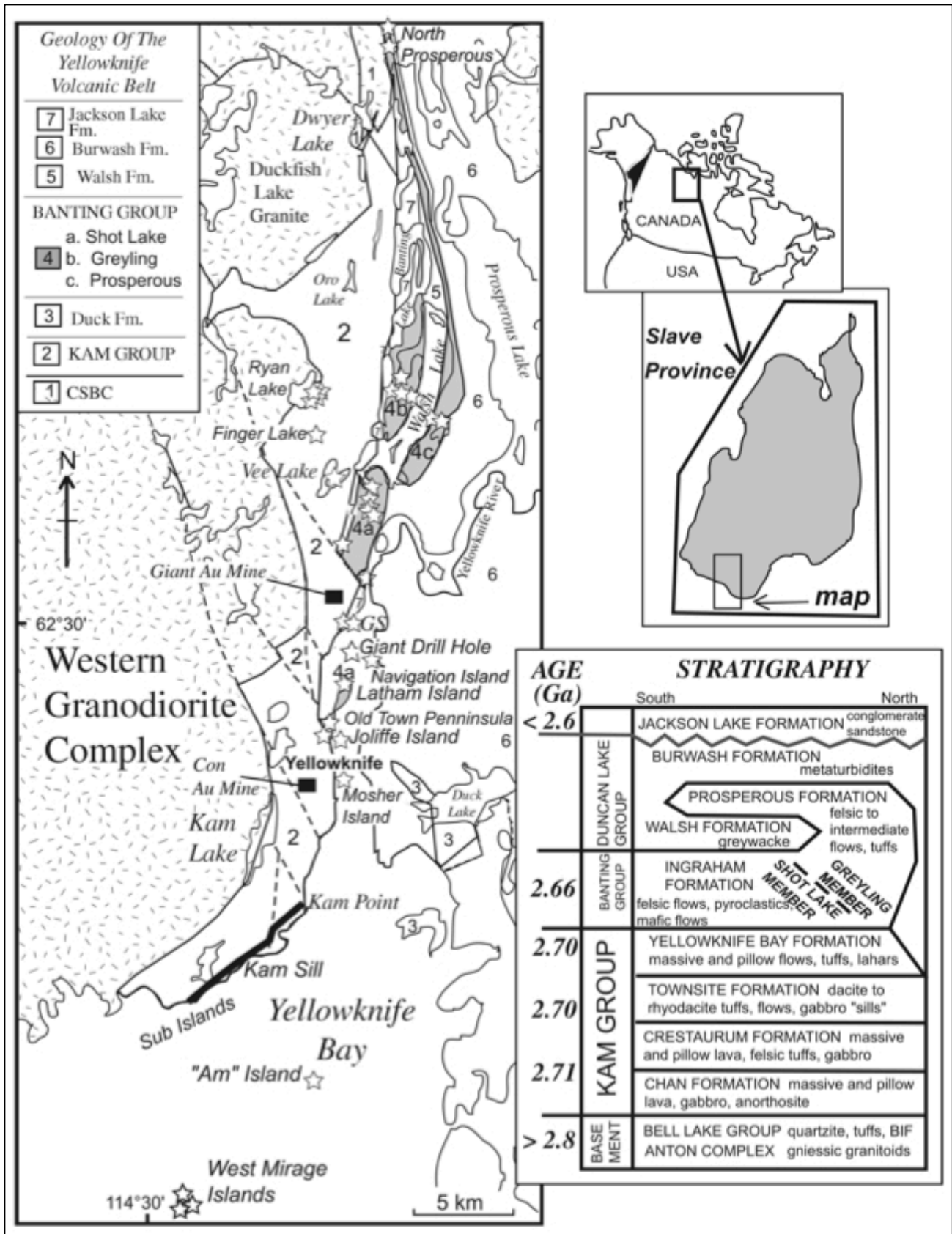
Figure 31. Simplified geological map of the YGB. Solid lines = geological contacts, dashed lines = faults. GS, Giant Section; CSBC, Central Slave Basement Complex. Lower inset: Stratigraphy of the YGB. BIF, banded iron formation; Fm., Formation (from Cousens et al., 2002).

The Chan Formation is the thickest (~6-7 km) formation of the Kam Group and consists entirely of basaltic lavas, dikes and sills without conformable felsic volcanic rocks (Cousens, 2000). At the base of the Chan Formation is a dike and sill complex, interpreted as a sheeted dike complex (Cousens, 2000). Pillow basalt and massive mafic flows largely compose the overlying Crestaurum Formation, but it also includes several thin, cherty, felsic tuffaceous units of dacite to rhyodacite composition (Cousens, 2000). Overlying Crestaurum is the Townsite Formation, composed of dacitic to rhyolitic flows, tuffs and breccias intruded by gabbroic sills, and interpreted as being displaced by younger faults into the southern Niven Brock and northern Vee Lake members (Cousens, 2000). Like Crestaurum, pillow basalts, massive flows and sills, along with several tuffaceous units dominate the Yellowknife Bay Formation (Cousens, 2000). Differences between bedding orientations suggest the Chan Formation was undergoing uplift and erosion in the north during deposition of the Yellowknife Bay Formation (Cousens, 2000). Hosted in the Yellowknife Bay Formation are the gold-bearing shear zones of the past-producing Con and Giant mines (Cousens, 2000). To the east, the Duck Formation is noted by Henderson (1985) as a potential eastward lateral extension of the main Kam Group volcanic pile.

Overlying the Kam Group and forming the eastern side of the homoclinal belt are the Banting Group volcanic rocks, divided into the Ingraham and Prosperous Formations (Cousens et al., 2002). The Ingraham Formation is comprised of the Shot Lake Member in the south and the Greyling Member in the north, both consisting mainly of quartz porphyries and ash flow tuffs with intercalated massive to pillowed mafic flows. The Greyling Member volcanic flows grade upwards into cherty felsic tuffs and are overlain by fine-grained turbidites of the Walsh Formation. Felsic tuffs, minor mafic flows and volcaniclastic sedimentary rocks comprise the Prosperous Formation, which grades conformably into the turbidites of the Burwash Formation. The contact between the Kam and Banting Groups is faulted and is commonly obscured by the infilling of younger conglomerates of the Jackson Lake Formation (Cousens et al., 2002).

The Western Granodiorite Complex is a multiphase granodioritic complex of the Defeat Suite that intruded west of the YGB between 2634 and 2605 Ma (MacLachlan and Davis, 2002; Shelton et al., 2004). Shear zone formation is thought to coincide with lateral shortening and tilting of the volcanic sequence and intrusion of the granodiorite. The Prosperous Lake granite intrudes to the north of the metasedimentary rocks and the Southern Granodiorite Complex to the south (Shelton et al., 2004).

6.2.2 STRUCTURAL FRAMEWORK

The steeply dipping to vertical Kam Group mafic volcanic rocks occur in northeasterly trending homoclinal successions bounded by basement blocks of the Anton Complex or granitoid plutons of

the Defeat Plutonic Suite towards the west and face towards the Burwash Formation sedimentary rocks in the east (Henderson, 1985). Two ages of faults displace the Kam Group (Figure 32). The younger, Proterozoic-aged set of faults (West Bay, Kam-Pud, and Hay-Duck) are north northwesterly striking and are connected by smaller cross-over faults (Akaitcho, Martin, AYE and Townsite faults), with movement causing the originally northeast-trending belt to assume a northerly trending aspect; these faults are related to the major gold deposits in the belt (Henderson, 1985; Shelton et al., 2004). Shear zones are either narrow zones paralleling the attitude of the volcanic flows and commonly associated with tuffaceous units within the pile or form as much larger discordant structures associated with the economic mineralization (Henderson, 1985).
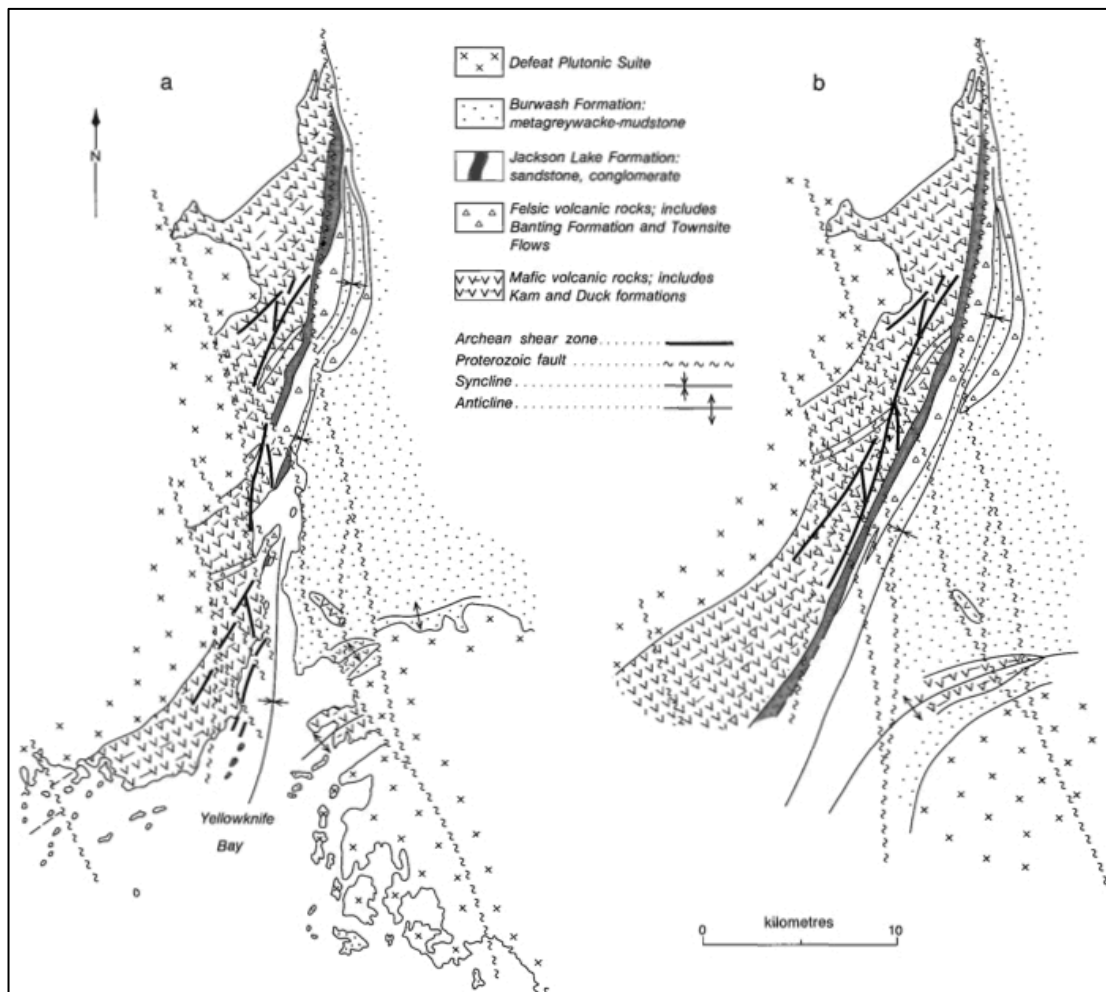
Figure 32. a) Geological map showing the location of early shear zones in, and unconformably above the mafic Kam Group in the Yellowknife Bay area. b) Restored offsets of late faults. Early shear zones displace the felsic volcanic marker horizon in the mafic sequence, however not displaced along the shear zone is the unconformable contact between the Kam and Jackson Lake Formation, suggesting the early shears predate the deposition of Jackson Lake Formation above the unconformity (from Henderson, 1985).

Individual shear zones range from and grade between distinct breccia with well-preserved clasts to schist zones where original rock textures are obliterated. Contacts are commonly gradational. Shear

zones, particularly the large discordant zones, consist of complex interlacing networks of sheared material bound up with blocks of relatively undeformed volcanic rocks (Henderson, 1985).

A major feature of the YGB is the north-striking Yellowknife River Fault Zone (YRFZ; Figure 16), which has been traced for over 30 km and is suggested to be a deep crustal structure (Martel et al., 2002). In the south of the belt, the YRFZ bends to the southwest where it is spatially associated with the eastern contact of the Jackson Lake Formation or, where Jackson Lake Formation is absent, the Kam-Banting Group contact. The fault zone is defined by a 10-30 m wide mylonite zone with a >400 m wide zone of intense deformation that extends east and west of the Jackson Lake Formation-Banting Group contact (Martel et al., 2002).

Siddorn (2011) describes the deformation in the YGB in four phases (D_1-D_4), and notes the Giant mine deformation zones display evidence for early D_1 deformation and associated gold mineralization that was overprinted by the main D_2 phase of deformation. D_1 represents an extensional phase subsequently overprinted by a compressional phase of deformation (D_2), which was reactivated during D_3 deformation and is later crosscut by D_4 Proterozoic faults (Siddorn, 2011). Two series of D_4 Proterozoic faults offset veins of the Con Mine: the Negus Fault and the West Bay series faulting (Siddorn, 2011).

Roughly corresponding to the deformations described by Siddorn (2011), Martel et al. (2002) recognize four generations (G_1-G_4) of ductile structures in the area and describe associated foliations, folds, and lineations respectively named S_1-S_4, F_1-F_4 and L_1-L_4, which vary depending on host rock and proximity to the YRFZ where deformation was focused (Martel et al., 2002). Of note, single episodes of progressive deformation may have lead to more than one structural feature being developed at the same time, as structural features are not well constrained to the deformational generations (Martel et al., 2002).

G_1 structures comprise crenulated, bedding-parallel, S_1 foliation defined by the alignment of mica. G_2 is well developed proximally and distally to the YRFZ, producing an S_2 foliation consistently oriented clockwise (~20°) to the shear zone boundary and bedding. S_2 is a continuous fabric in competent felsic volcanic beds of the Banting Group, compared to strongly developed differentiation layering exhibited in less competent Burwash and Walsh sedimentary rocks. Furthermore, S_2 is axial planar to varying scales of moderately to steeply, northeast plunging, S-shaped F_2 folds of both bedding and S_1 (Martel et al., 2002). Associated with S_2 are subparallel and either north or south striking, steeply plunging stretching (L_2) and intersection (L_0-L_2) lineations. An east-side-up dip-slip motion with a minor sinistral shearing component is indicated to have prevailed during G_2. Distinctive and ubiquitous structures were produced during G_3, including S_3 foliation consisting of

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strongly differentiated crenulation cleavage, open and upright, steeply plunging, Z-shaped F_3 folds and steep intersection lineations (L_3-L_0) (Martel et al., 2002).

S_3 is oriented counterclockwise to bedding, S_2 and the shear zone boundary, as well as being axial planar to F_3. Indicative of a dextral shear component localized along the YRFZ during G_3 is the orientation of S_3 to earlier structures and the F_3 fold asymmetry. Proximal to the YRFZ are G_4-related folds and foliation locally occurring in the Kam and Banting Groups. S_4 is strongly developed within the fault zone and is defined by a coarsely spaced cleavage paralleling the shear zone boundary and crenulating the S_3 foliation. Also, it reinforces the pre-existing parallel S_2 foliation. Generally steeply to moderately northeast plunging S-shaped F_4 folds of the S_3 foliation are common. 'C' shear bands associated with S_4 indicate a sinistral shear sense during G_4 (Martel et al., 2002).

6.2.3 **MINERALIZATION**

Gold has been mined from the YGB since the 1930's and the area ranks as a former world-class producer with the dominant Giant (+Lolar-Supercrest) Mine producing ~8 Moz (248 t) of gold from 13.9 Mt of ore at an average grade of 15.74 g/t between 1938 and 2004 and the Con (+Negus-Nerco) Mine producing ~6 Moz (187 t) gold grading 16.27 g/t between 1938 and 2003 (van der Velden and Cook, 2002; Goldfarb et al., 2005; Goodwin et al., 2006). The most productive gold orebodies occur along major late-stage shear zones as lode-gold deposits and are mainly confined to the Yellowknife Bay Formation of the Kam Group. Mineralization was synchronous with both D_1 and D_2 of the Yellowknife area and consists of broad zones of silicification and quartz-carbonate veining, which form gold-quartz alteration systems (van der Velden and Cook, 2002; Goodwin et al., 2006). Gold-bearing shears dip 40°–60° west and displacement is typically west-side up. The orientation and sense of displacement of the gold-bearing shears is consistent with the interpreted thrust and fold structures beneath Yellowknife (van der Velden and Cook, 2002).

A popular, yet controversial, genetic model attributes lode-gold mineralization to vertical migration of metamorphically derived auriferous fluids through a system of anastomosing shear zones with gold veins deposited in favourable dilatant zones (van Hees et al., 1999; Goodwin et al., 2006), which fits within the orogenic gold model described in CHAPTER 4. Henderson (1985) and earlier workers believed that shear-zone-hosted gold and associated mineralization in the YGB was likely derived entirely from the altered volcanic rocks during metamorphism, with early shear zones facilitating fluid movement and mobilization of the mineralizing elements.

Ore bodies occur as narrow discontinuous bodies within shear zones where deformation was especially intense and complex, as well as in dilatant zones with quartz vein accumulations. Displacement of 350 m has been noted on the Con system, whereas 200 m of displacement is noted on the Negus Rycon system and >450 m on part of the Giant Campbell system are noted by Henderson (1985). Some shear zones occur only within the volcanic rocks with no apparent displacement extending into the sedimentary rocks unconformably overlying the volcanic rocks along the Giant Campbell shear zone, suggesting movement is older than the unconformity and formed during the accumulation of the Yellowknife Supergroup (Henderson, 1985).

Two main styles of gold mineralization are noted in the YGB; 1) a refractory style that characterises most of the carbonate-rich ores hosted by early veins and sericite schist alteration with fine-grained pyrite, arsenopyrite and sulphosalts and 2) a free-milling vein-hosted style. The free-milling style includes five gold associations, including: a) gold with sphalerite, galena and chalcopyrite in late veins; b) gold contained within megacrystic pyrite and arsenopyrite; c) gold with sphalerite and galena in arsenopyrite-poor veins; d) gold in pyrite and chalcopyrite-rich veins; and e) molybdenite-bearing auriferous veins (Shelton et al., 2004). Numerous examples exhibit superposition of different styles, locally enhancing total metal endowment, though post-mineralization deformation and overprinting blur temporal relationships (Shelton et al., 2004).

6.3 CAMERON RIVER AND BEAULIEU RIVER GREENSTONE BELTS

The Cameron River and Beaulieu River greenstone belts (Figure 19) are exposed in arcutate belts around granitoid rocks of the basement Sleepy Dragon Complex (SDC; Section 5.4.1.1) and comprise strongly deformed mafic to felsic volcanic rocks of the Yellowknife Supergroup (Henderson, 1985; Lambert, 1988). Granitic-gneissic rocks of the SDC crop out in a north-south elongate ovoid area between these greenstone belts and contacts with the supracrustal rocks are typically highly strained, broad structurally complex faults.

The Beaulieu Group includes most of the volcanic rocks surrounding the SDC and where mapped in the south (Figure 33) is split into three separate subareas by Lambert (1988): 1) Cameron River to the northwest (Section 6.3.1.1); 2) Tumpline Lake to the south (Section 6.3.1.2); and 3) Sunset Lake to the northeast (Section 6.3.1.3), each with unique stratigraphy and styles of deformation. These three sections mainly summarize Lambert (1988), who mapped across the greenstone belts as part of a regional mapping program. Included in this study is the northern continuation of the Beaulieu River greenstone belt, here termed the Northern Beaulieu subarea (Section 6.3.1.4), which has some of the best orogenic gold potential in the Yellowknife domain.

Known mineralization in the belts is mainly limited to VMS style deposits and BIF-hosted gold, however only first pass exploration efforts have been carried out in this area. Second- and third-order structures related to the pan-Slave Beaulieu River Fault Zone have potential to host orogenic gold deposits. Stubley (1989) notes three known generalized deposit settings found in the Northern Beaulieu subarea similar to the orogenic gold model with anomalous gold concentrations (>100 ppb) in rock samples collected during mapping. These relatively underexplored areas deserve follow up work with modern techniques.
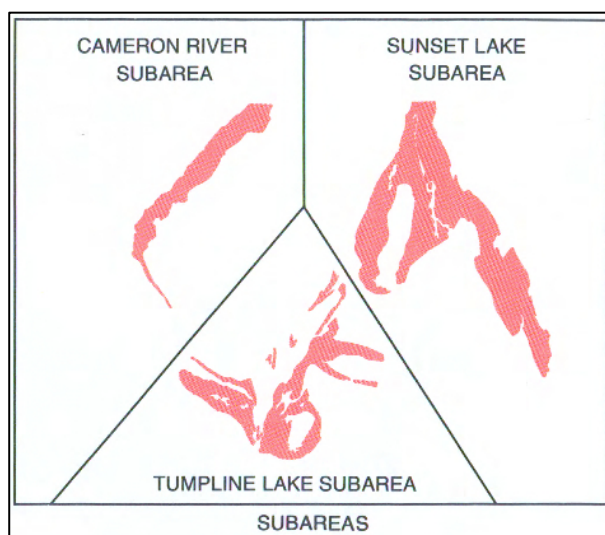
Figure 33. Southern subareas of the Cameron River and Beaulieu River greenstone belts (from Lambert, 1988).

6.3.1   LITHOLOGICAL FRAMEWORK

6.3.1.1   Cameron River Subarea

The Cameron River subarea is a 40 km long northerly-trending belt sitting between the Burwash Formation turbidites and the SDC granitic gneisses to the west and east, respectively (Figure 19 and Figure 20). The width of the belt varies from 3000-4200 m between Webb Lake and Fenton Lakes, tapering abruptly towards Upper Ross Lake and pinching out toward Victory Lake (Lambert, 1988). Stratigraphic thickness is difficult to determine due to high levels of deformation. The belt represents a series of westward, progressively overlapping flows representing a thin vertical pile that has been expanded by the intrusion of a huge swarm of dykes and sills (Lambert, 1988). To the east, the belt is irregular where it makes faulted contacts with the SDC granites and the contact has 2000 m of horizontal relief, compared to the gently undulating and smooth western contact with little relief (Lambert, 1988). Figure 34 shows a schematic stratigraphic cross section of the sub area.

Generally, the belt is a westward-facing homoclinal succession of metavolcanic rocks comprised of four formations: 1) Cameron River Basalt (CRB) dominated by basaltic pillow lavas encompassing

85% of the belt, 2) Rhyolite to dacites domes, flows, breccias and arenites (3% of the belt), 3) Webb Lake Andesite (WLA) pillows, breccias and volcaniclastic rocks (10% of the belt) and 4) Dome Lake Basalt (DLB) lavas and volcaniclastics that make up 2% of the belt (Lambert, 1988).
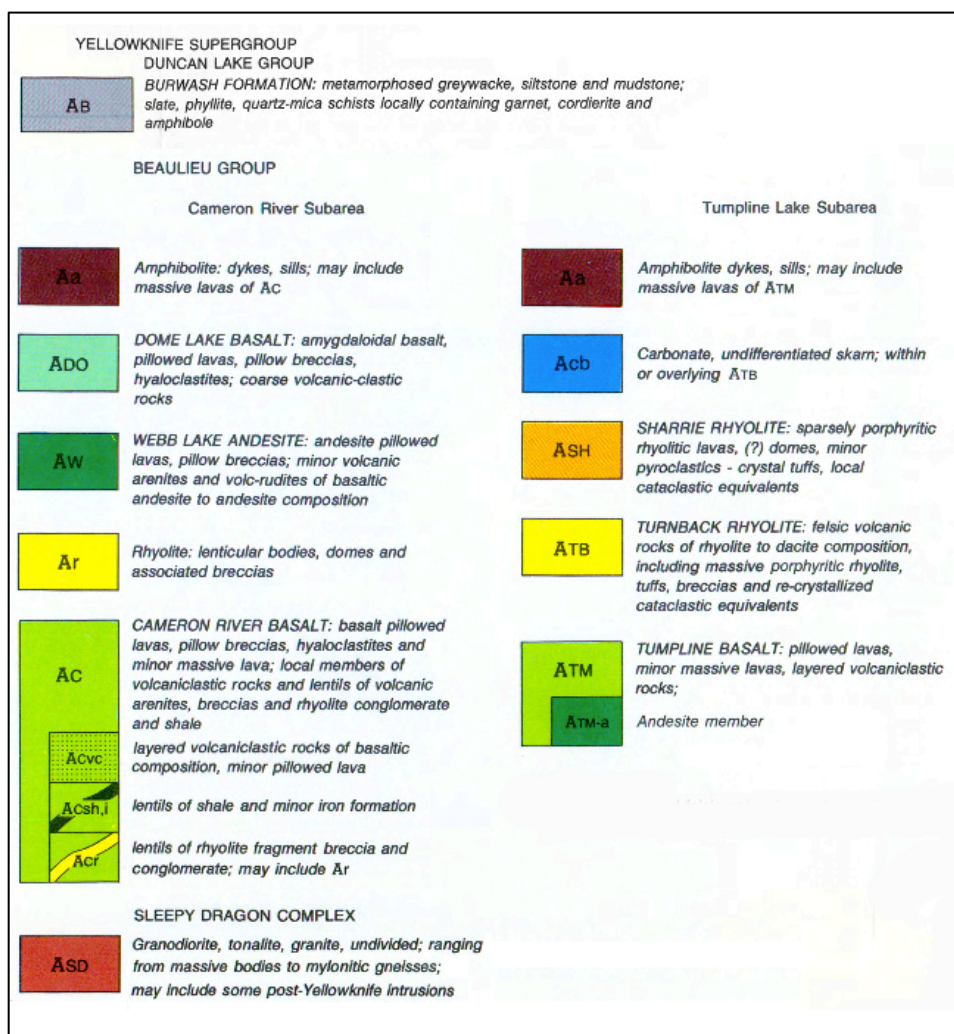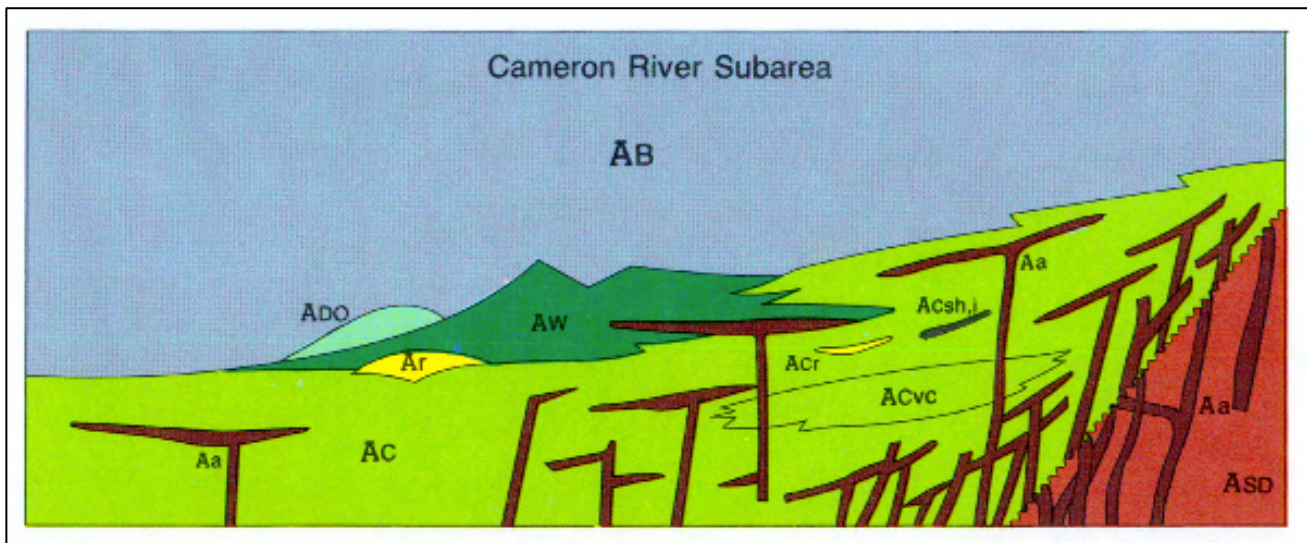
Figure 34. Schematic stratigraphic relationships of the Cameron River subarea. Stratigraphic legend for both Cameron River and Tumpline Lake subareas (modified from Lambert, 1988).

6.3.1.2   Tumpline Lake Subarea

The southeastern Tumpline subarea is a bimodal volcanic belt with near equal rhyolite and basalt, which is divided into three formations: Tumpline Basalts, Turnback Rhyolite and Sharrie Rhyolite, displayed schematically in Figure 35 (Lambert, 1988).

Pillowed lavas and layered basaltic volcaniclastic, locally andesitic, rocks of the Tumpline Basalts (TB) Formation, lie conformably on Turnback Rhyolite and Sharrie Rhyolite Formations. Overlying the basalts are metasedimentary rocks of the Burwash Formation (Lambert, 1988).

The Turnback Rhyolite (TR) Formation comprises all the rhyolite units lying directly above the Tumpline Basalts near Turnback Lake and all the rhyolites lying above and below the basalts south of Tumpline Lake (Lambert, 1988). It comprises 40% of the belt and consists of intensely deformed and metamorphosed lavas, domes, breccias and volcaniclastic rocks (Lambert, 1988).

Sparsely porphyritic lavas, domes, minor pyroclastic rocks and crystal tuffs comprise the Sharrie Rhyolite, which has an approximate maximum thickness of 850 m (Lambert, 1988). It appears to conformably overlie the Tumpline Basalts and is overlain by the metasedimentary rocks of the Burwash Formation (Lambert, 1988).
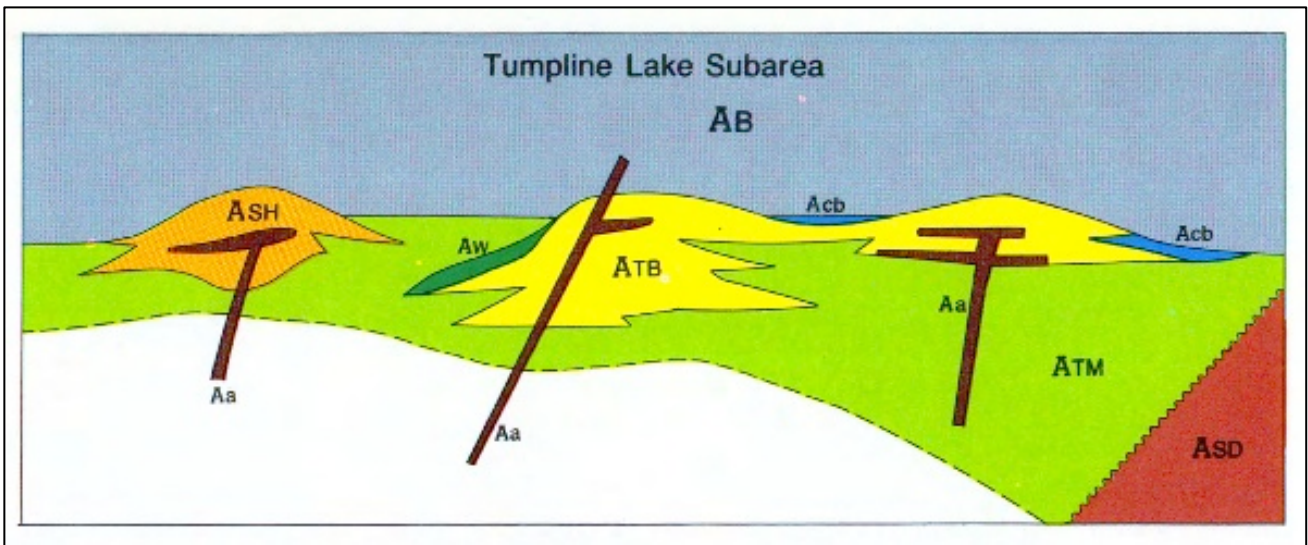
Figure 35. Schematic stratigraphic relationships for Tumpline Subarea. Legend in Figure 34 (from Lambert, 1988).

6.3.1.3   Sunset Lake Subarea

The Sunset Lake area, bounded by Sleepy Dragon Complex to the west and the Meander Lake Plutonic Suite to the east and south, is subdivided into three formal formations, 1) Sunset Lake

Basalt, 2) Alice Formation with andesite and dacite members, and the 3) Payne Lake Formation. It also features unnamed ultramafic and rhyolite units (Figure 36) (Lambert, 1988).

Figure 36. Schematic stratigraphic relationships and stratigraphy legend of the Sunset Lake subarea (modified after Lambert, 1988).

The ultramafics have been mapped for 3 km of strike length, pinching and swelling with a maximum thickness of 60 m along the highly complex boundary zone between the Sunset Lake Basalts and the SDC, eventually tapering out to the south into biotite schist (Lambert, 1988). Rhyolite bodies are found at the top, or near the top, of the volcanic succession, commonly forming between the Sunset Lake Basalts and the Burwash Formation (Lambert, 1988). A basal polymictic conglomerate unit is also present and contains metabasalt, metadiabase, vein quartz and granitic gneiss (Lambert, 1988).

The Sunset Lake Basalt (SLB) comprises 70% of the rocks in the subarea and is mainly composed of pillow basalts, pillow breccias, and hyaloclastites with minor iron formations, conglomerate and volcanic sedimentary rocks (Lambert, 1988). The SLB stratigraphically lies below the Alice Formation, or locally interfingers with rhyolites and sedimentary rocks of the Payne Lake Formation.

The Alice Formation consists of Lower Andesite and Upper Dacite members, which overlie or interfinger with the Sunset Lake Basalts (Lambert, 1988). The Lower Andesite is comprised of pillow lavas, breccias, massive flows and minor volcanic sedimentary and pyroclastic rocks, whereas andesite and dacite tuffs, volcanic breccias, lavas, and cataclastic equivalents represent the Upper Dacite (Lambert, 1988).

The Payne Lake Formation is found in and forms most of the southeastern part of the subarea (Lambert, 1988). It is comprised of successions of volcaniclastic sedimentary rocks that are dominantly layered schists and gneisses, which are divided into 1) rhyolite-derived quartz-feldspar schists with minor mica; 2) felsic volcanic-derived biotite-muscovite-quartz-feldspar schists; and 3) mafic volcanic-derived amphibolite-rich schists with variable amounts of mica (Lambert, 1988).

6.3.1.4   **Northern Beaulieu Subarea**

Extending north from the Sunset Lake subarea is the Northern Beaulieu River subarea, centred 150 km northeast of Yellowknife, consisting of the Central and Northern Beaulieu River greenstone belts as described by Corcoran et al. (2004), though here include the northern areas described by Stubley (1989). A major feature of the subarea is the north-striking Beaulieu River (a.k.a. Beniah Lake) Fault Zone (BRFZ), which cuts through the center of the belt (Figure 37a and b). The mafic, dominantly pillowed flows of the ca. 2680 Ma Central belt are inferred to have the Sleepy Dragon Complex as basement in the south, with a >2.9 Ga quartz arenite in fault contact with the basement gneiss and overlying mafic flows (Figure 38).

Tholeiitic and calc-alkaline basalts, andesites and rhyolites are featured in the volcanic sequence, with mafic and felsic autoclastic breccia and felsic volcaniclastic rocks of pyroclastic origin

increasing up-section (Corcoran et al., 2004). Mafic dykes cutting the pillow breccias and pillowed flows are somewhat common and are thought to be synvolcanic (Corcoran et al., 2004). Unconformably overlying the belt is the Beaulieu Rapids Formation, focused along the BRFZ (Corcoran et al., 2004).
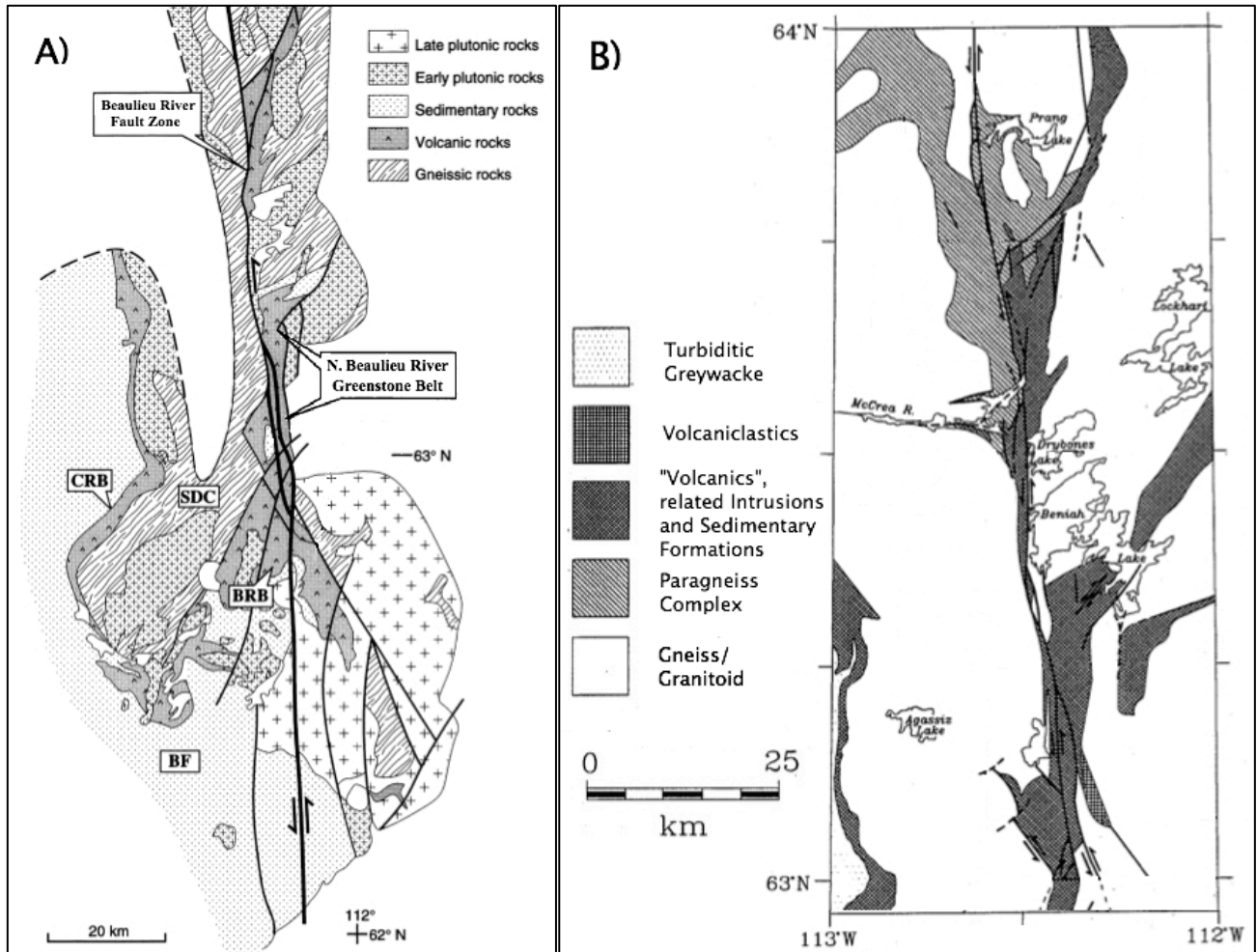
Figure 37. A) Regional Map of the CBGB, highlighting the Central and Northern Beaulieu greenstone belts and the Beaulieu River Fault. CRB=Cameron River greenstone belt; SDC=Sleepy Dragon Complex; BRB=Beaulieu River greenstone belt; BF= Burwash Formation (modified from Corcoran et al., 2004) B) Northern Beaulieu River greenstone belt extending from Sunset Lake subarea (modified after Stubley, 1989).

The basement of the mafic, tholeiitic pillow, pillow breccia and hyaloclastite-dominated Northern belt is considered to be granodiorite-tonalite gneisses of the Beniah Complex (similar to the Sleepy Dragon Complex) along with ultramafic intrusions, both of which underlie the quartz arenite– dominated, ca. 2.9-3.1 Ga Beniah Formation (Figure 39) (Corcoran et al., 2004). Within the volcanic sequence, felsic volcaniclastic units grade into pillowed flows, with abundant mafic intrusions cutting the quartz arenites and mafic flows, but are unconformably overlain by younger sedimentary rocks (Corcoran et al., 2004). In the Beniah Lake area, discrete north- to northeast-trending, up to 0.5 km wide and 1.8 km long, ultramafic units are locally preserved, though they do not appear to be

directly related to the volcanic belt (Corcoran et al., 2004). Locally in the north, small lenses of banded magnetite iron formation and Fe-amphibole and garnet-rich beds have been identified (Stubley, 1989). Accounting for approximately 25% of the volcanic facies in the belt are north-striking, parallel basaltic and gabbroic intrusions, though contacts are difficult to distinguish (Corcoran et al., 2004). Pillowed flows are less common and where present are separated by felsic tuff horizons, which are represented by planar- and crossbedded tuff and lapilli tuff, tabular and low-angle to wavy bedded tuff and planar laminated tuff (Corcoran et al., 2004).

A suggested tectonic setting of the Northern belt involves contemporaneous subaerial eruption of felsic arc volcanoes and fissure dominated eruptions of mafics in a back-arc basin, based on tholeiitic mafic and calc-alkaline felsic geochemistry (Corcoran et al., 2004). Underlying much of the northwest is a heterogeneous suite of paragneiss, injection gneiss and various intrusive phases; some with high Ca and Fe content that differentiates it from the typical turbidite sequences of the Yellowknife Supergroup (Stubley, 1989).
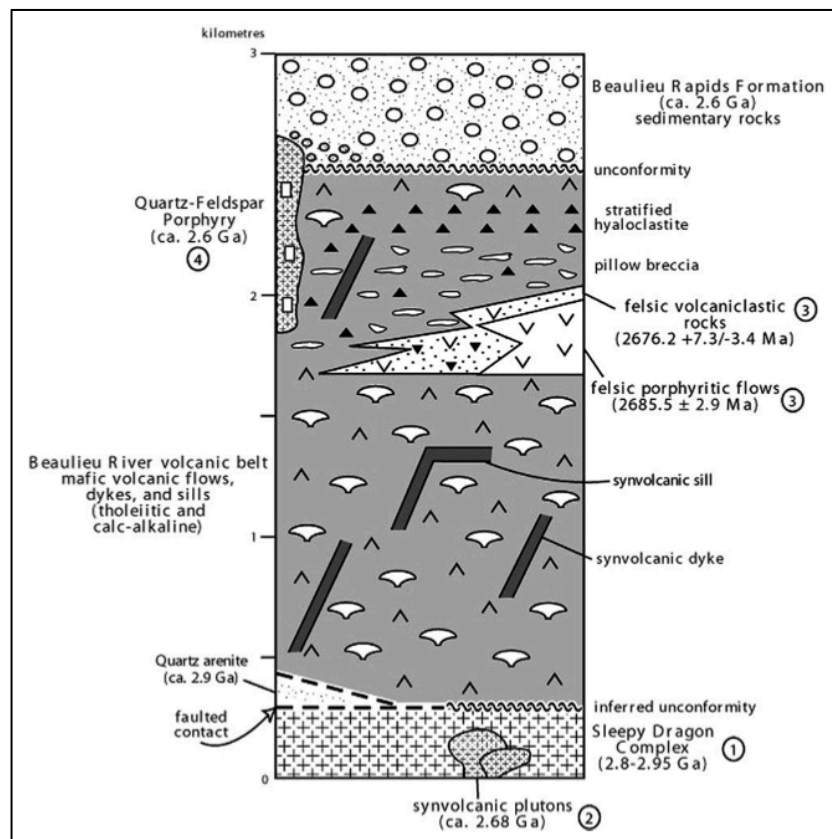
Figure 38. Schematic stratigraphy of the Central Beaulieu River greenstone belt (from Corcoran et al., 2004).
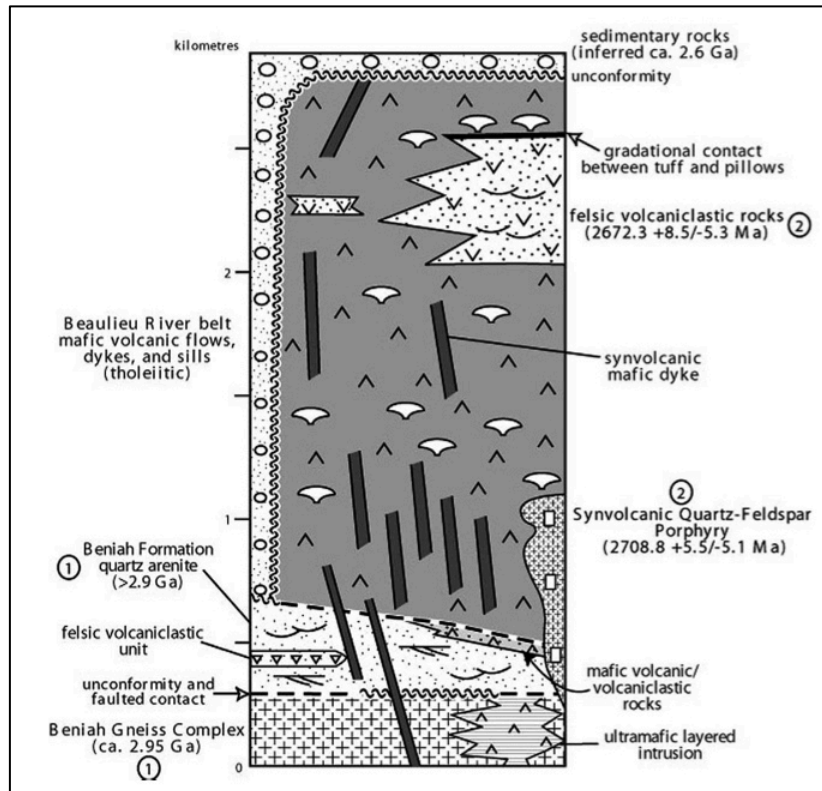
Figure 39. Schematic stratigraphy of the Northern Beaulieu greenstone belt (from Corcoran et al., 2004).

6.3.2   STRUCTURAL FRAMEWORK

In the Cameron River and southern Beaulieu River greenstone belts, faults and shear zones formed pre-, syn- and post-volcanism and deformation by folding (Figure 40). Particularly significant are the Archean high-strain zones delimiting the contact between the Sleepy Dragon Complex and the greenstone belts and the Proterozoic northerly-striking transcurrent faults (Lambert, 1988). Pre-volcanic faults are north to northwesterly striking, displacing the western side of the SDC and may have been reactivated during volcanism (Lambert, 1988). Synvolcanic faults are found within the volcanic rocks and offset volcanic formations, but are not recognized in the basement or Burwash Formation (Lambert, 1988). Nearly vertical shear zones within and roughly parallel to the volcanic belts are very common (Lambert, 1988). Shear zones and syndeformational faults, such as high strain zones along the SDC-volcanic contacts, discrete shear zones within the volcanic belts and narrow zones of cataclasis and/or ductile strain are interpreted as either coeval with or post-dating folds (Lambert, 1988). In the Sunset Lake and Beaulieu River area towards the east, a broad shear zone within the volcanic rocks is interpreted to represent movement during folding. Textures in the zone indicate both brittle and ductile deformation (Lambert, 1988).
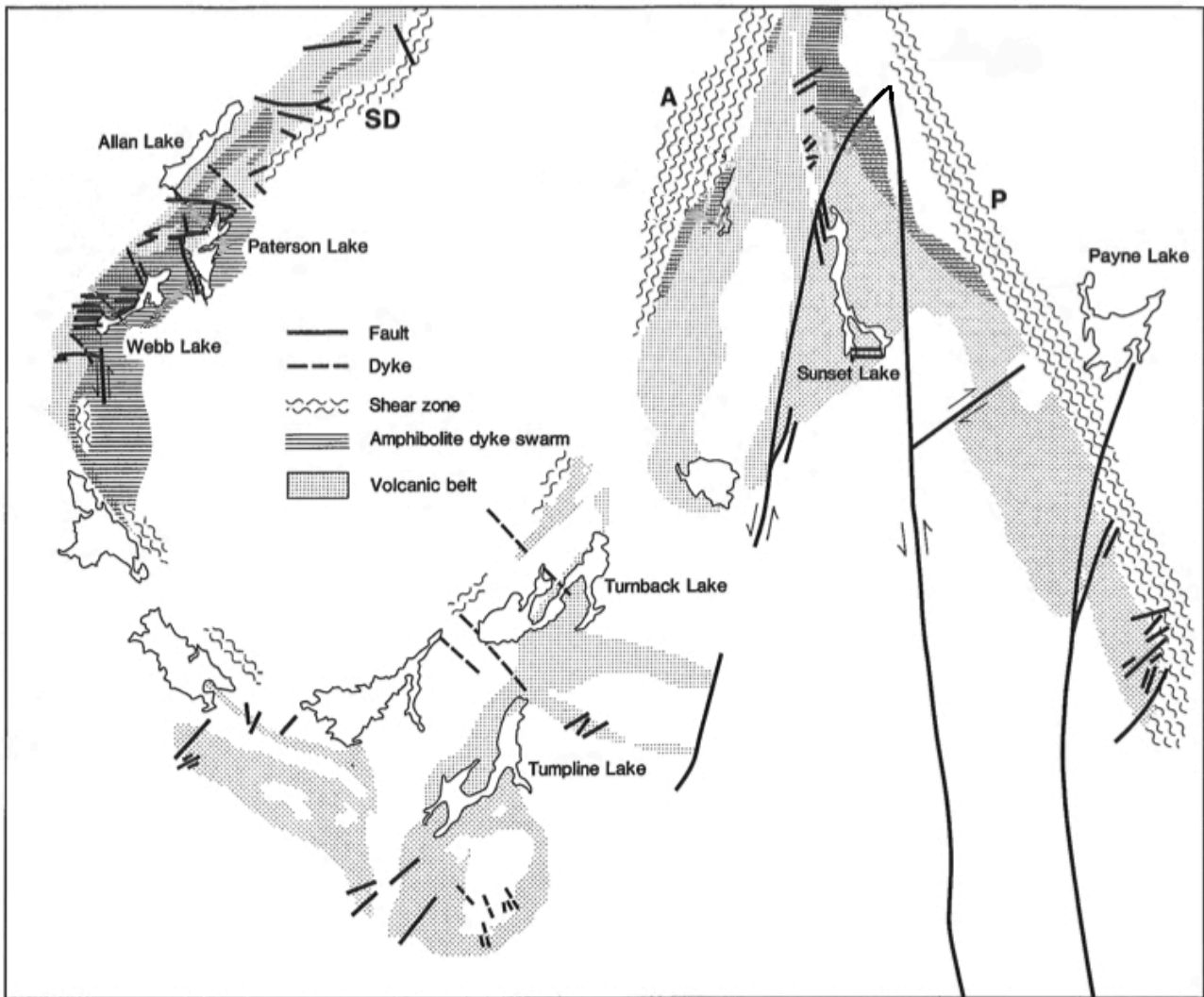
Figure 40. Faults, shear zones and major dyke swarms in the CBGB. SD=Sleepy Dragon shear zone; A=Amacher shear zone; P=Payne shear zone (modified after Lambert, 1988).

Faults, shear zones and major dyke swarms of the CBGB (Figure 40), including the Sleepy Dragon, Amacher and Payne shear zones. The Sleepy Dragon shear zone is 100-200 m wide (locally up to 500 m) and exhibits relatively high penetrative strain along the boundary of the Cameron River greenstone belt and the SDC with a family of discrete shear zones concentrated in the center of the and focusing along the greenstone belt (Lambert, 1988). These structures are interpreted as being related to thrusting of the Cameron River greenstone belt over the SDC. The 1-4 km wide north-northeasterly striking Amacher shear zone is a mylonitic belt bordering the eastern side of the SDC in the Sunset and Tumpline Lake subareas (Lambert, 1988). West of Amacher Lake and near the north end of the belt, large amphibole dykes intrude along the volcanic-granitic boundary, which exhibits intense deformation due to strain and deformation extends up to 1 km into granitic rocks, amphibole dykes and volcanic rocks of the Sunset Lake Basalt (Lambert, 1988). Structures in the Amacher shear zone suggest a dextral transcurrent motion rather than thrusting. The 1-2.5 km wide,

northwest-striking, steeply southwest-dipping Payne mylonitic shear zone occurs mainly in the Meander Lake Plutonic Suite, but cuts and penetrates the volcanic belt west and south of Payne Lake. It consists of mildly crushed to extensive breccia zones containing quartz stockworks to dense ultramylonites (Lambert, 1988).

In the Northern Beaulieu greenstone belt, there is a complex system of late strike-slip faults postdating all lithologies and likely all regional folding events (Stubley, 1989). Particularly between 63°N and 63.25°N (Figure 37b), the faults delineate "domains" with distinct combined differences in stratigraphy, fold style and orientation, strain history, younging directions and metamorphic grade (Stubley, 1989). Northeast-striking fault zones exhibit dextral displacement, whereas younger, north and northwest-striking fault zones exhibit sinistral displacement (Stubley, 1989). One fault zone of anastomosing brittle and ductile faults (up to 2 km in width) can be traced continuously for ~180 km and displays 15 km of movement (Stubley, 1989).

The contacts between contrasting lithologies are also commonly associated with shear zones in the region and likely result from strain gradients that develop where two units with contrasting rheological characteristics are deformed together (Lambert, 1988). In the Cameron River and Sunset Lake subareas, boundaries between rhyolite domes and mafic volcanic rocks feature brecciation and deformation, whereas contacts between Burwash Formation sedimentary rocks and Beaulieu Group volcanic rocks vary from highly schistose with related gossan zones to conformable contacts with limited anomalous strain (Lambert, 1988).

Proterozoic faults include regionally extensive, northerly to northeasterly striking major transcurrent faults and northwesterly striking fractures occupied by mafic and felsic dykes (Lambert, 1988). Faults east and south of Sunset and Payne lakes have been traced for 80-100 km, displacing volcanic belts and offsetting some granitic plutons. Major movement on the northerly striking faults is post-volcanism, and can predate plutons and some deformation by folding (Lambert, 1988).

Folding is very prominent in the belts, generally with steeply plunging fold axes (Lambert, 1988). The folds vary in size, shape and orientation, with multiple generations creating complex interference patterns, particularly in the metasedimentary rocks of the Burwash Formation (Lambert, 1988). Three generations of folds are noted in the metasedimentary rocks while the volcanic rocks do not exhibit the same complex deformation. This is partly due to the lack of consistent markers and layering in the volcanic rocks; however, a BIF in the Sunset Lake area provides evidence of polyphase deformation (Lambert, 1988). Only one regional foliation is apparent in most outcrops of the Northern Beaulieu greenstone belt, though a minimum of three, probably four, fold events are recorded in the Beaulieu Rapids formation (Stubley, 1989).

Early folds vary in the subareas, with a homoclinal succession rarely visible in the Cameron River subarea, whereas tight large-scale isoclinal folds roughly parallel to or wrapping around the margins of the granitic terrane and pluton are noted in the Tumpline Lake area (Lambert, 1988). The Sunset Lake subarea exhibits more open folds with axial traces trending parallel to the boundaries of the granitic terrane, both northeast and northwest of the volcanic belt (Lambert, 1988). The Northern Beaulieu subarea features a north-trending synclinal structure that crosses the BRFZ and bends to the east on the eastern side of the fault (Fyson, 2000). Late folds are small-scale cm- to m-scale features ranging from gently undulating or open concentric folding to tight crenulations of layering and foliations that deform planar structures related to earlier folding (Lambert, 1988). All subareas have north to northwesterly trending axial traces and cleavage commonly cutting across axial planes of earlier folds at moderate to high angles (Lambert, 1988). All subareas exhibit a constant west-southwest to east-northeast-trending fold plunge direction that implies regional shortening (Lambert, 1988).

6.3.3 MINERALIZATION

There are currently no mines in the CBGB, however there are a number of known deposits, including the Turnback Lake/XL, Sunrise and Bear VMS deposits, the Amacher and Patterson Lake gold-bearing BIF's at the top of the CSCG and the Peg Tantalum REE-enriched pegmatite (Section 5.8) (Bleeker and Hall, 2007). There is potential for the discovery of orogenic gold mineralization associated with the Beaulieu River Fault Zone, or the Sleepy Dragon, Amacher and Payne shear zones, as well as the BIF's.

Mineralization at the Turnback Lake/XL, located in the Tumpline subarea, occurs within silicified amphibolite as bedding concordant zones of disseminated sulphides. Pyrrhotite and sphalerite are concentrated along sedimentary horizons with irregularly distributed chalcopyrite, galena, and pyrite. It is suggested that mineralization is exhalative and distal to an intermediate to felsic volcanic centre (Government of Northwest Territories, 2007).

VMS mineralization at the Sunrise deposit in the Sunset Lake subarea is hosted by a brecciated rhyolite tuff and appears to have been deformed by a prominent block fault, indicative of a caldera-type setting (Government of Northwest Territories, 2007). The deposit forms a lens with an average thickness of 4 m (locally up to 16 m) with 250 m of strike length that extends to at least 700 m depth and is conformable with stratigraphy, dipping at 60° to 65° to the east and plunging 60° to the north (Government of Northwest Territories, 2007). In 2003, Silver Standard Resources Inc. estimated that the Sunrise Deposit contains 1.36 million tonnes at 280 g/t Ag (Silver Standard, 2003). The Bear (also referred to as Hart) deposit is also located in the Sunset Lake subarea. Mineralized

zones at the Bear deposit are located along the contact between gneisses and north-northeast trending, amphibolite facies, massive and pillowed basalt-andesites. The footwall is banded iron formation, consisting mainly of fine-grained magnetite (Government of Northwest Territories, 2007). Three layers of semi-massive to massive sulphides dominated by pyrite dipping at about 70° to the north-northeast have been traced by drilling over 160 m of strike length and to 400 m depth (NTGO, 2011).

In the Northern Beaulieu subarea, Stubley (1989) notes there are four generalized settings that returned anomalous gold concentrations (>100 ppb) from samples collected during regional mapping of the area: 1) in or adjacent to siliceous shear zones in mafic volcanic rocks; 2) pyritic paleoplacer deposits in the Beaulieu Rapids Formation; 3) with stratabound sulphides and Fe-amphibole, garnet and banded iron formation zones of the paragneiss complex; and 4) sporadic sulphide-bearing quartz veins in mafic volcanic rocks and gneisses and mafic intrusive complexes. The first three offer potential for significant gold discoveries (Stubley, 1989). Additionally, anomalous base metal concentrations between 0.25 and 2.5% are noted in relation to settings 1) and 4), primarily copper with lesser zinc and lead (Stubley, 1989) and could be related to VMS deposits.

Banded Iron Formations of the CSCG are mostly thin (1-10 m) and vary from oxide-iron formation into silicate-rich varieties or simply ferruginous chert along strike (Bleeker and Hall, 2007). However, local folding has substantially thickened highly magnetic Fe-oxide BIFs (e.g. at Amacher Lake, on the eastern flank of the Sleepy Dragon Complex), resulting in high amplitude total field magnetic anomalies. Generally of low economic value, the BIFs may possibly host orogenic gold mineralization, though most known iron formation-hosted gold mineralization across the craton is associated with younger BIFs intercalated within low- to medium-grade turbidite packages (Bleeker and Hall, 2007).

CHAPTER 7   ADDITIONAL DEPOSIT TYPES OF THE YELLOWKNIFE DOMAIN

7.1   INTRODUCTION

In addition to greenstone-hosted orogenic gold mineralization focused on in this study, the Yellowknife domain has potentially to host economic mineralization in the form of atypical greenstone gold deposits, turbidite- and BIF-hosted orogenic gold deposits, volcanogenic massive sulphide base metal deposits and pegmatite-hosted REE deposits, amongst others (Figure 41). This chapter introduces the key geological features of these deposit types and the implications for exploration.
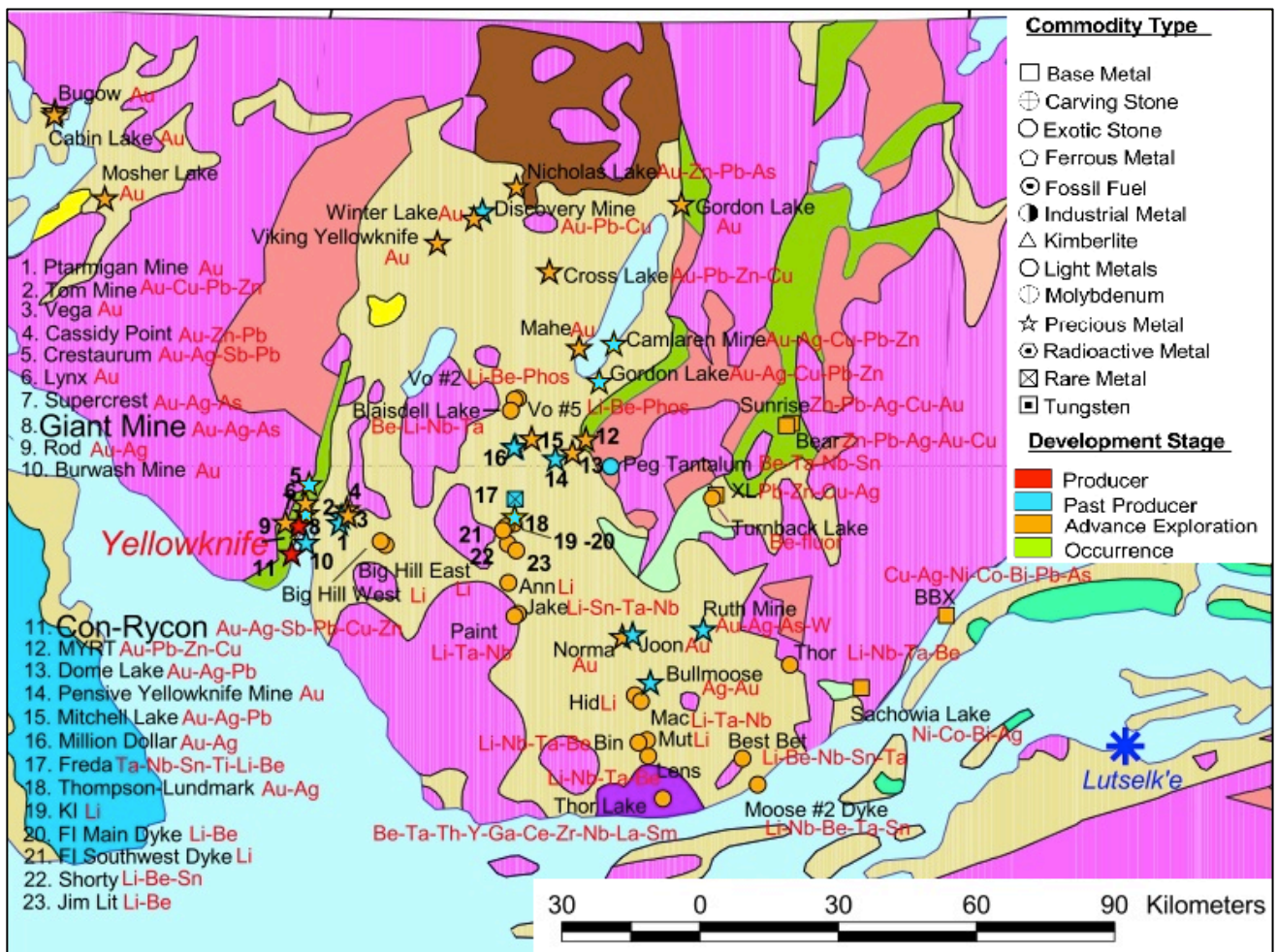
Figure 41. South Slave Mineral Deposits as of 1999 (modified after Bianchi, 1999).

7.2   GOLD

Including the past-producing Con and Giant Mines, the Yellowknife domain hosts a number of gold deposits, mainly hosted in shear zones and veins within the greenstone belts and turbidite sequences, as shown in Figure 27, Figure 41 and

. Many are past producers, though were typically mined on a small scale, as most deposits contain roughly between 50-1000 t gold within 10,000 to 100,000 t of ore averaging grades between >5 to <25 g/t (Schreiner, 2001).

7.2.1 ATYPICAL GREENSTONE

Gold-only and gold-base metal deposits not conforming to the orogenic model have been increasingly recognized in Archean greenstone belts, including Red Lake, Malarctic, and Boddington (Robert et al., 2007) and probably represent modified porphyry, VMS or epithermal deposits (Groves et al., 2003). Although this style of deposit displays similar regional-scale controls and occurs in the same camps as orogenic gold deposits, the mineralization style, metal associations, interpreted levels of crustal emplacement and relative ages are notably different (Robert et al., 2007). Globally, this style of deposit represents a significant proportion of greenstone belt gold budgets (Robert et al., 2007). Exploration in the underexplored areas of the Yellowknife domain should keep open the possibility of atypical greenstone belts occurrences being discovered. Even the Giant mine mineralization features some of the main characteristics of this deposit type, namely wall rock hosted disseminated mineralization, refractory gold and high Sb and Pb associations (van Hees et al., 1999).

7.2.1.1 Key Geological Features

The following characteristics of atypical greenstone gold are noted in Robert et al. (2007), Groves et al. (2003) and illustrated in Figure 42:
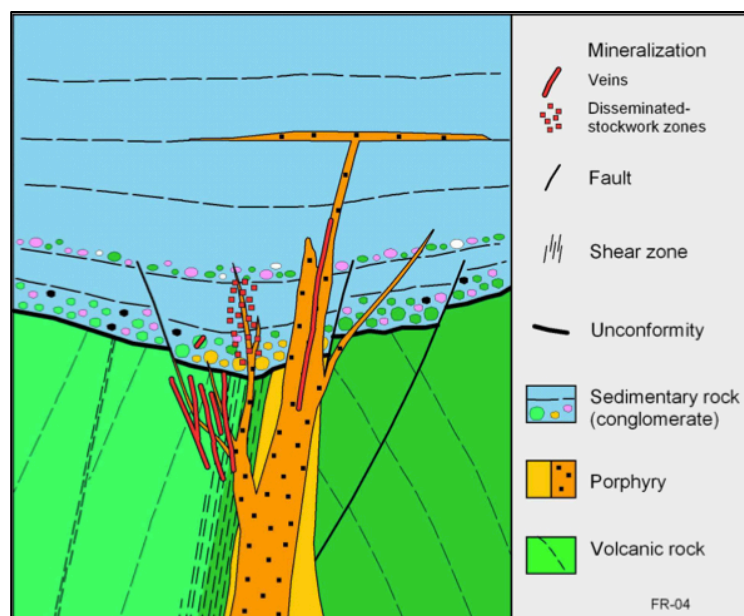
Figure 42. Geological model for the setting of disseminated-stockwork and crustiform vein deposits in greenstone belts, showing their close spatial relationship with high-level porphyry intrusions and unconformities at the base of conglomeratic sequences (from Robert, 2001; modified by Robert et al., 2007).

- Regional Scale Features

    o   Commonly occur near or above unconformities at the base of conglomeratic sequences

    o   Hosted in the upper, sedimentary section of the stratigraphic column

    o   Form pre-deformation and overprinted by orogenic veins

    o   Associated with major faults

- Local Scale Features

    o   Disseminated stockwork to crustiform-textured veins

    o   Sulphidic wallrock replacements, less commonly sulphide-rich veins

    o   Close spatial association with high-level porphyry dikes

    o   Aluminous mineral assemblages

    o   Au-Ag ± Ba ± Cu ± Hg ± Mo ± Pb ± Zn metal associations

    o   Enrichments in Te, Sb, Hg, suggestive of high-level emplacement

    o   Refractory gold

7.2.1.2   **Implications for Exploration**

Exploration efforts should assessing conglomeratic and sedimentary sequences proximal to major faults or porphyritic intrusions, such as the Beaulieu Rapids Formation in the Beaulieu River greenstone belt or Jackson Lake Formation in the YGB with geochemical surveying and use the metal associations and enrichments of Te, Sb and Hg to target for atypical greenstone gold.

7.2.2   **TURBIDITE-HOSTED OROGENIC**

Turbidite-hosted (or slate-belt-hosted) gold deposits are included in the orogenic gold deposit classification (Figure 8). The best examples of this deposit type exhibit vertically stacked saddle reefs in anticlinal fold hinges linked by fault-fill veins in reverse shear zones and associated extensional veins and are comparable to the mineralization in greenstone-hosted orogenic gold deposits (Robert et al., 2007). Numerous examples of turbidite-hosted gold deposits and past-producing mines are known in the Yellowknife domain (Figure 41 &
); however, most are currently uneconomic.

7.2.2.1   **Key Geological Features**

The key features of turbidite-hosted gold deposits as compiled by Robert et al. (2007) are:

- Regional Scale Features

    o   Thick, folded accretionary greywacke-mudstone sequences

    o   Granitic intrusions proximal to major crustal boundaries and faults

    o   Hydrated oceanic substrate is favourable

    o   Greenschist grade metamorphism

- Local Scale Features

    o   Doubly-plunging, upright anticlines

- High-angle reverse faults and cross structures
- Lack of significant volumes of felsic intrusions
- Fe-Mg-carbonate (siderite-ankerite) spotting haloes
- Increasing Au>Ag and As geochemical signatures in quartz veins towards deposits
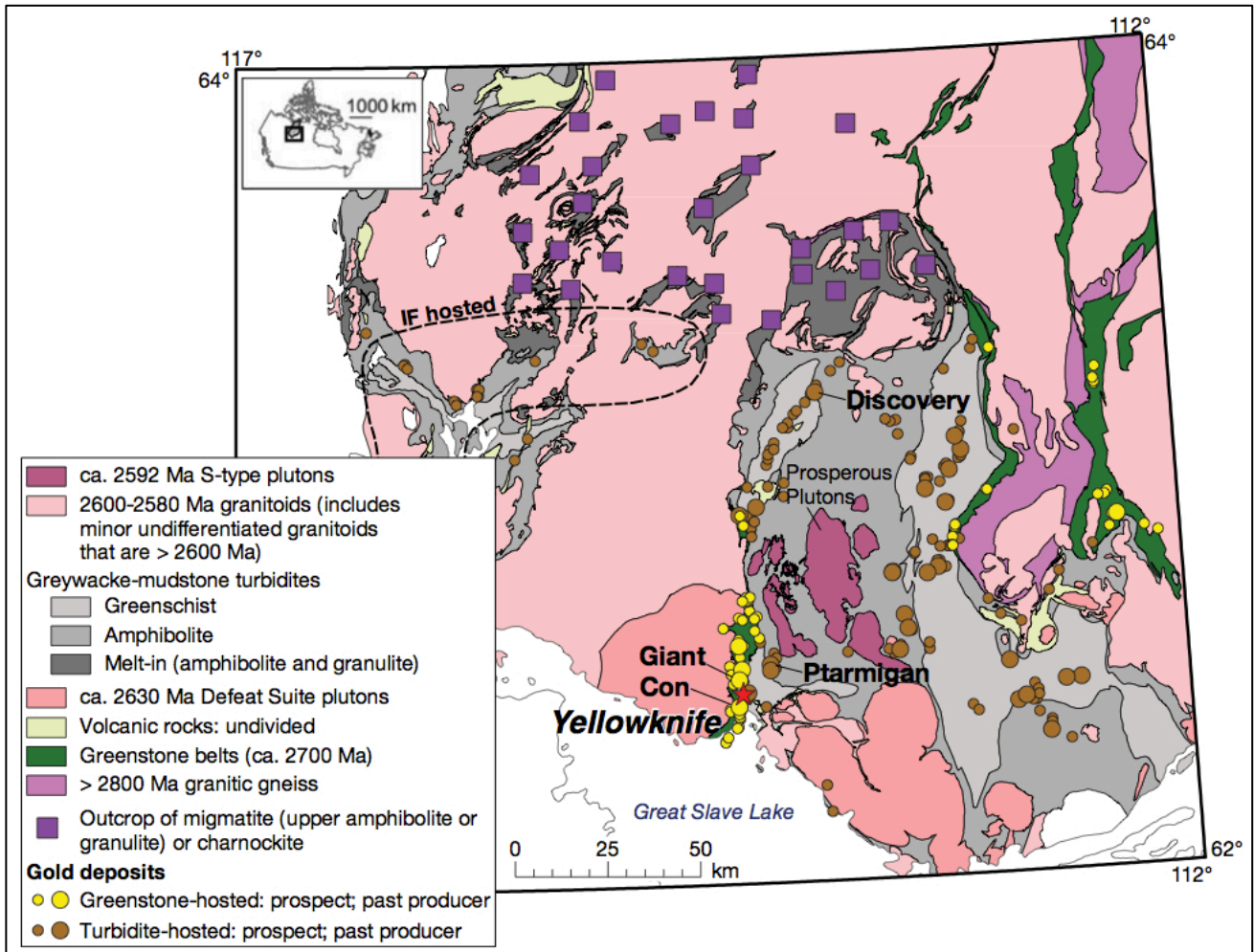
Figure 43. Geology map showing the location of gold prospects and past-producing mines (from Ootes et al., 2011).

7.2.2.2 Implications for Exploration

Of significance to the exploration of turbidite-hosted gold deposits are Fe-Mg-carbonate (siderite-ankerite) spotting haloes at vein-scale to kilometre-scale that provide a much larger footprint than the veins themselves, along with increasing concentrations of Au-quartz veins and a Au>Ag and As geochemical signatures. With numerous examples of turbidite-hosted gold veins found in the Burwash Formation metaturbidites between the YGB and CBGB, consideration of these deposits should be made when exploring the region, at or near volcanic-sedimentary rock contacts, however their small sizes typically limit their economic potential.

7.2.3   **BIF-HOSTED OROGENIC**

BIF-hosted orogenic gold deposits, such as Lupin (NWT), Homestake (North Dakota), Morro Velho (Brazil) and Geita (Tanzania) mainly form as sulphidic replacements of Fe-rich layers in silicate and magnetite BIF adjacent to variably developed quartz veins and veinlets (Robert et al., 2007). The timing of mineralization is ambiguous due to intense wall-rock replacement mineralization that obscures the epigenetic character of the deposits (Robert et al., 2007). The Amacher Lake, Patterson Lake, Dywer Lake and Bell Lake BIF deposits are examples of this style of mineralization in the Yellowknife domain (Bleeker and Hall, 2007). Though BIF's are relatively sparse in the Yellowknife domain, they remain potential hosts for orogenic gold mineralization.

7.2.3.1   **Key Geological Features**

The key features of BIF-hosted gold deposits as compiled by Robert et al. (2007) are:
- Regional Scale Features
  - Volcanic or sediment-dominated greenstone belts containing thick iron formations, commonly located stratigraphically near the volcanic-sedimentary transition
  - Proximal to margins of large clastic sedimentary basins, when volcanic rocks not present
  - Folded and metamorphosed
- Local Scale Features
  - Association with anticline or syncline fold hinges
  - Faults or shear zones intersecting iron formation
  - Stratiform/stratabound controls common
  - Plunges parallel to host rock fold hinge or lines of intersection of controlling shear zones with BIF unit
  - Common spatial association with intermediate to felsic porphyry stocks and dykes

7.2.3.2   **Implications for Exploration**

The key manifestations of BIF-hosted gold deposits with increasing proximity are sulphidation of iron formation, chlorite-carbonate or amphibolite alteration and Au>Ag and As signatures. Both the YGB and CBGB have known examples of BIF-hosted orogenic gold deposits and this style of mineralization should be taken into consideration when exploring the region, particularly at the contacts between sedimentary and volcanic rocks. Strong positive magnetic anomalies could be used to target this style of mineralization, such as in the Amacher Lake area.

7.3   BASE METALS

7.3.1   VOLCANOGENIC MASSIVE SULPHIDES

Volcanogenic massive sulphide (VMS) deposits are important sources of base and precious metals, including copper, lead, zinc, silver and gold. They generally consist of semi-massive to massive, concordant sulphide lenses underlain by discordant stockwork feeder zones of crosscutting veins and veinlets in a matrix of pervasively altered host rock and gangue (Dubé et al., 2007). Shanks and Thurston (2012) provide a comprehensive compilation of VMS deposits, classifying them into five systems based on host-rock lithologies. They also note metal associations in VMS deposits may be Pb-Zn-, Cu-Zn-, or Pb-Cu-Zn-dominated, while Dubé et al.(2007) discuss characteristics of Au-rich VMS deposits. Slave craton VMS deposits are noted for being Ag-Pb-Zn-rich and are associated with Hackett River-type volcanic belts or the felsic components of Yellowknife-type belts, as discussed in Section 5.8.3 (Padgham, 1992). The major VMS deposits and prospects found in the Yellowknife domain are the Sunrise, Bear, and Turnback Lake deposits, all located in the Beaulieu greenstone belt. A number of other known showings of the CBGB are described in Atkinson (1991).

7.3.1.1   Key Geological Features

The following key characteristics of VMS deposits are mainly taken from Shanks and Thurston (2012) and Robert et al. (2007):

- Regional Scale Features
  - Occur in marine volcano-sedimentary units including felsic or mafic lavas or tuffs, coarse breccias, and rhyolite domes
  - Rifted arcs and incipient back-arc environments, coinciding with greenstone belts
  - Other VMS deposits
- Local Scale Features
  - Well developed alteration zonation includes advanced argillic, argillic, sericitic, chloritic and propylitic types
  - Stratabound sulphides and discordant veins
  - High concentrations of Cu, Pb, Zn
  - Synvolcanic structures such as growth faults, calderas, and fault intersections
  - Fine-grained, highly carbonaceous or graphitic sedimentary rocks
  - Proximal to large synvolcanic sills and dykes
  - Abundant chlorite and white mica, along with metamorphosed equivalents
  - Na depletion in footwall; Tl, Sb, Ba/Sr addition in hanging walls
  - Presence of exhalites proximal to VMS source deposits

7.3.1.2 Implications for Exploration

Identifying VMS deposits should begin with identifying favourable regional geology, then further delimiting areas with favourable metal associations, alteration, and local geology. In the Yellowknife domain, the YGB and CBGBs have favourable characteristics for hosting undiscovered VMS deposits, particularly the presence of known VMS mineralization in the CBGB.

7.4 RARE EARTH ELEMENTS

7.4.1 PEGMATITE-HOSTED

Padgham (1992) notes rare-earth element (REE) pegmatites containing Be, Nb, Sn, Li and Ta have been found across the Slave craton and are most extensive and widespread in the Yellowknife domain (Figure 41) and includes the Thor Lake (Nechalacho) project with a NI 43-01 compliant resource, currently undergoing exploration in the Southern Slave. In the Yellowknife domain, REE pegmatites are typically directly associated with fertile granites and extensive areas of peraluminous, relatively evolved granitoids. Both are found cutting turbidites of the Burwash Formation. All known REE pegmatites in the Yellowknife domain lie within the high-pressure side of the cordierite isograd (Figure 20), delimiting the thermal aureoles of intrusions (Padgham, 1992).

7.4.1.1 Key Geological Features

The key geological features are derived mainly from Černý (1991), Long et al. (2010) and Thomas et al. (2011):

- Regional Scale Features
  - Associated with alkaline and carbonatitic intrusions
  - Found peripheral to or hosted in larger orogenic and anorogenic granite intrusions
- Local Scale Features
  - Comprised commonly of high density, radioactive and non-magnetic minerals
  - Small scale, generally circular, though can be ellipsoidal, lenticular, turnip- or mushroom-shaped
  - Can occur as fracture filling dykes in host plutons
  - Commonly zoned

7.4.1.2 Implications for Exploration

Due to the generally small size of pegmatite-hosted REE deposits and combined with the dense, radioactive and non-magnetic properties of this deposit type, the application of any magnetic (due to negative anomalies), radiometric and gravity geophysical methods in the Yellowknife domain should consider the possibility of encountering these types of anomalies in broad first pass exploration efforts, particularly proximal to large granitic intrusions.

CHAPTER 8 OROGENIC GOLD EXPLORATION IN THE YELLOWKNIFE DOMAIN

8.1 INTRODUCTION

The goal of exploration is to efficiently identify and detect the footprints of an economic mineral deposit by integrating various techniques with geology, where footprint means the combined characteristics of a deposit including the local and regional setting (Robert et al., 2007).

Geological understanding is commonly a key element in the discovery process in both greenfields and brownfields exploration environments (Robert et al., 2007). Geochemistry also plays an important role where deposits are exposed at surface, while geophysics aids the discovery of concealed deposits. Integration of the broadening and ever-improving knowledge base for these techniques to the exploration toolkit is essential, particularly considering new discoveries are occurring less often, are commonly deep, concealed by cover, harder to extract and typically have lower ore grades, yet exploration and extraction costs are simultaneously increasing (Robert et al., 2007). Successful strategies for exploration geologists will involve an understanding of geological features typical of a favourable setting as well as the hydrothermal manifestations of deposits, such as alteration and mineralization, along with how the elements of alteration and mineralization are dispersed in the surficial environment (Robert et al., 2007).

Robert et al.(2007) also recognize that people are the backbone of effective exploration. Ability and experience of individuals combined with an understanding of a given deposit's characteristics, as well as an excellent understanding of exploration methods, sufficient field time for testing targets, effective use of technology, enthusiastic and responsible leadership, confidence in corporate direction and ability to attract, train and retain young professionals are all important elements of a successful exploration team.

This chapter aims to review exploration tools and techniques (geological mapping, geochemistry, geophysics, remote sensing and drilling) followed by a review of a number of regional scale methodologies, which generally integrate many of the exploration tools and techniques for identifying target areas with the best potential for discovery of unknown mineral deposits.

8.2 EXPLORATION TOOLS AND TECHNIQUES

8.2.1 GPS AND GIS

The mining and exploration history in the Slave Province began in the 1930's, with much of the geological mapping and exploration activities in the region completed prior to widespread use of global positioning systems (GPS) and global information systems (GIS), which have advanced considerably during the past few decades. For instance, the extensive use of differential dual-GPS in airborne surveys has resulted in accuracy of positioning data to ±3 metres (Vallée et al., 2011). Also, with increasing amounts of GIS-capable data comes the need for robust relational databases to store quality data verified by established quality assurance and quality control protocols.

With respect to GIS packages, such as MapInfo and ArcGIS, they not only have the ability to display 2D surfaces, but also can include entire 3D data modelling, processing and visualization capabilities (Robert et al., 2007). 2D GIS platforms have become an essential tool for regional exploration; whereas 3D packages are more suited to near-mine and data-rich environments (Robert et al., 2007). It is now possible to fully integrate geological, geochemical and geophysical data into three dimensional space using sophisticated 3D visualization software, such as Datamine, Geosoft, GemCom, Vulcan, Micromine, Surpac, GoCad and Leapfrog, which can create new opportunities to explore data relationships (Jackson, 2007).

The lack of accurate positioning data combined with the inaccuracies and inefficiencies of hand-drawn maps would have likely hindered the ability of earlier explorers to pinpoint the locations of showings, lithological contacts, samples, air photos and geophysical measurements. For instance, Figure 43, Figure 44a and Figure 44b all show gold deposits and/or showings with a number of showings missing on the most recently compiled of the three figures (Figure 43). Figure 45 shows the results of recently accessing the Northwest Territories Geoscience Office GoMap and the NORMIN database, which still show discrepancies with Figure 43 and Figure 44a. Additionally, many of the historic assessment reports in the region prior to the advent of GPS and GIS contain hand-drawn geological maps with no relative position or coordinates and data must be digitized into digital format, which contains some inherent inaccuracy. Though not all figures can be accurately positioned, they can still be used for qualitative assessment and reference for future exploration programs. Today, data is spatially georeferenced in order for data at all scales to be visualized and interpreted using multi-layer analysis (Bonham-Carter, 1997).
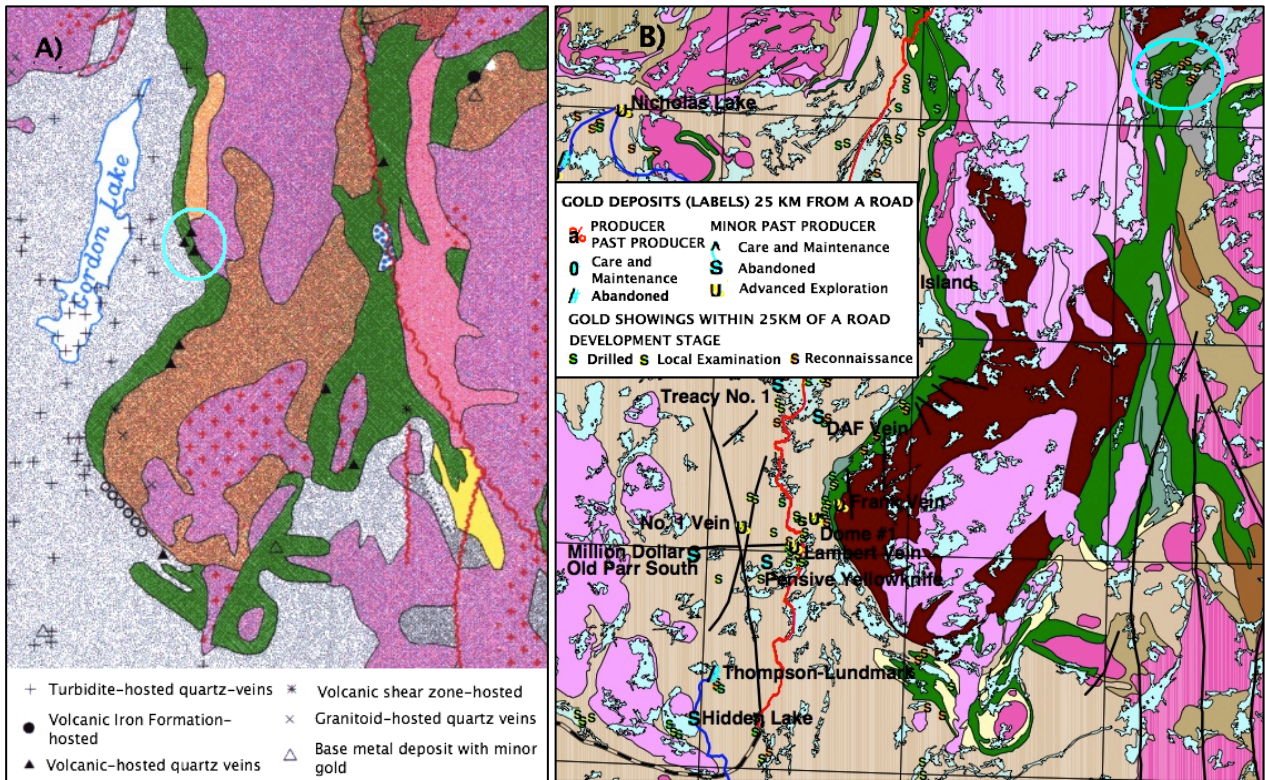
Figure 44. A) Gold deposits of the CBGB region. Note the circle with volcanic-hosted quartz veins, which are absent from Figure 43 and Figure 44b (modified from Padgham, 1994). B) Deposits and showings in the CBGB. Note circled showings not present in Figure 43 (modified after Schreiner, 2001).
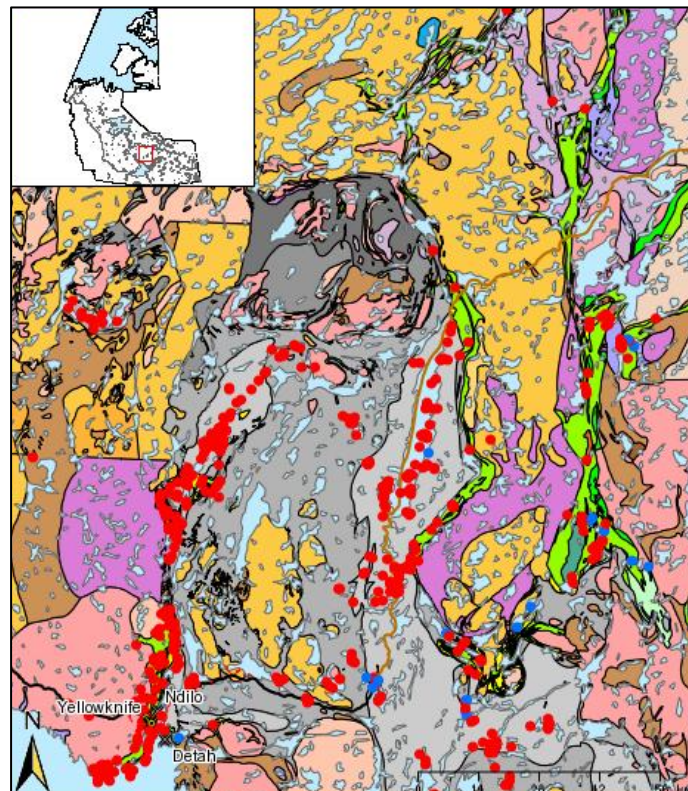
Figure 45. Yellowknife domain gold showings using NT GoMap (www.ntgomap.nwtgeoscience.ca), accessed on October 22, 2013. Red dots = precious metal showings, blue dots = base metal ± precious metals.

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The ability to visually display accurate spatial data collected using a GPS provides a strong foundation for geological mapping and exploration activities, particularly in greenfields and brownfields exploration areas such as the CBGB and the YGB, respectively. Using a GIS program can incorporate all layers of digital data and allow for improved geological interpretations, which also saves time and effort compared to when map layers were hand drawn and interpretations were made using only paper. On the contrary, non-digital information, such as geological insights from older work may be lost or ignored because it is not in digital format and does not fit into a GIS environment.

8.2.2 GEOLOGICAL MAPPING

The most basic step in exploration is geological mapping, because it is difficult to relate the other layers of data collected in the field to one another without a solid geological understanding and foundation. However, even with the advances and ubiquitous implementation of GPS and GIS in exploration, geological mapping on its own is still limited to the surface of the land and is reliant on the amount of outcrop in a given area. In the Yellowknife domain, the latest regional 1:250,000 scale geological maps were compiled by Henderson (1985) for the Yellowknife-Hearne region, while Lambert (1988) focused on the Sleepy Dragon area and Stubley (1996) mapped the area known as Carp Lakes north of the Yellowknife-Hearne area, which includes the Northern Beaulieu and Cameron River greenstone belts. A useful basis for geological mapping in the Slave Province are the lithology and structure compilation maps of the entire Slave Province, along with corresponding freely available data files, compiled by Stubley (2005). Using Stubley's map and data compilations, it is possible to make preliminary geological maps for more focused follow up (Lambert, 1988) mapping and interpretation as well as iterative maps using other geological data, such as remote sensing and geophysical data.

Recent advances in field-based infrared spectroscopy technology, such as the portable hyperspectral PIMA, Hylogger and Hychipper instruments, have allowed the technology to become a standard tool for alteration mapping in the field, as well as quickly collecting data from core, rock chips, pulps, outcrops, road cuts, trenches and open pitwalls (Robert et al., 2007). Interpretation of the spectra obtained from PIMA can determine whether certain minerals are present or absent, and in some cases relative abundance can be determined from the strength of the peaks in the spectra (Jackson, 2007). Another method commonly used is portable XRF's (X-Ray Fluorescence) devices. One example is the Niton XRF Analyzer (www.niton.com), which can conduct sample analysis for up to 40 elements using characteristic fluorescence x-rays emitted for each element. A limitation of portable XRF's is they cannot directly detect gold, however typical pathfinder elements, such as As, Sb, W and base metals can typically be detected.

8.2.2.1 Large Scale and Digital Mapping

Traditionally, large scale mapping has been an essential part of mineral exploration, with geologists mapping at scales of 1:10,000 for broader areal maps to 1:1,000 or larger for very detailed maps of specific features. With the advent of more powerful computing capabilities, geological mapping can now be carried out in the field using ruggedized computers (e.g. Panasonic Toughbooks) or tablets linked to a GPS and loaded with GIS software, as well as all the geological data (topography, geochemistry, regional geology, drillholes, etc.) for a project. There are a number of advantages to digital mapping, compared to traditional paper mapping, which includes: 1) real-time digital map making; 2) mapping at any scale; 3) reduced duplication and confirmation of historic mapping; 4) updating regional maps in the field; 5) relatively easy and quick compilations; 6) contributions and collaboration by multiple geologists; and 7) digitizing field maps is not necessary, saving time and reducing introduced inaccuracies. Ensuring proper data storage and backup, along with ensuring sufficient battery power, are essential when using digital mapping, otherwise one risks losing data or being unable to map while without power.

8.2.2.2 Structure Mapping

Orogenic gold systems are hosted by fault and shear zones commonly related to complex structures (CHAPTER 4). The geology of the Yellowknife domain is also structurally complex, therefore, a great deal of focus should be spent characterising structures when mapping in the Yellowknife domain. Using geophysical techniques (Section 8.2.4), such as magnetics, VLF-EM, radiometrics, as well as remote sensing data (Section 8.2.5) in greenstone belts can help identify structures prior to fieldwork, which can be followed up by ground truthing during mapping traverses. Additionally, having a strong understanding of the structural components of a target provides a solid basis for developing future cost-effective exploration campaigns as a project expands, particularly as drilling is introduced. In the Yellowknife domain, structural mapping and identifying faults, folds, synclines, anticlines and lineaments potentially hosting ore bodies will be critical for targeting and should be carried out early in the exploration phases. As drilling is introduced, re-interpretation and confirmation of structures using the logged core and borehole geophysics (Section 8.2.4.8) can be carried out.

8.2.2.3 Re-assessing Historic Mines, Showings and Deposits

In the Yellowknife domain, particularly in the areas with past-producing mines such as at the Con and Giant mines, emphasis should be placed on re-assessing the historic workings and geology, especially focusing on structures along strike and down-dip of the shear zones and faults hosting the mined-out ores. Siddorn (2011) discusses the Con and Giant mines as a once-linked system that underwent early offset during D_1 extensional events and later was overprinted by D_2 events. Perhaps similar ore bodies are also located further down-dip or along strike of this system. These

structures should be evaluated for their potential to host additional mineralization and ore bodies with targeted mapping and integration of geochemistry, geophysics (gravity, EM, IP, magnetics, etc., Section 8.2.4), remote sensing data for alteration mapping (Section 8.2.5) and even feasibly seismic surveys (Section 8.2.4.7) in the relatively mature Con and Giant mining camp of the YGB. Re-assessment of past-producing mines, deposits and showings with a focus on geological mapping and structural interpretations, such as strike and down-dip extensions, could also be applied to the turbidite-hosted orogenic gold veins in the Burwash Formation (Figure 43and Figure 45).

8.2.3   GEOCHEMISTRY

An essential tool in the exploration geologist's toolkit is geochemistry. Geochemistry is used to outline anomalous concentrations of elements of interest by systematically measuring one or more chemical components of naturally occurring, easily sampled substances, such as rocks, stream sediments, soil, water, core etc. An important geochemical technique for gold exploration at the regional scale of exploration is stream sediment geochemistry involving fine fraction, BLEG (Bulk Leach Extractable Gold), cyanide leach, or pan concentrate sampling, whereas local scale techniques include soil, lag and rock chip sampling, which are useful for defining anomalies associated with outcropping or sub-cropping deposits (Robert et al., 2007). Exploration geochemistry is best used in combination with other exploration techniques, such as mapping, geophysics and remote sensing. Historically, explorers assayed for only the major elements of interest, such as gold, copper, lead, zinc, silver, etc. because geochemical analyses were expensive and the techniques for more advanced geochemistry data collection had not yet been developed. With the improved knowledge regarding trace element geochemistry, for instance the identification of zoned element associations and their spatial relationships to ore bodies, combined with the advances in analytical methods and techniques, such as inexpensive, multi-element ICP-MS (inductively coupled plasma-mass spectrometry) with low detection limits (Jackson, 2007), the past limitations of geochemical sampling will be diminished.

Also, specific to the Slave Province were the vast exploration resources put into exploring for diamonds and kimberlites in the 1990's and 2000's, which brought significant exploration capital to the region, however put exploration for metals on the backburner. Most companies took broadly spaced samples and focused on looking for kimberlite indicator minerals from lake sediment and till samples, rather than analyzing for pathfinder elements of other deposit types. Gold grains would have been collected with the heavier kimberlite indicator minerals, although the systematic use of till/lake sampling for gold deposit targeting was typically not conducted in the region. Unfortunately, soil and stream sediment sampling will be hindered in the region by the abundance of glacial till and the lack of meaningful relief. When initiating an exploration program in the Yellowknife domain, a

geochemical orientation survey should be conducted in order to determine the best type of samples to collect in the target areas and the best analytical methods for defining anomalous geochemical samples. For regional sampling, lake sediments can be used to identify anomalous locations, followed by systematic regional till sampling lines then more detailed lines. Also, understanding the glacial flow directions will be vital in determining where the till source originated and could incorporate 3D geochemical methods (Section 8.3.4).

When targeting orogenic gold deposits, the elements to pay particular attention to include: Au, As, B, Bi, Hg, Sb, Te and W, as well as Cu, Pb and Zn (Section 4.4; for the other deposit types in the Yellowknife domain, refer to CHAPTER 7).

8.2.3.1   **Remote Detection**

As exploration is progressing into areas of deeper cover, non-conventional geochemical exploration methods are becoming increasingly important to the discovery of new deposits, such as the detection of far-field features (Robert et al., 2007). Far-field features of mineral deposits include mineralogical, geochemical or biological attributes that are recognizable beyond the limits of the deposits and can be detected through newer geochemical methods such as reduction-oxidation potential and microbial populations in soils, soil gas analysis, selective leaches, halogen concentrations and isotopic compositions (Kelley et al., 2006; Robert et al., 2007). Far-field features can be primary (syn-mineralization) or secondary (post-mineralization). Primary far-field features are formed in association with mineralization or alteration and are located in and adjacent to deposits. Primary far-field features include mineral and rock chemistry, isotopic or element haloes, hydrothermal alteration, fluid pathways and thermal anomalies in host-rock sequences, whereas secondary far-field features are formed from the interaction between ore deposits and the hydrosphere and biosphere. Secondary far-field features can be classified as either related to physical transport such as gravity, wind, water and ice, or chemical transport by water and biological processes (Kelley et al., 2006).

Secondary far-field features include supergene enrichment, the development of reduced columns by electrochemical processes in transported overburden, geochemical dispersion related to the expulsion of groundwater from tectonic and seismic compression, dispersion of vapour above deposits and geochemical dispersion related to biological processes (Kelley et al., 2006). Secondary dispersion is commonly laterally extensive away from mineral deposits making them useful for assessing mineral endowment at a regional to prospect scale. Detection of many of the far-field features requires careful sampling and the application of special non-routine analytical methods, with inherent complications that require stringent sampling protocols (Kelley et al., 2006). Many of these relatively newly recognized far-field features are only documented in a few case

studies, however incorporation of the methods for detecting far-field features into exploration programs may increase the probability of success, particularly in covered terrains (Kelley et al., 2006). There are five factors that far-field features as an exploration medium are dependent on: 1) consistency within a deposit type, or among different deposit types; 2) time dependency of some features; 3) the scale at which features can be detected; 4) the correlation between the intensity of features from metal endowment; and 5) the significance of overlapping features (Kelley et al., 2006).

A primary far-field feature detection technique applied to Archean orogenic gold exploration is the use of δ34 sulphur values from pyrite at Hemlo, Kalgoorlie and Kirkland Lake, which have relatively low values (to -17.5%) compared to other Archean gold deposits and the anomalies can extend for at least 15 to 30 km from the deposit, as noted at Hemlo (Kelley et al., 2006). The interpretation of the negative isotopic values of pyrite is due to the production of oxidation/reduction reactions in oxidized hydrothermal systems. Oxygen, carbon and hydrogen isotopic compositions have also been applied to exploration, particularly in settings where haloes display a large areal extent, have substantial differences in isotopic composition between mineralized zones and background values, and extend beyond the limits of distinct easily recognizable mineralogical alteration zones. Misinterpretation of isotopic anomalies can also be caused by water-wall rock interactions and interpretations should be integrated with geological and petrological investigation (Kelley et al., 2006). No specific examples of secondary far-field detection in gold deposits are noted by Kelley et al. (2006), however a number of techniques are discussed and could be applicable to exploration for orogenic gold and VMS in the Yellowknife domain.

8.2.4 GEOPHYSICS

Using geophysical techniques as an early-stage exploration tool is a relatively inexpensive method that can allow for collection of multiple data types with a single airborne survey over an entire region or property, although historically, poor positional accuracy, low resolution spatial data combined with limited data processing capabilities have been the major limitations to using geophysics for exploration in the past. Now, with numerous advances in the technology used by geophysicists in mineral exploration the application of geophysics is an evermore-important tool in the exploration geologist's toolkit especially with most easy to find deposits at or near the surface already discovered. Recent developments include greater precision of instrument readings (instrumentation improvements), greater positional accuracy (GPS), application of new techniques (gravity gradiometry, SQUID) and advances in data processing (new numerical algorithms) (Vallée et al., 2011). Recently, the integration of geophysical and geological into a common earth model to enhance the value of primary data well beyond traditional uses has gained considerable traction in the exploration and mining community and should be used from early exploration through to

discovery and into delineation, evaluation, and mining stages to reduce risk and create value (McMonnies et al., 2007).

The application of airborne versus ground geophysics is commonly determined by cost, accessibility, desired data resolution and survey area. Typically airborne data is much cheaper and quicker to acquire than ground geophysical data, plus multiple instruments can record data measurements for a number of parameters during one survey. Ground geophysics can require extensive ground preparations in thickly vegetated areas, though does offer the advantage of allowing for better survey coverage in mountainous regions (except for impassable terrain) where airborne surveys have to balance the attenuation of signals with the difficulty of maintaining a constant safe elevation above the ground surface. Historically, ground geophysics offered better resolution of data and spatial location, although with the modern advances in airborne techniques, such as helicopter-borne systems and gradiometry methods, airborne surveys can offer comparable data resolution to ground surveys at a much lower cost. Ground surveys still maintain an advantage if a survey area is relatively small or is conducted as an orientation survey, since the cost of mobilization of an airborne apparatus can be costly and inefficient if the survey area is small.

8.2.4.1 **Magnetics**

Magnetic geophysical methods are the oldest and most widely used of the geophysical techniques (Ford et al., 2007). Magnetic surveys are reliant on the presence of magnetic minerals (magnetite, pyrrhotite and hematite) in the rocks of the surveyed areas to map lithologies and structures and to delineate metallic ore bodies and associated anomalies, which are commonly positive and intense, but not always. Typically, aeromagnetic surveys are used for mineral exploration to aid mapping, particularly in areas with limited outcrop where magnetic surveying data can generally identify structural trends, as well as the extents and geometries of magnetic bodies (Figure 46) (Ford et al., 2007; Vallée et al., 2011). Numerous derivatives of processed magnetic data (Figure 47), such as the first vertical derivative, (= vertical gradient), 2nd vertical derivative, analytic signal and tilt, provide value-added products that can contribute to geological interpretations by presenting a filtered image of the magnetic field and emphasize narrow, near surface features (Ford et al., 2007). Lithological boundaries can be determined from vertical gradient maps due to contrasting magnetizations of adjacent lithologies, particularly where contacts are steep and the area is in high magnetic latitudes, such as northern Canada (Ford et al., 2007). Additionally, magnetics can be useful for differentiating graphitic from metallic conductors.

The development of improved data modelling and data interpretation methods as well as improved integration with other datasets are the most recent advances in the magnetic methods (Vallée et al., 2011). The main development for enhancing magnetic interpretation is the improvement in image

processing tools designed to help interpreters detect subtle patterns in aeromagnetic data, such as the enhancement of linear features and ability to outline the edges of potential field data that may reflect lithological contacts (Vallée et al., 2011).
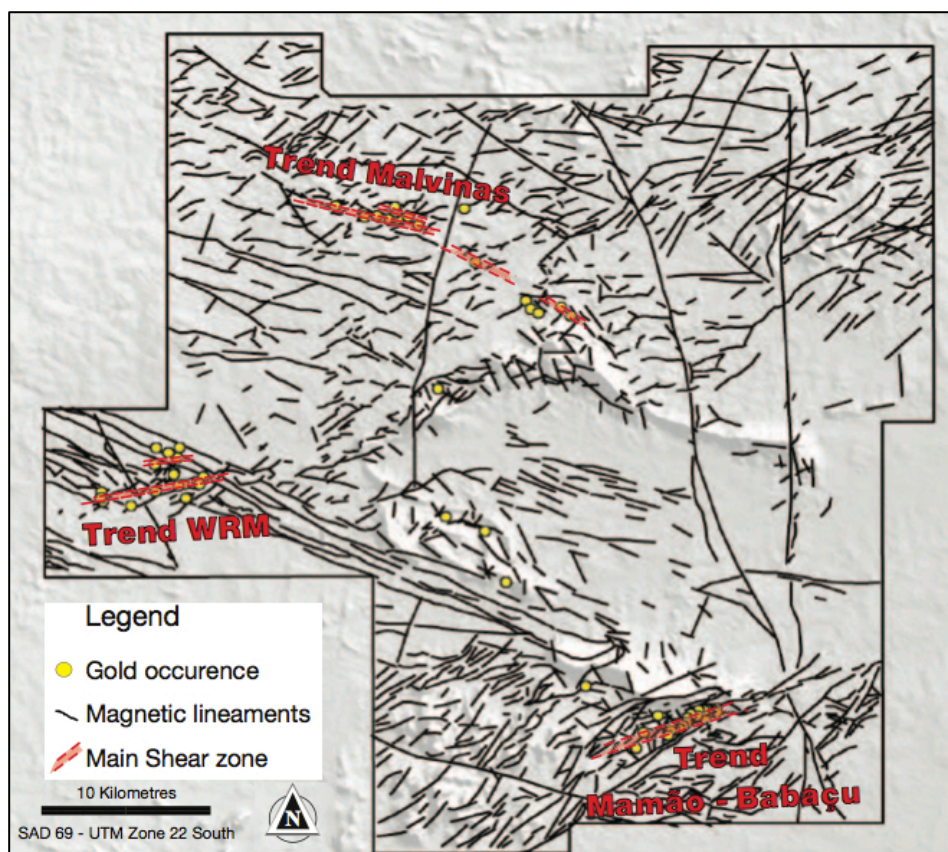
Figure 46. Map of lineaments and three main trends outlined by magnetic products in Figure 47, along with gold occurrences of the Rio Maria granite greenstone belt, Brazil (modified after Costa e Silva et al., 2012).

Gradient magnetic methods using multiple sensors can also help assist in the interpolation of information between flight lines by improving the quality of gridded data and also improve the ability to interpret the data (Robert et al., 2007). One example is the recent development of the full-tensor SQUID (superconducting quantum interference device) magnetic gradiometer system, which allows for better 3D modelling of magnetic bodies and improves detection of weak magnetic features by using liquid-helium-based thin-film technology (Vallée et al., 2011).

Airborne and ground magnetic surveys are highly effective for determining the geological framework of orogenic gold deposits, particularly with respect to mapping of potential ore body host structures (faults and shear zones) and delineating lithologies at the regional scale (Ford et al., 2007). While the technique is less useful for directly targeting ore bodies, magnetic lows can delineate areas of magnetite destruction associated with carbonate alteration at the deposit scale (Ford et al., 2007).
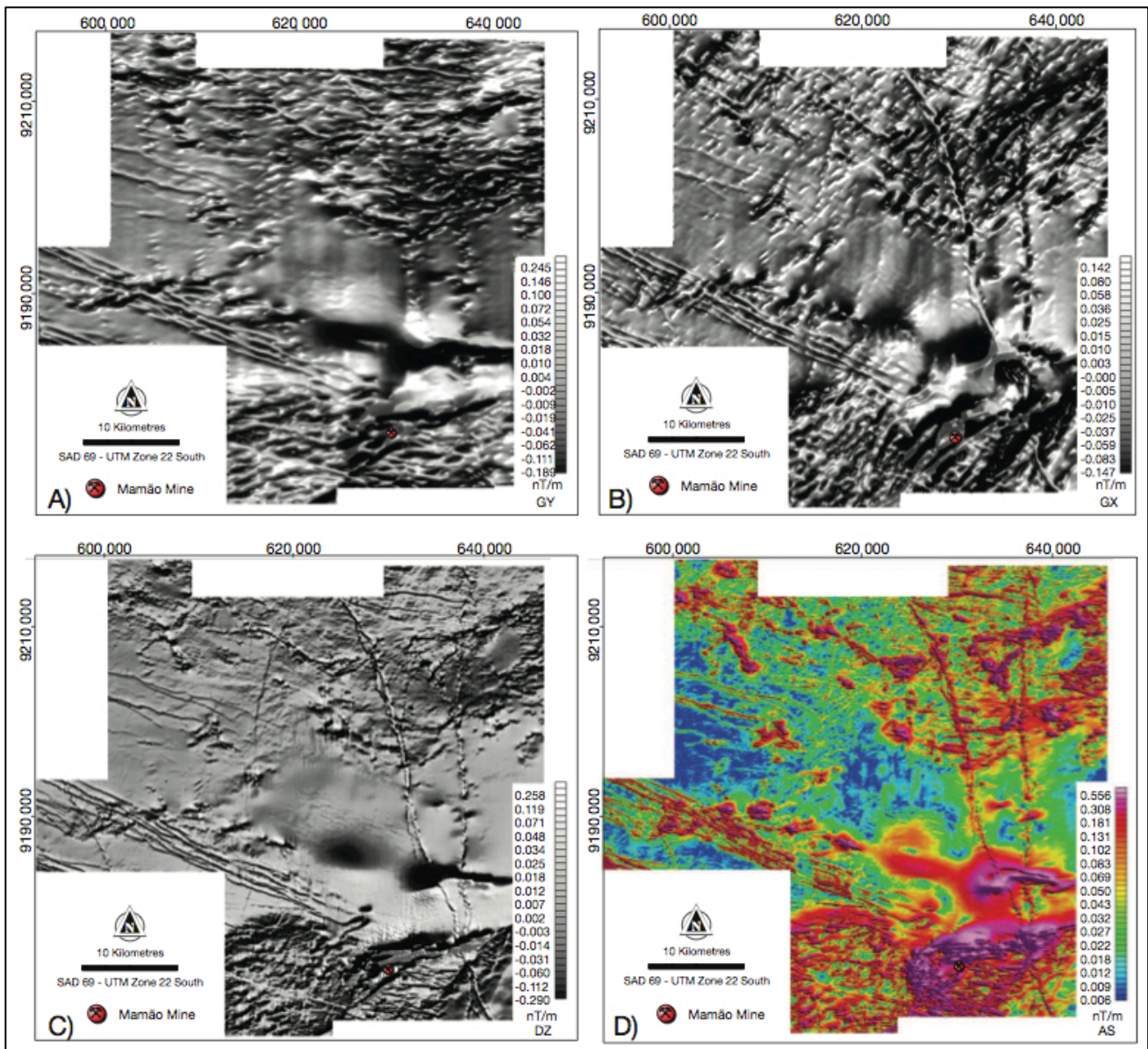
Figure 47. Examples of magnetic products used for interpretation of Figure 46. A) G_y gradient (G_y=Y component vector). B) G_x gradient. (G_x=X component vector) C) First derivative from TMI (Total Magnetic Intensity). D) Analytic signal image from TMI (modified after Costa e Silva et al., 2012).

8.2.4.2   Radiometrics

All rocks are naturally radioactive and contain various proportions of a number of radioactive elements, though potassium (K), uranium (U), and thorium (Th) are the three most abundant (Ford et al., 2007). The different chemical properties of each of these elements are useful for characterising normal and anomalous chemical or mechanical (transport) processes. K is a major component of most rocks and is commonly a dominant alteration element in mineral deposits, while relatively mobile U and relatively immobile Th are present in trace amounts (Ford et al., 2007). Unlike other geophysical methods that detect features at depths of 10's to 100's of metres, radiometric surveys can only measure the gamma rays from the top 20 to 60 cm of the earth's

surface due to rapid attenuation of gamma rays. Surveys will produce maps of K, eU, and eTh distributions and results do not necessarily correspond well with the results from other geophysical surveys (Ford et al., 2007).

A number of factors play a role in measurements collected during a survey, such as bedrock (fresh or weathered), overburden (glacial till, colluvium, alluvium, loess), soil type, soil moisture, water (lakes, rivers swamps) and vegetation (Ford et al., 2007). Because of the heterogeneous nature of sampled mediums, absolute values of the radioactive elements are less important than the patterns of the radioelements. In mineralized systems, all three elements can be enriched or depleted relative to unaltered, equivalent host rocks, although one or more may be preferentially affected for geologically valid reasons (Ford et al., 2007). The use of radioelement ratios can then be used as very sensitive vectors, possibly leading directly or indirectly to mineralization, even when individual radioelement patterns are equivocal (Ford et al., 2007). One example ratio is the F Parameter, expressed by the following formula:

$$F = (K*eU)/eTh$$

The F Parameter shows the K distribution related to U and Th and has been used for delimiting hydrothermal alteration zones in greenstone-hosted orogenic gold systems (Figure 48) (Costa e Silva et al., 2012).
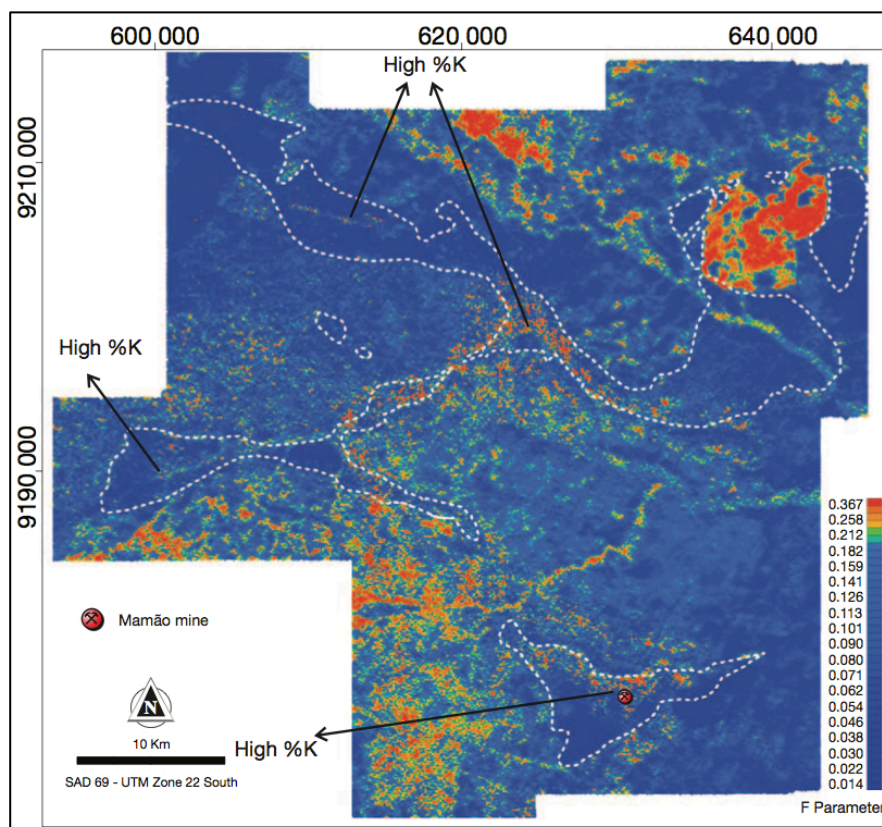
Figure 48. F Parameter image showing K enrichment within greenstone sequences, marked by the white dotted line; from same property as Figure 46 and Figure 47 (from Costa e Silva et al., 2012).

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There were relatively few developments in the first part of the millennium with respect to advances in radiometric surveying and processing (Vallée et al., 2011). Regardless, airborne and ground radiometric surveys remain highly effective methods for determining the geological framework of orogenic gold deposits and VMS deposits as well as for targeting the hydrothermal alteration zones of these deposits (Ford et al., 2007). Additionally, gamma ray spectrometry may have local applications to map potassium alteration associated with massive quartz veins (Ford et al., 2007). Due to the considerable glacial cover in the Slave Province, radiometrics will likely not be a particularly useful exploration method unless conducted over areas with substantial outcropping bedrock.

8.2.4.3 **Gravity**

Gravity surveys provide observations of the earth's gravity field by measuring the variations in rock densities in the gravity field; denser rocks create positive anomalies and less dense rocks negative anomalies. The primary use of gravity survey methods in exploration is to investigate the contrast between low-density graphite, high-density sulphides and/or other metallic mineralization previously identified using other geophysical exploration methods (Ford et al., 2007). It can also be used to map favourable geology (variations in host rock density) and structures, though it is less effective than magnetic and radiometric surveys (Ford et al., 2007). Gravity surveys are most effective as a ground technique for identifying VMS or SEDEX deposits, though are not generally effective for identifying orogenic gold deposits (Ford et al., 2007). Should other techniques identify potential for VMS mineralization, ground gravity surveys, though very expensive, could be carried out to delineate significant VMS mineralization in greenstone belts of the Yellowknife domain. Airborne gravity surveys could be carried out for regional targeting of VMS deposits.

Recent advances in gravity methods include the Airborne Gravity Gradiometer (AGG) system, which improved spatial resolution of airborne gravity data by an order of magnitude (Thomson et al., 2007). One example of an AGG system is the FALCON^{TM} technology developed by BHP Billiton (transferred to Fugro Airborne Services in 2008), which has discovered several mineral deposits, such as the Santo Domingo Sur (IOCG) in Chile (Vallée et al., 2011). Other advances in gravity methods include improvements for data interpretation and processing of data, such as improved noise reduction and terrain corrections (Vallée et al., 2011).

8.2.4.4 **Electromagnetics**

Electromagnetic (EM) techniques respond to the electrical conductivity of rocks and minerals with variations ranging by 20 orders of magnitude, which gives an indication to the complex nature of conductivity (Ford et al., 2007). Most metallic minerals are highly conductive, whereas most non-metallic minerals are essentially non-conductive. Both airborne and ground EM techniques are

among the most commonly used methods in mineral exploration (Ford et al., 2007). The techniques are capable of directly detecting conductive base-metal deposits, such as VMS and SEDEX deposits where large conductivity contrasts exist between relatively resistive host rocks and the rocks comprising a deposit. Other conductive sources, such as swamps, shear and fracture zones, faults, graphitic and barren metallic conductors can result in ambiguous interpretation of EM anomalies (Ford et al., 2007).

Operating in time-domain and frequency-domain, EM systems transmit an electromagnetic field, which penetrates the ground with the aim of encountering conductive materials (Ford et al., 2007). A secondary field is then generated by the conductive material and is measured by a receiver. Frequency-domain systems generate an alternating EM field, whereas the time-domain systems emit very short pulses (ms-scale). EM responses are frequency dependent so a broad frequency range is used to detect a range of conductivities (Ford et al., 2007).

A commonly used, low cost reconnaissance EM technique is the very-low-frequency EM (VLF-EM) method, which uses very low frequency radio communication signals to determine electrical properties of near-surface soils and shallow bedrock. The technique is particularly useful for mapping steeply dipping structures, such as faults and fracture zones (NGA, 2011). There are a number of limitations to the VLF technique, including topographic bias, outages of VLF transmitters due to maintenance and periodic unfavourable ionispheric conditions that may comprise data quality (Ford et al., 2007).

The most significant recent development in EM techniques was the introduction of time-domain helicopter-borne EM systems, which have recently taken huge leaps forward with several new airborne systems introduced (AeroTEM, THEM, VTEM, SkyTEM, RepTEM, and XTEM) and others improved (QUESTEM, MEGATEM, TEMPEST and RESOLVE) (Vallée et al., 2011). Ground EM saw the development of ground transient electromagnetic low-temperature and high-temperature SQUID (LTS and HTS, respectively) systems for mineral exploration (Vallée et al., 2011). EM data processing, interpretation and modelling (2D and 3D) tools have also steadily improved since 2000 (Vallée et al., 2011).

Airborne and ground EM surveys are moderately effective in determining the geological framework of orogenic gold systems, as EM methods have also been used to map faults, veins, contacts and alteration, however direct targeting is generally ineffective using EM techniques (Ford et al., 2007). Vallée et al. (2011) mention the successful use of airborne EM and magnetic data in resolving the geology in an area with limited outcrop within the South Ashanti greenstone belt in Ghana. In the reconnaissance phase, adding on an VLF-EM sensor to other EM systems is inexpensive and can

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be useful for interpreting structures. The use of more costly EM techniques, such as helicopter-borne EM systems, should be carefully considered in the exploration for orogenic gold deposits and, if employed, should be used to complement more effective airborne methods (magnetics and radiometrics). However, If VMS deposits are suspected, then an EM survey should absolutely be considered. Additionally, EM methods could be used to help resolve between overburden (till) and the underlying geology in order to create a depth to bedrock contour map. Due to the relatively flat terrain in the Yellowknife domain, airborne EM surveys could be carried out entirely by fixed wing, rather than with the more expensive heli-borne methods.

8.2.4.5   **Ground Penetrating Radar**

Ground Penetrating Radar (GPR) is a newer geophysical method and is similar to seismic surveys (Section 8.2.4.7), but much less expensive. The technique exploits the wave propagation characteristics of electromagnetic fields to map subsurface features by reflecting transmitted EM waves, which can provide very high-resolution sub-surface maps of the electromagnetic field (Annan and Davis, 1997). Reflections are caused by changes in the electrical character between the reflector and the surrounding host material, as well as small changes in material composition or water content (Annan and Davis, 1997). Conductive mineralized zones will reflect all incident signals and result in detectable radar reflection responses in GPR investigations (Annan and Davis, 1997). Lithological contacts, fracture zones and shear zones can also provide good radar reflection responses (Annan and Davis, 1997).

Commonly, GPR surveys acquire data through "reflection mode-single fold" coverage, though multi-fold and 3D surveys can be carried out as well (Annan and Davis, 1997). Single fold has a single transmitter and receiver transported over the configured survey area and collects data at each position, whereas multi-fold surveys record a number of measurements at different spatial separations between the transmitter and receiver (Annan and Davis, 1997). 3D GPR surveys consist of multiple single-fold sections acquired on tightly spaced parallel lines, which then put the acquired data into 3D processing software for visualization and interpretation (Annan and Davis, 1997).

Though not always applicable to mineral exploration due to the shallow depths of penetration (~10-100 m), GPR can be used to map veins and fracture zones as well as overburden thickness, locate old mine workings and define placer potential (Annan and Davis, 1997). Additionally, it can be used as an effective borehole geophysical tool (Section 8.2.4.8)

8.2.4.6 **Induced Polarization**

Having been used in mineral exploration since the mid-1950's, induced polarization (IP) is a complex phenomenon, but is easily measured (Ford et al., 2007). The strictly ground-based technique involves applying voltage between two electrodes; once the voltage is interrupted, a fast initial voltage decay followed by a slower voltage decay results (Ford et al., 2007). If the current is then switched on again, the voltage will initially increase rapidly then build up slowly. This phenomenon is known as induced polarization and the geophysical technique measures the electrical surface polarization of metallic minerals and the chargeability of the ground (Ford et al., 2007). Both frequency- and time-domain methods can be used (Ford et al., 2007).

IP surveys are oriented perpendicular to strike, typically along equally spaced, parallel lines (though other orientations can be used) with two current electrodes used to inject current into the ground and two voltage electrodes to measure the voltage decay (chargeability) and resistivity (inversely proportional to conductivity) (Ford et al., 2007). Various electrode layouts can be arranged (pole-dipole, dipole-dipole, etc.). Varying the distance between electrodes will result in soundings to different depths, allowing for mapping of changes in resistivity and chargeability with depth (Figure 49) (Ford et al., 2007). With a dipole-dipole setup, the distance between pairs of electrodes remains the same, but the current and voltage electrode separation is increased, and increased distances are recorded as multiples of the integer "n" between the voltage electrodes (Ford et al., 2007). 2D inversion of the depth data is standard practice for interpretation of IP in mineral exploration (Vallée et al., 2011).
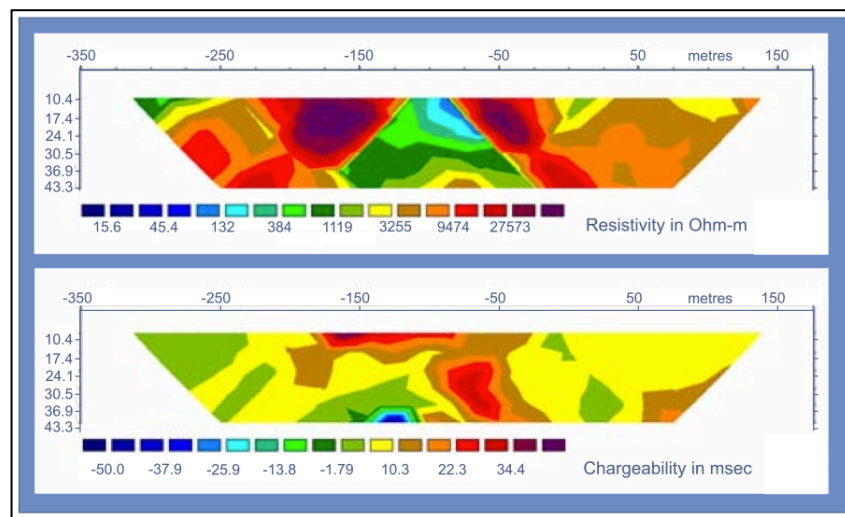
Figure 49. Pseudo-sections of resistivity and chargeability derived from dipole-dipole resistivity-induced polarization survey (from Ford et al., 2007).

A recent development in IP methods is the introduction of distributed acquisition, which deploys a number of small-channel-capacity receivers near the sensor outputs in order to achieve greater

depths of investigation, better productivity by reducing costs, improving noise-reduction and allowing for multiple data types (IP, resistivity, magnetotellurics and grounded-line EM) to be collected simultaneously (Vallée et al., 2011). Array systems, such as Titan 24, can allow for deep earth imaging of resistivity and chargeability to 750 m, as well as magnetotelluric resistivity to 1.5 km depth, making it an excellent option for obtaining subsurface pre-drilling structural information (McMonnies et al., 2007).

Clay minerals, graphite and disseminated sulphides have very good IP responses, while massive sulphides should theoretically have a lower response, but tend to also have very good responses in practice due to the mineralization haloes typically surrounding massive sulphides (Ford et al., 2007). IP methods may have local applications to map massive quartz veins (>20 m), resistive alteration around orogenic systems, and increased sulphide content in the centre of orogenic systems, which form resistivity and conductive highs, respectively (Ford et al., 2007). The use of IP in the exploration of orogenic gold in the Yellowknife domain could be considered, but not as a primary exploration tool. Should initial fieldwork and geophysical surveys indicate the potential for disseminated sulphides, as in the atypical greenstone mineralization style, or suspect massive sulphides (VMS) or quartz-vein bearing (orogenic gold) mineralization, then IP methods could be added to the exploration toolkit.

8.2.4.7   **Seismic**

Of any surface-based geophysical technique, 3D seismic exploration is capable of providing an indication of the deep subsurface picture and allow for deep (>500 m) mineral exploration, which is becoming more interesting and necessary as near surface ore bodies are exhausted and deeper (>2 km) mining becomes more profitable (Eaton et al., 1997; Eaton et al., 2010). While 3D surveys are best suited for discovery and delineation of ore bodies, 2D surveys can be used for structural reconnaissance (Salisbury and Snyder, 2007). Multichannel seismic surveys involve the areal deployment of sources and receivers on a 2D grid to illuminate the subsurface using acoustic waves, followed by processing and interpretation of the resultant densely sampled volumetric data in 2D or 3D (Eaton et al., 1997; Eaton et al., 2010). The seismic signals of interest are reflected, refracted and scattered at boundaries where abrupt changes in elastic properties occur. Anomalous elastic properties, especially density, generally characterise ore bodies, such as massive sulphides, that act as strong seismic reflectors in most geological settings (Milkereit et al., 2003; Eaton et al., 2010). In order for an ore body or any geological feature to be imaged using seismic methods, several geometric criteria (thickness, diameter and depth of burial) must first be met, which limits their applicability to larger features and orebodies (Eaton et al., 1997). A minimum thickness of 1/8th the seismic wavelength is about 5 m, whereas a minimum lateral extent of approximately 100 m is required for detection. Smaller bodies can be detected but will appear as "diffractive", rather than a

reflector (Eaton et al., 2010). Additionally, faults can be mapped based on vertical offsets of continuous marker reflections, such as sills (Eaton et al., 1997). Low signal to noise ratios of host rocks can make it more difficult to image structures and contacts, while steeply dipping structures (>60°) are not as effectively mapped using seismic methods (Salisbury and Snyder, 2007).

Comprehensive knowledge of physical properties (density, P- and S-wave velocity) of the country rocks is essential for quality interpretation of seismic data for mineral exploration purposes (Milkereit et al., 2003; Eaton et al., 2010). In previously unexplored or underexplored regions, laboratory physical rock property studies and borehole logging coinciding with new deep exploration holes need to be performed prior to conducting seismic exploration (Milkereit et al., 2003; Eaton et al., 2010). One of the earliest seismic studies for hard rock mineral exploration was carried out at Buchans, Newfoundland; a well mapped mining camp with extensive drilling and underground workings. The interpretation of prominent reflections from faults and shear zones revealed during seismic profiling was important for understanding the architecture and structural evolution at both mine and regional scales (Eaton et al., 2010). Additionally, in the Manitouwadge greenstone belt of Ontario, seismic surveying successfully mapped key horizons in the dominant synform and differentiated between mafic and felsic volcanic units (Eaton et al., 2010). In orogenic-style quartz-carbonate vein-hosted gold deposits, seismic is best suited for supporting conventional exploration by mapping local and regional structures (Salisbury and Snyder, 2007).

Compared to the traditional techniques, seismic surveys are considerably more expensive mainly due to the mobilization cost of a Vibroseis (Eaton et al., 1997). Also to consider is the technological risk of 2D and 3D data uncertainties and ambiguities in the data making it challenging to interpret, but this can be somewhat constrained by good borehole controls or other geophysical methods (Eaton et al., 1997; Eaton et al., 2010). Therefore, 3D seismic surveying is best suited for use in mature mining camps with extensive borehole controls and well-developed geological models (Eaton et al., 1997), such as proximal to the Con and Giant mines in the YGB. Although the 3D technique can be used for directly targeting massive sulphide deposits, such as VMS, (not noted in the YGB), 2D surveys could still be used for mapping deep structures potentially hosting additional orogenic gold mineralization. In the CBGB, seismic surveys could be used to map deep structures, such as faults or shear zones, and potentially map deep mafic-felsic contacts, or to directly target VMS deposits and associated alteration haloes. However, due to the high cost, using it for greenfields exploration activities is not practical, unless extensive laboratory work and borehole logging are carried out from a number of strategically spaced, deep (~1000 m) drill holes to determine the potential effectiveness of the technique.

8.2.4.8 **Borehole**

Borehole geophysical surveys involve the collection of measurements made by sensors (either receivers or detectors) housed inside a probe that is lowered down boreholes where measurements are taken (Killeen, 1997). Typically, a series of continuous measurements are made with data either stored on the instrument or transmitted to surface recording instruments via a logging cable, which can also power the sensors, if they are not run on batteries (Killeen, 1997). Several measurement configurations are possible, including 1) passive sensors used in detecting magnetic susceptibility, earth's magnetic field, and natural radioactivity measurements; 2) active source or transmitter plus a sensor used for acoustic velocity, conductivity, resistivity and density measurements; 3) surface source detected by the sensor in the probe used in several EM and IP methods and vertical seismic profiling (VSP); 4) measurement of fluid properties, such as temperature, or fluid flow, which may relate to thermal conductivity or fractures, respectively; 5) use of optical, electrical or acoustic televiewers to image borehole walls and 6) hole to hole configurations using electrical, IP, seismic or GPR methods to construct tomographic images between holes (Killeen, 1997).

The techniques used correspond to physical properties used in airborne and ground geophysics. Physical properties measured in the near-hole environment (cm- to m-scale) are magnetic susceptibility (magnetics), radioactivity (radiometrics), acoustic velocity (seismic), resistivity and conductivity, (IP) and density (gravity), whereas EM, GPR, IP and VSP (seismic) techniques measure the volume between the sensor and the transmitter in order to detect changes in the physical properties up to several hundred metres from the borehole (Killeen, 1997). Also, recording of the earth's magnetic field can detect the magnetic effects of magnetic bodies 100's of metres away (Killeen, 1997). A borehole technology commonly used in the oil and gas industry and recently adapted to mineral exploration is the neutron activation technique, primarily used for chemical analysis of a number of elements (McMonnies et al., 2007). Though it is a "rather bulky" instrument and can only be used in large diameter holes, the technology could be incorporated into mineral exploration with a reduction in the instrument's size (McMonnies et al., 2007).

Because of the typically low concentrations of gold in gold deposits, borehole surveys are most useful in gold exploration for measuring changes in the physical properties of the rocks caused by alteration associated with gold mineralization or to detect structures or lithological units known to host gold, rather than direct detection (Pflug et al., 1997). In the Yellowknife domain, the incorporation of borehole geophysics into the exploration toolkit should be strongly considered in order to maximize the effectiveness of drill holes. A number of different techniques could be employed, such as magnetics, radiometrics, IP, and gravity. Borehole magnetic surveys are considerably faster, but more expensive, at collecting measurements of magnetic susceptibility than

carrying out the same measurements on core, while gamma ray spectroscopy can help map potassic alteration and changes in lithologies (Killeen, 1997; Pflug et al., 1997). IP and gravity borehole methods could help map pyrite and other sulphides through increased chargeability and density measurements (Pflug et al., 1997). Greenfields and brownfields exploration in the Yellowknife domain should incorporate borehole-logging techniques to add an extra dimension of data for interpretation and ability to vector towards potential host structures and alteration haloes. Also, if seismic surveys are to be considered, borehole-logging data is essential for pre-determining some of the rock characteristics prior to conducting seismic surveys.

8.2.5   REMOTE SENSING

Another exploration technique to integrate into the exploration toolkit is remotely sensed data. According to Sabins (1999), "Remote Sensing is the science of acquiring, processing and interpreting images and related data acquired from aircraft and satellites that record the interaction between matter and electromagnetic energy." It can be used as an exploration tool that allows for more efficient mapping of large regions within shorter time spans than traditional mapping, particularly in northern Canada where mapping costs are high (Schetselaar et al., 2007). The two applications of remote sensing specific to mineral exploration are 1) the mapping of geology, faults and fracture zones that potentially host ore deposits and 2) recognition of hydrothermal alteration minerals by their spectral signatures (Sabins, 1999). Remote sensing allows geologists to create regional maps, interpret structures and aid in the prospecting of ores (van der Meer et al., 2012). There are numerous sources of remote sensing data (Table 6) with varying resolutions, measured data and applications. Remotely sensed data can be integrated with more traditional geological and geochemical data sets using a methodology called Remote Predictive Mapping (RPM), discussed in Section 8.3.2.

As shown in Table 6, a number of sets of remotely sensed data are available, both freely and for purchase, depending on the desired resolution of the data. Since the advent of the LANDSAT multispectral scanner and thematic mapper (TM), geologists have widely used the satellite images collected by LANDSAT and have developed band ratio techniques and selective principal component analysis to produce images of iron oxide and hydroxyls (clays) potentially related to hydrothermal alteration (van der Meer et al., 2012). The use of these alteration maps leads to better definition of the alteration footprint and zoning of mineral assemblages as well as providing new vectoring tools within large hydrothermal systems to potentially lower the drilling density of camp-scale targeting, particularly in areas with considerable cover (Robert et al., 2007). Table 7 provides a summary of the LANDSAT TM bands and their principal applications.

Table 6. Data sets available for Remote Predictive Mapping and associated costs (updated from Schetselaar et al., 2007).

Data	Data Provider	Cost (2007)
LANDSAT TM	Geogratis web-site http://geogratis.gc.ca/ MDA Geospatial Services http://landsatlook.usgs.gov/ http://earthexplorer.usgs.gov/	Free to download from Geogratis and USGS CDN $720 per scene from MDA
RADARSAT	Geogratis web-site (100 m pixel mosaic of Canada) MDA Geospatial Services (http://www.rsi.ca/) – for individual scenes from the archive or acquire new data – commercial users Canadian Space Agency (CSA) – government users	Mosaic –free to download MDA – CDN $3,000 - 4,000/scene CSA – CDN $300/scene
Magnetic data	Geophysical Data Centre (GSC) http://gdr.agg.nrcan.gc.ca	Free to download
Gamma-ray spectrometry data	Geophysical Data Centre (GSC) http://gdr.agg.nrcan.gc.ca	Free to download
DEM – CDED	Geobase http://www.geobase.ca/	Free to download
ASTER	USGS (http://glovis.usgs.gov/) Information can be found at: http://asterweb.jpl.nasa.gov/ https://lpdaac.usgs.gov/products/aster_overview	$40.0 US per scene
SPOT	Blackbird Geomatics http://blackbridge.com/geomatics/products/spot.html http://www.astrium-geo.com/en/143-spot-satellite-imagery	$1200.0 per scene for SPOT 4 $1.00 - $6.00 per km^2 – SPOT 5
IKONOS	MDA Geospatial Services (http://www.rsi.ca/) Information can be found at: http://www.satimagingcorp.com/satellite-sensors/ikonos.html http://www.landinfo.com/satprices.htm	$15.0 -$30.0 per km^2
QUICKBIRD	MDA Geospatial Services (http://www.rsi.ca/) Information can be found at: http://www.satimagingcorp.com/satellite-sensors/quickbird.html http://www.ballaerospace.com/page.jsp?page=77	See MDA web-site
ENVISAT	MDA Geospatial Services (http://www.rsi.ca/)	See MDA web-site
RESOURCESAT	MDA Geospatial Services (http://www.rsi.ca/)	$2750.0 per scene
IRS	MDA Geospatial Services (http://www.rsi.ca/)	$900.0 - $2,500.0
ERS-1 Radar	MDA Geospatial Services (http://www.rsi.ca/)	$660.0 per scene
Airborne hyperspectral data	Canada Centre for Remote Sensing (CCRS) and Geological Survey of Canada – Geophysical Data Centre http://gdr.agg.nrcan.gc.ca	Free to download

More recently, the development and launch in 1999 of the multispectral Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) with greater mineralogical resolution than Landsat TM imagery has allowed for the production of qualitative surface mineral maps and the identification of alteration facies (propylitic, argillic, etc.) (Robert et al., 2007). Furthermore, high spectral resolution (hyperspectral) remote sensing instruments such as Hymap and Hyperion have allowed for quantitative surface mineralogical mapping (Robert et al., 2007; van der Meer et al., 2012). A limiting factor for gold exploration using ASTER data is the relatively coarse 90 m spatial resolution of the thermal infrared (TIR) bands, which can identify silicification associated with quartz

veins and sulphidation systems, but cannot distinguish between primary quartz and hydrothermal silicification (Robert et al., 2007).

Table 7. Summary of LANDSAT 7 Thematic Mapper (TM) bands and principal remote sensing applications (from Harris et al., 2011).

Band	Wavelength (μm/microns) R = Reflected E = Emitted	Nominal Spectral Location	Principal Applications
1	0.45 – 0.52 R	Blue (V)	Designed for water body penetration, making it useful for coastal water mapping. Also useful for soil/vegetation discrimination, forest type mapping and cultural feature identification.
2	0.52 – 0.60 R	Green (V)	Designed to measure green reflectance peak of vegetation for vegetation discrimination and vigour assessment. Also useful for cultural feature identification.
3	0.63 – 0.69 R	Red (V)	Designed to sense in a chlorophyll absorption region, aiding in plant species differentiation. Also useful for cultural feature identification.
4	0.76 – 0.90 R	Near Infrared (NIR)	Useful for determining vegetation type, vigour, and biomass content. For delineating water bodies, and for soil moisture discrimination.
5	1.55 – 1 .75 R	Short Wave Infrared (SWIR)	Indicative of vegetation moisture content and soli moisture discrimination, and thermal mapping applications.
6	10.4 – 12 .5 E	Thermal Infrared	Useful in vegetation stress analysis, soil moisture discrimination, and thermal mapping (heat loss, forest fires etc) applications.
7	2.08 – 2.35 R	Short Wave Infrared (SWIR)	Useful for discrimination of certain mineral and rock types. Also sensitive to vegetation moisture content.

Another remote sensing technique called airborne laser scanning (ALS), or airborne laser altimetry (Lidar), can be used for remotely sensing high-resolution topographic data for integrating with other datasets. The technique provides range data in the form of 3D point clouds that can be interpolated in 3D-capable GIS software to create an accurate digital elevation model, a method that creates much more value to the data compared to simply creating topographic contours (Mallet and Bretar, 2009; Cowan, 2013). The data gives a very detailed map of the surface topography below vegetation and can be useful for interpreting fault patterns.

The integration of remote sensing data with other datasets in the Yellowknife domain should be carried out. The ability to create alteration maps to aid in the targeting of potential areas of hydrothermal alteration related to orogenic gold or VMS deposits could allow for better target selection of first pass exploration activities and improve the exploration success rate in the region.

8.2.6 DRILLING

A costly though essential exploration technique is drilling. The purpose of drilling is to locate and sample the subsurface geology for economic mineralization and test for down dip and/or along strike continuations of ore bodies and mineralization delineated by mapping, geochemistry and geophysics. Drilling should be carried out after all other data has been integrated and interpreted in order to define the best drilling targets and maximize the chance of success while reducing unnecessary costs and effort. Once a discovery is made, drilling is used to define the lateral and vertical extent of an ore body and sample the mineralization. Resource and reserve calculations are then carried out once an ore body has been well defined by drilling. The calculations require drilling sample data to meet stringent quality assurance and quality control (QA/QC) requirements that test the accuracy and precision of laboratory analyses carried out on drill core samples. Analyzing blank and duplicate samples can test the lab results for contamination and precision, while accuracy is tested by inserting standard reference materials with a known value of elements of interest blindly into the sample sequences sent to labs for analysis. QAQC methods should be implemented early in an exploration program to avoid later deletion of unverified analytical data.

Numerous techniques (diamond drilling, rotary mud, reverse circulation, sonic, etc.), hole and core widths (AQ, BQ, NQ, HQ, PQ, etc), drill rigs and drill contractors are available and the selection of the best technique, hole and core width and contractor will come down to the nature of the material being drilled, desired core size, safety record and cost.

Historic exploration in the Yellowknife domain tended to test only near-surface targets and it was not common for drill holes to extend past 100 m depth, as the focus was on shallow ore bodies that could easily be extracted. Deeper drilling with the integration of modern techniques and collection of geologically relevant data discussed above can now, more than ever, lead to significant discoveries.

8.3 REGIONAL SCALE EXPLORATION METHODOLOGIES

8.3.1 PREDICTIVE MODELLING

8.3.1.1 Stress Mapping

Groves et al. (2000) present the computer-based exploration technique of stress mapping, a numerical modelling technique developed to target structurally controlled hydrothermal mineralization located in dilatant, or low stress sites and is based on rock mechanic principles and stress-strain relationships. The technique uses geology maps as an input in areas that presently have rock geometries similar to those that existed during mineralization, which is commonly the case globally for orogenic gold deposits (Groves et al., 2000), as well as in the Yellowknife domain.

Stress mapping is a basis for predicting hydrothermal fluid flow, which examines the variation in local strain and stress within an inhomogeneous terrane (Groves et al., 2000). The main assumptions used for stress mapping are 1) low minimum principal stress (σ3) indicating proximity to failure and increases in deformation enhanced permeability; 2) at depths of more than a few kilometres, fluid pressure is near lithostatic pressure and the control on fluid pressure is mean stress; 3) variations in mean stress will cause variations in fluid pressure; 4) fluid flow is both upward and towards zones of low mean stress; and 5) structurally controlled orogenic gold mineralization is commonly late in the tectonic history of a terrain (Groves et al., 2000).

The inputs for stress mapping include 1) an accurate geological map; 2) estimates of the magnitudes and orientations of the far-field horizontal stresses; and 3) rock and fault deformation properties (Groves et al., 2000). It is important to note this technique can be applied at any scale, and can be carried out in three dimensions if there is sufficient drill data in the area (Groves et al., 2000). Geological map data is converted to a simplified solid-geology computerized base providing continuous lithological and structural information. The modeled area is treated as a mosaic of polygonal rock unit blocks and discontinuous joins, such as contacts, faults and shear zones. When external stress is applied to the system, blocks are rearranged and deformed internally until reaching equilibrium to identify areas of lower stress, such as dilation zones, which represent areas for ore-fluid flux and mineralization, resulting in exploration targets (Groves et al., 2000).

Groves et al. (2000) applied this technique at a 1:250,000 scale to the Kalgoorlie Terrane of the Yilgarn Craton in Western Australia (Figure 50a), a mature mining camp with numerous mines and deposits, in order to define the location of new major goldfields at the 1:250,000 scale, each potentially containing several individual gold deposits. The resulting map of stress mapping in the Kalgoorlie Terrane (Figure 50b) shows the sites of low minimum stress (σ3), typically related to changes in strike of first-order faults from the dominant NNW trend to a more restricted NW trend, as well as intersections of two or more first order faults, or of first- and second-order faults. All major goldfields in the area, as well as several new target areas of high prospectivity, were identified as anomalously low minimum stress zones (Groves et al., 2000).

Critical to the successful modelling of prospective zones are reasonably accurate input parameters for rock properties and the far-field stress field developed from extensive experience in the terranes (Groves et al., 2000). In the Kalgoorlie example, stress mapping demonstrates which faults are most likely to be dilational at a regional scale and can help assist with future data collection and interpretation by defining the direction of strike and magnitude of faults, likely critical in controlling the siting of goldfields and gold deposits (Groves et al., 2000). Evaluating broad crustal tracts to
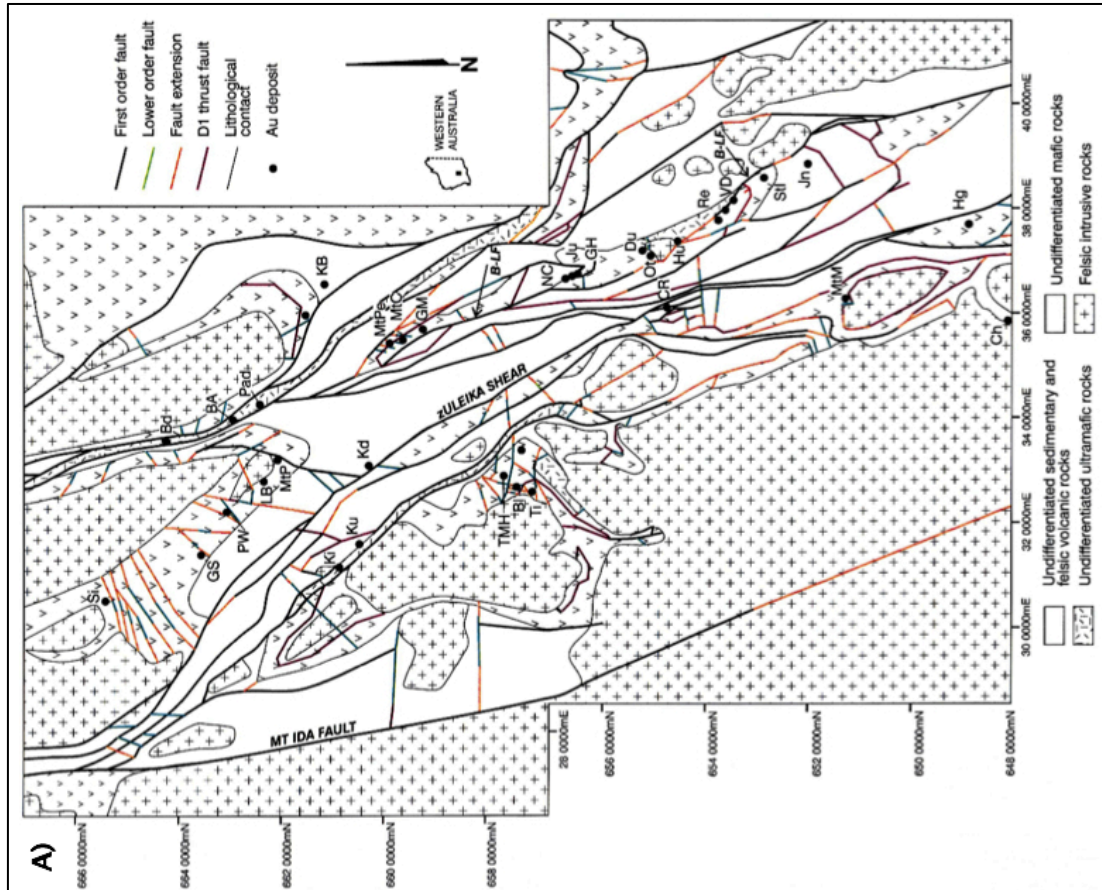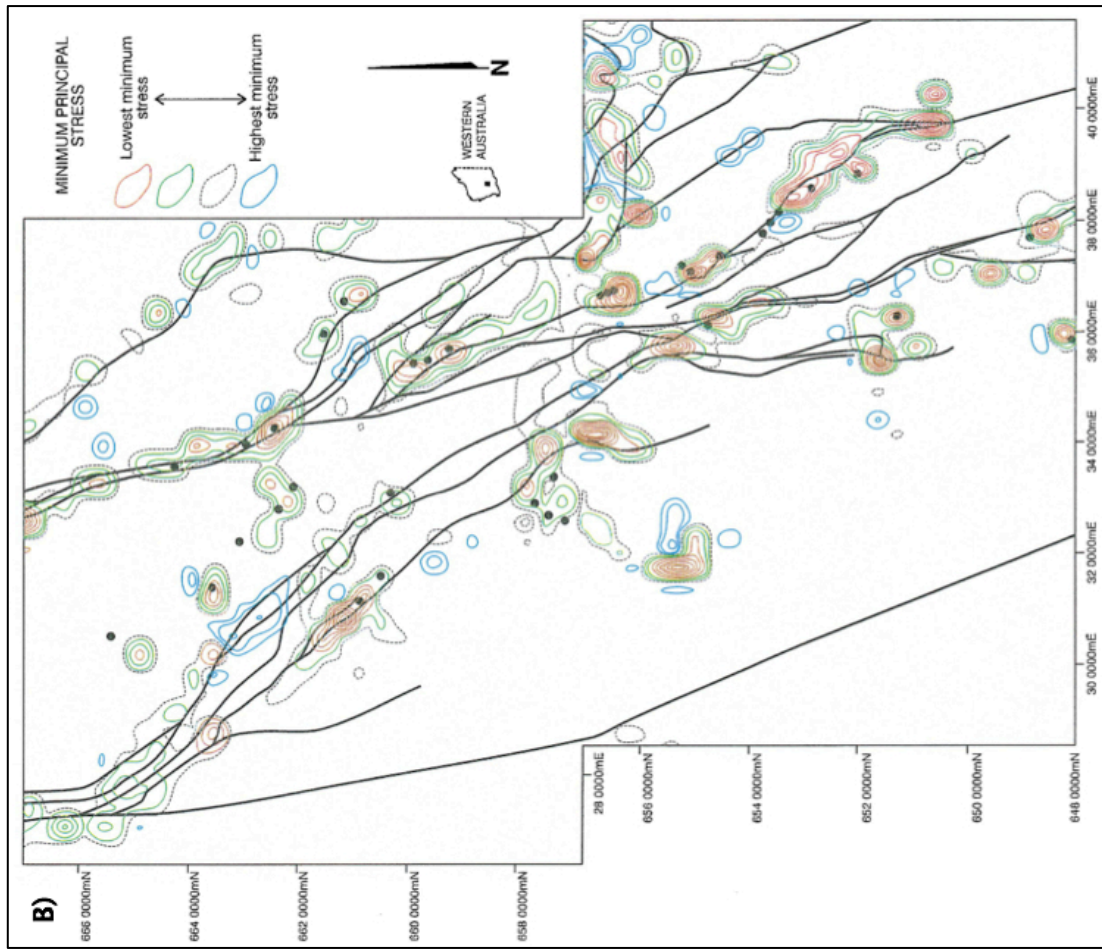
Figure 50. A) Digitized solid geology map of the Kalgoorlie Terrane B) Contoured values of minimum principal stress (σ3). Anomalously low values of σ3 have a strong correlation with locations of known goldfields in the Terrane, and there are also anomalies, which potentially define as-yet undiscovered goldfields or gold deposits (from Groves et al., 2000).

define zones of greatest favourability for orogenic gold deposits, provided sufficient good quality geological information is available, makes stress mapping a valuable exploration method, even in previously unexplored or underexplored terrains such as the CBGB, as it does not require a database of existing gold deposits, which is typically needed for prospectivity mapping, discussed below.

8.3.1.1 Mineral Prospectivity Mapping

Groves et al. (2000) also outline computer-based mineral prospectivity (also referred to in literature as potential or favourability) mapping, which aims to identify prospective areas at a goldfield scale using primarily conventional geological map data. Essential to performing prospectivity mapping is a comprehensive digital database covering the entire study area including layers for surficial geology, geochemistry, geophysics, gold occurrences, mineral deposits, topography and remote sensing data (Figure 51) (Costa e Silva et al., 2012).

Two approaches can be undertaken when prospectivity mapping: conceptual (knowledge-driven) and empirical (data-driven). In a conceptual approach, genetic concepts are represented as mappable criteria, which are ultimately integrated into a single prospectivity map, whereas the empirical approach relies on the characterisation of a number of defining factors from a significant number of known gold deposits, spatially quantified into a single prospectivity map by using the same techniques as the conceptual model (Groves et al., 2000).

Knowledge-driven approaches rely on a geologist's input to weigh the importance of each data layer (variable) related to the particular exploration model using Boolean logic, index overlay, analytical hierarchy process and fuzzy logic algorithmic methods (Costa e Silva et al., 2012 and references within). These approaches are more subjective, though they have the advantage of incorporating geological knowledge and expertise to build models and generate prospectivity maps (Costa e Silva et al., 2012).

Data-driven approaches require previous knowledge, or input data, about known mineral deposits or occurrences in the study area (Costa e Silva et al., 2012). Based on the spatial locations of the known deposits or occurrences (input data), spatial relationships between the input data are used to establish the importance (weight) of each input variable by using statistical techniques such as regression, discriminant analysis, data-driven evidential belief functions, cluster analysis, weights of

evidence modelling, neural networks and data mining (Table 8) (Costa e Silva et al., 2012 and references within).
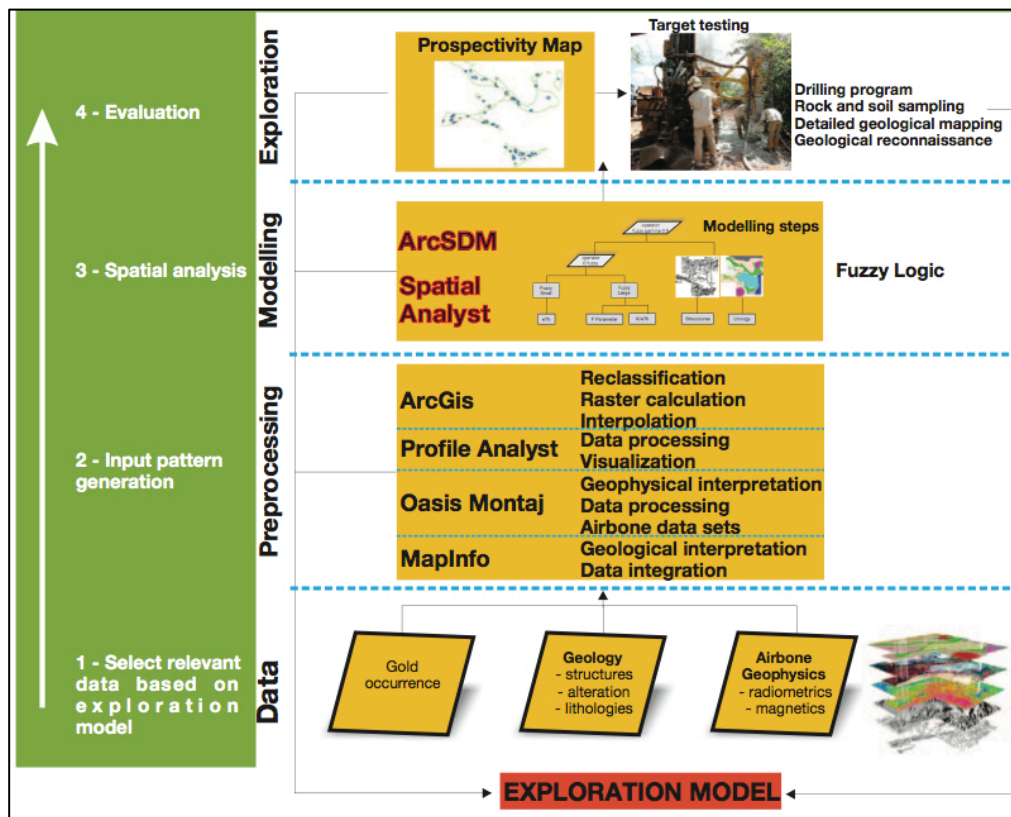
Figure 51. Flowchart describing the components involved in mineral potential modelling (from Costa e Silva et al., 2012 and references within).

The methodology for prospectivity mapping is flexible so relevant concepts can be tested to determine their importance for inclusion in the analysis and construction of the prospectivity map. The methodology involves three main steps:

1) Identify spatial relationships of factors potentially constraining the location of known gold deposits, such as crustal-scale faults and shear zones, as well as dilational jogs along shear zones and fold hinges.

2) Quantification of the identified relationships using a geological map to depict how the spatial relationships between factors vary.

3) Integration of multiple relationships into a single prospectivity map using one of the several different integration techniques, such as Boolean integration, index overlay Bayesian (Weights of Evidence), algebraic, and fuzzy logic methods

Compared to stress mapping, prospectivity mapping has an empirical basis and typically involves the analysis of a subset of known gold deposits and the relationship of deposits to particular

geological features (Groves et al., 2000). Without a significant number of known gold deposits, the data-driven type of prospectivity map cannot be built (Groves et al., 2000). This method has potential to be used in the YGB, because of the number of known deposits and gold occurences, but likely would not yet be feasible in the CBGB.

Table 8 Summary of the main integration techniques used to combine multiple spatial datasets into a single prospectivity map (from Groves et al., 2000)

Integration Technique	Description	Pros	Cons
Boolean integration	Input maps can only have two states: prospective and unprospective. Boolean logic rules are used to combine datasets. The resultant map has only two states	Easy to implement in most GIS	Boolean "AND" is too conservative in the definition of prospective areas, whereas Boolean "OR" is too liberal
Index Overlay	Input maps comprise two or more levels of prospectivity: the higher the prospectivity, the larger the number. Inputs are combined by spatial overlay and summation of index values	Easy to implement in most GIS. Better than Boolean method in that much internal structure is retained in the resultant prospectivity map	Prospectivity is represented by ordinal values where an index value of 10 is more prospective than an index value of 5, but not twice as much. Input maps split into numerous prospectivity levels will contribute more to the resultant map
Algebraic method	Essentially an extension of the index overlay method, except that prospectivity values are represented by ratio-scale numbers. That is, a region with an output value of 10 is twice as prospective as a region with an output value of 5	Deposit size can be incorporated into the analysis	Difficult to integrate spatial relationships quantified as continuous surfaces (raster)
Weights of Evidence	Uses Bayes' Rule of conditional probability to update a prospectivity map based upon new information	Provides a probabilistic result	Difficult to incorporate deposit size into the analysis. Difficult to implement in a vector GIS
Fuzzy Logic	Uses the fuzzy logic rules, a superset of Boolean logic, to combine datasets. Unlike Boolean logic, fuzzy logic variables can have an infinite number of values between '0' and '1', inclusive	Can be used to integrate spatial raster relationships	Dependent on the fuzzy logic rule used to combine datasets

Costa e Silva et al. (2012) use the term mineral potential modelling, another name for prospectivity mapping, for building an integrated GIS-based exploration methodology (Figure 51) to generate orogenic gold exploration targets from spatial models derived using GIS-based automated processing methods and fuzzy logic techniques (Costa e Silva et al., 2012). The method was recently applied to the Rio Maria granite-greenstone terrain in the southeastern part of the Carajás Mineral Province, located at the southeastern margin of the Amazon craton in Brazil (Costa e Silva et al., 2012). A mineral prospectivity model for gold targeting using a fuzzy logic technique was built

to include the results of a high-resolution airborne magnetics and radiometric survey (Figure 46 and Figure 48), along with geochemical, geological (structure, lithology and alteration) and known mineral prospects data (Figure 51).

The Rio Maria example employed the fuzzy logic knowledge-based approach because only one mine, the Mamão mine, is present in the study and did not provide an adequate amount of data to create a training set to enable the data-driven approach. Based on the metallogeny of the known mineral occurrences of the Rio Maria terrain, two separate fuzzy logic approaches were used in the mineral potential models. The first considered that orogenic deposits are hosted at the contact between mafic and felsic rocks, while the second considered that shear zone-hosted veins associated with mineralization are associated with mafic rocks and iron formations. Fuzzy logic parameters were then applied to lithology as well as structure data. As the model is generated, the fuzzy logic parameters take the various layers of data into consideration and result in a prospectivity map (Figure 52). Once the models are generated, it is important to validate the results by evaluating how well the prospectivity maps predicted known mineralization or prospects.
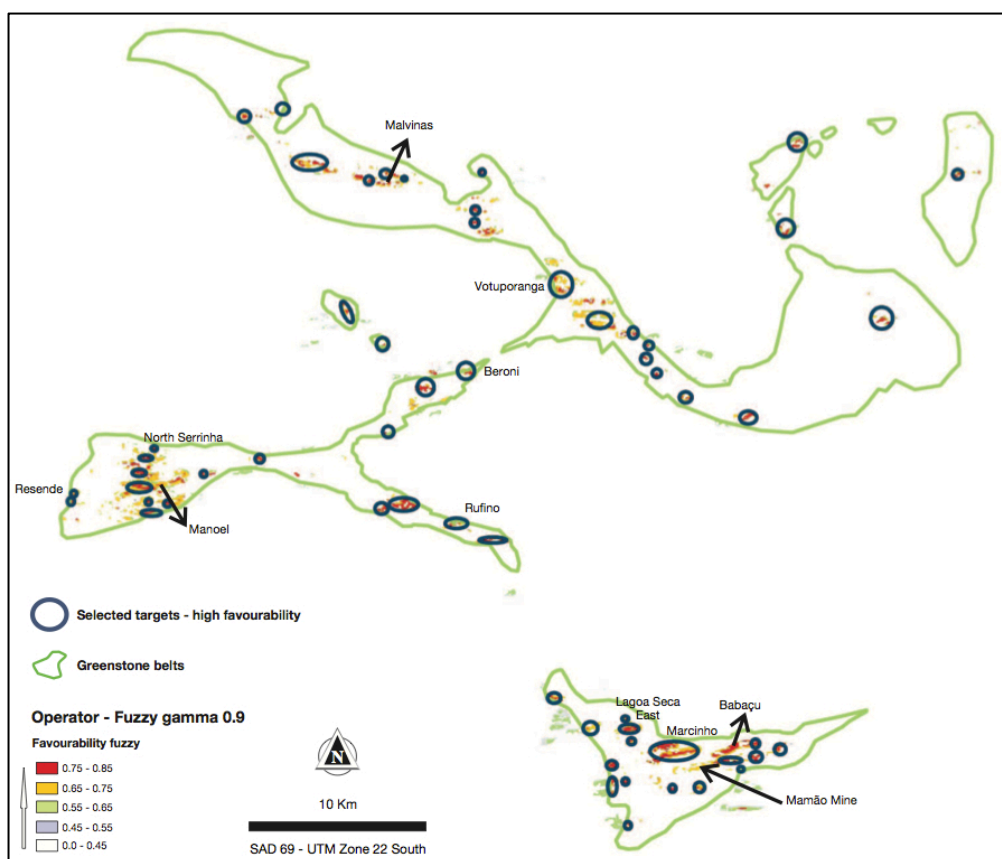
Figure 52. Final prospectivity map of the Rio Maria granite greenstone terrain (from Costa e Silva et al., 2012).

A total of 57 new potential orogenic gold targets were identified (Figure 52). The technique was verified by comparing the newly predicted targets with known gold occurrences as well as the

identification of anomalous trends from follow-up rock and grid soil sampling on selected targets, Also, the method led to the discovery of the Marchino deposit. Like the Yellowknife domain, the Rio Maria terrain features extensive surficial cover with a lack of outcrop where airborne geophysical surveys played a major role in mineral exploration of the region.

In addition to Costa e Silva et al.(2012) discussed above, a number of other papers employ prospectivity mapping for orogenic gold deposits using a combination of integration techniques, including: Harris et al. (2006) in the Red Lake greenstone belt in Ontario and Nykänen et al. (2007; 2011) in the Central Lapland greenstone belt in Finland. Also, Harris et al. (2003) compare the performance of favourability mapping by weights of evidence (WOE), probabilistic neural networks (PNN), logistical regression and discriminant analysis (DA) in a Carlin-type gold setting and Wang et al. (2011) use 3D modelling and non-linear methods (fractal, multifractal, and PNN) for regional predictive mapping of porphyry and skarn Mo deposits as well as hydrothermal vein-type Pb-Zn-Ag deposits; both papers demonstrate the methodology is not limited to orogenic gold exploration.

8.3.2 REMOTE PREDICTIVE MAPPING

Mapping of Canada's North is being carried out by Remote Predictive Mapping (RPM) techniques, which have been developed and refined by the Geological Survey of Canada (Schetselaar et al., 2007; Ford et al., 2008; Harris et al., 2011). To quote Schetselaar et al. (2007):

> RPM is an integral part of the geological mapping process designed to involve compilation, re-compilation and integration of data derived from existing geological maps, aerial photos, satellite imagery and airborne geological data. Predictive geological maps may be iteratively revised and upgraded to publishable geological maps by integrating remotely sensed data with newly acquired field and laboratory data, as RPM techniques are progressively tested and insight evolves. A predictive map, produced without collection of new, field-based data, may also serve as a first-order geologic map in areas where field-based studies cannot be accomplished due to expense of field access or remoteness. As a welcome consequence of adopting RPM into the normal workflow of any mapping or exploration project, there will, by necessity, be greater participation and integration of expertise of field geologists, geophysicists, Geographic Information System (GIS) and remote sensing specialists. Significantly, RPM also encourages geoscience organizations to make full use of all available geoscience data.

Remote Predictive Mapping can aid geologists in a number of ways:

1) Predicting areas of more complex and spatially heterogeneous geological patterns rocks versus more homogeneous signatures, which can allow for planning of field work to be prioritized in the former and scaled back in the latter

2) Planning of field traverses to focus on more detailed traverses where outcrop is present, versus setting up regularly spaced traverse lines

3) Map units are tentatively assigned rock types and/or geological formations using predictive maps, which can be followed up and defined with field work

4) Predicting physical structures and attributes, such as foliation traces, faults, dykes, lineaments, glacial flow directions, etc., interpreted from the remote data in advance of field work can complement field observations or

5) Predicting bedrock outcrop distribution, as well as other physiographic features

Also, there is a seven-step method for RPM, graphically displayed in Figure 53, which proceeds through the acquisition, processing and interpretation of geology from available datasets. The seven steps are: 1) define mapping focus and environment; 2) data acquisition; 3) georegistration; 4) data processing and enhancement; 5) data analysis and interpretation; 6) field logistics and planning; 7) validation of remote predictive maps.
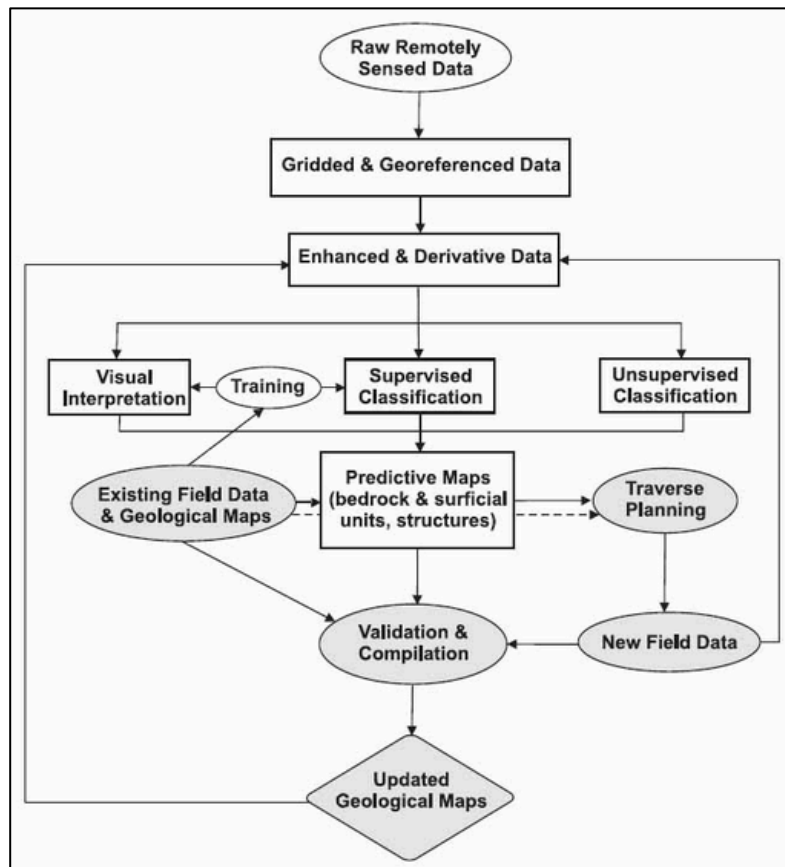
Figure 53. Flow chart showing how RPM methods can be integrated in a geological mapping project. Grey shapes represent traditional mapping methods whereas white shapes represent RPM methods. The interpretation and map compilations process can be integrated over multiple iterations of field mapping, as emphasized by the arrow looping from *Updated Geological Maps* to *Enhanced and Derivative Data* (from Schetselaar et al., 2007).

Figure 53 is a flowchart showing how RPM methods can be integrated into a geological mapping project. Table 9 shows the several types of data used and the maps generated using the RPM methodology. Production of predictive maps can be done by enhancing and fusing various remotely sensed data and visually extracting geological information from the products in Table 9. A different approach is to employ a computer to automatically produce a predictive map (unsupervised or data-driven approach) or by using the knowledge and expertise of the geologist in conjunction with computer analysis (supervised or knowledge-driven approach). Geological interpretations are constrained or 'trained" by existing geological maps and field data (Schetselaar et al., 2007).

Table 9. Remote Predictive Mapping Data Types (from Schetselaar et al., 2007).

Data Source (including various enhancements)	RPM Products (Maps)
Magnetics	Mapping of magnetic units (domains)
	Mapping of structures (faults (ductile, brittle), dykes, lineaments, foliation/ bedding traces, folds, potential lithologic contacts)
Gamma ray	Map of radioelement units (domains) that can provide insight into lithologies, different granitic phases and regional metamorphic conditions
Digital elevation data (DEM)	Map of terrain units (based on relief)
	Glacial landforms
	Map of structures (based on topographic expression) – bedrock or glacial (ice-flow features)
	Map of drainage basins (watersheds)
LANDSAT	Map of structures (faults (ductile, brittle), dykes, lineaments, foliation/ bedding traces, folds, potential lithologic contacts)
	Map of spectral units (spectral absorption features due to white mica, clay minerals (potentially associated to hydrothermal alteration) and carbonates) especially carbonates – may represent a combination of bedrock lithology and surficial units
	Fe –oxide map (3/1 – ratio)
	Clay-alteration map, Carbonate, white mica and other OH-group minerals (5/7 – ratio)
	Map of vegetation (4/3 ratio)
	Outcrop map (1+7/4 or 7/4 ratio)
	Map of wetlands (band 4)
	Map showing forest fire burns
	Map of snow and ice
	Drainage map (can provide more detail than topographic maps depending on scale)
Radarsat data	Map of terrain units that may represent surficial or lithologic units
	Map of structures (faults (ductile, brittle), dykes, lineaments, foliation/ bedding traces, folds, potential lithologic contacts)
Hyperspectral	Map of spectral units (can be calibrated to actual lithologic units or specific minerals in certain environments)
	Map of structures (as above)
	Alteration map (if good exposure)

This method is very useful for first-pass mapping or as an aid to field-based mapping of the vast northern regions of the Canada with world-class mineral potential. The method can contribute significantly to both green and brownfields projects. Acquisition of high resolution data over a property, whether it is from airborne geophysical surveys or is remotely sensed, and applying the RPM methodology over successive field campaigns can result in the creation of geological maps that incorporate many different data sets, such as structural, lithological, geophysical and surficial information, which could help define better drill targets.

Schetselaar et al. (2007) provide the details of the method, which are beyond the scope of this study. One advantage of the RPM approach is the production of iterative maps that can be easily reviewed and updated as further mapping, new datasets or better resolution data becomes available. In the Yellowknife domain, this methodology can prove very useful for the planning of field campaigns to maximize the exploration budgets and focus on areas of highest probability of finding undiscovered ore bodies.

8.3.3 3D GEOLOGICAL MODELLING

Construction of a 3D structural volumetric model at various scales (outcrop, camp or "terrane") containing geologically meaningful sub-volumes within the common Earth model consisting of the family of faults and contacts in an project area combined with their topological, geological and structural relationships will add value-added insight into an exploration project (Chalke et al., 2012). 3D models can act as inputs to and feedback mechanism for modelling, whereby the models are tested against observed potential field data and updated as needed, or they can provide information on any misfits in the data and interpretation (Chalke et al., 2012). The aim of the construction of a 3D model is to improve the decision-making process and increase the potential for successful exploration outcomes (Chalke et al., 2012).

3D visualization of geological data, maps and models, topography (DEM), drill holes, stereonets and other standard plots in a common space provides the opportunity for maximizing the use of all data for understanding relationships amongst the multi-disciplinary datasets for either geological modelling or orebody research (Chalke et al., 2012). Figure 54 shows an example from the Scotts West Case Study in northeastern Tasmania, linking stereonet data to geology and structural data to aid in the interpretation of the three dimensional geology (Chalke et al., 2012). This collaborative, interconnected environment for drawing qualitative and quantitative conclusions about multi-disciplinary data adds value to all data being collected and critically supports business making decisions with fact-based collaboratively interpreted models (Chalke et al., 2012). An example of the construction of a geological and structural model using interpreted observation from Mt Dore,

Queensland is shown in Figure 55, while Figure 56 highlights the process of creating a structural model in 3D space.
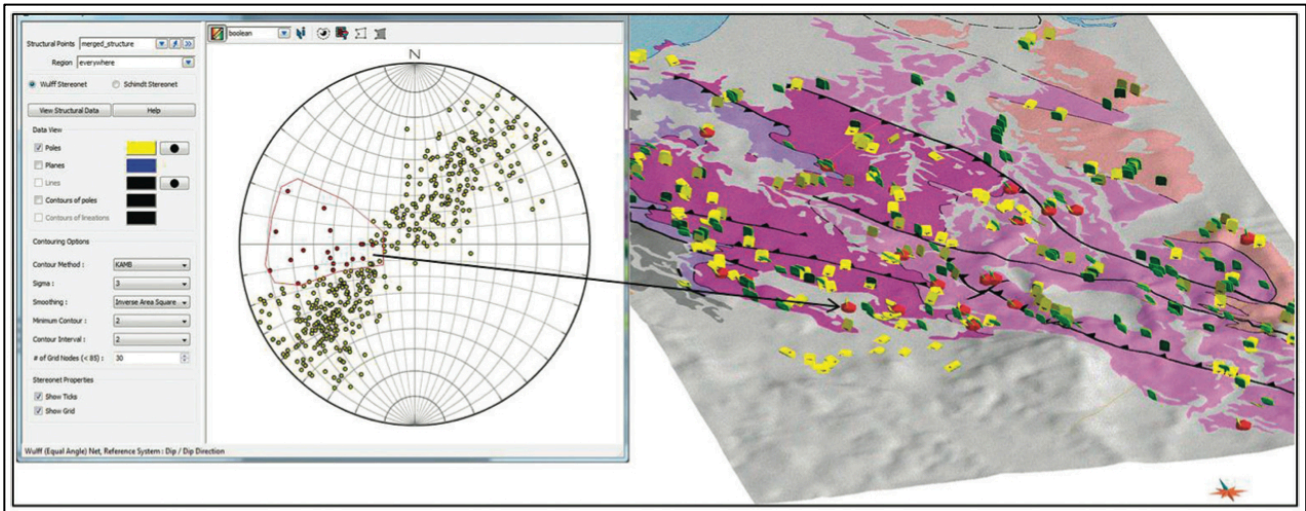
Figure 54. Linking structural measurements visualized on a topography surface draped with a geology map and stereonet view. A particular population of orientations is identified on the stereonet and shown on the 3D view as 'red' (from Chalke et al., 2012).

Implicit modelling is one method used for 3D structural modelling, providing a way for rapid construction and updating of models from a set of structural and stratigraphic rules, and observational and interpretational data (Chalke et al., 2012) by generating internally consistent geological models directly from borehole intersections, numerical data and structural data (Vollgger et al., 2012) without the need to manually digitize and manipulate polylines and polygons (Hodkiewicz, 2013). This is accomplished by using spatial interpolation calculations and mathematical fitting functions to generate 3D isosurfaces of ore grades and rock units (Vollgger et al., 2012). Implicit 3D models may recognize structural features and trends unrecognizable using traditional 3D explicit models and can be linked to local and regional structural patterns observed in the field (Vollgger et al., 2012). Chalke et al. (2012) conclude that deployment of a "software eco-system" that flexibly connects data structures and 3D visualization to computational capabilities for various modelling techniques greatly eases model building efforts, creates better structural models and provides a solid framework for basing business decisions than could be done in the past.

Gibson et al. (2013) provide a workflow using *GeoModeller* developed by Intrepid Geophysics and discuss the use of potential field data (gravity, magnetics, etc.) to help constrain geology and facilitate semi-automated structural interpretation using Multi-Scale Edge Detection, aimed at identifying depth, location and shape of sources reflected from potential field data. The seven-step workflow describes a non-deterministic geophysical inversion method to refine the geological model and generate drill targets centred on unexplained high-density clusters used as a proxy to unmapped sulphide mineralization. Here, it has been simplified for use with any potential field data.
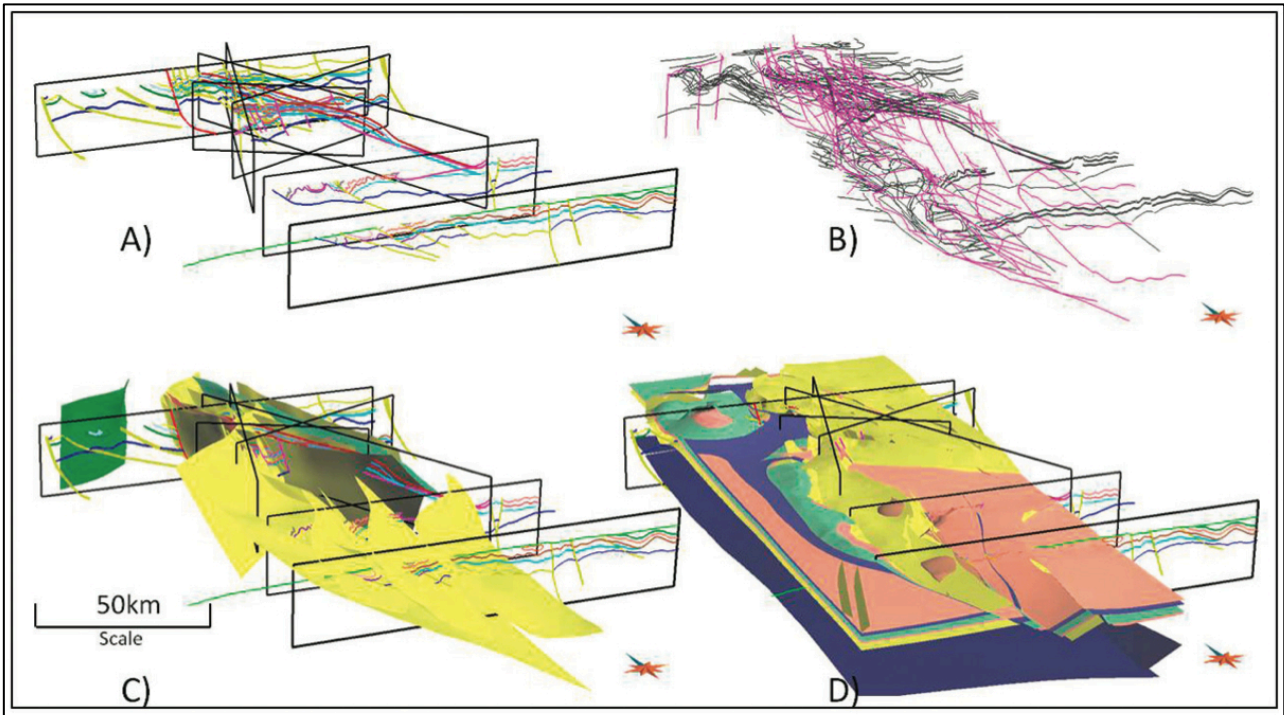
Figure 55. Construction of a 3D geological (D) and structural model (C) from section interpretations (A) and map traces (B) (from Chalke et al., 2012).

The following workflow from Gibson et al. (2013) is best applied to high-resolution prospect-scale models and can also include sensitivity testing and multiple inversion runs starting with different initial models.

1) Build an initial 3D geology model (using interpolation of 3D potential field data implicitly constrained by geology, faults and structural data)

2) Multi-Scale Edge Detection ("worming") of potential field data can help improve structural and geological models

3) Model discretization (creates a 3D "voxet" grid model from smooth 3D geology for computations and inversions)

4) Rock property optimization

5) Forward modelling of potential field response (enables comparison between observed and computed potential field responses)

6) Litho-constrained stochastic inversion (explores alternative 3D geology and property models within known limits)

7) Analysis of potential field anomalies: outcome of inversion (enables targeting of anomalies not explained in the best-known geology model and possibly related to mineralization with retrievable volumes and locations)
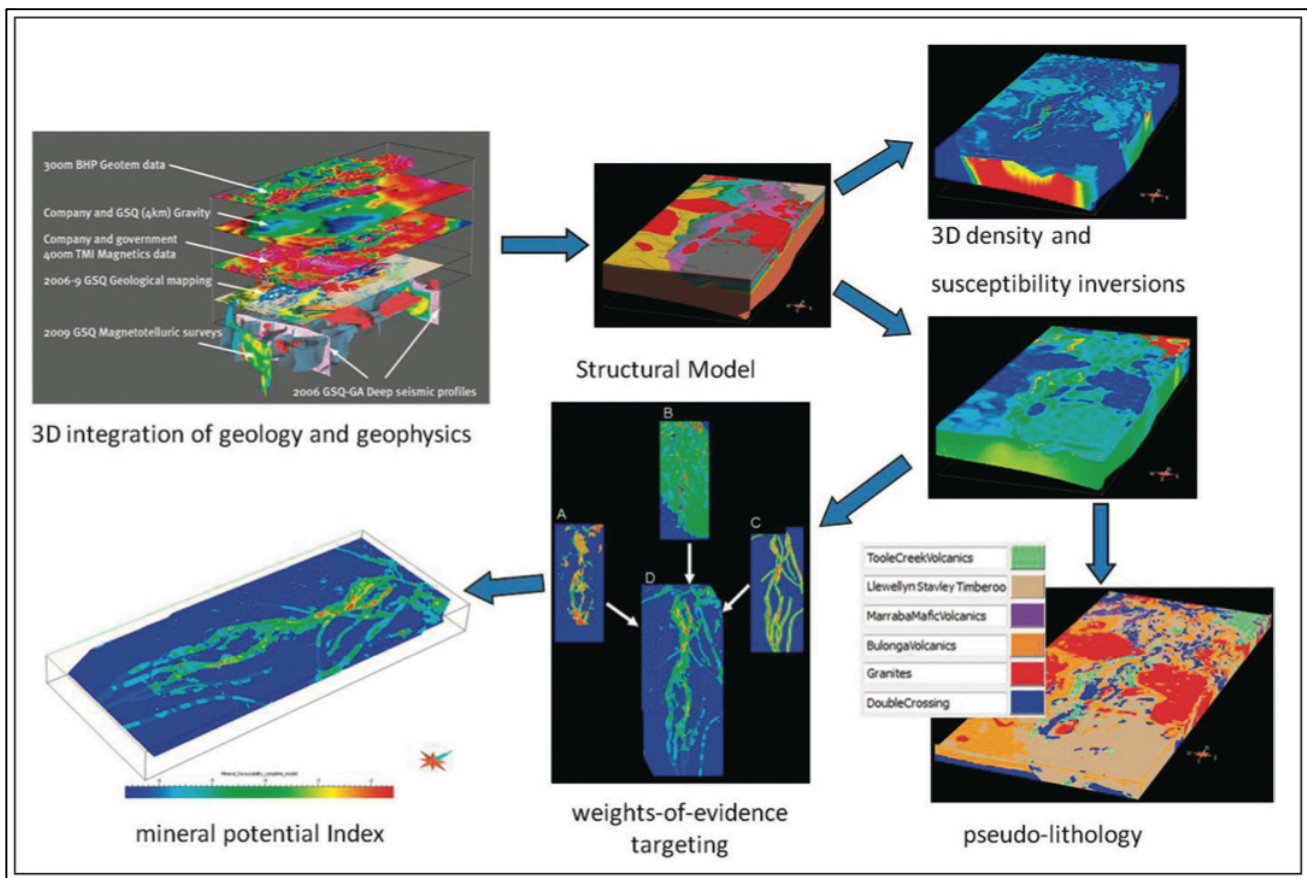
Figure 56. Regional structural modelling and targeting for IOCG-style mineralization in Mt Dore area, Queensland, Australia (from Chalke et al., 2012).

The application of 3D geological and structural modelling in the Yellowknife domain should absolutely be part of any advanced exploration project in the area once sufficient data is collected, as it will save time and effort in developing the understanding of complex structures hosting mineralization in orogenic gold systems and can help to integrate other 3D datasets, such as forward-modelled geophysics and geochemistry (discussed below) in a three-dimensional common space environment. Furthermore, it would allow for business decisions to be made using quantitative analysis of data in order to maximize the chances of successful exploration. Integration of all available and collected geology-related data can be used in building and refining a 3D geological model at the regional- to deposit-scale in the Yellowknife domain, adding value to each data type and allowing for the effective spending of exploration budgets.

3D GEOCHEMISTRY

Jackson (2007) describes geochemical modelling of downhole data and its integration with other data sets to allow for pattern recognition of geochemical data. This is facilitated by the creation of a 3D volume that interpolates elemental concentrations between drillholes. The advantage 3D geochemistry has over traditional 2D cross-sections and surface spatial maps is it provides an effective means of exploring geochemical relationships in the downhole data. Zoning of pathfinder elements during primary dispersion along ore-fluid pathways can be used to vector into zones of high-grade mineralization within a system using the imaging of conceptual 3D zonation relationships (Jackson, 2007). In a secondary dispersion environment, physical or chemical elements can be dispersed into unconsolidated overburden such as soil or glacial till, the latter of which can displace elements down-ice in three dimensions and create complex surface anomalies, especially when multiple till sheets representing different ice advances and dispersion directions are present (Jackson, 2007). Glacial till is present in the Yellowknife domain, and the application of 3D geochemistry can help to better understand these dispersion relationships by displaying and exploring the data distribution patterns in 3D space.

The following objectives of 3D geochemistry contribute to developing more effective targeting criteria and higher quality drill targets:

1) Stratigraphic correlation using elements not introduced or significantly re-distributed during mineralization events

2) Development of a conceptual zonation model for mineral systems

3) Identification of vector criteria for locating high grade mineralization based on zonation relationships

4) Distinguish between proximal and distal geochemical signatures

5) Improving interpretation of surface and sub-surface data

6) Improving the interpretation of surface data by understanding the effects of surface weathering

7) Locating the bedrock sources of anomalies in 3D overburden data

8) Increasing the understanding of mineral systems and dispersion phenomenon

Zonation vectoring of mineralogical and geochemical components in mineralized systems are commonly either lateral or vertical zonation sequences, vertical plumes or plunge alignments (e.g. plunge directions of fold noses and intersecting structures) and often exhibit one of the following:

1) Various element associations that define different zonation facies

2) District-scale layers or shells of anomalous geochemistry, oriented sub-horizontally or vertically

3) Plume-like zones of anomalous geochemistry

4) A proximal to distal zonation sequence

5) A geological context to the zonation of sequence relative to intrusions, host lithologies, structures or weathered surfaces and

6) An effect of scale that may be fractal in nature

Jackson (2007) outlines a methodology for collection of geochemical data for 3D geochemistry. Data is acquired through the systematic collection of representative samples throughout the entire hole with a constant width (e.g. 1 m, but should take into consideration lithological changes), and sample spacing (e.g. every 5 m downhole), which should be determined by an orientation study of several holes. Often in orogenic gold systems, sampling is restricted to visually altered or mineralized intervals, meaning much of the hole goes unsampled. Existing sample data can be normalized to the same width and same sample spacing, if necessary. Inconsistencies in laboratory and analytical methods between new and existing data need to be addressed. A fully validated and cleaned up drillhole database is also essential. The validated sample data is then interpolated with gridded algorithms (kriging or inverse distance squared) using data from the nearest holes. Kriging is used for gridding data that define patterns, commonly in one preferred orientation in 3D space (strike, dip, plunge), typically applied to resource and reserve calculations (Jackson, 2007). Inverse distance squares is useful for exploration data since near-ore or district scale patterns rarely have a preferred orientation beyond the attitude of the rocks, plus the method can represent multiple trends and orientations in the dataset (Jackson, 2007).

The applications of 3D geochemical models for exploration include: lithostratigraphic mapping, 3D vectoring based on geochemical and/or mineralogical data, and secondary dispersion (Jackson, 2007). Lithological mapping from geochemical models can be used if lithological members have distinctive geochemical signatures, aiding the geologist to consistently pick stratigraphic boundaries in different holes in cases where there are transitional facies, alteration or metamorphic overprints,

or limited textural information available. 3D vectoring based on geochemical and mineralogical data, though not always providing the same information, can both play an important role in the discovery process in mature mining camps where new deposits are no longer outcropping. Downhole gridding of systematically collected spectral data can help display the spatial relationships amongst the various mineral distributions, which can be assessed relative to other data types (geology, geochemistry and geophysics). 3D visualization of secondary dispersion patterns of surficial media can be used to interpret trace element data in complex glacial overburden. Jackson (2007) fully describes the procedure and methods for 3D geochemical sampling and analysis, which led to the discovery of a blind deposit at the Shoot gold zone in the Abitibi greenstone belt in northeastern Ontario, a glacially overlain terrain with complex glacial features.

Unfortunately, orogenic gold systems typically have minimal lateral zonation extending out into the wallrock of shear zones and faults, as well as very little vertical zonation, making vectoring towards high-grade mineralization difficult (CHAPTER 4). However, local changes in lithology (mafic-felsic contacts, faults and shears cutting across stratigraphy and stratigraphic variation) and proximity to intrusive centres within a fault or shear zone could result in mineral or elemental zoning (Jackson, 2007). Furthermore, the detection of secondary dispersion zonation around orogenic gold deposits in the Yellowknife domain could be tested with 3D geochemistry methods, particularly in areas where glacial till has obscured bedrock, making the interpretation of traditional geochemical surveys challenging. Also, 3D geochemical methods could be applied to targeting VMS deposits in the CBGB of the Yellowknife domain.

8.3.5 EXPLORATION TARGETING

The methodology and framework of the exploration targeting process for mineral exploration was first introduced by Hronsky (2004) and further developed by Hronsky and Groves (2008). Exploration targeting involves the initial area selection decision, which is based on applying geological concepts to pre-existing datasets in order to predict the probability of ore occurrence, prior to conducting direct detection activities of more advanced exploration stages (Hronsky, 2004). Exploration targeting involves the integration of economic geology-related disciplines with concepts from other fields, such as geophysics, spatial analysis, mineral economics, decision science and probability theory (Hronsky, 2004).

Figure 57 summarizes the sequential steps of the exploration targeting: 1) development of a business and targeting strategy; 2) creating a targeting model; 3) target identification and ranking; 4) target testing in high-priority domains and 5) performance evaluation. A feedback loop between

performance evaluation and target model creation helps to improve the target model and information in the database.

Part of the business and targeting strategy is to review previous exploration history of an area (Hronsky, 2004). A common mistake made in the targeting strategy is failing to recognize the significance of prior exploration history, since a finite area (district or province) can reduce its potential to host high-probability targets with time, which also drives the unit cost of exploration to systematically increase within a domain; however new concepts and techniques can expand the potential of a finite area (Hronsky, 2004). This implies that if a targeted area has been effectively explored, an exploration program will not likely lead to new discoveries, unless new concepts and techniques are developed (Hronsky, 2004). In the Yellowknife domain, the application of new concepts and techniques discussed earlier in this chapter provide increased potential for discovery of as-yet undiscovered ore bodies in the region.
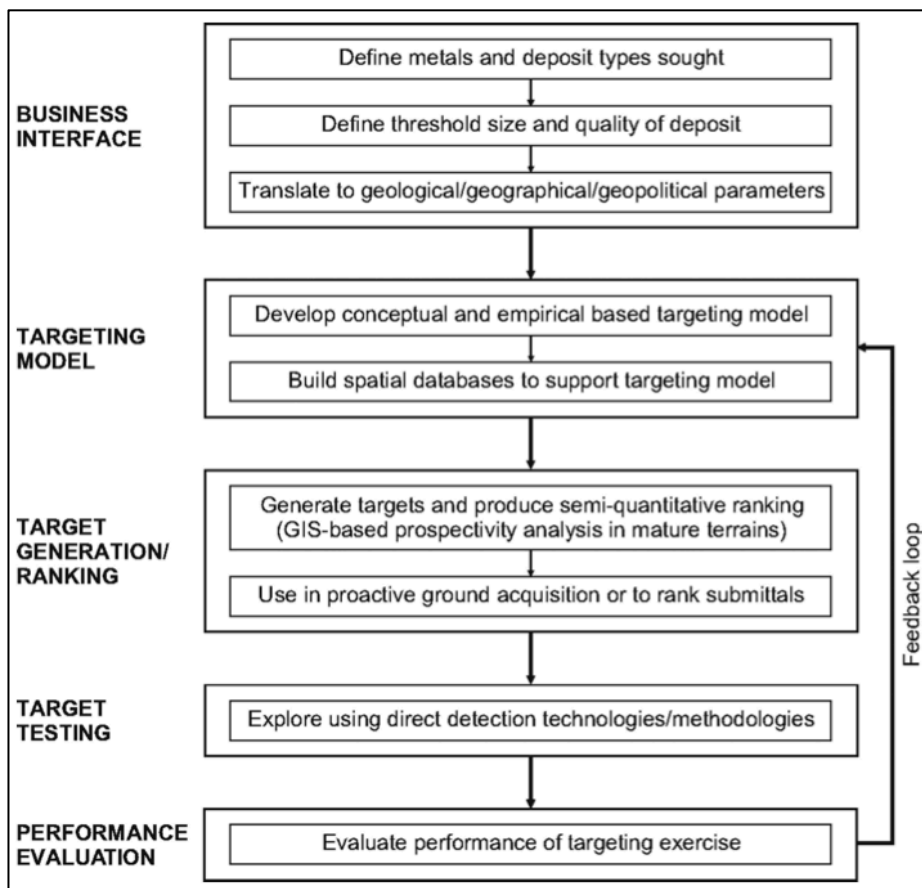
Figure 57. Summary of the mineral targeting process from the business interface through developing the target model and spatial databases to defining and testing targets, with a subsequent feedback loop to improve targeting model and information in the databases (from Hronsky and Groves, 2008).

Three fundamental geological facts must be taken into account when considering the effect of previous exploration history:

1) The occurrence of ore-deposits is extremely heterogeneous and a relatively small number of geological provinces are well-endowed, whereas most have very minor mineralization.

2) The size-frequency distribution of mineral deposits within any province shows a power-law relationship and individual provinces show characteristic power-law size-frequency distributions.

3) The size and contrast-to-background of the geological 'footprint' to an ore-system is generally proportional to its size; implying larger deposits are usually found first in any province.

Two conclusions derived from the above facts are that: 1) the best chance of finding a deposit is to explore where large deposits are already found and 2) the largest deposits are usually found in any particular province before many (if any) other large deposits are known, though this may not hold true if there is significant expansion of exploration concepts and techniques (Hronsky, 2004). From Hronsky's first conclusion, the Yellowknife domain, home to past-producing Con and Giant mines, has potential for discovery of new ore bodies in the YGB, especially since much of the historic exploration has been focused at delineating near surface targets, whereas contrary to the above statements, the CBGB may yield undiscovered orebodies that could potentially be detected using the latest exploration concepts and techniques described in this study.

Two basic area selection strategies employed in mineral exploration are the 'Elephant Country' strategy and the 'First Mover' (or fast follower) strategy (Hronsky, 2004; Hronsky and Groves, 2008). The Elephant Country strategy looks to exploit the characteristic size-frequency distributions of mineralized systems, although it is common for favourable ground to be held by competitors when employing this strategy and it is usually a highly competitive environment, requiring a competitive advantage, especially since these areas will typically have been extensively explored and exploration costs will be higher (deep drilling, borehole logging, etc). The First Mover strategy attempts to locate the first and commonly best deposits in a province, which are also usually discovered by the first group to move in. This approach can be successful if potential new exploration environments are recognized and rapidly moved into along with the assurance that a target province is genuinely immature in terms of exploration history. Targeting in the YGB would fall into the Elephant Country strategy, whereas the CBGB would fit the description of a First Mover approach.

Hronsky (2004) notes the targeting process consists of the construction of targeting models, target identification, target ranking and lastly performance measurement and feedback loops. General principles in target model construction are:

1) Different targeting parameters are important at different scales and recognition of scale dependence is needed to avoid confusion.

2) The manifestation of all components must be visible in relatively low cost, readily available exploration datasets such as geophysics, remote sensing data, regional geological maps, etc., particularly in areas of cover.

3) Focus on parameters absolutely essential to the presence of mineralization and where possible discriminate them from less relevant parameters

4) Address factors discriminating large from small ore systems

5) Focus on parameters with relatively low false-positive rate, which is an important governor of the quality of a particular targeting parameter.

The quality of the targeting model is crucial, because if the model is done poorly, any subsequent work will not be effective at discovering ore bodies, regardless of the exploration techniques employed (Hronsky, 2004). The target-modelling phase is the main geoscientific challenge where risk can be lowered and cost-effective direct-detection exploration ensured (Hronsky and Groves, 2008). Target modelling accounts for individual ore deposits being part of extensive systems and can be carried out at global through province to district scales (Hronsky, 2004; Hronsky and Groves, 2008).

Recently, Hronsky et al. (2012) presented a unified model for gold mineralization in accretionary orogens and the steps for applying the model to regional exploration targeting. This model could be used as a target model in the Yellowknife domain:

Step 1 - Define the underlying lithospheric architecture to provide the basic framework for analysis by identifying the first-order regional control on gold metallogeny within a convergent margin orogen.

How? - With integration and synthesis of available geophysical and geological datasets to determine features likely representing the basement architecture, particularly patterns in structural data, spatial distribution of mantle derived magmatic products, gravity data and high-resolution seismic tomography.

Step 2 - Spatially and temporally identify the major metallogenic events in the region, including the spatial mapping of the distribution of intrusions through time.

Step 3 - Relate each metallogenic event to the underlying lithospheric architectural framework, since gold endowment can be related at the regional scale to patterns in the lithospheric architecture.

Step 4 - Delineation of gold provinces with broadly uniform mineralization potential at the regional scale, which can commonly be associated with or proximal to orogen-parallel, trans-lithospheric structural corridors, particularly where similar-scale, approximately orthogonal transfer structures intersect.

Step 5 - Identify camp-scale targets defined by areas between the intersection of major trans-lithospheric structural-corridors and other trapping structures, such as the culminations of antiforms.

Once a target model is constructed, target identification can proceed by applying the model to available data to identify individual targets (Hronsky, 2004). Two end member approaches commonly used in tandem in the target identification process are the Venn diagram and hierarchical approaches (Hronsky, 2004; Hronsky and Groves, 2008). The Venn diagram approach views target generation as the process of locating areas where a number of targeting model components are coincident, as used in prospectivity mapping (Section 0) and also illustrated in Figure 12. It is best applied at the district scale, along with the Elephant Country strategy, in areas with good quality and relatively uniform data, typically indicative of relatively mature mining and exploration areas, such as the YGB. More applicable to regional and province-scale exploration is the hierarchical approach, based on the concept of targeting models typically comprising a series of parameters manifested at different scales, such as greenstone belts hosting orogenic gold mineralization, as described in 0 and CHAPTER 4, respectively. Additionally, the hierarchical approach is generally applied in the First Mover approach discussed above and could be applied to the CBGB (Hronsky and Groves, 2008).

Target ranking can go hand in hand with target identification, particularly when only a small number of targets have been identified, but usually is applied when numerous targets are identified (Hronsky, 2004). The general principles for a ranking scheme should:

- put substantial weight on coincidence of positive indicators derived from independent datasets, particularly when there are only a few positive indicators

- produce a clear numerical separation between the few best targets and the rest of the target population

- not penalize areas of low data-density, since these may still be areas for discovery

- separate a target's ranking from the confidence in the data supporting that ranking

- be a clear separation of model parameters from observations relevant to the parameters, such as inferred geology from geophysical or remotely sensed data

Additionally, Table 10 combined with Figure 58 show the critical processes and some of the key parameters and proxies detectable from geological maps or geophysical databases normally available to a targeting team in an exploration company for use in building a targeting model.

Table 10. Mineral systems model for orogenic-gold deposits (from Hronsky and Groves, 2008; adapted from Groves et al., 2000).

Key parameter	Proxies for parameter
Critical process—Thermal energy and ore-fluid source	
Thinned lithosphere	Short terrane history (Bierlein et al., 2006)
Major crust-forming event	Geochronological data
Orogenic-gold mineralisation	Known gold occurrences
Critical process—Plumbing fluid systems	
Deep fluid conduits	Crustal-scale shear zones preferably with lamprophyres
Focused fluid flow	High-strain shear zones in low-strain belts
High-damage zone in lower order faults	Jogs, thrust duplexes, fault intersections
Critical process—Trap (depositional) site	
Structural trap	Locked-up anticline, thrust-tip, dilational jogs and many more
Rheological trap	Rheologically indexed rock types—contacts with high contrast
Chemical trap	Reactive rocks with high Fe or C
Critical process—Fluid seal (cap)	
Stratigraphic cap	Impermeable rocks over structurally permeable rocks (e.g. sedimentary cap)
Structural cap	Impermeable thrust stacks
Critical process—Outflow zone	
Fluid dispersion	Metal dispersion halos
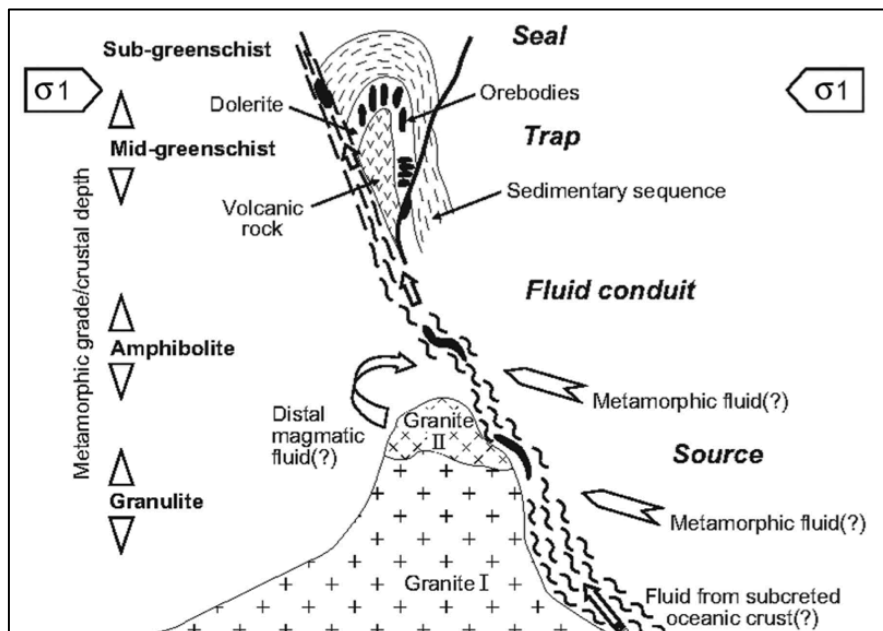
Figure 58. Schematic diagram illustrating the mineral system model for orogenic-gold deposits and the critical processes for the key proxy parameters of exploration targeting as shown in Table 10: source, fluid conduit, deposit trap and cap or seal. (from Hronsky and Groves, 2008; adapted from Groves et al., 2000).

The last step in exploration targeting is to measure performance using a feedback loop aimed at determining the effectiveness of the area selection model. This is vital to improving targeting performance. Once targets are generated, information obtained from the follow up work should feed back into the targeting model and the supporting database, which is especially important in less-developed countries where the information obtained from field assessment of province-scale target areas may have a big impact on the overall regional geological understanding underpinning the targeting model (Hronsky, 2004; Hronsky and Groves, 2008).

CHAPTER 9   **DISCUSSION**

This study presents characteristics of greenstone belts and orogenic gold deposits, with a particular focus on the Yellowknife domain greenstone belts of the Slave Province. A number of mineral exploration strengths and opportunities have been identified for the Yellowknife domain but there are also several important weaknesses and threats. In addition to the factors described in this study, there are a number of external factors that could affect the ability to conduct successful exploration in the Yellowknife domain. Table 11 outlines the various factors currently affecting the mineral economics of exploring in the Yellowknife domain using a SWOT (strengths, weaknesses, opportunities, threats) analysis. Each category is discussed below, starting with the disadvantages.

Table 11. SWOT analysis for mineral economics of conducting mineral exploration in the Yellowknife domain

Strengths	Weaknesses
-Proximal to Yellowknife and mining-related infrastructure -Winter road nearby -Road flagged to Sunrise deposit from Ingraham Trail -Newly constructed bridge over Mackenzie River -Favourable geological setting for orogenic gold, VMS and other deposit types (e.g. pegmatite-hosted REEs) -Abundant freely available data -Relatively mature mining camp (YGB) -Relatively little explored regions (CBGB) -Significant room for growth in the domain -Considerable increase in gold price over last 10-15 years -Initial greenfields exploration is relatively inexpensive compared to other parts of northern Canada	-High costs of exploration, particularly in winter -Long winters -Potential for not making a discovery -Need a range of staff to successfully implement exploration methods -Initial high cost of staffing and software -Akaitcho Agreement interim land withdrawals
Opportunities	**Threats**
-Employ 'First Mover' approach in CBGB -Employ 'Elephant Country' approach in YGB -Current lull in industry is a good time for target generation -Distressed junior mining sector potentially allows for inexpensive acquisition of existing properties -Diamond mining is beginning to wane -Possibility of data collected for diamond exploration not evaluated for gold and base metals -CBGB unexplored and YGB underexplored with modern exploration techniques -Integration of modern geoscience data -Application of updated geological models -Use of advanced modern exploration techniques -Generation of significant new data -Employ sustainable mining and exploration practices -Relatively low start-up capital needed for exploration -Future research	-Unpredictable winter weather potentially affecting winter road access -Sensitive environments (lakes, rivers) -Akaitcho Agreement affecting ability to prospect and explore the region -Difficulties obtaining water use permits -Permitting and approval difficulties and stakeholder opposition faced at Gahcho Kué, which could happen to future mining projects -Potential decreasing gold demand -Potential volatility in gold price -Currently difficult to finance exploration projects

Weaknesses and Threats

Several weaknesses presented in Table 11 are inherent to most exploration projects including the potential for not making a discovery, need for a range of staff to successfully implement exploration methods, initial high cost of staff and software (especially 3D packages, such as GoCad and Leapfrog, etc.). Many weaknesses, however, are particular to northern Canada including the high costs of exploration and mobilization, along with the long winters, which, if well-managed, can even work to the advantage of an exploration program by using the winter roads for mobilization and demobilization.

Unique to the Yellowknife domain is the uncertainty posed by the Akaitcho Agreement and its as-yet undecided terms, including the interim land withdrawal (Section 2.5). Depending on the final agreement between the NWT Government, Government of Canada and the Akaitcho Dene First Nations, exploration activities and staking of mineral rights may go unhindered. Should the right to mineral staking be restricted by the final agreement, however, the Royal Bafokeng Nation (RBN) in the North West Province of South Africa may be an analogue of direct community participation in mining and could provide a potential solution for working alongside the Akaitcho Nation. The RBN established the community-based investment company Royal Bafokeng Holdings (RBH) to manage and develop the commercial assets of the RBN with its activities aimed at generating income to fund sustainable projects benefiting the RBN community (Royal Bafokeng Holdings, 2013). The RBN, through RBH, directly participates in mining ventures of the platinum- and chrome-rich western limb of the Bushveld Complex and has also established Royal Bafokeng Platinum (RBPlats), which holds a majority interest (67%) and operates the joint venture (JV) at the Bafokeng Rasimone Platinum Mine, as highlighted in Figure 59 (Royal Bafokeng Nation, 2013; Royal Bafokeng Platinum, 2013a).

Development of a similar JV structure for Akaitcho-owned companies could help involve the Akaitcho community in exploration activities and, if a discovery is made, mining; however one drawback for the Akaitcho is their considerably smaller population compared to the Royal Bafokeng, who number approximately 300,000 people compared to 43,000 people in the entire Northwest Territories. Akaitcho-owned companies could also aid in training, educating and employing local Akaitcho people as well as negotiating partnerships and consulting with exploration and mining companies to ensure the concerns of the Akaitcho community are properly met.
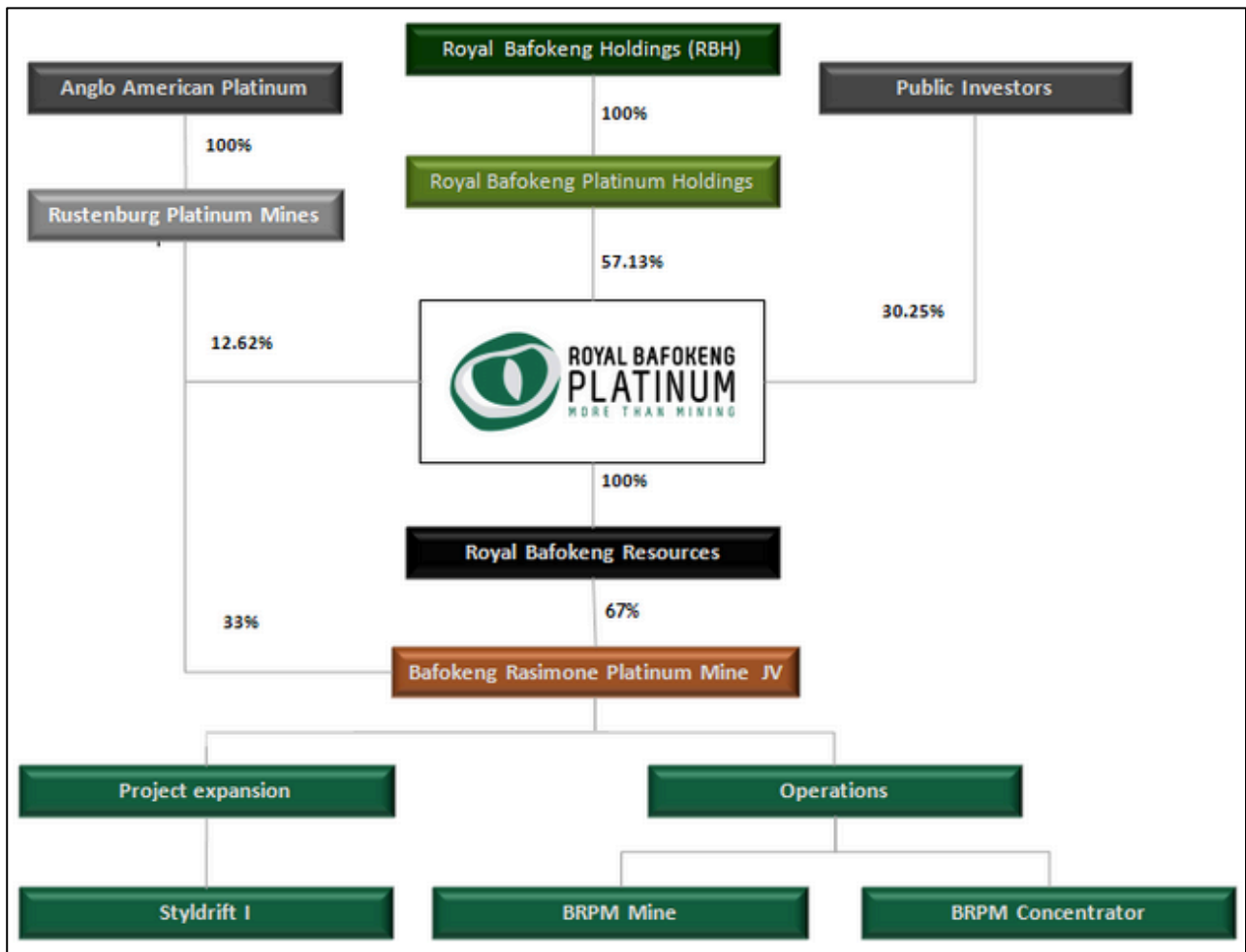
Figure 59. Royal Bafokeng Platinum company structure and joint ventures for the Bafokeng Rasimone Platinum mine (from Royal Bafokeng Platinum, 2013b)

A number of threats to exploration in the Yellowknife domain have also been identified (Table 11) and, similarly, many are not exclusive to the area, including a potential decrease in worldwide gold demand and the recent gold price volatility, as well as the difficulty of financing exploration projects during the current economic downturn. Also, threatening exploration in the area are environmental concerns, which include conducting exploration proximal to sensitive water bodies and unpredictable winter weather that may adversely affect the ability to plan the use of winter roads for mobilization and demobilization, potentially driving up costs significantly. Additionally, administrative aspects threatening exploration include difficulties in obtaining water-use permits from the NWT Government, though the process has recently been streamlined, lack of public and stakeholder support for permitting and approval of mining operations, as recently faced by the Gahcho Kué Diamond Mine, and, as discussed above, the uncertainty of the Akaitcho Agreement's affect on the ability of exploration companies to acquire mineral rights to prospect and explore the region.

The risks posed by the weaknesses and threats of the Yellowknife domain are generally comparable to most exploration projects in northern Canada, though the unique challenge imposed by the uncertain outcome of the Akaitcho Agreement could potentially be worked around by using the RBN example for direct community participation in mining.

Strengths and Opportunities

Mineral exploration in the Yellowknife domain has a number of geological and technological strengths increasing the potential for discovery of economically viable mineral deposits. Geological strengths include favourable geological settings for orogenic gold and VMS mineralization in the relatively mature Con and Giant mining camps, where other deposits may be present under cover presenting significant room for growth in the region. Additionally, the relatively unexplored CBGB – where no orogenic gold or base metal exploration has been carried out for at least a decade – presents an opportunity to apply modern exploration techniques. Moreover, historic exploration consisted of either first-pass and shallow exploration efforts or was focused on kimberlite diamond exploration. Technological strengths of the Yellowknife domain include the proximity to Yellowknife and mining-related infrastructure (e.g. winter road, power generation facilities, etc.), a newly constructed bridge over the Mackenzie River and the flagged right-of-way to the Sunrise deposit near the centre of the CBGB. Further strengths include the abundant freely available data and reports from the Northwest Territories Geoscience Office and numerous remotely sensed datasets (Table 6), combined with the substantial increase in the gold price over the past decade (<$500/oz. in 2000 to ~$1500/oz. in 2013; inflation adjusted) that could make marginal prospects and deposits economic. Lastly, exploration costs in the Yellowknife domain are relatively inexpensive compared to other parts of northern Canada, particularly where road access is not an option.

In addition to the strengths of Yellowknife domain, there are several opportunities present in the area making it attractive for exploration. External opportunities include the current lull in the mineral exploration and mining industry, which provides an effective time for target generation and data compilation, and also coincides with the waning of Slave Province's diamond mining with two of the three producers nearing the end of production in the next decade (Ekati, 2018; Diavik, 2023) (Falck and Gochnauer, 2013). In the YGB, the application of an Elephant Country approach to systematically apply and integrate modern exploration techniques (e.g. remote sensing and detection, 3D geochemistry, borehole logging, improved geophysics modelling and data collection, etc.) combined with updated geological models could result in new discoveries in the Con and Giant mining camps or elsewhere in the belt. However, this method may require significant capital to enter into JV agreements with companies currently holding mineral rights in the belt and will also likely require relatively deep drilling. Conversely, the presently distressed junior mining sector presents an opportunity to inexpensively acquire existing properties. Alternatively, the CBGBs present an

opportunity to use the First Mover approach by staking mineral claims over the most prospective ground in the belts, and then apply focused greenfields exploration with modern exploration techniques and updated geological models. Additionally, the start-up capital needed for greenfields exploration in the CBGB is relatively small compared to the brownfields exploration in the YGB. Furthermore, evaluating the data collected from diamond exploration for gold and base metal elements and pathfinders could help identify initial follow-up targets. Moreover, exploration in the Yellowknife domain will generate significant new data requiring proper database management and will contribute to renewed geological interpretations of the region, as well as presenting opportunities to implement sustainable exploration and mining practices that promote long-term sustainability. Lastly, if significant discoveries are made, further research can be conducted to better understand the mineralization in the domain. Further research questions include:

- What is the relationship between granites and greenstone belt mineralization, particularly around Sleepy Dragon Complex?

- Are there any similarities between unconformable conglomerates such as the Beaulieu Rapids Formation and Witwatersrand-type conglomerates? Is there paleoplacer gold potential?

- What is the gold potential of the Yellowknife domain using size-frequency plots?

- Is the refractory gold of Con-Giant related to the atypical-style of greenstone-hosted gold mineralization?

- What stratigraphic units host VMS deposits?

- What crustal-scale structures may have been fluid pathways in the Cameron River greenstone belt where juxtaposed onto the Sleepy Dragon Complex?

- What were sedimentation rates of volcanic and sedimentary rocks?

CHAPTER 10   CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

This study chiefly aims to present exploration geologists with the tools and approach for delineating gold deposits in the greenstone belts of the Yellowknife domain in the Slave Province of northern Canada. These deposits typically form in the following structural settings within granite-greenstone terranes (Groves, 1993; Groves et al., 1998; Goldfarb et al., 2001; Goldfarb et al., 2005; Dubé and Gosselin, 2007):

- Second- and third-order faults and shear zones linked or proximal to first-order crustal-scale faults and shear zones extending to considerable depths. These first-order structures act as conduits for auriferous fluid flow, particularly in areas of low minimum principal stress (σ3), such as dilational jogs and changes in strike of first-order faults (Sections 4.3 and 8.3.1.1)

- Lower contacts of greenstone belts, which are likely to be host rock independent shear zones and concentrate volumetrically large amounts of fluid flow late in a greenstone belt's history (Section 3.4)

- Steeply dipping shear zones and faults locally associated with extensional veins and hydrothermal breccias (Section 3.4)

- Long-lived structurally complex shear zones and faults associated with crustal shortening and high-angle reverse motion (Section 4.3)

- Fracture arrays, stockwork networks and breccias in competent (volcanic or granitoid) rocks or foliated zones and fold hinges in less competent turbiditic sequences (Section 4.3)

Furthermore, the greenstone-hosted orogenic gold mineralization of the Con and Giant mines in the Yellowknife domain is characterised by (Henderson, 1985; van Hees et al., 1999; van der Velden and Cook, 2002; Shelton et al., 2004; Goodwin et al., 2006; Siddorn, 2011):

- Quartz-carbonate veins intersecting both metasedimentary and metavolcanic rocks (Section 5.8.1)

- The most productive orebodies occurring along major late-stage shear zones confined to the Yellowknife Bay Formation in the Kam Group mafic volcanic rocks

whereas early shear zones facilitating movement and mobilization of mineralizing fluids (Section 6.2.3)

- Mineralization synchronous with D_1 and D_2 deformation events (Section 6.2.3)

- Mineralization coincident with broad zones of silicification, quartz-carbonate veins and gold-quartz alteration systems (Section 6.2.3)

- Mineralization associated with zones of intense and complex deformation as well as dilatant zones hosting quartz veins (Section 6.2.3)

- Refractory gold hosted in early carbonate-rich veins with sericite alteration and pyrite, arsenopyrite and sulphosalts (Section 6.2.3)

- Free-milling vein-hosted mineralization with numerous sulphide mineral associations commonly exhibiting superposition of styles due to post-mineralization deformation (Section 6.2.3)

In addition to targeting the geological environments of orogenic gold and the mineralization styles characterized by the Con and Giant mines described above, Hronsky et al. (2012) describe three essential elements for world-class gold deposit formation (Section 4.3, Figure 12) that can aid in targeting orogenic gold deposits: 1) a gold-fertile upper mantle, 2) a lithospheric-scale structure and 3) a transient remobilization event. For world-class orogenic gold deposits, Hronsky et al. (2012) define the overlap of the three essential elements by major tectono-magmatic and geodynamic setting as inversions of retro-arc pericontinental rifts located adjacent to continental margins forming at the terminal stage of collisional inversion and minor post-orogenic extension where mantle-derived components are significantly dominated by crustal magmatic contribution (Section 4.2).

The YGB is a former world-class gold producer and could be once again elevated to elite status with the application of modern exploration techniques and methods. The CBGBs, by contrast, have had very limited exploration for orogenic gold and could greatly benefit from the updated geological models, as well as the application of modern exploration techniques. Also, the CBGB have potential to host world-class gold deposits since they are cut by the regional-scale Beaulieu River Fault Zone (Section 6.3.2), a fertile upper mantle potentially related to the YGB (Section 5.6) and transient remobilization events involving abundant pluton emplacement dominated by crustal magmatic contributions (e.g. Prosperous and Morose Granite Suites; Sections 5.4.2.6 and 5.4.2.7) proximal to the greenstone belts and focused proximal to the Sleepy Dragon Complex (Section 5.4.2).

This study has defined the Yellowknife domain greenstone belts in Northwest Territories of northern Canada as a favourable geological, geographical and geopolitical environment where a conceptual and/or empirical-based targeting model (e.g. unified gold mineralization in accretionary terranes model; Section 8.3.5) supported by a spatial database of geologically relevant layers can be used to generate targets for identifying prospective ground to be proactively acquired and followed up with field-based testing. This follows the exploration targeting methodology (Section 8.3.5, Figure 57), whereby one can construct a business model for exploration (Section 10.2).

From a business perspective, it makes sense to employ the exploration targeting methodology and GIS-based prospectivity analysis of spatial databases using 3D geological models in order to make decisions based on semi-quantitative data. However, from qualitatively evaluating the geology of the Yellowknife domain and orogenic gold mineralization in this study, a number of targets exist. The highest priority targets in the YGB are shear zones that crosscut stratigraphic layers of the Yellowknife Bay Formation, particularly those proximal to the Con and Giant mines and the second- and third-order faults and shear zones along the Yellowknife River Fault Zone. In the CBGB, the highest priority targets include shear zones cross-cutting the Beaulieu Rapids Formation; faults and shear zones along base of Cameron River greenstone belt where it is thrust over the Sleepy Dragon Complex; the Sleepy Dragon, Amacher and Payne shear zones; BIF's, particularly where thickened due to folding, such as the Amacher Lake BIF; and second- and third-order shear zones and late strike-slip faults of the Beaulieu River greenstone belt proximal to dilational jogs and bends in the Beaulieu River Fault Zone.

10.2 RECOMMENDATIONS

An exploration business model should firstly define what deposit types and commodities are sought (e.g. primarily greenstone-hosted orogenic gold, secondarily VMS), along with a size threshold (e.g. >1 Moz) and deposit quality (e.g. >2 g/t gold) that aligns with the geological, geographical, and geopolitical parameters. The business model should also consider the desired personnel needed to successfully conduct the necessary tasks of collecting, managing, integrating and interpreting geologically relevant data. Structural geologists, geophysicists, GIS specialists and database managers are among the professionals required to work together for maximizing the value of data collected. Additionally, selecting appropriate GIS software for both 2D and 3D visualization and modelling of geological and geophysical data should be considered. The team of professionals should be competent at building a common earth model, integrating data and interpreting the geology in 3D, otherwise they should undergo the necessary training or third-party contractors can be hired to construct and manage the models, but this may add costs to the business.

Once a team of professionals or third-party contractors is assembled and software is selected, collection and compilation of regional historic assessment reports, government compiled data and reports, remotely sensed data, geology, geophysics and geochemistry should be conducted to build a spatial geological database of the region. The Northwest Territories Geoscience Office (www.nwtgeoscience.ca) provides the GoData and Gateway applications for accessing and collecting data and reports free for public use. Data should be assessed for quality and accuracy, particularly any digitized data, before being used in any predictive models for target generation. Once the database is verified, predictive models can be carried out to generate and semi-quantitatively rank targets (e.g. predictive modelling, Section 8.3.1; remote predictive mapping, Section 8.3.2). The predictive models used will depend on the availability of physical rock and fault deformation properties, magnitudes and orientations of far-field stresses (D_1 and D_2), geochemistry, geophysics, gold occurrences, mineral deposits, topography and remote sensing data. Alternatively, the qualitative targets noted above could be selected if insufficient data is available for producing predictive models, which is likely the case in the relatively unexplored CBGB.

After targets have been generated and ranked, proactively acquiring the mineral rights to the ground is the next step, although much of the available ground in the Yellowknife domain is currently located within the interim land withdrawals (Figure 4) while the Akaitcho Agreement is negotiated. The final terms of the agreement will dictate the procedures and ability of companies wishing to acquire new mineral rights in the region, however, JV partnerships with existing mineral rights holder could also be undertaken, particularly in the YGB (Figure 7). JV partnerships could even be discussed prior to the compilation of data so as not to duplicate compilations already completed by the existing mineral rights holder. Once mineral rights have been secured and all necessary permits are in place, field testing of the conceptual model and generated targets can begin. The use of remote predictive mapping should also be conducted prior to fieldwork as a field mapping aid for planning traverses in areas with outcropping bedrock and also to divert around other physiographic features (e.g. lakes and rivers), plus it will determine if there is sufficient outcrop for radiometrics to be an applicable airborne geophysical survey parameter.

Recommendations for exploration fieldwork aimed at greenstone-hosted orogenic gold targets in the Yellowknife domain include:

1) Conducting geophysics (Section 8.2.4) by flying an airborne (fixed-wing) gradient magnetic ± radiometrics ± EM survey with narrow line spacings (100-200 m), for increased resolution, oriented perpendicular to the structural trend of the target areas. This should be done prior to groundwork to allow for the incorporation of interpretations into base geological maps used for field mapping. Gradient magnetics will provide better resolution than non-gradient magnetics for identifying

lithological changes and structures, whereas radiometrics will only be effective if there is sufficient outcrop and EM should be used to help determine depth to bedrock in areas with glacial till and can be an aid in mapping faults, veins, alteration and contacts. Depending on the integrated and interpreted results from airborne geophysics, geological mapping, geochemical surveys and reconnaissance drilling, follow-up ground geophysical techniques, such as IP, GPR, EM and gravity can be carried out. If VMS deposits are suspected, these ground geophysical methods can also be carried out to locate VMS mineralization.

2) Geological mapping (Section 8.2.2) should use an iterative geological base map created prior to ground-based fieldwork from integration of the compilation map of Stubley (2005) with interpretations from remotely sensed data and geophysical surveys to focus mainly on structural mapping, verifying the base map and re-assessing historic showings, prospects, and deposits. Use of field-based XRF or infrared spectroscopy technology can be used to help vector on alteration, while digital field mapping should be carried out to update the base map in "real-time," regardless of scale.

3) Collection of geochemical samples (Section 8.2.3) should begin with an initial orientation survey to determine the best sampling and analytical methods for the domain and determine if any remote detection methods can be implemented. Sampling collection should begin with systematic lake sediment sampling for regional scale targeting (1 sample/km^2) and be followed by detailed grid (50-100 m sample spacing) till-profile sampling so surficial 3D geochemistry (Section 8.3.4) analysis can be carried out. Elements useful for vectoring towards orogenic deposits include Au, Ag, As, B, Bi, Hg, Sb, Se, Te, W, Cu, Pb and Zn.

4) Reconnaissance Drilling (Section 8.2.6) should be conducted once sufficient geological evidence has been collected, integrated and interpreted with all other data layers to determine the most likely orientation and depths of drilling for intersecting orogenic gold mineralization. Drilling can also be conducted to help define deep structures and confirm 3D geophysical and geological interpretations. Following successful reconnaissance drilling, definition drilling should be conducted to confirm mineralization extensions along strike and down dip. Ensuring proper QA/QC and database management of drill data and drill core samples is essential to maintaining the integrity of a drilling database. Conducting borehole logging (Section 8.2.4.8) should also be carried out as it adds value to drilling by creating more data layers for interpreting the downhole geology and can help facilitate seismic surveys. Seismic surveying (Section 8.2.4.7) also requires physical rock property studies from deep drill holes to determine the survey's potential effectiveness at imaging the subsurface. If seismic surveys are to be conducted, 2D seismic lines should be carried out first and if successful can be expanded to 3D seismic coverage, however seismic is very costly and should only be considered in areas with road access.

These recommendations for exploration fieldwork do not consider budget limitations surely to affect any exploration business model and instead represent an idealized approach without considering budget factors Budgeting will also be affected by the size of the project area, both in terms of the compilation and necessary field work to cover the project area.

As mentioned in CHAPTER 9 and above, exploration in the YGB will likely require JV agreements with current mineral rights holders and deep drilling. Both of these require significant capital to undertake, whereas in the CBGB, the mineral rights acquisition costs maybe low and will depend on the final Akaitcho Agreement. Also, early stage greenfields exploration in the CBGB will be less expensive and more flexible than in the YGB. This is well illustrated in Figure 60, which shows how initial regional targeting and exploration, as would be carried out in the CBGB, allows for increased flexibility and lower costs, whereas entering into a JV agreement and performing deep drilling in the YGB is less flexible, since the business is then tied to a particular project area, and more expensive as advanced exploration is carried out. A business will need to take these budget and capital-raising issues into consideration when planning exploration projects to allow for continued exploration in the area.
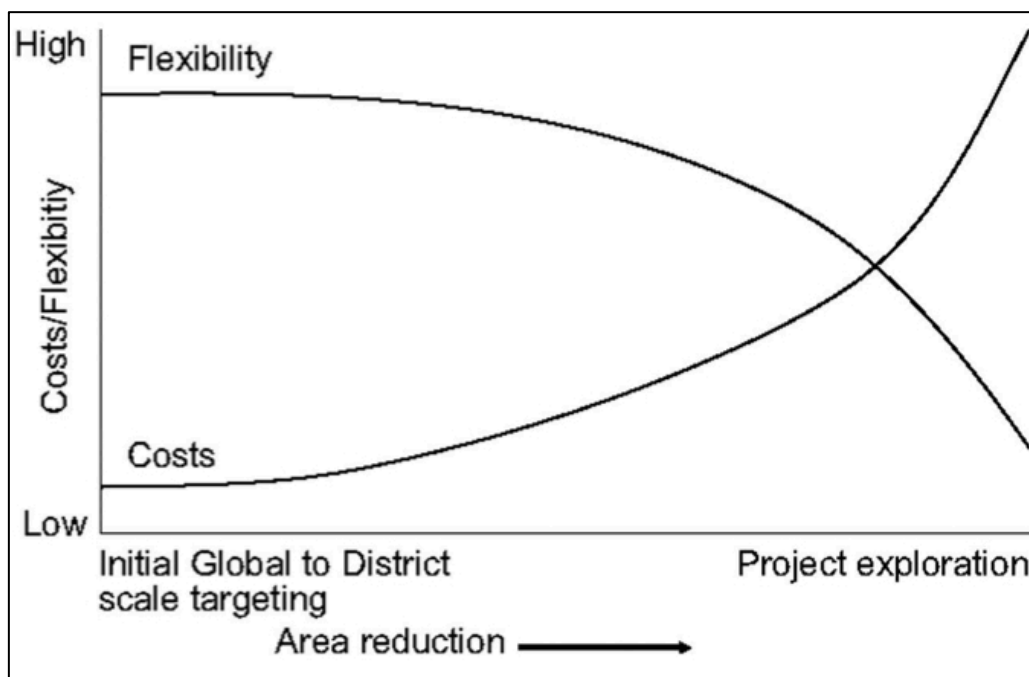

Figure 60. Contrast between global- to district-scale targeting and project scale exploration, highlighting the difference in flexibility and cost of prediction based on targeting model and project exploration. Note that poor targeting can lead to high costs with little chance of discovery (from Hronsky and Groves, 2008)

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