THE GIANT-CON GOLD DEPOSIT: A ONCE-LINKED ARCHEAN LODE-GOLD SYSTEM

James P. Siddorn

A thesis submitted in conformity with the requirements

for the degree of Doctor of Philosophy.

Graduate Department of Geology

University of Toronto

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ABSTRACT

The Giant and Con deposits, Yellowknife, Northwest Territories, represent a classic Archean lode-gold deposit now offset by a major Proterozoic fault (West Bay Fault). The link between the Giant and Con deposits is supported by their similarities. However, there are distinct differences between the two deposits in terms of the offset of stratigraphy, response to D_2 deformation, geometry, gold mineralization styles, and depth of gold mineralization.

Gold mineralization in the Giant-Con system formed over a protracted history of deformation and hydrothermal activity. Early D_1 extension resulted in offset and excision of stratigraphy and the formation of refractory gold mineralization within strongly deformed schistose zones and quartz-carbonate veins. The main D_2 deformation in the district resulted in the strong overprint of D_1 refractory gold mineralization and was associated with the northwest-southeast flattening of the Giant deposit and progressive reverse-dextral shear of the Con deposit. Free-milling gold mineralization is associated with the D_2 event, forming deeper in the Giant-Con system, creating a vertical zonation of free-milling quartz-carbonate veins overprinting earlier refractory gold mineralization that formed higher in the system.

Ore plunge in the Giant deposit is controlled by the interaction of the original geometry of D_1 deformation zones with the effects of D_2 flattening. Ore plunge in the Con deposit is controlled by the orientation of F_2 fold and B_2 boudin axes in auriferous quartz-carbonate veins.

 D_3 reactivation of the deformation zones (probably related to the end of the D_2 compressive event) caused local reactivation of structures and is not associated with gold mineralization.

D₄ Proterozoic faulting offset and segmented the two deposits, including the major offset by the West Bay Fault. A new reconstruction of the West Bay Fault shows that the Con deformation zone is the down dip extension of the Giant deposit and not the Campbell deformation zone as previously thought.

ACKNOWLEDGEMENTS

I would like to acknowledge Professor Alexander R. Cruden who invited me to come to Canada and oversaw my Ph.D. research. Dr. Cruden provided excellent guidance and direction, teaching me to recognize, observe, analyze, and interpret the important geological features of structurally controlled gold deposits and Archean greenstone belts. These skills I will utilize a great deal in my future career.

I would like to thank the Government of the Northwest Territories (Minerals, Oil and Gas Division), Geological Survey of Canada (Mineral Resource Division), Department of Indian and Northern Affairs (Geology Division), Miramar Mining Ltd., and Royal Oak Mining Ltd. for supporting this research before and as part of the Extech III project. The Extech III project would never have come to fruition without the work of Ms. Deborah Archibald and Dr. Lyn Anglin.

The majority of this research was conducted on the Giant and Con mine properties, both underground and on surface. I am indebted to Malcolm Robb, Tim Canam, and Bob Hauser who provided the access underground and on surface. I would like to thank especially Bob Hauser whose knowledge of the Con deposit provided an excellent database of its geology, and our many afternoon discussions helped test my ideas and observations. I would like to also acknowledge all of the mine staff at the Giant and Con mines, including geologists Steve Roebuck, Brad Mercer, Brenda Bilton, Jeff Kulas, Jahlil Mustafa, Sharon Cunningham, Rick Woodward, Morris Robinson, Dave Arthur, and Alf Silke.

I would like to thank all members of the Extech III research team for their collaboration; including: Dr. John Armstrong, Hendrik Falck, Dr. Danny Wright, Garth

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Kirkham, Dr. Ed van Hees, Dr. Peter Thompson, Edith Martel, Luc Ootes, Dr. Dave Lentz, Craig Finnigan, Dr. Norm Duke, Dr. John Ketchum, Dr. Val Jackson, Dr. Bill Davis, Dr. Kate McLachlan, Dr. Brian Cousens, John Kerswill, Dr. Dan Kerr, Dr. Jonathan Mwenifumbo, and Dr. John Katsube. I am grateful to Dr. Benoit Dube who posed excellent questions and provided insights during my Ph.D.

I want to express my gratitude to my committee members Dr. Pierre-Yves Robin and Dr. Ed Spooner for keeping me and my work on the right track over my many years at the University of Toronto, and for helpful reviews of the work presented here.

A special thank you goes out to my parents and grandfather, who readily supported me and my career choices throughout the years. Their constant enquiries as to when my Ph.D. would be completed added an extra push to finish.

Finally, I would like to especially thank my wife Nicole, whose patience in waiting for my Ph.D. to be completed is amazing; I could not have completed this without her.

This thesis is dedicated to Mrs. W. Young.

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CHAPTER 1

INTRODUCTION

RATIONALE

"From the description of this system it is readily apparent that the Giant-Campbell system is extremely complex, and it is a foregone conclusion that the last word on its nature has not been said."

Boyle (1953)

Since the work of Boyle (1953, 1961) the gold-quartz vein deposits of Yellowknife have been recognised as classic examples of structurally controlled shear hosted gold-quartz deposits. The subsequent work of Kerrich and Allison (1978), Webb (1983), Kerrich and Fyfe (1988), and Brown (1992) have presented the Yellowknife deposits as being typical of Archean shear hosted mesothermal gold mineralisation in terms of fluid geochemistry and deformation vein geometry. Although the geology of the Yellowknife Greenstone belt and of the gold deposits hosted within the belt have received a great deal of attention, the structural geology of the Giant and Con deposits have never been studied collectively or as in such depth as the present study, nor have the deposits been considered in the context of new insights on the deformation and formation of Archean lode gold deposits (Poulsen et al. 1994; Robert and Poulsen, 2001).

The characteristics of Archean lode gold deposits depend on the timing of mineralisation relative to deformation (pre- D_2 / syn- D_2), the structural styles and

1
kinematics of host deformation zones relative to the deformation regime (e.g., pure vs. simple shear, transpression), and the mechanical properties of the deformation zone, which influences the localisation of strain, mineralisation and reactivation (Poulsen et al., 1994).

The purpose of this study is to detail the structural history, controls and timing on mineralisation, subsequent deformation and modification of ore bodies within the Giant and Con gold deposits. Determining controls and timing of mineralisation relative to deformation are key factors for exploration in the area. Understanding the deformation zones that host the Giant-Con gold deposits provides a unique opportunity to resolve first order (D₁) structural characteristics with implications for the formation of the deposits and the subsequent history (D₂, D₃, D₄) of a classic gold camp.

Any structural hypothesis for the formation and deformation of the Giant and Con gold deposits must take into account the differences and similarities in (i) structure (geometry of deformation zones and fabrics, timing of deformation) and (ii) mineralisation (timing and styles) between the deposits, in conjunction with (iii) an estimation of the total dip and strike offset of the deposits by the West Bay Fault.

Key questions defined at the initiation of this study were:

 Are the Giant and Con gold deposits part of a linked system offset by Proterozoic faulting?

- Did the Giant-Con gold deposits form in a D₁ structure that was overprinted by deformation?
- iii) What was the D_1 and D_2 geometry of the Giant-Con gold deposit and under what tectonic conditions were these geometries established?

SIGNIFICANCE

The work presented here constrains the links between the Giant and Con Archean lode gold deposits, providing new evidence that the Con deformation zone is the down dip extension of the Giant deposit and not the Campbell zone (Campbell, 1947, 1948).

The structural model for the Giant deposit provides a new, coherent understanding of why the deformation zones at Giant are so complex in geometry, including the first recognition of mullion-structures in the geometry of a gold deposit. It outlines a new understanding for the timing of gold mineralization relative to deformation, explaining why the Giant deposit displays a 'folded' geometry while at the same time the surrounding wall rocks are not folded. It refutes the evidence for progressive reverse shear strain previously inferred for the deposit (Brown et al., 1959; Brown, 1992).

The structural model for the Con deposit presents a new explanation for the control on ore plunge by the rotation of fold and boudin axes in auriferous veins during progressive shear strain. An outline of the vertical zonation of gold mineralization is presented, with an understanding of the temporal relationships

between gold mineralization phases. A new estimate is provided for the amount of displacement along the Campbell deformation zone during the main phase of D_2 compression.

The work presented here includes a new solution for the West Bay fault, illustrating the problems with past interpretations of its movement (Campbell, 1947, 1948; Brown, 1955), and a new solution for reconstructing the Giant and Con deposits. New evidence is presented for the timing of deformation relative to metamorphism and the zonation of gold mineralization between the two deposits. New combined evidence is provided for early extensional deformation in the Yellowknife Greenstone Belt, which may be linked to the formation of the 'Timiskaming'-style Jackson Lake Formation. A comparison of controls on the formation of refractory verses free-milling gold is presented and compared to different deposits worldwide.

LOCATION, ACCESS AND PHYSIOGRAPHY

The Giant gold deposit (114°21W, 62°53'N) is situated 2 miles north of the City of Yellowknife. The Con gold deposit (114°25'W, 62°27'N) is situated immediately south of the City of Yellowknife, within the city limits. Yellowknife, the capital of the Northwest Territories is located on the west shore of Yellowknife Bay on the north arm of Great Slave Lake.

The topography of the area around both the Giant and Con deposits is rugged with low swampy areas bounded by steep scarps with topography ranging from 10-30 m. Outcrop exposure is excellent and averages around 70-

80%. The deformation zones that host the Giant and Con deposits form recessive weathering features, with clay and till cover to depths of up to 25 m, limiting the exposure of shear zone material to trenched areas and small exposures along the margins of valleys. The relationship between deformation zones and valleys has aided exploration in the past, with the Giant deposit deformation zones originally being traced by A.S. Dadson (Dadson and Bateman, 1948) along the broad valley of Baker Creek. The past operation of roasters at both gold mines has eliminated most lichen cover in the vicinity of each mine site with a gradual increase in lichen cover away from the mines.

FIELD WORK AND METHODOLOGY

Underground mapping, field mapping, diamond drill core logging, sampling, petrography, and three-dimensional modelling constitute the database for this study. Underground mapping, field mapping, sampling, and core logging were conducted on the Giant deposit in 1998 and 1999 over seven months, and on the Con deposit in 1999, 2000, and 2001 over twelve months. A total of nineteen months were spent conducting fieldwork in the Yellowknife area by the author. A compilation of all underground mapping conducted at the Giant and Con mines is provided in Appendix A and B. A total of 60 polished thin sections were prepared from samples collected during fieldwork for petrofabric and paragenetic analysis. Three samples were sent for whole rock geochemical analysis at Vancouver Petrographics Ltd. for the determination of the presence of altered and deformed lamprophyre dyke.

A series of 50 AutoCAD based geological sections and 10 AutoCAD based geological maps of the Con deposit were provided by Miramar Mining Ltd. for the compilation of a geological 3D model for the Con deposit. A series of 10 AutoCAD based geological sections of the Giant deposit were provided by Royal Oak Mining Ltd. for the compilation of a geological 3D model of the Giant deposit. Another 10 AutoCAD based geological maps and 2 AutoCAD based geological sections were prepared by the author of the underground geology at Giant. All maps and sections required editing to prepare the dataset for 3D geological modelling in gOcad.

THESIS STRUCTURE

This thesis is arranged in a series of three journal papers, in preparation. Aspects of the three papers have been published in one summary paper on the research (Siddorn et al., 2006); however, the papers presented here are broader and more comprehensive, covering more detail on the geology of each deposit and the links between them.

Although some repetition regarding study areas, data, background work, etc. is inevitable, each paper is in itself a complete research study. The papers build on one another in order to preserve a thesis-type flow within this work. Each of the three papers forms a chapter of this thesis.

The first two papers (Chapters 2 and 3) are written to document the individual structural analyses of the Giant and Con gold deposits respectively. The papers present results from each deposit, including the structural and

mineralization history, focused on aspects of their unique geological settings. The third paper (Chapter 4) presents a comparison between the two deposits, reconstructing the original geometry of the Giant-Con gold system. This includes a new analysis of the offset of the two deposits by the Proterozoic West Bay Fault.

Chapter 2:

EARLY GOLD MINERALIZATION VERSES LATE OVERPRINTING IN A STRUCTURALLY COMPLEX GOLD DEPOSIT: THE GIANT GOLD DEPOSIT, YELLOWKNIFE, CANADA.

Authorship: James P. Siddorn (1), Alexander R. Cruden (2).

Journal to be published in: Economic Geology.

Main topics addressed:

- (i) Role of original structure and overprinting deformation controlling gold distribution; and
- (ii) Correlation of early refractory gold mineralization with extensional deformation.

Statement of co-authorship:

- 1. Concept:
 - a. Structural relationships: 1 60%, 2 40%;
 - b. Mineralization styles: 1 80%, 2 20%; and
 - c. Ore plunge: 1 80%, 2 20%.
- 2. Structural analysis/field mapping: 1 90%, 2 10%;
- 3. 3D modeling: 1 100%;
- 4. Paper writing: 1 75%, 2 25%;
- 5. Editing: 1 80%, 2 20%; and
- 6. Diagrams: 1 90%, 2 10%.

Chapter 3:

MULTISTAGE GOLD MINERALIZATION IN THE CON GOLD DEPOSIT, YELLOWKNIFE, CANADA: INFLUENCE OF OVERPRINTING DEFORMATION ON THE GEOMETRY OF ORE ZONES.

Authorship: James P. Siddorn (1), Alexander R. Cruden (2), and Robert L. Hauser (3).

Journal to be published in: Economic Geology.

Main topics addressed:

- Multistage gold mineralization vertically zoned within the deposit; and
- (ii) Control on ore plunge by overprinting deformation combined with deformation zone thickness (strain intensity).

Statement of co-authorship:

- 1. Concept:
 - a. Structural relationships: 1 60%, 2 20%, 3 20%;
 - b. Mineralization styles: 1 70%, 2 15%, 3 15%; and
 - c. Ore plunge: 1 80%, 2 20%.
- 2. Structural analysis/field mapping: 1 70%, 2 10%, 3 20%;
- 3. 3D modeling: 1 100%;
- 4. Paper writing: 1 75%, 2 25%;
- 5. Editing: 1 80%, 2 20%; and
- 6. Diagrams: 1 80%, 2 10%, 3 10%.

Chapter 4:

THE GIANT-CON GOLD DEPOSITS: EVIDENCE FOR A ONCE-LINKED ARCHEAN LODE-GOLD DEPOSIT.

Authorship: James P. Siddorn (1) and Alexander R. Cruden (2)

Journal to be published in: Exploration and Mining Geology.

Main topics addressed:

- (i) Links between the Giant and Con gold deposits;
- (ii) New solution for the West Bay fault;
- (iii) New reconstruction of the Giant-Con deposit; and
- (iv) Timing constraints for gold mineralization in the Giant-Con deposit.

Statement of co-authorship:

- 1. Concept:
 - a. Structural analysis of the West Bay fault: 1 90%, 2 10%;
 - b. Comparison of mineralization styles: 1 85%, 2 15%;
 - c. Comparison of structural history: 1 80%, 2 20%; and
 - d. Timing constraints: 1 90%, 2 10%.
- 2. Structural analysis/field mapping: 1 90%, 2 10%;
- 3. 3D modeling: 1 100%;
- 4. Paper writing: 1 75%, 2 25%;
- 5. Editing: 1 70%, 2 30%; and
- 6. Diagrams: 1 90%, 2 10%.

REFERENCES

Boyle, R.W.

- 1953: Mineralisation of the Yellowknife greenstone belt, with special reference to the factors that controlled its localization. Ph.D. thesis, University of Toronto, 999p.
- 1961: The geology, geochemistry and origin of the gold deposits of the Yellowknife district, N.W.T. Geological Survey of Canada, Memoir 310.

Brown, I.C.

1955: Late faults in the Yellowknife area. Geological Association of Canada Proceedings, v. 7, p. 128-138.

Brown, N.N.

1992: Evolution of deformation and mineralisation styles within the Giant shear zone complex, Yellowknife, N.W.T., Canada. Ph.D. thesis, University of California, Santa Barbara, 445p.

Campbell, N.

- 1947: Regional structural features of the Yellowknife area. Economic Geology, v. 42, p. 687-698.
- 1948: West Bay Fault. *In:* Structural Geology of Canadian Ore Deposits. Canadian Institute of Mining & Metallurgy, Jubilee Volume, pp. 244-259.

Dadson, A.S., & Bateman, J.D.

1948: Giant Yellowknife Mine. *In:* Structural geology of Canadian ore deposits. Canadian Institute of Mining and Metallurgy, Jubilee Volume, pp. 273-283.

Kerrich, R., and Fyfe, W.S.

1988: The formation of gold deposits with particular reference to Archean greenstone belts and Yellowknife: I. geological boundary conditions and metal inventory, II. Source of hydrothermal fluids, alteration patterns and genetic models. Contributions to Geology of the Northwest Territories, NWT Geology Division, DIAND, v. 3, p. 37-95.

Kerrich, R., & Allison, I.

1978: Vein geometry and hydrostatics during Yellowknife mineralisation. Canadian Journal of Earth Sciences, v. 15, p. 1653-1660. Robert, F. and Poulsen, K.H.

2001: Vein formation and deformation in greenstone gold deposits. In: Richards, J.P., and Tosdal, R.M., eds., Structural Controls on Ore Genesis: Society of Economic Geologists, Reviews in Economic Geology, v. 14, p. 111-155.

Poulsen, K.H., Robert, F., & Dube, B.

1994: Structural analysis of lode gold deposits in deformed terranes. Geological Survey of Canada, Open File 2850.

Siddorn, J.P., Cruden, A.R., Hauser, R.L., Armstrong, J.P., and Kirkham, G.

2006: The Giant-Con Gold Deposits: Preliminary Integrated Structural and Mineralization History. In: Anglin, C.D., Falck, H., Wright, D.F. and Ambrose, E.J., eds., Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the EXTECH III Multidisciplinary Research Project, Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 213-231.

Webb, D.R.

1983: The Relationship of Ore to Structural Features of the Campbell Shear Zone and Hanging Wall Stratigraphy in the Con Mine Yellowknife, Northwest Territories; MSc. thesis, Queen's University, Kingston, Ontario, 181p.

CHAPTER 2

EARLY GOLD MINERALIZATION VERSUS LATE OVERPRINTING IN A STRUCTURALLY COMPLEX GOLD DEPOSIT: THE GIANT GOLD DEPOSIT, YELLOWKNIFE, CANADA

Siddorn, J.P.^{1, 2} and Cruden, A.R.¹

- ¹ Department of Geology, University of Toronto, 22, Russell St., Toronto. Ontario. M5S
- 3B1. ² Present Address: SRK Consulting (Canada) Inc., Suite 2100, 25, Adelaide St. East,

ABSTRACT

The Giant gold deposit is Canada's seventh largest gold deposit and the largest gold deposit in the Slave Province. It is a world-class deposit (>150t Au) and has produced more than 8,154,496 ounces of gold at a grade of 0.468 ounces per ton (~232 metric tonnes at 16 g/t). The deposit forms part of the Archean Giant-Con gold system, hosted within deformation zones that crosscut the Yellowknife Greenstone Belt, Slave Province. The Giant deposit is an atypical Archean mesothermal orogenic gold deposit; with gold mineralization largely forming early in its structural history, with a long strike extent and relatively short dip extent.

The Giant gold deposit is dominated by early, D₁ related, refractory gold mineralization that has been strongly overprinted by the main D_2 deformation. D_1 deformation at Giant is linked to early extensional deformation, potentially related to the formation of half grabens containing the adjacent 'Timiskaming' style Jackson Lake Formation.

 D_2 northwest-southeast shortening resulted in formation of the dominant S_2 foliation throughout the deposit, the structural remobilization, folding and boudinage of existing competent auriferous quartz-ankerite-sericite schist and quartz veins, and the formation of mullion structures at the deformation zone-wall rock interface. D_2 deformation at Giant was dominated by northwest-southeast directed flattening and not reverse shear as previously described. D_3 reactivation caused local reverse shear of the Giant deformation zones. The Giant deposit was subsequently offset and truncated by D_4 Proterozoic faults, including its offset from the Con deposit by the West Bay Fault. The interaction of the original geometry of the host deformation zones in the deposit, resulting in the formation of shallow northwest and southeast ore plunges.

Keywords

Early gold, Yellowknife, deformation, ore plunge, mullion structure.

INTRODUCTION

The Giant gold deposit is Canada's seventh largest gold deposit and the largest gold deposit in the Slave Province. It is a world-class deposit (>150 metric tonnes Au) and has produced more than 8,154,496 ounces of gold at a grade of 0.468 ounces per ton (~254 metric tonnes at 16 grams per tonne). The deposit forms part of the Archean Giant-Con gold system, hosted within deformation zones that crosscut the Yellowknife Greenstone Belt (YGB), Slave Province (Figs. 2.1A, B, and C). The Giant deposit is situated on the northern limit of the city of Yellowknife, Northwest Territories, on the north shore of Great Slave Lake in northern Canada.

The Giant gold deposit was discovered in 1938, when D.W. Cameron located an outcrop of a gold-bearing deformation zone widely recognized as the Giant discovery outcrop. However, at this time all other exploration drilling on the Giant property was generally inconclusive. It was in 1943 when A.S. Dadson examined the Giant property that he hypothesized that the drift-filled valleys, areas neglected by previous exploration, were underlain by a major system of gold-bearing deformation zones. From 1944 to 1946, 199 diamond drill holes, totaling 25.6 km, were completed over an interpreted 3.5 km strike length. This surface drill program confirmed the subsurface presence of several deformation zones that hosted numerous zones of gold mineralization that went on to form the Giant deposit.

Controversy over the Giant deposit has centered on both the timing of mineralization relative to deformation and the style of the main phase of deformation (flattening verses reverse shear dominated). The Giant deposit has been interpreted as both a classic reverse shear zone hosted gold deposit, with gold mineralization either argued or assumed to be synchronous with the main compressional deformation (Brown et al., 1959; Boyle, 1961; Henry and Richert, 1971; Kerrich & Allison, 1978; Brown,

1992), and as an atypical, flattened and folded gold deposit, with gold mineralization forming prior to the main compressional deformation (Dadson and Bateman, 1948; Bateman, 1952).

Despite a lack of conspicuous offset markers, a case was made early in the research history of the camp for the main phase of deformation at Giant being dominated by reverse shear, based on the observation that the mean foliation is generally oblique to and is more steeply dipping than the deformation zone boundaries (Campbell, 1947). This fit with the interpretation of the nearby Con deposit at the time, thought to be hosted by a series of reverse shear zones (Campbell, 1947; Brown et al., 1959).

The deformation zones that host gold mineralization in the Giant deposit display a complex geometry that is unlike any other Archean gold deposit. The deformation zones form synform-antiform and lobate-cuspate geometries and deformation zones that attenuate into the surrounding mafic metavolcanic rocks. No previous study has accurately described and demonstrated how this geometry formed.

This paper provides a new interpretation of the structural history of the Giant deposit, with specific reference to the timing of gold mineralization relative to deformation, including evidence for a previously unrecognized phase of deformation in the deposit. This study focuses on deformation history and styles, controls on the unusual geometry of the deposit, and the controls on the geometry and plunge of ore zones.

DEPOSIT GEOLOGY

The Giant gold deposit is hosted within a series of Archean deformation zones that crosscut the Kam Group in the YGB, between the Proterozoic West Bay and Akaitcho faults, north of the Con gold deposit (Figs. 2.1 and 2.2). The deformation zones consist of hydrothermally altered and deformed sericite or chlorite rich rocks, with or without an apparent schistosity.

The YGB lies between granodiorite intrusions of the Western Plutonic Complex of the Defeat Suite to the west (2.64–2.58 Ga., Atkinson and Van Breeman, 1990), and metaturbidites of the Duncan Lake Group to the east (2.66 Ga; Mortensen et al., 1992; Fig. 2.1).

The YGB consists of a northeast striking, steeply southeast dipping homocline of mafic metavolcanic and intrusive rocks of the Kam Group (2.72-2.7 Ga, Isachsen and Bowring, 1994, 1997), structurally overlain by northeast striking intermediate and felsic metavolcanic rocks of the Banting Group (2.66 Ga, Isachsen and Bowing, 1994; Figs. 2.1 and 2.2). The Kam Group is subdivided into four formations (Figs. 2.1 and 2.2): a lower mafic dyke complex (Chan Formation); a sequence of massive and pillowed metabasaltic flows, interlayered with cherts and felsic tuffs (Crestaurum Formation); rhyodacite breccias interbedded with felsic tuffs and pillowed dacites (Townsite Formation); and massive and pillowed metabasaltic flows, pillow breccias and interflow sediments (Yellowknife Bay Formation; Fig. 2.2). Tectonically juxtaposed between the Kam and Banting Groups are conglomerates and sandstones of the "Timiskaming" style Jackson Lake Formation (2.6 Ga, Isachsen and Bowring, 1994, 1997). The Jackson Lake Formation is regarded as the youngest unit in the region (Helmstaedt & Padgham, 1986; Isachsen & Bowring, 1997; Figs. 2.1 and 2.2).

The Kam and Banting Groups are crosscut by steeply dipping, gabbro dykes that

strike northwest-southeast to northeast-southwest, are sub-vertical (No. '8' series dykes, Henderson and Brown, 1966). MacLachlan and Helmstaedt (1995) consider the age of the gabbro dykes to be between 2.618 and 2.642 Ga based on crosscutting relationships with the Anton granite and the Defeat Suite Western Plutonic Complex. The gabbro dykes appear to preserve their original steeply dipping geometry, even though the Kam Group stratigraphy has been rotated and dips steeply to the southeast. This geometry suggests that the dykes were emplaced after tilting of the Kam and Banting groups and prior to the deposition of the Jackson Lake Formation (2.6 Ga).

The Giant deposit is largely hosted within deformation zones crosscutting the Yellowknife Bay Formation; however, sections of the deposit also occur in the Townsite and Crestaurum Formations. The deformation zones form a complex system of linked, quasi-planar zones that in map view display a simple northeast trending braided pattern up to 500 m wide, with individual alteration-deformation zones that are typically 30-60 m wide (Fig. 2.2). In cross section, the geometry of the deformation zones is more complex, defining intersecting zones with northwest, southeast and vertical dips defining synform-antiform shapes (Fig. 2.3). The deformation zones display complex contacts with the surrounding mafic metavolcanic rocks, with lobate-cuspate geometries, with cusps of deformation zone attenuating into the surrounding metavolcanic rocks. The Giant deformation zones truncate the Townsite Formation in plan view and cross section (Fig. 2.2).

The Giant deposit contains mainly refractory gold encapsulated within arsenopyrite that is disseminated within quartz-ankerite-sericite schist, surrounded by chlorite +/-sericite schist. Refractory and minor free-milling gold is also hosted in laminated fault-fill quartz-carbonate veins and breccias.

Gold mineralization in the Giant deposit is only known to extend to a depth of 600

m, but extends over a 6 km strike length (Figs. 2.2 and 2.3). This is atypical for mesothermal-orogenic lode gold deposits, which tend to have longer down-dip than strike extents (Groves et al., 1998).

PREVIOUS RESEARCH

Despite the extraction of over 8 million ounces of gold from the Giant deposit over its 50 year history, studies of its origin have been relatively few and largely focused on geochemical characteristics (Boyle, 1953, 1961; Coleman, 1957; Madeisky and Chernavska, 1995; and Van Hees et al., 1999). Studies of the structural geology of the Giant deposit are limited to Dadson and Bateman (1948), Bateman (1952), Brown et al., (1959), Henry and Richert (1971), Hodgson (1976), and Brown (1992).

Dadson and Bateman (1948), Bateman (1952), and Brown et al. (1959) observed that the internal structure and ore bodies at Giant provide evidence of folding and thus hypothesized that the Giant deformation zones were, in fact, one single horizon that had been folded. However, Bateman (1952) and Brown et al. (1959) could not account for how the Giant deposit could be folded when there is a lack of folding in the surrounding Kam Group, as recent mapping had shown the Kam Group to be a southeast facing homoclinal volcanic sequence (Henderson and Brown, 1966). Brown et al. (1959) also determine that different "folds" within the Giant deformation zones display opposing plunges, with an antiformal zone plunging north 15°-30° ('B' Shaft zone) and a synformal zone plunging 12° south ('C' Trough zone). This they regarded as unusual for folding. Following comparison with the nearby Con gold deposit, which displays none of the complex geometry observed at Giant, Brown et al., (1959) concluded that a folding solution was inapplicable. They conclude that the Giant deformation zones formed by

reverse shear that was synchronous with gold mineralization. This fit with the Con deposit and with the apparent offset and truncation of the Townsite Formation by the Giant deformation zones.

Henry and Richert (1971) and Brown (1992) proposed that the geometry of the Giant deformation zones represents a series of anastomosing shear zones. Both studies described the Giant deposit geometry as "fish" or "poisson" structures, with the deformation zones wrapping around undeformed mafic metavolcanic rocks (fish). Henry and Richert (1971) and Brown (1992) proposed that the Giant deformation zones were formed by east-west bulk inhomogeneous shortening and reverse shearing with gold mineralization forming syntectonically. They did not account for the apparent offset and truncation of the Townsite Formation by the Giant deformation zones.

Both the folding model proposed by Dadson and Bateman (1948), Bateman (1952), and Brown et al. (1959) and the reverse shear model proposed by Brown et al. (1959), Henry and Richert (1971) and Brown (1992) do not fully account for the unusual geometry of the Giant deformation zones or the truncation of the Townsite Formation.

DEFORMATION

The Giant deformation zones display evidence for early D_1 deformation and associated gold mineralization that was overprinted by the main D_2 phase of deformation. The evidence for early deformation in the Giant deposit is shown in the complex geometry of the host deformation zones, early crenulated fabrics within the deformation zones, and the offset of the Townsite Formation by the deformation zones. We attribute this early deformation to a D_1 phase of early extension that was subsequently overprinted by the D_2 main compressional phase of deformation,

reactivated during D_3 deformation, and crosscut by D_4 Proterozoic faults. The characteristics of these four phases of deformation and the supporting evidence for each is described below.

D₁ Extension

The complex geometry of the Giant deformation zones with synformal-antiformal intersecting zones and lobate-cuspate shaped contacts with the surrounding Kam Group country rocks is an indication of an early altered and mechanically/chemically weakened structure overprinted by deformation. We interpret this geometry to be similar to that displayed in mullion structures.

Mullion structures are lobate-cuspate deformation features that develop at the interface between rocks of different mechanical competence during layer parallel shortening (e.g. an incompetent deformation-alteration zone surrounded by competent wall rock; Smith, 1975, Sokoutis, 1987). In axial profiles, mullion structures consist of rounded lobes convex into the least competent material alternating with sharp cusps pointing towards the more competent material. This matches the geometry observed in the deformation zones that form the Giant deposit, where the rounded lobes are convex into the weaker deformation zones with sharp cusps pointing towards rock of the more competent Kam Group (Fig. 2.4).

Mullion structures are also displayed at stope and hand specimen scales within the Giant deposit. At the stope scale, weak sericite schist alteration zones surrounded by stronger chlorite schist alteration zones often display mullion structures (Figs. 2.5A and B). At the hand specimen scale, weak ankerite veins surrounded by stronger chlorite schist also display mullion structures (Figs. 2.5C and D).

The presence of mullion structures in the Giant deformation zone-wall rock interface suggests that the deformation zones are pre-existing D_1 weak deformation/alteration zones surrounded by stronger Kam Group metavolcanics that were shortened to form mullion structures during the later D_2 compressional deformation (see D_2 Compression below).

A locally preserved S_1 foliation displays evidence for D_1 early extensional deformation in the Giant deposit. The S_1 foliation is defined by the alignment of chlorite, sericite, and arsenopyrite (Figure 2.6A and B). The S_1 foliation is commonly completely transposed into S_2 and otherwise isoclinally folded by overprinting F_2 folds attributed to the D_2 main compressional phase of deformation (Figure 2.6A and B; see D_2 Compression below). The S_1 foliation is most often preserved in the core of deformation zones within zones of auriferous quartz-ankerite-sericite schist.

The enveloping surfaces of F_2 fold hinges of the S₁ foliation consistently dip at a shallower angle than the deformation zone boundaries (Figs. 2.7A, B, and C). In monoclinic progressive simple shear zones, foliations form initially at 45° to the shear zone boundary, parallel to the plane of instantaneous flattening (Ramsay and Graham, 1970; McClay, 1987). Therefore, in a deformation zone dipping 45°, the foliation will initially be vertical if the sense of shear is reverse (Fig. 2.7D), or horizontal if the sense of shear is normal (Fig. 2.7E). At Giant, the fact that the dip of enveloping surfaces of F_2 fold hinges of the S₁ foliation is shallow, suggests the original S₁ foliation was more gently inclined than the surrounding deformation zones. This angular relationship indicates that the S₁ foliation was most probably related to normal movement along the deformation zones (Figs. 2.7B, C, and D).

Further evidence for D₁ extensional deformation is provided by the offset of the Townsite Formation by the Giant deformation zones versus the Campbell deformation

zone in the Con gold deposit. The Giant and Campbell deformation zones display an opposing strike separation of the Townsite Formation. The Giant deformation zones display an 1100 m sinistral strike separation (Fig. 2.8A), whereas the Campbell deformation zone displays a 350 m dextral strike separation (Fig. 2.8B). This relationship has not previously been recognized and both offsets cannot be attributed to any phase of overprinting deformation (see Chapter 3, D_1 Deformation).

The opposing strike separation can be explained by early D₁ normal faulting along the Giant and Campbell deformation zones which have opposing dips (Fig. 2.8C). The Giant deformation zone that offsets the Townsite Formation dips southeast, whereas the Campbell deformation dips northwest. Given the orientation of the Townsite Formation (east-northeast strike, steep southeast dip), normal faulting along the southeast dipping Giant deformation zones would result in the down throw of the southeast block creating a sinistral strike separation of the stratigraphy (Fig. 2.8A). Normal faulting along the northwest dipping Campbell zone would result in the down throw of the northwest block creating a dextral strike separation of the stratigraphy (Fig. 2.8B). In this extensional fault system the opposing dip of the Giant and Campbell zone would create a graben (Fig. 2.8C). Southwest dipping strata in the graben would appear to move north creating the opposite strike separation across the Giant versus the Campbell deformation zone (Fig. 2.8C).

The combined evidence of mullion structures in the deformation zones, the pre-D₂ orientation of S₁ foliation planes, and the offset of stratigraphy suggests an D₁ early deformation event occurred in the Giant deposit that was dominated by normal displacement related to northwest-southeast extension.

D₂ Compression

The S₁ foliation is overprinted by an S₂ foliation, which can be correlated to the major regional D₂ deformation event in the Yellowknife Domain (Bleeker and Beaumont-Smith, 1995; Davis and Bleeker, 1999; Siddorn and Cruden, 2000; Martel and Lin, 2006). The S₁ foliation is crenulated by a steep axial planar S₂ foliation that strikes northeast, parallel to the strike of the deformation zones, and dips steeply northwest or southeast (Fig. 2.9A). The S₂ foliation is defined by the alignment of chlorite, sericite, quartz, and carbonate. The intersection of the S₁ and S₂ foliations forms a well-developed intersection lineation (L_{2i}) that rakes shallowly north. In zones of high D₂ strain the S₁ foliation is completely transposed into the S₂ foliation (Fig. 2.10A).

The S₂ foliation remains steep and is axial planar to upright, symmetrical, tight to isoclinal F₂ folds and B₂ boudins throughout the Giant deformation zones (Figure 2.9B and 2.10B and C). F₂ folds and B₂ boudins of quartz veins plunge shallowly northwest and southeast within the axial planar S₂ foliation (Fig. 2.9C). Syn-D₂ extensional sub-horizontal V_{2d} quartz-calcite veins formed orthogonal to the S₂ foliation and are preferentially developed within chlorite schist on the periphery of auriferous quartz-ankerite-sericite schist and auriferous quartz veins (Fig. 2.9D).

A progressive flattening of wall rocks can be observed moving from undeformed Kam Group mafic metavolcanic rocks into the Giant deformation zones. Mafic-pillowed metavolcanic rocks of the Yellowknife Bay Formation are increasingly flattened towards the deformation zone boundaries (Figure 2.10D). The deformation zone contacts at Giant are not sharp, instead foliation intensity increases over 5-10 m and relict pillow selvages can often be observed within chlorite-sericite schist (also noted by Brown et al., 1959).

Throughout the Giant deposit there is a lack of asymmetric D₂ fabrics that would

be indicative of progressive reverse simple shear strain at all scales, as proposed by Brown et al., 1959; Henry and Richert, 1971; and Brown, 1992. In zones of high D_2 strain a stretching lineation is absent. The Giant deposit is dominated by symmetrical fabrics that are indicative of progressive flattening strain. This, combined with the absence of a stretching lineation, indicates that D_2 in the Giant deposit was dominated by northwest-southeast progressive flattening strain and **not** northwest-southeast progressive reverse simple shear strain as previously described by Brown (1992) and Henry & Richert (1972).

This interpretation is further supported by the presence of mullion structures at the wall rock-deformation zone contact. These indicate that the Giant deformation zones were pre-existing incompetent D_1 deformation/alteration zones that were overprinted by D_2 progressive flattening strain resulting in mullion formation. D_1 deformation and alteration resulted in the growth of fine-grained phyllosilicate minerals (e.g. chlorite and sericite) in combination with fluid-assisted recrystallization of quartz and feldspar, which resulted in the formation of mechanical and reaction weakened incompetent deformation zones. D₂ flattening strain resulted in symmetrical F₂ folding and B₂ boudinage of pre-existing competent quartz-rich orebodies at deposit, stope, handspecimen and thin-section scales, simultaneous with mullion formation in the relatively incompetent host alteration-deformation zones. This is best displayed in several crosssections that illustrate the distribution of auriferous guartz-ankerite-sericite schist within the Giant deposit. Figure 2.11 shows representative cross-sections through the Giant deposit, displaying the complex geometry of folded, boudinaged and transposed auriferous quartz-ankerite-sericite schist (red) within the chlorite-sericite schist alteration-deformation zones (grey).

The flattening model we propose for the D₂ deformation is similar to the folding

model of Bateman (1952) and Brown et al. (1959). However, these authors could not account for the termination of the Townsite Formation against the Giant deformation zones or the lack of folding in the Kam Group. As discussed above, offset of the Townsite Formation likely occurred during early D_1 extensional deformation and therefore is not related to D_2 deformation. In addition, it has been recognized that the Kam Group stratigraphy was already steeply dipping prior to the intrusion of the '8' series gabbro dykes, and prior to D_2 deformation. In this orientation, the Kam Group would have responded to D_2 shortening by further tilting and flattening normal to the principal shortening direction, rather than folding, whilst the Giant deposit deformation zones were flattened, folded and mullioned.

D₃ Reactivation

The S₂ foliation is locally refolded forming F₃ folds and locally an S₃ crenulation cleavage. F₃ folding of the S₂ foliation forms upright, moderately plunging, open to tight, angular F₃ folds, with an occasional weak S₃ sub-vertical spaced crenulation cleavage (Figs. 2.12A and B, 2.13A, B, and C). S₃ forms a chloritic spaced cleavage, separating lithons of S₂ foliation displayed in quartz-carbonate-sericite and sulphide. In the Giant deposit, angular F₃ folds with spaced S₃ foliation are easily distinguished from the rounded, tight to isoclinal, F₂ folds of the S₁ foliation that is associated with the penetrative and pervasive S₂ foliation. The orientation of the S₃ foliation is sub-parallel to the S₂ foliation.

Locally, shallow northwest/southeast dipping D_3 shear band (C') structures are observed to cut and rotate the S_2 foliation with a reverse sense of shear. D_3 deformation may represent a late reverse shear reactivation of the Giant deformation zones as it affects all previously noted fabrics and mineralization styles, and is possibly a late

reverse shear increment of D₂ deformation.

D₄ Proterozoic faulting

The Giant gold deposit is segmented and offset by D_4 Proterozoic faults. D_4 Proterozoic brittle faulting resulted in the offset of D_1 , D_2 and D_3 structures, and auriferous zones in the Giant deposit. The Giant deposit is crosscut and truncated by the major West Bay, Townsite, 3-12, Muir, LAW and Akaitcho faults (Fig. 2.14). All major faults are primarily sinistral strike slip faults.

The West Bay Fault bounds the southern and western limits of the Giant deposit (Fig. 2.14). It is well exposed at surface, and is represented by a 10-30 cm wide, gouge or calcite and hematite filled fault (Figs. 2.15A and B). It often contains shallow north raking slickenlines (average orientation: 002/06) with steps indicating it is predominantly a sinistral strike slip fault (west side up and south; Fig. 2.15C). Northeast of the Giant deposit the West Bay Fault forms a 10-20 m wide quartz-hematite cataclasite zone where the fault bends to the northeast (Figs. 2.15D and 2.16A). Where the Giant deformation zones intersect the West Bay Fault, the S₂ foliation is overprinted by minor brittle faults, and the deformation zones are locally reactivated as sinistral strike-slip shears (Fig. 2.16B).

The Townsite Fault is well exposed on surface and underground, and is a narrow (2-10 cm wide) gouge filled fault (Figs. 2.14A and 2.16C). It crosscuts the southern portion of the Giant deposit (Fig. 2.14A). It can contain narrow (<0.5 m wide) zones of brecciated metavolcanics (Kam Group), and minor carbonate and hematite mineralization.

The 3-12 Fault is a wide (5-10 m) fault zone made up of numerous fault splays

(density ~5 fault planes over 2 m) that crosscuts the centre of the Giant deposit (Fig. 2.14A). It does not contain any mineralization or slickenlines, but does clearly crosscut and displace auriferous quartz-ankerite-sericite schist (Fig. 2.16D).

The Akaitcho Fault represents the northern limit of the Giant deposit (Fig. 2.14A). It is well exposed at surface, and is represented by a 10 cm wide gouge filled fault. The Akaitcho Fault has a sinistral strike separation of 1850 m shown by the offset of the Jackson Lake Formation.

The D₄ minor fault density in the Giant deposit is high relative to the Con deposit (e.g. Fig. 2.17), reflecting the proximity of the Giant deposit to the major West Bay, Akaitcho and Townsite D₄ faults. Measurements of D₄ minor faults define northwest-trending sinistral and northeast-trending dextral sets (Figs. 2.14 C and D; and 2.17). Both minor fault populations are best developed near the West Bay, Akaitcho, and Townsite faults. The two minor fault sets are conjugate, indicating a D₄ strike-slip fault regime with σ 1 trending west-northwest, vertical σ 2, and σ 3 trending north-northeast. These inferred paleostress directions are kinematically consistent with sinistral strike-slip movement along the West Bay, Akaitcho, and Townsite faults.

MINERALIZATION

The Giant gold deposit contains mainly refractory "invisible" gold mineralization but also minor free-milling "metallic" styles of gold mineralization. Refractory-gold mineralization contains gold-arsenopyrite assemblages that are not amenable to direct cyanidation. The refractory nature of the mineralization is due to the extremely fine grain size of the gold and to the fact that the microscopic and sub-microscopic particles are encapsulated preferentially within arsenopyrite and, to a lesser extent, pyritic host

sulphide. Free-milling gold mineralization contains native gold or gold-pyrite, goldpyrrhotite, gold-base metal assemblages that are amenable to direct cyanidation and with gold recoveries better than 90%.

Refractory and free-milling gold mineralization in the Giant deposit is mineralogically distinct. Refractory gold mineralization is characterized by assemblages of paragonitic muscovite, AI chlorite, Fe/Mg carbonate, arsenopyrite, and pyrite (Armstrong, 1997). The invisible refractory gold is hosted in As-enriched rims of As/S zoned arsenopyrite (up to 1900 ppm Au), and locally within As-enriched domains of pyrite grains (up to 450 ppm Au; Armstrong, 1997). The free-milling gold mineralization is characterized by a phengitic muscovite-chlorite-calcite-albite-pyrite-pyrrhotite-native gold assemblage (Armstrong, 1997). Locally, considerable amounts of stibnite and antimony sulphosalts occur. Except for rare aurostibnite (AuSb₂), the antimony minerals contain little gold (Dadson and Emery, 1968).

Alteration in the Giant deposit is typified by an outer propylitic assemblage (calcite-chlorite-pyrite) surrounding a zone of phyllic alteration (sericite-pyrite-quartz; sericite being either phengitic or paragonitic muscovite) with an inner zone of silicification and carbonatisation (ankeritisation) +/- quartz veining. The proximal position of ore zones can often be identified based on increasing sericite content, which increases gradationally from chlorite-calcite schist to chlorite-sericite schist to quartz-ankerite-sericite schist (Fig. 2.17). Gold mineralized zones can occupy 10-90% of the width of the host deformation zone. All gold mineralized zones in the Giant deposit are associated with sericite alteration with the mineralized zone devoid of calcite. One exception is the 'A' shaft zone where gold mineralization is hosted in chlorite schist with common calcite (Bateman, 1952).

Van Hees et al. (1999) attribute the elevated arsenic and antimony content of the

Giant deposit to a metasedimentary influence where hydrothermal fluids originating from the Duncan Lake Group metaturbidites were deposited in the Giant deformation zones within reactive Ti-rich tholeiitic basalts of the Kam Group.

Gold mineralization styles and their relationship to deformation

Four distinct styles of gold mineralization have been defined in the Giant deposit, including three styles of refractory-gold mineralization associated with D_1 deformation and one style of free-milling gold mineralization associated with D_2 deformation. All mineralization styles (auriferous and barren) are summarized in Table 2.1.

Three distinct types of refractory-gold mineralization (V_{1a} , V_{1b} , and V_{1c}) are present in the Giant deposit. All three types contain gold encapsulated within disseminated arsenopyrite and arsenian pyrite, and free gold is uncommon. Gold content is roughly proportional to the amount of quartz and arsenopyrite.

 V_{1a} gold mineralization is characterized by intensely deformed quartz-ankeritesericite (paragonite) schist (Figs. 2.18A, B, and C) containing finely disseminated pyrite and arsenopyrite, together with minor amounts of sphalerite, galena, stibnite, jamesonite, and other lead-antimony sulphosalts. V_{1a} mineralization commonly contains boudinaged quartz lenses that may represent earlier quartz veins that have been strongly deformed, transposed and boudinaged within the S₂ foliation. All styles of V_{1a} mineralization contain a strongly developed S₂ foliation. V_{1a} gold mineralization is the dominant gold mineralization type in the Giant deposit.

 V_{1b} gold mineralization is hosted by white laminated fault-fill quartz veins, with narrow sericitic (paragonitic) alteration halos (Figs. 2.19A and B). V_{1b} veins are observed to crosscut V_{1a} mineralization. Wall rock clasts captured within V_{1b} laminated

quartz veins do not contain an S₂ foliation (Fig. 2.19C).

 V_{1c} gold mineralization is hosted within quartz breccia zones and breccia veins (clasts of white quartz surrounded by darker 'smoky' quartz) that are often associated with V_{1b} laminated fault-fill veins (Fig. 2.19D).

All three phases of refractory-gold mineralization (V_{1a} , V_{1b} , and V_{1c}) are deformed by D₂. Evidence for the early timing of refractory gold mineralization relative to overprinting D₂ deformation is evident at all scales throughout the Giant deposit. Auriferous quartz-ankerite-sericite (paragonite) schist ore zones (V_{1a}) are intensely deformed by the D₂ deformation in the Giant deposit. V_{1a} mineralization is tightly folded (F₂), boudinaged (B₂), and transposed into the S₂ foliation on a stope and deposit scale relative to a cross-cutting axial planar S₂ foliation (Figs. 2.18A, B, and C). Numerous examples of isoclinally folded, boudinaged, and strongly transposed ore zones (quartzankerite-sericite schist) are present in deposit scale cross-sections (Fig. 2.11). This deformed geometry is also seen at the stope and hand specimen scale. In the 20-12 area, mapped auriferous quartz-ankerite-sericite schist is clearly folded and boudinaged with an axial planar S₂ foliation (Fig. 2.20).

Sulphide minerals (arsenopyrite and pyrite) associated with gold hosted in V_{1a} mineralization, together with an associated S₁ foliation, are deformed and crenulated by the S₂ foliation (Figs. 2.21A and B).

Sericite clasts within foliated chlorite schist are observed in the 3-70 area of the Giant deposit (Fig. 2.22A). The sericite clasts represent early alteration (possibly related to V_{1a} mineralization) that was brecciated, boudinaged and aligned within the S_2 foliation. This indicates substantial sericite alteration occurred pre-D₂ deformation, with the localised brecciation of alteration and transposition occurring during D₂ deformation.

Laminated fault-fill quartz veins (V_{1b}) are more openly folded and boudinaged by

 D_2 deformation, due to the large competency contrast between the V_{1b} quartz veins and the surrounding schist (Fig. 2.19B). This is confirmed by crosscutting quartz veinlets, which are undeformed in the V_{1b} quartz veins but are tightly folded (F₂) in the surrounding schist. Wall-rock xenoliths within V_{1b} quartz veins contain only an S₁ foliation, with no evidence of an S₂ foliation, indicating the veins formed prior to D₂ (Fig. 2.19C). Quartz breccia veins (V_{1c}) are also folded with an axial planar S₂ foliation (Fig. 2.19D).

The combined evidence suggests $V_{1a/b/c}$ refractory-gold mineralization formed during D₁ and was strongly overprinted by D₂ deformation. V_{1a} gold mineralization represents an early quartz-carbonate vein system that formed during D₁ and was subsequently brecciated, boudinaged, and strongly transposed into the S₂ foliation. The strong transposition of V_{1a} gold mineralization is a key indicator for the early nature of the ore, indicating it was overprinted by the entire D₂ deformation.

One distinct type of free-milling gold mineralization (V_{2a}) occurs in minor proportions in the Giant deposit. V_{2a} gold mineralization is typified by white to grey, mottled, laminated fault-fill quartz veins associated with phengitic muscovite-pyrite alteration halos (Fig. 2.22B). V_{2a} veins frequently contain pyrite, arsenopyrite, sphalerite, and lead-antimony sulphosalts, with free gold being commonly visible. Free gold often occurs within quartz and along wall-rock laminations inside the veins. Stibnite, galena, and sphalerite are often observed in vein interiors and are key gangue minerals associated with V_{2a} gold mineralization. V_{2a} vein quartz colour often changes from white to dark grey or blue along strike within a single vein, with a corresponding decrease in the number of laminations present. The discolouration of the quartz is attributed to the presence of sub-microscopic carbon grains (Boyle, 1953) and fine-grained arsenopyrite and stibnite (Coleman, 1957). Similar associations of auriferous quartz veining with

carbon have been found in the Owl Creek and Hoyle Pond deposits, Abitibi subprovince (Wilson and Rucklidge, 1987). At Giant, V_{1a} quartz-ankerite-sericite (paragonite) schist ores are crosscut by V_{2a} white-grey laminated quartz veins that can host free gold (Fig. 2.22B). V_{2a} white-grey laminated veins crosscut the S₂ foliation and are openly folded. Comparison with the nearby Con deposit suggests the V_{2a} veins formed during D₂ (see Chapter 3, Mineralization).

The Giant deposit contains undeformed late- D_2 barren extensional quartz-calciteepidote veins (V_{2d}; Fig. 2.22C). The V_{2d} quartz-calcite-epidote veins provide a key marker for the proximity of an auriferous zone in the Giant deposit, as they preferentially develop around the margins of ore zones (within 5 m) in the chlorite +/- sericite schist alteration halo.

Late V_{4a} stibnite-calcite-hematite-galena veins are associated with D₄ Proterozoic faulting in the Giant deposit, and form open space filling veins, often with spectacular, undeformed, stibnite-calcite crystal forms (Fig. 2.22D). Cousens et al. (2006) determined a Pb model age of ca. 1.24 Ga for stibnite-galena veins from the Giant deposit.

Control on the plunge and distribution of gold mineralization

All styles of gold mineralization in the Giant deposit have been overprinted by D_2 deformation, resulting in the modification of their original geometry and the resultant control on their distribution and plunge. Key locations within the deformation zones have been highlighted as good targets for high grade gold mineralization, most notably the greatest concentrations are found at: (a) the crest, or west of the crest, of an antiformal structure in the host deformation zone; and (b) in the trough, or west of the trough, of a

synformal structure in the host deformation zone (Brown et al., 1959). We propose this concentration of gold mineralization is related to F_2 folding, B_2 boudinage and redistribution of V₁ refractory gold mineralization during D₂ deformation.

The Giant deposit displays both shallow northeast and southwest ore plunges. This is well displayed in outlines of historical mining for the deposit (Fig. 2.23). Historically, ore plunges in the Giant deposit were thought to be related to the intersection of Kam Group stratigraphy with the deformation zone boundaries (Bateman, 1952). In the Giant deformation zones this intersection plunges 40° northeast. However, in comparison the Giant deposit ore zones display both shallow south and north plunges. Therefore, the intersection of Kam Group stratigraphy with the Giant deformation zones does not match the ore plunge at Giant.

There is a strong correlation between the different orientations of synformal and antiformal host deformation zones and ore plunge in the Giant deposit. In the centre of the deposit, gold mineralization is hosted in the 'C' Trough synformal deformation zone that plunges moderately to the southwest (Figs. 2.24A, B and C). The ore bodies contained within the deformation zone have a similar moderate southwest plunge that matches the moderate southwest ore plunge displayed in the long section.

In comparison, geological mapping in the vicinity of the Giant 'B' Shaft area shows that auriferous quartz-ankerite-sericite (paragonite) schist and the deformation zone have an antiformal shape. Both display a moderate northeast plunge. This trend matches the northeast moderate plunge for gold mineralization depicted in the long section of the Giant deposit (Figs. 2.25A, B and C).

We propose that the geometry of the host deformation zones and the gold mineralization they contain is a function of the original geometry of the Giant

deformation zones combined with the effects of the overprinting D_2 deformation. The 'C' Trough deformation zone may have been originally shallowly southeast dipping, which when shortened during D_2 created a southeast plunging F_2 synformal geometry. The 'B' Shaft deformation zone may have been northeast dipping, which when shortened during D_2 created a northeast plunging F_2 antiformal geometry.

We suggest that the geometry of Giant is so complex because of the original orientation of the deformation zones relative to the overprinting D_2 deformation. If the Giant deformation zones were originally gently dipping, D_2 deformation would have folded and multioned the deformation zones into their current geometry. This accounts for the observation that the Giant deposit is relatively shallow in comparison to typical mesothermal orogenic gold deposits.

CONCLUSIONS

The Giant gold deposit is dominated by early, D_1 related, refractory gold mineralization that has been strongly overprinted by D_2 deformation. D_1 deformation at Giant is linked to early extensional deformation, possibly related to the formation of half grabens containing the proximal 'Timiskaming' style Jackson Lake Formation.

 D_2 northwest-southeast shortening resulted in the formation of the dominant S_2 foliation throughout the deposit, the structural remobilization, folding and boudinage of existing competent auriferous quartz-ankerite-sericite schist and quartz veining, and the formation of mullion structures at the deformation zone-wall rock interface. D_2 deformation at Giant was dominated by northwest-southeast directed flattening and not reverse shear as previously described. The Giant deposit was subsequently offset and truncated by D_4 Proterozoic faults, including its offset from the Con deposit by the West Bay Fault. The original geometry of the host deformation zones combined with the

effects of D_2 deformation controls the geometry of ore zones in the deposit and the shallow northwest and southeast ore plunges.

The Giant deposit is an atypical Archean mesothermal orogenic gold deposit; with gold mineralization largely forming early in its structural history, with a long strike extent and relatively short dip extent.

The association of mesothermal gold and regional to deposit scale extension, and the role of early gold mineralization and the effects of overprinting deformation remain poorly studied. It is critical to understand the primary geometry of host deformation zones and how overprinting deformation modifies their geometry and the gold mineralization. Given the early history of alteration and mineralization, features such as mullion structures should be expected at the boundaries of deformation/alteration zones, depending on the orientation of overprinting deformation zones and the original geometry of the deformation/alteration zones. The Giant gold deposit represents an important example of a world-class gold deposit where gold mineralization formed early in its history and was strongly overprinted by compressional deformation resulting in the formation of a deposit with a complex geometry and short depth extent.

ACKNOWLEDGEMENTS

We are particularly grateful to the participants of the Extech III multidisciplinary program focused on the Yellowknife gold district, in particular Dr. John Armstrong, Dr. Wouter Bleeker, and Dr. Peter Thompson. Dr. Benoit Dube is thanked for his comments in the field and discussions on the geology of the Giant deposit. Siddorn also acknowledges the strong support, guidance and assistance of the Giant mine geology staff, including Malcolm Robb, Hendrik Falck, Steve Roebuck, Brad Mercer, Sharon Cunningham, Morris Robinson, Jahlil Mustafa, Brenda Bilton, and Jeff Kulas. This project was funded by the Government of the Northwest Territories, Geological Survey of Canada, Department of Indian and Northern Affairs Canada, Royal Oak Mines Ltd. and Miramar Mining Ltd. as part of the Extech III program.
REFERENCES

Armstrong, J.P.

1997: Variations in silicate and sulphide mineral chemistry between free-milling "metallic" and refractory "invisible" gold ores, Con mine, Yellowknife, N.W.T: Unpublished PhD thesis, University of Western Ontario.

Atkinson, D.J. and van Breeman, O.

1990: Geology of the Western Plutonic Complex, southwest Slave Province: Late Archean crustal granites and gold mineralization in the Yellowknife district; Geoscience Forum Program, Department of Indian and Northern Affairs., p. 4.

Bateman, J.D.

1952: Some geological features at Giant Yellowknife; Geological Association of Canada Proceedings, v. 5, p. 95-107.

Bleeker W. and Beaumont-Smith, C.

- 1995: Thematic structural studies in the Slave Province, Northwest Territories: Preliminary results and implications for the Yellowknife Domain, Northwest Territories; in Current Research 1995-C; Geological Survey of Canada, p. 87-96.
- Boyle, R.W.
- 1953: Mineralization of the Yellowknife Gold Belt with Special Reference to the Factors which Controlled Its Localization; Ph.D. thesis, University of Toronto, Toronto, Ontario, 257 p.
- 1961: The Geology, Geochemistry, and Origin of the Gold Deposits of the Yellowknife District; Geological Survey of Canada, Memoir 310, 193 p.

Brown, C.E.G., Dadson, A.S., and Wrigglesworth, L.A.

1959: On the ore-bearing structures of the Giant Yellowknife Gold Mine, N.W.T.; Canadian Institute of Mining and Metallurgy, Transactions, v. 62, p. 107-116.

Brown, N.N.

1992: Evolution of Deformation and Mineralization Style within the Giant Shear Zone Complex, Yellowknife, Northwest Territories, Canada; unpublished PhD thesis, University of California, Santa Barbara, California, 445 p.

Campbell, N.

1947: Regional structural features of the Yellowknife area; Economic Geology, v. 42, p. 687-698.

Coleman, L.C.

1957: Mineralogy of the Giant Yellowknife gold mine, N.W.T. Economic Geology, v. 52, p. 400-425.

Cousens, B.L., Falck, H., van Hees, E.H., Farrell, S., and Ootes, L.

2006: Pb isotropic compositions of sulphide minerals from the Yellowknife Gold Camp: Metal sources and timing of mineralization; Chapter 19. In: Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the EXTECH III Multidisciplinary Research Project, (ed.) C.D. Anglin, H. Falck, D.F. Wright, and E.J. Ambrose; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 286-300.

Dadson, A.S. and Bateman, J.D.

1948: Timing of plutonism, deformation, and metamorphism in the Yellowknife Domain, Slave Province, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1169-1187.

Dadson, A.S. and Emery, D.J.

- 1968: Ore reserve estimation and grade control at the Giant Yellowknife mine. In: Canadian Institute of Mining and Metallurgy, Special Publication, v. 9, p. 215-226.
- Davis, W.J. and Bleeker, W.
- 1999: Timing of plutonism, deformation, and metamorphism in the Yellowknife Domain, Slave Province, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1169-1187.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., Robert, F.

1998: Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types', Ore Geology Reviews, 13, pp. 7-27.

Helmstaedt, H. and Padgham, W.A.

1986: A new look at the stratigraphy of the Yellowknife Supergroup at Yellowknife, N.W.T. - Implications for the age of gold bearing shear zones and Archean basin evolution; Canadian Journal of Earth Sciences, v. 23, p. 454-475.

Henderson, J.F. and Brown, I.C.

1966: Geology and Structure of the Yellowknife Greenstone Belt, District of MacKenzie: Geological Survey of Canada, Bulletin 141, 87 p.

Henry, J. and Richert, J.P.

1971: Structural Analysis of the Mining Property of Giant Yellowknife Mines; Internal Report for Giant Yellowknife Mines, Translator: B. Lodge.

Hodgson, G.D.

1976: Structural studies of the gold mineralized shear zone at the Giant mine, Yellowknife, N.W.T. Unpublished M.Sc. thesis, University of Alberta.

Hoffman, P.F. and Hall, L.

1993: Geology, Slave Craton and Environs, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Open-File Report 2559, 1 sheet + 1 CD-ROM, scale 1:1,000,000.

Isachsen, C.E. and Bowring, S.A.

- 1994: Evolution of the Slave Craton; Geology, v. 22, p. 917-920.
- 1997: The Bell Lake group and Anton Complex: a basement cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation; Canadian Journal of Earth Sciences, v. 34, p. 169-189.

Kerrich, R. and Allison, I.

1978: Vein geometry and hydrostatics during Yellowknife mineralization; Canadian Journal of Earth Sciences, v. 15, p. 1653-1660.

Madeisky, H.E. and Chernavska, A.

1995: Quantitative analysis of hydrothermal alteration at the Giant mine, Yellowknife, NWT. Internal report from HEMAC Exploration Ltd. for Royal Oak Mines Ltd.

Martel, E. and Lin, S.

2006: Structural evolution of the Yellowknife Greenstone Belt, with emphasis on the Yellowknife River Fault Zone and the Jackson Lake Formation; Chapter 8. In: Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the EXTECH III Multidisciplinary Research Project, (ed.) C.D. Anglin, H. Falck, D.F. Wright, and E.J. Ambrose; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 95-115.

McClay, K.

McGlynn, J.C.

1977: Geology of the Bear-Slave structural provinces, District of Mackenzie; Geological Survey of Canada, Open File Report 445, 1 sheet, scale 1:1,000,000.

^{1987:} The mapping of geological structures. John Wiley and Sons, Chichester.

Mortensen, J.K., Henderson, J.B., Jackson, V.A. and Padgham, W.A.

1992: U-Pb geochronology of Yellowknife Supergroup felsic volcanic rocks in the Russell Lake and Clan Lake areas, southwestern Slave Province, N.W.T. In: Radiogenic age and isotopic studies 5, Geological Survey of Canada Paper, 91-2, 1-7.

Ramsay, J.G. and Graham, R.H.

1970: Strain variations in shear belts; Canadian Journal of Earth Sciences, v. 7, p. 786-813.

Robert, F., and Poulsen, K.H.

1997: World class Archean gold deposits in Canada: An overview; Australian Journal of Earth Sciences, v. 44, p. 329-351.

Siddorn, J.P. and Cruden, A.R.

2000: The timing of gold mineralization in the Giant and Con deposits, Yellowknife, Canada; in Program & Abstracts of Talks and Posters, 28th Yellowknife Geoscience Forum, November 22-24, 2000, p. 74-76.

Smith, R.B.

1975: Unified theory of the onset of folding, boudinage, and mullion structure; Geological Society of America Bulletin, v. 86, p. 1601-1609.

Sokoutis, D.

1987: Finite strain effects in experimental mullions; Journal of Structural Geology, v. 9, p. 233-242.

Van Hees, E.H.P., Shelton, K.L., McMenamy, T.A., Ross Jr., L.M., Cousens, B.L., Falck, H., Robb, M.E., and Canam, T.W.

1999: Metasedimentary influence on metavolcanic-rock-hosted greenstone gold deposits: Geochemistry of the Giant mine, Yellowknife, Northwest Territories, Canada. Geology, v. 27, p 71-74.

Wilson, G.C. and Rucklidge, J.C.

1987: Mineralogy and Microstructures of Carbonaceous gold ores. Mineralogy and Petrology, v.36, p 219-239.

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Figure 2.24. The southwest plunge of the synformal 'C' Trough zone corresponding to the plunge of ore shoots shown in the Giant deposit long section of mined out stopes. **A.** Distribution of mined-out stopes in the Giant deposit. Long-section projection looking towards 300° , which shows the northeast plunge within the 'C' trough zone. **B.** Representative cross-sections, looking towards 030° , showing the deformation zone contacts in the 'C' Trough zone at 2200N and 2000N (Giant mine geology co-ordinate grid), showing the moderate southwest plunge of the deformation zone. **C.** 3D wireframe of the deformation zone in the 'C' Trough zone in the 'C' Trough zone in the 'C' Trough zone showing the moderate southwest plunge down towards 000° . Deformation zone is coloured by elevation (yellow ~ 4050 feet <1235 m>, magenta ~6000 feet <1830 m>).

Figure 2.25. The northeast plunge of the antiformal 'B' Shaft zone corresponding to the plunge of ore shoots shown in the Giant deposit long section of mined out stopes. **A.** Distribution of mined-out stopes in the Giant deposit. Long-section projection looking towards 300°, which shows the northeast plunge within the 'B' Shaft zone. **B.** Representative geological maps of the distribution of V_{1a} quartz-ankerite-sericite schist mineralization on 100 (30 m below surface) and 250 mining levels (75 m below surface), showing the shallow northeast plunge of mineralization in the antiformal fold. **C.** Oblique view looking down towards 270° at the 3D solid modelled for the auriferous V_{1a} quartz-ankerite-sericite schist mineralization shown in 2.25B and a 3D wireframe of the

surrounding sericite-alteration halo. Sericite alteration halo is coloured by elevation (red

~ 5735 feet <1750 m>, magenta ~5910 feet <1800 m>).

Mineralization type	Description	Deformation event	Au mineralization			Cient
			Barren	Refractory	Free-milling	Giant
V _{1a}	Quartz-ankerite-sericite schist	D ₁		~		>
V _{1b}	White laminated quartz veins	D ₁		~		>
V _{1c}	Quartz breccia veins	D ₁		~		>
V _{2a}	Grey-white laminated quartz veins	D ₂			~	>
V _{2d}	Extensional quartz-calcite-epidote veins	D ₂	>			>
V _{4a}	Quartz-hematite-stibnite-calcite veins	D ₄	~			~























Figure 2.8





Figure 2.10









Figure 2.11













Canon









Figure 2.16



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Figure 2.17




































Figure 2.24





Figure 2.25

CHAPTER 3

MULTISTAGE GOLD MINERALISATION IN THE CON GOLD DEPOSIT,

YELLOWKNIFE, CANADA: INFLUENCE OF OVERPRINTING DEFORMATION

ON THE GEOMETRY OF ORE ZONES

Siddorn, J.P.^{1, 2}, Cruden, A.R.¹, and Hauser, R.L.³

- ¹ Dept. of Geology, University of Toronto, 22, Russell St., Toronto. Ontario. M5S 3B1.
- ² Present Address: SRK Consulting (Canada) Inc., Suite 2100, 25, Adelaide St. East, Toronto. Ontario. M5C 3A1.
- ³ Miramar Con Mine, Box 2000, Yellowknife, Northwest Territories. X1A 2M1.

ABSTRACT

The Con gold deposit is a world-class gold deposit (>150t Au) that since 1938 has produced more than ~180 metric tonnes at 18 grams per tonne. The deposit forms part of the Archean Giant-Con gold system, hosted within deformation zones that crosscut the Yellowknife Greenstone Belt, Slave Province. The Con deposit represents a unique example of a gold deposit largely hosted in one large scale, deformation zone (Campbell zone) that has a protracted history of reactivation, multistage gold mineralization and deformation.

Refractory gold mineralization probably formed during early D_1 extensional deformation, similar to the nearby Giant deposit. Refractory gold mineralization dominates the upper portions of the Con deposit, in the Con deformation zone and above 900 m depth in the Campbell zone. Free-milling gold mineralization formed during D_2 reverse-dextral progressive shear largely within the Campbell

zone below 900 m depth. Three phases of free-milling gold mineralization are present in the Campbell zone, sub-divided on the basis of the style of quartz-carbonate veining and associated gangue mineralogy. Early free-milling gold bearing quartz-carbonate veins (V_{2a}) in part helped localize the deposition of secondary auriferous quartz-carbonate veins (V_{2b} and V_{2c}). The different styles of free-milling gold mineralization are restricted within different zones of the Campbell zone. This represents a vertical zonation between refractory and different styles of free-milling gold mineralization within the Con deposit.

Ore plunge within different ore trends, regardless of whether it is refractory or free-milling, is strongly controlled by the magnitude of D_2 shear strain. F_2 fold and B_2 boudin axes in auriferous quartz-carbonate veins are rotated sub-parallel to the L_2 stretching lineation in zones of intense D_2 shear strain. This represents a key control on the distribution of gold mineralization in the Con deposit that is likely common in other world-class deposits worldwide.

KEYWORDS

Gold, deformation zone, gold zonation, ore plunge, boudin and fold axial plunge.

INTRODUCTION

The Con gold deposit is a world-class gold deposit (>150t Au) that since 1938 has produced more than 5,801,303 ounces of gold at a grade of 0.53 ounces per ton (~180 metric tonnes at 18 grams per tonne). The deposit forms part of the Archean Giant-Con gold system, hosted within deformation zones that crosscut the Yellowknife Greenstone Belt (YGB), Slave Province (Fig. 3.1). The Con deposit is situated on the southern limit of the city of Yellowknife, Northwest Territories, on the north shore of Great Slave Lake in northern Canada.

The Con deposit was staked for Consolidated Mining and Smelting Company in October 1935. The property was explored by trenches, pits, diamond drill holes totaling about 4,500 feet and by a 50-foot inclined prospect shaft on the C10 shear zone. By the end of 1936, plans were made for the erection of a 100-ton mill. A three-compartment vertical shaft was started near the prospect shaft in the summer of 1937 and mill construction was started in September of that year.

On September 5, 1938 the first gold brick was poured and the Con mine became the first gold producer in the Northwest Territories. About 6,794 ounces of gold were recovered in 1938 and approximately 33,750 ounces in 1939. In 1944, a geological investigation by Neil Campbell resulted in the discovery of the Campbell deformation zone on the Negus and Con-Rycon properties. The majority of ore mined came from the Campbell zone, but pre-1958 production also came from the Con and Negus-Rycon deformation zones.

The Con deposit represents a unique example of a gold deposit largely hosted in one large-scale, deformation zone (Campbell zone) that has a protracted history of reactivation, multistage gold mineralization and deformation.

DEPOSIT GEOLOGY

The Con deposit is hosted within a simple system of planar deformation zones (Con, Negus-Rycon and Campbell) that crosscut the YGB, between the Proterozoic West Bay and Pud faults, south of the Giant gold deposit (Figs. 3.1 and 3.2). The deformation zones consist of hydrothermally altered and deformed sericite or chlorite-rich rocks, with or without an apparent schistosity.

The YGB occurs between Defeat Suite granodiorite intrusions (2.64–2.58 Ga., Atkinson and Van Breeman, 1990), and Duncan Lake Group metaturbidites (2.66 Ga; Mortensen et al., 1992; Fig. 3.1). The YGB consists of a northeaststriking, steeply southeast-dipping homocline of mafic metavolcanic and intrusive rocks of the Kam Group (2.72-2.7 Ga, Isachsen and Bowring, 1994, 1997), structurally overlain by northeast striking intermediate and felsic metavolcanic rocks of the Banting Group (2.66 Ga, Isachsen and Bowing, 1994; Figs. 3.1 and 3.2). Conglomerates and sandstones of the "Timiskaming" style Jackson Lake Formation (2.6 Ga, Isachsen and Bowring, 1997) are tectonically juxtaposed between the Kam and Banting Groups. The Jackson Lake Formation is regarded as the youngest supracrustal unit in the region (Helmstaedt & Padgham, 1986; Isachsen & Bowring, 1997; Figs. 3.1 and 3.2).

The Kam Group is subdivided into the Chan, Crestaurum, Townsite, and

the Yellowknife Bay Formations (Figs. 3.1 and 3.2). The Chan Formation comprises a lower mafic dyke complex overlain by a sequence of massive and pillowed metabasaltic flows interlayered with cherts and felsic tuffs of the Crestaurum Formation. The Townsite Formation comprises a series of rhyodacite breccias interbedded with felsic tuffs and overlain by pillowed dacites massive and pillowed metabasaltic flows, pillow breccias and interflow sediments of the Yellowknife Bay Formation; Fig. 3.2). The Con deposit is largely hosted within deformation zones that crosscut the Yellowknife Bay Formation.

The Campbell deformation zone was mined over a strike length of 2500 m to a depth of 2000 m, and has been traced for at least 10 km along strike. It averages 100 m in thickness, strikes 187° and dips 50° to 60° to the northwest, but steepens to 65-75° below a flexure at the 5100 level (1550 m depth) of the Con mine (Fig. 3.3). The Campbell zone is truncated to the east by the West Bay Fault. In the subsurface the Campbell zone offsets the Townsite Formation with a 350 m dextral strike separation.

The Con deformation zone is sub-parallel to and lies 2500 m northwest of the Campbell zone (Fig. 3.2). It comprises several different shear strands that anastomose around a series of undeformed lenses, forming a 35 m wide shear zone that strikes 210° and dips 65° northwest (Fig. 3.3). At depth the Con zone crosscuts and deforms the Pud Stock (Armstrong, 1997).

The Negus-Rycon deformation zones are narrow, discontinuous, deformation zones that host auriferous quartz veins and transect the Kam Group between the Campbell and Con zones (Fig. 3.2). The Negus-Rycon zones strike

165° and dip between 55° to 67° southwest (Fig. 3.3). The zones and host veins are narrow with widths ranging from 30 cm to 9 m, but average less than 1.5 m. Quartz vein-wall rock contacts are sharp with minor development of chlorite schist. Practically all gold is found in quartz associated with pyrite, arsenopyrite, sulphosalts, scheelite and carbonate (Lord, 1951; Boyle, 1961). Negus-Rycon type veins are recognized at deeper levels within the Con deposit on the 3100, 3700 and 3900 levels, in the immediate hanging wall of the Campbell zone.

Steeply inclined sheeted joints are well developed in the hanging wall of the Campbell zone. The joints are spaced 0.5 cm to 3.0 cm apart and are typically hairline fractures infilled with chlorite-quartz-calcite-biotite ± pyrite, epidote and K-feldspar.

A lamprophyre dyke that transects the Yellowknife Bay Formation is subparallel and close to the hanging wall of the Campbell zone. The lamprophyre dyke has been traced along a strike for 2.8 km with a dip extent of 1.1 km (McDonald et al. 1995). The lamprophyre dyke has an average strike and dip of 007°/55° northwest, but is attenuated parallel to the Campbell zone (McDonald et al., 1995). The groundmass of the lamprophyre is comprised of primary paragasitic hornblende, plagioclase, and secondary phlogopite, biotite, carbonate, quartz, chlorite, epidote, prehnite and apatite. Granitic, gneissic and volcanic xenoliths are present locally in concentrations up to 70% in volume, but generally account for only 2% of the dyke (McDonald et al., 1995). The lamprophyre dyke does not contain textural evidence of a prograde metamorphic overprint, suggesting it was emplaced under peak to post-peak metamorphic

conditions in the YGB (Defeat Suite related, 2.64-2.62 Ga., Armstrong, 1997, and Strand, 1993).

The Con deposit hosts both free-milling (metallic) gold ores that occur in a series of quartz-carbonate veins and refractory ("invisible") gold ores that are disseminated within quartz-ankerite-sericite (paragonite) schist and quartzcarbonate veins surrounded by an alteration halo of chlorite +/- sericite schist. These metallurgically distinct ores occur in spatially and geologically distinct zones throughout the deposit (McDonald et al., 1993). Both free-milling and refractory gold mineralization occurs within five main discrete zones within the Campbell zone (Negus, 100, 101, 102, and 103 zones). Gold mineralization is not evenly distributed over the strike length of the zone and is confined to structurally controlled, deformed quartz-carbonate veins and alteration selvages. Refractory gold is restricted to the Con zone and the upper portion of the Campbell zone. Generally, in the Campbell zone refractory ore zones are situated towards the footwall above 1000 m, and free-milling ore zones are situated towards the hanging wall below 1000 m. However, refractory ores persist to a depth of 1100 m and free-milling ores exist from 700 m to below 2000 m. The Negus-Rycon zones contain only free-milling gold mineralization.

PAST RESEARCH

Past studies and reviews of the Con deposit have concentrated on the geology of the Campbell zone (Kerrich and Allison, 1978; Webb, 1983, 1987; Bullis et al., 1987; Duke et al., 1990; McDonald et al., 1995). They conclude that the Con deposit deformation zones formed by non-coaxial deformation resulting in progressive reverse-dextral oblique shear. Evidence cited for the sense of shear is: (i) the oblique trend of the foliation to deformation zone boundaries (10° steeper, 10° more northerly than the deformation zone boundaries), (ii) asymmetric drag folding of veins and foliation planes, (iii) a steeply raking mineral lineation, and (iv) the dextral offset of the Townsite formation at depth in the Campbell zone. However, many sinistral kinematic indicators have also been observed within the Campbell zone (Webb, 1983; Duke et al., 1990), suggesting the Campbell zone may have a complicated history of reactivation.

White et al. (1949) studied the different styles of gold mineralization in the deposit. They originally recognized three distinctly different types of auriferous mineralization. The first type is defined by sericite-carbonate schist containing thin, poorly defined veinlets and lenses of quartz with finely disseminated pyrite and arsenopyrite, together with minor amounts of sphalerite, galena, stibnite, jamesonite, and other lead-antimony sulphosalts, with most of the gold locked in the sulphides. The second type is defined by coarser textured, white to black, and commonly mottled or faintly banded quartz veins, containing pyrite and arsenopyrite, together with sphalerite, galena, and lead-antimony sulphosalts, with free-gold being commonly visible. White et al. (1949) describe this second

type of ore as being gradational into the first type. The third type of ore consists of veinlets of coarse-textured, faintly pinkish quartz containing some carbonate, scant sulphides, and visible gold. In 1949, no ore of this type had been processed.

Kerrich and Allison (1978) describe three vein systems within the Campbell zone, each with a distinct geometry and timing. Initial quartz veining occurred at ~45° to the shear zone boundary, and normal to the schistosity during initial translation on the Campbell zone (Kerrich and Allison, 1978). The orientation of the inferred maximum principal stress was oriented at 45° to the 70° dipping Campbell shear zone during initial veining. Secondary gold bearing quartz veins are oriented parallel to the schistosity, crosscutting early quartz veins. Kerrich and Allison (1978) attribute the second set of veins to a change in the stress regime such that the maximum principal stress was parallel to the schistosity, with an effective tensile stress normal to the schistosity. They attribute the change in stress orientation to high transient fluid pressure, which generated hydraulic fractures. Late-stage lenticular gold-bearing quartz veins were then emplaced as vertical arrays within the shear zones, orientated normal to schistosity. These tension fractures formed when the stress regime reverted to the ambient conditions of the initial period of veining during a second stage of movement on the shear zones Kerrich and Allison (1978).

Webb (1983) suggests that the geometry of quartz veins within the Campbell zone was the result of multiphase deformation, however he only described one main period of deformation in the Campbell zone. This was a

reverse displacement, indicated by the drag folding of quartz veins and joints, the attitude of schistosity relative to the shear zone boundaries, and the steep south raking mineral lineation. Webb (1983) estimated the offset of the Townsite Formation by the Campbell zone, assuming the movement to be parallel to the south plunging mineral lineation, to have been 900 m horizontally and 2,600 m hanging wall down relative to footwall. This is contrary to the sense of movement derived by Ransom (1974) who suggested the hanging wall had moved up and slightly north relative to the footwall. Webb (1983) classifies quartz veins in the Campbell zone into six types. He attributes the southerly rake of the stoping trends in the Campbell zone to be related to the stacking of multiple folded veins with south raking fold plunges, partly controlled by differential reverse movement across a pre-existing zone of sheeted joints observed in the hanging wall of the Campbell zone.

Armstrong (1997) studied the physical distribution and characteristics of the ore and gangue mineral assemblages associated with refractory and freemilling gold mineralization in the Con deposit. He determined that the Con and Campbell zones both host free-milling and refractory gold mineralization, although there is no physical continuum between the two types of gold ore. Freemilling gold mineralization is characterized by a muscovite-chlorite-calcite-albitepyrite-pyrrhotite-native gold assemblage, whereas refractory gold mineralization is characterized by a paragonitic muscovite-Al chlorite Fe/Mg carbonatearsenopyrite-pyrite assemblage, with refractory "invisible" gold occurring as structurally bound gold in As-enriched rims of As/S zoned arsenopyrite and

locally within As-enriched domains of pyrite (Armstrong, 1997). Armstrong (1997) showed that the sheeted joint systems developed in the hanging wall of the Campbell zone are locally infilled by Ca-amphibole-plagioclase-quartz veinlets indicating that the sheeted joint system was present during the Defeat Suite age prograde metamorphism of the YGB. He also argues that the Campbell and Con zones were active at near peak metamorphic conditions, synchronous with lamprophyre dyke intrusion.

Strand (1993) examined the intrusive history of the Con intrusive corridor. The Con intrusive corridor is a region in the Kam volcanics characterized by anomalous hornblende hornfels, potassic metasomatism and calc-silicate alteration related to a series of evolved tonalite-trondjhemite apophyses of Defeat Suite intrusions. Strand (1993) recognized that these intrusions were emplaced into breccia zones at peak metamorphic conditions, marked also by the intrusion of lamprophyre dykes. Both types of intrusion contain older basement fragments that occur as blocks within breccia zones localized in the hanging wall of the Con and Campbell zones. Strand (1993) recognized three stages of retrograde alteration overprinting the apophyses and surrounding wall rocks, including: 1) high temperature garnet-pyroxene replacement skarn; 2) joint-related quartzchlorite-prehnite-biotite-pyrrhotite-chalcopyrite; calcite-Mg and 3) low temperature shear-related sericite-ankerite-dolomite-arsenopyrite-pyrite-gold associated with quartz veining. Strand (1993) proposed that the Con intrusive corridor played a passive role in the gold mineralization acting as a structural trap

due to ground hardening that promoted shearing as well as a subtle chemical trap due to the enhanced presence of sulphides.

DEFORMATION

The Con deformation zones display evidence for early D_1 deformation and associated refractory gold mineralization that was overprinted by the main D_2 phase of deformation with associated multi-staged, zoned free-milling gold mineralization. D_2 deformation was reactivated during D_3 deformation, and crosscut by two stages of D_4 Proterozoic faults. The characteristics of these four phases of deformation and the supporting evidence for each is described below.

D₁ Extension

Evidence for an S_1 foliation is limited in the Campbell zone, however, examples of early chlorite-sericite alteration (S_1) that have been folded by F_2 are present (Figs. 3.4A and B). This indicates, similar to the nearby Giant deposit, (see Chapter 2, D_1 Extension) that the Con deposit records an early pre-main D_2 deformation history of alteration and deformation. Three phases of pre- D_2 refractory gold mineralization are present in the Con deposit that can be correlated with mineralizing phases associated with D_1 in the Giant deposit, suggesting it has a similar history of early refractory gold mineralization (see Mineralization section below). An S_1 foliation was previously noted in the Con deposit by Duke et al. (1990). The limited presence of an S_1 foliation in the Con deposit in comparison to the Giant deposit may be due to the greater intensity of D_2 deformation, resulting in the almost complete transposition of D_1 fabrics during D_2 .

Evidence for a D_1 displacement along the Campbell deformation zone is indicated by a pre- D_2 reconstruction of the Townsite Formation in the hanging wall and footwall of the Campbell zone. The Townsite Formation is presently offset by the Campbell zone by a 350 m dextral strike separation (Fig. 3.5A). At least a portion of this movement must have occurred during the D_2 reversedextral displacement (see D_2 Compression below).

The offset of the Townsite Formation by the Campbell zone during D_2 deformation was calculated using the orientation of the L_2 stretching lineation, the sense of shear of D_2 deformation, and the D_2 offset of metamorphic isograds by the Campbell deformation zone. The distribution of metamorphic isograds is based on metamorphic mapping underground by McDonald et al. (1995) and surface metamorphic mapping by Thompson (2006).

Figures 3.5A and B show the present day offset of the Townsite Formation and metamorphic isograds by the Campbell zone. In cross section the contact between transition zone (epidote-amphibolite) and amphibolite facies metamorphism is offset by 938 m by the Campbell zone (Figure 3.5B). This we assume represents the dip slip component of movement during D_2 . The average orientation of the L_2 stretching lineation (transport direction) is 78/198 (plunge/trend) whilst the average orientation of the hanging wall of the Campbell

zone is 187/60 (strike/dip). Therefore, the rake of the L_2 lineation in the plane of the Campbell zone hanging wall is 77° south. Using this rake and the D_2 dip slip component we can calculate the strike-slip component of movement during D_2 (Fig. 3.6):

This represents a strike slip component of 216 m, displacing the Townsite Formation in the hanging wall of the Campbell zone to the south, relative to the footwall (Fig. 3.6).

The orientation of the Townsite Formation is 055/74 (strike/dip). Given the orientation of the Campbell zone (187/60), the rake of the Townsite Formation in the plane of the Campbell zone hanging wall is 52° south. Using the rake of the Townsite Formation and the dip slip displacement during D_2 (938 m) we can calculate the strike separation of the Townsite Formation during D_2 ; for this we have to also remove the strike slip displacement during D_2 (216 m; Fig. 3.6):

Strike separation = tan 52° x 938 m = 732 m – 216 m = 516 m

Prior to the D_2 displacement along the Campbell zone, the Townsite Formation was 516 m further north (therefore a larger dextral strike separation) than its present day position (Fig. 3.6). As the Townsite Formation cannot be reconstructed using the D_2 displacement, a pre- D_2 movement must have occurred along the Campbell zone. This movement resulted in the horizontal offset of the Townsite Formation by 866 m (present day 350 m offset plus the D_2 516 m strike separation).

The 866 m dextral strike separation may have occurred during D_1 normal movement along the Campbell deformation zone. This is supported by the opposing strike separation of the Townsite Formation by the Giant versus the Campbell deformation zones. This offset is attributed to early D_1 normal faulting along the Giant and Campbell deformation zones (see Chapter 2, D_1 Deformation). Normal faulting along the northwest dipping Campbell zone and the southwest dipping Giant deformation zones created a graben resulting in the opposing strike separation.

Extensive steep jointing in the hanging wall of the Campbell deformation zone also displays evidence of early deformation in the Con deposit. These joints are often filled with epidote-chlorite-sericite alteration. Webb (1983) showed that this zone of steep jointing is spatially associated with the hanging wall of the Campbell zone. The joints are crosscut and deformed by D_2 deformation zones resulting in reverse shear drag folding of the joints. These steeply dipping joints are thought to be related to D_1 normal movement on the Campbell deformation zone, forming parallel to a vertical σ_1 and orthogonal to a horizontal σ_3 , consistent with regional extension.

The combined evidence of gold present in the Con deposit that can be correlated with gold associated with D_1 in the Giant deposit, the reconstruction of the Townsite Formation, the opposing strike separations of the Townsite

Formation, and the presence of early steep joints indicates D₁ normal movement occurred along the Campbell zone in the Con deposit.

D₂ Compression

In the Campbell zone, the S_1 foliation is overprinted by an S_2 foliation, which can be correlated to the major regional D_2 deformation event in the Yellowknife Domain (Bleeker and Beaumont-Smith, 1995; Davis and Bleeker, 1999; Siddorn and Cruden, 2000; Martel and Lin, 2006).

 D_2 in the Campbell zone resulted in the formation of a northwest dipping S_2 foliation (Figs. 3.7A, 3.8A and B) with a steeply south raking L_2 stretching lineation (Figs. 3.7B and 3.8C). The orientation of the L_2 lineation indicates that D_2 movement was dominantly dip slip with a minor component of strike slip displacement. The S_2 foliation defines a sigmoidal pattern, dipping steeply northwest in the centre of the Campbell zone and shallowly northwest approaching the Campbell zone footwall and hanging wall contacts (Figs. 3.8A and B).

Quartz veins are boudinaged and folded by D_2 , forming asymmetric, upright to recumbent, open to isoclinal F_2 folds and B_2 boudins that plunge mainly southwest, sub-parallel to the L_2 lineation (Fig. 3.7C). Asymmetric F_2 folds of quartz veins consistently verge towards the east, towards the footwall of the Campbell zone. V_{2d} extensional calcite veins formed orthogonal to the L_2 stretching lineation (Figs. 3.7D and 3.9A).

At the deposit and stope scales D_2 structures are asymmetric, as shown by the change in orientation of S_2 through the Campbell zone (Figs. 3.8A and B), asymmetric boudinage of quartz veins (Figs. 3.8A and B), and west-over-east vergence of F_2 folds (Fig. 3.8D). This is consistent with a regime of progressive reverse-dextral shear.

On 2300 Level (700 m depth), the undeformed lamprophyre dyke is exposed in the hanging wall of the Campbell zone (Figs. 3.10A and B). To the west, the lamprophyre is strongly deformed within the Campbell zone, with a well-developed S_2 foliation and L_2 lineation, associated with asymmetric porphyroclasts and the typical pink-green alteration assemblage (Figs. 3.10C and D). The deformed and altered lamprophyre dyke is cut by a tightly folded, freemilling gold-bearing V_{2c} pink-white quartz-carbonate vein (Fig. 3.10D; see Mineralization below). Armstrong (1997) and Strand (1993) showed it was emplaced under peak to post-peak metamorphic conditions (Defeat Suite related, 2.64-2.62 Ga.) Therefore, the lamprophyre was emplaced post or post-peak Defeat metamorphism and magmatism (2.64-2.62 Ga), pre-D₂ deformation, and pre-V_{2c} free-milling gold mineralization.

Armstrong (1997) also documented the presence of relict amphiboles in chlorite schist within the Campbell zone. We determined that the amphiboles are aligned within the S_2 foliation suggesting D_2 deformation was initiated during the waning stages of Defeat Suite metamorphism.

Mining was not active in the Con deformation zone during this study, so only limited access was available underground, but it is exposed in a surface

trench on the mine property. The Con deformation zone contains an S₂ foliation, F₂ folds and B₂ boudins in quartz veins, and V_{2d} extensional calcite veins that can be correlated with D₂ structural features in the Campbell zone (Figs. 3.11A and B, 3.12A and B). The Con deformation zone intersects the Pud Stock, a Defeat Suite granitoid intrusion, at depth in the Con deposit (Fig. 3.3). A spaced S₂ foliation is observed within the Pud Stock (Fig. 3.9C). Additionally, F₂ folds in aplite dykes associated with the Pud Stock with an axial planar S₂ foliation in chlorite schist are observed underground in the Con zone (Fig. 3.9D). This correlates D₂ deformation in the Con deposit with the regional D₂ deformation event (Davis and Bleeker, 1999).

The Negus-Rycon deformation zones transect the Kam volcanic stratigraphy between the Campbell and Con zones, with a strike of 165° and dip from 55° to 67° southwest (Fig. 3.2). The Negus-Rycon system represents some of the earliest mined zones in the Con deposit. No access was available to the Negus-Rycon zones underground during this study and only surface exposures of minor Negus-Rycon deformation zones were accessible.

Displacement along the Negus-Rycon zones is consistent with the hanging wall moving up and south relative to the footwall (sinistral-reverse; Fig. 3.13A and B). This is compatible with the D_2 reverse-dextral movement observed in the Con and Campbell zones, given the different orientation of the Negus-Rycon zones. This indicates that D_2 deformation was due to northwest-southeast compression.

D₃ Reactivation

The S₂ foliation is locally refolded in the Campbell deformation zone, forming F₃ folds, S₃ crenulation cleavage, and L₃ lineation (Figs. 3.14A, B, and C; 3.15A and B). F₃ folding of the S₂ foliation forms upright, moderate to steeply plunging, open to tight, angular F₃ folds, with a penetrative S₃ sub-vertical crenulation cleavage. The orientation of the S₃ foliation is sub-parallel to the S₂ foliation and the L₃ lineation is sub-parallel to the L₂ lineation. In places, shallow northwest dipping C' structures also cut the S₂ foliation (Fig. 3.14D). All fabrics associated with D₃ are consistent with reverse-dextral shear, indicating it likely represents a late increment of D₂ deformation.

D₄ Proterozoic Faulting

D_{4a} Negus Fault

The Con deposit is segmented and offset by D_4 Proterozoic faults. The earliest Proterozoic fault in the YGB is the Negus Fault (056/78) that offsets the Campbell zone with a 215 m sinistral separation (Figs. 3.2 and 3.16A). Movement along the Negus Fault reactivated the Campbell zone, forming steeply plunging F_4 chevron folds of the S_2 foliation close to the fault (Fig. 3.16B). The wavelength of the F_4 chevron folds increases away from the Negus Fault.

Structural analysis of the Negus Fault yielded a piercing point solution using the intersection of the hanging wall of the Campbell Zone with a

Proterozoic diabase dyke. This indicates that the Negus Fault has a 183 m sinistral-normal (hanging wall down and northeast) offset (Fig. 3.17).

The Negus Fault offsets the Campbell zone and its gold mineralization. A continuation of gold mineralization in the Campbell zone may lie to the south in the hanging wall of the Negus Fault. A minor set of northeast striking sinistral-normal faults are recognized in the southern end of the Con deposit, kinematically compatible with the movement along the Negus Fault.

*D*_{4b} West Bay series faulting

The Negus Fault is offset to the northeast by the West Bay Fault and to the southwest by the Pud Fault. No continuation of the Negus Fault has been determined in the footwall of the West Bay Fault to the northeast. The density of D_{4b} minor faults in the Con deposit is low, reflecting the relatively greater distance of the Campbell deformation zone from the major West Bay, Negus, and Pud faults. In comparison, the density of minor faults in the Giant deposit is high, reflecting its proximity to the major West Bay, Akaitcho, and Townsite faults. D_{4b} minor faults measured in the Con deposit define northwest-trending sinistral and northeast-trending dextral sets (Figs. 3.18A and B).

The Pud Fault is exposed on the 4100 (1250 m depth), 4500 (1370 m depth) and 5700 levels (1740 m depth) underground in the Con deposit (Figs. 3.16C and D). The Pud Fault is a 0.3 to 1 m wide zone of anastomosing, calcite filled faults. It displays a sinistral asymmetry. (Fig. 3.16D).

MINERALIZATION

The Con gold deposit contains mainly free-milling "metallic" styles of gold mineralization but also minor refractory "invisible" gold mineralization. Freemilling gold mineralization contains native gold or gold-pyrite, gold-pyrrhotite, gold-base metal assemblages that are amenable to direct cyanidation and with gold recoveries better than 90%. Refractory-gold mineralization contains gold-arsenopyrite assemblages that are not amenable to direct cyanidation. The refractory nature of the mineralization is due to the extremely fine grain size of the gold and to the fact that the microscopic and sub-microscopic particles are encapsulated preferentially within arsenopyrite and, to a lesser extent, pyritic host sulphide.

Free-milling and refractory gold mineralization in the Con deposit is mineralogically distinct. Free-milling gold mineralization is characterized by a phengitic muscovite-chlorite-calcite-albite-pyrite-pyrrhotite-native gold assemblage (Armstrong, 1997). Refractory gold mineralization is characterized by assemblages of paragonitic muscovite, Al chlorite, Fe/Mg carbonate, arsenopyrite, and pyrite (Armstrong, 1997). The invisible refractory gold is hosted in As-enriched rims of As/S-zoned arsenopyrite (up to 1900 ppm Au), and locally within As-enriched domains of pyrite grains (up to 450 ppm Au; Armstrong, 1997).

Alteration in the Con deposit is typified by an outer propylitic assemblage (calcite-chlorite-pyrite) surrounding a zone of phyllic alteration (sericite-pyritequartz; sericite being either phengitic or paragonitic muscovite) with an inner

zone of silification and carbonatisation (ankeritisation) +/- quartz veining. The proximal position of ore zones can often be identified based on increasing sericite content, which increases gradationally from chlorite-calcite schist to chlorite-sericite schist to sericite schist in narrow haloes (typically <20 cm wide) around quartz-carbonate veins (Fig. 3.19). Gold mineralized zones can occupy from 10-90% of the width of the host deformation zone (e.g. Fig. 3.19). All gold mineralized zones in the Con deposit are associated with sericite alteration with the auriferous zone being devoid of calcite.

Gold mineralization styles and their relationship to deformation

Six distinct styles of gold mineralization have been defined in the Con deposit, including three styles of refractory-gold mineralization associated with D_1 deformation and three styles of free-milling gold mineralization associated with D_2 deformation. All mineralization styles (auriferous and barren) are summarized in Table 3.1.

 V_{1a} gold mineralization is characterized by intensely deformed quartzankerite-paragonite schist (Figs. 3.20A and B) containing finely disseminated pyrite and arsenopyrite, together with minor amounts of sphalerite, galena, stibnite, jamesonite, and other lead-antimony sulphosalts. V_{1a} gold mineralization corresponds to the first style of mineralization documented by White et al. (1949). V_{1b} gold mineralization is hosted by white laminated fault-fill quartz veins, with narrow paragonitic alteration halos (Figs. 3.20C and D). V_{1c} gold mineralization is hosted within quartz breccia zones and breccia veins (clasts of white quartz

surrounded by darker 'smoky' quartz) that are often associated with V_{1b} laminated fault-fill veins.

All three phases of refractory-gold mineralization (V_{1a}, V_{1b}, and V_{1c}) can be correlated with similar styles of gold mineralization associated with D₁ deformation in the Giant deposit. All three styles are deformed by D₂. Quartzankerite-paragonite schist ore zones (V_{1a}) are intensely deformed by D₂. V_{1a} mineralization is tightly folded (F₂) and boudinaged (B₂) on a stope and deposit scale relative to an axial planar S₂ foliation (Figs. 3.20A and B). Laminated faultfill quartz veins (V_{1b}) are more openly folded and boudinaged by D₂ deformation, due to the large competency contrast between the V_{1b} quartz veins and the surrounding schist (Figs. 3.20C and D). Wall-rock xenoliths within V_{1b} quartz veins contain only an S₁ foliation, with no evidence of an S₂ foliation, indicating the veins formed prior to D₂. Quartz breccia veins (V_{1c}) are also folded with an axial planar S₂ foliation. This suggests V_{1a/b/c} refractory-gold mineralization formed during D₁.

Three distinct types of free-milling gold mineralization (V_{2a} , V_{2b} , and V_{2c}) are present in the Con deposit. V_{2a} free-milling gold mineralization occurs in large proportions in the Con deposit. V_{2a} gold mineralization is typified by white to black, mottled, laminated fault-fill quartz veins associated with narrow sericite alteration halos (Figs. 3.21A, B, C and D). Free-gold often occurs within quartz and along wall rock laminations within veins. Massive chalcopyrite, galena, and sphalerite are often observed in the vein interior (Figs. 3.21D; 3.22A and B). In V_{2a} veins the colour of the quartz may change from white to dark grey along

strike (also observed within the Negus-Rycon zones), with a corresponding decrease in the proportion of laminations. This discolouration of the quartz is attributed to the presence of sub-microscopic carbon (Boyle, 1953). V_{2a} gold mineralization corresponds to the second style of gold mineralization described by White et al. (1949). V_{2a} quartz-carbonate veins often contain tourmaline or are associated with tourmaline-quartz breccias (Fig. 3.22C). Tourmaline breccias can contain clasts of sericite alteration. Drift 2613XC (790 m depth) provides an example of tourmaline breccia, with a tourmaline matrix containing clasts of sericite alteration (Fig. 3.22D). Here the tourmaline breccia is boudinaged within the S₂ foliation and crosscut by extensional quartz veins. It may represent early sericite alteration associated with V₁ refractory gold mineralization within a matrix of V_{2a} related tourmaline mineralization.

V_{2a} gold mineralization dominates the Negus-Rycon zones where greywhite quartz veins, with associated pyrite, galena, sphalerite, chalcopyrite, and free gold, form within narrow deformation zones, with only a small chloritesericite alteration halo (<10 cm wide). The Negus-Rycon zones often change strike, and commonly veins are formed at dilational jogs. Examples of the Negus-Rycon veins are observed in the hanging wall of the Campbell zone. On 3100 level (945 m depth), a Negus-Rycon style vein is observed in the immediate hanging wall of the Campbell zone (Fig. 3.23A). It is a grey-white quartzcarbonate vein with a narrow sericite alteration halo, containing disseminated pyrite. Wall rock clasts are present within the vein but display no foliation.

However, the vein crosses into the hanging wall of the Campbell zone, where it is boudinaged and folded by the S₂ foliation.

No clear crosscutting relationships were observed between the V_{1a} refractory-gold mineralization and the V_{2a} free-milling gold mineralization in the Campbell zone. Most V_{2a} mineralization is situated towards the hanging wall and at depth, whereas V_{1a} refractory mineralization is situated towards the footwall and high up within the Campbell Zone. However, massive sphalerite and galena, key gangue minerals associated with V_{2a} free-milling gold mineralization, were observed to crosscut V_{1b} refractory mineralization potentially indicating that V_{2a} mineralization formed later (Fig. 3.23B).

In the Campbell Zone, V_{2a} grey-white quartz-carbonate veins are boudinaged (B₂) and folded (F₂) by D₂. Angular wall rock clasts containing an S₂ foliation are often observed in the interior of the quartz-carbonate veins (V_{2a}), indicating these veins were emplaced after the onset of S₂ formation, and were deformed during progressive D₂ deformation (Fig. 3.23C and D).

In the Campbell zone, V_{2a} veins are crosscut by extensional white quartz veins (V_{2b} ; Figs. 3.21A and C), that often contain spectacular free-gold, sphalerite, galena, and chalcopyrite. V_{2b} mineralization is thought to represent the last stages of V_{2a} mineralization, given the similarity in location within the Campbell zone and associated gangue mineralogy. The V_{2b} extensional veins are oriented normal to the L₂ stretching lineation, suggesting that V_{2b} veins were emplaced during D₂ deformation. V_{2b} veins commonly form within the interior of the grey-white quartz-carbonate veins (Fig. 3.21A) and display diffuse rather than

sharp contacts, indicating some reaction occurred with the existing V_{2a} vein (Fig. 3.21C).

 V_{2c} gold mineralization is characterized by coarse, pink-white, quartz veins (Figs. 3.24A, B, and C) containing some carbonate, scant sulphides, and visible gold. V_{2c} veins are associated with narrow sericitic and propylitic alteration halos (Fig. 3.24A). V_{2c} pink-white quartz-ankerite veins are often confined to the interior of V_{2a} grey-white quartz-carbonate veins, commonly in local extensional settings and oriented normal to the L₂ lineation (Fig. 3.24B). Therefore, V_{2c} mineralization is kinematically compatible with D₂ deformation. Similar to V_{2a} veins, angular wall rock clasts containing an S₂ foliation are often observed in the interior of the V_{2c} quartz-carbonate veins, indicating these veins were emplaced after the onset of S₂ formation, and were deformed during progressive D₂ deformation (Fig. 3.24C). V_{2c} quartz-carbonate veins crosscut V_{1b} refractory gold bearing quartz-carbonate veins high up in the Campbell zone (Figs. 3.25A and B). V_{2c} gold mineralization corresponds to the third style of gold mineralization described by White et al. (1949).

Auriferous V_{2c} quartz-carbonate veins crosscut the lamprophyre dyke in the Campbell zone, providing a timing constraint on V_{2c} gold mineralization (Fig. 3.11D). As described earlier (see D_2 Compression) Strand (1993) and Armstrong (1997) both determined that the lamprophyre dyke intruded at the peak of Defeat suite prograde metamorphism (ca. 2.63 Ga). Since V_{2c} veins crosscut the lamprophyre dyke, V_{2c} mineralization must have occurred post-peak metamorphism associated with Defeat Suite magmatism (ca. 2.63 Ga).

The Con deposit contains undeformed late- D_2 barren extensional quartzcalcite-epidote veins (V_{2d}; Fig. 3.25C). The V_{2d} quartz-calcite-epidote veins provide a key marker for the proximity of an ore zone in the deposit, as they preferentially develop around the margins of ore zones (within 5 m) in the chlorite +/- sericite schist alteration halo.

Both V_{2b} white quartz-carbonate and V_{2c} pink-white quartz-carbonate veins infill space during the extension and boudinage of pre-existing V_{2a} grey-white quartz-carbonate veins. The V_{2b} white quartz-carbonate veins are often associated with spectacular free-gold, representing significant late-D₂ gold enrichment to the existing gold mineralization. A theme in other world-class deposits is the similar superposition of vein systems within the same fault network, in particular during the boudinage and extension of existing auriferous and barren veins.

The introduction of quartz/carbonate veins into altered schist creates a large competence contrast that promotes a positive feedback for incremental deformation and mineralization. Depending on their geometry, pre-existing veins will fold, boudinage or fracture creating favourable low stress sites for subsequent mineralization. This promotes localization of subsequent veins into the same structural site during incremental deformation/hydrothermal activity and leads to the formation of complex superposed vein systems. Pre-existing veins may be barren or auriferous, whereas the younger veins are often highly enriched with gold, impacting significantly the local grade of a deposit (Fig. 3.26).

For example, in the Dome gold deposit, Timmins, Ontario, significant gold is related to quartz-tourmaline veins, that commonly infill boudin necks (low stress sites) during the boudinage of existing auriferous ankerite veining (Fig. 3.27A). In the Red Lake gold district, Ontario, a significant precursor to auriferous quartz-tourmaline veins are large-scale barren ankerite veining, often with associated colloform textures. This is important in the Cochenour deposit, Red Lake, where barren ankerite veins represent an important ground preparation event, creating the required competence contrast with surrounding deformed wall rock, localizing subsequent auriferous quartz-tourmaline veining (Fig. 3.27B; Sanborn, 1987). In the Detour Lake gold deposit, Cochrane, Ontario, auriferous white-grey quartz-carbonate veins are boudinaged and folded creating low stress sites for the emplacement of auriferous extensional chalcopyrite, pyrrhotite and pyrite veins (Fig. 3.27C). The sulphide veins are significantly enriched with gold.

We suggest that the deformation of early quartz and carbonate veining in a deformation zone is important for the further concentration of auriferous veins. Indeed, the combination of a long-lived deformation history and the introduction of competent, early barren or auriferous veins may be a prerequisite for the formation of a world-class shear zone hosted gold deposit.

Distribution of gold mineralization styles

At the scale of the Con deposit, the distribution of mineralization styles can be defined based on the colour and type of quartz-carbonate veins and

associated gangue mineralogy. Figure 3.28 displays the distribution of gold mineralization styles within individual stopes visited in the Campbell zone during the course of this study.

 V_{1a} , V_{1b} , and V_{1c} refractory-gold mineralization dominates ore zones throughout the Con zone and from surface to a depth of 900 m in the Campbell zone (Fig. 3.28, zone 4). V_{2a} grey-white vein-hosted and V_{2b} white vein-hosted free-milling gold mineralization dominates the deep portions of the Campbell zone (1600–2000 m depth; Fig. 3.28, zone 1). V_{2c} pink-white quartz-carbonate vein-hosted free-milling gold mineralization occurs between a depth of 1600 and 900 m in the Campbell zone (Fig. 3.28, zones 2 and 3). V_{2c} mineralization dominates ore zones between 1300m and 900m depth (Fig. 3.28, zone 3). Both V_{2a}/V_{2b} and V_{2c} mineralization occur between 1600 and 1300 m in the Campbell zone (Fig. 3.28, zone 2). Above a depth of 900 m, ore zones situated towards the hanging wall of the Campbell zone are dominated by $V_{1a/b/c}$ refractory mineralization (Fig. 3.28, zone 4). However, above a depth of 900 m, ore zones situated towards the footwall of the Campbell zone contain both V_{2c} and $V_{1a/b/c}$

This distribution of gold mineralization styles within the Con deposit represents a vertical zonation where refractory-gold formed higher in the system (Con and upper Campbell zone) and free-milling gold formed deeper in the system (lower Campbell zone).

CONTROL ON ORE PLUNGE IN THE CAMPBELL ZONE

The ore zones within the Campbell zone display three characteristic plunges (Fig. 3.29); most commonly steep south (e.g. 56, 68, and 202 trends), sub-horizontal (e.g. 103 trend), and steep north (e.g. 102 trend). The control on ore plunge was hypothesized to be the intersection of stratigraphy (S_0) with the hanging wall of the Campbell zone (White et al, 1949). However, this intersection is oriented 43/220 as defined from the intersection of the Townsite Formation (055/74) with the hanging wall of the Campbell zone (187/60). This is orientation is inconsistent with all three ore plunges in the Campbell zone.

A close correlation is observed between the orientation of F_2 fold and B_2 boudin axial plunges in auriferous quartz veins in the Campbell zone and the plunge of ore zones (Fig. 3.29; Siddorn and Cruden, 2001). In ore zones with steep south trends, the F_2 fold and B_2 boudin axes plunge steeply south (Fig. 3.29, Stereonets A, B, and C). In ore zones with shallow south ore trends, the F_2 fold and B_2 boudin axes plunge steeply location to retrends, the F_2 fold and B_2 boudin axes plunge shallowly south (Fig. 3.29, Stereonet D). In ore zones with steep north trends, F_2 fold and B_2 boudin axes plunge steeply north (Fig. 3.29, Stereonet E).

The correlation between F_2 -fold and B_2 -boudin axial plunges and ore plunges is also observed by geological mapping on different levels within individual stopes (6191M stope; Fig. 3.30). The 6191M stope is dominated by one large V_{2a}/V_{2b} grey-white laminated quartz vein that forms a large B_2 boudin, hosted within a 10 to 15 cm wide sericite alteration halo. The boudinaged vein plunges steeply south similar to the 91 ore trend (Fig. 3.30). F_2 fold and B_2 boudin axes of deformed quartz veins in the Con deposit deformation zones are expected to have formed initially perpendicular to the direction of D_2 shortening (and zone parallel shearing). This orientation would have been shallow north with an associated steep south L_2 stretching lineation. We attribute the present orientation of F_2 fold and B_2 boudin axes to their progressive rotation towards the stretching direction during D_2 progressive zone parallel shear. Zones that experienced higher shear strains recorded greater degrees of F_2/B_2 axial plunge rotation, into orientations closer to the L_2 lineation.

The orientation of the orebodies and plunge of F_2 fold and B_2 boudin axes can also be correlated with changes in deformation-zone thickness (Fig. 3.31; Siddorn and Cruden, 2001). Sub-horizontal ore trends are observed within thicker sections (>200 m) of the Campbell Zone, whereas the steeply south plunging ore zones occur in the narrower sections (<200 m). We propose that orebodies within the steeply south plunging ore zones experienced higher D_2 shear strains resulting in greater progressive rotation of F_2 fold and B_2 boudin axes into a direction sub-parallel with the L₂ stretching lineation. In thicker areas of the Campbell zone, D_2 strain was dissipated over a wider section of the deformation zone, resulting in significantly less rotation of the F_2 fold and B_2 boudin axes.

CONCLUSIONS

The Con deposit is a unique example of a gold deposit largely hosted in one large scale, deformation zone (Campbell zone) that has a protracted history

of reactivation, multistage gold mineralization and deformation. Refractory gold mineralization formed during early D_1 extensional deformation, similar to the nearby Giant deposit. Refractory gold mineralization dominates the upper portions of the Con deposit, in the Con zone and above 900 m depth in the Campbell zone. Free-milling gold mineralization formed during D_2 reverse-dextral progressive shear largely within the Campbell zone, below 900 m depth. Three phases of free-milling gold mineralization are present in the Campbell zone, sub-divided on the basis of the style of quartz-carbonate veining and associated gangue mineralogy. Early free-milling gold bearing quartz-carbonate veins (V_{2a}) in part helped to localize the deposition of secondary auriferous quartz-carbonate veins (V_{2b} and V_{2c}). The different styles of free-milling gold mineralization are restricted to different zones within the Campbell zone. Hence, there is a vertical zonation of refractory and different styles of free-milling gold mineralization within the Campbell zone.

Ore plunge within different refractory and free-milling ore trends is strongly controlled by D_2 shear strain. In zones of intense D_2 shear strain F_2 fold and B_2 boudin axes in auriferous quartz-carbonate veins are rotated sub-parallel to the steeply plunging L_2 stretching lineation. This is a key control on the distribution of gold mineralization in the Con deposit that is likely common in other world-class deposits worldwide.

ACKNOWLEDGEMENTS

The authors wish to thank all participants of the Extech III project for the valuable discussions on Yellowknife gold. This work would not have been possible without the assistance of production and exploration geologists at the Con mine, including Dave Arthur, Alf Silke, Brenda Bilton, and Jeff Kulas. This work was financially supported by the Geological Survey of Canada, Government of the Northwest Territories, Department of Indian and Northern Affairs, Miramar Mining Ltd., and Royal Oak Mines Ltd., as part of the Extech III project.
REFERENCES

Armstrong, J.P.

1997: Variations in silicate and sulphide mineral chemistry between free-milling "metallic" and refractory "invisible" gold ores, Con mine, Yellowknife, N.W.T: Unpublished PhD thesis, University of Western Ontario.

Atkinson, D.J. and van Breeman, O.

1990: Geology of the Western Plutonic Complex, southwest Slave Province: Late Archean crustal granites and gold mineralization in the Yellowknife district; Geoscience Forum Program, Department of Indian and Northern Affairs., p. 4.

Bleeker W. and Beaumont-Smith, C.

- 1995: Thematic structural studies in the Slave Province, Northwest Territories: Preliminary results and implications for the Yellowknife Domain, Northwest Territories; in Current Research 1995-C; Geological Survey of Canada, p. 87-96.
- Boyle, R.W.
- 1961: The Geology, Geochemistry, and Origin of the Gold Deposits of the Yellowknife District; Geological Survey of Canada, Memoir 310, 193 p.

Bullis, H.R., Pratico, V.V., and Webb, D.R.

- 1987: The Con Mine; in Yellowknife Guide Book: A Guide to the Geology of the Yellowknife Volcanic Belt and Its Bordering Rocks, (ed.) W.A. Padgham; Geological Association of Canada, Mineral Deposits Division, p. 175-181.
- Davis, W.J. and Bleeker, W.
- 1999: Timing of plutonism, deformation, and metamorphism in the Yellowknife Domain, Slave Province, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1169-1187.
- Duke, N.A., Hauser, R.L., and Nauman, C.L.
- 1990: A guide to the geology of the NERCO Con Mine, Yellowknife, NWT; in Mineral Deposits of the Slave Province, Northwest Territories (Field Trip 13), 8th IAGOD Symposium Field Trip Guide Book, (ed.) W.A. Padgham, and D. Atkinson; Geological Survey of Canada, Open File 2168, p. 41-52.

Helmstaedt, H. and Padgham, W.A.

1986: A new look at the stratigraphy of the Yellowknife Supergroup at Yellowknife, N.W.T. - Implications for the age of gold bearing shear zones and Archean basin evolution; Canadian Journal of Earth Sciences, v. 23, p. 454-475.

Hoffman, P.F. and Hall, L.

1993: Geology, Slave Craton and Environs, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Open-File Report 2559, 1 sheet + 1 CD-ROM, scale 1:1,000,000.

Isachsen, C.E. and Bowring, S.A.

- 1994: Evolution of the Slave Craton; Geology, v. 22, p. 917-920.
- 1997: The Bell Lake group and Anton Complex: a basement cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation; Canadian Journal of Earth Sciences, v. 34, p. 169-189.

Kerrich, R. and Allison, I.

1978: Vein geometry and hydrostatics during Yellowknife mineralization; Canadian Journal of Earth Sciences, v. 15, p. 1653-1660.

Lord, C.S.

1951: Mineral Industry of the District of Mackenzie, Northwest Territories. Geological Survey of Canada Memoir 261. 336 p.

Martel, E. and Lin, S.

2006: Structural evolution of the Yellowknife Greenstone Belt, with emphasis on the Yellowknife River Fault Zone and the Jackson Lake Formation; Chapter 8. In: Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the EXTECH III Multidisciplinary Research Project, (ed.) C.D. Anglin, H. Falck, D.F. Wright, and E.J. Ambrose; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 95-115.

McDonald, D.W., Duke, N.A., and Hauser, R.L.

1993: Geological setting of the Nerco Con mine and the relationship of gold mineralization to metamorphism, Yellowknife, NT. *Exploration and Mining Geology*, Volume 2, p.139-154.

McDonald, D., Hauser, R., Armstrong, J., & Strand, P.

1995: The Miramar Con Mine: Geological setting and the relationship to gold mineralization. In: *Guidebook to Field Trip C, Fifth Annual CIM Geological Society Field Conference Yellowknife, N.W.T.*

McGlynn, J.C.

1977: Geology of the Bear-Slave structural provinces, District of Mackenzie; Geological Survey of Canada, Open File Report 445, 1 sheet, scale 1000000.

Mortensen, J.K., Henderson, J.B., Jackson, V.A. and Padgham, W.A.

1992: U-Pb geochronology of Yellowknife Supergroup felsic volcanic rocks in the Russell Lake and Clan Lake areas, southwestern Slave Province, N.W.T. In: Radiogenic age and isotopic studies 5, Geological Survey of Canada Paper, 91-2, 1-7.

Ransom, D.M.

1974: The structural geology and controls of gold mineralization in the Con mine and environs, Yellowknife, N.W.T., Canada. Internal technical report for Cominco Ltd., 18p.

Robert, F., and Poulsen, K.H.

1997: World class Archean gold deposits in Canada: An overview; Australian Journal of Earth Sciences, v. 44, p. 329-351.

Sanborn, M.,

1987: The role of brittle-ductile shear in the formation of gold-bearing quartzcarbonate veins in the west carbonate zone of the Cochenour-Willans gold mine, Red Lake, Ontario. Unpublished MSc thesis, University of Toronto.

Siddorn, J.P. and Cruden, A.R.

- 2000: The timing of gold mineralization in the Giant and Con deposits, Yellowknife, Canada; in Program & Abstracts of Talks and Posters, 28th Yellowknife Geoscience Forum, November 22-24, 2000, p. 74-76.
- 2001: Structural analysis as an aid to exploration in the Yellowknife Greenstone Belt; Yellowknife Geoscience Forum, 29th, Indian and Northern Affairs Canada, Yellowknife, Northwest Territories, Abstracts Volume.

Strand, P.D.

1993: The Relationship of Gold Mineralization to Intrusive Breccia Centres at the Nerco Con Mine, Yellowknife, N.W.T.; M.Sc. Thesis, University of Western Ontario, London, Ontario, 288 p.

Thompson, P.H.

2006: Metamorphic constraints on the geological setting, thermal regime, and timing of alteration and gold mineralization in the Yellowknife Greenstone Belt, NWT, Canada. In: Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the Extech III multidisciplinary research project, Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 142-172.

Webb, D.R.

- 1983: The Relationship of Ore to Structural Features of the Campbell Shear Zone and Hanging Wall Stratigraphy in the Con Mine Yellowknife, Northwest Territories; MSc. thesis, Queen's University, Kingston, Ontario, 181 p.
- 1987: Evidence of large scale deformation of the ore zones at the Con mine, Yellowknife, N.W.T.; in Field Guide to the Yellowknife Mining District (ed.) W.A. Padgham; Northwest Territories Geology Division, Northern Affairs Program, Yellowknife, p. 183-190.

White, C.E., Ross, R.H., and Campbell, N.

1949: The Con-Rycon Mine, Yellowknife, N.W.T.; The Canadian Mining and Metallurgical Bulletin; v.42, no. 446, p.288-302.

TABLE CAPTIONS

 Table 3.1.
 Mineralization types in the Con deposit.

FIGURE CAPTIONS

Figure 3.1. Regional Geological setting of the Yellowknife Greenstone Belt. **A.** Geological map of the Yellowknife greenstone belt and surrounding geology (modified from Helmstaedt and Padgham, 1986a). **B.** Location of the Archean Slave Province and the Yellowknife District (modified from Robert and Poulsen, 1997). **C.** Geological map of the Archean Slave Province (modified from McGlynn, 1977 and Hoffman and Hall, 1993).

Figure 3.2. Con deposit surface geological map. Modified from Henderson and Brown (1966). Cross-section A-A' is shown in **Figure 3.3**.

Figure 3.3. Cross-section (19700N, Con Mine imperial grid co-ordinates) through the Con deposit. Section drawn looking towards 000°. Location of cross-section is shown in **Figure 3.2**.

Figure 3.4. Examples of early chlorite-sericite alteration (S_1 ?) folded by F_2 . **A.** F_2 folds in chlorite and chlorite-sericite alteration, cross-section, 4568AZ stope, station 20014. Note: F_2 folds in quartz vein below the folded alteration. **B.** F_2 folds in chlorite alteration, cross-section, 4174R stope, station 20015.

Figure 3.5. Offset of the Townsite Formation and metamorphic isograds by the Campbell zone. **A.** Schematic map showing the dextral strike separation of the Townsite Formation along the northwest-dipping Campbell deformation zone (Con mine imperial grid co-ordinates). **B.** Schematic cross-section showing the reverse 938 m dip separation of the metamorphic isograds by the Campbell zone (Con mine imperial grid co-ordinates). Metamorphic isograds are based on

mapping by McDonald et al. (1995) and Thompson (2006). We assume the 938 m separation represents the reverse dip slip component of D_2 .

Figure 3.6. Long section representing a plane along the hanging wall of the Campbell zone, showing a reconstruction of the Townsite Formation prior to D_2 displacement. This includes the calculation of the strike slip component of the D_2 displacement (216 m) and the strike separation of the Townsite Formation based on its intersection with the Campbell zone of 52 degrees. Inset: Lambert equal area lower hemisphere projection showing the orientation of the Campbell zone (187/60, green) and the Townsite Formation (055/74, yellow) as great circles.

Figure 3.7. D₂ structural data for the Campbell zone, Con deposit. **A.** Lambert equal area lower hemisphere projection of S₂ foliation orientations (polar data, 445 measurements, contour interval 1 σ ; great circle represents the average orientation of the S₂ foliation = 198/72). **B.** Lambert equal area lower hemisphere projection of L₂ lineation orientations (linear data, 119 measurements, contour interval 1 σ ; red dot represents the average orientation of the L₂ lineation = 79/198). **C.** Lambert equal area lower hemisphere projection of F₂/B₂ axial plunge orientations (linear data, 40 measurements, contour interval 1 σ ; red dot represents the average orientation of the F₂/B₂ axial plunge orientations (linear data, 40 measurements, contour interval 1 σ ; red dot represents the average orientation of D₂ (V_{2d}) extensional quartz-calcite vein orientations (polar data, 54 measurements, contour interval 1 σ ; great circle represents the average orientation of the extensional veins = 288/11).

Figure 3.8. Photographs of D_2 structural features in the Campbell zone, Part One. **A.** Asymmetric B_2 boudins and isoclinal upright F_2 fold in quartz vein within

an axial planar S_2 foliation. Note the steep dip to the S_2 foliation as this area occurs close to the centre of the Campbell zone. Cross-section, station 99032, 45202M stope. **B.** Asymmetric B_2 boudins in a quartz vein within the axial planar S_2 foliation. Note the shallow dip to the S_2 foliation as this area occurs close to the footwall of the Campbell zone. Cross-section, station 20036, 3166R stope. **C.** L_2 lineation in the S_2 foliation in chlorite-sericite schist, sub-parallel to the mechanical pencil. Long section, station 99030, stope 2788. **D.** Asymmetric, upright, tight folds in a quartz vein. Note the vergence to the east towards the footwall of the Campbell zone. All folds in quartz veins in the Campbell zone verge to the east towards the footwall. Cross-section, station 20015, 4174R stope.

Figure 3.9. Photographs of D_2 structural features in the Campbell zone, Part Two. **A.** Flat lying extensional calcite veins cross-cutting the S_2 foliation at a high angle (orthogonal), cross-section, station 99054, 5356 stope. **B.** Isoclinal boudinaged F_2 fold in quartz vein, back of the drift looking up, station 99045, 5797M stope. **C.** Spaced S_2 foliation in the Pud Stock, Con zone, cross-section, station 20071. **D.** F_2 tight, upright fold in aplite dyke with S_2 axial planar foliation in chlorite schist, Con zone, back of the drift looking up, station 20072.

Figure 3.10. Photographs of structural features associated with the lamprophyre dyke, Con deposit. **A.** Gneiss xenoliths in undeformed lamprophyre dyke in hanging wall of the Campbell zone, 3100 level (940 m depth), cross-section. **B.** Gneiss xenoliths in undeformed lamprophyre dyke in hanging wall of the Campbell zone. Quartz vein marks the contact between the lamprophyre dyke

and surrounding mafic metavolcanic rocks. 3100 level (940 m depth), crosssection. **C.** Sheared lamprophyre dyke with strongly deformed gneissic xenoliths and S₂ foliation. Cross-section, station 99030, 2788XC drift. **D.** F_2 folds in V_{2b} auriferous pink-white quartz-carbonate vein (contains 6.5 g/t Au), crosscutting intensely deformed lamprophyre dyke with a penetrative S₂ foliation. Crosssection, station 99030, 2788XC drift.

Figure 3.11. Photographs of D_2 structural features in the Con zone. **A.** S_2 foliation in V_{1a} quartz-ankerite-sericite schist, back of drift looking up, station 20070. **B.** S_2 foliation in V_{1a} quartz-ankerite-sericite schist, back of drift looking up, station 21023, C916 North drift.

Figure 3.12. D₂ structural data for the Con zone, Con deposit. **A.** Lambert equal area lower hemisphere projection of S₂ foliation orientations (polar data, 24 measurements, contour interval 1 σ ; great circle represents the average orientation of the S₂ foliation = 024/81). **B.** Lambert equal area lower hemisphere projection of L₂ lineation orientations (linear data, 3 measurements, contour interval 1 σ .

Figure 3.13. D₂ structural features in the Negus-Rycon deformation zones. **A.** Sinistral drag folds in tensional quartz veins along a Negus-Rycon deformation zone, plan view, station 20007. **B.** Asymmetric boudin in quartz vein within chlorite schist in a Negus-Rycon deformation zone. Asymmetry may represent sinistral movement along the deformation zone. Plan view, station 20008.

Figure 3.14. Photos of D_3 structural features in the Con deposit. **A.** F_3 asymmetric, upright, moderately plunging folds in S_2 foliation and quartz veining,

cross-section, station 99035, 6191M stope. **B.** F_3 tight, upright, steeply plunging folds in S_2 foliation and quartz veining, back of the drift looking up, station 20050, 4193Y stope. **C.** F_3 tight, upright, steeply plunging folds in S_2 foliation, alteration and quartz veining, with S_3 axial planar foliation, cross-section, station 20051, 26221B stope. **D.** D_3 C' shear bands with reverse offset of S_2 foliation, cross-section, station 20051, station 99035, 6191M stope.

Figure 3.15. D₃ structural data for the Con deposit. **A.** Lambert equal area lower hemisphere projection of S₃ foliation orientations (polar data, 12 measurements, contour interval 1 σ ; great circle represents the average orientation of the S₃ foliation = 188/77). **B.** Lambert equal area lower hemisphere projection of F₃ fold axial plunge orientations (linear data, 31 measurements, contour interval 1 σ).

Figure 3.16. Photos of D₄ structural features in the Con deposit. **A.** D_{4a} Negus fault infilled with quartz. Note strong fracturing of wall rocks either side of the fault. Back of the drift looking up, station 20037, 4501 drift south. **B.** F₄ chevron folds in S₂ foliation associated with movement along the Negus Fault, plan view, station 20000, B3 area. **C.** D_{4b} Pud fault, back of the drift looking up, station 20038, 4501 drift south. **D.** D_{4b} Pud fault, back of the drift looking up, station 20039, 4501 drift south.

Figure 3.17. Piercing point solution for the Negus fault, based on the intersection of a diabase dyke and the footwall of the Campbell zone either side of the Negus fault. **A.** Plan view of Negus fault showing the intersection of the diabase dyke and Campbell zone footwall in the hanging wall (southeast) and footwall (northwest) of the Negus fault (1950 level, 595 m depth). The plan view is based

on 3D surfaces for the Campbell zone, Negus fault and diabase dyke. Con mine engineering grid co-ordinates **B.** Lambert equal area lower hemisphere projection showing the orientation of the Negus fault (056/78, black), Campbell zone (187/60, green), and diabase dyke (135/90, magenta) as great circles. The line of intersection of the Campbell zone with the Negus fault is 56° southwest. The line of intersection of the diabase dyke with the Negus fault is 78° southeast. **C.** Long section drawn in the plane of the Negus fault showing the piercing point solution.

Figure 3.18. D₄ structural data for the Con deposit. **A.** Lambert equal area lower hemisphere projection of sinistral fault orientations (polar data, 52 measurements, contour interval 1 σ ; great circle represents the average orientation of the sinistral faults = 165/84). **B.** Lambert equal area lower hemisphere projection of dextral fault orientations (polar data, 32 measurements, contour interval 1 σ ; great circle represents the average orientation of the dextral fault orientations (polar data, 32 measurements, contour interval 1 σ ; great circle represents the average orientation of the dextral faults = 247/75).

Figure 3.19. 6191M, -275 foot elevation (-83 m), stope map showing a large boudinaged V_{2a} quartz vein surrounded by a narrow sericite alteration halo and the more distal chlorite-sericite and chlorite schist alteration. This vein forms approximately 30% of the thickness of the Campbell zone.

Figure 3.20. Examples of V₁ gold mineralization in the Con deposit. **A.** V_{1a} quartz-ankerite-sericite schist with a well developed S₂ foliation and abundant arsenopyrite. Cross-section, station 20053, 26220ZD stope. **B.** V_{1a} quartz-ankerite-sericite schist with a well developed S₂ foliation in the Con zone. Cross-

section, station 21026, 1250 level Con zone. **C.** V_{1b} boudinaged quartz veins, cross-section, station 20053, 26220ZD stope. **D.** V_{1b} boudinaged quartz-carbonate veins, cross-section, station 99027, 2796F stope.

Figure 3.21. Examples of V_{2a} gold mineralization in the Con deposit, Part One. **A.** V_{2a} grey quartz-carbonate vein crosscut by extensional V_{2b} white quartz veins, cross-section, station 99035, 6191M stope. **B.** Narrow sericite alteration halo around V_{2a} quartz-carbonate vein, cross-section, station 99026, 4958M stope. **C.** V_{2a} grey quartz-carbonate vein crosscut by extensional V_{2b} white quartz veins with diffuse contacts, cross-section, station 99042, 59202M stope. **D.** Boudinaged V_{2a} grey quartz-carbonate vein with massive chalcopyrite, cross-section, station 99047, 5571M stope.

Figure 3.22. Examples of V_{2a} gold mineralization in the Con deposit, Part Two. **A.** Massive chalcopyrite within a V_{2a} quartz-carbonate vein, cross-section, station 99035, 6191M stope. **B.** Massive pyrrhotite within a V_{2a} quartz-carbonate vein, cross-section, station 99047, 5571M stope. **C.** Tourmaline-quartz breccia on the margin of a V_{2a} quartz-carbonate vein, cross-section, station 99052, 4189XC. **D.** Tourmaline containing clasts of sericite alteration. Note the tourmaline breccia is boudinaged (pinch and swell) within the S₂ foliation and crosscut by extensional quartz veins, cross-section, station 20052, 2613XC.

Figure 3.23. Examples of structural relationships to V_{2a} gold mineralization in the Con deposit. **A.** V_{2a} Negus-Rycon quartz-carbonate vein in the hanging wall of the Campbell zone. This vein is deformed within the S₂ foliation where it intersects the Campbell zone. Cross-section, station 20027, 3100 Level. **B.**

Galena and sphalerite (associated with V_{2a} mineralization?) crosscutting a V_{1b} laminated quartz0carbonate vein, cross-section, station 20053, 26220ZD stope. **C.** Angular clasts of chlorite-sericite schist containing an S₂ foliation within a V_{2a} grey quartz-carbonate vein, cross-section, station 99059, 5757R stope. **D.** Angular clasts of chlorite-sericite schist containing an S₂ foliation within a V_{2a} grey quartz-carbonate vein, cross-section, station 99059, 5757R stope. **D.** Angular clasts of chlorite-sericite schist containing an S₂ foliation within a V_{2a} grey quartz-carbonate vein, cross-section, station 99035, 6191M stope.

Figure 3.24. Examples of V_{2c} pink-white quartz-carbonate veins. **A.** V_{2c} pink-white quartz carbonate vein with a narrow sericite alteration halo. Cross-section, station 20014, 4568 stope. **B.** V_{2b} pink-white quartz carbonate veins crosscutting V_{2a} grey laminated quartz-carbonate veins. Cross-section, station 99026, 4959 stope. **C.** Angular wall rock chlorite-sericite schist clasts containing an S₂ foliation within a V_{2c} quartz-carbonate vein. Cross-section, station 20014, 4568 stope.

Figure 3.25. Examples of V_{2c} and V_{2d} veins. **A.** V_{2c} pink-white quartz-carbonate veins (free-milling gold) crosscutting V_{1b} white carbonate veins (refractory gold), back of the drift looking up, station 20017, 2986AW stope. **B.** V_{2c} pink-white quartz-carbonate veins (free-milling gold) crosscutting V_{1b} white carbonate veins (refractory gold), back of the drift looking up, station 20034, 3365 stope. **C.** V_{2d} extensional calcite veins crosscutting S₂ foliation in chlorite schist, cross-section, station 99047, 5571M stope.

Figure 3.26. Circular diagram showing the positive feedback between the competence contrast between quartz-carbonate veining, surrounding schist and deformation localizing subsequent mineralization.

Figure 3.27. Examples of subsequent auriferous veining localized within preexisting veins (similar to V_{2b} and V_{2c} veins in the Con deposit). **A.** Auriferous ankerite veins boudinaged and crosscut by auriferous quartz-tourmaline veins. Back of the drift looking up. Dome gold deposit, Timmins, Ontario. Photograph by J. Siddorn. **B.** Barren ankerite veins with colloform textures crosscut by extensional auriferous quartz-tourmaline veins, plan view, Red Lake, Ontario. Photograph by J. Siddorn. **C.** Auriferous quartz-carbonate vein crosscut by extensional auriferous chalcopyrite-pyrrhotite-pyrite veins, cross-section view, drillhole DG-07-119, 313.5m depth, Detour Lake gold deposit, Ontario. Photograph by J. Siddorn.

Figure 3.28. Long section projection displaying distribution of auriferous mineralization types in the Campbell zone. Con Mine grid imperial co-ordinates.

Figure 3.29. Long section projection of the Campbell zone, displaying the distribution of mined-out stopes showing the various ore plunges with Lambert equal area lower hemisphere projections displaying F_2 fold and B_2 boudin axial plunges for the indicated (black fill) ore trends. Con Mine grid imperial coordinates. **A.** 202 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 18 measurements. **B.** 56 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 9 measurements. **C.** 68 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 9 measurements. **C.** 68 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 9 measurements. **C.** 68 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 9 measurements. **C.** 68 ore trend, steeply south plunging ore trend with steep south plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 9 measurements. **D.** 103 ore trend, shallowly south plunging ore trend with shallowly south plunging F_2 and B_2 axes

in auriferous quartz-carbonate veins, 6 measurements. **E.** 102 ore trend, steeply north plunging ore trend with steep north plunging F_2 and B_2 axes in auriferous quartz-carbonate veins, 12 measurements.

Figure 3.30. Ore plunge within the 6191M stope, Campbell zone. **A.** Geological map of the 6191M stope at -275 foot elevation (1789 m below surface). Grid co-ordinates are Con mine imperial grid. **B.** Geological map of the 6191M stope at -315 foot elevation (1801 m below surface). Grid co-ordinates are Con mine imperial grid. **C.** 3D perspective view looking northeast showing the outline of quartz-carbonate veining in the geological maps in **A** and **B** and a wireframe representing the plunge of the main boudinaged vein.

Figure 3.31. Long section projection of the Campbell zone, displaying the distribution of mined-out stopes with isopach thickness of the Campbell zone (feet). Con Mine grid imperial co-ordinates.

Mineralisation type	Description	Deformation event	Au mineralisation			Con
			Barren	Refractory	Free-milling	Con
V _{1a}	Quartz-ankerite-paragonite schist	D ₁		~		~
V _{1b}	White laminated quartz veins	D ₁		\checkmark		\checkmark
V _{1c}	Quartz breccia veins	D ₁		\checkmark		\checkmark
V _{2a}	Grey-white laminated quartz veins	D ₂			~	~
V _{2b}	White non-laminated quartz veins	D ₂			~	\checkmark
V _{2c}	Pink-white non-laminated quartz veins	D ₂			~	\checkmark
V _{2d}	Extensional quartz-calcite-epidote veins	D ₂	~			\checkmark
V _{4a}	Quartz-hematite-stibnite-calcite veins	D ₄	\checkmark			\checkmark













Figure 3.5













































<u>10cm</u>









Figure 3.17
















Figure 3.21

10cm















































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CHAPTER 4

THE GIANT-CON GOLD DEPOSITS: EVIDENCE FOR A ONCE LINKED

ARCHEAN LODE-GOLD DEPOSIT.

Siddorn, J.P.^{1, 2} and Cruden, A.R.¹

- ¹ Department of Geology, University of Toronto, 22, Russell St., Toronto. ON. M5S 3B1.
- ² Present Address: SRK Consulting (Canada) Inc., 2100-25, Adelaide St. East, Toronto. ON. M5C 3A1.

ABSTRACT

The Giant and Con deposits, located in the Yellowknife Greenstone Belt, Canada, represent a classic Archean lode-gold deposit now offset by a major Proterozoic fault (West Bay Fault). Combined, the two deposits produced 395 metric tonnes of gold. They formed within a system of extensional deformation zones, with associated early gold mineralization being strongly overprinted by northwest-southeast shortening that is associated with further deposition of gold mineralization. The two deposits were subsequently offset by the Proterozoic West Bay Fault.

This paper provides a new solution for the displacement along the West Bay fault, based on new field evidence, showing that the Con deposit was moved up and south relative to the Giant deposit. The vertical movement is opposite to that of the classic paper by Campbell (1949). The new solution demonstrates that

the Con deformation zone and not the Campbell deformation zone in the Con deposit is the down dip extension of the Giant deposit.

The link between the Giant and Con deposits is supported by their similarities. However, there are distinct differences between the two deposits in terms of the offset of stratigraphy, response to D₂ deformation, geometry, gold mineralization styles, and depth of mineralization; all of which have not been previously accounted for. This paper reviews the factors that controlled the differences and similarities between the two deposits, including examining evidence for early extensional deformation, stratigraphic thickness changes, the vertical zonation of gold mineralization, and the controls on refractory versus free-milling gold mineralization in the Giant-Con system.

KEYWORDS

Gold, West Bay fault solution, refractory and free-milling gold, zonation.

INTRODUCTION

The Giant and Con deposits, located in the Yellowknife Greenstone Belt (YGB), Canada, represent a classic Archean lode-gold system now offset by a major Proterozoic fault (West Bay fault; Fig. 4.1). The Giant and Con deposits combined produced 13,955,799 ounces or 395 metric tonnes of gold, making them a giant gold deposit system (Laznicka 1999).

The current understanding of the relationship between the Giant and Con gold deposits is largely based on the key papers of Campbell (1947, 1949) and Brown (1955) and their solutions for offset on the West Bay fault. Campbell (1947, 1949) and Brown (1955) both predicted that the Giant deposit was the upward extension of the Campbell deformation zone in the Con deposit. However, the two deposits display numerous differences in styles of deformation and mineralization that are not accounted for in any previous fault reconstructions.

Given their proximity there can be little doubt that the Giant and Con systems are related. Any acceptable theory of their formation must therefore take into account both occurrences (Brown et al., 1959), provide an estimate of the total dip and strike offset of the two deposits by the West Bay fault, and explain the differences/similarities in their structure (geometry of deformation zones and fabrics, styles and timing of deformation, offset of stratigraphy) and mineralisation (timing and styles).

Past research on the Giant and Con deposits has largely focused on individual deposit studies, with limited research comparing and contrasting their

geological setting (deformation, mineralization and alteration) (Helmstaedt and Padgham, 1986; Boyle, 1961, 1979). This is partly due to the scale of such a study and access to the deposits. This research represents the first comprehensive examination of both deposits.

It has been suggested that the Giant and Con gold deposits formed within normal extensional faults, during the gravitational collapse of the volcanic pile (Henderson and Brown, 1966; Henderson, 1985) or as reverse shear zones, contemporaneous with granite batholith intrusion (Brown et al. 1959; Helmstaedt and Padgham, 1986; and Brown, 1992). Early in the research history of the camp, a case was made for the deformation zones being dominated by reverse shear, despite a lack of conspicuous offset markers. This was based on the observation that the mean foliation is generally oblique to and is more steeply dipping than the deformation zone boundaries (Campbell, 1949). Past studies have either argued, or assumed, that mineralising fluids infiltrated the deformation zones syntectonically, and hence the deformation zones provided the main control over gold deposition and distribution (Boyle, 1961; Kerrich & Allison, 1978; Brown, 1992). Henderson (1985) and Helmstaedt & Padgham (1987) noted, however, that evidence for Giant-Con being a 'shear zone' hosted gold deposit is debatable. To date, the relationship between the Giant and Con gold deposits, in terms of deformation and mineralization, has not been rigorously proven. Comparing and contrasting the deformation and mineralization styles in the two deposits may aid in determining the link between them.

This paper provides new data on the dislocation of the Giant and Con gold deposits by the West Bay Fault, providing a new model for how they were originally connected. The model accounts for similarities between the two deposits including their proximal location, similar stratigraphic setting, deformation history, and gold mineralization; and differences including geometry, depth of gold mineralization, offset of stratigraphy, refractory verses free-milling gold mineralization, and response to overprinting deformation (Table 4.1). Understanding these similarities and differences combined with the dislocation of the two deposits by the West Bay fault aids in the generation of a more robust geological model for the formation of the two deposits and helps to identify potential deposit scale exploration targets.

REGIONAL GEOLOGICAL SETTING

The Giant and Con gold deposits are situated in the linear, north-south trending YGB, that occurs between the Defeat Suite Western Plutonic Complex (2.64–2.58 Ga., Atkinson and Van Breeman, 1990) to the west, and the Duncan Lake Group metaturbidites to the east (2.66 Ga; Mortensen et al., 1992; Fig. 4.1). The YGB consists of a northeast striking, steeply southeast dipping homocline of mafic metavolcanic and intrusive rocks of the Kam Group (2720-2700 Ga, Isachsen and Bowring, 1994, 1997), structurally overlain by northeast striking intermediate and felsic metavolcanics of the Banting Group (2660 Ma, Isachsen and Bowring, 1994, Fig. 4.1).

The Kam Group is subdivided into a four formations. A lower mafic dyke complex (Chan Formation), a sequence of massive and pillowed metabasaltic flows, interlayered with cherts and felsic tuffs (Crestaurum Formation), rhyodacite breccias interbedded with felsic tuffs and pillowed dacites (Townsite Formation), and massive and pillowed metabasaltic flows, pillow breccias and interflow sediments (Yellowknife Bay Formation; Fig. 4.2). The Giant and Con deposits are largely hosted within the Yellowknife Bay Formation.

The Banting Group is subdivided into three formations. Massive and brecciated felsic flows interlayered with lesser mafic flows and sediments (Ingraham Formation) overlain by greywackes (Walsh Formation) and massive to bedded felsic tuffs (Prosperous Formation; Helmstaedt & Padgham, 1987; Fig. 4.2).

The Duncan Lake Group conformably overlies the Banting Group (Figs. 4.1 and 4.2) and consists of interbedded greywackes and mudstones with many features characteristic of turbidites (Henderson, 1972). Internal sedimentary structures, paleocurrent data and clast composition suggests the sediments were derived from granites and the Kam Group to the west and were deposited in a submarine fan complex (Henderson, 1972).

Tectonically juxtaposed between the Kam and Banting Groups are conglomerates and sandstones of the "Timiskaming-like" Jackson Lake Formation (2605 Ga, Isachsen and Bowring, 1994, 1997). The Jackson Lake Formation is regarded as the youngest stratigraphic unit in the region (Helmstaedt & Padgham, 1986; Isachsen & Bowring, 1997; Figs. 4.1 and 4.2).

The Kam and Banting Groups are crosscut by a series of gabbro dykes (#8 dykes, Henderson and Brown, 1966) that do not intrude the Jackson Lake Formation and therefore formed before 2605 Ma. These gabbro dykes crosscut the Anton granite with a U–Pb age of 2642 +/-15 Ma (Dudas et al., 1990), but are crosscut by the Defeat Suite Western granodiorite with a U-Pb age of 2618 +7/-20 Ma (Henderson et al., 1987). MacLachlan and Helmstaedt (1995) considered the age of the #8 gabbro dykes to be between 2620 and 2642 Ma based on these crosscutting relationships. Type 8a of the #8 gabbro dykes contain phenocrysts of plagioclase and are easy to distinguish in the field. The gabbro dykes strike northwest-southeast to northeast-southwest, are sub-vertical and crosscut the Yellowknife Bay Formation at a high angle. The gabbro dykes therefore appear to preserve their original steeply dipping geometry, even though the Kam Group has been rotated and dips steeply to the southeast. This geometry suggests that the dykes were emplaced after tilting of the Kam and Banting Groups, and intrusion of the Anton granite and prior to deposition of the Jackson Lake Formation (2605 Ma).

Two distinct phases of granite intrusion occur in the Yellowknife region, Defeat Suite and Prosperous Suite plutonism (Fig. 4.2). The Defeat Suite represents a major, post-Duncan Lake Group plutonic event in the Yellowknife region. The plutonic complex west of the YGB (Western Plutonic Complex) belongs to this suite of granitoids. The Defeat Suite is characterised by massive to foliated, homogeneous to porphyritic biotite-trondjhemite-granodiorite-granite plutons (Atkinson and Van Breeman, 1990). Davis and Bleeker (1999) suggest

that the age of Defeat Suite plutonism in the Yellowknife region is restricted to 2620-2630 Ma (Fig. 4.2). This is supported by the age of the Pud Stock, a Defeat Suite pluton located near the Con gold deposit, which is dated at ca. 2634 Ma (Strand and Duke, 1991).

The Prosperous Suite comprises a number of discrete medium to coarsegrained muscovite-biotite granite plutons, which intrude the Duncan Lake Group metaturbidites east of Yellowknife. Plutons of this suite are typically two-mica leucogranites with extensive associated pegmatites. Prosperous Suite plutonism is restricted to 2596-2586 Ma in the Yellowknife region (Davis and Bleeker, 1999; Fig. 4.2).

The Giant and Con gold deposits are hosted within a series of Archean deformation zones that crosscut the Kam Group. The deformation zones consist of hydrothermally altered and deformed sericite or chlorite rich rocks, with or without an apparent schistosity. The deformation zones crosscut all YGB formations and dyke swarms except for late stage north-northwest trending Proterozoic diabase dykes (ca. 2150 Ma; Le Cheminant et al., 1997) of the Indin Lake swarm. The Proterozoic diabase dykes crosscut every lithology in the YGB including all ore bodies at Giant and Con.

The earliest recorded deformation in the YGB is represented by localised F_1 folds and associated S_1 foliation, and the tilting of stratigraphy (Davis and Bleeker, 1999). Defeat Suite plutons crosscut and postdate upright F_1 folds in the 2680-2660 Ma Duncan Lake Group. D_1 deformation is therefore bracketed between 2660 and 2630 Ma (Davis and Bleeker, 1999).

A second folding event (F_2), represented by northwest- to north-trending steeply plunging folds of bedding and D_1 structures, affected the Yellowknife Domain synchronously with intrusion of the 2596 ±2 Ma Sparrow Lake pluton, a member of the Prosperous suite (Davis and Bleeker, 1999).

A younger post- D_2 deformation event is also recognised and consists of rare, localised, steeply plunging folds (F_3) with an associated crenulation cleavage (S_3 ; Bleeker and Beaumont-Smith, 1995).

Late stage D_4 Proterozoic faulting offsets all of the YGB stratigraphy and associated gold deposits (Fig. 4.1). The north-northwest trending sinistral Proterozoic faults resulted in north-south alignment of fault bound blocks in the YGB and the offset of the Giant and Con gold deposits by the West Bay fault. A relative age for the D_4 West Bay-Indin Lake fault system is 1.96 Ga, based on crosscutting relationships with the Milt diabase sheets, Great Slave Supergroup, Compton intrusive suite and Mackenzie dykes (Kusky et al., 1993).

The metamorphic grade of the YGB decreases from amphibolite facies close to the contact with the Defeat Suite Western Plutonic Complex to greenschist facies close to the shore of Yellowknife Bay (Boyle, 1953b). Metamorphic isograds in the YGB are spatially related to Defeat Suite Western Plutonic Complex and therefore formed during the 2620-2630 Ma plutonism (Thompson, 2006).

GEOLOGICAL SETTING OF THE GIANT AND CON DEPOSITS

Giant Deposit

The Giant deposit is hosted by a complex system of linked, quasi-planar alteration-deformation zones. In map view, these zones appear to display a simple northeast-trending braided pattern up to 500 m wide, with individual alteration-deformation zones, typically 30 to 60 m wide, comprising the larger system (Fig. 4.3). In cross-section, the geometry of the deformation zones is more complex, defining intersecting zones with northwest, southeast, and vertical dips (Fig. 4.4). On the deposit scale, the deformation zones display lobatecuspate features, similar to mullion structures (Fig. 4.4). The presence of mullions in the Giant deformation zone-wall rock interface suggests the deformation zones were, at one time, pre-existing incompetent layers (deformation/alteration surrounded zones) by competent wall rocks (metavolcanics) that were shortened during overprinting deformation (see Chapter 2, D₁ Deformation). The Giant deposit is truncated to the southwest by the West Bay Fault (Fig. 4.3).

Con Deposit

The Con deposit is hosted by a system of planar deformation zones (Con, Negus-Rycon and Campbell; Figs. 4.3 and 4.4) that lack the complex geometries observed in the Giant deposit. The Con zone comprises several different anastomosing strands forming a 35 m wide zone that strikes 030° and dips 65°

northwest. The Negus-Rycon zones are narrow, discontinuous, deformation zones that host auriferous quartz veins that transect the Kam Group between the Campbell and Con zones. They strike 165° and dip 55° to 67° to the southwest. The Negus-Rycon zones are narrow (on average <1.5 m wide) and have sharp quartz vein-wall rock contacts, with only minor development of chlorite schist.

The Campbell Zone is sub-parallel in both strike and dip to the Con Zone. The Campbell Zone was mined over a strike length of 2500 m and to a depth of 2000 m. It averages 100 m in thickness, with a ~007° strike and 50° to 60° west dip. The Campbell Zone dip increases to between 65° and 75° west below a depth of 1550 m. The Campbell Zone is truncated to the east by the West Bay Fault (Fig. 4.3) and offset to the south by the Negus Fault.

The Giant, Con, and Campbell deformation zones all trend sub-parallel to the Jackson Lake Formation-Kam Group contact. The Jackson Lake Formation is believed to have formed in fault-bound basins and it is possible that the basincontrolling faults share a common genetic history with the auriferous deformation zones at Giant and Con.

THE WEST BAY FAULT

The nature of the offset along the West Bay Fault is key to understanding the original relationship between the Giant and Con deposits. The West Bay – Indin Lake fault system extends north-northwest from Yellowknife for over 240 km to Indin Lake and throughout its length forms a prominent topographic lineament.

The current understanding of the West Bay Fault is largely based on the key papers of Campbell (1947, 1949) and Brown (1955). These authors both predicted that the Giant deformation zones were the upward extension of the Campbell deformation zone in the Con deposit (Fig. 4.5).

Campbell's (1947, 1949) solution for the West Bay fault offset of the deposits used a piercing point solution for Proterozoic dykes in the footwall (Giant) and hanging wall (Con) of the fault (Fig. 4.6). Campbell (1947, 1949) determined that the offset on the West Bay Fault was 16,140 ft (4920 m) sinistral strike slip and 1,570 ft (479 m) normal dip slip with the west (Con) side moving down and south relative to the east (Giant) side. This predicts a shallow south raking oblique slip vector.

Brown's (1955) solution for the West Bay fault offset used a piercing point between a tuff unit and a large north-west trending diabase dyke. Brown (1955) calculated the displacement to be west side (Con) south (sinistral strike slip) 16,120 ft (4,913 m) and down (normal dip slip) 1,535 ft (468 m) relative to the east side (Giant). Brown's (1955) solution is very similar to Campbell's (1947, 1949), again suggesting the oblique slip vector should rake shallowly south in the plane of the West Bay fault.

To evaluate the accuracy of the Campbell (1947, 1949) and Brown (1955) solutions for the West Bay fault, the average displacement for both were converted into true X,Y,Z displacements using the estimated strike and dip slip displacements (Table 4.2). These calculations assume the West Bay fault has a

uniform 348° strike and 85° dip west. All measurements are recorded in metres, converted from the original units (feet).

The strike slip component (4,913 m) was reduced to a 1,021 m east and 4,806 m north displacement, using the strike of the West Bay fault (348°, Fig. 4.7A). The dip slip component (468 m) was reduced to a 41 m throw and 466 m heave, using the dip of the West Bay fault (85°; Fig. 4.7B). The throw (normal to fault plane, therefore trending 258°) was then reduced to a 40 m easting and 8 m northing displacement (Fig. 4.7C). Therefore, according to Campbell (1947, 1949) and Brown (1955) the total displacement of the Con fault block is 981 m west, 4,814 m north, and 466 m up (Fig. 4.8).

The geology on either side of the West Bay fault was reconstructed using a three-dimensional, Gocad-based, geological model of the present day geology of the Giant and Con gold deposits, the West Bay Fault, and the Townsite Formation. The geological entities representing the Con deposit (Campbell and Con deformation zones) and the Townsite Formation within the Con fault block were translated north, west and up using a C language script in Gocad.

Figure 4.8 shows a map and cross-section representing the pre-West Bay fault movement positions of the Con and Campbell deformation zones relative to the Giant deposit deformation zones. The Campbell (1947, 1949) and Brown (1955) West Bay fault solutions do restore the Campbell zone (Con deposit) to be coincident with the Giant deformation zones. The Campbell zone lies directly underneath the Giant deformation zones in the A shaft area (Fig. 4.8). However, the Townsite Formation on either side of the West Bay fault, does not line up.

Instead there is an 838 m separation between the hanging wall (Con) and footwall (Giant) (Fig. 4.8). Therefore, the Campbell (1947, 1949) and Brown (1955) solutions cannot be correct as they do not realign the stratigraphy of the Kam Group.

The dykes used by Campbell (1947, 1949) and Brown (1955) have irregular strikes and dips, and all are truncated by the Camp fault (a splay off the West Bay Fault) and not the West Bay fault, in the vicinity of the Con deposit. The irregularities in orientation and the fact that the dykes do not intersect the West Bay fault probably resulted in the errors in Campbell's (1947, 1949) and Brown's (1955) restorations.

Relying on Kam Group stratigraphy alone, the sinistral strike separation of the Townsite Formation by the West Bay fault is ~4000 m (~13,386 ft). However, if the Kam Group stratigraphy is correctly reconstructed the Giant deposit cannot be the upward extension of the Campbell zone. This is cryptically displayed in Fig. 4.9, modified from Helmstaedt and Padgham (1986), who didn't acknowledge the implications of this figure. Figure 4.9 shows that if the Kam Group stratigraphy is correctly reconstructed, the Campbell zone is required to bend 30° to realign it with the Giant deposit, across the West Bay fault.

Structural analysis of the West Bay Fault

A structural analysis of the West Bay fault was conducted to provide additional constraints on the reconstruction of the Giant and Con gold deposits.

This analysis utilized new field data, 2D reconstructions and estimates of displacements, and 3D reconstructions of the Giant and Con deposits.

The West Bay fault in the vicinity of the Giant and Con deposits is variable in terms of orientation and type of fault fill material. The fault is not exposed in the vicinity of the Con deposit, as it lies under Yellowknife Bay. It is first observed to the south of the Giant deposit as a discrete fracture trending 350°, forming a prominent lineament and scarp face throughout the Giant mine property (Fig. 4.10A). The best exposure of the West Bay fault is in the A1 open pit at Giant, where the fault dips steeply to the west and is a discrete fracture approximately 20 cm wide that is filled with gouge and quartz mineralisation (Fig. 4.10B). Slickenlines at this location rake shallowly north 6° with sinistral steps (Fig. 4.10C). The dip of the West Bay fault shallows with depth and it truncates auriferous quartz veins hosted in a Giant deposit deformation zone (Fig. 4.10D).

The West Bay fault is also exposed west of the Giant deposit close to the contact between Kam Group metavolcanics and Defeat Suite granitoids. Here the fault contains approximately 20 cm of quartz and hematite mineralisation with brecciated slivers of mafic metavolcanics and granite (Fig. 4.11A). Slickenlines at this location rake shallowly northwest 6° with sinistral steps (Fig. 4.11B).

Further north, the West Bay Fault changes strike to northwest, close to a large roof pendant of mafic Kam Group volcanics situated on top of Defeat Suite granitoids. Here the West Bay fault splays into a fault zone with numerous minor faults associated with an approximately 20 m wide zone of quartz, hematite and breccia (Figs. 4.11C and D). Further north the West Bay fault forms a discrete

zone which is poorly exposed along a scarp surface. The scarp surface contains well developed slickenlines that consistently rake 6° north with sinistral steps.

The West Bay Fault can be traced over a distance of 20 km (Fig. 4.12). Slickenlines observed on the West Bay fault plane all rake shallowly north ~6° with associated mineral steps indicating sinistral-normal (Fia. 4.12). displacement. This indicates that the Giant (east) footwall fault block has moved north and down relative to the Con (west) hanging wall fault block. The slickenline orientation (shallow north) represents the oblique slip vector for the West Bay fault. This is opposite to the slip vector predicted by Campbell (1947, 1949) and Brown (1955), whose reconstructions suggest it should rake shallowly south. Campbell (1949) acknowledged that in some minor faults on the Giant mine property; the easterly sides have dropped relative to the westerly sides. This is the reverse of the direction of movement Campbell (1947, 1949) and Brown (1955) assumed for the West Bay fault, but agrees with the slickenside evidence recorded here.

A new solution for the West Bay Fault offset

A new solution for reconstructing the geology on either side of the West Bay Fault was conducted using the slickenline orientation measured in the field and the sinistral strike separation of the Townsite Formation. The solution assumes that 1) the slickenline orientation represents the slip vector for movement along the fault, 2) only one displacement occurred along the fault, and 3) the fault is planar.

The West Bay Fault reconstruction was first calculated in 2D, using a plane oriented along the strike of the fault (Fig. 4.13). The strike separation of the Townsite Formation upper contact is plotted on the fault plane (4,080 m), including the pitch of the intersection of the Townsite Formation with the West Bay fault (71° south), along with the slip vector given by the slickenline orientation (6° north). Using the sine rule, the amount of true slip is calculated as 3959 m (Fig. 4.13. The amount of dip and strike slip calculated from the true slip and the slip vectors are 3937 m (strike slip) and 414 m (dip slip; Fig. 4.13):

The displacement required to move the Con fault block north and west relative to the Giant fault block was calculated using the strike and dip-slip estimates (Fig. 4.14). The strike-slip component was reduced to a 819 m east and a 3851 m north displacement (Fig. 4.14A). The dip slip component was reduced to the throw (36 m) and heave (412 m), using the dip of the West Bay fault (Fig. 4.14B). The throw (normal to fault plane) was then reduced to a 35 m east and a 8 m north displacement (Fig. 4.14C). Therefore the total displacement of the Con fault block is 854 m to the west, 3844 m to the north, and 412 m down (Fig. 4.14).

A three-dimensional, Gocad-based geological model of the Giant and Con gold deposits, West Bay Fault, and Townsite Formation was used to reconstruct the geology on either side of the West Bay Fault. The geological entities representing the Con deposit (Campbell and Con deformation zones) and the Townsite Formation, within the Con fault block, were translated using a C

language script in Gocad. The Gocad three-dimensional geological models are in imperial units, based on the Con mine imperial engineering local grid.

This reconstruction accurately realigns the Townsite Formation on either side of the West Bay Fault (Fig. 4.15). The up-dip projection of the Campbell deformation zone was plotted to test its correlation with the Giant deposit. The Campbell zone is not aligned with the Giant deposit and therefore does not form the down-dip extension of the Giant deposit (Fig. 4.15). Instead the Campbell zone projects to the southeast of the Giant deposit, and is predicted to reach the surface offshore in the Back Bay area of Yellowknife Bay. Previous exploration drilling intersected two wide deformation zones in this area (the A10 and Back Bay zones; Dean McDonald personal communication, 1999); however, both occurred within intermediate metavolcanic Banting Group rocks and not the Kam Group. The A₁₀ and Back Bay zones may therefore represent the up-dip extension of the Campbell zone within the Banting Group. The Campbell zone dips northwest underneath the Giant deposit and is predicted to occur at depth below the Giant deposit. The projection of the Campbell zone into the Back Bay area is aligned with the northward extension of the Yellowknife River fault zone. The Yellowknife River fault zone has been described as the major crustal break in the YGB, similar to the Porcupine-Destor fault in the Abitibi sub-province, Superior Province (Martel and Lin, 2006). We suggest the Yellowknife River fault represents the northward extension of the Campbell zone. This suggests that the Campbell zone represents an example of a large scale gold mineralizing system that formed in a major crustal break.

The up-dip projection of the Con deformation zone aligns with the Giant deposit. As this reconstruction correctly realigns the stratigraphy of the Kam Group, the Giant deposit therefore represents the up-dip projection of the Con deformation zone and not the Campbell deformation zone.

THE RELATIONSHIP BETWEEN THE GIANT AND CON GOLD DEPOSITS

This study has shown that the Giant deposit represents the up dip extension of the Con deformation zone and not the Campbell deformation zone as previously thought. The two deposits were therefore previously connected, and any hypothesis for the linkage between the two deposits must account for their differences and similarities.

A link between the Giant and Con deposits is supported by their similarities (as outlined in Table 4.1). However, there are distinct differences between them in terms of the offset of stratigraphy, response to D_2 deformation, geometry, gold mineralization styles, and depth of mineralization; all of which have not been previously accounted for (Table 4.1). This section reviews the factors that controlled the differences and similarities between the two deposits, including examining evidence for early extensional deformation in the YGB, stratigraphic thickness changes in the Kam Group, the vertical zonation of gold mineralization, and the controls on refractory versus free-milling gold mineralization in the Giant-Con system.

Opposing offset of stratigraphy and early extensional deformation in the Giant and Con deposits

Henderson and Brown (1966) recognized that early faulting along the Giant deformation zones had resulted in sinistral separation of the Townsite Formation (Fig. 4.16). In comparison, the Campbell zone of the Con deposit displays a dextral separation of the Townsite Formation. No previous reconstruction of the Giant and Con deposits has accounted for this opposing offset of stratigraphy. The pre-D₂ reconstruction of stratigraphy around the Campbell zone (Con deposit) does not remove the dextral separation of the Townsite Formation. This separation is attributed here to earlier D₁ deformation (see Chapter 3, D₁ Extension).

The opposing strike separation of the Townsite Formation is related to early D_1 normal faulting along the Giant and Campbell deformation zones (see Chapter 2, D_1 Deformation). Normal faulting along the northwest dipping Campbell zone and the southwest dipping Giant deformation zones created a graben resulting in the opposing strike separation.

The interpretation above is supported by the orientation of the S₁ foliation preserved in the Giant deposit and the presence of D₁ steep jointing in the Con deposit. The enveloping surfaces of F₂ folds of S₁ foliation consistently occur at a lower angle to the enveloping deformation zone in the Giant deposit. Since the F₂ enveloping surfaces provide an indication of the pre-D₂ orientation of S₁ it can be deduced that the S₁ foliation most likely formed during early normal displacement on the host deformation zones (see Chapter 2, D₁ Extension).

Steep joints in the Con deposit are crosscut and reversely dragged by D_2 deformation zones (see Chapter 3, D_1 Extension). The orientation of these pre- D_2 joints is also consistent with early D_1 extension.

Evidence for early extensional deformation was recognized by Henderson (1985), who suggested the Giant and Con deformation zones were first formed by synvolcanic, gravitational, extensional faulting prior to the rotation of the Yellowknife Greenstone Belt, and subsequently overprinted by later deformation. Henderson's (1985) model was based on:

- 1. The restriction of deformation zones to within the Kam Group;
- 2. Deformation zones being truncated by the Jackson Lake Formation;
- Porphyry dykes within the Kam Group that are both cut and are cut by deformation zones and are truncated by the unconformity at the base of the Jackson Lake Formation; and
- 4. When the Kam Group rocks are rotated into the paleo-horizontal, the deformation zones become a series of southeast dipping normal faults.

Helmstaedt and Padgham (1986) concluded that Henderson's (1985) model was incorrect based on the observation that the deformation zones not only crosscut the Kam Group, but also the Banting Group and Jackson Lake Formation. Helmstaedt and Padgham (1986) also recognized that previous research had shown that movement on the Giant and Con deformation zones was related to shortening and thrusting (Brown et al., 1959; Boyle, 1961) and not

normal faulting. Henderson (1978, 1985) implied that the Giant deformation zones represented an early fault system that was folded along with the surrounding country rocks during deformation, similar to a model proposed but rejected by Brown et al. (1959). Brown et al. (1959), Henderson and Brown (1966), and Helmstaedt and Padgham (1986) argued that the uniform facing direction of the Kam Group rules out the presence of major folds.

Helmstaedt and Padgham (1986) stated that:

"unless a reasonable argument can be made that all structures in rocks above the Kam Group are due to deformation during reactivation of earlier shear zones in the Kam Group, it must be concluded from the evidence above that shearing is not restricted to rocks of the Kam Group but affected all rocks of the Yellowknife Supergroup."

In light of the new evidence presented in this study Helmstaedt and Padgham's (1986) criticism of Henderson's (1985) normal faulting model can be re-evaluated. We suggest that the normal movement on the Giant and Con deformation zones occurred during an early camp-scale D₁ deformation event. This occurred prior to deposition of the Jackson Lake Formation and controlled the fault bound basins into which the Jackson Lake Formation was subsequently deposited. These early deformation zones formed during or after tilting of the Kam Group.

The association between gold deposits and early deformation is rarely documented, particularly those that have gold mineralization associated with early extension (Vearncombe, 1992; Williams and Currie, 1993; Witt, 2001; Davis and Maidens, 2003). Most mesothermal orogenic gold deposits formed late in the deformation history and are largely associated with compressional deformation (Groves et al. 1998).

Gold deposits in the Leonora district, Western Australia have been associated with early gold formed during extensional deformation similar to the Giant-Con system (Williams et al., 1989; Vearncombe, 1992; Witt, 2001). The Tower Hill, Sons of Gwalia, and Harbor Lights deposits in the Leonora district are associated with early D₁ extensional shear zone related gold that formed during the uplift and doming of a major granodiorite batholith. All three deposits are associated with the Sons of Gwalia shear zone, a zone of ductile deformation that lies on, or close to, the contact between the Raeside batholith and greenstones of the Gwalia domain (Kalgoorlie Terrane; Witt, 2001).

The quartz veins in all three deposits show evidence for complex and multiple deformations, with the isoclinal folding, boudinage and transposition of the vein system occurring within the dominant foliation. This includes the rotation of auriferous vein fold and boudin axes into parallelism with the stretching lineation similar to the Con deposit (see Chapter 3, Control on ore plunge in the Campbell zone).

Stratigraphic thickness changes in the Kam Group

Additional effects of D_1 early extensional deformation can be seen in stratigraphic thickness changes in the Yellowknife Greenstone Belt. The Yellowknife Bay Formation (Kam Group) at the Con deposit is ~4.7 km thick, when measured from the upper contact of the Townsite Formation to the Jackson Lake Formation. When the Yellowknife Bay Formation thickness is measured from the Townsite Formation to the Bode Tuff it is ~4.4 km thick at the Con deposit.

In comparison, the Yellowknife Bay Formation at the Giant deposit is either ~1.1 km (Townsite Formation to Jackson Lake Formation) or 1 km thick (Townsite Formation to the Bode Tuff) and at Walsh Lake it is not present (Figs. 4.17 and 4.18). This is partly related to the truncation of stratigraphy by the Jackson Lake Formation, which strikes 010° compared to the Kam Group, which strikes 030° (Fig. 4.17). The angular unconformity at the base of the Jackson Lake Formation consistently truncates older stratigraphy along strike to the north. At the Con deposit, the Jackson Lake Formation lies unconformably on the Yellowknife Bay Formation; by Walsh Lake it lies unconformably on the Crestaurum Formation (Fig. 4.17). However, this does not explain the thickness changes observed when the Yellowknife Bay Formation is measured from the Townsite Formation to the Bode Tuff. As the Jackson Lake Formation lies unconformably above the Bode Tuff in both the Giant and Con fault blocks, the truncation and excision of stratigraphy is most likely related to displacement along the Giant, Campbell and Con deformation zones. The deformation zones

strike sub-parallel to the Jackson Lake Formation, at an angle to the Kam Group. The influence of the deformation zones on the Kam Group can be seen when the Kam Group is viewed in relation to the Jackson Lake Formation unconformity and the Giant, Con, and Campbell deformation zones (Fig. 4.18).

The Jackson Lake Formation is thought to have formed in fault bounded basins, during exhumation, extension, and related uplift of the Yellowknife Greenstone Belt (Helmstaedt and Padgham, 1987; Mueller and Donaldson, 1994; Martel and Lin, 2006). The Jackson Lake Formation is considered to have a similar origin to the 'Timiskaming' sediments in the Abitibi Greenstone Belt, Superior Province. Given the similar strike orientation of the Giant-Con deformation zones and the Jackson Lake Formation, combined with the evidence that both formed during extensional deformation, it is reasonable to suggest that they are genetically linked. Early extensional faulting that resulted in the formation of the Giant-Con deformation zones may have also formed the fault bound basins into which the Jackson Lake Formation was deposited. The significant changes in thickness of the Yellowknife Bay Formation may therefore be due to extensional faulting along the Giant-Con deformation zones related to the formation of the Jackson Lake Formation.

Response to D₂ deformation

During D_2 deformation, the Giant and Con deposits underwent the same regional compressional phase of deformation; however, the response of the host deformation zones to this deformation is quite different. D_2 deformation in the
Con deposit is dominated by reverse-dextral shear with the strong development of a foliation, down-dip stretching lineation, and asymmetric fabrics (see Chapter 3, D₂ Compression). The Con deposit deformation zones display strong strain partitioning, with sharp deformation zone contacts and increasing strain over 3 m from unstrained mafic pillowed volcanics into chlorite schist. In comparison, D₂ deformation at Giant is dominated by flattening, mullion, boudin, and fold development, with poor development of a down-dip stretching lineation (see Chapter 2, D₂ Compression). The Giant deformation zones show weaker strain partitioning and gradational deformation zone contacts, with strain increasing over ~30 m from unstrained mafic pillowed volcanics into chlorite schist. D₂ resulted in the steepening of Kam Group stratigraphy, rather than folding, given its already tilted attitude.

The response of the Giant and Con deposits to D_2 deformation can be explained by the geometry of the deformation zones with respect to the imposed strain. During D_2 deformation the Giant deformation zones were gently inclined and at a low angle to the D_2 shortening direction. The Giant deformation zones were already schistose, altered and weakened during D_1 (see Chapter 2). Given the orientation of the deformation zones and the strong competence contrast with the surrounding mafic metavolcanics, D_2 overprinting resulted in the overall flattening of the Giant deposit, with the development of mullion structures at the deformation zone-wallrock contacts.

In comparison, the Con deformation zones during D_2 were relatively steeply dipping and at a high angle to the D_2 shortening direction. This resulted in

reverse-dextral shearing of the Con deposit with displacement of the hanging wall ~938 m northeast over the footwall (dip slip component of movement) of the Campbell zone (see Chapter 3, D_1 Extension).

The response of the Giant and Con deformation zones to D_2 deformation exaggerated the geometrical differences between the two deposits. D_2 mullion development and flattening of the Giant deposit complicated an already intricate system of gently dipping, intersecting deformation zones. In comparison, D_2 reverse-dextral shear of the Con deposit enhanced the planar geometry of the Con deformation zones.

Deposit Geometry

A change in deformation zone thickness and density is observed across the Yellowknife Greenstone Belt, from the Con fault block, through the Giant and Walsh Lake fault blocks (Fig. 4.19). Deformation zones within the Con deposit are wide (up to 100 m thick) and are dominated by the Con and Campbell zones. Deformation zones within the Giant deposit are more numerous (5 different interlinked deformation zones), but are narrower (30 m thick). In turn, there are approximately 8 deformation zones within the Walsh Lake fault block that are relatively narrow (10 m thick). The deformation zone systems encompass a broader volume of country rock, increasing from the Con deposit to the Giant deposit to the Crestaurum deposit in the Walsh Lake fault block.

This change in deformation zone width, abundance and the broadening of the total volume of rock in which they occur is analogous to an upward splaying

system of deformation or fault zones (Twiss and Moores, 1992). The fault system is dominated by one or two major first order deformation zones lower in the system (e.g. Con deposit), which branch into intermediate second order deformation zones higher up (e.g. Giant deposit), that in turn splay into numerous small third order deformation zones at the highest level (e.g. Crestaurum deposit). This suggests that the fault blocks that host the Con, Giant, and Crestaurum deposits represent different structural elevations within the same splaying deformation zone system (Fig. 4.19). This is consistent with the new solution for the West Bay Fault, which suggests the Con deposit is structurally lower than the Giant deposit. It is also supported by the change in metamorphic grade from the Con to the Giant to the Walsh Lake fault blocks (Thompson, 2006).

Gold mineralization styles

Alteration in both the Giant and Con gold deposits is typified by an outer propylitic assemblage (calcite-chlorite-pyrite) surrounding a zone of phyllic alteration (white mica-pyrite-quartz) with an inner zone of silification and carbonatisation (ankeritisation) +/- quartz veining. The proximal position of ore zones at Giant and Con can often be identified based on increasing sericite content, which increases gradationally from chlorite-calcite schist to chlorite-sericite schist to quartz-ankerite-sericite schist.

Six distinct styles of gold mineralization have been defined in the Giant and Con deposits, including three styles of refractory-gold mineralization

associated with D_1 deformation and three styles of free-milling gold mineralization associated with D_2 deformation (Siddorn et al., 2006). All mineralization styles (auriferous and barren) identified in the Giant-Con gold deposits are summarized in Table 4.3.

Both deposits contain refractory "invisible" and free-milling "metallic" styles of gold mineralization; however, the Giant deposit is dominated by refractory gold mineralization and the Con deposit is dominated by free-milling gold mineralization. In the Con deposit, refractory gold is restricted to the Con zone and towards the footwall of the Campbell zone above 1000 m depth. Free-milling ore zones in the Campbell zone are situated towards the hanging wall below 1000 m depth.

The refractory and free-milling gold mineralization styles in the Giant and Con deposits are mineralogically distinct. Armstrong (1997) demonstrated that refractory gold mineralization in the Con deposit is characterized by assemblages of paragonitic muscovite, AI chlorite, Fe/Mg carbonate, arsenopyrite, and pyrite. The invisible refractory gold is hosted in As-enriched rims of As/S-zoned arsenopyrite (up to 1900 ppm Au), and locally within As-enriched domains of pyrite grains (up to 450 ppm Au; Armstrong, 1997).

Gold in the three refractory gold mineralization styles (V_{1a} , V_{1b} , and V_{1c}) is encapsulated within disseminated arsenopyrite and arsenian pyrite, and free gold is uncommon. V_{1a} gold mineralization is characterized by intensely deformed quartz-ankerite-paragonitic white mica schist containing finely disseminated pyrite and arsenopyrite, together with minor amounts of sphalerite, galena,

stibnite, jamesonite, and other lead-antimony sulphosalts (Fig. 4.20A). V_{1b} gold mineralization is hosted by white laminated fault-fill quartz veins, with narrow paragonitic white mica alteration halos (Fig. 4.20B). V_{1c} gold mineralization is hosted within quartz breccia zones and breccia veins (clasts of white quartz surrounded by darker 'smoky' quartz) that are often associated with V_{1b} laminated fault-fill veins (Fig. 4.20C).

The three free-milling gold mineralization styles (V_{2a} , V_{2b} , and V_{2c}) contain native gold or gold-pyrite, gold-pyrrhotite, and gold-base metal assemblages that are amenable to direct cyanidation; direct gold recoveries are better than 90%. V_{2a} occurs in both Giant and Con, but V_{2b} and V_{2c} only occur deep in the Campbell zone of the Con deposit. V_{2c} gold mineralization in the Con deposit may be correlated to a series of barren veins with similar colour and texture in the Giant deposit.

 V_{2a} free-milling gold mineralization occurs in large proportions in the Con deposit, and in minor proportions in the Giant deposit. V_{2a} gold mineralization is typified by white to black, mottled, laminated fault-fill quartz veins associated with phengitic muscovite-pyrite alteration haloes (Fig. 4.20D). V_{2a} veins frequently contain pyrite, arsenopyrite, chalcopyrite, pyrrhotite, sphalerite, galena, tourmaline, and lead-antimony sulphosalts, with free gold being commonly visible. V_{2a} veins are crosscut by extensional white quartz veins (V_{2b}) that often contain spectacular free gold, sphalerite, galena, and chalcopyrite (Fig. 4.20D). V_{2c} gold mineralization is characterized by coarse, pink-white, quartz veins

containing some carbonate, scant sulphides, and visible gold (Fig. 4.21). V_{2c} veins are associated with narrow phengitic and propylitic alteration halos.

The Giant and Con deposits both contain undeformed late-D₂ barren extensional quartz-calcite-epidote veins (V_{2d}). V_{2d} quartz-calcite-epidote veins provide a key marker for the proximity of an ore zone in both Giant and Con, as they preferentially develop around the margins of ore zones (within 5 m) in the chlorite +/- sericite schist alteration halo. Late V_{4a} stibnite-calcite-hematite veins are associated with D₄ Proterozoic faulting in both deposits, and form open space filling veins, often with spectacular, undeformed, stibnite-calcite crystal forms.

Depth of gold mineralization in the Giant-Con system

The differences in gold mineralization (refractory versus free-milling dominated) between Giant and Con can be accounted for when the two deposits are viewed together. On both camp and deposit scales, the distribution of mineralization styles can be defined based on the style of gold mineralization (see Chapter 3, Distribution of gold mineralization styles).

 V_{1a} , V_{1b} , and V_{1c} refractory-gold mineralization dominate ore zones observed throughout the Con zone and the Giant deposit, and from the surface to a depth of 900 m in the Campbell zone (Fig. 4.22). V_{2a} grey-white vein-hosted and V_{2b} white vein-hosted free-milling gold mineralization dominates the deep portions of the Campbell zone (1600–2000 m depth; Fig. 4.22). V_{2a} mineralization also occurs in minor proportions in the Giant deformation zones, whereas V_{2b} mineralization is only present in the Campbell zone. V_{2c} pink-white quartz-

carbonate vein-hosted free-milling gold mineralization is also only present in the Campbell Zone, occurring between a depth of 1600 and 900 m (Fig. 4.22). V_{2c} mineralization dominates ore zones between 1300 and 900 m depth (Fig. 4.22). Both V_{2a}/V_{2b} and V_{2c} mineralization occurs between 1600 and 1300 m depth in the Campbell zone (Fig. 4.22). Above a depth of 900 m, ore zones situated towards the hanging wall of the Campbell zone are dominated by $V_{1a/b/c}$ refractory mineralization (Fig. 4.22). However, above a depth of 900 m, ore zones situated towards the footwall of the Campbell zone contain both V_{2c} and $V_{1a/b/c}$ mineralization.

In general, pyrrhotite is more abundant than pyrite deeper in the Giant-Con system. Within the Giant deposit the most abundant pyrrhotite occurs in the 'Lower B' zone, the deepest mined portion of the Giant deposit that is still associated with refractory gold within arsenopyrite. Pyrrhotite is also more prevalent deeper in the Campbell zone of the Con deposit. It is commonly observed within the '202' trend deep and north in the Campbell zone and is associated with a broad sericite alteration halo. This occurs where tuffaceous units occur in the hanging wall of the Campbell zone. The presence of pyrrhotite and the broad alteration halo in this area may therefore be related to the reaction of hydrothermal fluids with the tuffaceous wall rocks. Increased chalcopyrite, sphalerite, and galena also occur deeper in the Giant-Con system, spatially associated with V_{2a} and V_{2b} quartz-carbonate veining.

Breakey (1978) also recognized the zoning of gold mineralization within the Campbell zone, with the distribution of arsenopyrite and sulfosalts, variation

of iron content in sphalerite, variation in pyrite to pyrrhotite ratio, and distribution of minerals containing major bismuth.

Within the Giant-Con system, the distribution of gold mineralization styles represents a vertical zonation, where refractory-gold formed higher in the system (Giant, Con, and upper Campbell zones) and free-milling gold formed deeper in the system (lower Campbell zones).

Controls on the formation of refractory verses free-milling gold

The presence of both refractory and free-milling gold mineralization in mesothermal gold deposits is common (Boyle, 1979). Deposits containing both refractory and free-milling gold include the Archean Campbell, Goldcorp, and Cochenor-Willans gold deposits, Red Lake, Canada (Andrews et al., 1986) and the Proterozoic Obuasi and Bogosu-Prestea gold deposits, Ashanti, Ghana (Allibone et al., 2002a,b).

The Campbell, Goldcorp, and Cochenor-Willans gold deposits contain sheared, laminated, and brecciated quartz-carbonate veins and replacement zones that form arsenopyrite-quartz refractory gold zones that contrast with cross-cutting relatively sulphide poor, narrow free-milling gold bearing carbonatequartz veins (Armstrong, 1997). Arsenopyrite grains may contain up to 5600 ppm Au within As-rich portions of grains. Pyrite may also demonstrate gold enrichment of up to 168 ppm Au (Armstrong, 1997). The arsenopyrite-quartz zones are strongly overprinted by deformation resulting in their realignment subparallel to the foliation and stretching lineation (Andrews et al., 1986). In these

deposits refractory and free-milling gold mineralization formed at different times, similar to the Giant-Con deposits (Andrews et al. 1986). Van Hees et al. (1999) suggested that the high concentrations of arsenic and antimony in the Goldcorp deposit may indicate a metasedimentary influence on the genesis of the deposit. Similar to the Giant deposit, Van Hees et al. (1999) suggest the elevated arsenic and antimony values present were derived from hydrothermal fluids passing through a large turbidite basin.

The Proterozoic Obuasi deposit, Ashanti, Ghana, is the largest gold deposit in West Africa, with past production and current resources exceeding ~45 million ounces of gold. It contains both refractory gold sulphide lodes and free-milling gold quartz lodes throughout the deposit that are not restricted to particular zones as is the case in the Giant-Con deposits.

Quartz lodes are typically massive to laminated grey-white quartzcarbonate veins with associated chalcopyrite, galena, and sphalerite, with freemilling gold in graphitic deformation zones. Sulphide lodes comprise zones of disseminated auriferous arsenopyrite and pyrite, with trace amounts of pyrrhotite, chalcopyrite, sphalerite (Oberthür et al., 1994). Gold in the sulphide lodes is refractory and bound in the crystal lattice of arsenopyrite and arsenian pyrite.

The sulphide refractory gold lodes and the quartz free-milling gold lodes at Obuasi were traditionally described as separate mineralizing systems (Leube et al., 1990; Mumin et al., 1994) even though the two styles of mineralization are spatially related. Refractory gold (sulphide lodes) forms an alteration halo around quartz-carbonate veins (quartz lodes) that contain free-milling gold (Fig. 4.23).

Both mineralization styles are variably deformed, but formed synchronous with D_5 sinistral strike slip deformation (Allibone et al., 2002a). In this system both freemilling and refractory gold formed contemporaneously (Blenkinsop et al., 1994; Oberthür et al., 1994).

The Bogosu-Prestea gold deposit is situated ~100 km along strike to the southwest of the Obuasi deposit and is hosted within the same regional graphitic deformation zones that host gold mineralization at Obuasi. Bogosu-Prestea are thought to represent two different erosional levels within the same gold deposit; structurally higher and dominated by a brittle regime at Bogosu, and a structurally deeper, brittle-ductile regime in Prestea. The Bogosu-Prestea deposits host refractory sulphide gold in arsenopyrite and arsenian pyrite and quartz-carbonate veins containing free-milling gold (Allibone et al. 2002b). The Bogosu deposit (structurally higher) is dominated by refractory gold whereas Prestea (structurally lower) is dominated by free-milling gold. This is similar to the Giant-Con gold system, where the Giant (structurally higher) deposit is dominated by refractory gold and the Con (structurally lower) deposit is dominated by free-milling gold.

Mumin et al. (1994) suggested that gold was precipitated at Bogosu-Prestea as refractory gold in solid-solution with arsenopyrite and arsenian pyrite, and was subsequently remobilized to produce free-milling colloidal and microscopic gold particles. They suggested redistribution of refractory gold into free-milling gold increased with: 1) increasing hydrothermal and metamorphic grade, 2) decreasing refractory properties of host minerals, 3) increasing deformation, 4) increasing recrystallization of host minerals, 5) decrease in grain

size, and 6) the degree of interaction between host minerals and hydrothermal fluids. This resulted in the deeper Prestea deposit being dominated by freemilling gold (more recrystallization as the deposit is deeper) compared to the shallower Bogosu deposit that is dominated by refractory gold. Mumin et al. (1994) acknowledge that the free-milling gold that dominates the Prestea deposit could be a primary feature. They also suggest that the free-milling gold may have been precipitated directly from hydrothermal fluids after deposition of refractory gold.

A common aspect of the deposits outlined above, including the Giant-Con system, is the presence of large metaturbidite and sedimentary sequences in proximity to relatively restricted and small greenstone belts. For example the Duncan Lake Group in Yellowknife, the Slate Bay assemblage in Red Lake, and the Upper Birimian metaturbidite basin in Ghana. A genetic link between arsenopyrite-rich refractory gold deposits and areas with large volumes of sedimentary rock has been suggested (van Hees et al., 1999).

TIMING OF GOLD MINERALIZATION IN THE YGB

Shelton et al. (2004) suggested that both refractory and free-milling gold mineralization formed at the same time and from the same mineralizing fluid within the Giant deposit. Based on stable isotope and fluid inclusion analyses, refractory, sulphide hosted gold and free-milling, gold-bearing quartz veins within the Giant deposit deformation zones were deposited by H₂O-CO₂-NaCl fluids at

~300°-350°C, with δ^{18} O values of waters depositing the quartz ranging from 5.8 to 8.3 per mil (Shelton et al. 2004).

However, hydrothermal fluids associated with the free-milling gold in the Con deposit have lower δ^{18} O water values (5.4-6.8 per mil; Armstrong, 1997) than refractory sulphide hosted gold (9.1 per mil, Armstrong, 1997; 8.0 per mil, Kerrich and Fyfe, 1988). In guartz-vein-hosted free-milling gold veins that occur outside of the main deformation zones (for example the Negus-Rycon or Brock veins), δ^{18} O water values ranged from 2.8-5.6 per mil (Shelton et al. 2004). This suggests that δ^{18} O water values associated with refractory-gold mineralization are higher (>6.8 per mil) in contrast to lower δ^{18} O water values associated with free-milling gold mineralization (<6.8 per mil). Given the range of values (5.8 to 8.3 per mil) determined by Shelton et al. (2004), their results appear to have a mixed range of δ^{18} O water values from refractory and free-milling gold mineralization. Values closer to 5.8 per mil would correlate with quartz-carbonate veins hosting free-milling gold and values closer to 8.3 per mil would represent refractory sulphide hosted gold zones and veins. In contrast to Shelton et al. (2004) we interpret the stable isotope data to suggest two mineralizing events, a refractory gold event characterized by higher δ^{18} O water values and a free-milling gold event characterized by lower δ^{18} O water values. This agrees with the association between deformation and gold mineralization in the Giant-Con system.

Quartz-ankerite-sericite schist refractory gold mineralization (V_{1a}) is strongly deformed and overprinted by D_2 in the Giant and Con deposits. It is also

associated with an S_1 foliation in the Giant deposit likely formed during normal movement on the deformation zones (see Chapter 2, D_1 Extension).

In comparison, free-milling gold mineralization (V_{2a} , V_{2b} , and V_{2c}) in the Giant and Con deposits formed during D_2 compressional deformation (see Chapter 3, Mineralization). All three styles of free-milling quartz-carbonate veins commonly contain wall rock clasts that contain S_2 foliation, and often L_2 mineral lineations in quartz that are sub-parallel to the L_2 stretching lineation in the Campbell zone. V_{2b} and V_{2c} quartz veins also form in extensional settings compatible with the D_2 deformation. V_{2a} free-milling quartz veins that make up the Negus-Rycon system, formed during D_2 as a set of small reverse-sinistral deformation zones (see Chapter 3, D_2 Compression). Even though these veins occur outside the main deformation zones, they share many common characteristics with V_{2a} quartz veins in the Campbell zone.

The timing relationship between refractory and free-milling gold events is supported by crosscutting relationships between the V_{2c} pink-white quartz-carbonate veins (free-milling gold) and V_{1b} laminated quartz-carbonate veins (refractory gold). V_{2c} veins crosscut V_{1b} veins close to the footwall of the Campbell zone at ~900 m depth (Fig. 4.24A). Here a crossover occurs between refractory V_{1b} veining and free-milling V_{2c} veining.

In addition, sphalerite, galena, and chalcopyrite are strongly associated with quartz-carbonate free-milling gold veins that occur within the Campbell zone $(V_{2a} \text{ and } V_{2b} \text{ mineralization})$ and within the Negus-Rycon and Brock veins. Similar

sphalerite, galena, and chalcopyrite mineralization cross-cuts refractory gold bearing V_{1b} quartz-carbonate veins in the Campbell zone (Fig. 4.24B).

Correlation of Gold Mineralization with Regional Deformation Events in the Yellowknife Domain

No intrusive cross-cutting relationships providing well defined timing constraints on gold mineralization were observed in the course of this study. The deformation zones that host gold mineralization at Giant and Con crosscut all intrusive dykes and sills within the YGB apart from the Proterozoic Indin Lake diabase dykes (1.960 Ga.; Le Cheminant, 1997).

Henderson (1985) observed mutually crosscutting relationships and suggested that the #9 quartz-feldspar dykes formed coevally with the deformation zones. The authors found no evidence to support this within the Giant and Con deposits or during regional mapping within the YGB. Isachsen (1992), Cousens et al. (2004) and Ootes et al. (2004) have demonstrated that the #9 quartz-feldspar porphyry dykes are Banting Group in age (2.658 Ga.), and fed the Banting Group volcanics from a porphyritic intrusive centre at Ryan Lake. The only intrusive age constraint that exists in the YGB is that gold mineralization in the Giant and Con deposits formed between 2.658 Ga. and 1.960 Ga.

In the absence of intrusive crosscutting relationships, using the framework of refractory gold being associated with D_1 deformation and free-milling gold being associated with D_2 deformation, we can examine the evidence linking the

deposit scale deformation events with those defined regionally (Davis and Bleeker, 1999).

Regional and underground mapping suggests that D_2 in both the Giant and Con deposits can be correlated with the regional D_2 event (post-2.64-2.62 Ga Defeat magmatism, syn-2.58 Ga Prosperous magmatism). This is shown in the relationship between a lamprophyre dyke, metamorphism, and gold mineralization; the presence of amphibole in S_2 within the Campbell zone and in regional D_2 deformation zones; small scale deformation zones analogous to the Con deposit that crosscut the Defeat-age Western granodiorite; and in the Brock fold where early alteration is crosscut by gabbro and granite dykes and deformed by D_2 .

A lamprophyre dyke occurs in the hanging wall of the Campbell zone, Con deposit. The dyke does not exhibit textural evidence of any prograde metamorphic overprint, suggesting it was emplaced under peak to post-peak metamorphic conditions (Defeat related, 2.64-2.62 Ga., Armstrong, 1997). It is deformed within the Campbell zone with a well-developed S₂ foliation and L₂ lineation, and is cut by auriferous V_{2c} pink-white quartz-carbonate veins (Figs. 4.24 C and D). Therefore, the lamprophyre dyke was emplaced post or post-peak Defeat metamorphism and magmatism (2.64-2.62 Ga), pre-D₂ deformation, and pre-V_{2c} free-milling gold mineralization (see Chapter 3, D₂ Deformation). This correlates D₂ deformation in the Giant-Con system with the regional, post-Defeat metamorphism and magmatism, D₂ deformation event (Davis and Bleeker, 1999).

The correlation of D_2 in Giant-Con with D_2 regionally is supported by the Rod deformation zones that crosscut the Defeat Suite Western Plutonic Complex. The < 3 m wide Rod deformation zones contain free-milling gold and occur west of the Con deposit within the Western Plutonic Complex (Defeat age pluton; Fig. 4.25A). These deformation zones provide a small scale analogy to the Campbell and Con deformation zones in the Con deposit. The Rod deformation zones strike northeast and dip moderately northwest similar to the Con and Campbell deformation zones. They also display similar reverse-dextral shear kinematics to the D_2 deformation in the Campbell zone. This suggests that the Rod deformation zones formed syn- D_2 and since they crosscut the Defeat age Western Plutonic Complex, D_2 occurred post-Defeat Suite magmatism.

The correlation of Giant-Con D_2 deformation with regional D_2 deformation is confirmed by the presence of amphibolite schists within the Campbell zone and regional small scale deformation zones within the Yellowknife Greenstone Belt (Figs. 4.25B, C and D). Armstrong (1997) recognised the presence of amphibolite schists in the Campbell and Con zones, with epidote replacement and chlorite retrogression of medium grained idioblastic amphibole. Blue green, homogenous acicular euhedral amphibole is aligned and replaced by chlorite along the S₂ foliation. Other amphibolite grade deformation zones are present close to the contact with the Western granodiorite (e.g. Trapper Lake zone). The Trapper Lake deformation zone occurs north-west of the Giant deposit and contains an amphibolite grade S₂ foliation that is locally retrogressed to greenschist facies. The formation of amphibole within the S₂ foliation suggests

that D₂ deformation began in the YGB prior to the cessation of Defeat Suite related metamorphism (Siddorn and Cruden, 2000).

All evidence described above links or refines the correlation of D_2 (and therefore D_2 related free-milling gold mineralization) within the Giant-Con system with the regional D_2 event.

West of the Giant deposit, close to the granodiorite – mafic metavolcanic (Kam Group) contact, a unique timing history is displayed in the Brock Fold (Fig. 4.26). Here an S_1 fabric contained within calc-silicate, garnetiferous alteration, is cut by a porphyritic gabbro dyke and by granitic dykes that emanate from the granodiorite (Figs. 4.26 and 4.27). The calc-silicate, garnetiferous alteration and associated S_1 foliation are crosscut by a porphyritic gabbro dyke (~1.5 m wide) that contains well developed feldspar phenocrysts (Figs. 4.27A and B). This dyke correlates with the #8a gabbro dykes described by Henderson and Brown (1966), #8a being a porphyritic phase of the #8 gabbroic dykes. The #8 dykes crosscut the Anton granite (2642 ± 15 Ma, Dudas et al., 1990), but are crosscut by the Duckfish granite (2585 ± 4 Ma; Atkinson and Fyfe, 1991) and Defeat-age felsic intrusive rocks (U-Pb age of 2618 +7/-20 Ma; Henderson et al., 1987). The age of the #8 dykes is therefore bracketed between ca. 2620 and 2642 Ma (MacLachlan and Helmstaedt, 1995). As the #8a gabbro dyke crosscuts calcsilicate-garnet alteration and the S₁ foliation at the Brock Fold, this alteration and foliation developed pre-2620 Ma.

Henderson and Brown (1966) interpreted the #8 gabbro dykes to be feeders to the volcanic flows in the YGB. However more recent work suggests

the #8 dykes were emplaced after the rotation of the Kam Group volcanics to near vertical attitudes (Strand, 1993).

The #8a dyke, calc-silicate-garnet alteration, and S_1 foliation are also crosscut by small granitic dykes (<0.5 m wide) that can be traced back to the Defeat Suite granodiorite (Fig. 4.27C). The granitic dykes and the #8a gabbro dyke are folded and boudinaged by D₂. The #8a gabbro dyke forms a moderately southwest plunging, tight F₂ fold. A well developed S₂ foliation is present within the calc-silicate-garnet alteration, with a well-developed L₂ lineation defined by the alignment of amphibole in surrounding unaltered mafic pillow metavolcanics (Figs. 4.27D).

The #8a gabbro and alteration were metamorphosed to amphibolite grade after D_1 and the syn- D_1 alteration formed the garnet bearing assemblages. The metamorphism is most likely associated with Defeat Suite metamorphism given the proximity to the granodiorite contact.

Therefore, a sequence of events is well-defined at the Brock Fold, with early syn-D₁ alteration forming pre-2620 Ma, crosscut by a #8a gabbro dyke and Defeat Suite granitic dykes, and subsequently deformed by D₂. The post-Defeatage for D₂ correlates with the relationships observed in the Giant-Con system and regionally. However, this is the first identified example that shows that D₁ (including associated alteration) formed prior to Defeat Suite metamorphism.

Evidence to date suggests that D_1 in the Giant and Con deposits occurred pre-Defeat magmatism (2.63-2.62 Ga.) and was coeval with the formation of refractory gold (Fig. 4.28). D_2 initiated in the YGB towards the end of Defeat

Suite metamorphism (post 2.62 Ga., syn 2.58 Ga.) and was synchronous with the formation of free-milling gold (Fig. 4.28).

CONCLUSIONS

The Giant and Con deposits represent a classic Archean lode-gold deposit now offset by a major Proterozoic fault (West Bay Fault). A new solution for the West Bay Fault shows that the Con deformation zone and not the Campbell deformation zone is the down dip extension of the Giant deposit.

The Giant-Con system formed during or after tilting of the Kam Group as an upward-splaying fault zone, related to D_1 (pre-regional D_2 and Defeat magmatism/metamorphism) extension of the mafic volcanics. The formation of the Giant-Con system may be related to the formation of the fault bounded basin in which the Jackson Lake Formation was deposited.

The D_1 formation of the early Giant-Con fault system (with associated S_1 foliation), and associated gold mineralization resulted in alteration and the deposition of refractory gold.

D₂ regional northwest-southeast shortening of the Giant-Con fault system and associated gold mineralization resulted in further alteration and the deposition of free-milling gold. The gently dipping attitude of Giant deformation zones resulted in flattening of already incompetent deformation zones, resulting in the fold and mullion geometry. The moderately dipping attitude of the Con deformation zones resulted in reverse-dextral shear. D₂ deformation in the Giant-Con system was initiated at the end of Defeat-age peak metamorphism, and is

broadly correlated with the regional D_2 event (post-2.64-2.62 Ga Defeat magmatism, syn-2.58 Ga Prosperous magmatism).

The Giant-Con fault system was locally reactivated during the waning stages of D_2 northwest-southeast compression, resulting in the formation of localized D_3 reverse shear fabrics in both deposits.

The Giant-Con fault system was offset by Proterozoic faults resulting in the dip and strike slip separation of the two gold deposits. Different structural elevations within the original splaying Giant-Con deformation zones are now present within separate Proterozoic fault blocks. The Con deposit contains the deepest, highest order faults, moving up into the Giant deposit, and further into the lowest order faults, highest in the system in the Crestaurum deposit.

Gold mineralization was introduced into the Giant-Con system during at least two primary events; a refractory and free-milling gold event. Gold mineralization at the camp and deposit scale was vertically and temporally zoned with refractory gold forming at higher structural levels and earlier (D_1) and free-milling gold forming at lower structural levels and later (D_2).

The complexity of the Giant-Con system arises due to the multi-phase introduction of gold mineralization and associated alteration within an upward splaying fault system. This is further complicated by the interaction between a pre-existing extensional fault system and overprinting horizontal shortening strain, which dictated the final geometry of deformation and alteration zones and their associated gold mineralization.

ACKNOWLEDGEMENTS

We would like to thank Deb Archibald, Malcolm Robb, Lyn Anglin, and Bill Barclay for the initial invitation to study the Giant and Con deposits. Dr. Benoit Dubé and Dr. Herb Helmstaedt provided additional technical support and understanding of the Yellowknife Greenstone Belt. Dr. Eric de Kemp provided valuable Gocad training and assistance.

We wish to thank all participants of the Extech III project for the valuable discussions on YGB gold. This work would not have been possible without the unconditional assistance of production and exploration geologists at the Giant and Con mines, in particular, Bob Hauser, Dave Arthur, Alf Silke, Brenda Bilton, and Jeff Kulas at Con mine, and Tim Canam, Brad Mercer, Steve Roebuck, Sharon Cunningham, Morris Robinson, Jahlil Mustafa, and Rick Woodward at Giant mine. This work was financially supported by the Geological Survey of Canada, Government of the Northwest Territories, Department of Indian and Northern Affairs, Miramar Mining Ltd., and Royal Oak Mines Ltd., as part of the Extech III project.

REFERENCES

Allen, R.L., Weihed, P., and Svenson, S-A.

1997: Setting of Zn-Cu-Au-Ag Massive Sulphide Deposits in the Evolution and Facies Architecture of a 1.9 Ga Marine Volcanic Arc, Skellefte District, Sweden. Economic Geology, v. 91, p.1022-1053.

Allibone, A., McCuaig, T.C., Harris, D., Etheridge, M., Munroe, S., Byrne, D., Amanor, J., and Gyapong, W.

2002a: Structural Controls on Gold Mineralization at the Ashanti Deposit, Obuasi, Ghana. Society of Economic Geologists Special Publication 9, p. 65-93.

Allibone, A., Teasdale, J., Cameron, G., Etheridge, M., Uttley, P., Soboh, A., Appiah-Kubi, J., Adanu, A., Arthur, R., Mamphey, J., Odoom, B., Zuta, J., Tsikata, A., Pataye, F., and Famiyeh, S.

2002b: Timing and Structural Controls on Gold Mineralization at the Bogoso Gold Mine, Ghana, West Africa. Economic Geology, v. 97, p. 949-969.

Andrews, A.J., Hugon, H., Durocher, M., Corfu, F., and Lavigne, M.J.

1986: The Anatomy of a Gold-Bearing Greenstone Belt: Red Lake, Northwestern Ontario, Canada. *In:* Macdonald, A.J., ed., Proceedings of Gold '86, an International Symposium on the Geology of Gold, Toronto, p. 3-22.

Armstrong, J.P.

1997: Variations in Silicate and Sulphide Mineral Chemistry between Free-Milling "Metallic" and Refractory "Invisible" Gold Ores, Con Mine, Yellowknife, N.W.T. Unpublished Ph.D. thesis, University of Western Ontario, 317p.

Atkinson, D.J., Fyfe, W.S.

1991: The western Plutonic complex, southwestern Slave Province: Late Archean cratonization and granite gold connection at Yellowknife, Northwest Territories. Program with Abstracts, GAC–MAC of Canada, 16, A5. Bergman Weihed, J., Bergstrom, U., Billstrom, K., and Weihed, P.

1996: Geology, Tectonic Setting, and Origin of the Paleoproterozoic Boliden Au-Cu-As Deposit, Skellefte District, Northern Sweden. Economic Geology, v. 91, p. 1073-1097.

Blenkinsop, T., Mumm, A.S., Kumi, R., and Sangmor, S.

1994: Structural geology of the Ashanti Mine. Geologisches Jahrbuch, D100, p. 131-153.

Boyle, R.W.

- 1953a: On the Colour of Black and Grey Quartz from Yellowknife, Northwest Territories, Canada. American Mineralogist, v. 38, p. 528-535.
- 1953b: The Mineralization of the Yellowknife Gold Belt with Special Reference to the Factors which controlled its Localization. Unpublished Ph.D. thesis, University of Toronto.
- 1961: The geology, geochemistry, and origin of the gold deposits of the Yellowknife District. Geological Survey of Canada, Memoir 310, 193p.
- 1979: The geochemistry of gold deposits. Geological Survey of Canada, Bulletin 280, 584p.

Breakey, A.R.

1978: Zoning in gold-quartz lenses of the Campbell Shear, Con Mine, Yellowknife, N.W.T. Economic Geology, v.73, p.1388-1389.

Brown, C.E., Dadson, A.S., and Wrigglesworth, L.A.

1959: On the ore-bearing structures of the Giant Yellowknife Gold Mine. Canadian Institute of Mining and Metallurgy Transactions, LXII: 107-116.

Brown, I.C.

1955: Late faults in the Yellowknife Area. *In:* Proceedings of the Geological Association of Canada, v. 7, p. 123-138.

Brown, N.N.

1992: Evolution of Deformation and Mineralization Style within the Giant Shear Zone Complex, Yellowknife, Northwest Territories, Canada; unpublished PhD thesis, University of California, Santa Barbara, California, 445 p. Campbell, N.

- 1947: The West Bay Fault, Yellowknife. Canadian Institute of Mining and Metallurgy, v. 50, p. 509-526.
- 1949: West Bay Fault. *In:* Structural Geology of Canadian Ore Deposits. Canadian Institute of Mining and Metallurgy, Jubilee Volume, p. 244-259.

Cousens, B.L., Falck, H., Ootes, L., Jackson, V., Mueller, W., Corcoran, P., Finnigan, C.S., van Hees, E.H.P., Facey, C., Alcazar, A.

- 2006: Regional correlations, tectonic settings, and stratigraphic solutions in the Yellowknife greenstone belt and adjacent areas from geochemical and Sm-Nd isotopic analyses of volcanic and plutonic rocks. *In:* C.D. Anglin, H. Falck, D.F. Wright, E.J. Ambrose, eds., Gold in the Yellowknife greenstone belt, Northwest Territories: Results of the EXTECH III multidisciplinary research project. Special Publication - Geological Association of Canada. Mineral Deposits Division, v. 3, p. 70-94.
- Davis, W.J., and Bleeker. W.
- 1999: Timing of Plutonism, deformation, and metamorphism in the Yellowknife Domain, Slave Province, Canada. Canadian Journal of Earth Sciences, v. 36, p.1169-1187.
- Davis, B.K., and Maidens, E.
- 2003: Archean orogen-parallel extension: evidence from the northern Eastern Goldfields Province, Yilgarn Craton. Precambrian Research, v. 127, p. 229-248.
- Dudas, F.O., Henderson, J.B., Mortensen, J.K.,
- 1990: U–Pb ages of zircons from the Anton Complex, southern Slave Province, N.W.T. Radiogenic ages and isotope studies. Report 3, Paper 90-2, Geological Survey of Canada, p. 39–44.
- Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., and Robert, F.
- 1998: Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews, v. 13, p. 7-27.

Helmstaedt, H., and Padgham, W.A.

- 1986: A new look at the stratigraphy of the Yellowknife Surpergroup at Yellowknife, N.W.T. implications for the age of gold-bearing shear zones and Archean basin development. Canadian Journal of Earth Sciences, v. 23, p. 454-475.
- 1987. Stratigraphic and structural setting of gold bearing shear zones in the Yellowknife Greenstone Belt. *In:* L.A. Clark, ed., Gold in the Western Shield, CIM Symposium, v. 38, p. 322-346.

Henderson, J.B.

- 1978: Age and origin of the gold-bearing shear zones at Yellowknife, Northwest Territories. Geological Survey of Canada, Paper 78-1A, p. 259-262.
- 1985. Geology of the Yellowknife-Hearne Lake area, District of Mackenzie: A segment across an Archean basin. Geological Survey of Canada, Memoir 414, 135p.

Henderson, J.F., and Brown, I.C.

1966: Geology and structure of the Yellowknife Greenstone Belt, District of Mackenzie. Geological Survey of Canada, Bulletin 141, 87p.

Isachsen, C.E.

1992: U–Pb zircon geochronology of the Yellowknife volcanic belt and subjacent rocks, N.W.T., Canada: Constraints on the timing, duration, and mechanics of greenstone belt formation. Unpublished Ph.D. thesis, Washington University, St. Louis, Mo.

Isachsen, C.E. and Bowring, S.A.

- 1994: Evolution of the Slave Craton. Geology, v. 22, p. 917-920.
- 1997: The Bell Lake group and Anton Complex: a basement cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation. Canadian Journal of Earth Sciences, v. 34, p. 169-189.

Kerrich, R., and Allison, I.

1978: Vein geometry and hydrostatics during Yellowknife mineralization. Canadian Journal of Earth Sciences, v. 15, p. 1653-1660. Kerrich, R., Fyfe, W.S.,

1988: The formation of gold deposits with particular reference to Archean greenstone belts and Yellowknife. Contributions to the Geology of the Northwest Territories, Yellowknife, v. 3, p. 37-61.

Kusky, T.M., Lowman, P.D., Masuoka, P., and Blodget, H.W.

1993: Analysis of Seasat L-band radar imagery of the West Bay-Indin Lake fault system, Northwest Territories; Journal of Geology, v. 101, p. 623-632.

Laznicka, P.

1999: Quantitative relationships among giant deposits of metals. Economic Geology, v.94, p. 455–473.

Le Cheminant, A.N., Buchan, K.L., van Breeman, O., and Heaman, L.M.

1997: Paleoproterozoic continental break-up and reassembly: Evidence from 2.19 Ga diabase dyke swarms in the Slave and Western Churchill Provinces, Canada, Geological Association of Canada - Mineralogical Association of Canada, Annual Meeting, Program with Abstracts, v. 22, p.

Leube, A., Hirdes, W., Mauer, R., and Kesse, G.O.

1990: The Early Proterozoic Birimian Supergroup of Ghana and some aspects of its associated gold mineralization. Precambrian Research, v.46, p. 139-165.

MacLachlan, K., and Helmstaedt, H.,

1995: Geology and geochemistry of an Archean mafic dike complex in the Chan formation: basis for revised plate-tectonic model of the Yellowknife greenstone belt. Canadian Journal of Earth Sciences, v. 32, p. 614–630.

Martel, E. and Lin, S.

2006: Structural evolution of the Yellowknife Greenstone Belt, with emphasis on the Yellowknife River Fault Zone and the Jackson Lake Formation; Chapter 8. In: Gold in the Yellowknife Greenstone Belt, Northwest Territories: Results of the EXTECH III Multidisciplinary Research Project, (ed.) C.D. Anglin, H. Falck, D.F. Wright, and E.J. Ambrose; Geological Association of Canada, Mineral Deposits Division, Special Publication No. 3, p. 95-115.

Mueller, W., and Donaldson, J.A.

1994: Sedimentology of the late-orogenic sedimentary Jackson Lake Formation in the Slave Province. Department of Indian Affairs and Northern Development, Yellowknife, Northwest Territories, EGS 1994-10, 13p.

Mumin, A.H., Fleet, M.E., and Chrysoulis, S.L.

1994: Gold mineralization in the As-rich mesothermal gold ores of the Bogosu-Prestea mining district of the Ashanti gold belt, Ghana: Remobilization of "invisible" gold. Mineralium Deposita, v. 29, p. 445-460.

Oberthür, T., Vetter, U., Mun, A.S., Weiser, T., Amanor, J.A., Gyapong, W.A., Kumi, R., Blenkinsop, T.G.

1994: The Ashanti gold mine at Obuasi, Ghana: Mineralogical, geochemical, stable isotope and fluid inclusion studies on the metallogenesis of the deposit. Geologisches Jahrbuch, v. 100, p. 31-129.

Ootes, L., Lentz, D.R., Cabri, L.J., and Hall, D.C.

2006: Geology and gold mineralization in the Crestaurum Mine area, northern Yellowknife greenstone belt, N.W.T. *In:* C.D. Anglin, H. Falck, D.F. Wright, E.J. Ambrose, eds., Gold in the Yellowknife greenstone belt, Northwest Territories: Results of the EXTECH III multidisciplinary research project. Special Publication - Geological Association of Canada. Mineral Deposits Division, v. 3, p. 249-269.

Shelton, K.L., McMenamy, T.A., van Hees, E.H.P., Falck, H.

2004: Deciphering the complex fluid history of a greenstone-hosted gold deposit; fluid inclusion and stable isotope studies of the Giant Mine, Yellowknife, Northwest Territories, Canada. Economic Geology, v. 99, p. 1643-1663.

Sibson, R.H.

1981: Controls on low-stress hydrofracture dilatancy in thrust, wrench and normal fault terrains. Nature, v. 289, p. 665-667.

Siddorn, J.P. and Cruden, A.R.

- 2000: The timing of gold mineralization in the Giant and Con deposits, Yellowknife, Canada; in Program & Abstracts of Talks and Posters, 28th Yellowknife Geoscience Forum, p. 74-76.
- 2001: The Giant-Con Gold Deposits: Evidence for a Once-Linked Archean Lode-Gold Deposit. Geological Association of Canada Abstract Volume, v. 25, unpaginated.

Siddorn, J.P., Cruden, A.R., Hauser, R.L., Armstrong, J.P., and Kirkham, G.D.

2006: The Giant-Con gold deposits: Preliminary integrated structural and mineralization history. *In:* C.D. Anglin, H. Falck, D.F. Wright, E.J. Ambrose, eds., Gold in the Yellowknife greenstone belt, Northwest Territories: Results of the EXTECH III multidisciplinary research project. Special Publication - Geological Association of Canada. Mineral Deposits Division, v. 3, p. 213-231.

Strand, P.D.

1993: The relationship of gold mineralization to intrusive breccia centres at the NERCO Con Mine, Yellowknife, N.W.T. Unpublished M.Sc. thesis, University of Western Ontario, 288 p.

Thompson, P.

2006: Metamorphic constraints on the geological setting, thermal regime, and timing of alteration and gold mineralization in the Yellowknife Greenstone Belt, NWT, Canada. *In:* C.D. Anglin, H. Falck, D.F. Wright, E.J. Ambrose, eds., Gold in the Yellowknife greenstone belt, Northwest Territories: Results of the EXTECH III multidisciplinary research project. Special Publication - Geological Association of Canada. Mineral Deposits Division, v. 3, p. 142-172.

Twiss, R.J. and Moores, E.M.

1992: Structural Geology. W.H. Freeman Publisher, New York.

van Hees, E.H.P., Shelton, K.L., McMenamy, T.A., Ross, L.M., Cousens, B.L., Falck, H., Robb, M.E., Canam, T.W,

1999: Metasedimentary influence on metavolcanic-rock-hosted greenstone gold deposits; geochemistry of the Giant Mine, Yellowknife, Northwest Territories, Canada. Geology, v. 27, p. 71-74.

Vearncombe, J.R.

1992: Archean gold mineralization in a normal-motion shear zone at Harbour Lights, Leonora, Western Australia. Mineralium Deposita, v. 27, p. 182-191.

Webb, D.R.

1983: The Relationship of Ore to Structural Features of the Campbell Shear Zone and Hanging Wall Stratigraphy in the Con Mine, Yellowknife, Northwest Territories. Unpublished MSc. thesis, Queen's University, Kingston, Ontario, 181 p.

Williams, P.R., and Currie, K.L.

1993: Character and regional implications of the sheared Archean granitegreenstone contact near Leonora, Western Australia. Precambrian Research, v. 62, p. 343-365.

Witt, W.K.

2001: Tower Hill gold deposit, Western Australia: an atypical, multiply deformed Archean gold-quartz vein deposit. Australian Journal of Earth Sciences, v. 48, p. 81-99.

TABLE CAPTIONS

 Table 4.1. Differences and similarities comparing the Giant and Con gold deposits.

Table 4.2. Historical solutions for the movement of the West Bay fault, fromCampbell (1947, 1949) and Brown (1955).

Table 4.3. Mineralization styles in the Giant and Con gold deposits.

FIGURE CAPTIONS

Figure 4.1. Regional Geological setting of the Yellowknife Greenstone Belt. **A.** Geological map of the Yellowknife greenstone belt and surrounding geology (modified from Helmstaedt and Padgham, 1986). **B.** Location of the Archean Slave Province and the Yellowknife District (modified from Robert and Poulsen, 1997). **C.** Geological map of the Archean Slave Province (modified from McGlynn, 1977 and Hoffman and Hall, 1993).

Figure 4.2. A schematic stratigraphic column for the Yellowknife Greenstone Belt. Age dates listed as follows: ¹Isachsen, 1992; ²Isachsen and Bowring, 1994; ³Mortensen et al., 1992; ⁴Davis and Bleeker, 1999; ⁵Strand and Duke, 1991; ⁶McLachlan and Helmstaedt, 1995; and ⁷LeCheminant et al., 1997.

Figure 4.3. Surface geological maps of the Giant and Con deposits. Modified from Henderson and Brown (1966). Cross-sections A-A' and B-B' are shown in Figure 4.4.

Figure 4.4. Cross-sections through the Giant gold deposit (2000N, Giant geology imperial mine grid co-ordinates) and the Con gold deposit (19500N, Con imperial mine grid co-ordinates). Location of cross-sections are shown in Figure 4.3.

Figure 4.5. Schematic representation of the Giant-Campbell Zone deformation system based on the Campbell (1947) solution for the offset of the West Bay Fault. Modified from Lewis (1985).

Figure 4.6. Campbell's (1947, 1949) piercing point fault solution for the West Bay Fault, with the position of the Giant and Campbell deformation zones added. Modified from Campbell (1947).

Figure 4.7. Conversion of average Campbell (1947, 1949) and Brown (1955) strike and dip slip displacements into X, Y, Z components.

Figure 4.8. Gocad based reconstruction of the geology either side of the West Bay fault using the average Campbell (1947, 1949) and Brown (1955) strike and dip slip displacements. **A.** Plan view showing the pre-West Bay Fault movement position of the Con, Campbell and Giant deformation zones, and Townsite Formation. **B.** Cross-section showing the pre-West Bay Fault movement position of the Con, Campbell and Giant deformation zones, and Townsite Formation.

Figure 4.9. Reconstruction of the Giant and Con gold deposits across the West Bay fault based on Campbell's (1947, 1949) and Brown's (1955) fault solutions. Note the 30 degree bend required to realign the Campbell deformation zone to the Giant deformation zones. Adapted from Helmstaedt & Padgham (1987).

Figure 4.10. West Bay fault photographs, Part One. **A.** Aerial photograph looking down to south along the West Bay fault, where Kam Group mafic metavolcanics are juxtaposed against granodiorite of the Western Plutonic Complex. Note red hematite along the West Bay fault in the granodiorite. Location D, **Fig. 4.12**. **B.** Aerial photograph looking down to south along the West Bay fault within the A1 open pit. Location B, **Fig. 4.12**. **C.** Slickensides along the West Bay fault observed at location A, **Fig. 4.12**, long section view. **D.** West Bay fault within the A1 open pit. Here the West Bay fault juxtaposes undeformed Kam Group mafic metavolcanics against the Giant deformation zones. Location B, **Fig. 4.12**.

Figure 4.11. West Bay fault photographs, Part Two. **A.** Wallrock (granite and mafic metavolcanics) slivers within quartz-hematite mineralization within the

West Bay fault. Location C on **Fig. 4.12**. **B.** Slickensides along the West Bay fault observed at location F on **Fig. 4.12**. **C.** Brecciated granite with infilling hematite mineralization, location E, **Fig. 4.12**. **D.** Aerial photograph of cataclasite zone close to mafic metavolcanic roof pendant, location E, **Fig. 4.12**.

Figure 4.12. Geological map showing the location of measurements of the fault plane and associated slickenlines along the West Bay fault. Lambert equal area projections showing the orientation of the West Bay Fault (great circles) and associated slickenlines (linear data).

Figure 4.13. 2D estimation of the oblique slip, strike slip and dip slip components of displacement along the West Bay fault. Long section looking east orientated normal to the West Bay fault plane. This 2D estimation uses the strike separation of the Townsite Formation by the West Bay fault (shown in yellow) and the average slickenside orientation (6° north). The strike separation is shown in red (4080 m), oblique slip in black (3959 m), strike slip in blue (3937 m) and dip slip in green (414 m).

Figure 4.14. Conversion of strike slip and dip slip components of displacement along the West Bay fault shown in **Figure 4.14** into X, Y, Z components.

Figure 4.15. Gocad based reconstruction of the geology either side of the West Bay fault using this studies strike and dip slip displacements. **A.** Plan view showing the pre-West Bay Fault movement position of the Con, Campbell and Giant deformation zones, and Townsite Formation. **B.** Cross-section showing the pre-West Bay Fault movement position of the Con, Campbell and Giant deformation zones, and Townsite Formation.

Figure 4.16. Zone of early faulting shown by a Proterozoic fault reconstruction around the Giant deposit. Adapted from Henderson and Brown (1966).

Figure 4.17. Simplified geological map of the Yellowknife Greenstone Belt, highlighting the thickness of the Yellowknife Bay Formation (Kam Group) relative to the position of the Jackson Lake Formation unconformity and the Bode Tuff.

Figure 4.18. Schematic stratigraphic sections of the Con, Giant, and Walsh Lake fault blocks (shown on Fig. 4.17). Note the change in thickness of the Yellowknife Bay Formation relative to the Jackson Lake Formation unconformity and the Bode Tuff.

Figure 4.19. Giant-Con deformation zones represent a splaying fault system. Deformation zones shown in black. Changing fault order from the Con (**A**; first order) to the Giant (**B**; second order) to the Walsh Lake (**C**; third order) fault blocks.

Figure 4.20. Gold mineralization styles in the Giant-Con system. **A.** V_{1a} quartzankerite-paragonite schist, 3-12N stope, Giant deposit. **B.** V_{1b} laminated quartz vein, 750-35N stope, Giant deposit. **C.** V_{1c} breccia vein, 2785N stope, Campbell zone, Con deposit. **D.** V_{2a}/V_{2b} quartz-carbonate veining, 6191M stope, Campbell zone, Con deposit.

Figure 4.21. V_{2b} pink-white veins forming during B_2 boudinage of V_{2a} veins.

Figure 4.22. Schematic figure displaying the distribution of mineralization types in the Giant and Con deposits. (Bold labels = refractory-gold mineralization; dark grey italic labels = free-milling mineralization; light grey labels = barren mineralization).

Figure 4.23. Examples of gold mineralization from the Obuasi deposit, Ashanti, Ghana. **A.** Refractory gold hosted in arsenopyrite halo surrounding free-milling gold bearing quartz-carbonate veins, 24164 stope, Sansu zone. **B.** Laminated quartz-carbonate vein hosting free-milling gold, in graphitic schist, cross-section, Sansu zone. **C.** Laminated quartz-carbonate vein hosting free-milling free-milling gold, in graphitic schist, cross-section, Sansu zone. **D.** Quartz vein stockwork hosting free-milling gold with arsenopyrite hosting refractory gold in the graphitic schist, drillcore from the Sansu zone.

Figure 4.24. Gold mineralization age relationships. **A.** V_{1b} laminated quartzcarbonate veins with refractory gold crosscut by V_{2c} pink-white quartz veins (freemilling gold), 2985AW stope, Campbell zone, Con deposit. **B.** V_{1b} laminated quartz-carbonate veins with refractory gold crosscut by sphalerite-galena (commonly associated with V_{2a} and V_{2b} free-milling gold, quartz-carbonate veining), 26220ZD stope, Campbell zone, Con deposit. **C.** Deformed lamprophyre dyke, with a well developed S₂ foliation, 2300 level, Campbell zone, Con mine. **D.** V_{2C} pink-white quartz vein crosscutting the deformed lamprophyre dyke then folded by S₂, 2300 level, Campbell zone, Con mine.

Figure 4.25. Photographs of structural features used to correlate regional to deposit scale deformation. **A.** Small scale deformation zone at the Rod claims, Western Plutonic Complex, cross-section, station 98039. **B.** Trapper Lake amphibolite schist deformation zone, plan, station 20026. **C.** Amphibolite-chlorite schist, Campbell deformation zone, plane polarized light, sample from 5960M

stope, field of view 1.25mm. **D.** Amphibolite-chlorite schist, Con deformation zone, plane polarized light, sample from 27625 stope, field of view 1.25mm.

Figure 4.26. Map of the Brock fold, close to the granite-greenstone contact.

Figure 4.27. Photographs of structural features at the Brock Fold. **A.** Aerial view of Brock fold showing the gabbro dyke crosscutting tan coloured alteration and tightly folded by F_2 , looking towards 270°. **B.** Gabbro dyke with feldspar phenocrysts crosscutting tan coloured alteration, plan view. **C.** F_2 folds in granitic dyke, plan view. **D.** Well-developed L_2 lineation in amphibole in altered mafic pillow metavolcanic, plan view. Note this location displays a strong L_2 lineation but not an S_2 foliation.

Figure 4.28. Schematic diagram illustrating the timing of gold mineralization compared to the deformation events in the Giant and Con deposits and the principal geological events in the Yellowknife Domain. Modified from Davis and Bleeker, 1999.
Deposit	Giant	Con				
Similarities	Proximal location (7.7km apart) within the YGB, both deposits truncated either side of West Bay fault (Fig. 4.1, 4.3)					
	Hosted in deformation zones that crosscut the Kam Group (2.72-2.7 Ga., Isachsen, 1992, Fig. 4.3)					
	Host deformation zones trend oblique to strike of Kam Group stratigraphy, therefore along strike to north the host deformation zones crosscut older stratigraphic units					
	Economic gold mineralization occurs where the deformation zones crosscut the Yellowknife Bay Fm., Kam Group					
	Contain quartz veins with very high grade gold, within the vicinity of the main deposits, but outside the main deformation zones (Giant - Brock vein, Con - Negus-Rycon veins)					
	Contain refractory and free-milling gold mineralization					
	Experienced the same 4 phases of deformation, D ₁ extension, D ₂ compression, D ₃ Reactivation, D ₄ Proterozoic faulting					
Differences	Complex deformation zone geometry, with intersecting zones with northwest, southeast, and vertical dips, defining an antiformal/synformal geometry (Fig. 4.4)	Moderately northwest dipping, planar deformation zones (Fig. 4.4)				
	600m depth (Fig. 4.4)	2000m depth (Fig. 4.4)				
	Sinistral separation of the Townsite Fm. (Fig. 4.5)	Dextral separation of the Townsite Fm. (Fig. 4.5)				
	Dominated by refractory gold, with minor free-milling gold	Dominated by free-milling gold, with minor refractory gold				
	During D_2 deformation, deposit was dominated by flattening strain	During D_2 deformation, deposit was dominated by reverse-dextral shear				

Solution	Strike Slip (ft)	Dip Slip (ft)	Strike Slip (m)	Dip Slip (m)	Displacement	Fault type	
Campbell (1947, 1949)	16140	1570	4919.47	478.54	Con block south and up	Sinistral-reverse	
Brown (1955)	16100	1500	4907.28	457.20	Con block south and up	Sinistral-reverse	
Average	16120	1535	4913.38	467.87	Con block south and up	Sinistral-reverse	
Siddorn & Cruden (this paper)	12918	1358	3937.41	413.92	Con block south and down	Sinistral-normal	

Mineralisation type	Description	Deformation event	Au mineralisation			Giant	Con
			Barren	Refractory	Free-milling	Giant	Con
V _{1a}	Quartz-ankerite-paragonite schist	D ₁		✓		\checkmark	~
V _{1b}	White laminated quartz veins	D ₁		~		✓	✓
V _{1c}	Quartz breccia veins	D ₁		~		✓	✓
V _{2a}	Grey-white laminated quartz veins	D2			✓	✓	✓
V _{2b}	White non-laminated quartz veins	D2			✓		✓
V _{2c}	Pink-white non-laminated quartz veins	D2			✓		✓
V _{2d}	Extensional quartz-calcite-epidote veins	D2	~			✓	✓
V _{4a}	Quartz-hematite-stibnite-calcite veins	D ₄	~			✓	✓



Intrusives



Figure 4.2

















































Figure 4.18















Figure 4.20

10cm

































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CHAPTER 5

CONCLUDING REMARKS

The main conclusions of this thesis are:

GIANT DEPOSIT

- Gold mineralization formed early, prior to the main phase of deformation;
- Early (D₁) extensional deformation occurred prior to the main phase (D₂) of deformation;
- D₁ deformation resulted in the offset of the Townsite Formation (Kam Group) by the Giant deformation zones;
- The complex geometry of the deposit is partly inherited from its original geometry and partly related to the overprinting deformation (D₂) flattening the deposit. This latter created complex mullion structures in the deformation zone-wallrock contacts, and boudins and folds within quartz rich auriferous zones;
- The interaction of the original geometry with the overprinting deformation controlled the geometry of auriferous zones within the deposit, creating opposing south and north ore plunges; and
- D₂ deformation was dominated by northwest-southeast directed flattening and not progressive reverse shear.

CON DEPOSIT

- Early (D₁) extensional deformation occurred prior to the main phase (D₂) of deformation as shown by the pre-D₂ reconstruction of the Townsite Formation on either side of the Campbell deformation zone;
- A multistage history of gold mineralization is present, with six identified styles of gold mineralization, both refractory and free-milling gold;
- Gold mineralization is vertically zoned, with refractory gold mineralization forming higher and free-milling gold forming lower in the deposit;
- D₂ deformation was dominated by progressive reverse-dextral shear;
- The emplacement of competent auriferous quartz rich veins into incompetent chlorite +/- sericite schist creates a large competence contrast. During progressive deformation the existing veins are boudinaged and fractured creating low stress sites localizing the deposition of subsequent hydrothermal fluids; and
- Ore plunge is strongly controlled by the orientation of F₂ fold and B₂
 boudin axes in auriferous quartz veins. In a number of auriferous zones
 these have been rotated parallel to the L₂ lineation.

THE GIANT-CON

- The West Bay Fault offsets the Giant and Con deposits with a sinistralnormal movement (Con, hanging wall, block down and to the south);
- The reconstruction of the Giant and Con deposits shows the Con deformation zone is the down dip extension of the Giant deposit and not the Campbell zone;
- The Giant-Con deposits originally formed as an upward splaying fault system, moving from a first order large deformation zone at depth (Campbell zone) into second order (Giant) and third order deformation zones (Crestaurum) from south to north within the Yellowknife Greenstone Belt;
- The Giant-Con system displays an opposing offset of the Townsite Formation. This is related to early extensional D₁ deformation creating a graben within the Giant-Con system;
- D₁ extensional deformation caused the excision of stratigraphy from the Yellowknife Bay Formation along the Giant and Con deformation zones;
- D₁ deformation is probably linked to the formation of fault bound basins in which the Jackson Lake Formation was deposited;
- D₂ northwest-southeast shortening resulted in the flattening of the Giant deposit and the reverse-dextral shear of the Con deposit. This was controlled by the orientation of the deformation zones to the imposed strain;

- A vertical zonation of refractory and free-milling gold mineralization is present from within the Giant-Con system. Refractory gold mineralization primarily formed high in the system and free-milling gold mineralization at depth;
- Refractory and free-milling gold mineralization in the Giant-Con system is mineralogically distinct. Refractory gold mineralization is associated with a paragonitic white mica whilst free-milling gold mineralization is associated with a phengitic white mica;
- Refractory gold mineralization likely occurred during early D₁ deformation prior to the deposition of the Jackson Lake Formation; and
- Free-milling gold mineralization occurred during D₂ deformation, which was initiated during the waning stages of Defeat Suite metamorphism.

FURTHER RESEARCH

Several aspects of this research have identified broad topics that should be investigated further. This includes:

The association of early deformation (prior to the main compressive deformation event) and Archean/Proterozoic orogenic gold deposits.
 Evidence for early stages of deformation in gold deposits is often cryptic and hard to decipher. Previous research has focused on the association of orogenic gold deposits and late stage gold (Groves et al. 1998), but evidence for long lived fault zones with a history of reactivation could be important for the formation of world class gold deposits.

- The association of early extensional deformation with the excision of stratigraphy in greenstone belts. Several greenstone belts worldwide (Yellowknife, Gwalia) have large variations in stratigraphic thicknesses across known fault zones (this study; Bateman, 2001; Witt, 2001). Each of these areas has an association with a significant gold district. Overall, the role of extensional deformation in Archean and Proterozoic tectonics is poorly defined, when it is clear from the presence of 'Timiskaming' style sedimentary rocks and major turbidite sequences that extensional tectonics must have a role in the evolution of greenstone belts in some form.
- The relationship between refractory and free-milling gold mineralization in districts and individual deposits. Only limited research on the relationship, timing and geochemical evolution of refractory versus free-milling gold ores is available. In most deposits that contain both forms of gold mineralization the relationship between the two is not well studied, including major deposits in Red Lake and West Africa.
- The role of overprinting deformation in the structural modification of gold deposits and its control on ore plunge. This thesis has demonstrated an excellent example of the rotation of fold and boudin axes in auriferous quartz-carbonate veins into parallelism with the stretching lineation. This is a well-known phenomenon in high strain shear zones but poorly documented in orogenic gold deposits. It is likely a much more important

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factor in controlling the distribution of gold mineralization in orogenic gold deposits than presently acknowledged.

 The presence of mullion structures within deformed orogenic gold deposits. This thesis outlines how early deformation-alteration zones in the Giant deposit were flattened forming mullions at the wallrockdeformation zone interface. Given the expected competence contrast between alteration zones and surrounding greenstone belts it is likely that more deposits show mullion geometries, dependent on their orientation to the overprinting deformation.

REFERENCES

Bateman, R.J., Hagemann, S.G., McCuaig, T.C., Swager, C.P.

2001: Protracted gold mineralization throughout Archaean orogenesis in the Kalgoorlie camp, Yilgarn Craton, Western Australia: structural, mineralogical, and geochemical evolution. World-class gold camps and deposits in the eastern Yilgarn Craton, Western Australia, with special emphasis on the Eastern Goldfields Province, Record 2001/17.Western Australia Geological Survey, p. 63–98.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., Robert, F.

1998: Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types', Ore Geology Reviews, 13, p. 7-27.

Witt, W.K.

2001: Tower Hill gold deposit, Western Australia: an atypical, multiply deformed
Archean gold-quartz vein deposit. Australian Journal of Earth Sciences, v.
48, p. 81-99.

APPENDIX A

GIANT MINE UNDERGROUND GEOLOGY MAPS

This appendix contains geology maps of different stopes within the Giant mine at either 20 scale (1inch:20feet) or 30 scale (1inch:30feet).





































APPENDIX B

CON MINE UNDERGROUND GEOLOGY MAPS

This appendix contains geology maps of different stopes within the Con mine at either 20 scale (1inch:20feet) or 30 scale (1inch:30feet).






































