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Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration

Precambrian lode gold deposits — a summary of TGI-4 contributions to the understanding of lode gold deposits, with an emphasis on implications for exploration

Benoît Dubé[1], Patrick Mercier-Langevin[1], Sébastien Castonguay[1], Vicki J. McNicoll[2], Wouter Bleeker[2], Christopher J.M. Lawley[2], Stéphane De Souza[1], Simon E. Jackson[2], Céline Dupuis[1], Jian-Feng Gao[2], Valérie Bécu[1], Pierre Pilote[3], Jean Goutier[4], Gary P. Beakhouse[5], David Yergeau[6], William Oswald[6], Vivien Janvier[6], Arnaud Fontaine[6], Mireille Pelletier[6], Anne-Marie Beauchamp[6], Michel Malo[6], Laura R. Katz[7], Daniel J. Kontak[7], Zsuzsanna Tóth[7], Bruno Lafrance[7], Blandine Gourcerol[7], Phillip C. Thurston[7], Robert A. Creaser[8], Randolph J. Enkin[9], Najib El Goumi[9], Eric C. Grunsky[2], David A. Schneider[10], Colter J. Kelly[10], and Kathleen Lauzière[1]

[1]Geological Survey of Canada, Québec, Quebec
[2]Geological Survey of Canada, Ottawa, Ontario
[3]Ministère de l'Énergie et des Ressources naturelles, Montréal, Quebec
[4]Ministère de l'Énergie et des Ressources naturelles, Rouyn-Noranda, Quebec
[5]Ontario Geological Survey, Sudbury, Ontario
[6]Institut national de la recherche scientifique – Centre Eau Terre Environnement, Québec, Quebec
[7]Laurentian University, Sudbury, Ontario
[8]University of Alberta, Edmonton, Alberta
[9]Geological Survey of Canada, Sidney, British Columbia
[10]University of Ottawa, Ottawa, Ontario

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Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

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[1]Geological Survey of Canada, 490 rue de la Couronne, Québec, Quebec G1K 9A9
[2]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E9
[3]Ministère de l'Énergie et des Ressources naturelles, 201 avenue du Président-Kennedy, Montréal, Quebec H2X 3Y7
[4]Ministère de l'Énergie et des Ressources naturelles, 70 avenue Québec, Rouyn-Noranda, Quebec J9X 6R1
[5]Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5
[6]Institut National de la Recherche Scientifique, Centre Eau-Terre-Environnement, 490 rue de la Couronne, Québec, Quebec G1K 9A9
[7]Mineral Exploration Research Centre, Laurentian University, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5
[8]University of Alberta, 126 Earth Sciences Building, Edmonton, Alberta T6G 2R3
[9]Geological Survey of Canada, P.O. Box 6000, Sidney, British Columbia V8L 4B2
[10]Department of Earth Sciences, University of Ottawa, Ottawa, Ontario K1N 6N5
*Corresponding author's e-mail: bdube@nrcan.gc.ca
†Corresponding author's e-mail: pmercier@nrcan.gc.ca

ABSTRACT

The TGI-4 Lode Gold project, which comprises numerous site-specific and thematic research activities, covers the entire spectrum of crustal settings for lode gold deposits, from orogenic banded iron formation-hosted and greenstone-hosted quartz carbonate vein-type gold deposits formed deep in the crust (>5 km), to intrusion-related deposits that are formed at shallower crustal levels (~2–5 km), and to deposits formed at or near the seafloor. Herein we synthesize a number of important project contributions that have significant implications for on-going mineral exploration for hidden deposits. Among the key findings is a newly established link between major faults, their early evolution, syntectonic magmatism and synorogenic sedimentary basin evolution, and gold metallogenesis in various greenstone belts. The revised model incorporates a phase of tectonic extension—a distinct feature recognized in gold-rich settings worldwide—that is applicable to mineral exploration targeting across the Canadian Shield. Importantly, the simultaneous multidisciplinary study of a number of large banded iron formation-hosted gold deposits and districts allows for the development of a unifying genetic model for such deposits that integrates critical structural, stratigraphic, hydrothermal, and metamorphic elements. Several key features that are common to all of the studied deposits, but elements specific to dominantly banded iron formation-hosted gold deposits or to deposits that are only partly hosted in banded iron formation, were also established. The Lode Gold project also bridges a major knowledge gap by characterizing a spectrum of "unusual" or "atypical" gold deposits in the Superior Province. The new and revised models incorporate synvolcanic as well as pre-deformation and synorogenic synmagmatic or intrusion-related gold deposits that represent a large part of the newly discovered resources in the Canadian Shield in both "brownfield" and "greenfield" exploration environments.

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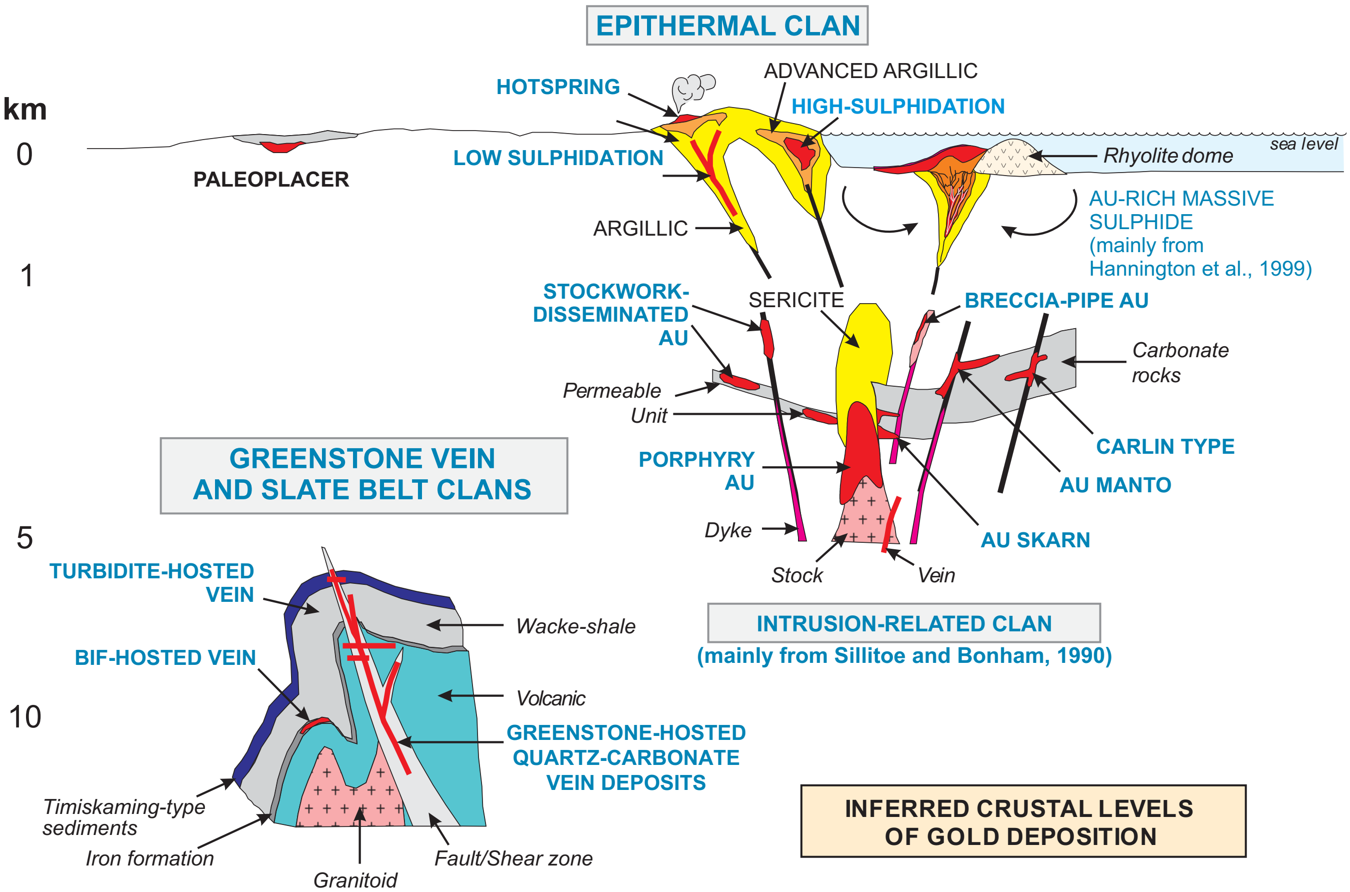

Figure 1. Schematic crustal section showing the inferred levels of gold deposition for the different types of lode gold deposits and their inferred clan (modified from Poulsen et al., 2000 and from Dubé and Gosselin, 2007).

INTRODUCTION

Gold is a major commodity that drives the Canadian mineral production and exploration industries (Mining Association of Canada, 2014). Over 90% of the historical gold production in Canada originates from Precambrian terranes, with as much as 85% coming from the Superior Province (based on 2009 figures; B. Dubé and V. Bécu, unpub. data). Despite a preponderance of Archean greenstone-hosted orogenic quartz-carbonate vein-type gold deposits, other types or styles of Precambrian gold deposit significantly contribute to the overall Canadian gold production, including BIF-hosted gold, intrusion-related, stockwork-disseminated gold (sediment- and volcanic-hosted), and gold-rich and auriferous volcanogenic massive sulphide (VMS) deposits (Fig. 1). Recent major discoveries in Canada (e.g. Côté Gold, Rainy River, Borden and Westwood; Fig. 2) illustrate that some deposit types and favourable geological settings are relatively poorly understood and/or underexplored, providing great scientific and exploration challenges that must be addressed prior to improving exploration models and guides. Most lode gold deposits, irrespective of deposit type, occur in deformed and metamorphosed terranes and are distributed along major structures, such as the Larder Lake-Cadillac or the Porcupine-Destor fault zones in the Southern Abitibi (Fig. 3; Miller and Knight, 1915; Groves, 1993; Hodgson, 1993; Kerrich and Cassidy, 1994; Groves et al., 1998; Kerrich et al., 2000; Goldfarb et al., 2005; Robert et al., 2005; Dubé and Gosselin, 2007). However, the key geological parameters controlling the fertility of such crustal-scale fault zones and the distribution and preservation of adjacent large gold deposits represent major knowledge gaps in lode gold systems that require further investigation (Robert et al. 2005; Dubé and Gosselin, 2007; Dubé et al., 2011).

MAIN RESEARCH THEMES

To develop a new generation of geological and exploration models based on modern, multi-parameter documentation of lode gold deposits, three main research themes were prioritized: 1) BIF-hosted gold deposits, 2) intrusion-related and stockwork-disseminated gold deposits, and 3) crustal-scale fault zones fertility. There are commonalities among these three research themes, and there are some linkages with other TGI-4 projects, including precious metal-rich VMS deposits. Methodology development is another common aspect of most of the research activities undertaken under the

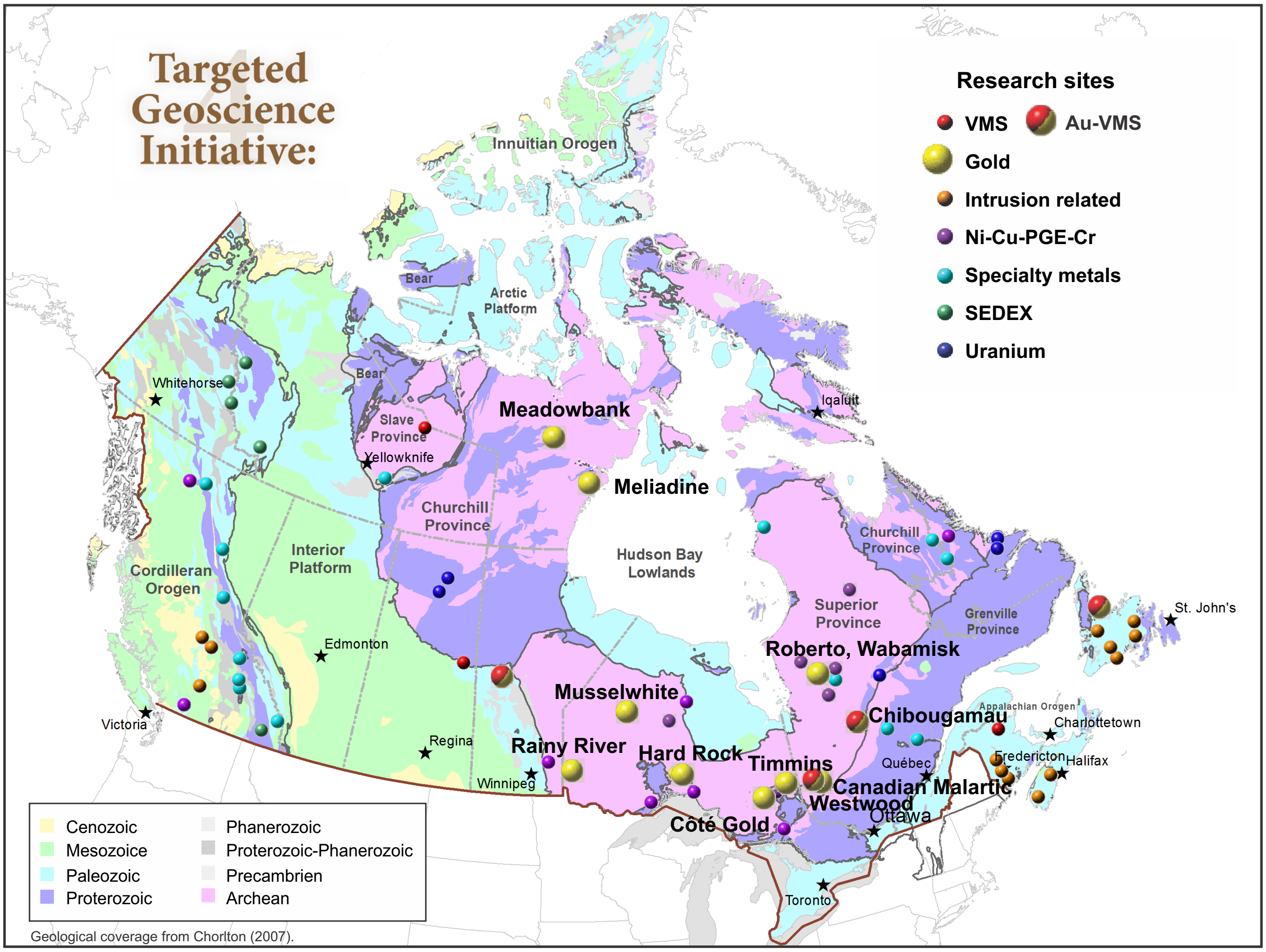

Figure 2. Location map of the TGI-4 Lode Gold project research activities. Geology from Chorlton (2007).

Lode Gold project. Selected key findings from each research theme are highlighted below.

Banded Iron Formation-Hosted Gold Deposits

Globally, BIF-hosted gold deposits significantly contribute to the gold endowment of Precambrian terranes, partly due to giant, high-grade deposits (e.g. Homestake Mine, South Dakota; 40 Moz: Caddey et al., 1991). These deposits represent a prime exploration target in northern Canada. Although various origins (syngenetic versus epigenetic: Fripp, 1976; Phillips et al., 1984) and classifications were proposed in the past for BIF-hosted gold deposits (e.g. stratiform syngenetic versus non-stratiform epigenetic deposits: Kerswill, 1993), the selected case studies differentiate two distinct groups of BIF-hosted gold deposits in Canada: 1) large deposits in which the ore is mainly hosted in Algoma-type (Gross, 1995) BIF (i.e. Musselwhite Mine, Ontario, and Meadowbank Mine, Nunavut; Fig. 4), and 2) deposits where only part of the mineralization is hosted in BIF. In the latter, the mineralized zones, which generally consist of orogenic greenstone-hosted quartz±carbonate vein gold, tend to cluster along a major fault zone (e.g. Meliadine district, Nunavut, and Geraldton district, Ontario; Figs. 1, 4). The simultaneous study of these four selected sites facilitated the description and comparison of the various geological setting, tectonic evolution, and primary and hydrothermal signature of BIF-hosted gold deposits. Each of the selected sites also represent different time periods (e.g. Archean versus Paleoproterozoic), and metamorphic grade (e.g. greenschist versus amphibolite facies) that together define a set of common and specific processes and exploration criteria for a variety of settings favourable for BIF-hosted gold deposits. (Fig. 2; Tóth et al., 2013a,b, 2014, 2015; Gourcerol et al., 2014, 2015a,b; Oswald et al., 2014, 2015a,b; Kelly and Schneider, 2015; Lawley et al., 2015; Janvier et al., 2015a,b). Some key aspects of BIF-hosted gold deposits are summarized in Figure 4.

Geological and Structural Settings

Favourable geological settings for BIF-hosted gold deposits are variable and range from BIF-rich

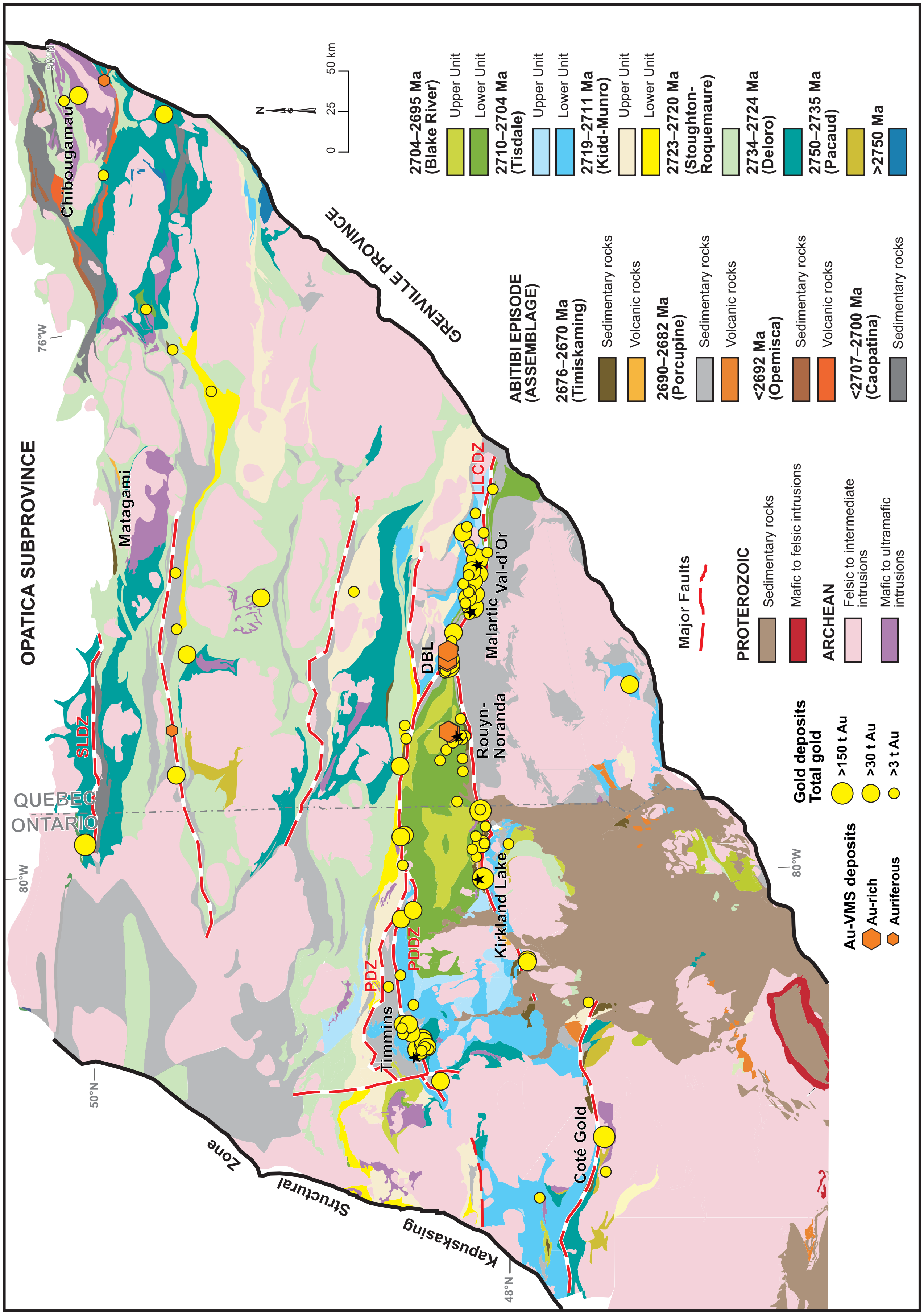

Figure 3. Simplified geological map of the Abitibi Subprovince with location of major gold deposits. From Ayer et al. (2010). Data for major gold and gold-rich VMS deposits modified from Gosselin and Dubé (2005) and Mercier-Langevin et al. (2011).

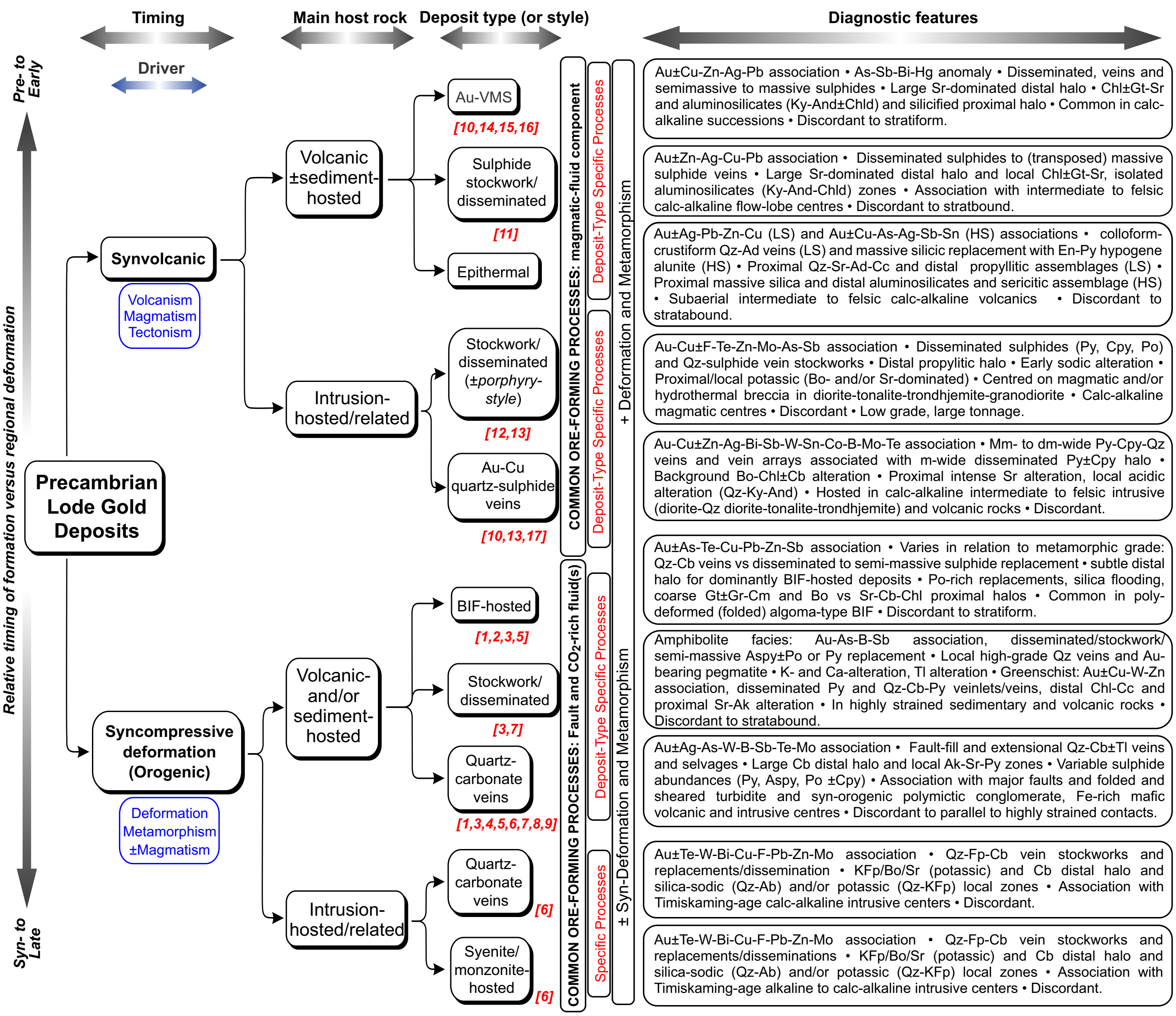

Figure 4. Graphic summary of the many different possible settings and main characteristics of lode gold deposits, with an emphasis on Precambrian lode gold deposits, more particularly on those studied as part of the TGI-4 Lode Gold project. The numbers in brackets refer to the deposits studied through the project. 1 = Musselwhite (Ontario), 2 = Meadowbank (Nunavut), 3 = Vault (Nunavut), 4 = Meliadine (Nunavut), 5 = Geraldton (Ontario), 6 = Canadian Malartic (Quebec), 7 = Roberto (Quebec), 8 = Wabamisk (Quebec), 9 = Timmins (Ontario), 10 = Westwood (Quebec), 11 = Rainy River (Ontario), 12 = Côté Gold (Ontario), 13 = Doyon (Quebec), 14 = Bousquet 2-Dumagami (Quebec), 15 = Lemoine (Quebec), 16 = Lalor (Manitoba), 17 = Chester (Ontario). Modified and adapted from Poulsen et al. (2000) and Mercier-Langevin (2014, unpublished). Abbreviations: Ab = albite, Ad = adularia, Ak = ankerite, And = andalusite, Aspy = arsenopyrite, Bo = biotite, Cb = carbonate, Cc = calcite, Chl = chlorite, Chld = chloritoid, Cm = cummingtonite, Cpy = chalcopyrite, En = enargite, Fp = feldspar, Gr = grunerite, Gt = garnet, HS = High-Sulphidation, KFp = potassium feldspar, Ky = kyanite, LS = Low-Sulphidation, Po = pyrrhotite, Py = pyrite, Qz = quartz, Tl = tourmaline. Modified from Poulsen et al. (2000).

volcano-sedimentary basins (e.g. Meadowbank and Musselwhite) to lithotectonic settings that are relatively BIF-poor (e.g. Meliadine and Geraldton). Both geological settings are prospective for large BIF-hosted gold deposits. Banded iron formations are volumetrically and laterally much more important in deposits dominantly hosted in BIF horizons, whereas these rocks are not as abundant in districts where deposits are only partly hosted in BIF units. The BIF units can be tens of metres thick and extend for thousands of metres as at Meadowbank and Musselwhite, or the ore-hosting BIF units can generally be much thinner and discontinuous at deposit to district scales as at Meliadine and Geraldton. Similarly, ultramafic flows form an integral part of the host stratigraphy in some dominantly BIF-hosted gold deposits (e.g. Meadowbank and Musselwhite), and appear sparse to minor in districts where BIFs represent a minor host. In such cases, a good understanding of the stratigraphy and of the structures controlling its geometry becomes essential for developing more effective exploration strategies. For example, at Musselwhite, reappraisal of stratigraphic and polyphase structural relationships, supported by U-Pb geochronology, indicates that the mine stratigraphy is inverted, i.e., part of the overturned limb of a kilometre-scale refolded F_1 syncline (McNicoll et al., 2013; Oswald et al., 2015a,b). The previously underestimated regional F_1 folding event, which is strongly overprinted by the dominant D_2 deformation associated with the main mineralizing event at Musselwhite, has influenced the distribution and geometry of the BIF units hosting the bulk of the gold (Oswald et al., 2014, 2015a,b) and provides new key information for exploration models at local and regional scales.

The complex stratigraphic and polyphase structural settings of the Meadowbank deposit represent a good scientific challenge. The region comprises four major BIF units, with only the Central BIF hosting significant gold mineralization (Janvier et al., 2015a,b) in what are otherwise largely similar BIFs (Gourcerol et al., 2015a). Targeted geochronology suggests that the deposit is located along the boundary between two distinct Archean assemblages (ca. 2717 Ma and ca. 2711 Ma) that are possibly separated by long-lived fault(s) and splays. The presence of this major structure affecting the Central BIF points to a large-scale structural-control on BIF-hosted gold at the Meadowbank deposit and may explain why only this BIF is mineralized with gold and not in BIF units that are located away from that structure (Janvier et al., 2015a,b). It suggests that such first-order fault zones control the formation and distribution of other auriferous mineralized zones in the area.

The structural setting at Meadowbank is complicated by Paleoproterozoic tectonometamorphic events superimposed on Archean rocks and fabrics, as described elsewhere in the western Churchill Province (e.g. Sherlock et al., 2004; Carpenter et al. 2005; Pehrsson et al., 2013; Lawley et al., 2015). Previous research in the Meadowbank area (e.g. Armitage et al., 1996; Sherlock et al., 2001a,b, 2004; Hrabi et al., 2003) has indicated that gold was introduced during the second phase of regional Proterozoic deformation at ca. 1.85–1.83 Ga. Based on detailed mapping, structural analysis, and Re-Os geochronology, Janvier et al. (2015a,b) suggest that gold mineralization occurred earlier, possibly prior to, or at least very early during the second phase of regional Proterozoic deformation. Similarly, the Vault deposit, located approximately 8 km north of Meadowbank, is characterized by finely disseminated pyrite mineralization hosted in a major D_2 shear zone that separates two distinct Archean volcaniclastic rock packages (Dupuis et al., 2014) and that is parallel to the Proterozoic Third Portage thrust (Hrabi et al., 2003). Although entirely shear-zone hosted, the ore at Vault is spatially associated with a swarm of Archean (V. McNicoll et al., unpub. data) felsic dykes and sills. Auriferous pyrite at this deposit records a complex growth history that suggests an early, pre-main deformation mineralization (Dupuis et al., 2014), perhaps suggesting a pre- (Archean ?) or early-thrusting hydrothermal activity.

A similar complex and protracted hydrothermal and deformation history is suggested for the Meliadine district south of Meadowbank, which is located at the boundary between the Hearne and the Chesterfield block of the Western Churchill Province (Lawley et al., 2015) (Fig. 2). Detailed surface and underground mapping reveal a very complex structural setting with several strain increments and polyphased folding. The ore zones are associated with high-strain zones or second-order fault zones, such as the Lower Fault located a few hundred metres north of the first-order Pyke Fault (Carpenter and Duke, 2004; Carpenter et al., 2005; Lawley et al., 2014, 2015). The latter also parallels a particularly favourable lithostratigraphic setting that comprises structurally thickened BIF intervals structurally imbricated with turbidite and mafic volcanic rock packages. Geochronology (zircon and xenotime U-Pb and arsenopyrite Re-Os dating) suggest that gold at the Meliadine district was introduced during an early hydrothermal event(s) (ca. 2.27 and/or 1.90 Ga) that predates gold remobilization, coupled with arsenopyrite recrystallization, during the latest stage of the Trans-Hudson orogeny at 1.86–1.85 Ga (Carpenter et al., 2005; Lawley et al., 2015).

Establishing the exact timing of gold mineralization and metamorphism in BIF-hosted gold deposits represents a significant challenge. Kelly and Schneider (2015) used secondary ion mass spectrometry (SIMS) U-Pb depth profiles on unpolished detrital zircon from the Musselwhite deposit area to better constrain the age of hydrothermal activity and metamorphism in the mine area. Hydrothermal zircon rim ages range from 2788 to 2703 Ma, which is up to 250 million years younger than igneous zircon cores and possibly represents the age of a gold-bearing episode in the Musselwhite deposit area.

Primary Composition, Hydrothermal Alteration, and Metamorphic Assemblages

The primary chert composition of auriferous BIF intervals does not appear to exert a major control on gold mineralization, based on LA-ICP-MS analysis at Meadowbank, Musselwhite and Meliadine (Gourcerol et al., 2014, 2015a,b). However, ongoing systematic in situ geochemical analysis of chert samples collected outward from the gold zones at all three deposits is expected to provide more data that will help define the primary depositional setting of the ore-associated BIF as well as the hydrothermal footprint of the deposits in the chert chemistry (Gourcerol et al., 2015b).

The extent and intensity of hydrothermal alteration in the studied BIF-hosted gold deposits depend on several aspects: 1) the setting of the deposit, i.e., dominantly BIF-hosted (Musselwhite and Meadowbank) versus partly BIF-hosted (Meliadine and Geraldton), 2) fluid chemistry and the composition of the host rock and their capacity to react with the fluid (e.g. chert-magnetite versus garnet-grunerite facies), 3) the metamorphic grade, and 4) the state of preservation of the original distribution and geometry of the hydrothermal system.

Gold deposits that are dominantly BIF-hosted are associated with a rather subtle mineralogical hydrothermal footprint (e.g. local chlorite alteration) compared with gold deposits that are only partly hosted in minor BIF units (e.g. large Fe-carbonate alteration halo). This may in part be due to variations in metamorphism grade and host rock types (e.g. poorly reactive chert), but nevertheless represents a fundamental difference between the two styles of deposits that must be taken into account when for exploring for BIF-hosted gold deposits.

In deposits that are only partly BIF-hosted and have undergone greenschist-facies metamorphic conditions, gold is quartz±carbonate±tourmaline vein-hosted and also occurs within hydrothermally altered and sulphidized vein selvages containing variable amounts of disseminated arsenian pyrite and/or arsenopyrite (Lawley et al., 2015; Tóth et al., 2015). Discontinuous auriferous BIF-hosted sulphide-rich replacements (pyrite, arsenopyrite, pyrrhotite) of magnetite bands typify high-strain zones, and/or transposed quartz-sulphide stockworks in magnetite and chert bands (Tóth et al., 2013a,b, 2014, 2015; Janvier et al., 2015a,b; Lawley et al., 2015). Key sulphide mineral assemblages within BIF, even in minor amounts, represent a potential guide to gold ore (Boyle, 1979; Phillips et al., 1984; Kerswill, 1993; Bierlein et al., 1998, 2000). Silicification occurs as quartz (± carbonate) replacement (flooding) within BIF and mafic volcanic host rocks. The latter is characteristic of high-grade ore at Meliadine (Lawley et al., 2015) and Meadowbank (Janvier et al., 2015a,b). In mafic/ultramafic rocks, a strong and extensive carbonate (ankerite-calcite) alteration is associated with various proportions of sericite and sulphides (arsenopyrite-pyrite-pyrrhotite-galena-chalcopyrite: Lawley et al., 2015; Tóth et al., 2015). The partial to semi-massive sulphide replacement of magnetite in BIF units is associated with sericite-carbonate and/or chlorite replacement surrounding quartz-carbonate±chlorite veins. Local pervasive chlorite alteration or chlorite «clots» represent a good visual indicator to mineralization and occur within auriferous quartz (±ankerite) veins and mineralized BIF intervals (Janvier et al., 2015a; Lawley et al., 2015). Hydrothermal chlorite is generally Fe-rich compared to hydrothermal chlorite and, where present, occurs with gold within quartz-carbonate veins and hydrothermally altered BIF (Lawley et al., 2015). In greywacke, mudstone, or intermediate to mafic volcaniclastic rocks, gold is associated with pyrite and arsenopyrite in sericite-carbonate (ankerite, dolomite, or calcite) and sericite±chlorite alteration selvages around the quartz-carbonate±tourmaline± pyrite±pyrrhotite veinlets and is characterized by K_2O gains and associated Na_2O losses. Such potassic alteration is expressed as hydrothermal sericite or biotite and is recognized as an important exploration vector at Meliadine and Geraldton (Lawley et al., 2015; Tóth et al., 2015).

At amphibolite grade, and especially in deposits that are dominantly hosted in thick Algoma-type BIF units, the hydrothermal alteration assemblages are commonly more difficult to visually distinguish from regional metamorphism due to syn-peak metamorphism hydrothermal mineral assemblages that are largely similar to regional metamorphism-related paragenesis, which hampers the development of vectors towards mineralization. In such cases, the use of pathfinder elements becomes critical for recognizing alteration haloes (e.g. Lawley et al., 2015). At amphibolite grade, the ore zones are dominated by stratabound pyrrhotite-rich (±pyrite) replacements and are locally associated with silica flooding of the BIF in the high-grade ore zones. Part of the ore is also hosted in discordant syntectonic grey quartz-pyrrhotite±pyrite veins that cut chert-magnetite BIF (Oswald et al., 2014, 2015). Volcanic and volcaniclastic rocks occurring proximal to the ore zones can display a biotite (±carbonate) alteration. The high-grade pyrrhotite-rich ore zones are associated with Fe-carbonate, Ca-amphibole, and Ca-Fe clinopyroxene (hedenbergite) minerals and display a metasomatic⁄ metamorphic layering delineated by abundant coarse-grained almandine garnet porphyroblasts, intergrown with fine- to medium-grained grunerite-cummingtonite and biotite (e.g. Musselwhite and Meadowbank Goose zone: Janvier et al., 2015a,b; Oswald et al., 2015). Several of the ore-associated minerals may also be part of the regional metamorphic paragenesis; a careful characterization is instrumental to distinguish and map the hydrothermal footprint of the deposit. Silicate minerals such as garnet, grunerite, ferro-tschermakite, and biotite are found in both regional metamorphic and ore-related mineral assemblages. The differentiation between proximal and distal alteration assemblages relative to gold mineralization with regional metamorphism resides partly in mineral textures, composition, and abundance. For example, the distal, least altered garnet-grunerite facies at

Musselwhite contains anhedral to subhedral almandine garnet whereas typical ore has abundant and coarse, subhedral to euhedral, fractured red calium-rich almandine garnet with associated pyrrhotite (Moran, 2008; Kolb, 2011; Oswald et al., 2014, 2015a,b). Pathfinder elements common to the investigated deposits are Au, S, Te, As, Cu, and Sb. For example, anomalous pathfinder element concentrations and domains of hydrothermally altered rocks can be traced from 10s to 100s of metres beyond high-grade lodes at Meliadine (Lawley et al., 2015). Critically, this multivariate hydrothermal footprint (e.g. S and As) can be mapped in real time utilizing a conditional probability-based approach and portable X-Ray Fluorescence (pXRF) spectrometry (Lawley et al., 2015).

Discussions and Implications for Exploration — Banded Iron Formation-Hosted Gold

The results from our study at Meliadine and Meadowbank indicate that gold is not solely Trans-Hudson in age (1.9–1.8 Ga) but may be associated with earlier tectonic events. New age determinations also suggest that the Proterozoic gold metallotect model as defined by Miller et al. (1994) in fact represents the end-product of successive auriferous hydrothermal events and/or younger gold remobilization. A good understanding of this complex Archean to Paleoproterozoic tectonic and metallogenic history is fundamental to define efficient exploration models in northern Canada. It also has implications for assessing the prospectivity of other reworked Precambrian cratonic margins, which represent prospective settings for world-class orogenic gold deposits (Lawley et al., 2015).

Our work indicates or confirms that BIF-hosted gold zones are the product of several structurally and stratigraphically controlled phases of gold mineralization (or remobilization) associated with various generations of Archean to Proterozoic deformation zones. Ore zones are concentrated along thickened fold hinges and strongly attenuated limbs of shallow-plunging folds (syn- and/or post-ore) as well as second- and third-order deformation zones (Oswald, 2014, 2015; Tóth et al., 2014, 2015; Lawley et al., 2015). The location of the ore zones is also strongly influenced by competency contrasts between sheared ultramafic/mafic volcanic rocks versus BIF, or BIF versus siliciclastic rocks. The layer anisotropy of the host BIFs induces significant structural complexities pre- and post-gold deposition; understanding these complexities is critical to optimize exploration models and mine development (e.g. Janvier et al., 2015a,b; Oswald et al., 2015; Tóth et al., 2015). The capacity of the rocks to buffer the gold-bearing hydrothermal fluid (chemical trap) is also fundamental in the process; in some cases, the ore is almost entirely (>80%) hosted within a specific competent and highly reactive silicate BIF facies (e.g. Musselwhite), and indicating that BIF-hosted gold deposits are not the sole product of ductile deformation (Oswald et al., 2015). The broader lithotectonic setting of BIF-hosted deposits is perhaps the area with the greatest potential for improving regional-scale targeting. Understanding the volcano-sedimentary basin increases the chance of finding the most favourable host units within a rock sequence that has recorded polyphase deformation.

Intrusion-Related and Stockwork-Disseminated Gold Deposits

Diverse styles of gold deposits are commonly spatially associated with, and/or hosted in intrusive rocks, including porphyry Cu-Au, syenite-associated disseminated gold, and reduced Au-Bi-Te-W intrusion-related deposits as well as stockwork-disseminated gold (e.g. Sillitoe, 1991; Thompson et al., 1999; Rowins, 2000; Robert, 2001; Goldfarb et al., 2005; Hart et al., 2007). In the Abitibi greenstone belt, several multi-million ounce Archean gold deposits, including Canadian Malartic, Kirkland Lake, Camflo, Young Davidson, Doyon, Westwood, and the McIntyre Cu-Au-Mo zone at Hollinger-McIntyre, are spatially associated with intrusions. A genetic link with intrusions is inferred for some of these deposits and indicates that there is a potential for finding such large intrusion-related deposits in greenstone terranes (Robert, 2001; Robert et al., 2007; Mercier-Langevin et al., 2012b, and references therein; Helt et al., 2014). This hypothesis is supported by examples located elsewhere in the Superior Province (e.g. the ~2 Moz Au-Cu Troilus deposit in the Frotet-Evans belt, and the ~7 Moz Au(-Cu) Côté Gold deposit in the Swayze belt: Figs. 2, 3). The Superior Province, due to its exceptional gold endowment, constitutes a prime laboratory to develop geological models and exploration criteria for such intrusion-related and stockwork-disseminated deposits. As the genesis of these «atypical» deposits remains controversial, the processes responsible for their formation are still highly debated (e.g. Pyke and Middleton, 1971; Davies and Lutha, 1978; Mason and Melnyk, 1986; Pilote et al., 1995; Brisbin, 2000; Robert, 2001; Groves et al., 2003; Goldfarb et al., 2005; Beaudoin and Raskevicius, 2014; Helt et al., 2014). During the course of the project, the key characteristics, and geological and hydrothermal footprints of some of the best examples of such gold deposits in the Superior Province were investigated, highlighting parameters responsible for their formation and distribution (e.g. Fig. 4). In the context of this report, the term stockwork-disseminated is essentially descriptive and does not infer a genetic process.

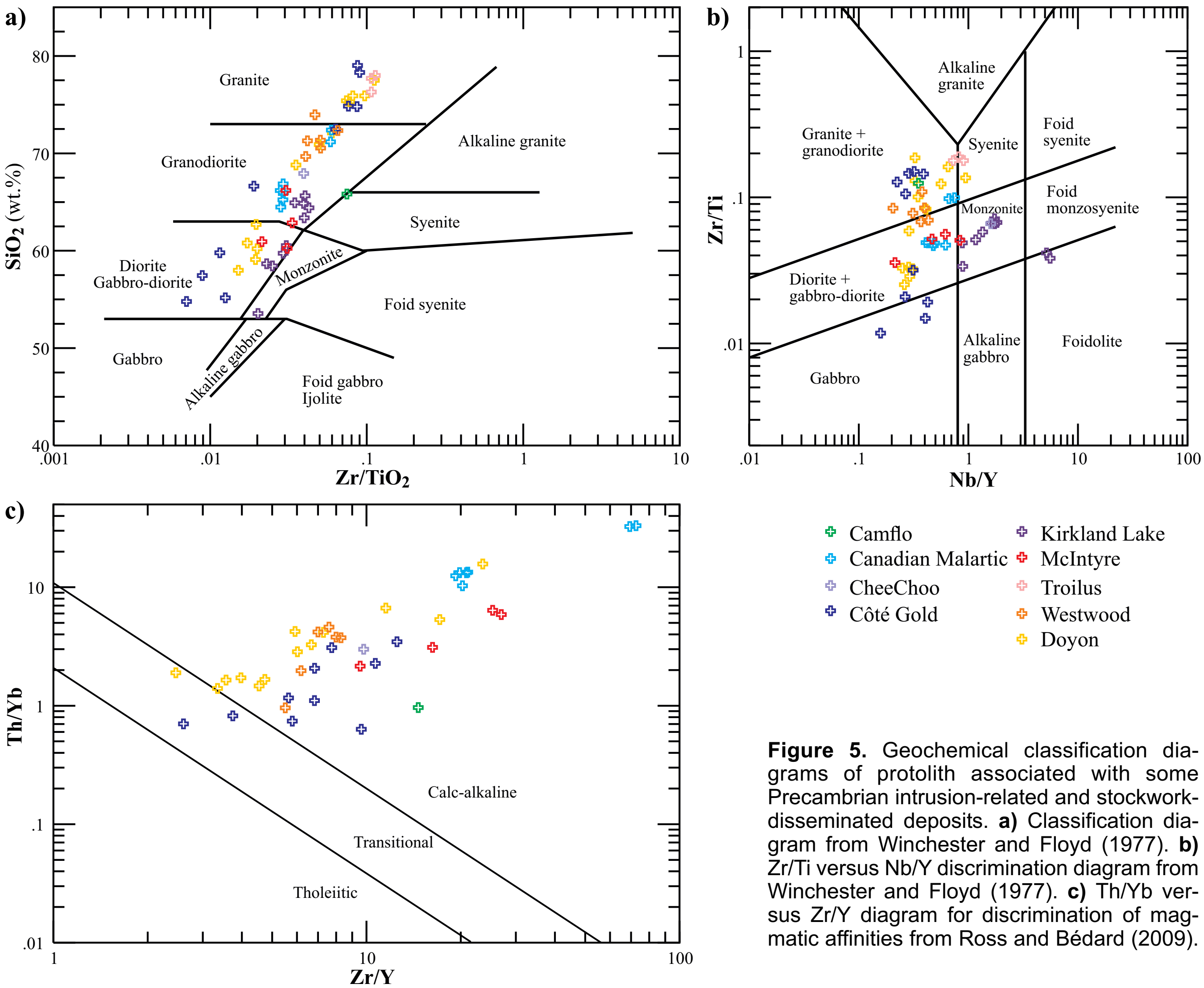

Figure 5. Geochemical classification diagrams of protolith associated with some Precambrian intrusion-related and stockwork-disseminated deposits. **a)** Classification diagram from Winchester and Floyd (1977). **b)** Zr/Ti versus Nb/Y discrimination diagram from Winchester and Floyd (1977). **c)** Th/Yb versus Zr/Y diagram for discrimination of magmatic affinities from Ross and Bédard (2009).

Relative and Absolute Timing of Ore-Forming Events versus Geological and Structural Settings

Most of the intrusion-related and stockwork-disseminated gold deposits investigated through the Lode Gold project (Fig. 2) are located near or within a major fault zone and its splays, which constitute favourable, but transient pathways to the upper crust for magma and/or gold-bearing fluids. The ore-associated intrusions can be located on either side of these fault zones, as illustrated by the Canadian Malartic and Camflo deposits, which are associated with ca. 2678–2677 Ma quartz monzodiorite to granodiorite (Canadian Malartic: De Souza et al., 2015) and with 2680 ± 4 Ma quartz monzonite (Camflo: Jemielita et al., 1990) but are located south and north of the Larder Lake – Cadillac fault zone, respectively (Fig. 3, Trudel and Sauvé, 1992; Pilote, 2013). Some of the intrusion-related gold deposits, which generally consist of stockwork- and disseminated-style mineralized zones, are entirely or partly hosted in clastic sedimentary rocks and/or volcanic rocks, whereas others are mainly confined to the associated intrusion or intrusive complex. The distribution and perhaps the composition of these intrusions are potentially linked to early stage extension along the main faults (e.g. Bleeker, 2012, 2015) and/or associated to flexures in major fault zone orientation, allowing the magma and ore-bearing fluids to invade the dilation zones and to form magmatic centres (e.g. Malartic area).

There is a large spectrum of ages of Archean intrusion-related and stockwork-disseminated gold systems in the Superior Province, and most are associated with diverse magmatic suites that include gabbro, diorite, granodiorite, monzodiorite, monzonite, syenite, tonalite, trondhjemite, granite, lamprophyre/albitite dykes and lithium, cesium, and tantalum (LCT) pegmatite dykes (Fig. 5a,b, Table 1). One recurring characteristic is the calc-alkaline to transitional subalkaline affinity of these ore-associated intrusions (Figs. 4, 5c). However, the diversity of the host intrusion's age

Table 1. Spectrum of ages and composition of selected deposits interpreted as Archean intrusion-related and/or stockwork-disseminated Au and Au-Cu deposits and prospects.

Deposit	Interpreted age(s) of Au (U-Pb host intrusion and/or Re-Os)	Associated Intrusion(s)	Selected References
Troilus	ca. 2782 Ma (U-Pb)	diorite and felsic dykes	Boily, 1995; Pilote et al., 1995; Dion et al., 1998; Rowins, 2011
Côté Gold	ca. 2740 Ma (U-Pb and Re-Os)	low-Al tonalite-diorite complex	Katz et al., 2015
Chibougamau Cu-Au	ca. 2714 Ma (U-Pb)	tonalite	Pilote et al., 1995, 1997; Dion et al.,1998; Leclerc et al., 2012
Doyon	ca. 2698 Ma (U-Pb)	diorite to trondhjemite	Galley and Lafrance, 2014; McNicoll et al., 2014
Young-Davidson	ca. 2680–2672 Ma (U-Pb)	syenite	Martin, 2012; Zhang et al., 2014
Kirkland Lake	ca. 2675 Ma (Re-Os)	alkalic intrusive	Ispolatov et al., 2008
Canadian Malartic	2678–2664 Ma (U-Pb and Re-Os)	granodiorite to quartz monzodiorite	De Souza et al., 2015
Camflo	ca. 2680 Ma (U-Pb)	monzonite	Jemielita et al. 1990
Cu-Au-Mo McIntyre	≤2689 ± 1 Ma (U-Pb); ca. 2672 Ma (Re-Os)	quartz-feldspar porphyry	Corfu et al., 1989; Bateman et al., 2004, 2005
CheeChoo	ca. 2612 Ma (U-Pb)	tonalite to granodiorite	Fontaine et al., 2015

and composition, and disparate gold events across the Superior Province highlights that conditions favourable for gold are not unique. Alternatively, deposits assigned to the intrusion-related group are commonly diverse and may include deposits of unrelated types, which partially explains the variability of ore deposits settings and styles (e.g. Sillitoe, 2000).

Superimposed tectonometamorphic events can significantly modify the original ore deposit characteristics, mask genetic relationships between intrusions and gold, and cause significant remobilization of the ore (e.g. Mercier-Langevin et al., 2012a,b). Moreover, geochronology and crosscutting relationships reveal that some deposits are the product of multiple auriferous hydrothermal and remobilization events. For example, the sediment-hosted stockwork-disseminated Canadian Malartic and Roberto deposits are the product of multi-phased auriferous events and/or remobilization (Ravenelle et al., 2010; De Souza et al., 2015; Fontaine et al., 2015). The Canadian Malartic deposit is hosted in clastic sedimentary rocks and quartz monzodiorite to granodiorite dykes and stocks, but the actual geometry and distribution of the ore zones are controlled by younger brittle-ductile structures associated with the main regional deformation event (De Souza et al., 2015). In some cases, the intrusion-related mineralization becomes part of a much larger ore system, as illustrated by the McIntyre Cu-Au-Mo zone (2689–2672 Ma: Mason and Melnik, 1986; Corfu et al., 1989; Brisbin, 1997; Bateman et al., 2004, 2005) that is overprinted by the ≤2673 Ma giant Hollinger-McIntyre greenstone-hosted orogenic quartz-carbonate vein system (Dubé and Gosselin, 2007; Bateman et al., 2008). Therefore, a good understanding of the relative timing of the intrusive, tectonic, and ore-forming event(s) combined with high-precision geochronology become essential to understand the causative role of the host intrusion(s) (i.e. active or passive) and the superposition of events in the formation of the deposits. Both factors are critical for effective mineral exploration in such complex geological environments. In very broad terms, pre-main compressive deformation intrusions seems to play an active role in the deposits genesis, whereas early- to syn-main compression intrusions, which may partly play an active role, seem to also act as passive hosts (Fig. 4) as the ore is often preferentially associated to structural features as discussed below.

Distribution and Diversity of Deposit Styles

Mineralization at some intrusion-related deposits is hosted in sedimentary and volcaniclastic rocks and ore distribution is controlled, at least in part, by folds, faults, and associated vein networks or stockworks (e.g. Canadian Malartic and Roberto). Elsewhere, such as at the Côté Gold Au(-Cu) deposit, the ore zones are centred on a multiphase magmatic-hydrothermal breccia, including a mineralized Au-Cu±Mo±Ag hydrothermal breccia that intrudes tonalitic (transitional to calc-alkaline) and dioritic (tholeiitic) phases of the Chester Intrusive Complex (CIC) (Katz et al., 2015 and references therein). The magmatic-hydrothermal breccia is itself overprinted by several ore-related hydrothermal alteration types (biotite, sericite, silica-sodic). The overlapping Re-Os age of syn-gold molybdenite with U-Pb zircon ages for the CIC highlight the spatio-temporal link between magmatism and gold-bearing hydrothermal events (Kontak et al., 2013; Katz et al., 2015). As such, the Côté Gold deposit shares some analogies with Phanerozoic porphyry Cu-Au systems (Katz et al., 2015). At Westwood, intrusion-associated gold-sulphide veins and gold-rich VMS-type mineralization are considered to represent various components of an Archean auriferous synvolcanic magmatic-hydrothermal system (Yergeau et al., 2015 and references therein) and is reminiscent, at least in terms of geometry, of telescoped porphyry-epithermal systems (Yergeau, 2015; Yergeau et al., 2015). The quartz-carbonate-chalcopyrite veins of the former Chester 1, 2, 3 gold deposits, which are located in the immediate vicinity of the Côté Gold deposit, are also interpreted as pre-main deformation vein systems (Smith et al., 2014). The composition and relative timing of formation of the Chester veins are analogous to the intrusion-related Doyon and Westwood Zone 2 Extension high-grade quartz-pyrite-chalcopyrite vein systems.

Some stockwork-disseminated deposits are not readily associated with intrusions and represent synvolcanic gold in the seafloor/subseafloor environment. For example, at the Rainy River deposit, ca. 2717 Ma calc-alkaline dacite and rhyodacite host disseminated pyrite-sphalerite-chalcopyrite mineralized bodies and minor quartz-sulphide-tourmaline-carbonate veinlets and stockworks that are transposed in the main foliation (Pelletier et al., 2015). The setting and ore-style at the Rainy River deposit suggest that it may represent a subseafloor analogue to Archean gold-rich VMS systems (e.g. LaRonde Penna, Westwood, and Bousquet 1 deposits; Mercier-Langevin et al., 2015; Pelletier et al., 2015).

Hydrothermal Alteration, Mineral Assemblages, and Metallic Signature

To help develop geological and exploration models, hydrothermal vectors and fertility indicators have been defined. At Canadian Malartic and Coté Gold, these include a distal biotite or biotite-calcite dark-colour assemblages (disseminations and veins), which constitute the largest footprint and earliest alteration, and a proximal fracture-controlled, light colour to red-pink pervasive silica-sodic (quartz-albite) and/or potassic (quartz-microcline) alteration with sericite-carbonate±phlogopite, rutile, and pyrite replacement assemblage (De Souza et al., 2015; Katz et al., 2015). Traces of chalcopyrite are present in both the distal and proximal zones at Côté Gold. At present, biotite (Mg#, F, and Ti content) offers the best potential for mineral chemistry vectoring (De Souza et al., 2015; Katz et al., 2015). The whole-rock geochemistry of intrusive and sedimentary rocks reveals progressive distal to proximal gains in K_2O, Na_2O, CO_2, and S towards mineralization (De Souza et al., 2015; Katz et al., 2015). Furthermore, at Canadian Malartic, the ore (i.e. ≥0.3 ppm Au) is associated with the most strongly carbonatized rocks. Irrespective of the rock type, molar ratios (CO_2/CaO and CO_2/(CaO+MgO)) appear to represent a better proxy to estimate the intensity and style of carbonate alteration (e.g. molCO_2/molCaO >0.8) than the raw, whole-rock CO_2 content in wt% (De Souza et al., 2015).

At the Westwood deposit, manganiferous (Mn-garnet) and potassic (sericite and biotite) alteration haloes combined with sodium depletion are good indicators of modified seawater circulation in the volcanic edifice and VMS potential, whereas, barium and potassium enrichment (white micas) are associated with intrusion-related ore zones at the same deposit (Yergeau, 2015; Yergeau et al., 2015). Quartz-sericite and quartz-biotite-garnet schist with anomalous Zn, Cu, Au, and Ag values represent the distal footprint of deformed and metamorphosed gold-rich polymetallic VMS deposits in the Doyon-Bousquet-LaRonde district (Dubé et al., 2007, 2014; Yergeau et al., 2015). At Rainy River, the ore zones are directly associated with a diffuse potassic, sericite-dominated alteration. Manganiferous garnet, chloritoid, and kyanite also occur, at least locally, proximal to ore zones (Pelletier et al., 2015). At the metamorphosed Roberto deposit, the gold-bearing hydrothermal system shows distal calcic metasomatism that increases in intensity toward the ore zone, where it forms auriferous quartz±actinolite±diopside±biotite±arsenopyrite±pyrrhotite stockworks and veinlets. Quartz±actinolite±diopside±biotite±arsenopyrite±pyrrhotite vein stockworks and quartz-dravite-arsenopyrite veinlets contained within microcline, phlogopite, dravite, and arsenopyrite-pyrrhotite replacement zones comprise the bulk of the ore at the Roberto zone (Ravenelle et al., 2010; Ravenelle, 2013; Fontaine et al., 2015 and references therein).

A common feature to some of the studied deposits is the presence of gold-bearing pegmatite in the deposit's vicinity. At Roberto, a series of 2620–2603 Ma LCT pegmatite locally carries gold (Ravenelle et al., 2010; Fontaine et al., 2015) and as such could share analogies with the mineralized pegmatite at Canadian Malartic (Derry, 1939) and with the auriferous pegmatite that host some of the mineralized zones at the metamorphosed Borden gold deposit (e.g. Probes Mines Ltd, 2014). Both Roberto and Borden are metamorphosed deposits partly hosted in high-grade metamorphic rocks and share similar styles of mineralization, including a preferential association with deposit-scale fold hinges and the occurrence of late, locally auriferous pegmatite.

The metallic signature of the studied deposits is variable with a Au-Cu-F-Te-Zn ± Mo association at Côté Gold (Katz et al., 2015), a Au-Te-W-Bi-Ag ±Pb-Mo association at Canadian Malartic (De Souza et al.,

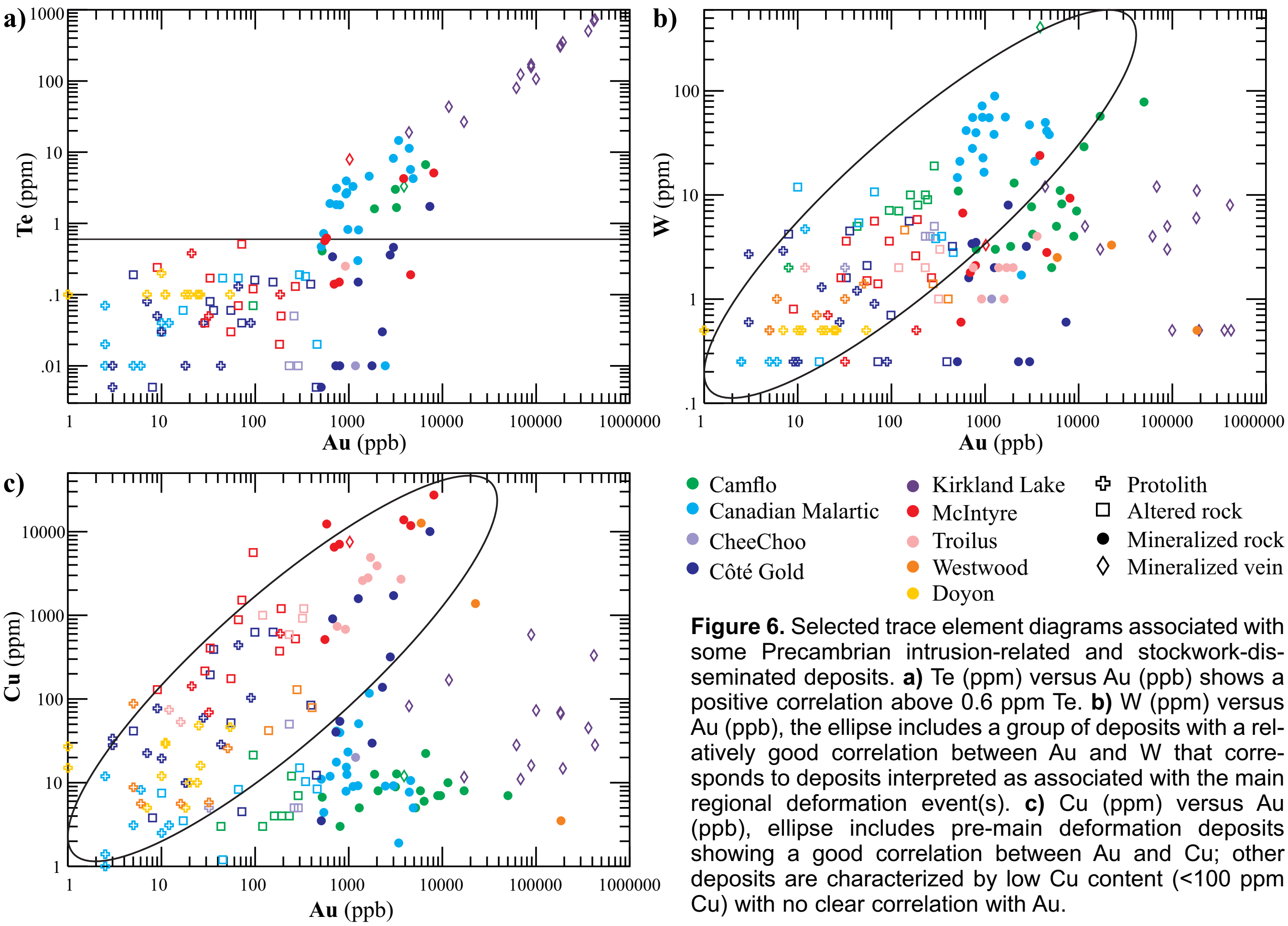

Figure 6. Selected trace element diagrams associated with some Precambrian intrusion-related and stockwork-disseminated deposits. **a)** Te (ppm) versus Au (ppb) shows a positive correlation above 0.6 ppm Te. **b)** W (ppm) versus Au (ppb), the ellipse includes a group of deposits with a relatively good correlation between Au and W that corresponds to deposits interpreted as associated with the main regional deformation event(s). **c)** Cu (ppm) versus Au (ppb), ellipse includes pre-main deformation deposits showing a good correlation between Au and Cu; other deposits are characterized by low Cu content (<100 ppm Cu) with no clear correlation with Au.

2015), and a Au-Cu-Zn-Ag-Pb association at Westwood (Yergeau, 2015; Yergeau et al., 2015). Among the studied deposit, there is an overall good correlation between Au and Te (>0.6 ppm Te), as shown in Figure 6a. There is an overall weak correlation between Au and W, although two trends or groups of deposits can be distinguished in Figure 6b: one with a relatively good Au-W correlation that corresponds to deposits that are associated with the main regional deformation event, and one with a very poor Au-W correlation that corresponds to deposits interpreted to have been formed prior to the main regional deformation. Similarly, two trends can be distinguished in the Au versus Cu diagram (Fig. 6c): one with a good correlation between Au and Cu (e.g. pre-main deformation deposits: Côté Gold, Westwood, Troilus, McIntyre) and a low-Cu (<100 ppm Cu) trend with no clear Au correlation (e.g. syn- to late-main deformation deposits: Camflo, Canadian Malartic, Kirkland Lake).

Pyrite is the most common sulphide in the studied deposits, with the exception of the Roberto deposit, and LA-ICPMS element and textural mapping systematically reveals several generations of pyrite, including inclusion-poor and inclusion-rich pre-, syn-, and post-ore pyrite (Dupuis et al., 2014; Pelletier et al., 2014, 2015; Gao et al., 2015; Yergeau, 2015), suggesting a very complex interplay between primary (synsedimentary and synvolcanic) processes and precipitation-dissolution episodes related to hydrothermal activity, deformation, and metamorphic recrystallization. Despite complex relationships, in most of the deposits that were studied, gold is largely concentrated in the inclusion-rich pyrite, together with Ag, Sb, Te, Pb, Bi, Zn, Cu, and Pb (Gao et al., 2015; Pelletier et al., 2015; Yergeau, 2015). Details about paragenesis and trace-metal distribution and associations in pyrite are presented in the site-specific studies and will be further investigated as ongoing research (e.g. thesis projects) progresses.

Discussions and Implications for Exploration – Intrusion-Related Gold Deposits

The Côté Gold and Canadian Malartic deposits represent two distinct end-members of intrusion-related and stockwork-disseminated deposits investigated in detail over the course of this project. While Coté Gold is a ca. 2740 Ma synvolcanic magmatic-hydrothermal system, Canadian Malartic represents a 2678–2664 Ma syndeformation system in which early tectonic (ca. 2678 Ma) subalkaline porphyritic quartz monzodiorite and granodiorite intrusions have potentially contributed part of the metals to the system (De Souza et al., 2015). Despite distinct settings and origins, both deposits are associated with stockwork and disseminated-style mineralization (Fig. 4). Each deposit is also enveloped by distal potassic alteration haloes (biotite or biotite-calcite, sericite) that are anomalous in gold and proximal silica-sodic or silica-potassic alteration assemblages characterized by the presence of minor amounts of molybdenite. The presence of Cu and magmatic-hydrothermal breccia, which commonly characterize Cu-Au porphyry systems, are notable at the Côté Gold deposit but absent at Canadian Malartic. In the case of the Canadian Malartic deposit, combined potassic (biotite-sericite) and carbonate (calcite) alteration zones are coincident with brittle-ductile faults, high-strain zones, and fold hinges. These hydrothermally altered deformation-corridors represent interesting sub-kilometre exploration targets in the vicinity of the Larder Lake-Cadillac fault zone. As such, Canadian Malartic shares analogies with a group of structurally controlled stockwork, disseminated, and replacement sediment-hosted intrusion-related deposits (e.g. Sillitoe, 1991; Robert et al., 2007).

The results of the ongoing Côté Gold deposit study define a new and significant early stage gold metallogenic event in the Swayze greenstone belt at ca. 2740 Ma (Katz et al., 2015), significantly older than the gold-rich VMS deposits (ca. 2728 Ma and 2700 Ma), the syenite-associated gold deposits (ca. 2678 Ma), and the greenstone-hosted quartz-carbonate vein deposit (2670–2660 Ma) of the southern Superior Province. Together with deposits such as the ca. 2790–2780 Ma reduced porphyry-style Troilus gold deposit in the Frotet-Evans belt in Northwestern Quebec (Boily, 1995; Pilote et al., 1995, 1997; Dion et al., 1998; Rowins, 2011), Côté Gold provides a guide for future exploration associated with early stage composite, subvolcanic, low-Al trondhjemite-tonalite-diorite (TTD) and/or trondhjemite-tonalite-granodiorite (TTG)-intrusions in the Superior Province (Katz et al., 2015).

Unequivocal examples of typical porphyry Au or Cu-Au deposits and Au deposits genetically related to intrusions in Archean greenstone belts in Canada remain contentious (Sinclair, 2007). Attributes and processes driving their formation, including specific age and/or composition of the fertile magmatic source, fluid transport, and stratigraphic and structural traps are still debated (e.g. Sinclair, 1982; Mason and Melnyk, 1986; Fraser, 1993; Robert, 1994; Sinclair et al., 1994; Pilote et al., 1995; Brisbin, 2000; Goodman et al., 2005; Rowins, 2011; Beaudoin and Raskevicius, 2014; Helt et al., 2014; De Souza et al., 2015). However, several Archean deposits clearly share analogies with porphyry systems, including Troilus (Boily, 1995; Dion, 1998; Sinclair, 2007; Rowins, 2011 and references therein), the McIntyre Cu-Au-Ag-Mo mineralized zones at Hollinger-McIntyre (Griffis, 1962; Burrows and Spooner, 1986; Melnik-Proud, 1992, Brisbin, 2000; Bateman et al., 2008), and the porphyry-type mineralization in the Doré Lake complex (Robert, 1994; Sinclair et al., 1994; Pilote et al., 1995, 1997). Although the geometry of these ore zones and particularly their relationship to hydrothermal alteration facies and the geometry of the intrusive complex still need to be established in greater detail in many of these ancient systems, and in the absence of key data, such as pressure-temperature estimates and details on terrane-arc context at the inferred timing of the ore-forming events, we can nonetheless mention that exploration models based on Phanerozoic-type examples need to be adapted. These adapted models must take into consideration possibly slightly different genetic conditions in Precambrian settings (e.g. Mercier-Langevin et al., 2012b and references therein), as well as the common post-ore tectonometamorphic reworking of the original characteristics, as well as superposition of gold-bearing systems, which appear to be a common feature of such deposits in ancient deformed and metamorphosed terranes (Poulsen et al., 2000; Mercier-Langevin et al., 2012a,b and references therein).

Fingerprinting Fertile Fault Systems as Vectors to Large Gold Deposits

The geological parameters controlling the fertility of major fault zones and the formation, distribution, and preservation of diverse types of large gold deposits (greenstone-hosted orogenic quartz-carbonate veins, syenite-associated disseminated gold, gold-rich VMS, etc.; Fig. 3) along such structures was identified as a major knowledge gap in lode gold systems (Robert et al., 2005; Dubé and Gosselin, 2007; Dubé et al., 2011). The Timmins gold district is the largest Archean gold district in the world and represents by far the main source of gold in Canada (>68 Moz Au) for the last century, hosting the largest Canadian gold deposit ever found (Hollinger-McIntyre; >36 Moz Au: Gosselin and Dubé, 2005; Dubé and Gosselin, 2007). The Timmins district, due to its unique endowment, exposure, and complexity, represents a prime area to gather essential knowledge on several key topics: 1) the structural evolution and kinematics of large-scale gold-bearing fault zones that control the distribution of large gold deposits, including the nature and significance of pre-ore, early stage deformation; and 2) the tectonic and metallogenic significance of Timiskaming-type sedimentary basins and their spatial and/or genetic relationship with large fault zones, subvolcanic intrusions, and large gold deposits (Dubé et al., 2011). Although, the focus was on Timmins for the Faults Fertility research theme, most deposits or areas investigated as part of the Lode Gold project have also contributed to this theme because of their location near major deformation zones and/or metamorphic fronts (e.g. Beauchamp et al., 2015; De Souza et al., 2015, Fontaine et al., 2015; Lafrance, 2015; Lawley et al., 2015; Tóth et al., 2015).

Deposits Distribution

Irrespective of ore type or style, most large Precambrian gold systems are distributed along major, first-order fault zones and their splays (e.g. Miller and Knight, 1915; Hodgson, 1993; Kerrich and Cassidy, 1994; Groves et al., 1998; Goldfarb et al., 2005; Robert et al., 2005; Dubé and Gosselin, 2007) or metamorphic fronts that demarcate the fault zones and characterize some boundaries between subprovinces (Gauthier et al., 2007). However, gold is preferentially associated with second- and third-order compressional reverse-oblique to oblique, brittle-ductile, high-angle shear zones that are commonly located within 5 km of the first-order fault (Robert, 1990). The various sites investigated in the Superior and Churchill provinces during the course of the project all support this historical exploration criterion. These structural corridors represent the pathways towards higher crustal levels for hydrothermal fluids and/or magma of diverse compositions, precious and base metal contents and origins. The fault zones are also responsible for the juxtaposition and preservation of deposits formed at different times and at different crustal depths (Poulsen et al., 2000; Dubé and Gosselin, 2007). For example, the ca. 2698 Ma synvolcanic Westwood deposit and the ca. 2678–2664 Ma Canadian Malartic deposit are located next to the Larder Lake-Cadillac fault zone, but were formed at different times and at different crustal levels. As part of the project, a gold fertility model has been developed for the two main fertile fault zones («breaks») of the Abitibi greenstone belt (Porcupine-Destor and Larder Lake-Cadillac) incorporating a critical phase of extension and coeval alkaline magmatism (Bleeker, 2012, 2015, Lafrance, 2015). According to this model, the main “breaks” were initiated as deep-seated, listric, synorogenic extensional faults that were coeval with a flare-up in «alkaline» magmatism and were then reactivated as thick-skinned thrusts that buried the synorogenic clastic rocks (Timiskaming basins) in their immediate structural footwall; thus explaining the preservation of gold deposits mainly on one side (footwall) of the long-lived structures (Bleeker, 2012, 2015). This model helps explain a long-standing empirical link between unconformities, major faults and major gold deposits (Miller and Knight, 1915; Poulsen et al., 1992; Hodgson, 1993; Cameron, 1993; Robert, 2001; Dubé et al., 2003, 2004; Robert et al., 2005; Dubé and Gosselin, 2007).

Deposit Characteristics versus Orogenic Pressure-Temperature-Time Path

Gold deposits are characterized by their geological setting, style(s) and types of mineralization, and also on the timing of mineralization relative to the orogenic pressure-temperature-time path. Several of the studied deposits are coeval with the main compressive phase of deformation (orogenic gold) and are all variably deformed and metamorphosed (prograde and retrograde paths). Other deposits are synvolcanic and were strongly overprinted and modified during younger deformation and metamorphic events (e.g. Westwood and Rainy River). Several deposits are syndeformational, but have recorded younger deformation and metamorphic events that may have remobilized gold (e.g. Roberto, Meadowbank, Meliadine, and Hard Rock). Many gold systems are the result of superimposed gold-bearing mineralizing events (e.g. Hollinger-McIntyre, Hard Rock, and Roberto), contributing to their complex geological and hydrothermal footprints. Moreover, evidence for gold remobilization is common and in some cases may control the geometry of high-grade gold ore zones (e.g. Meliadine, Westwood, Musselwhite, Hard Rock, and Bousquet 2-Dumagami).

Exploration Implications

The occurrence of alkaline magmatism concomitant with fault-bounded, clastic «Timiskaming-type» basins is a diagnostic criterion for recognizing potentially fertile major faults (e.g. Bleeker, 2012, 2015). The presence of «Timiskaming-type» conglomerate not only provides an indication for the potential presence of a major fault, it also indicates a favourable level of erosion and thus signals the potential for preservation of large gold deposits hosted lower in the stratigraphy by more competent and reactive rocks (e.g. Tisdale Formation, Timmins; Balmer basalt, Red Lake: Poulsen et al., 1992; Robert, 2001; Dubé et al., 2003, 2004; Robert et al., 2005; Bleeker, 2012 and references therein). This is illustrated by the occurrence of such a panel of synorogenic clastic rocks in the Penhorwood area of the northern Swayze greenstone belt, 80 km west of Timmins (Bleeker et al., 2014). This panel suggests that a major fault, most likely the western extension of the highly fertile Porcupine-Destor fault zone, is probably nearby and buried these clastic rocks in its structural footwall during the late thick-skinned thrusting phase (Bleeker et al., 2014). The presence of highly deformed and metamorphosed Timiskaming-age polymictic conglomerate, proximal to, or hosting, gold mineralization at the recent major Borden gold discovery (Probe Minerals, 165 km southwest of Timmins in high-grade metamorphic rocks of the Kapuskasing structural zone), strongly supports the link between such synorogenic clastic sedimentary rocks, major fault zones, and large gold deposits. It opens significant new exploration ground for potential large gold deposits (Atkinson, 2014). Such a potential has been earlier emphasized by the correlation of major Archean gold-bearing fault zones across the Kapuskasing uplift by Leclair et al. (1993). Using a combination of high-strained rocks, linear belts of Timiskaming-type conglomerate, and calc-alkaline to alkaline igneous rocks, Leclair et al. (1993) extended the Porcupine-Destor and Larder Lake-Cadillac fault zones by hundreds of kilometres east and west of the Kapuskasing structural zone (Fig. 3), with both major tectonic and exploration implications. The newly discovered occurrence of Timiskaming-age polymictic conglomerate immediately to the north of the Larder Lake-Cadillac fault zone in the Malartic area adds new key information on the structural history of the Larder Lake-Cadillac fault zone and its potential fertility in an area where there are several Timiskaming-age intrusions and significant gold deposits (e.g. Camflo, Canadian Malartic: Pilote et al., 2014). The presence of the Canadian Malartic deposit immediately south of the Larder Lake-Cadillac fault zone, the Barnat (Sansfaçon and Hubert, 1990) and Lapa (Simard et al., 2013) deposits within the fault zone, and the Camflo deposit ~7 km north of the fault zone highlight that significant gold deposits can be formed (and preserved) within the footwall and hanging-wall successions of such major fault zones. The preservation potential of these deposits depends, in part, on the amplitude of the throw of the reverse faulting and the level of erosion (e.g. Bleeker et al., 2012, 2015).

In the Musselwhite deposit area, the presence of a newly discovered polymictic conglomerate in the upper stratigraphic sequence of the mine may indicate the presence of a major structure and provide guidelines for exploration throughout the North Caribou greenstone belt, especially if combined with tightly folded silicate-rich BIF horizons (Oswald et al., 2014, 2015a,b). The past-producing gold mines in the Geraldton area were all located in the southern sedimentary assemblage, including polymictic conglomerate, and mostly within the kilometre-wide Tombill-Bankfield deformation zone (Tóth et al., 2013). A similar setting may also characterize the Meadowbank area with the presence of Archean, polymictic basal-type conglomerate. These conglomerate units structurally overly the Meadowbank host succession, although the primary geometry of these relict sedimentary basins is unknown due to a major Paleoproterozoic overprint (Janvier et al., 2015a,b).

Early massive iron-carbonate veins pre-main-stage gold mineralization are present at the Hard Rock deposit in the Beardmore-Geraldton gold district (Tóth et al., 2015), as well as in numerous deposits in Timmins including Dome, Paymaster, and at the Campbell-Red Lake deposit in Red Lake (Dubé et al., 2003, 2004). These veins may represent a key hydrothermal event in the formation of large gold deposits and illustrate the protracted nature of hydrothermal activity and more particularly large-scale CO_2 metasomatism.

Technology Development

The Lode Gold project was also the opportunity to contribute to the development of advanced analytical and material characterization methodologies, either as specific research activities or as components to field-based and site-specific studies. These include in situ geophysical measurements and their correlation with mineralogy and geochemistry (Canadian Malartic Mine: El Goumi et al., 2015), the classification of ore samples based on whole-rock geochemistry (OSNACA project: Grunsky et al., 2015), pXRF spectrometry (e.g. Lawley et al., 2015), and the systematic use of LA-ICP-MS geochemistry in all site-specific research activities and a thematic fertility fingerprinting project (Gao et al., 2015).

In direct collaboration with the Canada Mining Innovation Council's footprint project at the Canadian Malartic Mine (Linnen et al., 2014), variability of rock physical properties was measured in the open-pit area to relate lithology and alteration assemblages to physical properties. The objective of this collaborative research was to better constrain geophysical surveys on this type of ore deposit and help define and detect the footprint of the deposit. The results indicate that no single geophysical technique can provide a particularly useful measure of the presence of hydrothermal alteration or gold content (El Goumi et al., 2015). However, a combination of decreasing density and magnetic susceptibility with increasing chargeability coincides with changes in the alteration assemblages (e.g. carbonate saturation index), gold concentration, and proximity to ore, especially in the sedimentary rocks that host ≥70% of the ore. A petrophysical proxy has been established as representative of this gradual hydrothermal mineralization process by assessing composite petrophysical properties (density, magnetic susceptibility, and chargeability) and quantifying their principal component analysis. Such proxy could potentially improve the geophysical approach in exploration for such low-grade bulk-tonnage deposits (El Goumi et al., 2015).

The OSNACA (Ore Samples Normalized to Average Crustal Abundance) international project is a new approach jointly developed by the mineral exploration industry, the Centre for Exploration Targeting, University of Western Australia, and the TGI-4 Lode Gold project to characterize and classify representative ore samples from a wide spectrum of lode gold deposit types based on whole-rock geochemistry (Grunsky et al., 2015). The developed classification scheme, based on a statistical analysis of chemical concentrations, consists of a log-centred-ratio transformation of a suite of 24 ore-associated trace elements, which helps discriminate ore deposit types according to specific trace-element correlations. This can therefore become an extra tool to assess exploration potential in both greenfield and brownfield areas by providing another way of recognizing well known ore types at an early stage.

CONCLUSIONS

The integration of many site studies (Canadian Malartic, Coté Gold, Geraldton, Meadowbank, Meliadine, Musselwhite, Rainy River, Roberto, Timmins, Vault, Wabamisk, Westwood), thematic research, and the interaction with other TGI-4 projects (e.g. VMS) has broadened the knowledge base for a large spectrum of Precambrian gold deposit types and their footprints at various metamorphic grades, leading to a more targeted approach in greenfield terranes (e.g. Rainy River, Wabamisk, and Roberto deposits) while stimulating a reappraisal of models in mature (brownfield) districts at depth. The classic Abitibi «orogenic» quartz-carbonate vein exploration model used in Archean terranes for decades is being revised, as there is clearly a much broader spectrum of gold deposit types/styles, including "syngenetic/synmagmatic" and metamorphosed gold deposits that are distinct from the orogenic model (e.g. Poulsen et al., 2000; Goldfarb et al., 2005, Robert et al., 2005; Ravenelle et al., 2010), as well illustrated here. Such a reappraisal has an impact on exploration models in deformed and metamorphosed Precambrian and younger terranes in Canada.

Collectively, the TGI-4 Lode Gold project provides a wealth of new data and descriptions of selected key deposits or districts and new greenfield discoveries (e.g. Wabamisk), as well as ideas and concepts that will be applicable to exploration and that broadly contribute to our general understanding of the geological and metallogenic evolution of Archean cratons and Paleoproterozoic belts that represent major sources of metals worldwide, including most of the gold production in Canada. The unique gold endowment, or heritage of the southern Abitibi greenstone belt, in addition to specific ore-forming processes, must also be taken into account when trying to understand key ore-forming processes in uniquely endowed areas such as the southern Superior Province (e.g. Sillitoe, 2008). The huge amount of gold present in districts such as Timmins and Doyon-Bousquet-LaRonde may be related to specific, fundamental geological characteristics in terms of favourable source-rock environments, gold reservoirs, and/or early gold enrichment (i.e. provinciality concept: Hodgson, 1993; Hutchinson, 1993; Sillitoe, 2000; Gray and Hutchinson, 2001; Dubé and Gosselin, 2007; Sillitoe, 2008; Mercier-Langevin et al., 2012b) as summarized on Figure 7. Enriched gold "reservoirs" could have been tapped at different times during the evolution of the greenstone belt to form various types of gold deposits (e.g. Au-rich VMS, syenite associated Au, orogenic quartz-carbonate Au veins, etc). In such a model, the major fault zones that had access to these gold-enriched reservoirs through time acted as conduits to auriferous hydrothermal fluids and are associated with the development large deposits and districts. Advances in our understanding of key deposits and ore systems in the southern Abitibi belt, which was largely generated through the Targeted Geoscientific Initiative, puts us into a good position to tackle a major remaining knowledge gap that is the reason why there is so much gold in such a small part of Earth's crust.

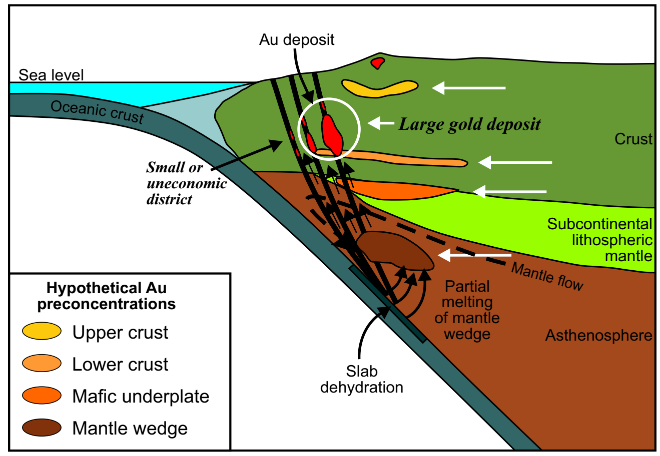

Figure 7. Schematic section of a convergent margin showing hypothetical sites of gold preconcentration(s) in the lower crust and upper mantle that may constitute a common source of gold for magmatic-hydrothermal and orogenic deposits. Modified from Sillitoe (2008).

Finally, but not the least, the Lode Gold project has also considerably contributed to the training of highly qualified personnel for the mineral industry and research institutions by supporting two visiting fellows, eight doctoral projects, five master's projects, and four undergraduate honours' theses. These talented young research scientists have directly interacted with the industry and academia, and gained academic and hands-on experience to be part of the new generation of young economic geologists.

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