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

Banded iron formation-hosted gold mineralization in the Geraldton area, northwestern Ontario: Structural setting, mineralogical characteristics, and geochronology

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ABSTRACT

Renewed exploration activities in the Beardmore-Geraldton belt in the Archean Superior Province, northwestern Ontario, produced large stripped outcrops and new drill cores that revealed a wealth of new information on the structural and lithological settings of gold mineralization in this past-producing mining camp. The aims of this project are to establish the key geological parameters that controlled the genesis and distribution of gold mineralization in the area and to define geological and exploration models that incorporate the revised knowledge of the geological and structural setting, relative timing, mineralogical characteristics and geochemical footprints of the gold mineralization to fill in knowledge gaps about the gold distribution and geometry in the belt. The Beardmore-Geraldton belt consists of 0.15 to 10 km-wide panels of Archean metasedimentary rocks alternating with 1 to 5 km-wide panels of metavolcanic rocks. The older, ca. 2725 Ma metavolcanic panels are in fault contact with the younger metasedimentary panels. The deposition of the sedimentary rocks started at <2700 Ma, as indicated by the youngest detrital zircons dated from the Central and Southern Metasedimentary units and was complete by 2694.0 ± 1.0 Ma, the crystallization age of the crosscutting quartz-feldspar porphyry.

The Beardmore-Geraldton belt underwent four deformation events. During D_1 deformation, the metavolcanic-metasedimentary sequences and the quartz-feldspar porphyry were thrust-imbricated and folded by F_1 folds. The D_1 event occurred between 2694 Ma, the age of the quartz-feldspar porphyry dyke in Geraldton, and 2690 ± 1 Ma, the age of the post-D_1 Croll Lake stock. During D_2 deformation, south-to-north shortening, regional-scale, west-plunging F_2 folds and axial-planar, east-trending, steeply dipping S_2 foliation were formed. The S_2 foliation has been folded by S-shaped F_3 folds that are associated with an east-trending, spaced axial-planar S_3 cleavage, indicating a previously unrecognized D_3 sinistral shear event in the belt. These three deformation events were overprinted by a D_4 dextral transpression event. In the Beardmore-Geraldton belt, gold mineralization is typically hosted by mudstone, sandstone, banded iron formation and quartz-feldspar porphyry. Gold mineralization is commonly associated with locally auriferous quartz-carbonate veins. The mineralized quartz-carbonate±tourmaline vein selvages are characterized by semi-massive sulphide-sericite-carbonate replacement alteration halos where hosted in banded iron formation. A similar alteration halo is present in veins that are hosted in mudstone, sandstone and quartz-feldspar porphyry, although the sulphides are less abundant than when the veins are hosted in banded iron formation.

At least two gold-mineralizing events, including possible remobilization, took place during the tectonic evolution of the belt. Gold-rich quartz-carbonate±tourmaline veins and the associated sericite-carbonate-sulphide alteration halos are folded by F_1 folds, suggesting that the first gold-bearing event is related to the early phases of the D_1 deformation. East-northeast- to east-trending, locally auriferous quartz-carbonate-tourmaline-sulphide veins cut F_2 fold hinges but are folded by S-shaped F_3 folds, suggesting a second, early D_3 auriferous episode in the district. Northwest-trending sulphide-rich veins, which cut across early D_3 tourmaline-rich veins and are folded by gentle Z-shaped F_4 folds, may also have carried or remobilized some gold mineralization during D_4 dextral transpression. An increase in gold grade is associated with elevated As, Te, Sb, and W concentrations and sericitization index. It is hoped that the new data and interpretation generated as part of this project will contribute to further mineral exploration success by defining new structural targets and establishing geochemical footprint vectors.

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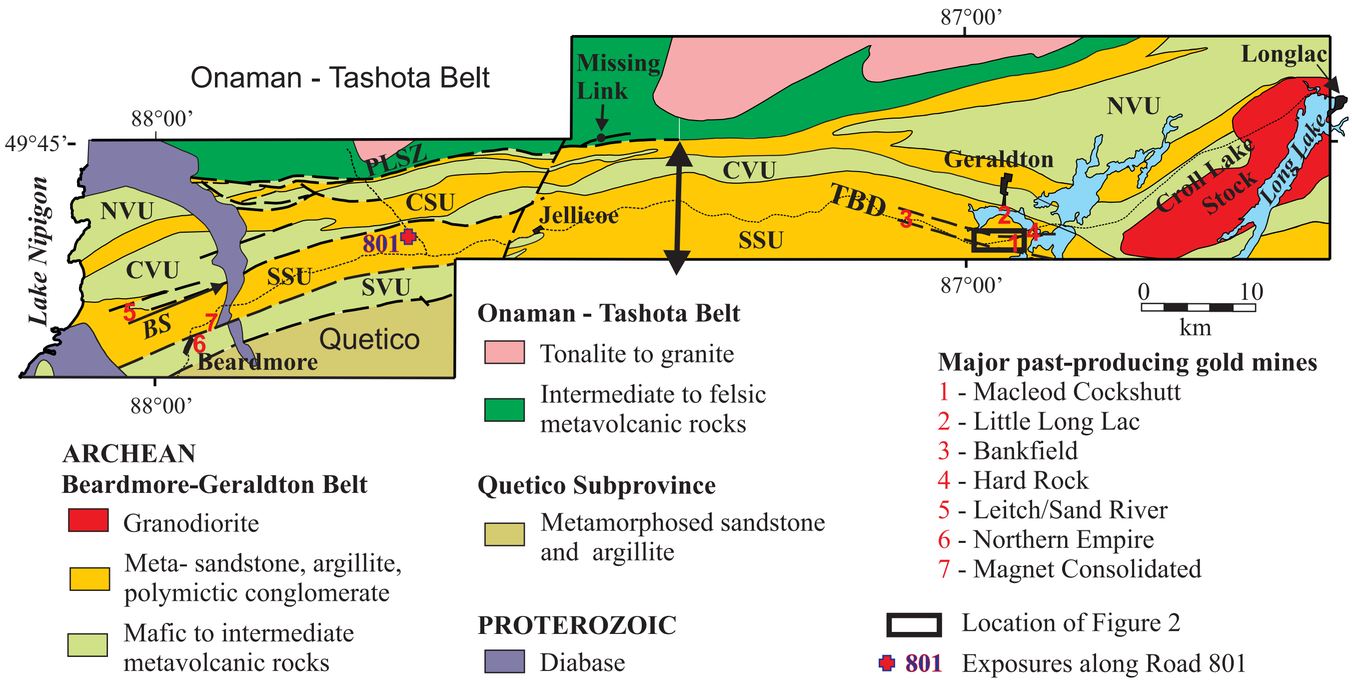

Figure 1. Regional geological map of the Beardmore-Geraldton greenstone belt (modified after Lafrance et al., 2004 and references therein). Abbreviations: BS = Beardmore syncline; NSU, CSU, SSU = Northern, Central, and Southern Metasedimentary units; NVU, CVU, SVU = Northern, Central, and Southern Metavolcanic units; PLSZ = Paint Lake Shear Zone; TBD = Tombill-Bankfield Deformation zone.

INTRODUCTION

The Beardmore-Geraldton belt (BGB) is a transitional terrane at the boundary between the Quetico and the Wabigoon subprovinces in the western Superior Province, northwestern Ontario (Devaney and Williams, 1989). Over 4.1 million ounces of gold were produced from several deposits between 1933 and 1970, after which mining ceased in the area (Pye, 1952; Horwood and Pye, 1955; Mason and McConnell, 1982; Mason and White, 1986). Renewed exploration has significantly increased the known gold resources in Geraldton. Premier Gold Mines Ltd. delineated an additional 4.87 Moz and 2.74 Moz in indicated and inferred resource categories, respectively, and, at the time this paper was written, is planning open-pit operations on two of the deposits (Press Release on July 8, 2014; www.premiergoldmines.com).

In order to better define the controls on gold mineralization and thereby refine existing geological and exploration models, new research activity was initiated in the BGB as part of the Lode Gold project of the Targeted Geoscience Initiative 4 program (TGI-4) of Natural Resources Canada (Dubé et al., 2011). The main objective of the project was to determine the geological parameters that controlled gold mineralization in the BGB and their relative timing, thereby contributing to a better understanding of lode gold deposits. Our specific objectives were to (1) determine the structural and lithological setting of the deposits; (2) characterize the geochemical footprint of the gold mineralization and its associated hydrothermal alteration envelope; (3) interpret the chronology of gold-mineralization event(s) relative to the tectonic evolution of the belt; and (4) develop tectonic and metallogenic models for the belt.

REGIONAL GEOLOGY

The BGB consists of six, east-trending, intercalated metavolcanic and metasedimentary units, which are separated by dextral shear zones (Fig. 1). The Northern (NVU), Central (CVU) and Southern Metavolcanic (SVU) units formed in back-arc, island arc, and oceanic crust environments, respectively (Tomlinson et al., 1996). The Northern (NSU), Central (CSU), and Southern (SSU) Metasedimentary units consist dominantly of polymictic conglomerate (NSU), conglomerate and turbiditic sandstone interbedded with Algoma-type banded iron formation (CSU), and turbiditic sandstone interbedded with polymictic conglomerate and banded iron formation (SSU) (Pye, 1952; Horwood and Pye, 1955; Mackasey, 1975, 1976; Barett and Fralick, 1985; Devaney and Fralick, 1985; Devaney and Williams, 1989). From north to south, the metasedimentary units represent alluvial fan or braided-plain fluvial environments (NSU), subaqueous fan and/or prodelta environments (CSU), and submarine fan and/or basin-plain environments (SSU) (Mackasey, 1975, 1976; Barrett and Fralick, 1985; Devaney and Williams, 1989; Fralick and Pufahl, 2006).

Previous structural studies documented three tectonic events across the BGB. The D_1 deformation is interpreted as a regional thrusting event, which imbricated the metavolcanic and metasedimentary units during closure of foreland basin, the Quetico subprovince, between the converging Wabigoon subprovince and the Wawa subprovince (Devaney and Williams, 1989; Williams, 1990). Outcrop-scale, isoclinal, F_1 folds with no associated cleavage formed during D_1 deformation (Williams, 1986, 1987a,b, 1989, 1990; Devaney and Williams, 1989; Lafrance et al., 2004), which was bracketed between 2696 ± 2 Ma, the youngest detrital zircon age in the Central and Southern Metasedimentary units (Hart et al., 2002; Fralick et al., 2006) and 2691 $^{+3}/_{-2}$ Ma, the crystallization age of a crosscutting quartz feldspar porphyry dyke (Anglin, 1987; Anglin et al., 1988; Lafrance et al., 2004). During the D_2 south-to-north shortening, the BGB underwent tight, upright, regional F_2 folding producing an east-trending, steeply dipping, axial-planar S_2 cleavage and a steeply plunging mineral stretching lineation (L_2) (Lafrance et al., 2004). During D_3 dextral transpression, the unit-bounding thrust faults were reactivated as dextral shear zones and a second regional cleavage formed axial-planar to asymmetrical, west-plunging F_3 folds (Lafrance et al., 2004). During the same progressive deformation event, F_3 and S_3 were refolded and overprinted by Z-shaped $F_{3'}$ folds and axial-planar $S_{3'}$ crenulation cleavage (Lafrance et al., 2004; DeWolfe et al., 2007).

Gold in the area occurs in quartz-carbonate veins and their hydrothermal alteration selvages. Previous work indicates that the veins are parallel to S_3 and overprint F_2 and F_3 fold hinges, and thus were interpreted to have been formed during the D_3 dextral transpression (Pye, 1952; Horwood and Pye, 1955; Beakhouse, 1984; Anglin and Franklin, 1985; Macdonald, 1988; Kresz and Zayachivsky, 1991; Lafrance et al., 2004; DeWolfe et al., 2007). Our work in the belt indicates that some of these interpretations may need to be revisited.

STRUCTURAL EVOLUTION OF THE BEARDMORE-GERALDTON BELT

Detailed mapping and description of 8 large stripped exposures, including lithology, primary texture, structure, veining, alteration and mineralization, were completed to improve the understanding of the relative timing of the gold mineralization, as well as the deformation history of the Beardmore-Geraldton belt. Mapping was aided by the use of a differential GPS, which proved to be essential for taking precise structural measurements on magnetic banded iron formation. Seven of these exposures are located south of Geraldton (Fig. 2), and the other is located west of Road 801, in the western part of the Beardmore-Geraldton greenstone belt (Fig. 1).

The complex, polyphased tectonic evolution of the BGB is summarized in Table 1. Excellent examples of F_1 folds (Fig. 3a) with an axial-plane S_1 cleavage are present in several outcrops. S_1 cleavage, which had not been recognized in previous studies, is expressed as a spaced, chlorite-defined cleavage parallel to bedding in metasedimentary rocks, as a continuous chloritic cleavage in mafic dykes (Fig. 3b), and as a strong crenulated, spaced cleavage (with an average spacing of ~1 mm) defined by sericite in quartz-feldspar porphyry dykes within the hinge of F_2 folds (Tóth et al., 2013a). During the D_2 compression, F_1 folds and the S_1 axial-planar foliation were refolded by regional, east-trending F_2 folds and overprinted by the associated S_2 axial-planar cleavage (Fig. 3c) (Lafrance et al., 2004; Tóth et al., 2013a, 2014b). S_2 cleavage is folded by tight to open S-shaped F_3 folds with an axial-planar, east-trending, and steeply dipping, S_3 crenulation cleavage (Fig. 3d). These structures formed during a previously unrecognized D_3 sinistral transcurrent shearing event (Tóth et al., 2013a). The D_4 dextral shearing event (D_3 of Lafrance et al., 2004) resulted in the formation of Z-shaped F_4 drag folds and an S_4 axial-planar cleavage (Fig. 3e) (Tóth et al., 2013a, 2014b). The S_4 cleavage is folded by Z-shaped $F_{4'}$ folds and overprinted by an $S_{4'}$ foliation in shear zones (Fig. 3f) (Lafrance et al., 2004; DeWolfe et al., 2007).

GOLD MINERALIZATION

Numerous samples were collected from stripped outcrops and drill core to characterize the host rocks, the nature of the gold mineralization and the associated hydrothermal footprint in the Geraldton area. Styles of gold mineralization differ according to their host rocks. In mudstone and sandstone, auriferous quartz-carbonate±tourmaline veins are surrounded by a strong yellow-brown sericite-Fe-carbonate-sulphide±chlorite alteration halo (Fig. 4a) (Tóth et al., 2013b, 2014b). In magnetite-rich banded iron formation, gold is associated with semi-massive sulphide-sericite-carbonate± chlorite alteration selvages surrounding quartz-carbonate±chlorite veins (Fig. 4b) (Tóth et al., 2013b). When hosted in quartz-feldspar porphyry, the auriferous quartz-carbonate±tourmaline veins are surrounded by a well developed sericite-iron-carbonate-sulphide alteration halo (Fig. 4c) (Tóth et al., 2013b, 2014b). Regardless of host rock, the dominant sulphide is pyrite; however, arsenopyrite, pyrrhotite and chalcopyrite are also present (Tóth et al., 2013b). Where arsenopyrite is present, the sulphides are zoned with a greater abundance of pyrite occuring next to the vein margins and a greater abundance of arsenopyrite further away from the vein margins (Tóth et al., 2013b). Gold occurs as fracture-fills or as inclusions in pyrite and arsenopyrite grains, but is also present as free grains in the veins (Tóth et al., 2013b).

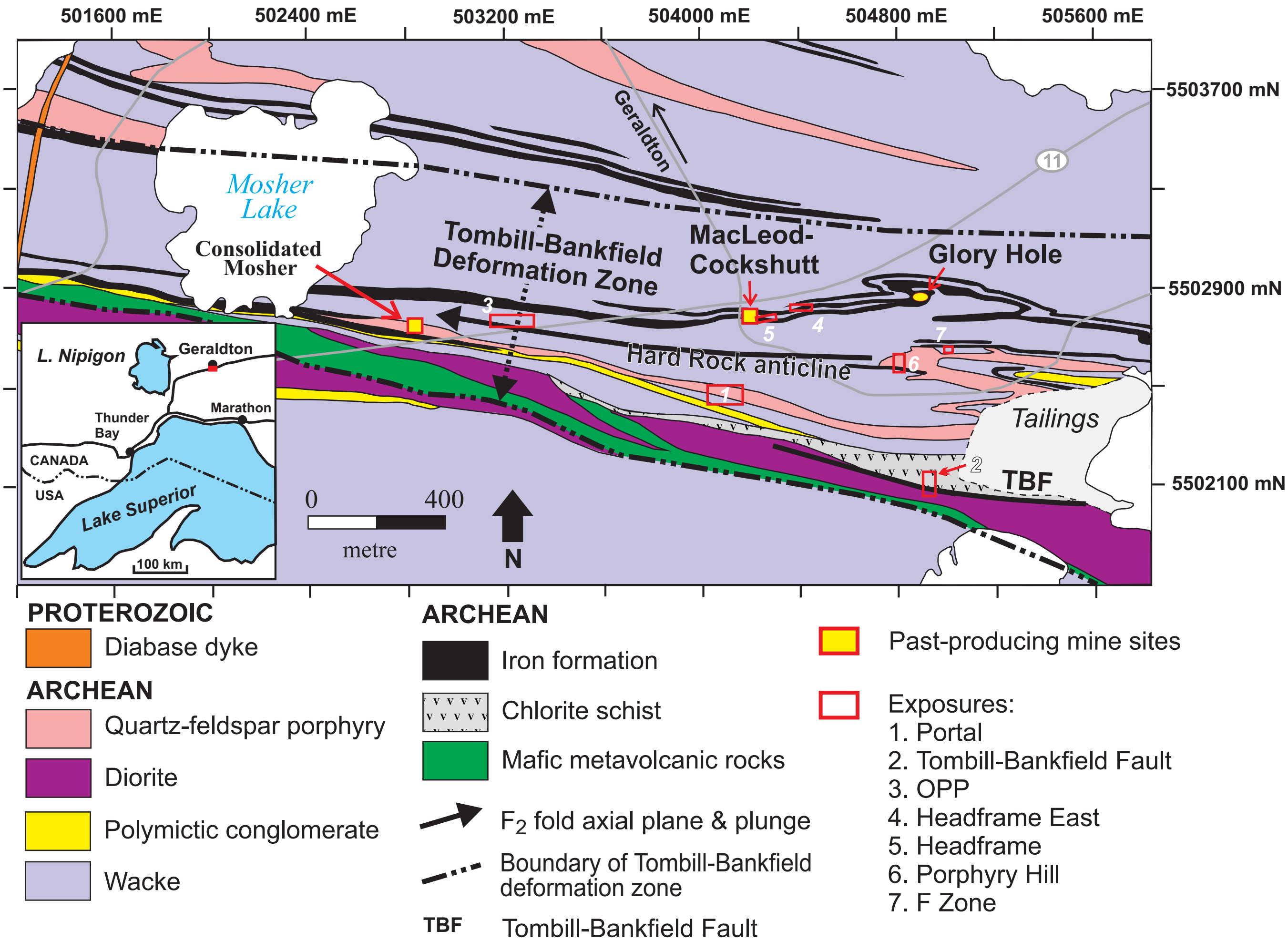

Figure 2. Simplified geological map of the Geraldton area showing the location of the mapped exposures (geology modified after Horwood and Pye, 1955, and Pye, 1952). The red rectangle in the inset shows the regional-scale location of the study area. Universal Transverse Mercator (UTM) co-ordinates are based on North American Datum 1927 (NAD27), zone 16.

Table 1. Summary of deformation and gold mineralization events in the Beardmore–Geraldton greenstone belt (Lafrance et al., 2004; Tóth et al., 2013a, 2014a,b). Abbreviations: ACW = anticlockwise; CW = clockwise; QFP = quartz-feldspar porphyry.

Regional Deformation Style	Description of Structures: Folding	Foliation
	Gold mineralization	
D_1 thrusting	Isoclinal, recumbent F_1 folds; up to 1 m in amplitude	Strong; appears in some mafic dykes and QFP; bedding-parallel in sedimentary rocks
D_2 north-south compression	Tight upright regional F_2 folds; plunge: 20–70°W; amplitude up to several km	East-trending, steeply-dipping S_2; axial-planar to F_2 folds; parallel or slightly CW/ACW of bedding
	Gold mineralization (or remobilization)	
D_3 sinistral transcurrent shear	Tight to open S-shaped F_3 folds; amplitude up to 10s of cm	East-trending, steeply-dipping S_3; axial-planar to F_3
	Gold mineralization (or remobilization)	
D_4 dextral transpression *(D3 in Lafrance et al., 2004)*	Z-shaped F_4 folds; plunge: 20–60°W; amplitude up to several km	East-northeast-trending, steeply-dipping regional S_4; axial-planar to F_4; oriented ACW to bedding
	Dextral east-trending shear zones localized along S_2 and lithological contacts	
	Z-shaped $F_{4'}$ drag folds over-printing foliation in shear zones	Sinistral-slip $S_{4'}$ crenulation clevage; axial-planar to $F_{4'}$

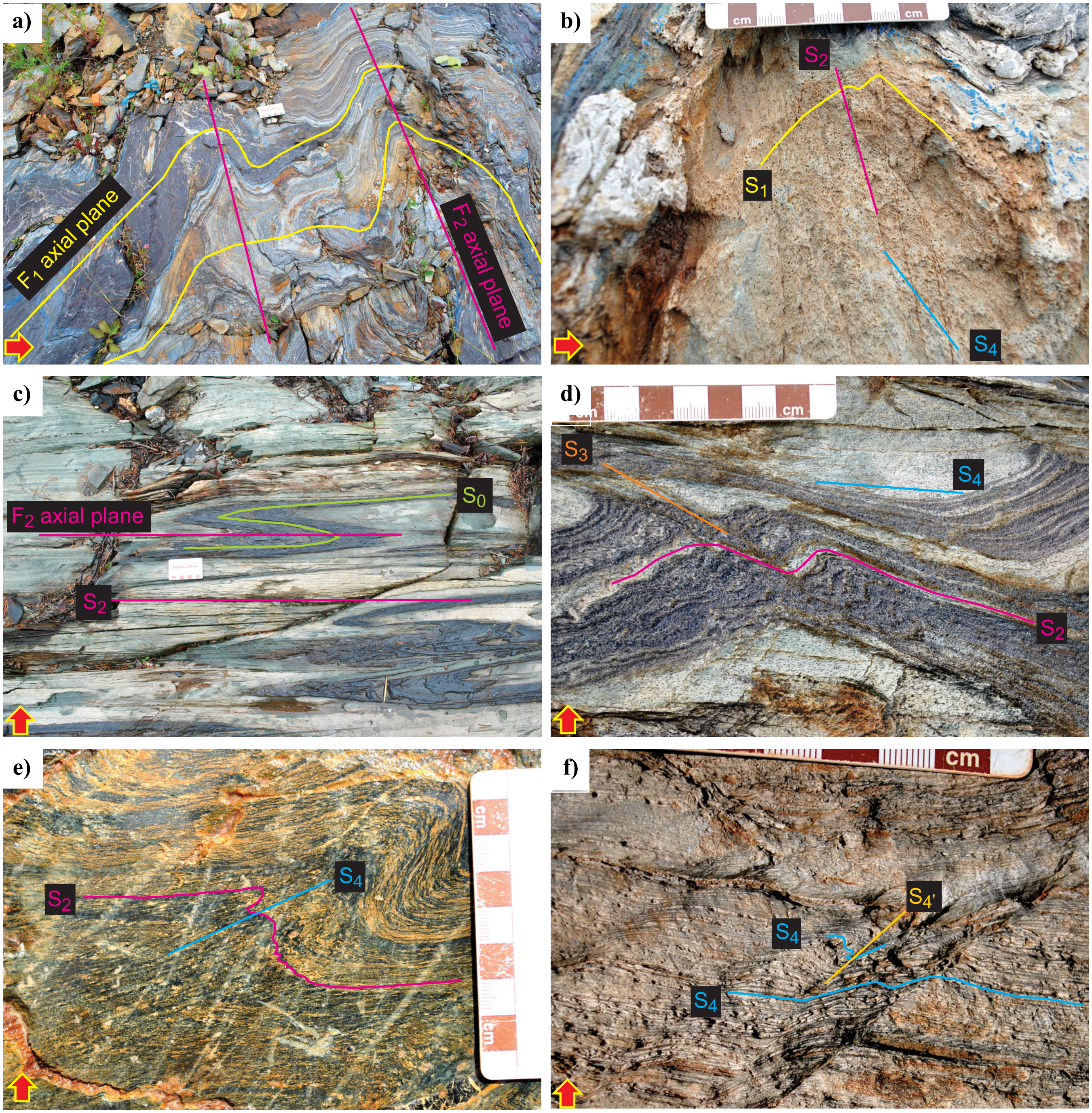

Figure 3. Structural elements in the Beardmore-Geraldton greenstone belt (Lafrance et al., 2004; DeWolfe et al., 2007; Tóth et al., 2013a, 2014b). The yellow-outlined red arrows indicate north on each photograph. **a)** F_1 folds refolded by west-plunging F_2 folds in banded iron formation. **b)** Strong chloritic S_1 cleavage folded by F_2 folds and overprinted by S_2 and S_4 foliation in a mafic dyke. **c)** Tight S-shaped F_2 folds with axial-planar S_2 foliation folding bedding (S_0) in banded iron formation. **d)** S_2 cleavage folded by S-shaped F_3 folds that are overprinted by S_4 foliation. **e)** Chloritic S_2 foliation folded by Z-shaped F_4 folds and overprinted by axial-planar S_4 cleavage. **f)** In shear zones, S_4 foliation is folded by another Z-shaped $F_{4'}$ fold generation that has axial-planar $S_{4'}$ sinistral-slip cleavage.

There were two main gold-mineralizing events that occurred during deformation. Iron-carbonatized beds and quartz-carbonate±tourmaline veins are folded by F_1 folds (Fig. 5a). Some of these early quartz-carbonate±tourmaline veins are surrounded by a strong sericite-carbonate-sulphide alteration halo (Fig. 5b) and commonly yield gold values between 2 and 15g/t (B. Cleland, Premier Gold Mines Ltd. pers. comm., 2014), suggesting that the first gold mineralization event occurred at the onset of the D_1 thrusting (Tóth et al., 2014b). Other banded iron formation-hosted quartz-carbonate veins associated with traces of pyrite

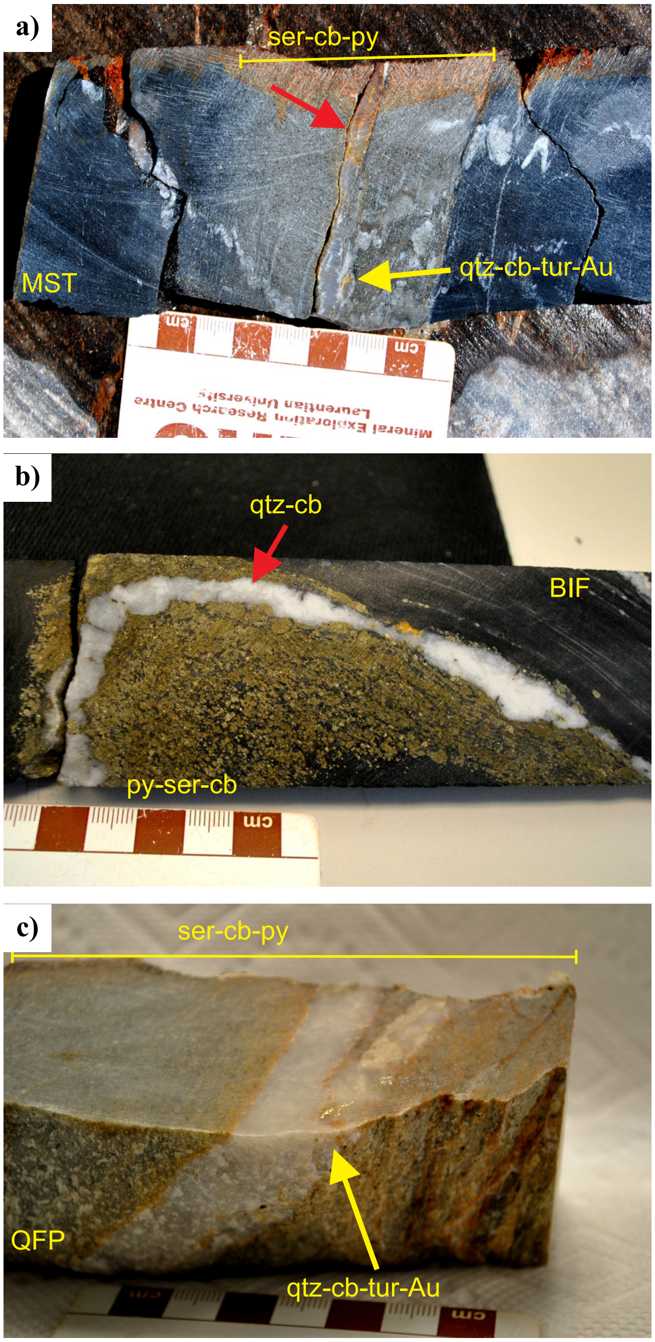

Figure 4. Photographs of mineralization styles. **a)** Auriferous quartz-carbonate-tourmaline vein surrounded by intense sericite-carbonate-pyrite alteration in turbiditic mudstone and sandstone (MST). **b)** Semi-massive pyrite-sericite replacement alteration surrounding a quartz-carbonate vein in banded iron formation (BIF). The semi-massive pyrite replacement yielded 65.1 g/t Au. **c)** Auriferous quartz-carbonate-tourmaline veins surrounded by sericite-carbonate-sulphide alteration in quartz-feldspar porphyry (QFP). Abbreviations (Siivola and Schmid, 2007): Au = gold; cb = carbonate; py = pyrite; qtz = quartz; ser = sericite; tur = tourmaline.

replacement cut the limbs of F_1 folds but are folded in the hinge of the same folds (Fig. 5c), suggesting that gold-bearing veins were emplaced throughout D_1 deformation. East-northeast- to northeast-trending tourmaline-rich (Fig. 5d) and auriferous quartz-carbonate-tourmaline-sulphide veins (Fig. 5e) and their carbonate-sericite-pyrite alteration halo cut F_2 fold hinges and are folded by S-shaped F_3 folds (Tóth et al., 2014b). These northeast-trending veins have an anticlockwise relationship with S_2, which is consistent with sinistral shearing parallel to S_2 during a syn-D_3 reactivation of the S_2 foliation. This suggests that the second gold-mineralizing event is syn-D_3 deformation (Tóth et al., 2014b). These results differ from previous studies that proposed a late-D_4 dextral transpression timing for the gold mineralization in the BGB (Lafrance et al., 2004; DeWolfe et al., 2007). Some quartz-sulphide veins, which fill northwest-trending tension gashes that cut across northeast-trending tourmaline-dominated veins, are folded by gentle Z-shaped F_4 folds (Fig. 5f) and were likely emplaced during D_4 dextral shear (Tóth et al., 2014b). Similar auriferous veins were described in the western part of the BGB (DeWolfe et al., 2007), implying a possible third gold-bearing event, or a syn-D_4 remobilization of gold.

GEOCHRONOLOGY

U-Pb Sensitive High Resolution Ion Microprobe (SHRIMP II) analyses of detrital zircon grains were completed at the Geological Survey of Canada (GSC) Geochronology Laboratory in Ottawa. Representative conglomerate and sandstone samples from the three BGB metasedimentary units and a sandstone sample from the Quetico Subprovince near the boundary with the BGB were selected for analysis. An auriferous quartz-feldspar porphyry dyke was dated using high-precision U-Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) techniques at the GSC. A gold-mineralized arsenopyrite-rich sample was dated using the Re-Os isotopic system in an attempt to directly date the gold-mineralizing event. These analyses were completed using isotope dilution negative thermal ionization mass spectrometry (ID-NTIMS) methods at the Canadian Centre of Isotopic Microanalysis (CCIM), University of Alberta.

Over three hundred U-Pb detrital zircon analyses reveal very similar age distributions in all samples. In the CSU and SSU sandstone samples, the youngest dominant detrital zircon populations were dated at ca. 2700 Ma. The youngest dominant zircon populations in the sandy matrix of the NSU conglomerate and the Quetico sandstone were determined to be ca. 2711 Ma (Tóth et al., 2014a). These U-Pb ages are consistent with the previous interpretation of the BGB as a transitional terrane between the Wabigoon and Quetico subprovinces (Devaney and Williams, 1989; Williams, 1990; Fralick et al., 2006). The deposition of the metasedimentary units therefore started at ≤2700 Ma

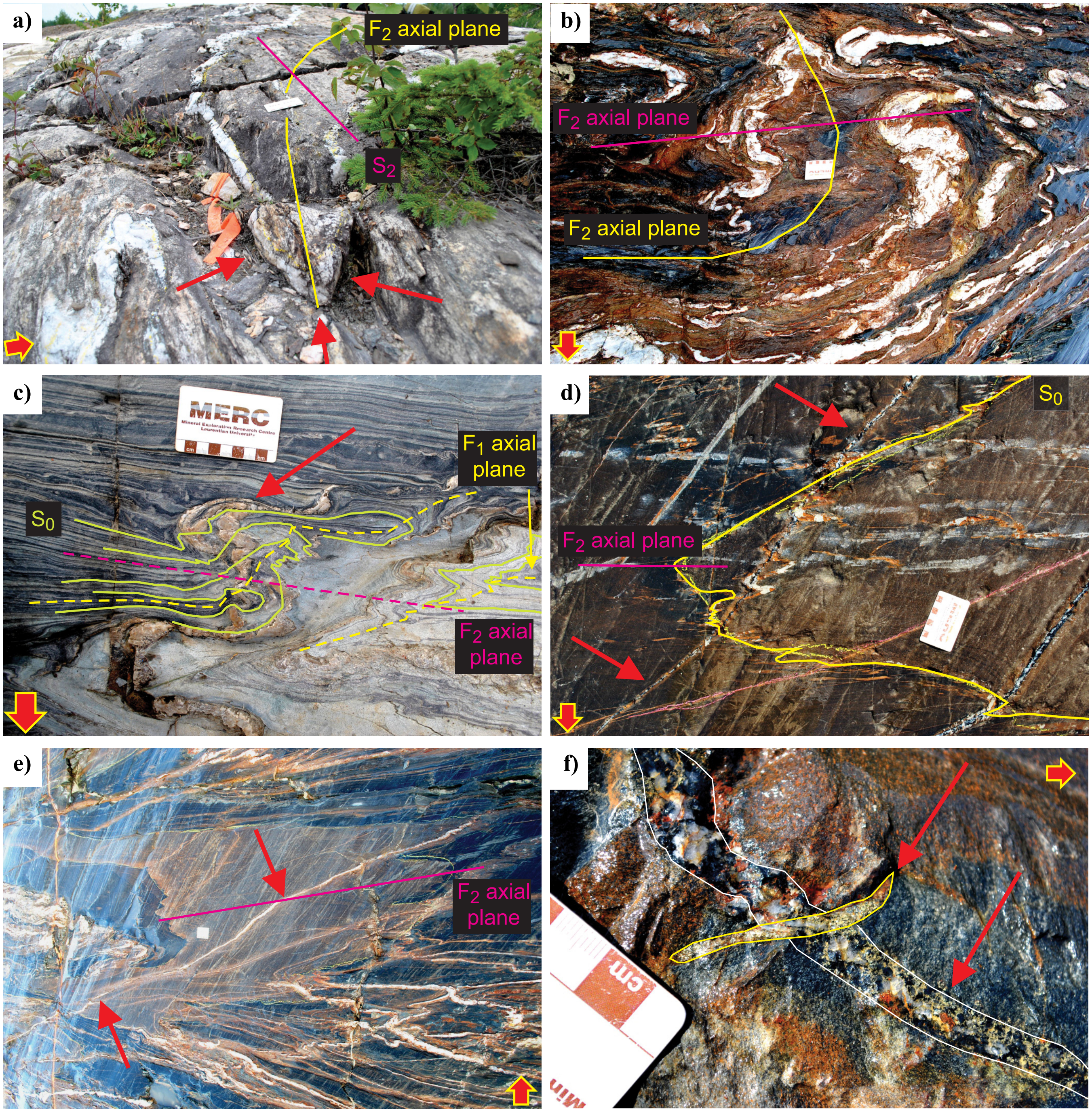

Figure 5. Field relationships between hydrothermal activity including gold mineralization events and the deformation history of the Geraldton area (Tóth et al., 2014b). The yellow-outlined red arrows indicate north on each photograph. **a)** Early quartz-carbonate-tourmaline vein folded by F_1 and refolded by F_2 folds in quartz-feldspar porphyry in the hinge of Hard Rock anticline. **b)** Gold-mineralized quartz-carbonate-tourmaline veins surrounded by intense sericite-carbonate-pyrite alteration that has been folded by F_1 and refolded by F_2 folds. **c)** Quartz-carbonate vein surrounded by traces of sulphidic alteration cuts across a F_1 fold hinge and is folded by a F_1 fold. **d)** Northeast- to east-northeast-trending tourmaline-rich veins cutting across a F_2 fold hinge. **e)** Gold-mineralized, east-northeast- to east-trending, quartz-carbonate-tourmaline vein cuts across a F_2 fold hinge and is locally folded by S-shaped F_3 folds. **f)** Northwest-trending quartz-pyrite vein (outlined by yellow) cuts across a northeast-trending tourmaline-rich vein (outlined by white) and is gently folded by a Z-shaped F_4 fold.

and ceased by 2694.0 ± 1.0 Ma, the crystallization age of the crosscutting quartz-feldspar porphyry that was sampled at the Porphyry Hill exposure south of Geraldton. The D_1 deformation event is younger than the 2694.0 ± 1.0 Ma quartz-feldspar porphyry, as indicated by its internal folding, but it is older than ca. 2690 ± 1 Ma (Corfu, 2000), the age of the post-D_1 Croll Lake stock that cuts the thrusted Northern Metavolcanic

(NVU), Northern Metasedimentary (NSU), and Central Metavolcanic units (CVU) (Kresz and Zayachivksy 1991) at the eastern boundary of the BGB.

Conglomerate in the NSU and SSU differ in clast composition and detrital zircon ages from Timiskaming conglomerate in the Abitibi greenstone belt, which contains alkali volcanic rocks (Bass, 1961; Legault, 1993) and that was deposited between 2676 and 2670 Ma (Ayer et al., 2005). Nevertheless, both the Timiskaming and the BGB conglomerates formed in similar, alluvial, fluvial and deltaic environments and represent similar regional-scale processes, such as syntectonic continental island arc-fed sedimentation (Mackasey, 1975, 1976; Barrett and Fralick, 1985; Devaney and Williams, 1989; Mueller et al., 1994; Born, 1995; Ayer et al. 2002; Fralick and Pufahl, 2006). The Timiskaming-like sedimentary rocks and the underlying unconformity are considered important features in many lode gold systems because they mark the beginning of major tectonic events that form pathways for gold-mineralizing hydrothermal fluids (Dubé and Gosselin, 2007).

A gold-mineralized sandstone sample (BGBZT 2013_362; 7.42 g/t Au) with abundant arseno-pyrite was collected from drillhole MM276 for Re-Os geochronology, yielding an age of 2579 ± 25 Ma. Lead isochron dating of pyrite samples collected from mineralized felsic porphyry bodies yielded a similar age of 2560 Ma (Anglin, 1987; Anglin and Franklin, 1989). These ages are not likely to represent the true radiogenic age of any of the gold-mineralizing phases because the tectonic evolution of the BGB is thought to have ceased much earlier, and no further processes have been identified that could have been responsible for such a late gold-bearing event. The meaning of the Re-Os age presented by this study will be further examined by detailed petrographic analysis to achieve a better interpretation.

HYDROTHERMAL FOOTPRINT (PRELIMINARY RESULTS)

A total of 216 samples were collected from drillholes and mapped exposures to characterize the footprint of the hydrothermal auriferous system in the Geraldton area. The samples were analyzed for major oxides, 46 trace elements, CO_2, total S, Au, As, Bi, Se, Sb, Te and FeO by Activation Laboratories Ltd. in Ancaster, Ontario.

As expected, there is a strong positive correlation between Au and total S, which is in agreement with the presence of pyrite in the ore zones (Tóth et al., 2013b). In addition, higher Au grades are typically accompanied by anomalous As and Te values (Tóth et al., 2013b). Gold is generally, but not exclusively, associated with high sericite alteration index values ($K_2O/(K_2O+Na_2O)$; Saeki and Date, 1980). Samples with elevated Au values are typically enriched in Sb as well, but elevated Sb values are not restricted to Au-mineralized samples, suggesting that Sb has a larger footprint than Au. Gold and W commonly show a positive correlation. However, non- to weakly mineralized, banded iron formation samples yielded higher W values than samples from the semi-massive sulphide replacement zone flanking iron-carbonate quartz veins in the iron formation.

MODEL FOR THE RELATIVE CHRONOLOGY BETWEEN HYDROTHERMAL ACTIVITY, GOLD MINERALIZATION, AND DEFORMATION EVENTS

The new data and interpretation presented herein suggest a much more complicated deformation and mineralization history than previously proposed. Quartz-feldspar porphyry dykes intruded the sedimentary rocks prior to any deformation (Tóth et al., 2013a, 2014b). The first gold mineralization event involving iron-carbonate alteration and gold-mineralized quartz-carbonate-tourmaline veins were emplaced parallel to bedding at the onset of D_1 deformation and were subsequently folded by F_1 folds (Tóth et al., 2014b) (Stage 1-2 on Fig. 6). Another set of quartz-carbonate veins, which are associated with a pyrite replacement halo, cut across F_1 fold hinges but are themselves folded when located in the F_1 fold hinges, which suggests late-D_1 timing for their formation. If these veins and their alteration halo carried gold, it would then imply that the first gold-bearing event might have extended throughout D_1 (Stage 2 on Fig. 6). During the D_2 north-south compression, F_1 folds and the first gold-bearing structures were refolded by regional F_2 folds, without significant hydrothermal activity (Stage 3 on Fig. 6). East-northeast- to northeast-trending tourmaline-dominated veins cut across F_2 fold hinges and are locally folded by F_3 folds; therefore they were introduced during early D_3 sinistral shear (Stage 4 on Fig. 6) (Tóth et al., 2014b). The second gold-mineralizing event occurred early during D_3 deformation and is characterized by a set of northeast- to east-trending quartz-carbonate-sulphide-tourmaline±gold veins (Stage 4 on Fig. 6) (Tóth et al., 2014b). Some short, northwest-trending quartz-sulphide-bearing tension gashes cut across northeast-trending tourmaline-rich veins and are folded by F_4 folds, suggesting a syn-D_4 timing of emplacement (Stage 5 on Fig. 6) (Tóth et al., 2014b). Based on analogies with the western part of the BGB (DeWolfe et al., 2007), these syn-D_4 veins might be gold-bearing (Tóth et al., 2014b). The geometry of auriferous veins, documented to be parallel to S_4 and overprinting F_2 and F_4 fold hinges (Pye, 1952;

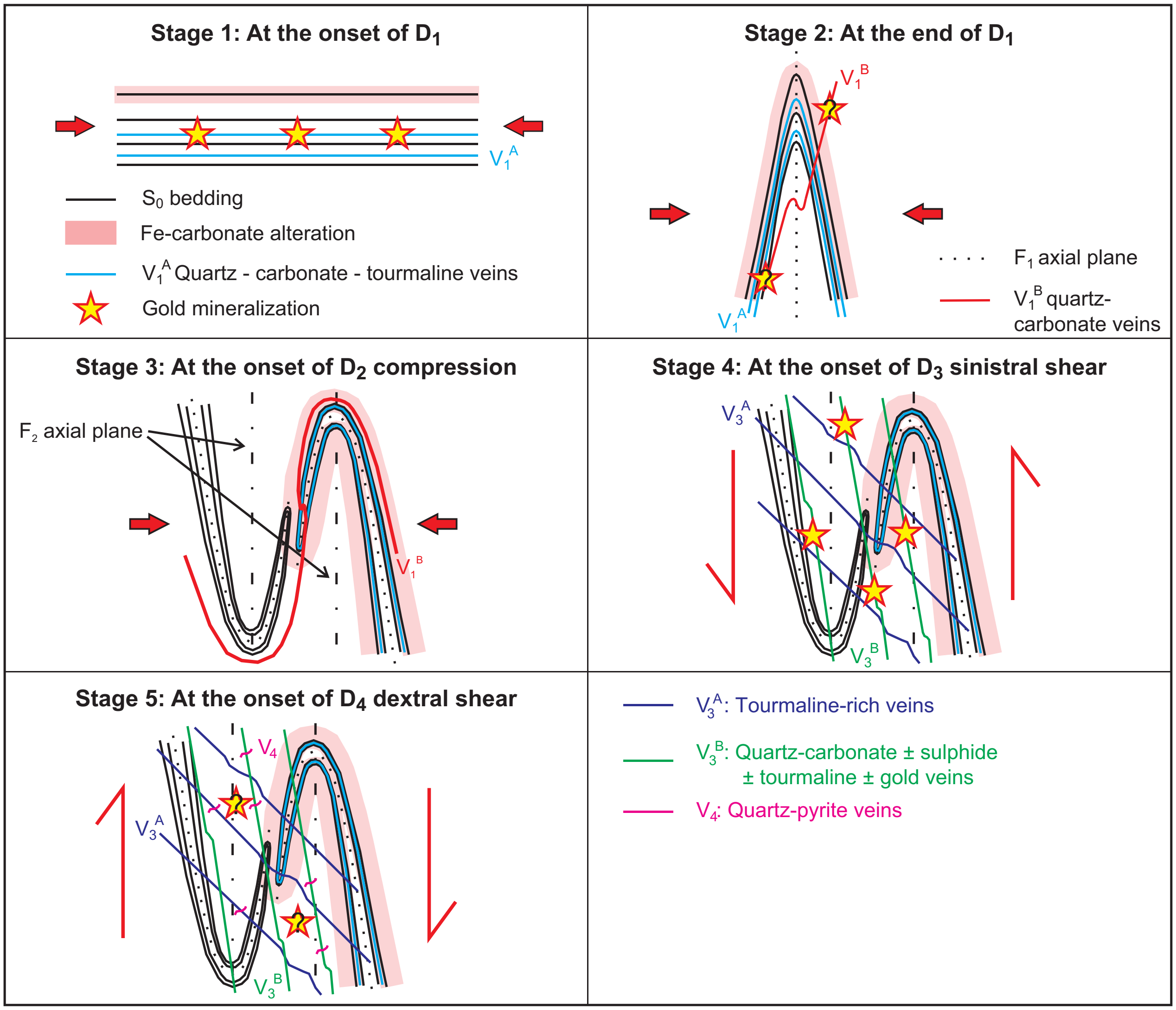

Figure 6. Summary of the hydrothermal activity, gold mineralization and deformation events in the Geraldton area (based on Tóth et al., 2014b). **Stage 1.** Iron-carbonate alteration and gold-mineralized quartz-carbonate-tourmaline veins were emplaced at the beginning of D_1 deformation. **Stage 2.** Oblique quartz-carbonate veins were emplaced late during D_1 deformation, but before the final closure of F_1 folds. Thus, these veins are also folded by F_1 folds in the fold hinges. **Stage 3.** Formation of regional F_2 folds by (re)folding older structural elements. **Stage 4.** Tourmaline-rich and auriferous quartz-carbonate-sulphide-tourmaline vein sets were introduced early during D_3 sinistral shear. **Stage 5.** Northwest-trending quartz-sulphide veins were emplaced syn-D_4. Analogies from the BGB suggest that these veins might also carry gold.

Horwood and Pye, 1955; Beakhouse, 1984; Anglin and Franklin, 1985; Macdonald, 1988; Kresz and Zayachivsky, 1991; Lafrance et al., 2004; DeWolfe et al., 2007), suggests that the majority of the gold mineralization was introduced during D_3 sinistral shear. The syn-D_1 and syn-D_3 timing of gold emplacement differs from that of other greenstone belts (e.g. Timmins-Val d'Or, Red Lake), where the bulk of the quartz-carbonate veining-related gold mineralization is commonly considered as having been emplaced during a main D_2 deformation event (Robert and Poulsen, 2001; Dubé et al., 2002; Robert et al., 2005).

IMPLICATIONS FOR EXPLORATION

This study presents detailed mapping of newly stripped outcrops and drill-core analysis placing new constraints on and interpretations of the chronology and structural setting of gold mineralization in the BGB. Based on this evidence, mineral exploration should focus on east- to northeast-trending vein systems emplaced in sinistral shear zones, rather than in late dextral shear zones. All the gold mineralization is expected to be deformed due to successive progressive deformation and mineralizing events. The early, syn- to late-D_1 auriferous veins will be strongly discontinuous and folded, whereas younger veins emplaced during the second, early to syn-D_3 mineralizing event occur as parallel veins that were locally S-folded during D_3 deformation and Z-folded during D_4 deformation. Both mineralization events produced similar mineralogy and alteration halos and each deformation event is favourable for locally remobilizing gold.

FUTURE WORK

Future work includes the following:

- Additional optical and SEM petrography to fully characterize the mineralogical assemblages associated with the gold mineralization, in all host rock types;
- LA-ICP-MS study on mineralized samples to identify different generations of pyrite and arsenopyrite and the element associations related to gold;
- Final assessment of geochemical data;
- Submission of manuscripts to peer-reviewed journals about the structural geology of the BGB and the chronological, structural setting, and footprint of the gold mineralization in the BGB.

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