Structural evolution and orogenic gold metallogeny of the
western Wabigoon subprovince, Canada

by

Kendra Zammit

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Thesis Examiners/Examinateurs de thèse:

Dr. Stéphane Perrouty
(Supervisor/Directeur(trice) de thèse)

Dr. Ben Frieman
(Committee member/Membre du comité)

Dr. Bruno Lafrance
(Committee member/Membre du comité)

Dr. Mary Louise Hill
(External Examiner/Examinateur externe)

Approved for the Faculty of Graduate Studies
Approuvé pour la Faculté des études supérieures
Dr. Serge Demers
Monsieur Serge Demers

Acting Dean, Faculty of Graduate Studies
Doyen intérimaire, Faculté des études supérieures

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Abstract

Some of the world’s largest orogenic gold deposits are hosted within granite-greenstone subprovinces of the Superior Province of Canada. The apparent gold endowment of the western Wabigoon subprovince is much less than that of the Abitibi subprovince, despite both Neoarchean subprovinces sharing similar structural and metallogenic histories. Further, the relationship between regional deformation and orogenic gold mineralizing events in the western Wabigoon subprovince is poorly constrained in comparison to other greenstone belts within the Superior Province. New structural mapping of the Dryden area of the western Wabigoon subprovince indicates that it experienced a N-S shortening event (D₁), 2705-2695 Ma, which reactivated, or initiated the formation of, the E-W-trending Wabigoon and Mosher Bay-Washeibemaga deformation zones (Wdz and MBWdz, respectively). Following the D₁ event, after 2695 Ma, a protracted period of NNW-SSE shortening (D₂) localized transpression along the Manitou Dinorwic deformation zone (MDdz), which is spatially associated with orogenic gold systems, including the Goldlund deposit (~1.7 Moz Au) and Kenwest prospect (~0.3 Moz Au). During D₂, the MDdz experienced sinistral transpression, while the Wdz and MDdz experienced dextral-sense movement. U-Pb geochronology of vein-hosted xenotime from the Goldlund deposit and Kenwest prospect indicate that hydrothermal events, and likely gold mineralization, occurred syn- to late-D₂ deformation at 2664 ± 8.3 Ma and 2580 ± 12 Ma, respectively. The structural evolution and orogenic metallogeny of the western Wabigoon subprovince is similar to that of anomalously gold-rich subprovinces of the Superior Province. Therefore, it is proposed that the structural evolution of individual greenstone belts is not the primary controlling factor on their bulk gold endowment. Nevertheless, orogenic gold deposits are spatially associated with major deformation zones and linked to widespread hydrothermal event(s), spanning 2680-2580 Ma across the southern Superior Province.

Keywords

Precambrian, Superior Province, greenstone belts, crustal-scale shear zones, orogenic gold, xenotime geochronology
"What of the Manitou in the future? Your guess is as good as mine. But you may rest assured that the old timer of the Manitou, has still unbounded faith. To him Red Lake, Patricia, Larder Lake, Cobalt, Porcupine, Kirkland Lake, Little Long Lac, are only pan flashes. Man’s mismanagement has kept the Manitou from its own. Some day it will be discovered that the riches of the continent are in the Manitou. He will not live to see the glories of the discovery. That is forbidden to him. But some day, some day!"

-Arthur R. Pitt, 1938

(citation in Parker 1989, page 119)
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Thesis Structure and Co-authorship

The thesis is written as a journal manuscript and supported by additional supplementary material. The manuscript, entitled “New structural and geochronological constraints on orogenic gold mineralization in the western Wabigoon subprovince, Canada” is intended for submission to a peer-reviewed journal, and is co-authored by K. Zammit, B.M. Frieman, S. Perrouty, J.H. Marsh and K.A. Holt.

Manuscript structure

The manuscript is divided into 7 subsections:

1. **Introduction** – Introduction to the formation of Archean orogenic gold deposits, and the purpose of this study.

2. **Geologic setting** – The geologic setting of the study area is discussed. This section includes a brief description of the geology of the Superior Province, and provides an introduction to the geology of the study area. This section also describes the results of previous geological mapping and structural studies conducted in the study area.

3. **Methods** – Methods used to conduct this study are discussed; including field mapping and sampling, thin section preparation, petrographic analyses, lithogeochemistry, and laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) analysis of xenotime used for U-Pb geochronology.

4. **Results** – Results of field mapping, structural data, lithogeochemical data, and isotopic data from LA-MC-ICP-MS analysis of xenotime grains are presented.

5. **Discussion** – The results of this study are used to propose a structural evolutionary model for the western Wabigoon subprovince that incorporates constraints on the relative timing of deformation and the absolute timing of orogenic mineralization in the region. This model is then compared with other domains of the southern Superior Province,
providing insight into the role of structural evolution of greenstone belts on their bulk gold endowment.

6. Conclusion – The conclusion summarizes the results and interpretations of this study.

7. Perspective – The manuscript is supplemented by a “Perspective” section, that considers the implications of this study in relation to the formation of Archean orogenic gold deposits worldwide, and suggests future research directions.

Appendices

- **Appendix A** contains a comparative synthesis between structural interpretations of this study and previous studies in the Wabigoon Lake and Manitou Lakes areas.
- **Appendix B** contains new structural measurements collected in the field and previously reported measurements from Ontario Geological Survey investigations used to conduct stereographic analysis. All structural data presented in this thesis is formatted using Right Hand Rule (RHR).
- **Appendix C** contains results of selected, concordant U-Pb isotopic results from the LA-MC-ICP-MS analysis of xenotime grains.

Co-authorship statement

K. Zammit is the author of all sections. The LA-MC-ICP-MS analysis section received major contributions from J.H. Marsh. K. Zammit completed field mapping of the Wabigoon and Manitou Lakes areas, and the Goldlund deposit. She was responsible for sample collection and preparation, structural plots, petrographic characterization of samples, and interpretations. K.A. Holt created Figure 3.10A, which was modified by K. Zammit for this contribution. All sections of the thesis were edited following input from B.M. Frieman and S. Perrouy.
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New structural and geochronological constraints on orogenic gold mineralization in the western Wabigoon subprovince, Canada

1 Introduction

Orogenic gold deposits are commonly associated with late-stage transpressive deformation localized along crustal deformation zones that form as a result of accretion of juvenile terranes (Kerrich and Wyman, 1990; Hagemann and Cassidy, 2000; Goldfarb et al., 2005; Percival, 2007; Groves et al., 2018). The deformation zones act as conduits that accommodate the transport of auriferous fluids, which are generated in the middle to lower crust by metamorphic devolatization reactions, to depositional sites in the middle to upper crust (Cox et al., 2001; Phillips and Powell, 2010; Groves et al., 2018). In the Abitibi subprovince of the southeastern Superior Province, the Larder Lake-Cadillac and Porcupine-Destor deformation zones are spatially associated with some of the Earth’s largest orogenic gold deposits of Neoarchean age (~194 Moz gold; Monecke et al., 2017). In such anomalously gold-rich terranes, spatial and temporal constraints on the deformational history and orogenic gold mineralization events are well-established (Robert, 1989; Couture et al., 1994; Robert et al., 2005; Bateman et al., 2008, Ispolatov et al., 2008; Simard et al., 2013; Lafrance, 2015; Perrouty et al., 2017, Frieman and Kuiper, 2019; De Souza et al., 2020). In contrast, the western Wabigoon subprovince contains less known gold (~37 Koz gold; Ontario Geological Survey, 2020) and lacks broad-scale stratigraphic, structural and metallogenic investigations. Both the western Wabigoon and Abitibi subprovinces are predominantly composed of mafic to intermediate successions of metamorphosed volcanic and sedimentary rocks, that were intruded by tonalitic to granitic plutons (Percival, 2007; Percival et al., 2012). Furthermore, both subprovinces contain crustal-scale deformation zones that are comparable in strike-length, that are
interpreted to have acted as conduits for gold-bearing hydrothermal fluids (Blackburn, 1979; Devaney and Williams, 1989; Blackburn et al., 1991; Robert et al., 2005; Bleeker, 2012).

This study provides the first absolute age constraints for orogenic gold mineralization in the western Wabigoon subprovince, and places results in a regional structural framework. Observations collected during two seasons of field mapping, previously published structural data, and U-Pb isotopic analysis of vein-hosted xenotime associated with orogenic gold mineralization are integrated in a subprovince-scale structural and metallogenic evolution model for the western Wabigoon subprovince. These results are used to compare temporal and spatial patterns of orogenic gold mineralization in similar, but variably gold-endowed domains throughout the southern Superior Province. This study demonstrates that, although differentially endowed in orogenic gold, the western Wabigoon and Abitibi subprovinces experienced comparable structural and metallogenic histories. Therefore, this study suggests that the bulk gold endowment of greenstone belts is, in part, controlled by factors that are independent of their overall structural evolution.
2 Geologic setting of the western Wabigoon subprovince

The Superior Province represents the Earth's largest Archean craton (Goldfarb, 2001). It is variably composed of Paleo- to Neoarchean (3500-2600 Ma) crustal fragments that amalgamated during a progressive Neoarchean accretionary event (Hoffman, 1988; Percival, 2007; Percival et al., 2012; Bédard, 2018). In the southern Superior Province, crustal fragments are commonly bounded to the north and south by ~E-trending deformation zones that accommodated significant strain during terrane accretion (Card and Ciesielski, 1986; Card, 1990; Kerrich and Wyman, 1990; Percival, 2007; Stott et al., 2010; Percival et al., 2012). The Wabigoon subprovince is bounded to the north by the >3100 Ma Winnipeg River subprovince (Tomlinson, 2004; Bjorkman, 2017), and to the south by the 3000-2800 Ma Marmion terrane (Backeberg et al., 2014; Bjorkman, 2017) and 2710-2700 Ma Quetico subprovince (Davis et al., 1990). The Wabigoon subprovince is subdivided based on age and spatial relationships into two distinct domains (Figure 1): the eastern Wabigoon subprovince contains Meso- to Neoarchean rocks (3000-2660 Ma) while the western Wabigoon subprovince only contains Neoarchean rocks (2775-2680 Ma, Stott et al., 2002; Tomlinson et al., 2004; Percival et al., 2004). This study focuses on an 80 km x 60 km area of the western Wabigoon subprovince, near Dryden, Ontario.

2.1 The Dryden area of the western Wabigoon subprovince

The Dryden area of the western Wabigoon subprovince (Figure 2) is mostly composed of 2745-2710 Ma mafic to felsic volcanic rocks that are interpreted to represent Neoarchean oceanic crust or plateau, stagnant lid, or arc-related environments (Davis, 1988; Davis et al., 1989; Corfu and Davis, 1992; Ayer and Davis, 1997; Wyman et al., 2000; Percival et al., 2004; Bédard, 2018). Up
Figure 1 – Location of study area within the southern Superior Province. A) Subdivisions of the southern Superior Province, modified from Stott et al. (2010). The study region is indicated by the red box. B) Subdivisions of the study region modified from Tomlinson et al. (2004). The Dryden area is indicated by the red box. The blue boxes denote the (1) Lake of the Woods study area of Davis and Smith, 1991, and (2) the Sturgeon-Savant Belt study area of Sanborne-Barrie and Skulski, 2006.
Figure 2 – Geology of the Dryden area of the western Wabigoon subprovince. The map displays the distribution of major rock types, regional deformation zones, and gold prospects/occurrences with the location of detailed mapping areas indicated. Geology modified from Blackburn (1978a). Gold occurrences were derived from the Ontario Geological Survey Mineral Deposit Inventory (2020). **Abbreviations:** Wdz = Wabigoon deformation zone, MBWdz = Mosher Bay-Washeibemaga deformation zone, MDdz = Manitou-Dinorwic deformation zone.
to 10 km wide, 50 km long, belts of 2710-2695 Ma turbiditic, volcaniclastic, alluvial, and chemical sedimentary rocks unconformably overlie the volcanic successions, and are interpreted to represent shallow- to deep-marine syn-volcanic to alluvial-fluvial syn-orogenic sedimentary basins (Beakhouse et al., 1995; Percival et al., 2004). The supracrustal successions are intruded by syn-volcanic, 2740-2710 Ma gabbros, tonalites, granodiorites (Tomlinson et al., 2004, Percival et al., 2004), syn-deformational, 2700-2640 Ma monzodiorites and granites (Davis et al., 1982a; 1982b; Blackburn et al., 1991; Larbi et al., 1999; Dostal et al., 2004; Percival et al., 2012), and are metamorphosed to greenschist or amphibolite facies. Despite metamorphism, in many locations primary sedimentary and igneous textures are well-preserved. Thus, for clarity, the prefix “meta” will not be used in subsequent rock descriptions. The region is also cross-cut by diabase dikes of the ~1890 Ma NW-trending Wabigoon swarm (Buchan and Ernst, 2004) and a ~1140 Ma N-trending swarm (Heaman et al., 2007; Stone, 2010).

The Dryden area is host to several, crustal-scale deformation zones (Parker, 1989; Pumuula et al., 2015), including the E-trending Wabigoon and Mosher Bay-Washeibemaga deformation zones (Wdz and MBWdz, respectively), and the NE-trending Manitou-Dinorwic deformation zone (MDdz; Figure 2). This work focuses on two representative areas that are coincident with these major deformation zones: (1) the Wabigoon Lake area (Figure 3), which contains the intersection of the Wdz and MDdz and hosts the Goldlund deposit, and (2) the Manitou Lakes area (Figure 4), which contains the intersection of the MBWdz and MDdz, and hosts the Kenwest prospect.
Figure 3 – Structural map of the Wabigoon Lake area. The map displays major lithological subdivisions, structural measurements (from this study), and inferred structural trends. Geology modified from Blackburn (1978a, 1981), Butler et al. (1989), Berger et al. (1989), MacMillan et al. (1989), Berger (1990), Beakhouse and Pidgeon (2003), and Beakhouse and Idziszek (2006).
Figure 4 – Structural map of the Manitou Lakes area. The map displays major lithological subdivisions, structural measurements (from this study), and inferred structural trends. Geology modified from Blackburn (1976, 1978b, 1980a, 1980b, 1981)
2.1.1 The Wabigoon Lake area

The Wabigoon Lake area represents a ~1350 km² area, located at the intersection of the Wdz and MDdz (Figure 2). The map area is bounded to the southwest by the syn-volcanic 2740-2720 Ma Atikwa-Lawrence batholith (Davis et al., 1982; Edwards and Davis, 1991), to the north by the syn-deformational ~2685 Ma Ghost Lake batholith (Breaks and Moore, 1992), and to the east by the Basket Lake batholith and ~2735 Ma Revell batholith (Larbi et al., 1999).

The Wdz separates the Wabigoon Lake area into two distinct domains defined by differing metamorphic grades and structural styles. Lithologies north of the Wdz include the 2735-2730 Ma Brownridge and Thunder River mafic to intermediate volcanic rocks (Davis et al., 1988; Beakhouse, 2000), and the 2715-2710 Ma Brownridge, Thunder Lake, and Zealand clastic and chemical sedimentary rocks (Figure 2, Davis and Trowell, 1982). The sedimentary successions consist of greywacke and sandstone, with minor oxide-facies banded iron formation. These supracrustal units form alternating panels of complexly-folded volcanic and sedimentary rocks that display upper-greenschist to amphibolite facies metamorphic grades (Beakhouse et al., 1995).

Lithologies south of the Wdz include mafic to intermediate volcanic rocks of the 2745-2730 Ma Wabigoon and Kawashegamuk groups (Figure 2, Davis et al., 1982), and are metamorphosed to greenschist facies (Parker, 1989).

The Wdz is defined as an ~E-trending deformation zone that extends for >150 km along strike and records a protracted deformation history (Parker, 1989). Locally, intense carbonate alteration and quartz veining occurs in a >100 m wide zones along its strike-length (Satterly, 1943; Beakhouse and Idziszek, 2006). To the east, the Wdz is truncated by NE-trending shear zones at Dinorwic Lake (Figure 3). The dominant structural fabric in the Wabigoon Lake area is documented as either
a moderately S-dipping foliation that is axial planar to E-trending isoclinal folds, and subparallel to bedding in fold limbs (Trowell et al., 1978), or a steeply SE-dipping, spaced cleavage that is axial planar to NE-trending asymmetric z-folds (Berger, 1990). According to Chorlton (1987, 1990) and Beakhouse (2000), the latter fabric locally crenulates the former. In contrast, Berger (1990) interpreted that E- and NE-trending shear zones formed coeval with one another. A minor structural fabric is also described as a steeply-dipping variably-oriented foliation that is locally subparallel to syn-deformational pluton margins, and is associated with a steeply-plunging lineation (Chorlton, 1990).

Previous studies support the interpretation that the Wabigoon Lake area experienced progressive shortening from N-S to NW-SE during terrane accretion. An early regional N-S shortening event resulted in thrusting of the volcanic successions and inversion of the sedimentary basins (Chorlton, 1987; Berger, 1990; Chorlton, 1990). Subsequent minor and localized phases of deformation have been attributed to the emplacement of intrusive bodies (e.g., D2 of Chorlton, 1987; D2 of Berger, 1990; D2 and D3 of Chorlton, 1990). They were followed by a late regional NW-SE shortening event (e.g., Chorlton, 1987; Berger, 1990; D4 of Chorlton, 1990; Beakhouse, 2000), which resulted in dextral transpression along the Wdz and similarly oriented structures, and sinistral transpression along NE-trending shear zones (Chorlton, 1987, 1990). A comparative table of previous structural studies in the Wabigoon Lake area is provided in Appendix A. Herein, these township-scale investigations are integrated into a broader structural model to describe the evolution of major deformation zones in the Wabigoon Lake area, and their relationships with orogenic gold mineralization.


2.1.2 The Manitou Lakes area

The Manitou Lakes area represents a ~400 km$^2$ area, located at the intersection of the MBWdz and MDdz (Figure 2). The map area is bounded to the northwest by the 2740-2720 Ma Atikwa-Lawrence batholith (Davis et al., 1982b; Edwards and Davis, 1991), and to the southeast by the syn- to late-orogenic 2705-2695 Ma Taylor Lake and Scattergood stocks (Davis et al., 1982; Kamo, 2014).

The MDdz truncates the stratigraphy of the region into two distinct areas. Lithologies to the northwest of the MDdz are composed of mafic to felsic volcanic and volcanioclastic rocks of the 2755-2730 Ma Blanchard Lake, Upper Manitou Lake, and Pincher Lake groups (Figure 4, Thomson, 1934; Goodwin, 1965; Blackburn, 1978b, 1982). Lithologies to the southeast of the MDdz are composed of mafic to felsic volcanic rocks of the 2755-2700 Ma Wapageisi and Boyer Lake groups (Davis et al., 1982). Volcanic successions in both domains locally contain thin mudstone or chemical sedimentary units (Davis et al., 1982; Blackburn et al., 1982). They are unconformably overlain by, or structurally juxtaposed with, younger 2705-2695 Ma clastic and volcanioclastic sedimentary rocks of the E-SE-trending Manitou group (Figure 4, Teal and Walker, 1977; Dostal et al., 2004).

The MBWdz and the MDdz represent regional, possibly crustal-scale, brittle-ductile deformation zones that are E- and NE- trending, respectively. The MBWdz is identified based on the structural juxtaposition of the Boyer Lake and Manitou groups. Adjacent to the MBWdz, penetrative fabric is E- to ENE-trending, steeply dipping (Blackburn, 1981; Kresz, 1987), and is axial planar to tight km-scale folds (Blackburn, 1981). The MBWdz is interpreted to have accommodated north-over-south reverse displacement (Blackburn, 1982). The MDdz is
primarily identified by NE-trending steeply dipping zones of penetrative chlorite-mica foliation (Blackburn, 1982; Melling et al., 1988), and occurs as a ~30 m wide high-strain corridor and locally, with pervasive carbonate alteration and abundant quartz veins (Parker, 1989). NE-trending kink folds have also been documented in the Manitou Lakes area, which are more common adjacent to the MDdz (Wallace and Clifford, 1983).

Early deformation in the Manitou Lakes area has been interpreted as the result of N-S shortening (Blackburn 1980c, 1982). A comparative table of previous structural interpretations for the Manitou Lake area is provided in Appendix A. This study combines results of prior studies with new observations to propose a regional-scale structural model for the Manitou Lakes area, to refine the kinematic and evolutionary histories of the MBWdz and MDdz, and to determine their relationships with orogenic gold mineralization.

2.2 Gold metallogeny of the Dryden area

Orogenic gold occurrences in the Dryden area (Figure 2) largely occur within ~5-10 km of the major E- and NE-trending deformation zones (i.e., the Wdz, MBWdz, and MDdz). Developed prospects include the Goldlund deposit (past production of ~18 Koz Au from 1982 to 1985, measured and indicated resource of ~809 Koz Au, inferred resource of ~877 Koz Au; McCracken, 2019), the Kenwest prospect (past production of ~15 Koz Au from 1902 to 1943, inferred resource of ~307 Koz Au; Maunula, 2010), and the Van Horne prospect (past production of ~0.6 Koz Au from 1900 to 1943; Chiang et al., 2012). Another notable gold deposit in the region, the Goliath gold deposit (measured and indicated resource of ~1230 Koz Au, inferred resource of ~227 Koz Au; Puritch et al., 2019), is located north of the Wdz near Thunder Lake (Figure 2). The genetic nature of the Goliath deposit is uncertain and is not investigated in detail herein, but has been
proposed to represent a gold-rich volcanogenic system overprinted by orogenic gold mineralization (Puritch et al., 2019; McRae et al., 2019).

### 2.2.1 Goldlund deposit

The Goldlund deposit is located approximately 37 km northeast of Dryden, Ontario (Figure 2), and is spatially associated with an inferred second-order, MDdz-parallel, deformation zone (Figure 3). The deposit is hosted by granodioritic and gabbroic intrusive bodies that may have acted as a rheological trap and are cross-cut by feldspar and quartz-feldspar porphyry dikes (McCracken, 2019). The gold-bearing quartz veins generally trend NNE-NE and have moderate to steep dips. Based on their orientation and proximity to regional structure, they have been interpreted as fracture-filling veins that formed late during a regional NW-SE transpressive event (Chorlton, 1990).

Ore mineralogy includes carbonate and sulfide minerals, rutile, scheelite, monazite, xenotime and gold-silver-lead-tellurides that occur within native gold-bearing quartz veins, and in disseminated zones proximal to vein margins (Giddings and Perkins, 1987). These lithological, structural, and mineralogical characteristics are consistent with the Goldlund deposit representing an orogenic gold deposit (McCracken, 2019).

### 2.2.2 Kenwest prospect

The Kenwest prospect is situated ~40 km south of Dryden, Ontario, near the MDdz (Figure 4). The prospect is part of the Gold Rock Mining Camp and is within the area encompassed by the Big Master deposit, which was mined from 1900 to 1906 and from 1942 to 1943 (Parker, 1989). The prospect is hosted by mafic volcanic flows of the Pincher Lake group that were intruded by syn-deformational felsic dikes (Thomson, 1942; Blackburn, 1981; Parker, 1989).
Holt (2019) documented multi-stage deformation at the Kenwest prospect and along the MDdz in the immediate vicinity of the Big Master deposit. Early deformation was interpreted as a WNW-ESE shortening event, which produced a penetrative fabric defined by aligned grains of chlorite and biotite and axial planar to NE-plunging isoclinal folds such as the Manitou Anticline (Figure 4). Early fabrics were reactivated during subsequent northwest-over-southeast sinistral-sense thrust displacements, represented by ductile strain localization within NE-trending shear fabrics, that are associated with sinistral-sense shear indicators such as C-S fabrics and quartz-carbonate-chlorite pressure shadows of rotated pyrite grains. Fabrics associated with this phase of deformation include a NE-trending, steeply-dipping, mineral foliation defined by aligned grains of chlorite. The foliation is commonly associated with a well-developed, NE-plunging mineral lineation that is also defined by aligned aggregates of chlorite grains. Based on the prevalent NE-trending structural grain, associated NE-plunging mineral lineation, and sinistral-sense kinematic indicators on horizontal erosional surfaces, deformation at the Kenwest prospect is interpreted to reflect sinistral transpression.

Gold is primarily hosted in NE-trending fracture-filling quartz veins that are interpreted to relate to brittle-ductile deformation that occurred during sinistral transpression along the MDdz (Blackburn, 1981; Parker, 1989; Holt, 2019). Ore mineralogy includes carbonate and sulfide minerals, chlorite, sericite, and tourmaline within native gold-bearing quartz veins and in disseminated zones proximal to vein margins (Maunula, 2010). The presence of quartz-carbonate veins within highly-strained volcanic rocks, and an elevated gold:silver ratio suggest that the Kenwest prospect represents an orogenic gold system (Maunula, 2010).
3 Methods

In order to produce a comprehensive structural and metallogenic model for the Dryden area, regional- to outcrop-scale bedrock mapping, (micro)structural analysis, whole-rock lithogeochemical analysis, and isotopic dating of hydrothermal xenotime by U-Pb laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) were conducted.

3.1 Structural mapping

Bedrock mapping was conducted at regional- and outcrop-scales in the Wabigoon Lake (Figure 3) and Manitou Lakes (Figure 4) areas. Regional mapping aimed to document the nature of the intersection between the Wdz, MBWdz, and MDdz, in order to: (1) establish the relative timing of deformation in the various domains of the Dryden area; (2) determine if the NE-trending structures observed in the Wabigoon Lake area are correlative with the MDdz at the Manitou Lakes area, and; (3) constrain the temporal relationship between deformation and orogenic gold mineralization along the MDdz. The bedrock geology for these areas has been well-documented by the Ontario Geological Survey (Blackburn, 1976, 1978a, 1978b, 1980a, 1980b, 1981, 1982; Berger et al., 1989; Berger, 1990; Beakhouse, 2000; Beakhouse and Pigeon, 2003; Beakhouse and Idzisek, 2006, Beakhouse et al., 2011). Thus, this study focused on collecting new structural data in order to contextualize previous observations and constrain them within a broader structural framework.

Outcrop-scale mapping at the Goldlund deposit and Kenwest prospect aimed to: (1) document the lithological and structural setting of major orogenic gold occurrences in relation to the MDdz, (2) contextualize samples of gold-bearing quartz veins used in whole-rock lithogeochemistry and geochronological analysis of vein-hosted xenotime, and; (3) constrain the relative timing of
hydrothermal activity and associated deformation that produced the orogenic gold systems in the Dryden area.

Newly collected structural data (e.g., bedding, foliations, lineations) were combined with previously published structural data (Appendix B) and were plotted using ESRI ArcMap 10.7.1 (https://www.esri.com/). In order to assess the statistical distribution and significance of the structural orientations, they were plotted as equal-area, lower hemisphere projections using REFLEX ioGAS (https://reflexnow.com/). Results were used to determine average fold geometries, correlate structural trends between maps areas, and interpret kinematic histories of the major deformation zones.

3.2 Sampling, petrographic and microstructural analyses

Hand samples for petrographic (99 samples) and geochronological analyses (2 samples) were collected from using a hammer, chisel and/or rock saw. Samples for structural analyses were oriented relative to magnetic north and “way up” was marked. In order to constrain microstructural characteristics, thin section billets were mostly cut perpendicular to the foliation plane and parallel to the lineation (i.e., XZ orientation). Thin sections were cut at Laurentian University using a tile saw. They were sent to Precision Petrographics (https://precisionpetrographics.com/) for thin section preparation. Microstructures (i.e., shear-sense indicators and subtle cross-cutting fabric relationships), and petrographic characteristics (i.e., composition of metamorphic and ore-forming minerals), were observed using a transmitted/reflected light microscope and scanning electron microscope (SEM).
3.3 Whole-rock geochemical analysis

Whole-rock geochemistry of the two mineralized vein samples from the Goldlund deposit and Kenwest prospect were analyzed by ALS Laboratories (https://www.alsglobal.com/en-ca). Carbon and sulfur were analyzed via induction furnace (LECO) using packages C-IR07 and S-IR08. Tungsten was analyzed via lithium borate fusion, acid digestion, and ICP-MS using package ME-MS81. Copper and zinc were analyzed via four-acid digestion and ICP-MS using the ME-4ACD81 package. Gold, silver, arsenic, molybdenum, lead and tellurium were analyzed via aqua regia digestion and ICP-MS using the ME-MS41L package.

3.4 LA-MC-ICP-MS analysis of xenotime

Two mineralized vein samples from the Goldlund deposit and Kenwest prospect were chosen for U-Pb isotopic analysis of vein-hosted xenotime. Datable minerals and their petrogenetic context were identified in thin section using a SEM, and related samples were sent for heavy mineral separation preformed by Overburden Drilling Management (https://www.odm.ca/). Samples were crushed using electronic pulse disaggregation, and the heavy fraction (>3g/cm³) of the crushed samples was separated using a Wilfley table, with the heavy fractions split into magnetic and non-magnetic fractions using a Franz magnetic separator. The magnetic fraction was not processed further, while the non-magnetic fraction was passed through a 150 μm sieve to remove coarse-grained pyrite and lithic fragments. A portion of the residual material was mounted into 1” epoxy pucks and imaged using SEM.

Polished mounts and thin sections were imaged using a Tescan Vega 3 LMH SEM in high vacuum, using a 10-15 kV accelerating voltage and a beam current of 300 pA to 10nA. Mineral identification was assisted by energy dispersive spectroscopy (EDS) using a Bruker Flash 6 EDS
detector that was operated at 15 kV. Xenotime grains selected for U-Pb isotopic analysis were primarily chosen based on their size (>20 µm).

U-Pb isotopic analyses of selected xenotime grains was conducted at the Mineral Exploration Research Centre - Isotope Geochemistry Lab (MERC-IGL), at Laurentian University using a Thermo Scientific Neptune Plus multicollector (MC) ICP-MS equipped with a Photon Machines Analyte G2 ArF excimer laser. Laser ablation sampling was performed using a 193 nm wavelength, <5 ns pulse width, and HelEx II cell. Ablation spot diameter (~10-15 µm), laser fluence, and durations of 10-15 µm, 2-3 J/cm², and 20 s were used at a 7 Hz repetition rate. Backgrounds were measured 60 s at the beginning and end of the analytical session, with 30 s of background measured between each ablation. The raw U-Pb data were processed in Iolite v3.6 (https://www.iolite-software.com), with baseline subtraction, instrumental drift, and downhole fractionation corrections performed with the VizualAge data reduction scheme (Petrus and Kamber, 2012). These data were filtered for discordance and anomalously high 2σ errors, all results that were <5% discordant were rejected from further analysis. Filtering was completed using Isoplot 4.1 (Ludwig, 2012).

The reference material used to normalize U-Pb isotope ratios, model downhole fractionation, and evaluate data accuracy was the ~1001 Ma xenotime standard z6413 (Stern and Rayner, 2003). This xenotime standard was analyzed three times: at the beginning and end of each session, and once every five to ten unknowns. Typically, 2-3 s at the beginning and 1 s at end of the ablation period were excluded from the post-processed data in order to minimize fractionation effects, meaning typical signal integrations for individual spot analyses were ~17 to 27 s. Within run variance in the measured ratios for primary reference material (i.e., the additional percent error required to achieve
a mean square weighted deviation, MSWD, of 1) was propagated into the $2\sigma$ uncertainty for all unknowns.
4 Results

Regional mapping of the Wabigoon and Manitou Lakes areas (Figures 3 and 4, respectively) aimed to define the extent, nature, and relative timing of deformation related to the Wdz, MBWdz, and MDdz. Observations at the regional scale (Tables 1 and 3) were complemented by outcrop mapping. Petrographic and geochemical characterization of samples used for U-Pb isotopic analysis on xenotime were also conducted (Table 2).

4.1 Regional structural observations in the Wabigoon Lake area

Despite metamorphism and deformation, bedding and/or primary compositional layering (SW₀) in volcanic and sedimentary units to the north of the Wdz are commonly preserved. In these locations, bedding is primarily ~E-striking and is steeply-dipping to vertical. In volcanic protoliths (i.e., the Brownridge and Thunder River groups), SW₀ is defined by pillow selvages and compositional variation in volcanic/volcaniclastic layers. In clastic sedimentary protoliths (i.e., the Brownridge, Thunder Lake, Thunder River, and Zealand groups), SW₀ is defined by compositional and grain size variations.

The younging direction of sedimentary and volcanic units in domains north of the Wdz is variable, defining two primary generations of regional- to outcrop-scale folds (Figure 3). In the west-northwest portion of the map area, structural fabrics are dominated by an ~E-trending, steeply-dipping to vertical foliation (SW_M; Figure 5C), that is axial planar to FW_M isoclinal folds (Figure 3), and subparallel to bedding in FW_M fold limbs. These fabrics are most commonly defined by aligned grains of biotite and/or chlorite, and are best preserved along the northern shore of Wabigoon Lake (Figure 5C; Figure 6A). Throughout the Wabigoon Lake area, the SW_M fabric is spatially associated with dextral-sense shear indicators such as boudinaged quartz veins and rotated quartz pods (Figure 5C). In the western portion of the Wabigoon Lake area, the SW_M
Figure 5 – Representative field photographs and photomicrographs of structures observed in the Wabigoon Lake area. A) Bedding (SW_0) observed at the deformed contact between greywacke and basalt north of the Wabigoon deformation zone (Wdz). Hammer head points north, hammer is ~30 cm long. B) Isoclinally folded greywacke observed north of the Wdz defined by compositional variation of bedding (SW_0). Note the associated E-trending axial planar fabric. C) The dominant foliation (SW_M) is parallel to bedding (SW_0) and contains quartz σ-clasts that display asymmetry consistent with dextral shear. D) An intensely strained and altered mafic volcanic unit with elongate carbonate-filled amygdules that define a well-developed lineation (LW_M), in the Van Horne area to the south of the Wdz. E) Crenulation of the SW_M foliation by the SW_M+1 cleavage, observed in sedimentary units north of the Wdz. F) An carbonate-chlorite altered, highly-strained volcanic rock affected by the SW_M foliation at Dinorwic Lake. G) An asymmetric quartz pod within the SW_M foliation indicative of dextral shear, that is affected by the SW_M+1 foliation in a greywacke unit adjacent to the Wdz. H) The SW_M foliation, defined by aligned grains of biotite and quartz that is crenulated by the SW_M+1 cleavage with recrystallized laths of chlorite, observed to the north of Wdz.
Figure 6 – Structural data from the Wabigoon Lake area. Data from this study (red dots) and previously published data (blue dots) displayed as equal–area, lower hemisphere projections. A) Poles to SW$_{M}$ foliation with the mean orientation indicated. B) LW$_{M}$ lineation associated with the SW$_{M}$ foliation with the mean orientations indicated. C) Poles to the SW$_{M+1}$ foliation planes with the mean orientations indicated. D) Plunge and trend of LW$_{M+1}$ lineation measurements with the mean orientations indicated. Previously published data were derived from Beakhouse et al. (2011) and references therein (see Appendix B).
foliation is penetrative, and is associated with a steeply W-SW-plunging mineral or stretching lineation (LW_M) that is defined by aligned aggregates of biotite, chlorite and/or elongated carbonate-filled amygdules (Figure 5D; Figure 6B). In these areas, and in particular near the Van Horne prospect, sedimentary and volcanic rocks host pervasive carbonate alteration (i.e., calcite and ankerite).

E-trending structures are overprinted by a NE-trending fabric (SW_{M+1}) that is axial planar to regional- to outcrop-scale, asymmetric z-folds (Figures 3 and 5). Locally, in the sedimentary units, SW_{M+1} is associated with a well-developed crenulation cleavage of SW_{0/M} (Figure 5E, G). The SW_{M+1} fabric becomes more intense, and the dip angle increases, with proximity to Dinorwic Lake (Figure 3), where it affects volcanic and sedimentary units, and forms a NE-trending, steeply-dipping to vertical foliation, commonly defined by chlorite (Figure 5F; Figure 6C). The SW_{M+1} fabric is associated with a well-developed, steeply-plunging mineral lineation (LW_{M+1}), defined by aligned aggregates of chlorite (Figure 6D). The SW_{M+1} fabric can be continually traced within and to the northeast of Dinorwic Lake (Figure 3), and forms up to 5 km wide zones of intensely-developed SW_{M+1} foliation that obscures all earlier structures. The fabric is commonly accompanied by carbonate-chlorite alteration (Figure 5F).

### 4.2 The Wdz at Elm Bay

Regional-scale structural observations were supported by mapping an approximately 300 m² outcrop of Thunder River sedimentary rocks near the northern shore of Wabigoon Lake at Elm Bay (Figures 3 and 7A, B). Beds of greywacke and sandstone are folded into E-trending, steeply-plunging, tight isoclinal folds (FW_M). The FW_M folds that are interpreted to occur throughout the outcrop, however, their fold hinges are only locally visible near the central portion of the outcrop
Figure 7 – Outcrop map of deformed rocks observed at Elm Bay. A) Map of the outcrop area that displays the axial trace of FW_M isoclinal folds and the orientations of SW_M and SW_{M+1} foliations. The area of detail shown in B is indicated by the red box. B) A detailed sketch of structural features observed in outcrop that constrain the relationships between the SW_M and SW_{M+1} foliations, and FW_{M+1} asymmetric z-folds.
(Figure 7B). The dominant foliation (SW\textsubscript{M}) at the outcrop is axial planar to the isoclinal folds, subvertical, and is mostly defined by aligned grains of biotite, but occasionally chlorite. The foliation is also spatially associated with abundant boudinaged quartz veins and mafic dikes, and dextrally-rotated quartz σ-clasts (Figure 7B). The SW\textsubscript{M} foliation is crenulated by a NE-trending, moderately-dipping SW\textsubscript{M+1} fabric, that is axial planar to FW\textsubscript{M+1} folds. The SW\textsubscript{M+1} fabric is observed throughout the outcrop, but is more pronounced where FW\textsubscript{M+1} folds are present.

**Table 1** – Summary of structural features observed in the Wabigoon Lake map area.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Orientation</th>
<th>Associated structure</th>
<th>Associated deformation zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW\textsubscript{0} (bedding)</td>
<td>E-striking, steeply-dipping to vertical (~270/75-90)</td>
<td>Bedding in sedimentary or volcanic rocks</td>
<td>N/A</td>
</tr>
<tr>
<td>FW\textsubscript{M} (folds)</td>
<td>E-trending axial planes, locally steeply-plunging hinges</td>
<td>Isoclinal folds of SW\textsubscript{0}</td>
<td>N/A</td>
</tr>
<tr>
<td>SW\textsubscript{M} (foliation)</td>
<td>E-striking, steeply-dipping, axial planar to FW\textsubscript{M} (~270/80; ~090/80)</td>
<td>Aligned grains of biotite and/or chlorite, boudinaged quartz veins, dextral-sense shear indicators</td>
<td>Wdz</td>
</tr>
<tr>
<td>LW\textsubscript{M} (mineral lineation)</td>
<td>W-SW-trending, moderately-to steeply-plunging (~75→200)</td>
<td>Aligned aggregates of biotite and/or chlorite, stretched amygdules (where present)</td>
<td>Wdz</td>
</tr>
<tr>
<td>FW\textsubscript{M+1} (folds)</td>
<td>NE-trending axial planes, moderately-plunging fold hinges</td>
<td>z-folds of SW\textsubscript{0/M}</td>
<td>N/A</td>
</tr>
<tr>
<td>SW\textsubscript{M+1} (foliation)</td>
<td>NE-striking, moderately-dipping crenulation cleavage, axial planar fabric, local, small-scale NE-trending brittle faults distal to Dinorwic Lake, increasing schistosity and dip angle approaching Dinorwic Lake (~045/85; ~210/85)</td>
<td>Sinistral offset of SW\textsubscript{0/M} along small-scale fault planes, sinistral-sense shear indicators approaching and within Dinorwic Lake</td>
<td>MDdz</td>
</tr>
<tr>
<td>LW\textsubscript{M+1} (mineral and stretching lineation)</td>
<td>S-SE-trending, steeply-plunging mineral or stretching lineation (~77→189)</td>
<td>Aligned aggregates of chlorite in areas of intensely developed SW\textsubscript{M+1} fabric, most apparent at Dinorwic Lake</td>
<td>MDdz</td>
</tr>
</tbody>
</table>
In thin section and in outcrop, this crenulation cleavage is associated with kink bands, and is also locally defined by recrystallized laths of biotite and chlorite (Figure 5H).

4.3 The MDdz at the Goldlund deposit

The Zone 1 Pit Trench of the Goldlund Gold Project was mapped in order to constrain the structural setting for the emplacement of gold-bearing quartz veins and to contextualize the setting of samples used in geochronological analyses (Figure 8A). The Zone 1 Pit Trench is comprised of gabbro, locally silicified at contact margins, that was intruded by tonalite (and/or granodiorite) and quartz-feldspar porphyry dikes (Figure 9A). All three units are crosscut by three generations of quartz-carbonate veins, although they predominately occur in the tonalite.

On horizontal erosional surfaces, a weak NE-trending foliation defined by biotite and chlorite was observed, which corresponds to the regional SWM+1 foliation (Figure 9B). Locally, it is associated with a steeply S- to SE-plunging mineral lineation defined by aggregates of biotite (Figure 8A). The foliation is cross-cut by, and approximately parallel to, S- to SW-striking, steeply dipping, quartz-carbonate vein sets (Figure 9C).

Gold mineralization is associated with two vein sets that are well-exposed in Zone 1 Pit Trench (Figure 8). These are subdivided into two mutually cross-cutting vein sets based on their orientation: a vein set (VG\textsubscript{A}) that displays an average orientation of ~233/65, and a vein set (VG\textsubscript{B}) that displays an average orientation of ~188/46 (Figure 8B; Figure 9C). These vein sets (VG\textsubscript{A} and VG\textsubscript{B}) form up to 10 cm wide conjugate fracture-filling and extensional networks, and are texturally differentiated based on the presence of blocky (VG\textsubscript{A}) and comb (VG\textsubscript{B}) quartz (Figure 8, Figure 9C). Locally, these vein sets are cross-cut by thin (<2 cm),
Figure 8 – Outcrop map of the Zone 1 Pit Trench at the Goldlund deposit. A) Map displays the major lithological units, structural orientations, and the location of sample GC-GL that is discussed in the text. B) Equal-angle, lower hemisphere projection displaying the poles to planes for measured vein orientations with the two dominant vein sets (VG_A and VG_B) and their mean orientations indicated.
Figure 9 – Representative field photographs of textures observed in the Zone 1 Pit Trench at the Goldlund deposit. A) Contact between altered tonalite and gabbro. Hammer handle points north, hammer is ~30 cm long. B) Silicified and altered tonalite cross-cut by a quartz feldspar phryic dike and a quartz vein set (VG_B). C) Mutually cross-cutting vein sets (VG_A and VG_B) that cross-cut the SW_M+1 foliation. D) Macroscopically observed alteration assemblage observed adjacent to the VG_A vein set, proximal to sample GC-GL. The alteration assemblage is defined by macroscopically observed ankerite, pyrite, and/or chalcopyrite within veins and as disseminated zones in the host tonalite.

<table>
<thead>
<tr>
<th>Sample</th>
<th>C (%)</th>
<th>S (%)</th>
<th>W (ppm)</th>
<th>Cu (ppm)</th>
<th>Zn (ppm)</th>
<th>Au (ppm)</th>
<th>Ag (ppm)</th>
<th>As (ppm)</th>
<th>Mo (ppm)</th>
<th>Pb (ppm)</th>
<th>Te (ppm)</th>
<th>Au/Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC-GL</td>
<td>2.39</td>
<td>1.30</td>
<td>12</td>
<td>28</td>
<td>25</td>
<td>1.5</td>
<td>0.54</td>
<td>7.1</td>
<td>2.4</td>
<td>26.1</td>
<td>3.5</td>
<td>2.8</td>
</tr>
<tr>
<td>GC-KW</td>
<td>1.75</td>
<td>1.89</td>
<td>14</td>
<td>12</td>
<td>65</td>
<td>13.6</td>
<td>2.92</td>
<td>32.9</td>
<td>29.7</td>
<td>18.6</td>
<td>1.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>
NNW-trending, steeply-dipping quartz veins. The late NNW-trending vein set is rare, having been observed in few locations, and is not associated with mineralization.

A VGₐ vein sample that contained sulfide mineralization (sample GC-GL) was collected for whole-rock lithogeochemical analysis and isotopic analysis of vein-hosted xenotime. This sample contains elevated gold (1.5 ppm), and silver (0.5 ppm) concentrations as well as anomalously high values for lead, tellurium, arsenic, and molybdenum (Table 2). Within veins and adjacent altered wall rock, mineralization is most commonly associated with an alteration assemblage of quartz, calcite, ankerite, sericite, pyrite, chalcopyrite, and sphalerite (Figure 9D).

4.4 Regional structural observations in the Manitou Lakes area

In the Manitou Lakes area, northwest of the MDdz, compositional layering in the mafic to intermediate volcanic and volcaniclastic rocks of the Upper Manitou Lake, Blanchard Lake, and Pincher Lake groups defines kilometer-scale NE-plunging isoclinal folds (FMₘ), such as the Manitou Anticline (Figure 4; Table 3). Southeast of the MDdz, near Mosher Bay, bedding (SM₀) in sandstones and conglomerates of the Manitou Group is well-preserved, ENE-trending, and moderately- to steeply-dipping to the north or northwest. Similarly, where observed, younging is consistently towards the N or NW (Figure 4).

The Manitou Lakes area is dominated by a pervasive, NE-trending, steeply-dipping to vertical foliation (SMₘ), typically defined by aligned grains of chlorite, and less commonly biotite, depending on the host rock composition (Figure 4). The SMₘ fabric is observed within a ~2-5 km wide high-strain corridor that extends for >20 km along-strike throughout the region, affects volcanic and sedimentary stratigraphy, and marks the occurrence of the MDdz (Figures 10A and 11A; Table 3). The SMₘ foliation is commonly associated with a well-developed, SE-trending,
Figure 10 – Representative field photographs and photomicrographs of structure observed in the Manitou Lakes area. A) Carbonate-chlorite alteration in strongly foliated (SM_{M}) volcanic rocks observed in Upper Manitou Lake. Outcrop is approximately 2.5 m wide. B) Intensely foliated sedimentary rocks of the Manitou group that display a well developed SM_{M} foliation and associated LM_{M} mineral lineation. C) A carbonate-replaced δ-porphyroblast that displays asymmetry consistent with sinistral shear within the SM_{M} foliation in a sedimentary rock, Manitou Lakes. D-E) Photomicrographs in plane polarized light (PPL) that display asymmetric quartz (and feldspar) σ-clast indicative of sinistral shear. F) Bedding (SM_{0}) observed in sedimentary rocks of the Manitou group observed south of Mosher Bay. Note the sinistral-sense of offset across a small-scale, NE-trending faults with a parallel SM_{M} foliation. G) ENE-trending fabrics (SM_{M1}) that are crenulated by NE-trending SM_{M} fabrics observed in a quartz-feldspar dike on the southern shore of Mosher Bay. H) The SM_{M1} foliation (defined by flattened quartz and aligned grains of biotite) and associated C’ shear bands within a sandstone in the Stormy Lake group.
Figure 11 – Structural data from the Manitou Lakes area. Data from this study (red dots) and previously published data (blue dots, dips have been rounded up to nearest 5 degrees) is displayed as equal–area, lower hemisphere projections. A) Poles to SM\textsubscript{M} foliation planes with mean orientations indicated. B) LM\textsubscript{M} lineation with the mean orientations indicated. Previously published structural data was derived from Beakhouse et al. (2011) and references therein (see Appendix B).

steeply-plunging mineral lineation (LM\textsubscript{M}), typically defined by aligned aggregates of chlorite (Figures 10B and 11B). Commonly, the SM\textsubscript{M} foliation is further associated with sinistral kinematic indicators on horizontal erosional surfaces such as asymmetric carbonate-replaced δ-porphyroblasts in sedimentary rocks, and plagioclase or lithic σ-clasts in volcanic and sedimentary protoliths, respectively (Figure 10C-E). Locally, to the east of the MDdz, sinistral offset along NE-trending cm-scale faults was observed to affect sedimentary bedding (Figure 10F). In many locations, the MDdz is further defined by strongly foliated zones with pervasive carbonate-chlorite alteration and silicification of the host rocks, forming fissile to strongly weathered outcrop exposures. The SM\textsubscript{M} foliation can be traced along strike for >60 km to the northeast, into the
Wabigoon Lake area (Figure 4), where it similarly forms anastomosing domains of highly-strained and pervasive carbonate-chlorite altered volcanic and sedimentary rocks.

In the southeast Manitou Lakes area, sedimentary and volcanic successions are intruded by quartz-feldspar porphyries that preserve a weakly-developed ENE-trending fabric (SM_{M-1}) defined by aligned grains of biotite and spacing of feldspar phenocrysts. In this region, the SM_{M-1} fabric is crenulated by the SM_{M} foliation (Figure 10G). To the east of the Taylor Lake Stock, within the MBWdz, the E-trending SM_{M-1} fabric occurs in conjunction with an E-trending foliation that is also defined by aligned grains of biotite. In thin section, this structural relationship, marked by biotite, is interpreted as a C-S fabric that displays dextral shear sense (Figure 10H).

### 4.5 The MDdz at the Kenwest prospect

In order to constrain the relative timing of deformation and mineralization along the MDdz, detailed mapping was conducted at the Big Master Trench of the Kenwest prospect (Figure 12A). This outcrop area is comprised of massive, to pillowed, to plagioclase-phyric intermediate volcanic flows. The volcanic units were intruded by NE-trending quartz-feldspar porphyry dikes, and cross-cut by three generations of ~NE-trending quartz to quartz-carbonate veins (Holt, 2019; Figure 13A-B).

Three structural fabrics are observed in the Kenwest prospect and surrounding areas (Holt, 2019). The first (SM_{M-1}) is a NNE-trending, moderately-dipping, and defined by chlorite and biotite. SM_{M-1} is cross-cut by and locally transposed into the dominant NE-trending, subvertical foliation (SM_{M}) that is also defined by chlorite. A well-developed mineral lineation (LM_{M}) was observed within the SM_{M} foliation, and is defined by aligned aggregates of chlorite that are
Figure 12 – Outcrop map of the Big Master Trench at the Kenwest prospect. A) Map displaying the major lithological units, structural orientations, and the location of sample GC-KW. B) Rose diagram showing the strike of gold-bearing quartz veins (VK_B). Modified from Holt (2019).
Figure 13 – Representative field photographs of textures observed at Big Master Trench of the Kenwest prospect. A) Contact between altered massive to plagioclase-phryic intermediate volcanic units and an ~1.5 m wide quartz-carbonate vein (VK_B). Hammer handle points north, hammer is ~30 cm long. B) Representative calcite-ankerite-chlorite alteration observed next to a boudinaged VK_A vein and a planar, weakly deformed VK_B vein. C) Two vein generations and the SM_M fabric. D) Calcite-ankerite-epidote alteration proximal to sample GC-KW. Photos provided by K.A. Holt and R.M. Montsion.

steeply NE-plunging (Figure 11B). A third fabric (SM_{M+1}), also NE-trending, crenulates the SM_M foliation, however, it is poorly developed and only locally observed.

Based on cross-cutting relationships and composition, three generations of NNE- to NE-trending quartz to quartz-carbonate veins are identified (Figure 13). The first vein set (VK_A) is a NE-trending, steeply dipping and solely comprised of milky quartz. These veins are isoclinally folded and boudinaged with stretching directions that parallel the dominant NE-plunging lineation (LM_M). The second vein set (VK_B) is gold-bearing, NE-trending, steeply dipping and composed of quartz-carbonate (Figure 13B). The third vein set (VK_C) is a NNE-trending, steeply dipping quartz-carbonate vein set that cross-cuts the two earlier generations of veins, but is not volumetrically significant.
At the outcrop scale, alteration associated with the main NE-trending fabric is characterized by pervasive calcite-ankerite alteration and disseminated pyrite with chlorite, epidote, and sericite. It forms wide (>5 m) alteration halos (Holt, 2019; Figure 13D). The main VK_B vein was sampled for whole-rock geochemistry and isotopic analysis of vein-hosted xenotime (sample GC-KW; Figure 12). Whole-rock geochemical analysis of sample GC-KW indicates the presence of elevated concentrations of gold (13.6 ppm), and silver (2.9 ppm) as well as anomalously high values for arsenic, molybdenum, lead and tellurium (Table 2).

**Table 3 – Summary of structural features observed in the Manitou Lakes area.**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Orientation</th>
<th>Structure</th>
<th>Associated deformation zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM_b (bedding)</td>
<td>E-to -ESE striking, steeply dipping to vertical (~100/85)</td>
<td>Bedding in conglomerates and sandstones</td>
<td>N/A</td>
</tr>
<tr>
<td>SM_m-1 (foliation)</td>
<td>E-to ENE striking, vertical (~080/90)</td>
<td>Aligned feldspar phenocrysts in felsic dikes, aligned grains of biotite, dextral C-S fabric, becomes less apparent approaching MDdz from the E, not preserved W of MDdz</td>
<td>MBWdz</td>
</tr>
<tr>
<td>LM_m-1 (lineation)</td>
<td><em>Not observed</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM_m (folds)</td>
<td><em>Not observed at outcrop scale</em></td>
<td>Transposition of the nose of the Manitou Anticline into MDdz</td>
<td>N/A</td>
</tr>
<tr>
<td>SM_m (foliation)</td>
<td>NE-striking, steeply-dipping to vertical (~045/85), locally crenulates S_mLA1</td>
<td>Aligned grains of chlorite within volcanic and sedimentary protoliths</td>
<td>MDdz</td>
</tr>
<tr>
<td>LM_m (mineral lineation)</td>
<td>SE-trending, moderately to steeply plunging</td>
<td>Aligned aggregates of chlorite on SM_m planes</td>
<td>MDdz</td>
</tr>
</tbody>
</table>
4.6 Petrographic observations and results of LA-MC-ICP-MS analysis

Two samples (GC-GL and GC-KW) were selected for detailed petrographic and isotopic analysis of vein-hosted xenotime in order to directly constrain the timing of mineralization along the MDdz. The characteristics of these textural relationships and the results of the isotopic analysis are presented below.

Sample GC-GL represents a gold-bearing quartz-carbonate-pyrite vein (VGₐ) from the Zone 1 Pit Trench at the Goldlund deposit (Table 2; Figure 8). In thin section, petrographic SEM observations coupled with EDS assisted mineral identification show an association of quartz, calcite, ankerite, albite, sulfide minerals (mainly pyrite and chalcopyrite), rutile, apatite, monazite and xenotime (Figure 14). Calaverite (a gold-telluride) is present as inclusions and along fractures in sulfide minerals and, rarely, within monazite/xenotime grains (Figure 15A). These textural relationships indicate that gold tellurides were crystallized concomitantly with phosphate minerals used in isotopic dating. Xenotime is also observed as inclusions in rutile grains that display apatite overgrowths (Figure 15B). Epoxy mounts of the bulk heavy mineral separates from GC-GL yielded 5 xenotime grains that ranged in size from 25 μm to 80 μm as well as tens of native gold grains. The largest xenotime grain (~80 μm in diameter; Figure 15C) displays compositional zoning defined by variations in the intensity of backscattered-electron response. Based on these variations two growth zones were identified: a lighter outer rim, and a darker inner core. Due to the large size, multiple spot analyses were placed in the zoned xenotime grain. Analyses (26 in total) yielded three distinct age populations (Figure 16A). The oldest population is defined by a set of 10 analyses that yielded $^{207}\text{Pb}/^{206}\text{Pb}$ ages that range from 2674 ± 28 Ma to 2651 ± 25 Ma, and correspond to a weighted average age of 2664 ± 8.3 Ma (Figure 16B; Table 4). An intermediate set of ages are defined by 6 analyses that range in
Figure 14 - Inferred paragenetic history of alteration assemblages at the Goldlund deposit and Kenwest prospect. Modified from Giddings and Perkins (1987) and Holt (2019).
Figure 15 – Backscattered SEM photos of samples used in geochronological analysis. A) Monazite with inclusions of calaverite, associated with pyrite, calcite, ankerite, and electrum in the alteration assemblage. Goldlund deposit. B) Xenotime inclusions in rutile, with rims of apatite and ankerite. Albite forms part of the host rock assemblage at the Goldlund deposit. C) A zoned xenotime grain selected for U-Pb analysis, Goldlund deposit. D) A xenotime grain texturally associated with native gold-bearing pyrite, quartz and ankerite, Kenwest prospect. E) Inclusions of native gold and galena within a pyrite grain, and free native gold mineralized within the vein matrix, Kenwest prospect. F) A homogenous xenotime grain selected for U-Pb analysis, Kenwest prospect. Abbreviations: Ab=albite, Ag=silver, Ank=ankerite, Ap=apatite, Au=gold, Cal=calcite, Ccp=chalcopyrite, Gn=galena, Mnz=monazite, Py=pyrite, Qtz=quartz, Rt=rutile, Ser=sericite, Te=telluride, Xtm=xenotime.
Figure 16 – Results of isotopic analysis of xenotime from the Goldlund deposit (sample GC-GL). A) A linearized probability plot of all accepted, concordant that displays the three age groups displayed in B-F. B-D) Weighted average age calculations for the oldest (B), intermediate (C), and youngest (D) age populations with corresponding MSWD, probability of fit, and population ages with their 2σ errors indicated. E-F) Concordia plots displaying the $^{207}\text{Pb}/^{235}\text{U}$ ratios versus $^{206}\text{Pb}/^{238}\text{U}$ results for the (E) intermediate to oldest and (F) youngest age populations.
Figure 17 – Results of isotopic analysis of xenotime from the Kenwest prospect (sample GC-KW). A) Weighted average age calculations with corresponding MSWD, probability of fit, and population ages with their 2σ errors indicated. B) Concordia plot displaying the $^{207}\text{Pb}/^{235}\text{U}$ ratios versus $^{206}\text{Pb}/^{238}\text{U}$ ratios for the data displayed in (A)

$^{207}\text{Pb}/^{206}\text{Pb}$ age from 2639 ± 21 Ma to 2630 ± 19 Ma, and correspond to a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2634 ± 8.0 Ma (Figure 16C; Table 4). The youngest range of ages are defined by a set of 9 analyses that range in $^{207}\text{Pb}/^{206}\text{Pb}$ age from 2607 ± 21 Ma to 2570 ± 20 Ma, and correspond a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2590 ± 6.9 Ma (Figure 16D; Table 4).

Sample GC-KW represents a gold-bearing (Table 2) quartz-carbonate vein (VKB) from the Big Master Trench at the Kenwest prospect (Figure 12). Petrographic analysis of this sample indicates that the gold-bearing quartz veins contain an alteration assemblage of chalcopyrite, arsenopyrite, and galena with trace amounts of rutile, monazite, and xenotime (Figure 14).

In thin section, petrographic SEM observations coupled with EDS assisted mineral identification show that the mineralized vein consists of quartz, sericite, calcite, ankerite, pyrite, chalcopyrite, and galena with trace amounts of xenotime (Figure 15D). Pyrite, carbonate and sericite grains display spatial association with xenotime. Chalcopyrite, galena and native gold are commonly present as inclusions and along fractures within pyrite (Figure 15E). A texturally homogenous
xenotime grain that was ~60 µm in diameter was selected for analysis (Figure 15F). Nine spot analyses of this xenotime grain yielded a range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages, from $2605 \pm 35$ Ma to $2567 \pm 40$ Ma to that correspond to a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2580 \pm 12$ Ma (Figure 17).

**Table 4** – Selected concordant U-Pb isotopic results from LA-MC-ICP-MS analysis of vein-hosted xenotime.

<table>
<thead>
<tr>
<th>Spot #</th>
<th>$^{238}\text{U}/^{206}\text{Pb}$</th>
<th>±</th>
<th>$^{207}\text{Pb}/^{206}\text{Pb}$</th>
<th>±</th>
<th>Disc. (%)</th>
<th>$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)</th>
<th>± (Ma)</th>
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<td>GC-GL-Rim_6</td>
<td>1.929</td>
<td>0.050</td>
<td>0.171</td>
<td>0.002</td>
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</table>
5 Discussion

5.1 Structural synthesis of the western Wabigoon Subprovince

New structural mapping was integrated with previously published geologic observations to establish the role of major regional deformation zones in the localization of strain and hydrothermal fluid flow during the structural evolution of the western Wabigoon subprovince. Based on work in the Wabigoon Lake and Manitou Lakes areas, a generalized, two-phase deformation model (D₁ and D₂) is proposed (Figure 18), where the hydrothermal event associated with gold mineralization is inferred to have occurred during the late stages of D₂. These two main deformation events are broadly associated with two deformational regimes: early N-S shortening (D₁), followed by NNW-SSE shortening and localized transpressional shear (D₂). Isotopic dating of vein-hosted xenotime associated with the mineralized samples along the MDdz was used to provide absolute timing constraints on gold-bearing hydrothermal events during D₂. This model is used to provide a framework for comparison with other well-studied domains of the southern Superior Province.

5.1.1 D₁ deformation event

In the Wabigoon Lake area, D₁ is marked by the regional development of E-trending foliations (SWₘ) that are axial planar to regional- to outcrop-scale isoclinal folds (FWₘ) in sedimentary and volcanic protoliths (Figures 3, 5B, and 7; Trowell et al., 1978; Chorlton, 1987; Parker, 1989; Chorlton, 1990; Beakhouse, 2000). The SWₘ fabric is most strongly developed with increasing proximity to the Wdz (Figure 3), where 10 to >100 m-wide high-strain zones are defined by a penetrative foliation with aligned grains of biotite and/or chlorite. E-W striking, elongate quartz pods and steeply-dipping to vertical boudinaged quartz veins are commonly observed. A well-developed, W- to SW-trending mineral to stretching lineation (LWₘ) is observed throughout the
Figure 18 - Schematic structural synthesis of the western Wabigoon subprovince. Diagram displays major episodes of volcanism, sedimentation, deformation, and hydrothermal events.
Wabigoon Lake area, though it is best developed along the northern shore of Wabigoon Lake, where the \( SW_M \) foliation is most intense. The \( LW_M \) lineation is variably defined by aligned aggregates of biotite, or stretched carbonate-filled amygdules within volcanic protoliths (Figure 5D). Similar to the Manitou Lakes area, \( D_1 \) is marked by the development of a ENE- to E-trending, vertical to subvertical foliation (\( SM_{M,1} \)) that is best preserved in sedimentary and intrusive rocks of the Manitou group in proximity to the MBWdz. At Mosher Bay (Figure 4), the \( SM_{M,1} \) foliation is weakly preserved and defined by aligned grains of biotite in sedimentary rocks and/or as spaced feldspar phenocrysts in felsic dikes (Figure 10G). East of Mosher Bay, towards the Taylor Lake Stock, the \( SM_{M,1} \) foliation is better preserved, where the MBWdz is well exposed and the deformation overprint by the MDdz is minor (Stone et al., 2010).

The presence of an E-trending \( S_1 \) foliation (i.e., \( SW_M \) and \( SM_{M,1} \)) that is axial planar to isoclinal folds, and E-NE-trending clastic sedimentary basins bounded by deformation zones (i.e., the Manitou and Stormy Lake groups, Dostal et al., 2004), suggests that the \( D_1 \) deformation event represents a period of N-S shortening in the Dryden area, with north-over-south displacements accommodated by the Wdz and MBWdz (Chorlton, 1987; Berger, 1990; Chorlton, 1990; Beakhouse et al., 2000). The \( S_1 \) foliation is associated with the dynamic crystallization of biotite and chlorite, and locally garnet north of the Wdz, which suggests upper-greenschist metamorphic conditions during \( D_1 \).

The relative age of \( D_1 \) deformation can be constrained between the deposition of the Manitou and Stormy Lake groups, at 2705-2695 Ma (angular unconformity at the base, and the age of detrital zircons in turbidites; Dostal et al., 2004). The lower age constraint is also supported by the ~2695
Ma emplacement age of the Taylor Lake Stock, which cross-cut D₁ structures, such as the MBWdz (Davis et al., 1982).

5.1.2 D₂ deformation event

In the Wabigoon and Manitou Lakes areas, D₂ is characterized by ductile localization in the Wdz, MBWdz, and MDdz. In the MDdz, D₂ resulted in the regional development of a NE-trending, penetrative to anastomosing S₂ foliation (SW_{M+1} and SM_{M}), that crenulates earlier structural fabrics (i.e., bedding and S₁). Along NE-trending deformation zones, the S₂ foliation is associated with a steeply SE-plunging mineral lineation, and abundant sinistral-sense shear indicators, such as sinistrally-rotated σ- and δ-clasts or porphyroblasts. The S₂ foliation is also axial planar to regional- and outcrop-scale tight folds in the Wabigoon Lake area (FW_{M+1}, Figure 3) and isoclinal folds (e.g., the Manitou Anticline) in the Manitou Lakes area (FM_{M}, Figure 4). Penetrative S₂ fabrics are associated with pervasive carbonate-chlorite alteration and the emplacement of abundant quartz carbonate vein sets (Figure 5F, Figure 10A), indicating that the MDdz acted as a hydrothermal fluid conduit during the D₂ deformation.

The presence of a NE-trending S₂ foliation, NE-plunging lineation, sinistral-sense shear indicators on horizontal erosional surfaces, and NE-plunging folds suggest that the D₂ deformation event represents a period of NNW-SSE transpression in the Dryden area (Figures 3 and 4). The S₂ foliation is predominantly defined by chlorite, which suggests that D₂ occurred under greenschist facies metamorphic conditions. Dextral-sense reactivation of the Wdz and MBWdz is evidenced by the dynamic recrystallization of chlorite within E-trending deformation zones, dextrally-rotated quartz pods and boudins, z-folds of bedding and S₁ (Figure 5C, G), and the C-S fabric observed east of the Taylor Lake Stock (Figure 10H). In contrast, the MDdz predominately records northwest-over-southeast displacements, with a sinistral component of shear (SW_{M+1} and SM_{M};
Figure 10C, D, E, Figure 4) and, locally, is inferred to relate to sinistral offsets observed along NE-trending faults (Figure 10F), such as the Taylor Lake Fault (Figure 4). Alternatively, sinistral-sense movement along the MDdz and related D2 structures could post-date dextral sense movement along the Wdz and MBWdz. However, this hypothesis is not supported by cross-cutting observations. Based on the interpreted NNW-SSE stress regime of D2, it is more likely that the movements occurred concomitantly (i.e., dextral strike-slip along E-trending deformation zones and northwest-over-southeast sinistral transpression along NE-trending deformation zones).

The upper age constraint on the D2 deformation is provided by the emplacement of ~2695 Ma Taylor Lake and Scattergood Lake Stocks (Figure 4). At the Goldlund deposit and Kenwest prospect, isotopic dating of vein-hosted xenotime from syn-D2 gold-bearing quartz-carbonate vein yielded three distinct populations, corresponding to three weighted average 207Pb/206Pb ages of 2664 ± 8.3 Ma, 2590 ± 6.9 Ma (Figure 16B, D), and 2580 ± 12 Ma (Figure 17A). These ages constrain the D2 deformation and indicate that two major episodes of hydrothermal activity, and gold mineralization may have occurred along the MDdz. A third, intermediate age population was identified at the Goldlund deposit and yielded a weighted average 207Pb/206Pb age of 2634 ± 8.0 Ma (Figure 16C). It is possible that this intermediate age represents a different hydrothermal event, although it is more likely that it corresponds to mixed analysis of core and rim domains that were observed in the SEM image (Figure 15C). Therefore, it is not interpreted as a separate hydrothermal event.

5.1.3 Comparison to previous regional studies in the western Wabigoon subprovince

West of the Dryden area, in the Lake of the Woods region (Figure 1B), Davis and Smith (2001) interpreted two primary deformation events: an early D1 deformation event associated with
isoclinal folds, equivalent to the N-S shortening event in the Dryden area, and a protracted D2 NW-SE shortening event that corresponds to localized transpressional shear and hydrothermal alteration along E-trending deformation zones. Metamorphic zircon grains in amphibolite gneisses constrain peak metamorphism around 2709 ± 2 Ma (U-Pb age, Corfu, 1988; Davis and Smith, 1991), which is older than the inferred timing of the D1 deformation in the Dryden area at 2705-2695 Ma. To the northeast of the Dryden area, in the Sturgeon-Savant Belt (Figure 1B), Sanborn-Barrie and Skulski (2006) also inferred two primary deformation events, which occurred in a narrow 2703-2696 Ma age range. However, the presence of <2698 Ma alluvial-fluvial clastic sedimentary rocks metamorphosed to greenschist facies (i.e., the Ament Bay assemblage, contemporaneous with the Manitou and Stormy Lake groups), and continuous intrusive magmatic activity until ~2680 Ma suggest that the inferred timing of the deformation may extend to younger ages than previously described. In contrast, this study interprets that the western Wabigoon subprovince experienced N-S compression between 2705-2695 Ma, which later transitioned to NNW-SSE shortening with localized transpression <2695 Ma and likely 2680-2580 Ma.

5.2 Comparison to the structural evolution of the Abitibi subprovince

The structural and metallogenic evolution of the Abitibi subprovince has been well-documented, as is host to some of the world’s largest orogenic gold deposits (Ayer et al., 2003; Bateman et al., 2008; Ispolatov et al., 2008; Bleeker, 2012; Bedeaux et al., 2017; Monecke et al., 2017; Nassif et al., 2018; Frieman et al., 2017; Frieman and Kuiper, 2019). An early N-S shortening event (2690-2670 Ma) is marked by local development of E-trending fabrics that are axial planar to isoclinal folds in volcanic and sedimentary rocks of the Porcupine assemblage (Bleeker, 2012; Lafrance, 2015; Bedeaux et al., 2017). During this early phase of deformation, the Abitibi subprovince experienced local syn-orogenic extension (2680-2670 Ma), recorded by the formation of
Timiskaming basins along the Larder Lake-Cadillac and Porcupine-Destor deformation zones (Robert, 1989; Wilkinson et al., 1999; Daigneault et al., 2002; Bleeker, 2012; Lafrance, 2015; Bedeaux et al., 2017). This early deformation event is younger, but similar to the D₁ N-S shortening event in the western Wabigoon subprovince (2705-2695 Ma), which also produced E-trending, steeply dipping foliations that are axial planar to regional E-trending isoclinal folds, and the Manitou and Stormy Lake basins.

The final stage of deformation in the Abitibi subprovince involved a transition to a NW-SE shortening event with localized dextral transpressive strain along the regional deformation zones. This event (2665-2625 Ma, De Souza et al., 2020) is marked by the formation of a well-developed E-NE-trending crenulation cleavage that is axial planar to asymmetric χ-folds (Robert, 1989; Wilkinson et al., 1999; Zhang et al., 2014; Lafrance, 2015). This deformation event is similar to the D₂ NNW-SSE shortening event in the western Wabigoon subprovince (<2695 Ma, likely 2680-2580 Ma), which involved formation and sinistral transpression along the NE-trending structures, such as the MDdz and the Taylor Lake Fault, and dextral-sense reactivation of the E-trending structures, such as the Wdz and MBWdz (Figure 18). In summary, both the Abitibi and western Wabigoon subprovinces record a similar structural evolution, transitioning from an early N-S compressional regime, to a protracted ~NW-SE shortening with localized transpressional strain.

5.3 Timing of orogenic gold mineralization in the southern Superior Province

Along the MDdz, gold is associated with the emplacement of quartz-carbonate veins with calcite-ankerite alteration and disseminated sulfide minerals (Figures 9C-D and 13A-B). Based on the age of vein-hosted xenotime in mineralized samples, gold-bearing fluid flow occurred at ~2665 Ma and 2590-2580 Ma along the MDdz. At the Kenwest property, gold-bearing quartz veins within the S₂ fabric cross-cut earlier, locally folded, barren veins that are transposed into the S₂ fabric,
indicating that the gold-bearing veins were emplaced syn- to late-D2 deformation. At the Goldlund property, the orientation of gold-bearing, fracture-filling and extensional vein sets indicate they were likely emplaced during a NNW-SSE shortening regime (i.e., syn- to late-D2).

Direct geochronologic constraints on the timing of gold-bearing hydrothermal events using reliable mineral and isotopic systems is quite rare in the Superior Province. To the north of the western Wabigoon subprovince, in the Red Lake gold district (>27 Moz Au; Lichtblau et al., 2012) of the Uchi subprovince, gold-bearing quartz-veins have been approximately dated at 2704 ± 60 Ma based on an upper-intercept age from U-Pb analysis of two vein-hosted titanite grains (Gallagher et al., 2018). To the southeast, in the Wawa subprovince, gold mineralization has been estimated using a wide variety of minerals at the Hemlo gold deposit (>21 Moz Au; Cox et al., 2017), where U-Pb analysis of monazite and rutile within mineralized and altered rocks indicate that gold mineralization occurred between 2671 ± 5 Ma and 2632 ± 5 Ma (Corfu and Muir, 1989). Further east, in the Abitibi subprovince, the timing of mineralization in orogenic gold deposits has been constrained along the Porcupine-Destor deformation zone at the Dome mine and along the Larder Lake-Cadillac deformation zone at the Canadian Malartic, Camflo, and Sigma-Lamaque mines (Figure 19). At the Dome mine, Re-Os analysis of ore-related molybdenite yielded an age of 2661 ± 13 Ma while vein-hosted monazite yielded younger U-Pb ages of 2639 ± 3 and 2590 ± 11 Ma (Ayer et al., 2003). At the Canadian Malartic mine, Re-Os dating of molybdenite and U-Pb dating of titanite from mineralized veins yielded ages of 2664 ± 11 Ma and 2661 ± 10, respectively (De Souza et al., 2020). In contrast, approximately ~5 km to the NE of Canadian Malartic, U-Pb dating of vein-related titanite and rutile from the Camflo Mine yielded much younger ages of 2627 ± 2 and 2600 ± 3, respectively (Jemielta et al., 1990). At the Sigma-Lamaque mine, Sm-Nd dating of scheelite and U-Pb dating of vein-hosted rutile yielded ages of 2602 ± 20 Ma and 2599 ± 9 Ma,
respectively (Anglin, 1990; Wong et al., 1991). Thus, based on published isotopic ages, major pulses of orogenic gold mineralization are documented at ~2660-2640 Ma, ~2625 Ma, and ~2600 Ma in the Abitibi subprovince.

The older age of gold mineralization in the western Wabigoon subprovince, recorded at the Goldlund deposit (2664 ± 8.3 Ma; Figure 16), is broadly correlative with the timing of orogenic gold mineralization elsewhere in the southern Superior Province (Figure 19). This relationship suggests the upflow of hydrothermal fluids within structural conduits occurred during the same timespan (~2660 Ma) for 100’s of kilometers across the southern Superior Province, similar to modern orogenic gold systems such as those in the North American Cordillera (Goldfarb et al., 2001). The younger ages of hydrothermal activity, recorded at the Goldlund deposit and Kenwest prospect (2590 ± 6.9 Ma and 2580 ± 12 Ma), could represent a late stage of hydrothermal activity (and possible gold remobilization) that was experienced across the entire southern Superior Province. This late hydrothermal activity could have affected isotopic concentrations in older accessory minerals, and therefore, could possibly explain the intermediate hydrothermal ages (~2630 Ma) obtained at the Goldlund, Hemlo, Dome, and perhaps, Camflo deposits. Alternatively, it is possible that multiple episodes of hydrothermal activity were experienced across the southern Superior Province between 2660-2580 Ma, and have yet to be documented.
Figure 19 - Inferred timing of orogenic gold mineralization in the southern Superior Province from single-mineral isotopic constraints. The age including 2σ errors for the western Wabigoon subprovince (this study) are plotted with published results from the Uchi, Wawa, and Abitibi subprovinces.
6 Conclusions

Based on new structural observations, two main deformation events are inferred to have occurred in the western Wabigoon subprovince. The earliest was a N-S shortening event (D₁, 2705-2695 Ma) that resulted in the formation or reactivation of E-trending structures, such as the Wdz and MBWdz, and was coeval with sedimentation in the Stormy Lake basin. It was followed by a protracted period of NNW-SSE shortening and localized transpression (D₂, <2695 Ma, likely 2680-2580 Ma), which resulted in the formation of the NE-trending MDdz. During D₂, the MDdz experienced sinistral transpression, whereas the Wdz and MBWdz record dextral shear. When compared with the Abitibi subprovince, the western Wabigoon subprovince shows a similar structural history: deformation in both subprovinces consisted of an early N-S shortening event associated with the formation of crustal-scale deformation zones, and was followed by a protracted, ~NW-SE shortening event that resulted in localized transpressive strain.

Gold mineralization at the Goldlund deposit and Kenwest prospect are temporally associated with syn-D₂ sinistral transpression along the MDdz. Isotopic dating by U-Pb LA-MC-ICP-MS analysis of vein-hosted xenotime in gold-mineralized samples yielded two distinct age groups. At the Goldlund deposit, an early phase of hydrothermal activity is dated at ~2665 Ma, and coincides with reported ages of hydrothermal activity and gold mineralization in other world-class gold districts of the southern Superior Province. A later phase of hydrothermal activity, dated at ~2590-2580 Ma, could represent a second period of widespread hydrothermal activity, and possibly gold remobilization, throughout greenstone belts of the southern Superior Province.
7 Perspective

7.1 Orogenic gold endowment in greenstone belts

At a broader scale, this study suggests that the structural evolution of major deformation zones does not influence the bulk orogenic gold endowment of greenstone belts. The western Wabigoon and Abitibi subprovinces both display similar structural and metallogenic evolutionary histories, as do most orogenic gold-hosting terranes (Goldfarb, 2018). Nonetheless, their relative gold endowment is drastically different (~194 Moz vs. ~37 Koz, Monecke et al., 2017, Ontario Geological Survey, 2020). Thus it is likely that other factors, such as geodynamic setting, crustal composition and inheritance, and hydrothermal fluid source(s) may have a greater influence on the gold endowment of the crust. The interaction of mafic to intermediate magma with older crustal material of the Winnipeg River subprovince and Marmion terrane (Tomlinson et al., 2004) could explain the relatively low gold endowment of the region, as the presence of such evolved continental crust may limit the fluid (and gold) availability. Metamorphic devolatization is commonly considered as the main source of fluids in orogenic gold systems (Goldfarb and Groves, 2015), however, the relative contribution magmatic fluid sources remains unclear and could also influence the overall gold endowment of greenstone belts. Although this study has shown the structural and metallogenic similarities between differentially gold-endowed Archean terranes, the presence and evolution of crustal-scale deformation zones ultimately determines favourable locations for deposit formation.

7.2 Suggestions for continued research

1) The MDdz is interpreted as a gold-bearing deformation zone that extends for >60 km along-strike. It would be useful to delineate and constrain the along-strike extent of the MDdz in order
to generate prospective orogenic gold targets in other regions of the western Superior Province that host this structure.

2) Lower crustal metamorphism (2660-2585 Ma; Krogh, 1993), preserved and exhumed in the Kapuskasing Structural Zone, could have provided the fluid source for widespread hydrothermal activity and orogenic gold deposits across the Superior Province. This hypothesis could be tested using structural, metamorphic and geochronological approaches to determine possible age correlation between the NE-trending MDdz and Kapuskasing Structural Zone.

3) Another topic of interest would be to determine if the MDdz represents a reactivated lithospheric-scale structure, similar to the Red Paint Lake Shear Zone in the Marmion terrane (Backeberg et al., 2014). Reactivation of such inherited structures could generate pathways for mantle-derived, gold-bearing fluids.
References


mineralization from titanite, rutile, and monazite U-Pb geochronology. Chemical Geology (Isotope Geoscience Section) 79, 201-223.


Appendices

Appendix A – Table of previous structural interpretations
This appendix contains a table that synthesize the structural interpretations from this study and prior studies conducted in the western Wabigoon subprovince. The appendix is attached as an excel file, entitled AppendixA.xlsx.

Appendix B – Structural orientation data
This appendix contains structural data from this study, and those derived from Beakhouse et al. (2011). The appendix is attached as an excel file, entitled AppendixB.xlsx.

Appendix C – LA-MC-ICP-MS isotopic results
The appendix contains select concordant U-Pb geochronological from xenotime dating that was used to interpret hydrothermal fluid histories in this thesis. Information about the standards used in analyses is also included. The appendix is attached as an excel file, entitled AppendixC.xlsx.