



Multi-stage orogenic gold-mineralizing systematics at the Seabee gold Operation, northern Saskatchewan, Canada: Constraints from pyrite chemistry and geochronology

D. Beaudin^a, C.A. Partin^{a,*}, K. Ansdell^a, A. Voinot^b, R. Creaser^c, R.B. Ickert^d

^a Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2, Canada

^b Department of Geological Sciences and Geological Engineering, Queen's University, Bruce Wing/Miller Hall, 36 Union Street, Kingston, ON K7L 3N6, Canada

^c Department of Earth and Atmospheric Sciences, University of Alberta, 11223 Saskatchewan Drive NW, Edmonton, AB T6G 2E3, Canada

^d Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051, USA

ARTICLE INFO

Keywords:

Pyrite chemistry
Re-Os geochronology
Orogenic
Gold
Trans-Hudson orogen
Laser ablation
U-Pb geochronology

ABSTRACT

Gold mineralization occurs in several different deposits hosted in the Paleoproterozoic Pine Lake greenstone belt of the Trans-Hudson orogen in northern Saskatchewan, Canada, where over 2 million ounces of gold have been produced. The connections between deposits throughout the Seabee Gold Operation are not well understood, including the role of ca. 1875 Ma intrusions in the mineralization. The focus of our study is comparing the ore systems of the Santoy mine and the Fisher property, which are connected by the Santoy shear system, using sulfide mineral chemistry from LA-ICP-MS, mineral paragenesis, and geochronology (U-Pb, Re-Os) to link with regional tectonic events. Our results show i) an early influx of potentially magmatic-hydrothermal, polymetallic fluids prior to deformation (Py₁); ii) early- to syn-deformation mineralization (Py₂); iii) mainstage orogenic-style mineralization, which includes inclusion-bearing, trace metal-rich Py_{3a}, inclusion-free Py_{3b}-Cpy₂-Po₁-native gold mineralization from metamorphic fluids or sub-crustal fluids from slab devolatilization syn- to late-deformation; iv) and remobilization, which includes fracture-filling Py₄-Po₂-Cpy₃-native gold-Tbi-Ttd mineralization. The source of the fluids is not known but was likely a combination of metamorphic fluids or from dehydration of mantle lithosphere. New geochronology addresses the age of main-stage mineralization: ca. 1764 Ma (pyrite Re-Os) remobilized, gold-associated Py₄ at Fisher, and igneous host rocks: ca. 1882 Ma and 1886 Ma (zircon U-Pb). These data show that an intrusion-related model does not fit the main-stage mineralization. We demonstrate a multi-stage, orogenic-dominated gold-mineralizing system along the Santoy shear system that culminated in a remobilization event at ca. 1764 Ma, generating a better understanding of gold systematics within the Trans-Hudson orogen.

1. Introduction

Here we present a study of gold mineralization within the Glennie domain of the Reindeer zone of the Trans-Hudson orogen in northern Saskatchewan, Canada. The Glennie domain forms part of a district well-known for orogenic gold endowment that formed during or after transpressional deformation linked to the collision of juvenile terranes and the Archean Hearne, Sask, and Superior cratons during the ca. 1.8 Ga Trans-Hudson orogen (Corrigan et al. 2007, Morelli and MacLachlan 2012, Lawley et al. 2020). These deposits formed through either metamorphic devolatilization (Goldfarb et al. 2005) or sub-crustal fluids during enriched mantle wedge devolatilization (Goldfarb and Groves

2015, Groves et al. 2020) and followed by structure-focused fluid flow. Earlier collisional or magmatic settings, however, may have contributed to gold mineralization via magmatic-hydrothermal fluids (Meffre et al. 2016). These ore forming processes could be followed by varying degrees of subsequent fluid events that further upgraded, introduced, or remobilized metals, as seen in other Precambrian deposits (e.g., the Chalice deposit, Yilgarn craton; Bucci et al. 2004; the Wasamac deposit, Abitibi greenstone belt; Mériaud and Jébrak 2017). The development of shear zones and fluid pathways at contrasting rheological boundaries (e.g., supracrustal-intrusion contacts) that generates dilatational zones for gold mineralization is an example of how intrusions play a role and must be considered alongside orogenic gold models (Groves et al. 2018).

* Corresponding author.

E-mail address: camille.partin@usask.ca (C.A. Partin).

<https://doi.org/10.1016/j.oregeorev.2026.107257>

Received 28 November 2024; Received in revised form 1 April 2026; Accepted 4 April 2026

Available online 6 April 2026

0169-1368/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Understanding the spatial relationship between auriferous quartz veins and intrusions, the identification of hydrothermal fluid origins, and mineralizing systematics are crucial for understanding ore genesis. Furthermore, sulfide minerals associated with gold mineralization, including pyrite and pyrrhotite, take up trace elements reflecting hydrothermal fluid chemistry (Deditius et al. 2011; e.g., Reich et al. 2005, Keith et al. 2018, Belousov et al. 2016, Babedi et al. 2022), and thus can be used in metallogenic studies to clearly identify multi-stage components of gold mineralization. Pyrite trace-element analyses from the Wamac deposit, Abitibi greenstone belt, Canada, for example, revealed early porous inclusion-rich pyrite phases within potassic alteration with Te-Ag-Au-Mo-Pb-Bi-W magmatic-hydrothermal signatures, while later pyrite phases associated with fracture-controlled sulfide-gold-telluride in albite-rich alteration had Te-Ag-Au-Pb-Bi-Ti compositions from overprinting orogenic processes (Mériaud and Jébrak 2017). Another example from the Yilgarn craton, Australia identified pyrite with Au-Ag $\pm$ As-Sb-Bi-Te-Co-W compositions from orogenic processes, as well as earlier hydrothermal contributions (Belousov et al. 2016). Pyrite is particularly useful to differentiate between these models since pyrite from orogenic gold systems typically exhibit enrichment in Au-Ag $\pm$ As-Sb-Bi-Te (e.g., Belousov et al. 2016, Dubosq et al. 2018, Gao et al. 2019, Wu et al. 2019, Babedi et al. 2022, Cao et al. 2023), while magmatic-hydrothermal pyrite shows enrichment in Au-Te-Bi-As $\pm$ W, Mo, Cu, Pb, Zn, Sn, Sb (e.g., Sung et al. 2009, Cook et al. 2016, Mériaud and

Jébrak 2017, Mathieu 2019).

Gold deposits in the Reindeer zone are typically hosted in ductile shear systems found along contacts between granitoid intrusions and volcanic, volcanoclastic, and siliciclastic rocks (Van Schmus et al. 1987, Thomas and Heaman 1994, Maxeiner and Kamber 2011). Estimates for timing of emplacement of gold mineralization regionally ranges from ca. 1830 Ma to ca. 1720 Ma, aligning dominantly with terminal collisional episodes and reactivation of structures post-peak metamorphism, however, the older ages suggest the potential for earlier magmatic-hydrothermal mineral deposits during arc development. In support of this, genetic relationships between gold deposits and felsic intrusions are proposed for the La Ronge, Kisseynew, and Glennie domains (Morelli and MacLachlan 2012). One of the main objectives of this study is to understand the gold deposits of the Seabee Gold Operation, including the Seabee and Santoy deposits, and if they are linked to an orogenic-style model (e.g., Tourigny et al. 2004, McEwan 2013, Wood 2016), linked to felsic intrusions (Helmstaedt 1986, Tourigny 2003, Tourigny et al. 2004), or a combination of orogenic and intrusion-related gold mineralization.

The objectives of this study overall are to: i) characterize the chemistry of sulfide mineral phases (pyrite-pyrrhotite) at the Fisher property and Santoy Mine Complex at the Seabee Gold Operation that occurs within the Glennie domain of the Reindeer zone of the Trans-Hudson orogen in northern Saskatchewan, Canada; ii) use

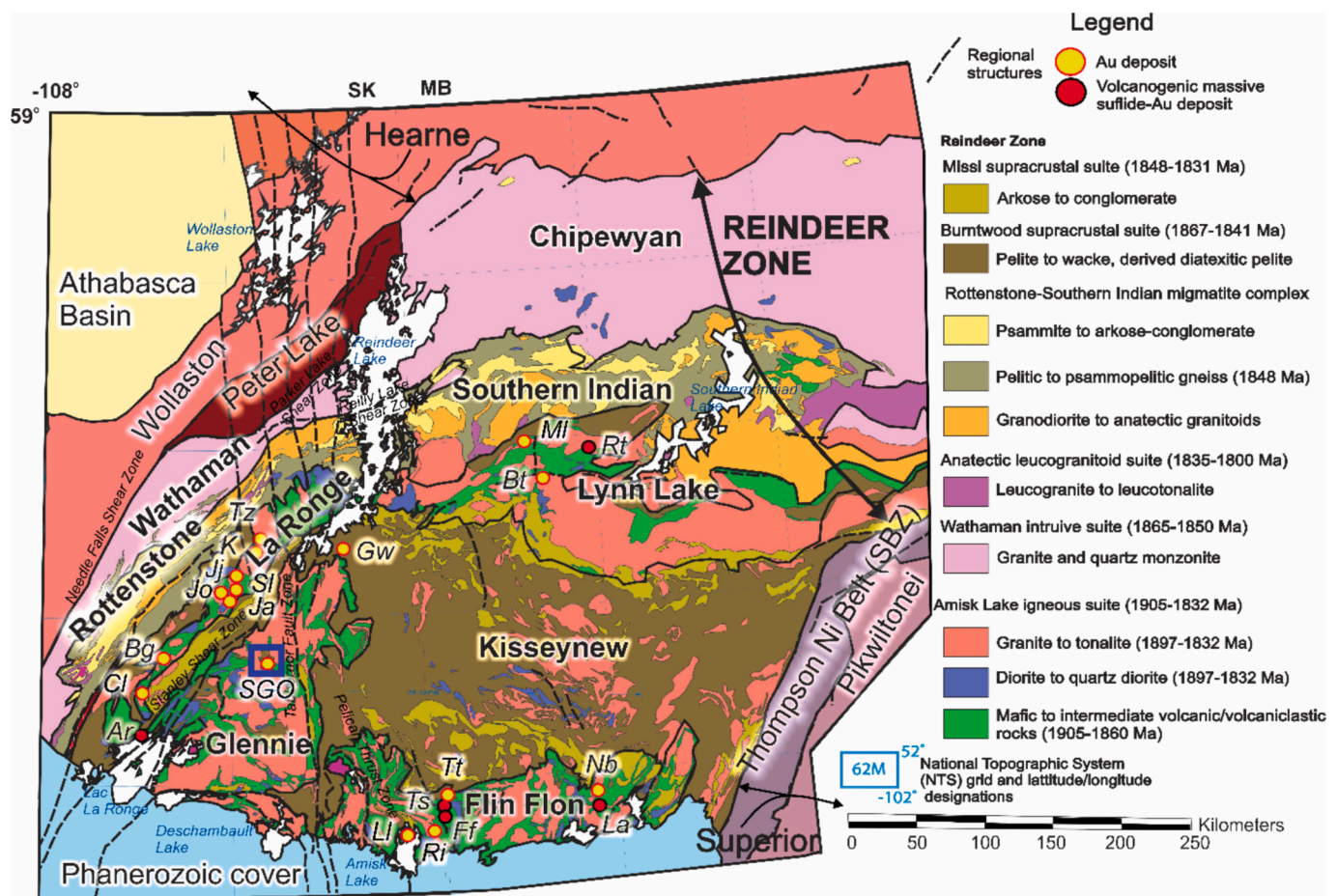


Fig. 1. Geological map showing the lithostructural subdivisions of Precambrian rocks in Saskatchewan (SK) and Manitoba (MB), which includes the Hearne craton (Wollaston, Peter Lake domains), Reindeer zone, Superior craton (Pikwitonei, Thompson Ni Belt) and the Athabasca Basin. Blue box shows study area of Glennie domain in Fig. 2. The detailed geology and ages for domains within the Reindeer zone is based on Maxeiner et al. (2021) and Manitoba Geological Survey (2018). Lithological classifications in Manitoba are correlated to the lithology outlined in Maxeiner et al. (2021); SBZ: Superior boundary zone. The following are deposit annotations: Tz: Twin Zone; K: Komis; Sl: Star Lake; Jo: Jojay; Bg: Bingo; Ar: Anglo-Rouyn; Cl: Contact Lake; Gw: Greywacke; SGO: Seabee Gold Operation; Seabee, Santoy; ML: MacLellan; Bt: Burnt Timber; Ll: Laurel Lake; Ts: Triple Seven; Nb: New Britannia; Tt: Tartan Lake; Ri: Rio/Bootleg; La: Lalor Lake; Rt: Ruttan; Ff: Flin Flon.

geochronology to better constrain the ages of the host rocks and the mineralization; and iii) use these data in conjunction with the structural framework to test the existing orogenic gold model and test the link of a potentially interconnected gold mineralizing system across the Pine Lake greenstone belt.

The two study areas are connected by the Santoy shear system (Fig. 1), which is a splay of the crustal-scale Tabernor fault system crosscutting volcanic and intrusive units that host auriferous quartz veins. In both areas, the spatial association of auriferous quartz veins and intrusions has led to some doubt over an entirely orogenic mineralization model. To address this, we present new mineral chemistry of sulfide mineral phases associated with gold, and new geochronology data, including a pyrite Re-Os model age, and zircon U-Pb crystallization ages for intrusive and extrusive volcanic host rocks, both by thermal ionization mass spectrometry (TIMS), to constrain the mineralization. These data help constrain the overall temporal framework of the Pine Lake greenstone belt, its mineralization history, and how ore genesis fits into the wider context of the Reindeer zone of the Trans-Hudson orogen.

2. Geological setting

2.1. Regional geology

2.1.1. Reindeer zone of the Trans-Hudson orogen

The Trans-Hudson orogenic belt in Manitoba and Saskatchewan is generally divided into the internal Paleoproterozoic Reindeer zone and the Hearne and Superior craton margins to the west and east, respectively (Stauffer 1984). The Reindeer zone features a complex litho-structural arrangement of juvenile domains, namely the Wathaman-Chipewyan, Rottenstone-Southern Indian, La Ronge-Lynn Lake, and Kiseynew domains, and the Flin Flon-Glennie complex (Fig. 1; Lewry et al. 1994, Corrigan et al. 2005). The Reindeer zone is a structural amalgam of supracrustal and associated intrusive rocks emplaced within the Manikewan Ocean between ca. 1.91 to 1.83 Ga, which formed in primitive to evolved successor volcanic arc and back-arc settings, and marginal sedimentary basins (Hoffman 1988, Ansdell 2005, Corrigan et al. 2009).

The formation of the rocks in the Reindeer zone occurred as the Manikewan Ocean started to close, with the formation of juvenile arcs and associated plutons from 1.92–1.88 Ga (Stauffer 1984, Lewry and Collerson 1990, Ansdell 2005, Corrigan et al. 2005). From ca. 1.88 to 1.865 Ga, widespread regional D₁ deformation resulted from intra-oceanic accretion, forming the Flin Flon-Glennie complex (Lewry et al. 1990, Lucas et al. 1996, Ashton 1999). Accretion of the La Ronge and Lynn Lake arcs and associated marginal basins, along the eastern Hearne margin occurred during the same period and extended to ca. 1.85 Ga (Corrigan et al., 2005, 2009; Meyer et al., 1992), resulting in the emplacement of a continental-arc, the Wathaman-Chipewyan batholith (ca. 1.865–1.855 Ga; Fumerton et al. 1984, Meyer et al. 1992). Similar age plutonic rocks formed in the Flin Flon-Glennie complex (1.86–1.846 Ga; (Bickford et al. 1987, Whalen et al. 1999), possibly due to collisions between the already accreted La Ronge-Lynn Lake arc domains and the Flin Flon-Glennie complex (Zwanzig, 2000, Corrigan et al. 2005). Extension of the Flin Flon-Glennie complex, potentially from slab roll-back, resulted in back-arc basin development, and deposition of ca. 1.85 to 1.83 Ga fluvial and alluvial sediments on the exhumed accreted arc terranes (Ansdell et al. 1995, Corrigan et al. 2009). This period preceded the development of the Pelican décollement due to the underthrusting of the northward-moving Sask craton (Ashton et al. 2005, Corrigan et al. 2009).

The final closure of the Manikewan Ocean during the collision of the Superior and Rae-Hearne cratons with the Reindeer zone (ca. 1.83–1.80 Ga) is marked by the cessation of successor arc plutonism ca. 1.83–1.825 Ga (Van Schmus et al. 1987, Ansdell 2005, Corrigan et al. 2009). During this collisional phase, there was widespread deformation (D₂) and regional greenschist and amphibolite facies metamorphism

(Lewry and Collerson 1990). The final stage (ca. < 1.80 Ga) recorded late- to post-collisional deformation (D₃) across the Reindeer zone, during which some regional-scale shear zones underwent brittle reactivation, including the Tabernor system (Lewry et al. 1990, Elliott 1995, Wood 2016). Orogenic gold deposits in the Reindeer zone share a broad spatial and temporal association with these ductile-brittle systems, reactivated during D₃ deformation (Corrigan et al., 2007). Volumetrically small, late- to post-peak metamorphic granitoid and pegmatite occur throughout the Reindeer zone, including the Jan Lake granite suite (ca. 1770–1760 Ma) in the Flin Flon-Glennie complex (Bickford et al. 1987).

2.1.2. The Pine Lake greenstone belt in the Glennie domain

The Glennie domain, which is bounded by the Stanley shear zone and Tabernor fault system (Delaney and Cutler 1992), comprises volcanic and siliciclastic assemblages between plutonic rocks. The Pine Lake greenstone belt is divided into three assemblages (Fig. 2): Assemblage A (ca. 1884–1870 Ma), Assemblage B (ca. 1840 Ma), and the Porky Lake Group (>1842 Ma). Mafic to intermediate, volcanic to volcanoclastic rocks of Assemblage A are unconformably overlain by the felsic volcanic to volcanoclastic and sedimentary rocks of Assemblage B. The siliciclastic Porky Lake Group occurs primarily within the core of the Ray Lake synform in contact with Assemblage A rocks (Fig. 2; Delaney and Cutler 1992, McNicoll et al. 1992). The age of the Porky Lake Group is > 1842 ± 4.5 Ma, based on the age of a cross-cutting granodiorite intrusion (Dixon et al. 2026). Various intrusive units cut Assemblage A (Fig. 2) including: the gabbroic to dioritic rocks of the Laonil Lake intrusive complex near the Seabee deposit (1879 ± 1.3 Ma; Witvoet 2023), granodioritic Eyahpaise Lake pluton (1859 ± 5 Ma; Van Schmus et al. 1987), the multiphase Eisler intrusive complex near the Fisher property (1883.8 ± 0.9 Ma; Witvoet 2023), and the tonalitic Lizard Lake pluton near the Santoy deposits (1874.6 ± 1.9 Ma; Wood 2016). The Santoy shear system primarily crosscuts adjacent Assemblage A and intrusive units and hosts auriferous quartz veins (Delaney and Cutler 1992, Durocher et al. 1992, Wood 2016). These supracrustal units were cut by late granodioritic plutons and pegmatite dykes, including the 1807 ± 7 Ma anatectic Packman Lake pluton near Santoy (Lewry et al. 1990, Wood 2016).

The structural history of the Pine Lake greenstone belt is summarized by the regional deformation history. Southwest directed thrusting during the intra-oceanic accretion event resulted in regional D₁ deformation, which includes north- to northwest trending isoclinal folds (F₁) (Lewry et al. 1990). Glennie domain rocks were then involved with the collision with the Sask craton, and the subsequent collision between the Superior and Hearne craton (ca. 1840–1800 Ma). This phase of ductile deformation (D₂) generated i) east-west-trending folds (F₂); ii) transposed regionally pervasive, axial-planar S₂ foliation (S_{0/1/2}); and iii) shear zones and domain-bounding high-strain zones (Lewry et al. 1990, McEwan 2013, Wood 2016). Late- to post-collisional deformation (D₃; ca. 1800–1735 Ma) is characterized by regional scale, north-northwest-plunging folds, including i) the Ray Lake synform; ii) the Carruthers Lake antiform; and iii) the Carruthers Lake synform, from west to east, respectively (McEwan 2013, Wood 2016). Additionally, D₃ resulted in i) north-south-trending transposed axial planar foliation (S₃) parallel with shear zone development and reactivation; ii) Type 2 and 3 interference folds (F₂₋₃); and iii) the Tabernor system exhibited shear movement from dextral-reverse oblique-slip (early-D₃) to terminal ductile D₃ sinistral strike-slip (Elliott 1995, Wood 2016). Post-collisional shortening between the Rae-Hearne and Superior cratons and associated brittle deformation (D₄; <1735 Ma) lead to the formation of northeast-plunging Type I interference folds (F₄), forming regional dome-basins structures (Lewry 1977, McEwan 2013). Rocks of the Glennie domain were subjected to temperatures and pressures around 500–650°C and 2.5–7 kbar during D₂ (Durocher 1997) and 655–705°C and 6.1–7.3 kbar during D₃ (Durocher et al. 2001), peaking at 1810 ± 10 Ma (Schneider et al. 2007) resulting in regional upper greenschist to lower amphibolite

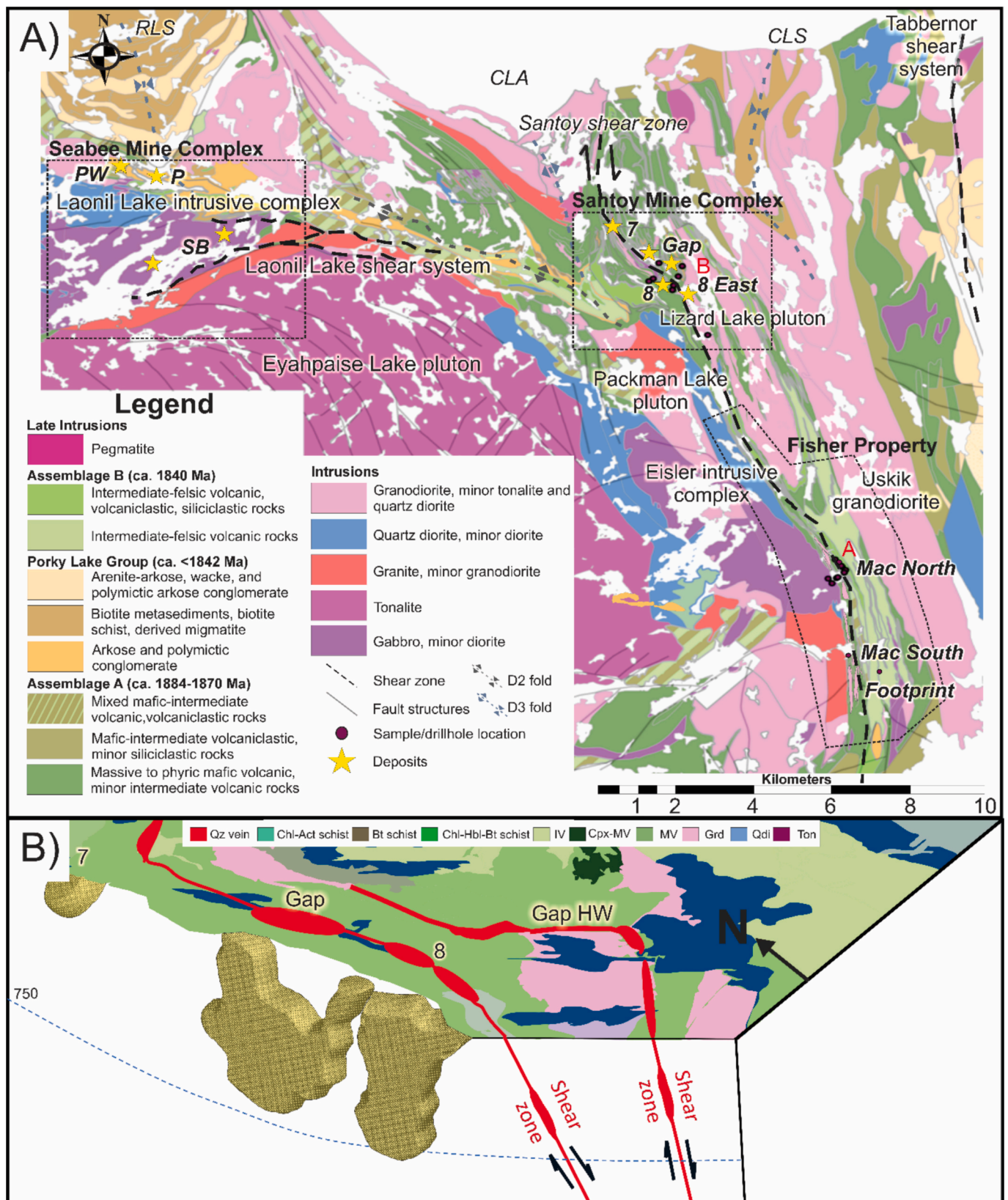


Fig. 2. A) Geology of the Pine Lake greenstone belt at the Seabee Gold Operation of the area highlighted in Fig. 1, showing the Seabee Mine Complex, Santoy Mine Complex, and Fisher property, as well as important units and surrounding structure. Deposit labels: SB: Seabee; 7: Santoy zone 7; 8: Santoy zone 8; Gap: Santoy gap; 8E: Santoy zone 8 east; P: Porky Main; PW: Porky West (modified from Delaney 2016, Beaudin et al. 2024). RLS: Ray Lake synform; CLA: Carruthers Lake antiform; CLS: Carruthers Lake synform. B) Santoy deposit model showing that gold deposits are contained within a releasing bend on the Santoy shear zone. The following are the labels for B) 7: Santoy zone 7; 8: Santoy zone 8; Gap: Santoy gap; Gap HW: Santoy gap hanging wall; IV: intermediate volcanic; Cpx-MV: clinopyroxene-phyric mafic volcanic; MV: mafic volcanic; Grd: granodiorite; Qdi: quartz-diorite; Ton: tonalite.

grade metamorphism.

2.2. Geological characteristics of the host rocks and mineralization at the Seabee gold Operation

Gold mineralization characteristics at the Seabee Gold Operation, including the Seabee and Santoy Mine complexes and the Fisher property are variable (e.g., Durocher et al. 1992, Tourigny 2003, Wood 2016, Kenwood 2017). The Laonil Lake shear system at Seabee hosts high grade ore (~7 g/t; SRK Consulting 2017) within auriferous quartz-tourmaline-carbonate veins, which include free to sulfide-bound gold and cut through the Laonil Lake intrusive complex adjacent to felsic dykes (Basnett 1999, Tourigny 2003, Tourigny et al. 2004). At Santoy, higher grade (~10 g/t; SRK Consulting 2017) native to sulfide-bound gold is hosted by quartz-carbonate veins within the Santoy shear system, cutting Assemblage A and adjacent intrusions (Durocher et al. 1992, McEwan 2013, Kremer and Carlson 2017). Increased fracture density associated with a compressional jog along the Santoy shear system and the buttressing effect of the Packman Lake pluton during D₃ may explain the mineralized zones at Santoy (Wood 2016). The deposits adjacent to Porky Lake (Porky Main and Porky West) show indicated gold grades of 5.2 g/t (SLR International Corporation, 2024), are mostly vein-hosted and occur as visible gold.

Host rocks at the Seabee Gold Operation typically comprise sheared and altered Assemblage A volcanic rocks and various intrusive rocks. Fisher and Santoy properties contain similar rock types, mineral assemblages, and textures, suggesting that the lithology and structures at Santoy extend south through the structural corridor onto the Fisher property (e.g., McEwan 2013, Wood 2016, SRK Consulting 2017, SSR Mining 2019, Onstad 2021, Witvoet 2023). Three quartz vein generations (V₁-V₃) occur at Fisher and Santoy, cutting lower amphibolite-grade sheared *meta*-basalt to chlorite-hornblende-biotite ± garnet schist, and granodiorite to tonalite host rocks (Figs. 3, 4). The V₁ quartz veins are deformed and in places mylonitized, and contain minor pyrite and pyrrhotite; the V_{2a} veins are weakly crenulated and boudinaged, cm-scale quartz-albite ± diopside-sulfide-K-feldspar-carbonate veins; the V_{2b} veins are weakly deformed, cm- to m-scale recrystallized quartz-carbonate ± sulfide veins; V₃ veins are crosscutting cm-scale quartz and/or carbonate-hematite veins (Beaudin et al. 2024). Similar alteration-mineralization assemblages were identified at Fisher and

Santoy (Fig. 3C-F), including distal sericite-biotite-chlorite-clinozoisite ± albite, titanite (Fig. 3C,E) to vein-adjacent, coarse-grained diopside-K-feldspar-albite-actinolite ± apatite, titanite calc-silicate alteration (Fig. 3E,F), associated with main-stage pyrite_{3a}, _{3b}-chalcopyrite₂-pyrrhotite₁-gold mineralization (*syn*-late-D₃); remobilized, fracture-filling pyrite₄-pyrrhotite₂-chalcopyrite₃-gold-tetradymite-tellurobismuthite mineralization within the calc-silicate assemblage (Fig. 3F) (late-D₃); and early colloform pyrite₂ (late-D₂ to *syn*-D₃) and intrusion-hosted, inclusion-rich pyrite₁ (pre-D₁) (Beaudin et al. 2024). This study builds on this framework, providing a comprehensive analysis of sulfide mineral phases and trace-element chemistry to further understand hydrothermal processes associated with gold mineralization along the Santoy shear system.

By contrast, the Porky deposits in the Seabee Gold Operation do not occur along the Santoy shear system and are hosted in both Assemblage A and Porky Lake Group. The Porky deposits (Porky Main and Porky West) occur primarily along the late-D₂ Pine Lake shear zone and within the D₃ Ray Lake synform (Fig. 1.). While the mineral paragenesis of the Porky deposits is considered to be similar to that of the Santoy and Fisher system, the V₂ veins that contain visible gold and their Apy-Py4a/b-Po3-Ccp3 association are considered the main gold stage that predated peak metamorphism associated with D₂ (Dixon et al. 2026). Gold was remobilized during exhumation associated with the transition to brittle deformation, likely coeval with other deposits in the belt ca. 1.76 Ga (Dixon et al. 2026).

3. Materials and methods

Polished thin sections were prepared from core samples with variable alteration and mineralization (Appendix A) collected from the Santoy 7 and Santoy Gap deposits and the Fisher property. They were analyzed by transmitted and reflected light petrography using a Nikon Eclipse E200 polarizing microscope to determine mineral assemblages, textures, and rock type. A detailed analysis of vein and vein-adjacent mineralogy was performed to identify mineral phases associated with progressive alteration and mineralization to facilitate construction of the paragenetic sequence. Prefixes were assigned to the unaltered to vein-adjacent alteration mineral assemblages, where “WR-” denotes the unaltered and foliated mineral phases, and “H-” denotes the wider halo-shear alteration located in the unaltered and distal alteration

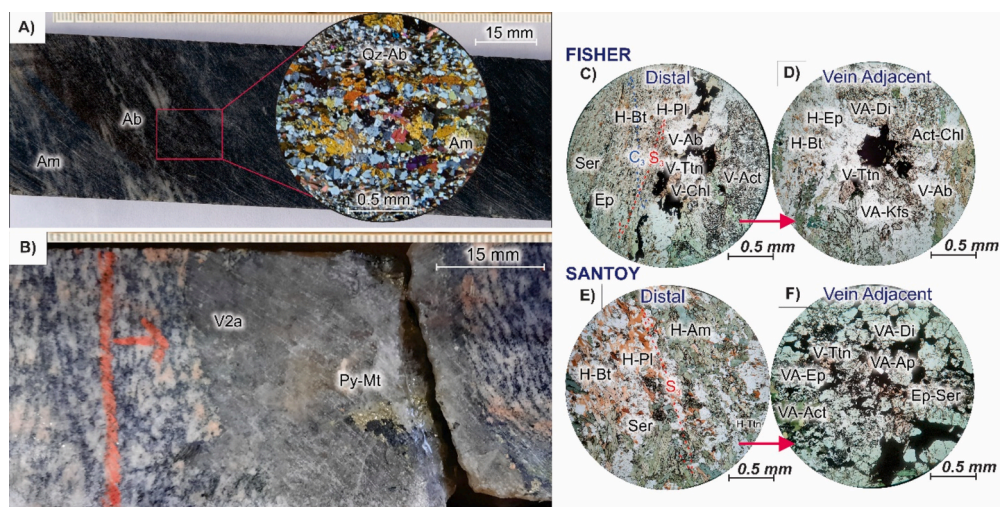
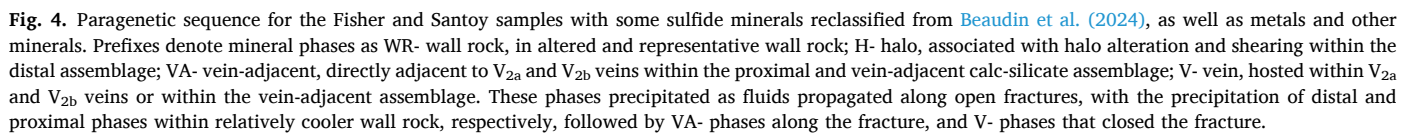


Fig. 3. Representative and altered lithologies from the Fisher and Santoy properties, modified from (Beaudin et al. 2024). A) representative mafic volcanic rock with minor albite alteration. B) Altered granodiorite with moderate Ser-Kfs-Ab alteration adjacent to V_{2a} vein, hosting Py-Mt-Cpy mineralization from Santoy Gap HW. C) Distal Ser-Bt-Ep ± Ab-Ttn alteration associated with V_{2a} vein and vein-hosted Py_{3a}-Chl-Act within a Chl-Hbl-Bt schist. D) V_{2a} vein associated with vein-adjacent Di-Kfs-Ab-Act-Ttn ± Ap alteration and Py with proximal Ser-Bt-Chl-Am-Ttn-Ep alteration within a Chl-Act schist. E) Bt-Ser-Ab-Ttn ± Ep alteration distal to V_{2b} vein within a Chl-Bt-Hbl Schist. F) Coarse grained Di-Act-Ttn-Kfs-Ap ± Ab alteration within fine-grained Ep-Ser. Associated with Au-Po mineralization adjacent to V_{2b} vein within a Chl-Ep-Hbl schist.



3.1. Imaging and geochemistry methods

(Appendix B).

The analytical runs utilized a beam size of 15, 25, and 35 μm for spot analyses, based on grain size, and a laser frequency of 20 Hz. Line analyses (lines or maps) were performed using a scan speed set to half the beam size in $\mu\text{m/s}$ (i.e. scan speed of 10 $\mu\text{m/s}$ for a beam size of 20 μm) to maximize image resolution and decrease potential cross-contamination from one area to the next during the ablation. Line analyses were conducted across both inclusion-poor and inclusion-rich minerals. Data was reduced using Iolite 4 (using NIST 610 and FeS_4

for external standard normalization) and further processed using a constructed Python program Appendix D; [Beaudin and Beaudin 2023](#)) which normalizes the line data to electron microprobe Fe values (Appendix B) as the internal standard and generates the element stack plot. Quantitative results obtained from line analyses were compiled and summarized by location and phases, with the mean and median values present in Appendix B and [Table 1](#), and spot analyses extracted from line data to construct a box-whisker diagram.

3.2. U-Pb geochronology methods

For zircon U-Pb geochronology (Appendix C), a granodioritic sill from Mac South (KE-19–090), and an Assemblage A tuff (PK-19–047) from the Footprint area ([Fig. 2](#)) were collected in the field and subsequently sent to Zirchron LLC in Arizona, U.S.A. for mineral separation. The Z1 and Z2 fractions of both samples show clear to weakly orange, prismatic to weakly rounded zircon grains of group G1 and P morphologies or clear, prismatic to weakly rounded, stubby, zircon grains of group L3-L5 and S3-S5 morphologies, respectively ([Pupin 1980](#)). The best quality zircon grain populations were chosen and analyzed at the Radiogenic Isotope Geology Lab at Purdue University, U.S.A. via isotope dilution-thermal ionization mass spectrometry (ID-TIMS). Grains were chemically abraded by annealing in a muffle furnace at 900°C for 60 h followed by partial dissolution in 24 mol/L HF and 1 mol/L HNO₃ while held at 210°C for 10 h in a steel jacketed PTFE digestion vessel. Residual grains were rinsed, mixed with the ET535 spike ([Condon et al. 2015](#), [McLean et al. 2015](#)), dissolved, and the Pb and U fractions were

separated using ion chromatography methods. Both Pb and U isotopic ratios were measured on an Isotopx *Phoenix* TIMS instrument at Purdue University.

3.3. Re-Os geochronology methods

For Re-Os analyses (Appendix C), pure Py mineral separates were produced from a Fisher sample of gold-Py-mineralized mafic volcanic rock at the Re-Os Crustal Geochronology Laboratory at the University of Alberta, Canada. The Re-Os dating of pyrite was conducted to establish temporal relationships between potential mineralization events and regional magmatic, volcanic, and metamorphic events. As discussed later in this study, macroscopic observations determined this phase was fracture-controlled, porous, associated with gold mineralization, and hosted within V_{2b} veins, of which coincide with the textural characteristics of remobilized Py₄. Py aliquots (MD1 and MD2) were processed for Re-Os isotope geochemistry by isotope dilution ([Hnatyshin et al. 2020](#)) using weighed aliquots of mixed “¹⁸⁵Re+¹⁸⁸Os+¹⁹⁰Os” spike solution. Purified aliquots of Re and Os were loaded onto nickel and platinum filaments, respectively, for analysis by negative thermal ionization mass spectrometry (N-TIMS) on a ThermoScientific Triton mass spectrometer ([Hnatyshin et al. 2020](#)). Laboratory blanks of < 5 pg Re and < 0.1 pg Os were reported in the course of analysis. The Reference Material 8599 Henderson molybdenite ([Markey et al. 2007](#)) was routinely analyzed as a standard, and during the past 8 years returned an average Re-Os date of 27.78 ± 0.08 Ma (n = 45), indistinguishable from the reference age value of 27.66 ± 0.1 Ma ([Wise and Watters 2011](#)). Rhenium-osmium

Table 1

Summary of elemental concentrations of intrusion-hosted Py₁ and Assemblage A mafic volcanic- hosted colloform Py₂, Py₃, Py₄, and Po₂, showing a quartile range, mean, and median. Calculated from averaged quantitative line analyses. S- from Santoy, F- from Fisher.

Mineral Phase		Co	Ni	Cu	W	Pb	As	Ag	Te	Bi	Au
Py ₁ n = 110	Q1	1.9	91.1	15.4	1.0E-02	21.5	208	0.24	1.1	0.41	1.0E-02
	Q3	15.2	1870	580	4.6	46.6	502	1.5	6.3	4.6	3.0E-02
	Mean	12.1	1602	783	1.2	101.00	416.00	1.30	5.4	5.30	0.34
	Median	5.21	678	109	1.0E-02	123	331	0.65	3.1	1.4	1.0E-02
Py ₂ n = 75	Q1	329	766	5.2	27.2	0.30	0.36	0.01	1.2	3.0E-02	1.0E-02
	Q3	444	141	9.5	53.6	0.72	1.2	0.16	2.2	9.0E-02	0.1
	Mean	388	1116	124	41.8	5.5	2.0	0.45	2.2	0.12	1.6
	Median	387	114	7.0	38.5	0.46	0.58	0.14	1.3	6.0E-02	1.0E-02
F-Py _{3a} n = 457	Q1	2.4	343	7.5	1.0E-02	0.10	1.2	1.0E-02	1.0E-02	0.10	1.0E-02
	Q3	334	2350	22.1	34.7	3.9	7.7	1.1	2.2	3.9	1.0E-02
	Mean	328	1630	254	18.2	290	9.0	0.97	4.1	3.4	0.43
	Median	24.7	962	22.1	1.4	5.7	2.3	0.32	1.0E-02	0.48	1.0E-02
S-Py _{3a} n = 22	Q1	68.5	47.8	1.7	1.0E-02	34.7	112	1.0E-02	8.7	5.1	1.0E-02
	Q3	560	94.0	23	5.3	172	908	2.0	78.1	25.4	1.5
	Mean	487	108	16	5.3	251	550	0.92	49.7	18.5	0.90
	Median	311	67.8	8.8	5.3	102	377	0.41	26.0	13.9	0.62
F-Py _{3b} n = 355	Q1	4.0	69.8	6.2	1.0E-02	0.72	4.9	1.0E-02	1.0E-02	1.0E-02	1.0E-02
	Q3	426	3830	77.0	1.0E-02	25.1	130	5.0	5.3	1.2	1.0E-02
	Mean	2300	3640	509	3.0	54.2	94.2	5.6	6.6	1.5	1.1
	Median	49.0	556	14.8	1.0E-02	2.5	71.6	1.0E-02	1.0E-02	0.30	1.0E-02
S-Py _{3b} n = 520	Q1	12.3	1.9	5.2	0.0	5.6	1.6	0.30	1.0E-02	1.0E-01	1.0E-02
	Q3	144	120	338	3.1	39,000	156	44.2	81.4	128	0.930
	Mean	292	371	1020	2.3	34,600	105	33.0	49.0	79.3	43.7
	Median	41.7	5.8	28.6	1.0	248	11.1	2.1	5.4	1.7	1.0E-02
F-Py ₄ n = 617	Q1	12.8	96,000	13.9	1.0E-02	3.8	5.6	1.0E-02	1.0E-02	0.28	1.0E-02
	Q3	154	1350	1240	1.0E-02	119	40.9	5.7	20.4	4.2	0.69
	Mean	213	1310	14,000	0.65	1060.0	34.2	411	14.2	3.0	15,000
	Median	71.0	382	57.5	1.0E-02	31.1	17.9	1.1	3.3	1.20	1.0E-02
S-Py ₄ n = 77	Q1	124	1.2	375	1.0E-02	4540	298	50.8	62.4	154	0.88
	Q3	339	7.9	917	0.45	10,900	685	86.5	149	245	2.00
	Mean	238	13.0	996	0.50	9190	519.0	79.1	108	197	2.10
	Median	250	4.4	650	1.0E-02	6240	419	64.9	99.5	204	1.33
F-Po ₂ n = 98	Q1	15.5	69.8	16.2	1.0E-02	1.9	1.9	1.0E-02	1.0E-02	0.15	1.0E-02
	Q3	236	3830	141	3.1	56.7	12.4	3.4	1.0E-02	0.59	0.34
	Mean	136	3020	2590	3.9	765	11.3	2.4	1.3	0.4	27.9
	Median	53.9	1400	33.7	1.0E-02	5.8	5.6	0.90	1.0E-02	0.28	1.0E-02
S-Po ₂ n = 253	Q1	818	774	8.95	0.00	2.6	3.9	1.0E-02	12.6	2.1	1.3
	Q3	1800	1490	62.3	3.87	52.6	13.8	2.0	48.7	15.6	20.9
	Mean	1320	1120	67.5	4.97	1160.0	10.7	81.6	51.2	25.0	8410
	Median	1270	1160	24.7	1.0E-02	10.3	6.6	1.0E-02	26.6	5.7	3.6

model dates are calculated by using the value for the decay constant of ^{187}Re according to Smoliar et al. (1996). Precision of individual dates is reported at the 2 sigma (2σ) level.

4. Results

4.1. Fisher and Santoy sulfide mineral phase characteristics and association with gold mineralization

Paragenetic relationships among alteration, sulfide, and vein minerals at Fisher and Santoy, and their relationship to phases of deformation (Fig. 4), were initially established by Beaudin et al. (2024). This section describes the Py generations and associated sulfide minerals to provide context for the new mineral chemistry data. In summary, Py₁ is pre-D1; Py₂ is late-D2 to syn-D3, syn V1, and wall rock hosted; Py₃ is late D3, syn V2, and wall rock hosted; and Py₄ is late D3 or even post D3 (Fig. 4).

Py₂ occurs within schistose altered rocks at Fisher, where the earliest subhedral cubic or colloform (Fig. 5A, B) pyrite (Py₂) is commonly overprinted by subsequent sulfide and silicate mineral phases. Py₂ is present as relic crystals within cm-scale Py₃-Po₂-Cal lenses (Fig. 5A), cut by Cpy₂-Sp₂ veinlets. Py₂ has minor Ilm-Cpy₁ inclusions and high μm -scale porosity, replacing adjacent Hbl and Bt minerals. Py₂ occurs adjacent to thin V_{2a} veins semi-concordant to S₃ foliation, weakly associated with distal to vein-adjacent alteration, indicating formation during late-D₂ to early-syn-D₃.

Py₃ is associated with gold mineralization. Py_{3a} is primarily associated with subhedral, pitted to fractured, replacement-style and occurs within schists and intrusive rocks, containing Cpy₁-Bt < Pl < Sp₁-Mt-Po-Ilm inclusions (Fig. 5D). Py_{3a} occurs among the distal to vein-adjacent alteration assemblages, aligned semi-concordant to S₃ foliation, defined by strongly aligned Bt-Chl-Am, and adjacent Qz veins (Fig. 5A). Py_{3a} also occurs in thin, deformed V_{2a} and larger, recrystallized V_{2b} veins, both of which are locally observed concordant to S₃ foliation. Inclusion-poor, sub-euhedral, homogenous, medium-grained Py_{3b} is present as replacement-style or fracture-filling within the wall rock and V_{2a,2b} veins, cross-cutting and enveloping Py_{3a} and earlier phases (Fig. 5D,E,F,G). Porous, anhedral to subhedral, replacement-style Po₁ forms around both Py₃ phases, overprinted by porous, anhedral Cpy₂ (Fig. 5B,C). Associated oxide minerals include subhedral, pitted Mt and disseminated fine-grained Ilm. Both Py_{3a} and Py_{3b} phases are also associated with fine-grained Sp₁, trace Apy, trace Hm, trace medium-grained Sch, typically within the vein-adjacent calc-silicate assemblage and associated with Py₃-Po₁ and trace fine-grained, disseminated Au-Ttd-Tbi mineralization. These phases correspond to mineralization during syn-late-D₃ deformation, highlighted by i) the concordance of these Py phases with S₃ foliation and V_{2a} and V_{2b} veins; ii) abundance within the distal, proximal, and locally vein-adjacent alteration assemblages; and iii) association with fine-grained, disseminated native gold and Bi-telluride mineralization.

Py₄ occurs as fracture-filling, inclusion-rich (Qz < Pl < Ilm-Gn < Py-Cpy), sieve-textured, pitted, and is fine-grained anhedral- to locally euhedral. Py₄ occurs in schists and intrusive rocks at the Fisher and Santoy properties, primarily filling foliation-concordant fractures throughout the wall rock (Fig. 5F,I), or locally concentrated within fractured competent grains, such as Di, within the calc-silicate alteration assemblage (Fig. 5J,K). This phase forms around Py₃ and other associated sulfide phases (Fig. 5B,C,F), is associated with an-subhedral medium- to coarse-grained Po₂, Cpy₃, and Sp₂ mineralization (Fig. 5G), and is distributed throughout the vein-adjacent assemblage and V_{2a} and V_{2b} veins, locally occurring in vein microfractures. Po₂ and Cpy₃ phases are an-subhedral, pitted, porous, sieve-textured and form thin veinlets with Py₄ within fractured wall rock and earlier sulfide phases (Fig. 5C), or, locally, they form around replacement-style, fine- to medium-grained Py₄ within the vein-adjacent assemblage of the wall rock (Fig. 5F).

Santoy yields higher grade gold mineralization (notable intercept

include 15–110 g/t gold over 0.25–3 m; OreWin, 2021) relative to Fisher (notable intercept – 10.0 g/t gold over 1 m; SSR Mining 2019), coupled with a modal increase in Po₂, which locally replaces Py₃ mineralization (Fig. 5L) and is associated with minor fracture-filling Gn, locally filling the pores of earlier Py_{3a} (Fig. 5G,M), subhedral Mt, trace Hm and isolated Apy, euhedral, replacement-style Mol, and trace replacement-style Sch within the vein-adjacent alteration (Fig. 5K). A minor occurrence of subhedral, fine- to medium-grained, less porous, inclusion-free Py_{4b} over-growth is present, locally, on the edge of Py₄ (Fig. 5M). Significant gold mineralization is associated with fracture-filling Py₄-Po₂ mineralization in Fisher and Santoy samples (Fig. 5J,K), and is typically enveloped by Tbi, which also forms around Ttd. Gold is locally present as thin veinlets within the wall rock and as inclusions within fracture-filling Py₄ mineralization (Fig. 5J). The fracture-filling and late paragenetic relationships that Py₄ and associated sulfide-gold-telluride phases share with the proximal to vein-adjacent alteration assemblages suggests that these phases were remobilized during continuous late-D₃ deformation (Fig. 4).

Similar sulfide phases are observed at the Fisher property and Santoy Mine Complex adjacent to or within V_{2a} and V_{2b} veins that cut intrusive lithologies (Fig. 5M,N). Py₁, which is inclusion-rich (Ilm-Gn-Cpy < Pl-Qz), sub-euhedral, pitted, fractured, and deformed, occurs as disseminations within intrusive wall rock (Fig. 5N,O). Py₁ is overprinted and enveloped by Py_{3b} and Py₄ within the proximal to vein-adjacent assemblages (Fig. 5M,N). Thus, Py₁ formed prior to D₃ deformation and broadly coeval with pre-kinematic intrusions, which is evidenced by significant fractures and deformed fabrics within Py₁, occurrence solely within intrusive host rocks, and an early paragenetic relationship with other phases. Although Py₁ is not apparent in V_{2a} and V_{2b} veins, a modal percentage increase of base metal minerals is observed in V_{2b} veins that cut intrusive lithologies, comprising i) fine-grained, fracture- and pore-filling galena, typically filling porous Py_{3a} (Fig. 5M); ii) medium-grained, an-subhedral Mt associated with Py_{3a} and Py_{3b} mineralization; iii) fine- to medium-grained, anhedral, fracture-filling Sp₂, typically associated with Py_{3b}; and iv) fine- to medium-grained, anhedral, porous Cpy₂ and Cpy₃ which form around earlier phases and fill fractures. Similar to schists, V_{2b} veins that cut intrusive lithologies host inclusion-rich, subhedral, porous, medium-grained Py_{3a}, enveloped by inclusion-free, sub-euhedral Py_{3b}, of which is rimmed by anhedral, sieve-textured, fine-grained Py₄ (Fig. 5M,P). This latter Py₄ phase is typically associated with other remobilized minerals, such as Gn, Mt, Sp₂, Cpy, trace Hm, and locally trace gold-telluride mineralization (Fig. 5N,P,Q).

4.2. Fisher and Santoy sulfide mineral chemistry

Composite mineral element maps (Figs. 6, 7) show variable concentrations of elements within the four pyrite generations, some of which appear to be hosted in the pyrite lattice, and others in inclusions within grains. Table 1 summarizes the range of concentrations for Co, Ni, Cu, W, Pb, As, Ag, Te, and Bi in pyrite and pyrrhotite. The values for Au are typically low (<1 ppm), and the highest values are observed in Py₃ from Santoy (Table 1). Overall, the element abundances and patterns are consistent across equivalent pyrite phases (Py₁-Py₄) at Fisher and Santoy.

Py₁ shows elevated concentrations of lattice-bound and inclusion-controlled Se, Pb and As (Fig. 6A). Py₄ envelopes Py₁ and shows elevated concentrations of As, Bi, Pb and Te (Fig. 6A). The element variations in Py₄ appear to be controlled by inclusions, which are not discernible in BSE (Fig. 6A). In Py₄ As, Se, Te, Pb, and Bi are spatially related, but heterogenous in their distribution within the grain, and likely occur in elevated concentrations within inclusions (Fig. 6A,C). In contrast Co, Ni, and Se are more homogeneously distributed throughout the lattice. In contrast, Py₂ is enriched in Co and Ni, with subtle variation in W and Cs towards the contact with Py_{3b} (Fig. 6B).

Compared to Py₁ and Py₂, the concentrations of most elements are

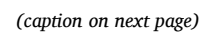


Fig. 5. Photomicrographs, BSE images, and core photo showing multiples stages of sulfide mineralization in Assemblage A mafic volcanic rock and felsic intrusive rock samples (modified from Beaudin et al. 2024). A) Py_{3b} overprinting Py_{3a} with anhedral Po₂ forming around earlier phases and relict Py₂ (20DBF-24). B) Porous Py_{3a} overprinting colloform Py₂ with Py₄ forming along the grain boundaries and overprinting Po within a sulfide lens (20DBF-24). Red box shows a zoomed view of colloform Py₂. C) Py_{3a} overprinted by Py_{3b} and Py₄ forming around the edges of earlier phases (Po₂ and Cpy₂ which form around Py₃) (20DBF-13B). D) Py_{3b} forming around porous Py_{3a} core with Py₄ along the outside (21DBS-12). E) V_{2b} vein hosting Py_{3a} with enveloping Py_{3b} and fine-grained Py₄ filling fractures and forming along the edges of earlier phases (20DBF-2B). F) Anhedral Py_{3b} with Po₂ forming around and fracture-filling Py₄ and Cpy₃ mineralization (20DBF-13B). G) V_{2b} vein hosting Py_{3b} mineralization with fine-grained Py₄ forming along the outside and filling fractures associated with Gn and Sp₂ (20DBF-16B). H) Zoomed insert of D; showing minor Au-Tld mineralization associated with Py₃ (20DBF-24). I) Py₄ forming around euhedral Py_{3b} core (21DBS-12). J) fracture-filling Py₄ associated with gold mineralization adjacent to V_{2b} vein (20DBF-1A). K) Py₄ associated with Po₂, minor Sch, and gold-telluride mineralization (SAN7-05). L) Po₂ replacing Py_{3b} associated with gold elsewhere in the sample (SAN7-05). M) V_{2b} vein hosting Py_{3b} with Py_{3a} cores with Py_{4/4b} forming along the edge associated with Sp₂ and Gn (21DBS-04). N) Porous, inclusion-rich Py₁ with Py₄ forming along the edges (20DBF-10A). O) Inclusion-rich Py₁ core with Py₄ forming along the outside adjacent to a V_{2b} vein (20DBF-10A). P) Corresponding Py-Au mineralization occupying a microfracture in a V_{2b} vein that cuts altered granodiorite (21DBS-03). Q) V_{2b} vein cutting altered granodiorite, hosting Py-Au mineralization (21DBS-03).

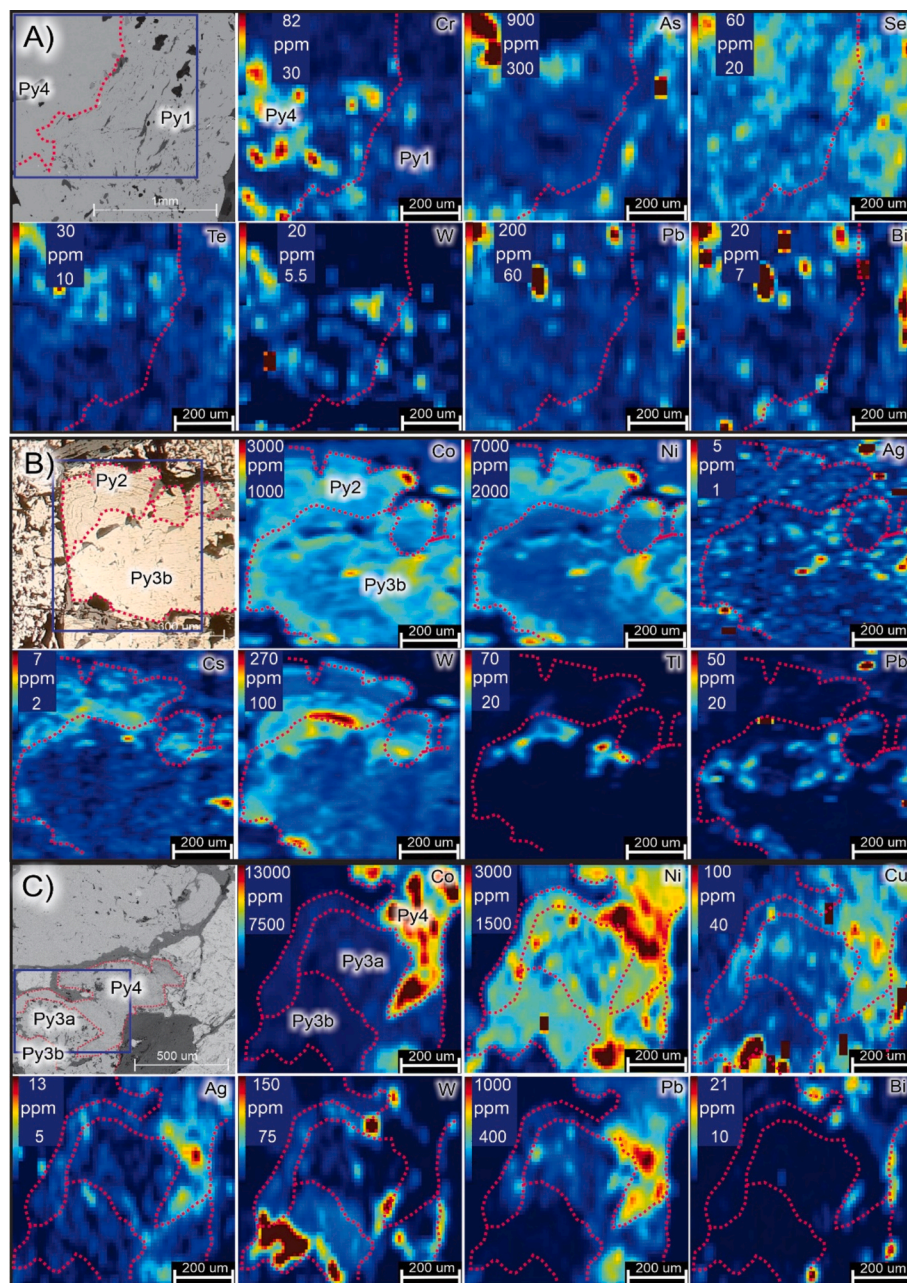


Fig. 6. Semi-quantitative LA-ICP-MS element maps showing the elemental distribution of selected elements within Py phases. Element maps are of the area identified with the blue box on respective BSE images. A) 20DBF-10A (granodiorite), B) 20DBF-24 (Hbl-Bt-Chl schist), and C) 20DBF-24 (Hbl-Bt-Chl schist). BSE images and photomicrographs of sulfide minerals are outlined in red, which correspond to the area outlined in red on the element maps. Elements are in order of atomic weight.

generally higher in Py_{3a} and Py_{3b}, although the distribution is complex (Fig. 7A-C). In Py_{3a}, lattice-bound Co and Se are homogenous, however,

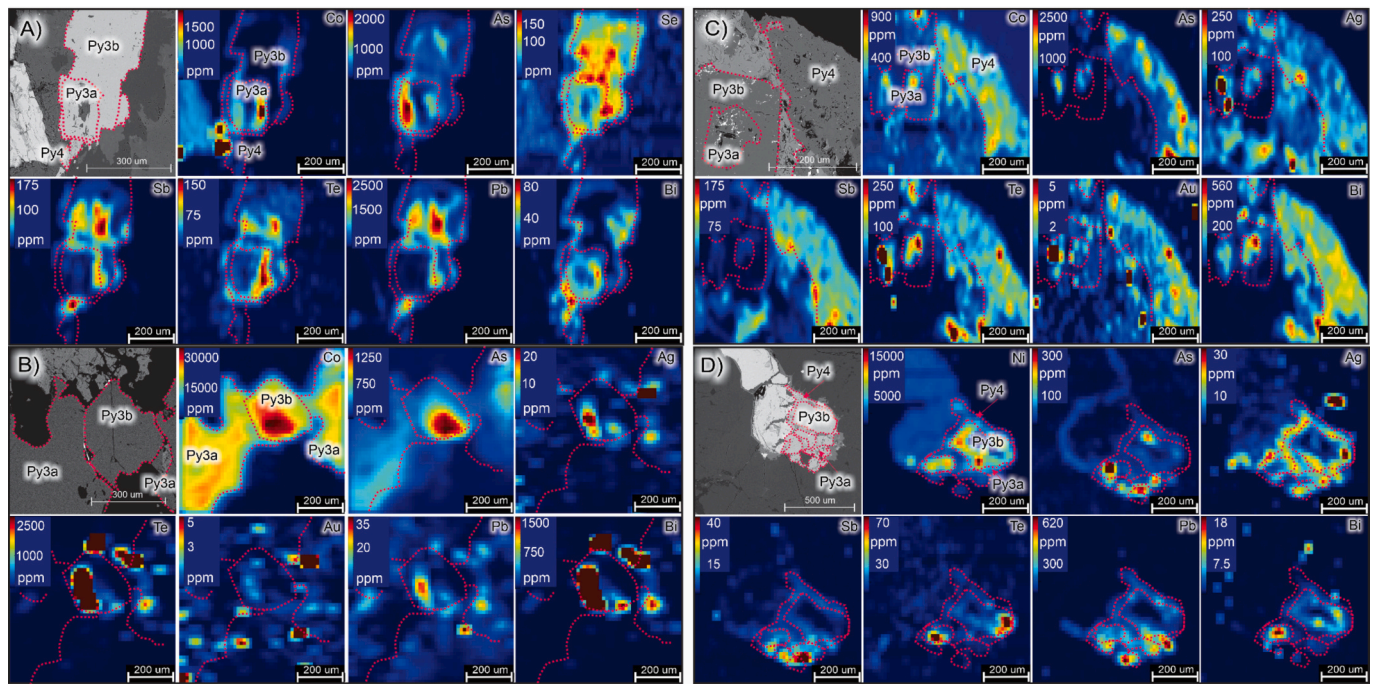


Fig. 7. Semi-quantitative LA-ICPMS element maps showing the elemental distribution of selected elements within Py_3 and Py_4 phases. The corresponding elements encompass the entire area of the respective BSE image, however, figures maps C and B are zoomed out from the BSE image. A) 21DBS-12 (Bt-Hbl schist), B) 20DBF-24 (Hbl-Bt-Chl schist), C) 21DBS-04 (tonalite) and D) 20DBF-13B (Chl-Di-Bt-Hbl schist). BSE images and photomicrographs of sulfide phases are outlined in red, which correspond to the area outlined in red on the element maps. Elements are in order of atomic weight.

As, Ag, Te, and Bi concentrate at- or near inclusions, and generally increase towards the rim (Fig. 7A-C). Similarly, Py_{3b} displays similar

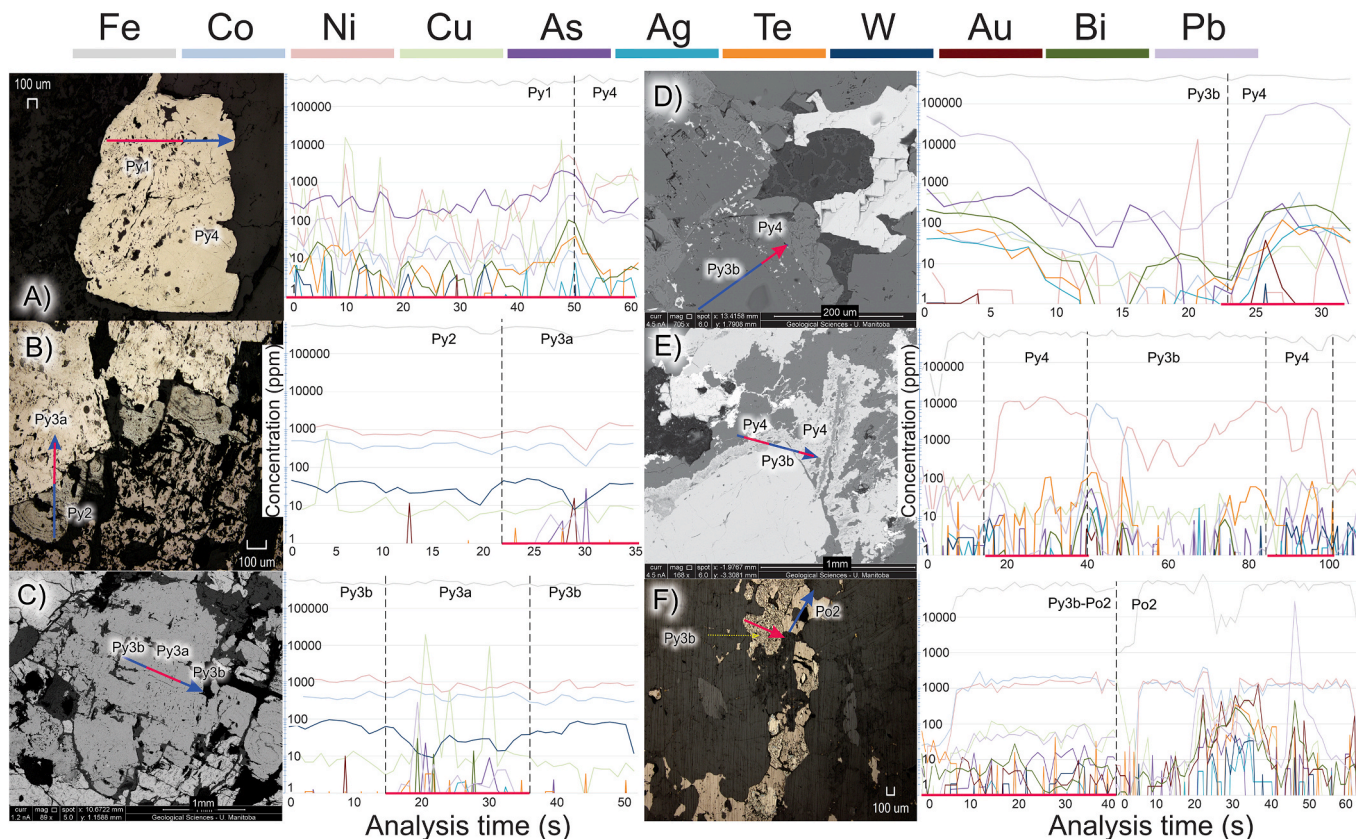


Fig. 8. Elemental stack plots, showing the concentration of selected elements along the line portrayed on the respective BSE or photomicrograph images of Py and Po phases. A) 20DBF-10A (granodiorite), B) 20DBF-24 (Hbl-Bt-Chl schist), C) 20DBF-24 (Hbl-Bt-Chl schist) D) 21DBS-04 (tonalite), E) 20DBF-16B (Hbl-Chl Bt schist), F) Combined analyses from SAN7-05 where Po_2 replaces Py_{3b} (Ep-Chl-Hbl schist).

elemental relationships to Py_{3a}, albeit in higher abundances that concentrate towards the rim, and which are not controlled by inclusions (Fig. 7A,B). Relative to Py_{3a}, however, Py_{3b} exhibits higher concentrations in lattice-bound Co, Sb, and Pb coupled with a decrease in Ni (Fig. 7A-C).

Although each of the Py₁ to Py₄ phases yield rare gold inclusions, µm- to cm-scale free gold is primarily associated with inclusion-rich Py_{3a}, Py_{3b}, and Py₄ (Fig. 5J,Q 7D). Gold and associated elements (As, Ag, Te, Bi), as well as other elements (Co, Ni, Sb), locally increase in abundance within fine-grained, fracture-filling Py₄ (Fig. 7C,D). Within this phase, Au, As, Ag, Te, and Bi are heterogeneously distributed and are locally concentrated within the core of individual grains or controlled by inclusions (Fig. 7C). In contrast, lower concentrations of these elements display a homogenous distribution within the inclusion-poor zones of the pyrite lattice (Fig. 7C). This phase hosts around 3 ppm lattice-bound Au, although Py₄ is also associated with free gold and other remobilized metals (Fig. 7C). Elemental information from quantitative LA-ICP-MS line analyses (Fig. 8) helps address lattice-bound vs. inclusion-controlled chemistry.

Quantitative LA-ICP-MS line analyses (Fig. 8, Appendix B2) and compiled extracted spot analyses (Fig. 9) determined elemental composition within individual mineral phases, including coeval sulfide mineral phases of Fisher and Santoy. Quartile and median values are reported to limit the effects that outliers have on the dataset because mean values can overestimate concentrations due to the nugget effect and/or micro-inclusions (Table 1). Thus, a high quartile range reflects a more homogenous elemental distribution within the crystal lattice of the sulfide phase. Py₁ (Fig. 8A) yields high but variable concentrations of lattice-hosted Co, Ni, Cu, Pb, and the maximum range of invariant As (Fig. 9, Table 1). Within the inclusion-rich areas, Py₁ contains fluctuating concentrations of Cu, Ni, Co, as well as Ag, Te, W, Bi, and 0.01 to 16.8 ppm trace gold as micro-inclusions or nanoparticles (Fig. 8A, 9, Table 1). Colloform Py₂ shows elevated abundances of lattice-bound Co, Ni, Cu, and W, associated with relatively low, inclusion-controlled As, Ag, Te, Pb, Bi, and 0.01 to 51.9 ppm gold micro-inclusions (Fig. 9, Table 1). Zoning present in semi-quantitative images of colloform Py₂ is less apparent in the element stack plots (Fig. 8B).

In subsequent pyrite phases, only minor variations between the Fisher and Santoy properties are present. All Py_{3a} shows similar elemental abundances of inclusion-controlled/lattice-hosted Cu, W and Pb, which are primarily hosted within the pyrite lattice (Fig. 8B,C, 9, Table 1), whereas Fisher Py_{3a} (Fig. 8B,C) bears significantly more lattice-bound Ni and lower Co concentrations in comparison to Santoy Py_{3a} (Fig. 7A, 9, Table 1). Although concentrations of inclusion-controlled As, Ag, Te, and Bi (Fig. 8B,C) are variable between Fisher and Santoy Py_{3a}, within this phase, they are broadly similar (Fig. 9, Table 1). Gold concentration, however, is notably higher in Santoy Py_{3a} (0.01–1.46, up to 3.36 ppm) than Py_{3a} at the Fisher property (0.01, up to 1.02 ppm) (Fig. 9, Table 1) and comprise gold inclusions and micro-inclusions. Additionally, Fisher and Santoy Py_{3b} phases show similar elemental concentrations to the Py_{3a} from both properties (Fig. 8, Table 1), including lattice-enriched, internally zoned Ni, Co, W, and variable Cu (Fig. 8C,D,E). Py_{3b} phases present at Santoy, however, contain significantly more Pb than Fisher Py_{3b} (Fig. 9, Table 1). Additionally, both Fisher and Santoy Py_{3b} contain higher Pb concentrations than Fisher and Santoy Py_{3a} phases (Fig. 9, Table 1). In some Py_{3b} analyses, high concentrations of zoned Te, As, Bi, and Ag are observed and decrease towards the rim (Appendix B2, Table 1). However, Ag exhibits higher concentrations within Santoy Py_{3b} phases than Fisher equivalents (Fig. 9, Table 1). Within this Py_{3b} phase, trace gold inclusions and micro-inclusions are present (Fig. 8C,E) and are in higher abundance in Santoy Py_{3b} (0.01–0.93, up to 16,500 ppm) in comparison to Fisher Py_{3b} (0.01, up to 5.23 ppm), resulting in higher Au concentrations (Fig. 9, Table 1).

Similar relationships were determined for Py₄, which displays comparable Co and Cu concentrations to the earlier phases (Fig. 9). In contrast, however, Ni is enriched in Fisher and Santoy Py₄ (Fig. 8D,E, 9)

but is depleted in earlier phases at Santoy (Fig. 9, Table 1). Within Fisher and Santoy Py₄, elevated lattice- and inclusion-controlled concentrations of As, Ag, Te, and Bi were identified (Fig. 8D,E) in comparison to previous phases (Fig. 9, Table 1). Py₄ from both properties show increased Au concentrations, which is present as inclusions and invisible Au (Fig. 7A,C, 8D), although Santoy Py₄ contains higher concentrations of invisible Au (0.88–2.00, up to 89.2 ppm) in comparison to Fisher Py₄ (0.01–0.69, up to 22,300 ppm) (Fig. 7C, 9, Table 1). Arsenic, Ag, Te, and Bi concentrations are similar between Fisher and Santoy, however, Santoy Py₄ exhibits slightly higher concentrations and less variability (Fig. 9, Table 1). An important observation is that Po₂ exhibits the lowest variability between the Santoy Mine Complex and the Fisher property (Table 1), in the elements closely associated with Au (Ag, Bi, Te, As). Contrasting with previous phases, Santoy Po₂ (Fig. 8F, 9) exhibits higher lattice-controlled Co concentrations than Fisher Po₂ (Fig. 9, Table 1) and earlier phases, with consistent Ni, Cu, As, Ag, W, Pb, and Bi hosted within the lattice, which are within the range of concentrations identified within Py phases (Fig. 8F, Table 1). Santoy Po₂, however, is slightly more enriched in Te than Po phases present at the Fisher property (Table 1). Of note is the elevated concentration of invisible Au present in Po₂, specifically in Santoy Po₂ (1.29–20.9, up to 1367 ppm) that replaces Py_{3b}, in comparison to Fisher Po₂ (0.01–0.34, up to 62.07 ppm) (Fig. 8F, Table 1).

4.3. Zircon *u-pb* and pyrite *Re-Os* geochronology

4.3.1. Zircon *u-pb* geochronology

Zircon from a low-strain granodiorite from Fisher at Mac South (KE-19-090) and Assemblage A Hbl-phyrlic dacitic tuff from the Footprint area (PK-19-047) were analyzed for U-Pb geochronology. Regressions from Concordia plots utilize Isoplot model 1 constraints with $n = 4$ and $n = 1$ discordant data points for the PK-19-047 and KE-19-090 samples, respectively. The weighted mean ²⁰⁷Pb/²⁰⁶Pb crystallization age for the granodiorite (KE-19-090) is 1882.1 ± 1.7 Ma ($n = 5$, MSWD = 0.19) (Fig. 10A), whereas the weighted mean ²⁰⁷Pb/²⁰⁶Pb crystallization age for the Assemblage A Footprint tuff (PK-19-047) is 1885.58 ± 0.80 Ma ($n = 13$, MSWD = 0.98) (Fig. 10B).

4.3.2. Pyrite *Re-Os* geochronology

Py grains that occur within pyrite-rich vein samples (V2b) equate to the characteristics of Py₄ and are associated with gold mineralization through remobilization (Fig. 4, 5 J). Preliminary analyses of four Py₄ samples recovered from Fisher sample 20DBF-01 revealed adequate concentrations of Re to warrant further Re-Os geochronology analyses. This sample was also identified to be a low level-highly radiogenic (LLHR) sample by an initial Re-Os analysis. Both MD1 and MD2 separates have similar Re and Os contents: 22.56–26.02 ppb Re, 14.18–16.38 ppb ¹⁸⁷Re, 0.4236–0.4877 ppb ¹⁸⁷Os, and 1.1–1.4 pg total common Os (Appendix C). The Re and Os concentrations of these Py separates are consistent with lower-range values determined for Py₄ by LA-ICP-MS analyses, which range from < 0.5 to 3.6 ppm Re. The two Re-Os model dates for the MD1 and MD2 separates were determined to be 1761.4 ± 8.4 and 1766.6 ± 7.7 Ma, respectively. The weighted mean Re-Os model age for Fisher LLHR Py separates from this sample (Table 2) was determined to be 1764.2 ± 5.6 Ma ($n = 2$, MSWD = 0.84, probability = 0.36, 95% CI).

5. Discussion

5.1. Sulfide mineral textures, chemical heterogeneity, and hydrothermal constraints

The paragenetic relationship between sulfide phases (Fig. 4), and the textural and geochemical observations of these sulfide minerals are used to develop a model for the mineralization stages along the Santoy shear system (Fig. 11). Element heterogeneity within phases is likely from the

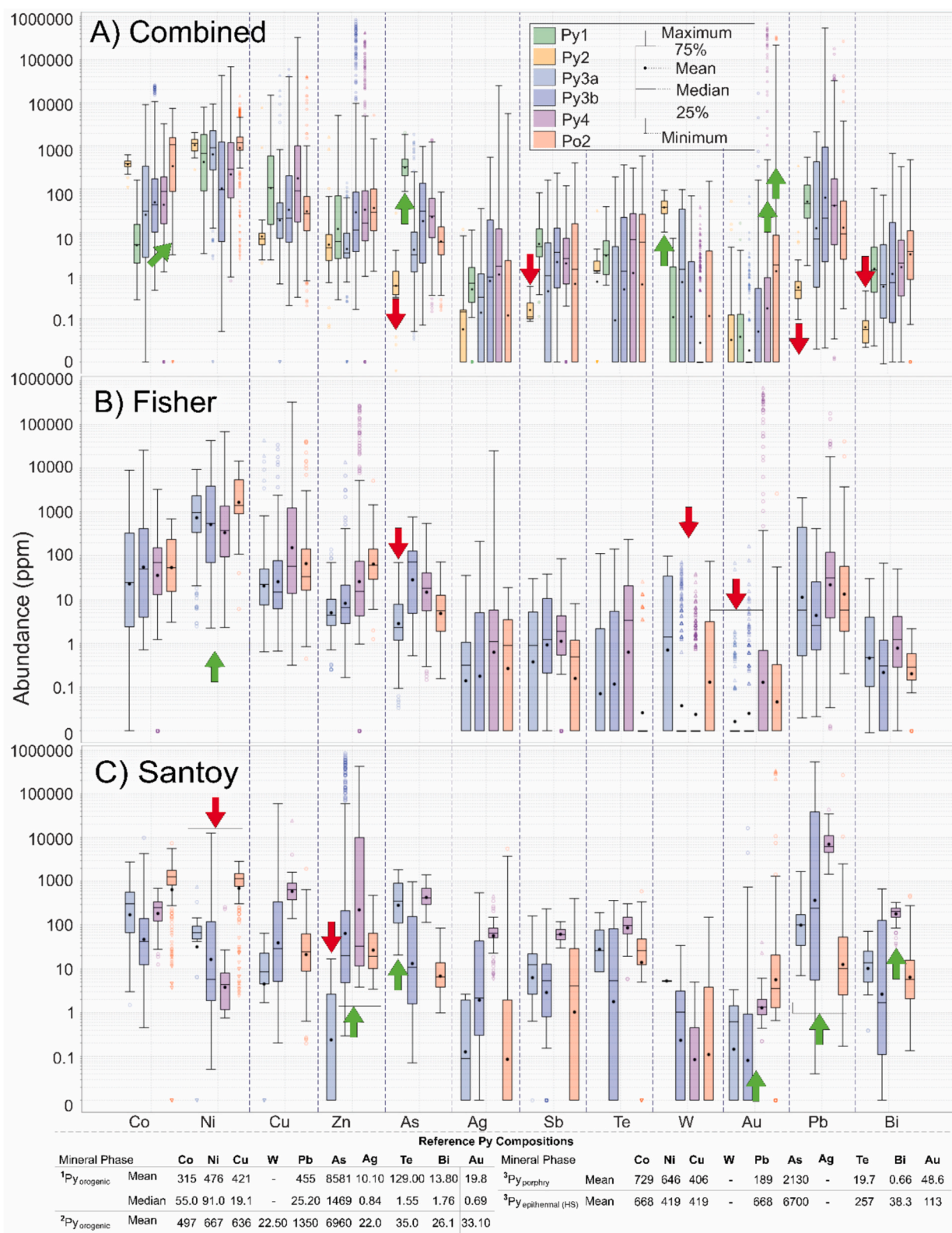


Fig. 9. Box and whisker plot from spots extracted from line data, showing the averaged trace-element compositions from various Py and Po phases. Green and Red arrows show relative anomalous element enrichments and depletions within phases, respectively. A) averaged combined Fisher and Santoy samples, Green arrows: i) linear increase in Co amongst evolving sulfide phases, and anomalously high concentrations of ii) As in Py₁, iii) W within Py₂, and iv) Au within Py₄ and Po₂ phases; Red arrows: anomalously low concentrations of i) As, ii) Sb, iii) Pb, and iv) Bi with Py₁. B) and C) shows Fisher and Santoy sulfide phases where the arrows define trends between the two diagrams, from left to right being i) An increase in Ni within Fisher sulfide phases relative to equivalent Santoy phases, ii) a decrease in Zn within Santoy Py_{3a} compared to Fisher Py_{3a}, but overall increase in the abundance of Zn within Santoy phases, iii) anomalously high As in Santoy Py_{3a} relative to Fisher Py_{3a}, which is lower than subsequent Fisher phases, and iv) decrease in W within Fisher Py_{3a} and Py_{3b} phases compared to equivalent Santoy phases. Additionally, Santoy phases show an overall increase in the concentration of v) Au, vi) Pb, and vii) Bi compared to Fisher sulfide phases. Reference values of pyrite phases from other settings from ¹Cao et al. (2023), ²Belousov et al. (2016), ³Babedi et al. (2022).

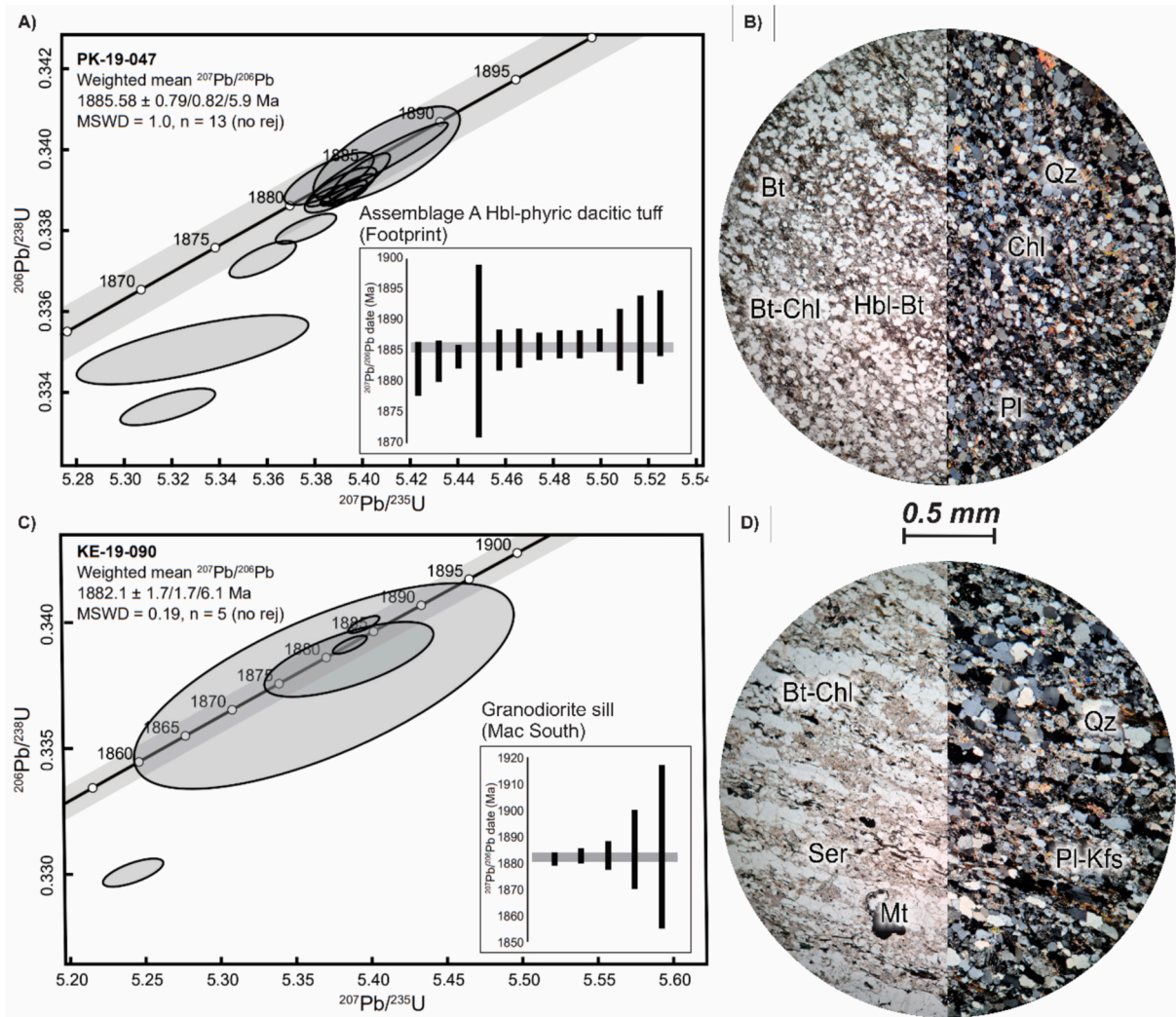


Fig. 10. Concordia diagram for ID-TIMS U-Pb zircon results from Fisher A) Assemblage A Hbl-phyric tuff (PK-19-047) from Footprint. B) Photomicrograph of the Assemblage A tuff from Footprint. Left: transmitted light, right: cross-polarized light C) MAC south granodiorite (KE-19-090) Concordia diagram. All uncertainties are 2σ . Grey band around represents the Concordia location uncertainty from decay constant uncertainties. Weighted mean age uncertainties X/Y/Z represent the sequential inclusion of analytical/tracer/decay constant uncertainties. Insets: Ranked age plots of the $^{207}\text{Pb}/^{206}\text{Pb}$ dates from individual crystals. Grey band is the weighted mean age and uncertainty. Decay constants are those defined by Jaffey et al. (1971). D) Photomicrograph of the granodiorite sill from Fisher at Mac South. Left: transmitted light, right: cross-polarized light.

Table 2
Rhenium-osmium isotope geochemistry data for two aliquots of Py-001 MD1 and MD2.

Sample	Composition		^{187}Re (ppb)	$\pm 2\sigma$	^{187}Os (ppb)	$\pm 2\sigma$	Total common Os (pg)	Dates (Ma)	
	Re (ppb)	$\pm 2\sigma$						Model Age	$\pm 2\sigma$
20-DBF-001 PY-001 MD1	26.06	0.07	16.38	0.05	0.4877	0.0011	1.4	1761.4	8.4
20-DBF-001 PY-001 MD2	22.56	0.06	14.18	0.04	0.4236	0.0005	1.1	1766.6	7.7
Weighted Mean Age (Ma)									
Model Age	$\pm 2\sigma$	MSWD	P						
1764.2	5.6	0.84	0.36						

inclusion-controlled nature of elements as well as the recrystallization or precipitation of minerals during later hydrothermal events as discussed below.

Sulfide phases found in altered granitoid intrusions that cut Assemblage A volcanic rocks (Fig. 11A), were interpreted to have formed early in the paragenetic sequence. The intrusion-hosted, inclusion-rich Py_1 phase, which contains anhedral porous textures and numerous inclusions, is consistent with crystallization from Py -supersaturated solutions under low fluid/rock ratios and non-equilibrium conditions (Craig et al. 1998, Cioacă et al. 2014, Wu et al. 2021, Liu et al 2023). These

conditions promote lattice deformities and resulting vacancies, favouring the uptake of As, Au, Te (Fig. 9A), and other associated elements (Reich et al. 2005, Keith et al. 2018). The characteristics of Py_1 demonstrate these traits, including i) presence of gold inclusions or Au nanoparticles, and porous textures; ii) isolated occurrence in intrusive units; iii) presence of deformed fabrics and fractures from subsequent deformation events; and iv) Ni-Cu-Zn-As lattice-controlled and inclusion-controlled As-Te-Au trace-element anomalies (Fig. 6A, 8A, 9). The latter are known polymetallic signatures in intrusion-hosted systems (Sillitoe and Thompson 1998, Ispolatov et al. 2008) and in magmatic-

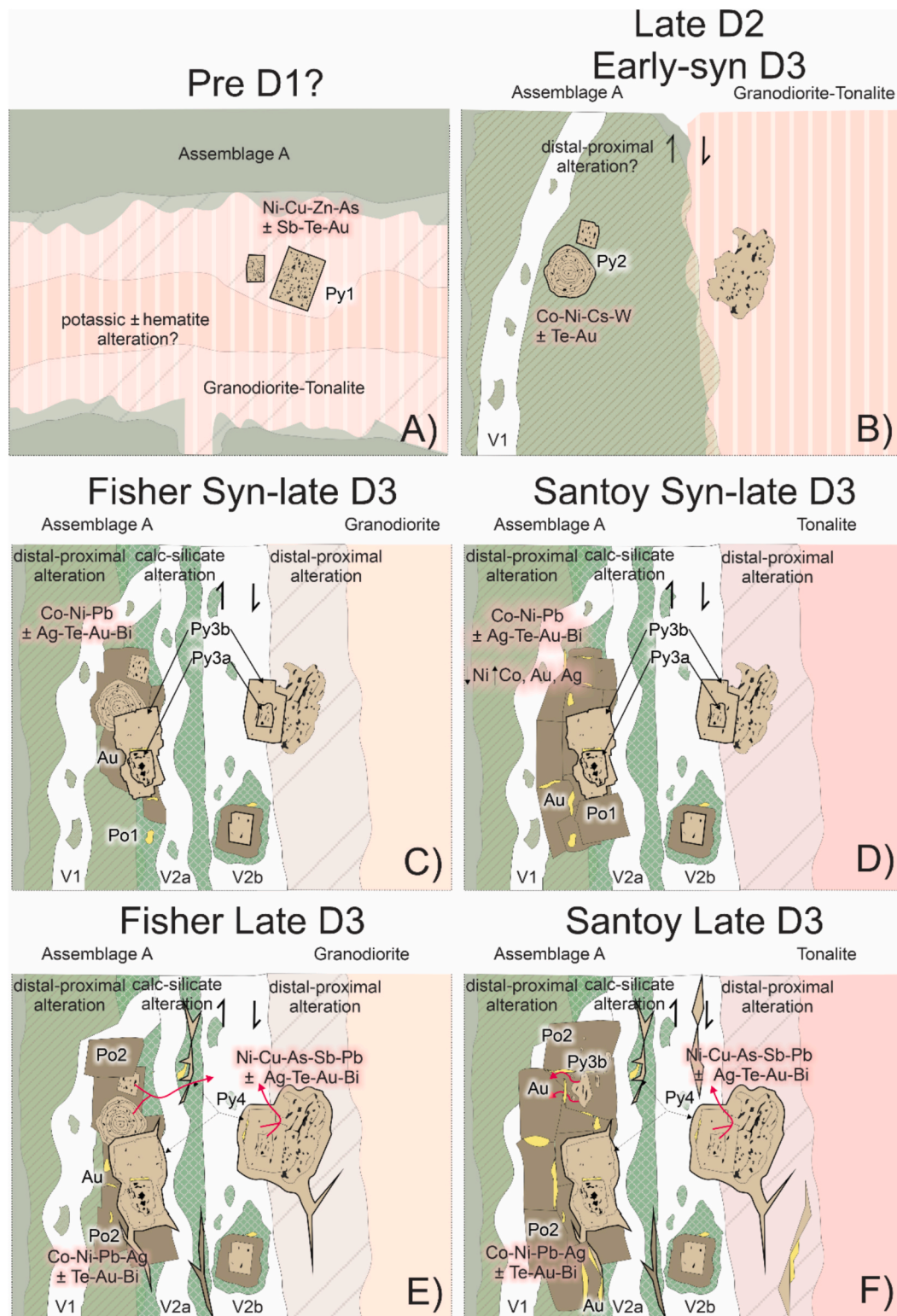


Fig. 11. Metallogenic sulfide mineral-gold model for the Fisher property and Santoy Mine Complex, highlighting the characteristics and relative timing of alteration and minerals. Sulfide minerals and gold are enlarged in this diagram to portray textural characteristics. A) Pre-D₁ Py₁ mineralization and associated proposed alteration assemblage. B) Rotation of stratigraphy from orogenesis and development of shear zones, late-D₂ to early-syn-D₃ Py₂ mineralization, proposed V₁ vein generation, and associated distal-proximal alteration. C-D) Syn-late-D₃ main-stage Py_{3a}-Py_{3b}-Po₁-Au mineralization, V_{2a} and V_{2b} vein generation, and associated distal to vein-adjacent calc-silicate alteration at C) Fisher and D) Santoy, with an increase in Po₁ and Au. E-F) late-D₃ remobilization and Py₃-Po₂-Au mineralization at E) Fisher and F) Santoy, with an increase in Po₂ replacement and Au. Red arrows show remobilized metals.

hydrothermal Py (Fig. 9; e.g., Sung et al. 2009, Cook et al. 2016, Mériaud and Jébrak 2017, Mathieu 2019, Babedi et al. 2022). Accordingly, Py₁ and associated mineral phases suggest an early component of Au-associated Ni-Cu-Zn-As ± Sb-Te polymetallic input from potentially magmatic-hydrothermal fluids, particularly as they are hosted by pre-D₁ intrusions. The new zircon U-Pb age of 1882 ± 2 Ma for the granodiorite sill on the Fisher property (Fig. 10C) provides a maximum age for Py₁, which was affected by later deformation events, suggesting trace elements could have been remobilized during recrystallization (e.g., D₂/M₁ and D₃ events) (e.g., Sung et al. 2009, Dubosq et al. 2018, George et al. 2018).

In contrast to previous studies that interpreted the presence of a colloform pyrite at Fisher and Santoy to reflect a late overprinting phase during D₄ (cf. Wood 2016, Onstad 2021), those studies lacked clear overprinting relationships to determine relative timing. This study identified a colloform pyrite phase (Py₂) that is overprinted by other phases and is interpreted to have formed relatively early in the paragenetic sequence. The inclusion-rich nature and colloform textures can be characteristic of magmatic-hydrothermal pyrite (Craig et al. 1998, Zhang et al. 2017), although this is not diagnostic of its mineral deposit setting. Py₂ is characterized by its occurrence within sulfide lenses adjacent to V_{2a} veins. As such, the textural characteristics of mafic schist-hosted Py₂ likely represents an early influx of Co-Ni-Cs-W ± Te-Au in sulfur-bearing fluids (Mathieu 2019) from which pyrite precipitated (Barrie et al. 2009, Atanassova 2010, Shang et al. 2016) during late-D₂ or early- to syn-D₃ deformation (Fig. 11B). However, this phase has the lowest abundance of Au-associated elements (As, Ag, Sb, Te, Bi) (Fig. 9A), which are typical pathfinder elements in orogenic gold deposits (Fig. 9; e.g., Belousov et al. 2016, Dubosq et al. 2018, Gao et al. 2019, Wu et al. 2019, Babedi et al. 2022, Cao et al. 2023).

The textural characteristics of subsequent pyrite phases, such as subhedral, moderately cubic, inclusion-rich Py_{3a}, which is enveloped by euhedral, cubic, inclusion-poor Py_{3b}, represent a transition in hydrothermal processes. The presence of numerous inclusions in the slightly earlier Py_{3a} phase, may suggest a rapid rate of crystallization (Craig et al. 1998, Cioacă et al. 2014, Wu et al. 2021), or growth via coupled dissolution-reprecipitation (Putnis, 2009, Hastie et al., 2020).

Py_{3b} likely crystallized more slowly based on i) inclusion-free and euhedral-cubic crystal habit; ii) enveloping mode of Py_{3b} formation around Py_{3a}; and iii) the chemical similarity of Py_{3b}, but slight reduction in trace element abundances compared to Py_{3a} (Huston et al. 1995, Craig et al. 1998, George et al. 2018). Thus, several lines of evidence suggest that main-stage orogenic-style mineralization occurred syn-late-D₃, with the overlap in timing of the Py₃ phases, V₂ veins, and alteration assemblages (Fig. 4, 11C, D). The similar chemical characteristics of Py_{3a} and Py_{3b} at both the Fisher property and Santoy Mine Complex (Fig. 9A, 11C,D) suggest they formed in an interconnected system under similar conditions. The pyrite minerals have elevated Co-Ni-Pb ± Ag-Te-Au-Bi concentrations, which agree with metal associations determined for numerous orogenic gold systems (Fig. 9; e.g., Belousov et al. 2016, Dubosq et al. 2018, Gao et al. 2019, Wu et al. 2019, Babedi et al. 2022, Cao et al. 2023). However, there is a slight difference in element concentrations between Santoy Py_{3a} and Santoy Py_{3b} phases hosted within mafic volcanic rock, with lower Ni along with Co and Au in Santoy Py_{3a}, whereas Santoy Py_{3b} exhibits higher Ag, Au and Pb (Fig. 11D).

The textures and chemical variation observed in Py₄ suggest hydrothermal remobilization of metals and sulfur during late-D₃ deformation (transition to ductile–brittle conditions). Py₄ share similar trace element patterns at both Fisher and Santoy and is associated with native gold and gold inclusions while also exhibiting higher Au concentrations (Fig. 9A, 11E,F). This suggests an interconnected hydrothermal system during late-D₃ deformation. Although Fisher and Santoy Py₄ analyses show an increase in the concentration of all trace elements, this phase exhibits a decrease in Ni in Santoy Py₄, and a small decrease in W in all Py₄. An overall elevated concentration of Ni-Cu-As-Sb-Pb ± Ag-Te-Au-Bi (Fig. 9B,C) suggests interaction of hydrothermal fluids with previous

sulfide phases (Py_{1-3b}), resulting in a homogenization of their geochemical compositions. Concentrations of Au, along with As-Ag-Bi are significantly higher in Santoy Py₄, however, similar relationships with Au have also been observed in other gold deposits (Hastie et al., 2020). Although continuous D₃ deformation and the consequent episodic fluid injections and remobilization are interpreted to be broadly consistent along the Santoy shear system, this discrepancy in lattice-bound Au and associated elements is attributed to more active fluid fluxing at Santoy.

At Santoy, there is a significantly higher modal amount of native gold and pyrrhotite observed in comparison to the Fisher property (Beaudin et al. 2024; illustrated in Fig. 11F). We interpret this to be related to higher fluid flux during and after D₃ deformation associated with the Santoy shear system, which provided longer-lived structural conduits to facilitate hot fluids that could explain higher heating at Santoy relative to Fisher (Cox et al. 2001). Two distinct alteration-associated trends in amphibole compositions at Santoy also support this (Beaudin et al. 2024). The local replacement of Py₄ and Py_{3b} phases with Po₂ and Po₁-Po₂, respectively, and association with an increase in native gold mineralization at Santoy, further alludes to the evolving and longer-lived nature of these hot fluids throughout D₃ deformation. This mineralogical relationship, as well as the similar trace-element patterns between Fisher and Santoy Po₂, suggest that these fluids were likely cogenetic, leading to formation/precipitation of Po₂ with a high Co-Ni-Pb-Ag ± Au-Te-Bi concentrations during late-D₃. The presence of Au and Te (0.01–8.96 and 12.59–48.70 ppm, respectively) within the Po₂ lattice and increased occurrence of gold inclusions (up to 1367 ppm) also indicate an association between the release of Au from the pyrite structure and replacement by pyrrhotite. Wood (2016) suggested that a zone of low pressure had been established at Santoy, linked to a compressional jog (buttressed by the Packman Lake pluton), which increased fracture density and facilitated fluid flow during D₃ (Cox et al. 2001). Thus, the higher fluid flux at Santoy during late-D₃ deformation could promote the replacement of pyrite by pyrrhotite, which would i) be associated with the release of lattice-bound Au within Py phases that would be upgraded and further remobilized during syn-late-D₃ deformation; ii) precipitate the gold in preferential areas of low pressure; and iii) potentially result in higher grade gold mineralization at Santoy.

The interconnectivity between hydrothermal activity at Fisher and Santoy, as suggested by consistent sulfide mineral characteristics, textures, and mineralogical associations during the evolution of the system (Fig. 11), and similarities in trace-element compositions (Fig. 9A), is also supported by similar host rock lithologies, characteristics, and fabrics (Onstad 2021, Beaudin et al. 2024) and similar alteration assemblages, comprising distal Ser-Bt-Chl-Czo ± Ab, Ttn to vein to coarse-grained Di-Kfs-Ab-Act ± Ap, Ttn calc-silicate alteration (syn-late-D₃) (Beaudin et al. 2024). Additionally, we previously documented a change in major and minor elements within Fisher and Santoy alteration minerals associated with progressive alteration and mineralization (Beaudin et al. 2024). These mineralogical changes are similar to other orogenic gold systems, corresponding with the orogenic trace-element compositions identified in dominant sulfide phases in this study (Py₂, 3a, 3b, 4). Furthermore, Beaudin et al. (2024) identified similar geothermobarometric constraints of fluid conditions between the Fisher property and Santoy Mine Complex (Fisher: ~310–320°C, 3 kbar; Santoy: ~360°C, 2–3 kbar under cooling conditions), which are comparable to the 366–386°C and 1.1–2.5 kbar conditions determined for the Seabee gold deposit by a fluid inclusion study (Tourigny et al. 2004) and between 360 and 430°C based on a stable isotope study (Schultz, 1996). These fluid conditions during mineralization are similar to other orogenic gold systems (Goldfarb and Groves, 2015) and therefore are consistent with an orogenic-style model for main-stage late D₃ mineralization at the Seabee Gold Operation.

5.2. Age constraints

Comparable features between the Fisher property and Santoy Mine Complex indicate an interconnected gold-mineralizing system along the Santoy shear system. According to the lithological and structural framework, Assemblage A and intrusive host rocks at both Fisher and

Santoy underwent similar deformation along the Santoy shear system (e.g., Stauffer 1984, Lewry and Collerson 1990, SRK Consulting 2017, Onstad 2021). Additionally, the Assemblage A Footprint tuff U-Pb age of 1885.58 ± 0.8 Ma in this study (Fig. 10A) provides the first direct age of the Assemblage A volcanic package, which was previously only constrained with a minimum age of ca. 1879 Ma by the cross-cutting Laonil

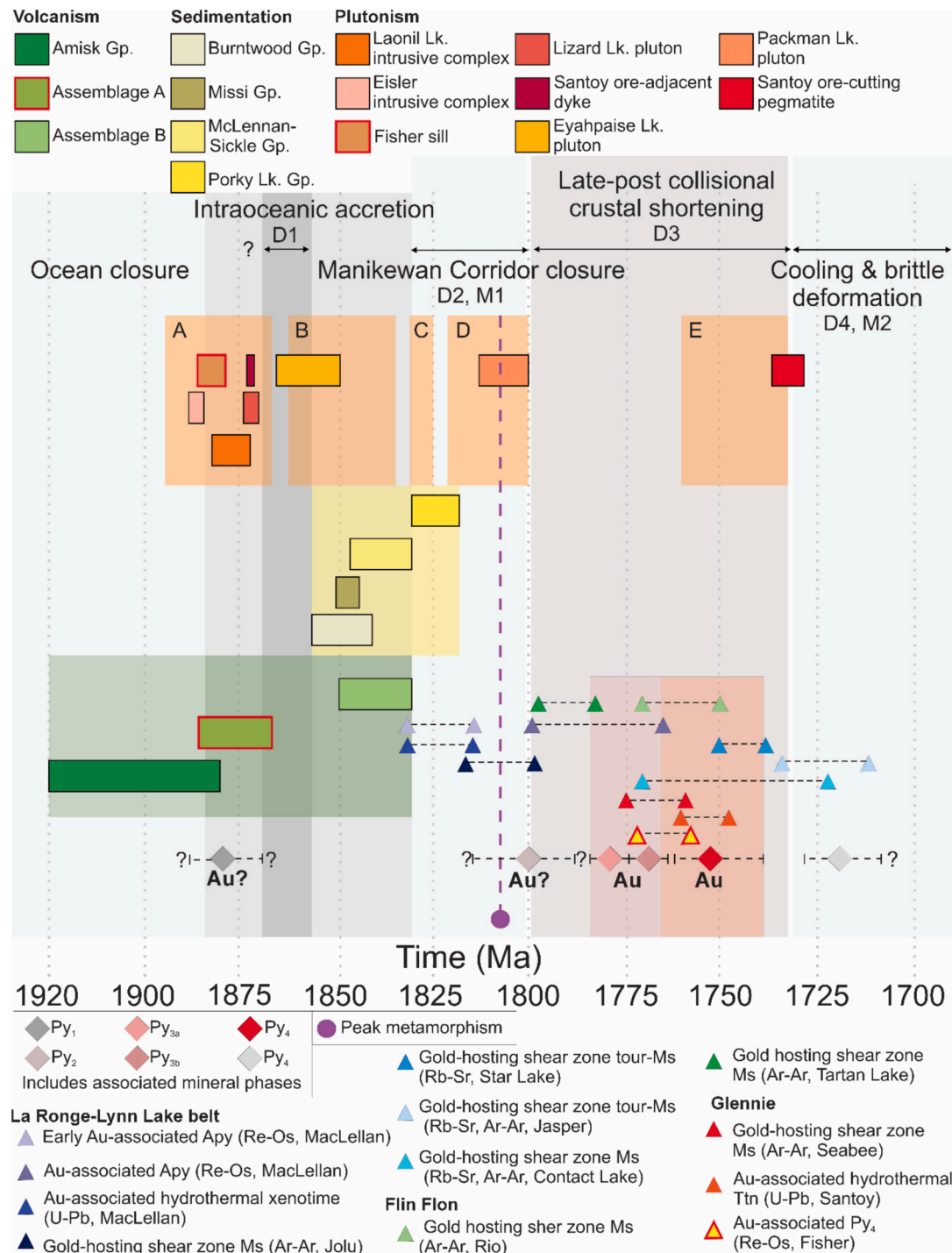


Fig. 12. Time-event chart highlighting significant events in the Pine Lake greenstone belt relative to rocks elsewhere in the Glennie domain. Red outlined boxes represent geochronologic constraints defined in this study. Volcanism ages from this study, Durocher et al. (1992), Stern et al. (1999), and Witvoet (2023). Sediment ages from Ansdell and Kyser (1992), Durocher et al. (1992), Ansdell (1993), Zwanzig (1999), and Maxeiner and Kamber (2011). Labels A-E represent Glennie domain plutonism suites from Wood (2016). Intrusion ages from this study, Bickford et al. (1987), Van Schmus et al. (1987), Chiarenzelli (1989), and Wood (2016). U-Pb hydrothermal Ttn age from Wood (2016). Peak metamorphic age from Schneider et al. (2007). Mineralization ages from Ansdell and Kyser (1992), Thomas and Heaman (1994), Fayek and Kyser (1995), Hrdy and Kyser (1995), Fedorowich et al. (1995), He (1997), Lafrance (1999), Lafrance and Heaman (2004), Morelli and MacLachlan (2012), Wood (2016), and Lawley (2020,2023).

Lake intrusive complex (Witvoet, 2023).

In this study, gold-associated, LLHR Py₄ was dated by Re-Os geochronology at ca. 1764.2 ± 5.6 Ma (Table 2). This defines the proxy-age of a remobilized gold mineralization event at Fisher (Fig. 11E) and constrains the latter stages of mineralization spanning from syn to late-D₃. This Re-Os age overlaps with the 1756 ± 8/9.76 Ma U-Pb age of calc-silicate-associated titanite at the Santoy deposit, which is interpreted as an alteration mineral that formed at the same time as gold (Wood 2016). These two ages are consistent with synchronous and connected hydrothermal activity that reflects gold remobilization at the Fisher property and Santoy Mine Complex. The earlier pyrite generations have not been dated directly. We interpret Py₁ as early and pre-deformation (Fig. 4), whereas Py₂, Py_{3a}, 3b formed during D₂ and D₃ deformation which are more closely related in time to peak regional metamorphism (Fig. 4). Thus, there is likely a direct linkage between the production of metamorphic fluids in the crust and the main-stage orogenic-style mineralization. The ca. 1764 Ma Re-Os age of remobilized gold-associated Py₄ significantly post-dates peak metamorphism (ca. 1810 Ma; Schneider et al., 2007) and implies a time-disconnect between the favored orogenic-style model and associated metamorphic fluids from devolatilization. This discrepancy could be a result of either diachronous metamorphism at different levels in the crust (Goldfarb et al. 2005), or the presence of sub-crustal fluids from the devolatilization of lithospheric mantle related to the final cessation of slab subduction (Seno and Kirby, 2014, Goldfarb and Groves 2015). Further studies are needed to delineate the composition and source of fluids associated with the Py₄ yielding the ca. 1764 Ma age.

5.3. Tectonic context within the Trans-Hudson orogen

Orogenic-style gold mineralization occurs throughout the evolution of the Reindeer zone of the Trans-Hudson orogen (Fig. 12) (Corrigan et al. 2007). Accreted terranes during early stages of the Reindeer zone evolution (ca. 1.88–1.865 Ga) included variably auriferous, volcanic-hosted massive sulfide deposits (Fig. 1), as well as possible epigenetic, and porphyry-style mineralization, but orogenic-style gold-mineralization was not present at this stage (Corrigan et al. 2007, Morelli and MacLachlan 2012). In the earliest (ca. 1.88 to 1.87 Ga) phase of the Pine Lake greenstone belt, Assemblage A hosts Au-bearing Py₁, suggesting an early magmatic-hydrothermal introduction of gold associated with Assemblage A intrusions (Fig. 12) (e.g., ca. 1874 Ma Santoy ore adjacent dyke; Wood 2016, ca. 1882 Ma Fisher granodiorite sill, this study). In this study, early colloform Py₂ was identified to be associated with sulfide-gold mineralization (Py_{3a}, 3b-Cpy₂-Po₁-Au), alteration assemblages, and V_{2a} and V_{2b} veins, thus providing evidence for an additional early introduction of gold (Fig. 12). This stage of mineralization along the Santoy shear system is thus proposed to have occurred during the onset of late- to post-collisional regional D₃ (ca. 1.80–1.78 Ga; Corrigan et al. 2007, 2009). Other studies have recognized early orogenic-style gold mineralization during regional D₂ deformation based on Re-Os model age of 1824 ± 12 Ma for arsenopyrite within an auriferous quartzvein at the MacLellan deposit in the Lynn Lake belt (Lawley et al. 2020) structural relationships at the New Britannia deposit in the Flin Flon belt (Rubingh et al. 2024), and paragenetic relationships at the Porky deposits in the Seabee Gold Operation area (Dixon et al. 2026).

Regional orogenic-style mineralization throughout the Reindeer zone also occurs during the D₃ late- to post collisional deformation (ca. 1800–1735 Ma) (Corrigan et al. 2007, Morelli and MacLachlan 2012). In this study, main-stage orogenic mineralization during syn-late-D₃ (ca. 1780–1755 Ma) is defined by structurally-controlled Py_{3a}, 3b-Cpy₂-Po₁-Au mineralization within- and adjacent to V_{2a} and V_{2b} veins (Fig. 12). Similar characteristics of mineralization, alteration assemblages, and timing of gold mineralization are also apparent from numerous La Ronge-Lynn Lake belt and Flin Flon domain studies. This includes i) the ca. 1720 Ma Jasper deposit and ca. 1740–1750 Ma Star Lake deposit (He 1997) in the La Ronge domain (Fayek and Kyser 1995, Hrdy and Kyser

1999); ii) the ca. 1769–1751 Ma Rio deposit (Ansdell and Kyser 1992) and ca. 1795–1787 Ma Tartan Lake deposit (Fedorowich et al. 1995) in the Flin Flon domain; and iii) the 1782 ± 16 Ma MacLellan gold deposit within the Lynn Lake belt (Lawley et al. 2020). During the later stages of D₃ deformation in the Reindeer zone continual fluid focussing and hydrothermal activity along reactivated structures potentially triggered remobilization throughout many deposits in the Reindeer zone (Lafrance and Heaman 2004, Corrigan et al. 2007, Morelli and MacLachlan 2012). In this study, fracture-controlled Py₄-Po₂-Cpy₃-Au-Ttd-Tbi mineralization represents the continual influx of fluids and consequential remobilization during progressive D₃ deformation (1755–1736 Ma) in the Pine Lake greenstone belt and overprinting of earlier mineralization (Figs. 11, 12). Additionally, the 1764.2 ± 5.6 Ma Re-Os model age determined for Fisher LLHR Py and 1756 ± 8 Ma U-Pb age for gold associated hydrothermal titanite at Santoy (Wood 2016) agree with these ages and suggest that gold mineralization and remobilization was a prominent factor during late- to post collisional D₃ deformation in the Reindeer zone.

6. Conclusion

In summary, host rocks along the Santoy shear system, including the Santoy Mine Complex and Fisher property at the Seabee Gold Operation, portray characteristics of an interconnected multi-stage mineralizing system, within a greenschist- to lower amphibolite-grade Paleoproterozoic greenstone belt. Aspects of gold mineralization within this overall orogenic system, however, were complex and included an early introduction of Au, and growth of Py₁, from a potential magmatic-hydrothermal source prior to metamorphism. The Assemblage A volcanic and intrusive rocks in the Pine Lake greenstone belt host coeval sulfide mineral phases in the Fisher property and Santoy Mine Complex. Pre- to early-syn-D₃ influx of fluids, likely generated during the early stages of regional metamorphism led to the growth of Py₂, which in places exhibits a colloform texture, and preserve generally low concentrations of trace metals. The main-stage V_{2a} and V_{2b} veins, distal- to vein-adjacent alteration, and Py_{3a}, 3b-Cpy₂-Po₁-native gold mineralization formed during syn- late-D₃, Py_{3a} is inclusion-rich, and has elevated trace metal concentration, whereas Py_{3b} is inclusion-free and often overgrows Py_{3a}. Continued flux of fluids during late-D₃ caused the remobilization of metals from earlier sulfides, including Au, and precipitation of fracture filling Py₄-Po₂-Cpy₃- native gold-Ttd-Tbi mineralization. Our new Re-Os age of 1764.2 ± 5.6 Ma from Py₄ provides a constraint on the timing of this late remobilization event. Additionally, structural features at Santoy likely produced a higher degree of focused fluid fluxes relative to the Fisher property, which bolstered pyrite replacement by pyrrhotite under changing physio-chemical parameters, amplified the release of invisible Au, and produced higher modal pyrrhotite-native gold at the Santoy Mine Complex.

Recent metallogenic studies in the Reindeer zone of the Trans-Hudson orogen have revealed multi-stage mineralizing processes in orogenic systems, resulting from a complex evolutionary history. Most studies have highlighted the development of orogenic gold deposits during the latter stages of the closure of the Manikewan Ocean associated with late-post collisional deformation, spanning from D₂ to late-D₃, respectively. Our results provide support for orogenic-style mineralization during these deformation events, and thus are in agreement with the relative timing of other orogenic gold deposits in the Reindeer zone, such as those in the La Ronge, Lynn Lake, and Flin Flon domains, as well as the Porky deposits in the Seabee Gold Operation area (Dixon et al. 2026). Additionally, we document an early stage which may be related to a magmatic-hydrothermal fluid, previously unrecognized, that introduced gold into the Santoy shear system during the early stages of mineralization. This provides further support for the existence of earlier stages of pre-D₂ gold mineralization, which are rarely preserved, within other orogenic-dominated systems across the Reindeer zone, related to the complex collisional history during the closure of the

Paleoproterozoic Manikewan Ocean.

Conflict of Interest

This research was funded by a Natural Sciences and Engineering Research Council of Canada Alliance grant (grant ALLRP 555177—20 to K.A. and C.A.P.). The authors have no additional competing interests to declare that are relevant to the content of this article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by a Natural Sciences and Engineering Research Council of Canada Alliance grant (grant ALLRP 555177 - 20 to K.A. and C.A.P.) and a Natural Sciences and Engineering Research Council Canada Graduate Scholarships - Masters (to D.B.). This paper forms part of a MSc thesis at the University of Saskatchewan by D.B. Staff at SSR Mining Inc. (especially A. Carlson, P. Kremer, D. Stuebing) are thanked for their expertise and access to the resources pertinent to this research. We thank two anonymous reviewers and reviews by C. Lawley, R. Morelli, and N. Saintilan on an early version of the draft that helped improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.oregeorev.2026.107257>.

Data availability

I have shared the link to my data/code at the attach file step

References

- Ansdell, K.M. 1993. U-Pb zircon constraints on the timing and provenance of fluvial sedimentary rocks in the Flin Flon and Athapapuskow basins, Flin Flon Domain, Trans-Hudson Orogen, Manitoba and Saskatchewan. Geological Survey of Canada, Papers, p. 49.
- Ansdell, K.M., 2005. Tectonic evolution of the Manitoba-Saskatchewan segment of the Paleoproterozoic Trans-Hudson Orogen, Canada. *Can. J. Earth Sci.* 42, 741–759. <https://doi.org/10.1139/e05-035>.
- Ansdell, K.M., Kyser, T.K., 1992. Mesothermal Gold Mineralization in a Proterozoic Greenstone Belt: Western Flin Flon Domain, Saskatchewan, Canada. *Econ. Geol.* 87, 1496–1524.
- Ansdell, K.M., Lucas, S.B., Connors, K., Stern, R.A., 1995. Kiseeynew metasedimentary gneiss belt, Trans-Hudson orogen (Canada): Back-arc origin and collisional inversion. *Geology* 23, 1039–1043. [https://doi.org/10.1130/0091-7613\(1995\)023<1039:KMGBTH>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<1039:KMGBTH>2.3.CO;2).
- Ashton, K.E., 1999. A proposed lithotectonic domain re-classification of the southeastern Reindeer Zone in Saskatchewan; Summary of Investigations 1999, volume 1. Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 99-4 (1), 92–100.
- Ashton, K.E., Lewry, J.F., Heaman, L.M., Hartlaub, R.P., Stauffer, M.R., Tran, H.T., 2005. The Pelican Thrust Zone: Basal detachment between the Archean Sask Craton and Paleoproterozoic Flin Flon - Glennie complex, western Trans-Hudson Orogen. *Can. J. Earth Sci.* 42, 685–706. <https://doi.org/10.1139/e04-035>.
- Atanassova, R., 2010. Environmental significance of pyrite with colloform textures. *Comptes Rendus De L'academie Bulgare Des Sciences* 63 (9), 1335–1340.
- Babedi, L., Von Der Heyden, B.P., Tadie, M., Mayne, M., 2022. Trace elements in pyrite from five different gold ore deposit classes: a review and meta-analysis. *Geol. Soc. Lond. Spec. Publ.* 516, 47–83.
- Barrie, C.D., Boyce, A.J., Boyle, A.P., Williams, P.J., Blake, K., Ogawara, T., Akai, J., Prior, D.J., 2009. Growth controls in colloform pyrite. *Am. Mineral.* 94 (4), 415–429. <https://doi.org/10.2138/am.2009.3053>.
- Basnett, R. 1999. Seabee Mine. Ashton, K. E. and Harper, C. T. (eds), MinExpo'96 symposium; Advances in Saskatchewan Geology and Mineral Deposits, Saskatchewan Geological Society, Special Publication 14: 72–80, 14: 72–79.
- Beaudin, D., and Beaudin, J. 2023. Python script for the Fe-normalization of sulfide minerals using internal standards. Unpublished Python script. Open Source.,
- Beaudin, D., Camille, P., Ansdell, K., and Yang, P. (2024). Comparative lithology and alteration mineral chemistry of host rocks at the Seabee Gold Operation, northern Saskatchewan, Canada: Implications for a connected orogenic gold-mineralizing system. *In* Submission to Ore Geology Reviews.
- Belousov, I., Large, R.R., Meffre, S., Danyushevsky, L. V., Steadman, J., and Beardsmore, T. 2016. Pyrite compositions from VHMS and orogenic Au deposits in the Yilgarn Craton, Western Australia: Implications for gold and copper exploration. doi: 10.1016/j.oregeorev.2016.04.020.
- Berthier, C., Perret, J., Eglinger, A., André-Mayer, A., Feneyrol, J., Voinot, A., Teitler, Y., Bosc, R., 2023. Pyrite as a Microtextural and Geochemical Tracer of Ore-Forming Processes, Central Zone Orogenic Gold Deposit, Gabgaba District. Sudan. *Economic Geology* 118 (5), 1031–1053.
- Bickford, M.E., Van Schmus, W.R., Collerson, K.D., Macdonald, R., 1987. U-Pb zircon geochronology project: new results and interpretations. Summary of Investigations 1987. Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 87-4, 76–79.
- Bucci, L.A., McNaughton, N.J., Fletcher, I.R., Groves, D.I., Kositcin, N., Stein, H.J., Hagemann, S.G., 2004. Timing and duration of high-temperature gold mineralization and spatially associated granitoid magmatism at Chalice, Yilgarn Craton, Western Australia. *Econ. Geol.* 99, 1123–1144. <https://doi.org/10.2113/gsecongeo.99.6.1123>.
- Cao, G., Zhang, Y., Zhao, H., Cheng, J., Hao, J., Lei, J., Song, S., Wang, X., 2023. Trace element variations of pyrite in orogenic gold deposits: Constraints from big data and machine learning. *Ore Geol. Rev.* 157, 105447.
- Chiarenzelli, J.R. 1989. The Nistowiak and Guncoat Gneisses: implications for the tectonics of the Glennie and La Ronge domains, northern Saskatchewan, Canada. Unpublished PhD thesis, University of Kansas, p. 229.
- Cioacă, M.E., Munteanu, M., Qi, L., Costin, G., 2014. Trace element concentrations in porphyry copper deposits from Metaliferi Mountains, Romania: a reconnaissance study. *Ore Geol. Rev.* 63, 22–39. <https://doi.org/10.1016/j.oregeorev.2014.04.016>.
- Condon, D.J., Schoene, B., McLean, N.M., Bowring, S.A., Parrish, R.R., 2015. Metrology and traceability of U-Pb isotope dilution geochronology (EARTHTIME Tracer Calibration Part I). *Geochim. Cosmochim. Acta* 164, 464–480. <https://doi.org/10.1016/j.gca.2015.05.026>.
- Cook, N., Ciobanu, C.L., George, L., Zhu, Z.Y., Wade, B., Ehrig, K., 2016. Trace element analysis of minerals in magmatic-hydrothermal ores by laser ablation inductively-coupled plasma mass spectrometry: Approaches and opportunities. *Minerals* 6, 1–34. <https://doi.org/10.3390/min6040111>.
- Corrigan, D., Galley, A., and Pehrsson, S. 2007. Tectonic evolution and metallogeny of the southwestern Trans-Hudson Orogen. Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication N: 881–902.
- Corrigan, D., Hajnal, Z., Németh, B., Lucas, S.B., 2005. Tectonic framework of a Paleoproterozoic arc-continent to continent-continent collisional zone, Trans-Hudson Orogen, from geological and seismic reflection studies. *Can. J. Earth Sci.* 42, 421–434. <https://doi.org/10.1139/e05-025>.
- Corrigan, D., Pehrsson, S., Wodicka, N., de Kemp, E., 2009. The Palaeoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes. Ancient orogens and modern analogues, Geological Society (of London). Special Publications 327, 457–479. <https://doi.org/10.1144/SP327.19>.
- Cox, S.F., Knackstedt, M.A., and Braun, J. 2001. Principles of Structural Control on Permeability and Fluid Flow in Hydrothermal Systems. *In* Richards, J.P. and Tosdal, R.M. (eds), Structural Controls on Ore Genesis. Society of Economic Geologists, 14: 1–24. doi:10.5382/Rev.14.01.
- Craig, J.R., Vokes, F.M., Solberg, T.N., 1998. Pyrite: Physical and chemical textures. *Miner. Deposita* 34, 82–101. <https://doi.org/10.1007/s001260050187>.
- Deditius, A.P., Utsunomiya, S., Reich, M., Kesler, S.E., Ewing, R.C., Hough, R., Walshe, J., 2011. Trace metal nanoparticles in pyrite. *Ore Geol. Rev.* 42, 32–46. <https://doi.org/10.1016/j.oregeorev.2011.03.003>.
- Delaney, G.D. 2016. Geology of the Pine Lake Greenstone Belt, Laonil-Uskik Lakes Area (Parts of NTS63M-11 and 12). Saskatchewan Geological Survey, Ministry on the Economy, Geoscience Map 2016-1, 1:50000 scale map..
- Delaney, G.D., Cutler, S.A., 1992. Geological setting of the "Santoy Lake" Gold Camp (Part of NTS 63M-11 and -12). Summary of Investigations 1992, Saskatchewan Geological Survey, Saskatchewan Energy Mines. Misc. Rep. 92-4, 30–40.
- Dixon, D., Partin, C.A., Ansdell, K., Voinot, A., Ickert, R., 2026. Orogenic gold in the Trans-Hudson orogen, Saskatchewan, Canada: Petrographic and geochemical insights from the Porky Lake system. *Can. J. Earth Sci.* in press.
- Dubosq, R., Lawley, C.J.M., Rogowitz, A., Schneider, D.A., Jackson, S., 2018. Pyrite deformation and connections to gold mobility: Insight from micro-structural analysis and trace element mapping. *Lithos* 310–311, 86–104. <https://doi.org/10.1016/j.lithos.2018.03.024>.
- Durocher, K.E. 1997. A study of the P-T-t-fluid evolution of the Glennie domain, Trans-Hudson Orogen. Unpublished PhD thesis, University of Saskatchewan, p. 302.
- Durocher, K.E., Cutler, S.A., Delaney, G.D., Kyser, T.K., 1992. Gold Occurrences in the "Santoy Lake" Area, Glennie Domain, Trans-Hudson Orogen. Summary of Investigations 1992. Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 92-4, 41–50.
- Durocher, K.E., Kyser, T.K., Delaney, G.D., 2001. Thermotectonic studies in the paleoproterozoic glennie domain, trans-Hudson orogen, Canada. *Precamb. Res.* 109, 175–202. [https://doi.org/10.1016/S0301-9268\(01\)00144-9](https://doi.org/10.1016/S0301-9268(01)00144-9).
- Elliott, C.G., 1995. The Tabernor fault and Proterozoic and Phanerozoic movements in Saskatchewan and Manitoba. LITHOPROBE Trans-Hudson Orogen Transect, 5th Transect meeting. LITHOPROBE Secret, University of British Columbia, Report 48, 148–155.
- Fayek, M., Kyser, K., 1995. and Barren Fluids Associated with the Proterozoic Contact Lake Lode Gold Deposit, Saskatchewan, Canada. *Economic Geology* 90, 385–406.

- Fedorowich, J.S., Kerrich, R., Stauffer, M.R., 1995. Geodynamic evolution and thermal history of the central Flin Flon Domain, Trans-Hudson Orogen: Constraints from structural development, 40Ar/39Ar, and stable isotope geothermometry. *Tectonics* 14, 472–503.
- Fumerton, S.L., Stauffer, M.R., Lewry, J.F., 1984. The Wathaman batholith: largest known Precambrian pluton. *Can. J. Earth Sci.* 21, 1082–1097. <https://doi.org/10.1139/e84-113>.
- GabroSoft. 2011. Spreadsheets for atoms per formula unit calculations.
- Gao, F., Du, Y., Pang, Z., Du, Y., Xin, F., Xie, J., 2019. LA-ICP-MS trace-element analysis of pyrite from the huanxiangwa gold deposit, xiong'er shan district, China: Implications for ore genesis. *Minerals* 9, 1–15. <https://doi.org/10.3390/min9030157>.
- George, L.L., Cook, N.J., Crowe, B.B.P., Ciobanu, C.L., 2018. Trace elements in hydrothermal chalcopyrite. *Mineral. Mag.* 82, 59–88. <https://doi.org/10.1180/minmag.2017.081.021>.
- Goldfarb, R.J., Baker, T., Dubé, B., Groves, D.L., Hart, C.J.R., Gosselin, P., 2005. Distribution, Character, and Genesis of Gold Deposits in Metamorphic Terranes. *Economic Geology 100th Anniversary*. 100, 407–450.
- Goldfarb, R.J., Groves, D.L., 2015. Orogenic gold: Common or evolving fluid and metal sources through time. *Lithos* 233, 2–26. <https://doi.org/10.1016/j.lithos.2015.07.011>.
- Groves, D.L., Santosh, M., Goldfarb, R.J., Zhang, L., 2018. Structural geometry of orogenic gold deposits: Implications for exploration of world-class and giant deposits. *Geosci. Front.* 9, 1163–1177. <https://doi.org/10.1016/j.gsf.2018.01.006>.
- Groves, D.L., Santosh, M., Deng, J., Wang, Q., Yang, L., Zhang, L., 2020. A holistic model for the origin of orogenic gold deposits and its implications for exploration. *Miner. Deposita* 55, 275–292. <https://doi.org/10.1007/s00126-019-00877-5>.
- He, J. 1997. Structural setting, geochemistry, and temporal relationships of the lode gold deposits in the Star Lake-McLennan Lake area, northern Saskatchewan.
- Helmstaedt, H. 1986. Report on the geology and structure of the Seabee and Currie Rose properties, Laonil Lake, Saskatchewan. Internal Report, Placer Development Ltd. p. 714.
- Hastie, E., Kontak, D.J., Lafrance, B., 2020. Gold remobilization: insights from gold deposits in the Archean swazye greenstone belt, Abitibi subprovince. *Canada Economic Geology* 115 (2), 241–277.
- Hnatyshin, D., Creaser, R.A., Meffre, S., Stern, R.A., Wilkinson, J.J., Turner, E.C., 2020. Understanding the microscale spatial distribution and mineralogical residency of Re in pyrite: examples from carbonate-hosted Zn-Pb ores and implications for pyrite Re-Os geochronology. *Chem. Geol.* 533 (119427). <https://doi.org/10.1016/j.chemgeo.2019.119427>.
- Hoffman, P.F., 1988. United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *Annu. Rev. Earth Planet. Sci.* 16, 543–603. <https://doi.org/10.1146/annurev.ea.16.050188.002551>.
- Hrdy, F., Kyser, T.K., 1995. Origin, timing, and fluid characteristics of an auriferous event: the Proterozoic Jasper lode gold deposit, Saskatchewan, Canada. *Econ. Geol.* 90, 1918–1933. <https://doi.org/10.2113/gsecongeo.90.7.1918>.
- Huston, D.L., Sie, S.H., Suter, G.F., Cooke, D.R., Both, R.A., 1995. Trace elements in sulfide minerals from eastern Australian volcanic-hosted massive sulfide deposits: part I. Proton microprobe analyses of pyrite, chalcopyrite, and sphalerite, and part II. Selenium levels in pyrite: comparison with 834S values and impli. *Econ. Geol.* 90, 1167–1196. <https://doi.org/10.2113/gsecongeo.90.5.1167>.
- Ispolatov, V., Lafrance, B., Dubé, B., Creaser, R., Hamilton, M., 2008. Geologic and structural setting of gold mineralization in the Kirkland Lake-Larder Lake gold belt, Ontario. *Econ. Geol.* 103, 1309–1340. <https://doi.org/10.2113/gsecongeo.103.6.1309>.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., Essling, A.M., 1971. Precision measurement of half-lives and specific activities of U235 and U238. *Phys. Rev. C* 4, 1889–1906. <https://doi.org/10.1103/PhysRevC.4.1889>.
- Kadel-Harder, I.M., Spry, P.G., Matthews, D.L., Voinot, A., Handt, A.V., McCombs, A., 2020. Paragenetic relationships between low- and high-grade gold mineralization in the Cripple Creek Au-Te deposit, Colorado: Trace element studies of pyrite. *Ore Geol. Rev.* 127, 103847.
- Keith, M., Smith, D.J., Jenkin, G.R.T., Holwell, D.A., Dye, M.D., 2018. A review of Te and Se systematics in hydrothermal pyrite from precious metal deposits: Insights into ore-forming processes. *Ore Geol. Rev.* 96, 269–282. <https://doi.org/10.1016/j.oregeorev.2017.07.023>.
- Kenwood, S. 2017. NI 43-101 Technical Report, Fisher Property. Internal Report, SSR Mining Ltd p 51.
- Kremer, P., and Carlson, A. 2017. Fisher Property Annual Exploration Report - 2017. Internal Report, SSR Mining Ltd. p. 12; 1–12.
- Lafrance, B., 1999. Gold Studies in the Byers Fault-Waddy Lake Area, La-Ronge Domain. Summary of Investigations 1999, volume 2, Saskatchewan Geological Survey. Saskatchewan Energy and Mines, Miscellaneous Report 99-4 (2), 202–207.
- Lafrance, B., Heaman, L.M., 2004. Structural controls on hypozonal orogenic gold mineralization in the La Ronge Domain, Trans-Hudson Orogen, Saskatchewan. *Can. J. Earth Sci.* 41, 1453–1471. <https://doi.org/10.1139/E04-101>.
- Lawley, C.J.M., Yang, X.M., Selby, D., Davis, W., Zhang, S., Petts, D.C., and Jackson, S.E. 2020. Sedimentary basin controls on orogenic gold deposits: New constraints from U-Pb detrital zircon and Re-Os sulphide geochronology, Lynn Lake greenstone belt, Canada. *Ore Geology Reviews*, 126: 1–21. Elsevier. doi:10.1016/j.oregeorev.2020.103790.
- Lawley, C.J.M., Schneider, D.A., Camacho, A., McFarlane, C.R.M., Davis, W.J., and Yang, X.M. 2023. Post-orogenic exhumation triggers gold mineralization in the Trans-Hudson orogen: New geochronology results from the Lynn Lake greenstone belt, Manitoba, Canada. *Precambrian Research*, 395 (107127). doi:10.1016/j.precamres.2023.107127.
- Lewry, J.F. 1977. The Geology of the Glennie Lake Area. Saskatchewan Department of Mineral Resources, Report, 143: 1–59.
- Lewry, J.F., and Collerson, K.D. 1990. The Trans-Hudson Orogen: extent, subdivisions and problems. In Lewry, J. F. and Stauffer, M. R. (eds) The Early Proterozoic Trans-Hudson Orogen of North America. Geological Association of Canada, Special Paper 37: 35–41.
- Lewry, J.F., Hajnal, Z., Green, A., Lucas, S.B., White, D., Stauffer, M.R., Ashton, K.E., Weber, W., Clowes, R., 1994. Structure of a Paleoproterozoic continent-continent collision zone: a LITHOPROBE seismic reflection profile across the Trans-Hudson Orogen, Canada. *Tectonophysics* 232, 143–160. [https://doi.org/10.1016/0040-1951\(94\)90081-7](https://doi.org/10.1016/0040-1951(94)90081-7).
- Lewry, J.F., Thomas, D.J., Macdonald, R., and Chiarenzelli, J. 1990. Structural relations in accreted terranes of the Trans-Hudson Orogen, Saskatchewan: telescoping in a collisional regime? In Lewry, J.F. and Stauffer, M.R. (eds.), The Early Proterozoic Trans-Hudson Orogen of North America, Geological Association of Canada, Special Paper 37: 75–94.
- Liu, W., Deng, X., Han, S., Chen, X., Li, X., Aibai, A., Wu, Y., Wang, Y., Shan, W., Li, Z., Chen, Y. 2023. Pyrite Textures and Compositions in the Dunbasitao Gold Deposit, NW China: Implications for Ore Genesis and Gold Mineralization Processes. *Minerals* 2023 13: 534. <https://doi.org/10.3390/min13040534>.
- Lucas, S.B., Stern, R.A., Syme, E.C., Reilly, B.A., Thomas, D.J., 1996. Intraoceanic tectonics and the development of continental crust: 1.92–1.84 Ga evolution of the Flin Flon Belt, Canada. *Bull. Geol. Soc. Am.* 108, 602–629. [https://doi.org/10.1130/0016-7606\(1996\)108<0602:ITATDO>2.3.CO;2](https://doi.org/10.1130/0016-7606(1996)108<0602:ITATDO>2.3.CO;2).
- Manitoba Geological Survey. 2018. Geology of Manitoba, 1:1000000 Scale. Version 18.04.11. In Manitoba Geological Survey, Manitoba Mineral Resources.
- Markey, R., Stein, H.J., Hannah, J.L., Zimmerman, A., Selby, D., Creaser, R.A., 2007. Standardizing Re-Os geochronology: a new molybdenite Reference Material (Henderson, USA) and the stoichiometry of Os salts. *Chem. Geol.* 244. <https://doi.org/10.1016/j.chemgeo.2007.06.002>.
- Mathieu, L., 2019. Detecting magmatic-derived fluids using pyrite chemistry: example of the Chibougamau area, Abitibi Subprovince, Québec. *Ore Geol. Rev.* 114, 1–20. <https://doi.org/10.1016/j.oregeorev.2019.103127>.
- Maxeiner, R.O., Ashton, K.E., Bosman, S., Card, C., Kohlruess, D., Love, T., Marsh, A., Morelli, R.M., and Slimmon, W.L. 2021. Geological map of Saskatchewan, 1: 1000000 scale. Saskatchewan Geological Survey, Saskatchewan Energy and Resources.
- Maxeiner, R.O., Kamber, B.S., 2011. La Ronge ‘Horseshoe’ Project : Bedrock Geology of the Hebden Lake Area at the transition between the Western Glennie Domain and Southern Kisseynew and La Ronge Domains (parts of NTS 73P / 07); in Summary of Investigations 2011, volume 2. Saskatchewan Geological Survey, Ministry of Energy and Resources, Miscellaneous Report 2011–4 (2), 1–20.
- McEwan, B. 2013. Summary of Geological Mapping of the Santoy Mine Area during the Summer of 2012. Internal Report. Claude Resources Inc. p. 24.
- McLean, N.M., Condon, D.J., Schoene, B., Bowring, S.A., 2015. Evaluating uncertainties in the calibration of isotopic reference materials and multi-element isotopic tracers (EARTHTIME Tracer Calibration Part II). *Geochim. Cosmochim. Acta* 164, 481–501. <https://doi.org/10.1016/j.gca.2015.02.040>.
- McNicoll, V.J., Delaney, G.D., Parrish, R.R., and Heaman, Larry, M. 1992. U-Pb age determinations from the Glennie Lake Domain, Trans-Hudson Orogen, Saskatchewan. Radiogenic Age and Isotopic Studies, Report 6, Geological Survey of Canada, paper , 92-2: 57–72.
- Meffre, S., Large, R.R., Steadman, J.A., Gregory, D.D., Stepanov, A.S., Kamenetsky, V.S., Ehrig, K., Scott, R.J., 2016. Multi-stage enrichment processes for large gold-bearing ore deposits. *Ore Geol. Rev.* 76, 268–279. <https://doi.org/10.1016/j.oregeorev.2015.09.002>.
- Mériaud, N., Jébrak, M., 2017. From intrusion-related to orogenic mineralization: the Wasamac deposit, Abitibi Greenstone Belt, Canada. *Ore Geol. Rev.* 84, 289–308. <https://doi.org/10.1016/j.oregeorev.2017.01.021>.
- Meyer, M.T., Bickford, M.E., Lewry, J.F., 1992. The Wathaman Batholith: an early Proterozoic continental arc in the Trans-Hudson Orogenic Belt, Canada. *Geol. Soc. Am. Bull.* 104, 1073–1085. [https://doi.org/10.1130/0016-7606\(1992\)104<1073:TWBAEP>2.3.CO;2](https://doi.org/10.1130/0016-7606(1992)104<1073:TWBAEP>2.3.CO;2).
- Morelli, R.M., MacLachlan, K., 2012. Saskatchewan Gold : Mineralization Styles and Mining history. Saskatchewan Ministry of Energy and Resources, Report 262, 171.
- Onstad, C. 2021. Geology, Petrography, and Geochemistry of Fisher Property Rocks and Their Altered Equivalents, and Relationship to Auriferous Quartz Veins, Glennie Domain, Northern Saskatchewan. Unpublished Msc Thesis, University of Saskatchewan, p. 184.
- OreWin. 2021. Seabee 2021 Technical Report Summary. External Report , SSR Mining, p. 149.
- Perret, J., André-Mayer, A.S., Eglinger, A., Feneyrol, J., Voinot, A., Morlot, C., Barou, F., Teitler, Y., Seira, D., Bosc, R., 2021. Structural and geochemical ore-forming processes in deformed gold deposits: towards a multiscale and multimethod approach. *Geological Society, London, Special Publications* 516, 211–242. <https://doi.org/10.1144/SP516-2021-37>.
- Pouchou, J.L., Pichoir, F., 1984. New model for quantitative x-ray microanalysis. Part II: Application to in-depth analysis of heterogeneous samples. *Recherche Aerospatiale (english Edition)* 47–65.
- Pupin, J.P., 1980. Zircon and granite petrology. *Contrib. Miner. Petrol.* 73 (3), 207–220. <https://doi.org/10.1007/BF00381441>.
- Putnis, A., 2009. Mineral replacement reactions. *Reviews in Mineralogy and Geochemistry* 70, 87–124.
- Reich, M., Kesler, S.E., Utsunomiya, S., Palenik, C.S., Chrysosoulis, S.L., Ewing, R.C., 2005. Solubility of gold in arsenian pyrite. *Geochim. Cosmochim. Acta* 69, 2781–2796. <https://doi.org/10.1016/j.gca.2005.01.011>.

- Rubingh, K., Lafrance, B., Gibson, H.L., 2024. The Snow Lake deposits in Manitoba, Canada: Formation of metamorphosed amphibolite facies orogenic gold deposits during a progressive and prograde orogenic event. *Econ. Geol.* 119, 421–444.
- Schneider, D.A., Heizler, M.T., Bickford, M.E., Wortman, G.L., Condie, K.C., Perilli, S., 2007. Timing constraints of orogeny to cratonization: Thermochronology of the Paleoproterozoic Trans-Hudson orogen, Manitoba and Saskatchewan, Canada. *Precamb. Res.* 153, 65–95. <https://doi.org/10.1016/j.precamres.2006.11.007>.
- Seno, T., Kirby, S.H., 2014. Formation of plate boundaries: the role of mantle devolatilization. *Earth Sci. Rev.* 129, 85–99.
- Shang, G., Fei, H., Yinghui, W., Wenyuan, G., 2016. A Review of Research Progress in the Genesis of Colloform Pyrite and its Environmental Indications. *Acta Geologica Sinica (English Edition)* 90, 1353–1369. <https://doi.org/10.1111/1755-6724.12774>.
- Sillitoe, R.H., Thompson, J.F.H., 1998. Intrusion-Related Vein Gold deposits: Types, Tectono-Magmatic Settings and Difficulties of Distinction from Orogenic Gold Deposits. *Resour. Geol.* 48, 237–250. <https://doi.org/10.1111/j.1751-3928.1998.tb00021.x>.
- SLR International Corporation. 2024. Technical Report Summary on the Seabee Gold Operation, Saskatchewan, Canada. S-K 1300 Report for SSR Mining Inc.
- Smoliar, M.I., Walker, R.J., Morgan, J.W., 1996. Re-Os ages of group IIA, IIIA, IVA, and IVB iron meteorites. *Science* 271, 1099–1102. <https://doi.org/10.1126/science.271.5252.1099>.
- SRK Consulting. 2017. NI 43-101 Technical Report for the Seabee Gold Operation, Saskatchewan, Canada. External Report, SRK Consulting. p. 127.
- SSR Mining. 2019. Fisher Property Annual Exploration Report - 2019. Internal Report. Internal Report, SSR Mining, p. 153.
- Stauffer, M.R., 1984. Manikewan: an early proterozoic ocean in central Canada, its igneous history and orogenic closure. *Precamb. Res.* 25, 257–281. [https://doi.org/10.1016/0301-9268\(84\)90036-6](https://doi.org/10.1016/0301-9268(84)90036-6).
- Stern, R.A., Machado, N., Syme, E.C., Lucas, S.B., David, J., 1999. Chronology of crustal growth and recycling in the Paleoproterozoic Amisk collage (Flin Flon Belt), Trans-Hudson Orogen, Canada. *Can. J. Earth Sci.* 36, 1807–1827. <https://doi.org/10.1139/e99-028>.
- Sung, Y.H., Brugger, J., Ciobanu, C.L., Pring, A., Skinner, W., Nugus, M., 2009. Invisible gold in arsenian pyrite and arsenopyrite from a multistage Archaean gold deposit: Sunrise Dam, Eastern Goldfields Province, Western Australia. *Miner. Deposita* 44, 765–791. <https://doi.org/10.1007/s00126-009-0244-4>.
- Thomas, D.J., Heaman, L.M., 1994. Geologic setting of the Jolu gold mine, Saskatchewan: U-Pb age constraints on plutonism, deformation, mineralization, and metamorphism. *Econ. Geol.* 89, 1017–1029. <https://doi.org/10.2113/gsecongeo.89.5.1017>.
- Tourigny, G. 2003. Preliminary Structural Study of the Gold-bearing Shear Zone System at the Seabee Mine, Northern Saskatchewan. Summary of Investigations 2003, Saskatchewan Geological Survey, Saskatchewan Industry Resources, Miscellaneous Report 2003-4.2, Paper B-1: p. 11.
- Tourigny, G., Chi, G., Yuhasz, C., Olson, R., Berger, J., and Soloman, J. 2004. Structural controls and temperature-pressure conditions of gold-bearing quartz vein systems at the Seabee mine, northern Saskatchewan. Summary of Investigations 2004, Volume 2, Saskatchewan Geological Survey, Saskatchewan Industry Resources, Miscellaneous Report 2004-4.2, Paper A-2, p. 18.
- Van Schmus, W.R., Bickford, M.E., Macdonald, R., 1987. U-Pb geochronology in the Trans-Hudson Orogen, northern Saskatchewan, Canada. *Can. J. Earth Sci.* 24, 407–424.
- Whalen, J.B., Syme, E.C., Stern, R.A., 1999. Geochemical and Nd isotopic evolution of Paleoproterozoic arc-type granitoid magmatism in the Flin Flon Belt, Trans-Hudson orogen, Canada. *Can. J. Earth Sci.* 36, 227–250. <https://doi.org/10.1139/e98-026>.
- Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. *Am. Mineral.* 95, 185–187.
- Wise, S.A., and Watters, R.L. 2011. Reference Material 8599 Henderson Molybdenite. National Institute of Standards and Technology Report of Investigation, March.
- Witvoet, L. 2023. Petrological and geochemical comparison of the Eisler intrusive suite and the Laonil Lake intrusive complex, Glennie Domain, Northern Saskatchewan. Unpublished Msc Thesis, University of Saskatchewan, p. 99.
- Wood, C.R. 2016. Structural study of the auriferous Santoy shear zone, northeastern Glennie domain, Saskatchewan. Unpublished MSc thesis, University of Regina, p. 154.
- Wu, Y.F., Evans, K., Li, J.W., Fougereuse, D., Large, R.R., Guagliardo, P., 2019. Metal remobilization and ore-fluid perturbation during episodic replacement of auriferous pyrite from an epizonal orogenic gold deposit. *Geochim. Cosmochim. Acta* 245, 98–117. <https://doi.org/10.1016/j.gca.2018.10.031>.
- Wu, Y.F., Evans, K., Hu, S.Y., Fougereuse, D., Zhou, M.F., Fisher, L.A., Guagliardo, P., Li, J.W., 2021. Decoupling of Au and As during rapid pyrite crystallization. *Geology* 2021 (49), 827–831.
- Zhang, Y., Shao, Y.J., Chen, H.Y., Liu, Z.F., Li, D.F., 2017. A hydrothermal origin for the large Xinqiao Cu-S-Fe deposit, Eastern China: evidence from sulfide geochemistry and sulfur isotopes. *Ore Geol. Rev.* 88, 534–549.
- Zwanig, H.V., 1999. Structure and stratigraphy of the south flank of the Kiseynew Domain in the Trans-Hudson Orogen, Manitoba: Implications for 1.845–1.77 Ga collision tectonics. *Can. J. Earth Sci.* 36, 1859–1880. <https://doi.org/10.1139/e99-042>.
- Zwanig, H.V. 2000. Geochemistry and Tectonic Framework of the Kiseynew Domain-Lynn Lake Belt Boundary (Part of NTS 63P/13). Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 91-96.