Structural Settings of Gold Deposits in Low to High Metamorphic Grade Terranes

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Material and examples in this presentation are from many sources, including:

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Kate Rubingh (PhD thesis Laurentian in progress)
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......as well as cited references from scientific literature.
Outline of Presentation

1. Changing character of faults with depth
2. Sub-greenschist facies orogenic gold deposits – General features
   Case example: Wiluna deposit
3. Greenschist facies orogenic gold deposits – General features
   Case example: Cheminis (Kerr Addison) and Sigma-Lamaque deposits
   Discussion: Intrusion-related versus orogenic gold deposits using the Renabie gold deposit as an example
4. Amphibolite – lower granulite facies orogenic gold deposits – General features
   Case example: Hemlo deposit
   Discussion: Continuum model versus metamorphic model using the New Britannia (Snow Lake) deposit as an example
5. Implications for mineral exploration
Brittle Fault and Cataclasite

Brittle Faults

Gradation from mylonite cataclasite

Cataclasite contains small clasts of mylonite and very fine-grained trains of opaque minerals, epidote, and quartz.

(Mark R. Handy, 1998)

Mylonites

Greenschist grade

Upper amphibolite to granulite grade

Hard Rock mine, Geraldton

Parry Sound, Ontario
Orogenic gold deposits

Greenschist grade terrane
- Formed syn- to post-peak metamorphism late during a convergent orogenic event
- Associated with faults or shear zones
- Gold-only deposits with gold in quartz-carbonate veins and their altered wallrocks
- Sulphide minerals: pyrite, arsenopyrite, pyrrhotite
- Alteration minerals: Sericite-ankerite-albite-chlorite
- Ore fluids: aqueous-carbonic, near neutral pH, slightly reduced, dominated by sulfide complexes

Sub-Greenschist facies orogenic gold deposit

Characteristic features
1. Hosted by low- to very-low-grade metamorphic rocks
2. Formed at T=150-300°C, P=0.5-1.5 kbar (depth<6 km)
3. Along brittle faults
4. Multiply brecciated ore and gangue
5. Abundance of open-space filling textures
6. Low-temperature ore minerals (tellurides, Ag-rich sulphasalts, stibnite)

Gebre-Mariam et al. (1995) Mineralium Deposita
Archean Wiluna gold deposits, Yilgarn craton, west Australia

**Metal association:** Au-As and Au-Sb deposits

**Host structures:** Cataclastic brittle dextral transcurrent faults

**Host rocks:** Archean mafic and ultramafic rocks

**Metamorphic grade:** Prehnite – pumpellyite facies; faulting is syn to post peak metamorphism

**Sulphide minerals:** Pyrite, arsenopyrite, stibnite ± chalcopyrite, scheelite, tetrahedrite

**Alteration minerals:** quartz - (dolomite) ± fuchsite, sericite, chlorite, epidote; overprint and replace metamorphic minerals

**Internal brittle structures along faults:** fractured discontinuous fault-fill veins, implosion and net-veined breccias

**Open-space-filling textures:** veins with vugs and comb textures, breccias with cockade textures

**Structural traps:** fault intersections, divergent bends, dilational jogs; result in steep ore plunges

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(B) Massive stibnite in a fracture zone, Moonlight deposit

(C) Stibnite breccia with wallrock clasts, West Lode deposit

(D) Breccia with quartz fragments surrounded by stibnite matrix, West Lode deposit
Cockade texture: Forms in breccias as concentric crustiform bands surrounding isolated fragments of wallrocks or early vein material (Low S veins, Stallion prospect, central Newfoundland).

Comb texture: Quartz vein with comb texture (quartz with rhomb terminations) (Tangkelak Epithermal Low Sulphidation Gold Project, Sebek, Central Sumbawa, Indonesia).

Greenschist facies orogenic gold deposit:

- Giant gold deposits (e.g. Kerr-Addison, Sigma-Lamacque, Dome)
- Major pulses of fluids produced by metamorphic devolatilization, cratonization /granulitization of the lower crust, liberation of fluids during melting of subducted slab
- Formed within brittle-ductile transition zone
An assessment of Precambrian gold deposit models from deep to shallow crustal levels

Orogenic Gold Deposits along the Larder Lake – Cadillac deformation zone

Greenschist terrane

Cheminis (Kerr-Addison)

Sigma-Lamaque

Abitibi Gold Deposits
(Poulson et al., 2000)

Cheminis Mine (Kerr-Addison)

Huronian Supergroup

Timiskaming assemblage (2677-2669 Ma) Tisdale, Kinojevis, Blake River assemblages (2710-2696 Ma)

Syenitic intrusions

Sandstone and conglomerate

Alkaline pyroclastics and flows

Mafic volcanic rocks
An assessment of Precambrian gold deposit models from deep to shallow crustal levels

Larder Lake – Cadillac deformation zone

Omega Mine
Type 1: “Flow ore”
Disseminated pyrite in mafic Fe-tholeiites – replacement ore
Type 1: “Flow ore“

**Strong sericite, ankerite, chlorite, and pyrite alteration**

Pyrite overgrows LLCDZ foliation in flow ore and quartz crystallized in pressure shadows around pyrite

Quartz et carbonate cristallisent dans les zones abritées autour de la pyrite qui contient également des inclusions de carbonate
Type 2: “Carbonate ore”

Gold-bearing quartz-carbonate veins in green fuchsitic ultramafic rocks

Before deformation!

Alteration minerals: talc, chlorite, magnesite-siderite, calcite, albite, fuchsite, muscovite, quartz

After deformation!

Spinifex texture
An assessment of Precambrian gold deposit models from deep to shallow crustal levels

Orogenic Gold Deposits along the Larder Lake – Cadillac deformation zone

Greenschist terrane

Cheminis (Kerr-Addison)

Kirkland Lake

Sigma-Lamaque

Abitibi Gold Deposits
(Poulsen et al., 2000)

Sigma-Lamaque and Pamour mines

Robert and Poulsen (2001)
An assessment of Precambrian gold deposit models from deep to shallow crustal levels
Veins in Orogenic gold deposits are syn-kinematic with formation of shear zone because:

1. Intersection lineation between steep and shallow vein is perpendicular to slip lineation along fault.
2. Principal maximum stress direction as given by orientation of shallow extensional vein is consistent with slip direction along fault.
3. Drag or rotation of shallow extensional vein consistent with slip direction.

Renabie Gold Mine

Wawa Subprovince

Laminated quartz-gold veins within shear zones

Interpreted as an Orogenic Gold Deposit because the veins hosted by shear zones cut across the regional foliation in the host tonalite pluton and metavolcanic rocks

Jordan McDiVitt (MSc 2016 Laurentian) McDivitt et al. 2017, 2018 Econ Geol
Laminated quartz vein (LQV) in shear zone (SZ) or quartz-sericite-pyrite schist

East-facing wall of Nudulama pit

Jordan McDiVitt (MSc 2016 Laurentian)

McDivitt et al. 2017, 2018 Econ Geol
Laminated quartz vein with saccharoidal texture at Nudulama East

McDivitt et al. 2017, 2018 Econ Geol

An assessment of Precambrian gold deposit models from deep to shallow crustal levels
An assessment of Precambrian gold deposit models from deep to shallow crustal levels

Isoclinal F1-folded laminated quartz vein refolded by F2 folds at Pileggi No.1

Jordan McDiVitt (MSc 2016 Laurentian)
An assessment of Precambrian gold deposit models from deep to shallow crustal levels

Laminated quartz vein transposed parallel to S2 at Pileggi No.1

Jordan McDiVitt
(MSc 2016
Laurentian)

McDivitt et al. 2017,
2018 Econ Geol

Proterozoic
- Matachewan Mafic Dikes
- Biotite-Bearing Tonalite (Missinaibi Lake Batholith)
- Intermediate to felsic volcanioclastic rocks
- Massive to pillowed mafic volcanioclastics
Quartz veins are pre-foliation and shear zone.

They predate regional deformation of their host tonalite and metavolcanic rocks.
In metamorphic terranes, sheeted veins or arrays of parallel veins may be associated with orogenic gold deposits or intrusion-related gold deposits.

Concentric and radial fracture patterns reflect magmatic processes and are more common above or in the upper parts of the stocks.

Concentric and radial mineralized fractures and veins developed at high levels in the San Juan mine area, Safford Mining District, Arizona.

*Tosdal and Richards (2001) Reviews in Econ Geol*

More linear arrays of veins reflect tectonic influences and dominate at depth, forming as the system cools and the pluton solidifies. The resulting different vein arrays are therefore commonly vertically and temporally distributed in the porphyry system.

*Tosdal and Richards (2001) Reviews in Econ Geol*
Orogenic gold deposits: Veins and mineralization are emplaced in active shear zones. Orogenic veins are kinematically consistent with the movement along the shear zones. They formed during or after peak metamorphism.

Intrusion-related gold deposits typically formed early during the tectonic history of a greenstone belt. The veins and deposits record most or all the tectonic events that affected the greenstone belt.

Renabie gold deposit: Laminated quartz-gold veins predate the formation of regional cleavage and stretching lineation in the Wawa gold camp.

The veins and their weak alteration envelope acted as a planar anisotropy that localize the nucleation and propagation of the shear zones hosting them.

Renabie is interpreted as an intrusion-related gold deposit.

Using basic structural principles, veins associated with intrusion-related gold deposits can be differentiated from orogenic veins. This is important because for:

Intrusion-related deposits:
- Exploration target is the intrusion itself
- Regional exploration focus on intrusions with similar compositional, alteration, and textural features

Orogenic gold deposits:
- Exploration target is the shear zone hosting the veins
- Regional exploration focus on shear zones with similar kinematic features
Amphibolite – Lower Granulite orogenic gold deposit

**Characteristic Features**
- Type gold deposits (e.g. Big Bell, Renco, Marvel Loch, Hemlo?)
- T = 500-700°C, P = 3-6 kb, Depth > 12 km
- In deformation zones (wide shear zones)
- Minor to negligible carbonate alteration
- Partial melting at the highest grades with formation of pegmatites
- Lack of major quartz veins
- **Sulphides:** Pyrrhotite, arsenopyrite, loellingite
- **Alteration minerals:** Quartz, biotite, diopside, calcic amphibole, plagioclase, garnet, K-feldspar

The deeper, the greater the controversy on the formation of orogenic gold deposits!

Red square: amphibolite-lower granulite orogenic gold deposits

Blue square: Atypical gold deposits; interpreted as orogenic gold deposits or overprinted/metamorphosed porphyry or epithermal gold deposits

**HEMLO Deposit**

Goldfarb et al. (2005) Economic Geology 100th Anniversary Volume
Hemlo deposit

Characteristic features:

- Au, Mo, Ag, Ba, As, Hg, Sb, V metal association
- Lack of major quartz or carbonate veins
- Pre- to syn-peak amphibolite grade metamorphism
- Hosted in high strain zones within quartz-feldspar felsic porphyry and felsic fragmental rocks (Moose Lake volcanic complex), and metasedimentary rocks
- K-feldspar – sericite (green) – biotite – albite alteration minerals
- Disseminated pyrite, molybdenite, barite, stibnite, realgar

Proposed models:

Synvolcanic exhalative, epithermal, porphyry, skarn, orogenic gold


Time Constraints

- 2677 Ma: Late-tectonic sanukitoid pluton
- 2680 Ma – 2677 Ma: Deformation, mineralization, plutonism
- 2680 Ma: Cedar Lake Pluton
- 2693 Ma - 2685 Ma: Deposition of volcanic and sedimentary rocks
- 2720 Ma: Older Black-Pic batholith

U/Pb ages from Davis & Lin (2003) Econ Geol
Strong Structural Controls on Mineralization

Ore zones are in high strain zones along the limbs of asymmetrical S-shaped folds.

Lin (2001) Econ Geol

Altered and mineralized, highly strained, felsic fragmentals

Lin (2001) Econ Geol

Tight fold in sedimentary rocks

Lower mineralized zone

Lin (2001) Econ Geol
Interpretation

**Magmatic hydrothermal component** indicated by
Au-Mo-As-Hg-Sb metal association; presence of barite; strong K-feldspar-sericite alteration; disseminated gold, pyrite, molybdenite; close time association between deformation, mineralization, metamorphism, sanukitoid plutonism

Mineralization
- Syn-deformation
- Pre-deformation

Atypical, disseminated-replacement, “Orogenic” gold deposit resulting from magmatic-metamorphic hydrothermal fluids

Atypical, overprinted, stockwork-disseminated Porphyry-type Deposit
Kuhns et al. 1984; Lin (2001); Poulsen et al. (2000)

Magmatic fluids

Pre-deformation

Syn-deformation

Lin (2001)
Econ Geol
Continuum Model of Orogenic Gold Deposits

Groves (1993) Mineralium Deposita

Model postulates the formation of orogenic gold deposits over an interval of 25 km from sub-greenschist (3 km) to lower granulite (>12km) levels from fluids generated during the granulitization of the lower crust and/or melting of the subducted slab.

Hypozonal orogenic gold deposits form at amphibolite to lower granulite facies conditions.

Diagram from Gebre-Mariam et al. (1995) Min Dep

Metamorphic Model


Deposits form as metamorphic devolatilization at the amphibolite – greenschist transition liberates fluids that are channelized upward along major structures (shear zones) and deposit quartz-carbonate veins and gold within the brittle-ductile transition at greenschist facies conditions.

Amphibolite to lower granulite orogenic gold deposits form as greenschist grade orogenic deposits are buried to amphibolite to lower granulite levels during continued movement along the major structures.

Amphibolite to lower granulite orogenic gold deposits are metamorphosed deposits that initially formed at greenschist facies conditions.
Hypozonal versus metamorphosed amphibolite-granulite facies Orogenic Gold Deposits

**Similar features:**
(1) Hosted by high-strain zones (wide shear zones)
(2) Strongly deformed with penetrative foliation and lineation
(3) High metamorphic grade alteration assemblages
(4) Sulfide minerals: pyrrhotite – arsenopyrite – (loellingite FeAs2)
(5) Partial melting

**Different features:**

**Hypozonal deposit**
(1) Lack of major quartz veins
(2) Replacement of metamorphic by alt. mineral
(3) Syn- to slightly post-peak metamorphism
(4) Low number of mineral phases indicating open metasomatic system
(5) Oscillatory zoning in vein minerals (diopside) indicating growth under high fluid flux
(6) Loellingite (higher T) rimmed by pyrrhotite

**Metamorphosed deposit**
(1) May contain major quartz veins
(2) No replacement of alteration by metamorphic minerals
(3) Pre-peak metamorphism
(4) Gold grains as inclusions in high T alteration min
(5) Overgrowth of higher T on lower T sulfide minerals
(6) Barren pegmatite dikes cutting mineralization

Phillips and Powell 2009
Groves 1993
MERC/PDAC Short Course
March 03, 2018

Phillips et al. 2010
Mueller 1991

Southeastern Trans Hudson Orogen

**New Britannia (Snow Lake) mine**

Phillips et al. (1993)
An assessment of Precambrian gold deposit models from deep to shallow crustal levels
Strongly foliated alteration and mineralization zone!

**Middle amphibolite** alteration mineral assemblage: Diopside-oligoclase-(calcic amphibole)
Sulfide minerals: Pyrrhotite, arsenopyrite

Arsenopyrite replacing older zoned corroded pyrite

Arsenopyrite and pyrrhotite in stable equilibrium
Multiple strongly deformed quartz veins!

Garnet porphyroblast with arsenopyrite (Asp) and ilmenite (Ilm) inclusions

Kate Rubingh (PhD thesis in progress, Laurentian)

No. 3 zone

Three ore zones in the hinge of the Nor-Acme anticline

Kate Rubingh (PhD thesis in progress, Laurentian); Rubingh et al. (2017) CJES
Overprinting of quartz vein and alteration halo by cleavage axial planar to Nor Acme anticline

Legend:
- Metamorphic rocks - unit 5
- Pink brecciated quartz veins
- White quartz veins
- Main white quartz veins locally with tourmaline
- Iron carbonate veins
- S2 foliation defined by the flattening of the clasts
- Brittle fracture (late devital offset)

Assay values, 2014, gold in g/t

The 3 Zone

Boundary Zone

Three ore zones in the hinge of the Nor-Acme anticline

Kate Rubingh (PhD thesis in progress, Laurentian); Rubingh et al. (2017) CJES
Boundary Zone

Folded quartz vein in hinge of parasitic fold to Nor Acme anticline

Strong refraction of Nor Acme axial planar cleavage in hinge of fold

Nor Acme anticline is the oldest of several generations of folds that formed during thrusting of the Kisseynew basin over the Flin Flon Belt and culminated in amphibolite peak metamorphism.

Kraus & Williams (1999)
Is New Britannia a hypozonal or metamorphosed Orogenic Gold Deposits?

**Similar features:**

1. Hosted by high-strain zones (wide shear zones)  **Yes!**
2. Strongly deformed with penetrative foliation and lineation  **Yes!**
3. High metamorphic grade alteration assemblages
   - Diopside - K-feldspar – calcic amphibole – plagioclase – biotite – (garnet)  **Yes!**
4. Sulfide minerals: pyrrhotite – arsenopyrite – (loellingite FeAs2)  **Yes!**
5. Partial melting  **No – higher metamorphic grade needed**

New Britannia is a middle amphibolite facies orogenic gold deposit.

**Next Question:** Did it form at middle amphibolite conditions or was it metamorphosed to those conditions?

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Is New Britannia a hypozonal or metamorphosed Orogenic Gold Deposits?

**Different features:**

**Hypozonal deposit**

1. Lack of major quartz veins
2. Replacement of metamorphic by alt. mineral
3. Syn- to slightly post-peak metamorphism
4. Low number of mineral phases indicating open metasomatic system
5. Oscillatory zoning in vein-minerals (diopside) indicating growth under high fluid flux
6. Loellingite (higher T) rimmed by pyrrhotite

New Britannia is an orogenic gold deposit that formed at greenschist facies conditions and was buried and metamorphosed to middle amphibolite facies conditions during thrusting.

**Metamorphosed deposit**

1. May contain major quartz veins  **Yes!**
2. No replacement of alteration by metamorphic minerals  **Yes!**
3. Pre-peak metamorphism  **Yes!**
4. Gold grains as inclusions in high T alteration min
5. Overgrowth of higher T on lower T sulfide minerals  **Yes!**
6. Barren pegmatite dikes cutting mineralization

In addition, field relationships suggest:

Veins and their alteration halo are overprinted by the regional cleavage and folds that formed during overthrusting of the Flin Flon belt by the Kisseynew basin.
Implications for Mineral Exploration

(1) Changes in orogenic gold deposits with increasing metamorphic grade
   Review of the features that can be used in the field to identify orogenic gold deposits
   that formed at different crustal levels

(2) Using basic structural principles, veins associated with intrusion-related gold deposits
   can be differentiated from orogenic veins. This is important because:
   - Intrusion-related deposits:
     Exploration target is the intrusion itself
     Regional exploration focus on intrusions with similar compositional, alteration, and textural features
   - Orogenic gold deposits:
     Exploration target is the shear zone hosting the veins
     Regional exploration focus on shear zones with similar kinematic features and orientation

(3) Criteria for differentiating between hypozonal and metamorphosed orogenic ore deposits at high metamorphic grade.
   Important for understanding the controlling structures on mineralization

(4) Multiple controls on the formation of atypical gold deposits
   Importance of understanding their determinant effect (or not) on the formation of deposits