Multi-Scale Controls on Orogenic Gold Precipitation and Remobilization in the Malartic-Val-d'Or District (Abitibi Subprovince, Québec)

Michael Herzog (PhD candidate)

Prof. Crystal LaFlamme, Prof. Georges Beaudoin

Département de Géologie et de Génie Géologique

Université Laval, Québec City, QC, Canada

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Mineral Exploration Research Centre

at the HARQUAIL School of Earth Sciences

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- Geological Survey of Canada / Commission géologique du Canada (Canada, 1842)
- Canada

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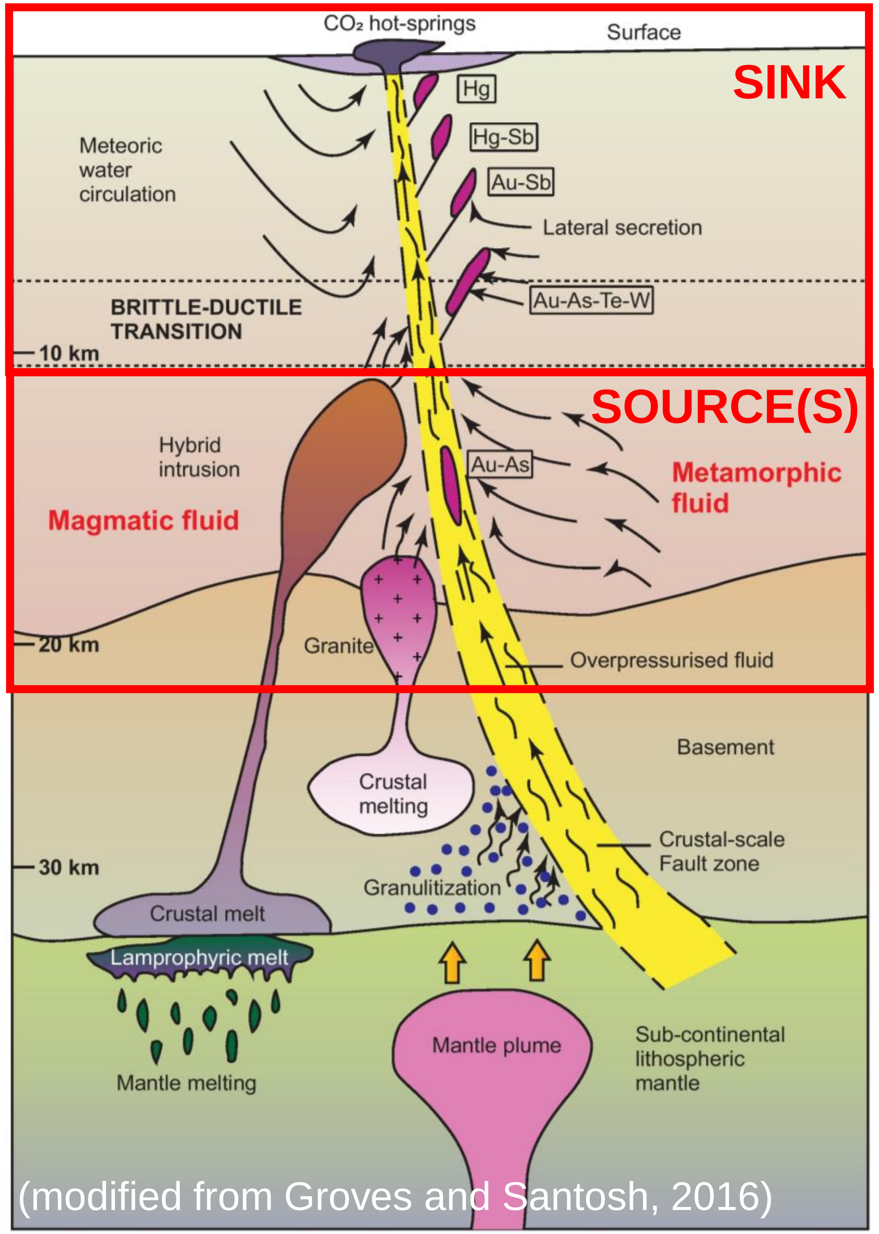
What Controls Gold Endowment?



(modified from Groves and Santosh, 2016)

Sink:

- What is the timing of gold mineralization?
- What are fluid flow conditions? Successive events?

Source(s):

- What geological processes drive fluid release?
- What are the source(s) of fluid(s) and volatiles?

Towards an integrated understanding of auriferous hydrothermal fluid flow system(s) in the mid- to upper crust (<20 km)

Strategy – Endowed vs. Less Endowed

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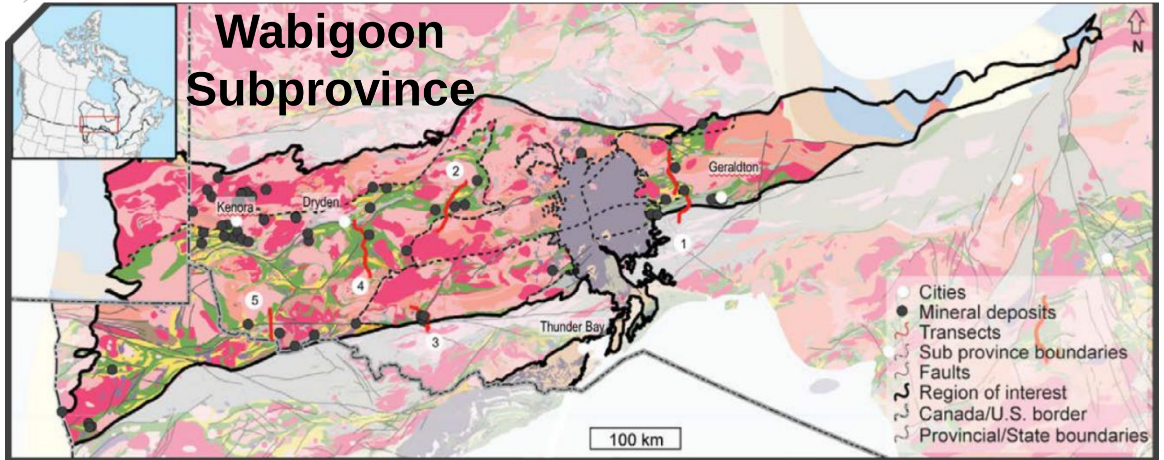

Figure 5: Geological compilation of the Wabigoon Subprovince with locations of the transects. 1. Geraldton-Onaman, 2. Sturgeon River, 3. Atikokan, 4. Dryden-Stormy, 5. Rainy River

Less endowed endmember

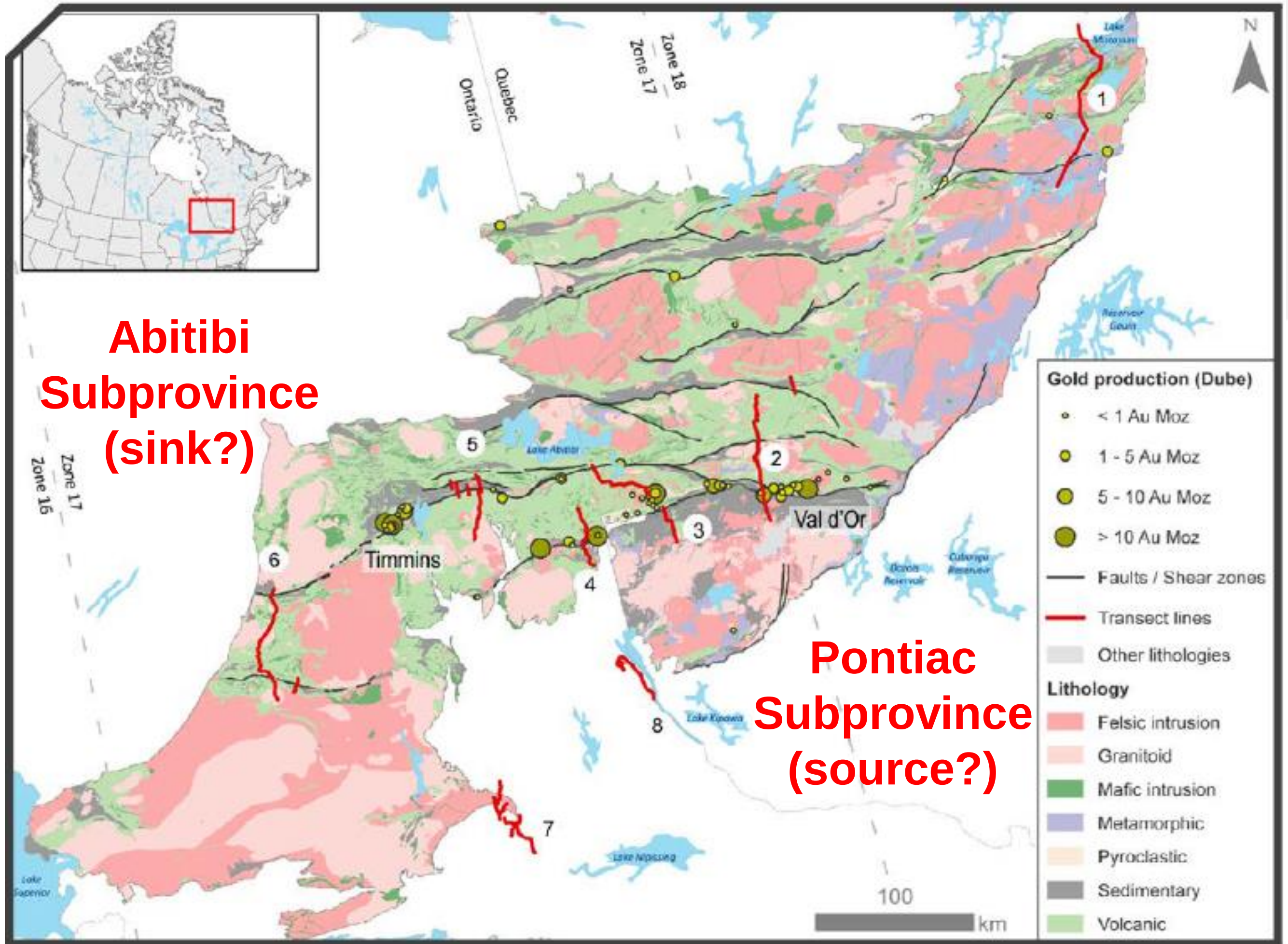

Figure 4: Geological compilation of the Abitibi Subprovince with locations of transects. 1. Chibougamau, 2. Malartic, 3. Rouyn-Noranda, 4. Ben Nevis-Larder Lake, 5. Matheson, 6. Swayze, 7. Sudbury, 8. Cobalt

Abitibi: Endowed endmember

Gold endowment at different scales:

- Superior scale (x100 km)
- Transect scale (x10 km)
- Deposit scale (x1 km)

Overview – Projects at ULaval

- **Metamorphic fluid generation (Isaac Siles Malta)**
  - Transect- to regional-scale
  - Composition, volume and timing of fluid generation from Pontiac metasediments

- **Regional Isotopic Survey (Benoit Quesnel & Christophe Scheffer)**
  - Transect- to regional-scale
  - Isotopic fluid composition variation at Superior scale

- **Mapping / Modelling Fluid Flow (Guillaume Raymond)**
  - Deposit-scale
  - Mechanisms of gold endowment; H, O, C

SOURCE → SINK

Huston & Gutzmer eds. (2023) Isotopes in EG, metallog. & explo.

- **The Source of Gold (Antoine Godét; coll. Iain Pitcairn)**
  - Transect- to regional-scale
  - Mobilization of Au and related elements and associated geological processes

"Gold Fluid Window"

- **Sulfur DNA of Fluids (Michael Herzog)**
  - District- to deposit-scale
  - Source of fluid(s) and volatiles (S); timing of mineralization

- **Physical ID of altered rocks (Yasaman Nemati; coll. F. Ghoraishi and C. Hébert)**
  - Deposit-scale
  - Mapping physical properties of Hydrothermal Alteration halo

Outline – Gold Sinks at Malartic-Val-d'Or

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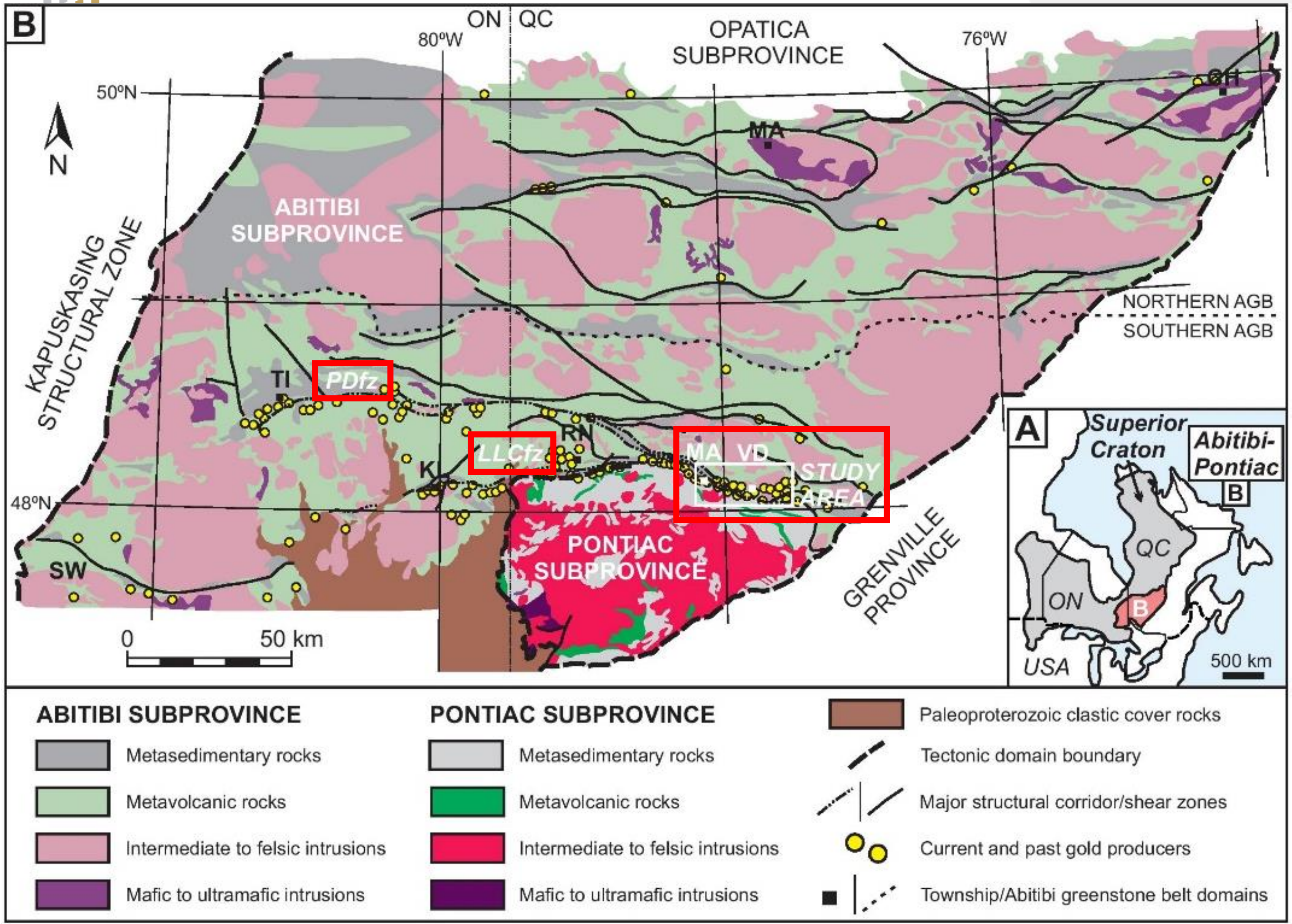
- **Timing of Gold Mineralization**
  - **=> misfit between structural record & previous bulk dates**
  - => QC & QTC veins (xenotime: in-situ U-Pb)

- **Orogenic Gold Precipitation Mechanisms**
  - => QTC (pyrite: multiple S isotopes & trace elements)

- **Amorphous Carbon & Nanoparticle Formation**
  - => QTC (BiTe-nanoparticles: transmission electron microscopy)

Neoarchean Abitibi Subprovince



- Abitibi-Wawa Orogeny
  - => ~2700-2580 Ma
- Major N-S shortening
  - => **D2 in MVD = D3**
  - => ~2669-2643 Ma
- Peak metamorphism
  - => 2670 Ma
- Gold mineralization
  - => PDfz & LLCfz

(modified from Monecke et al., 2018; SIGÉOM)

Structural Timing of Gold Mineralization

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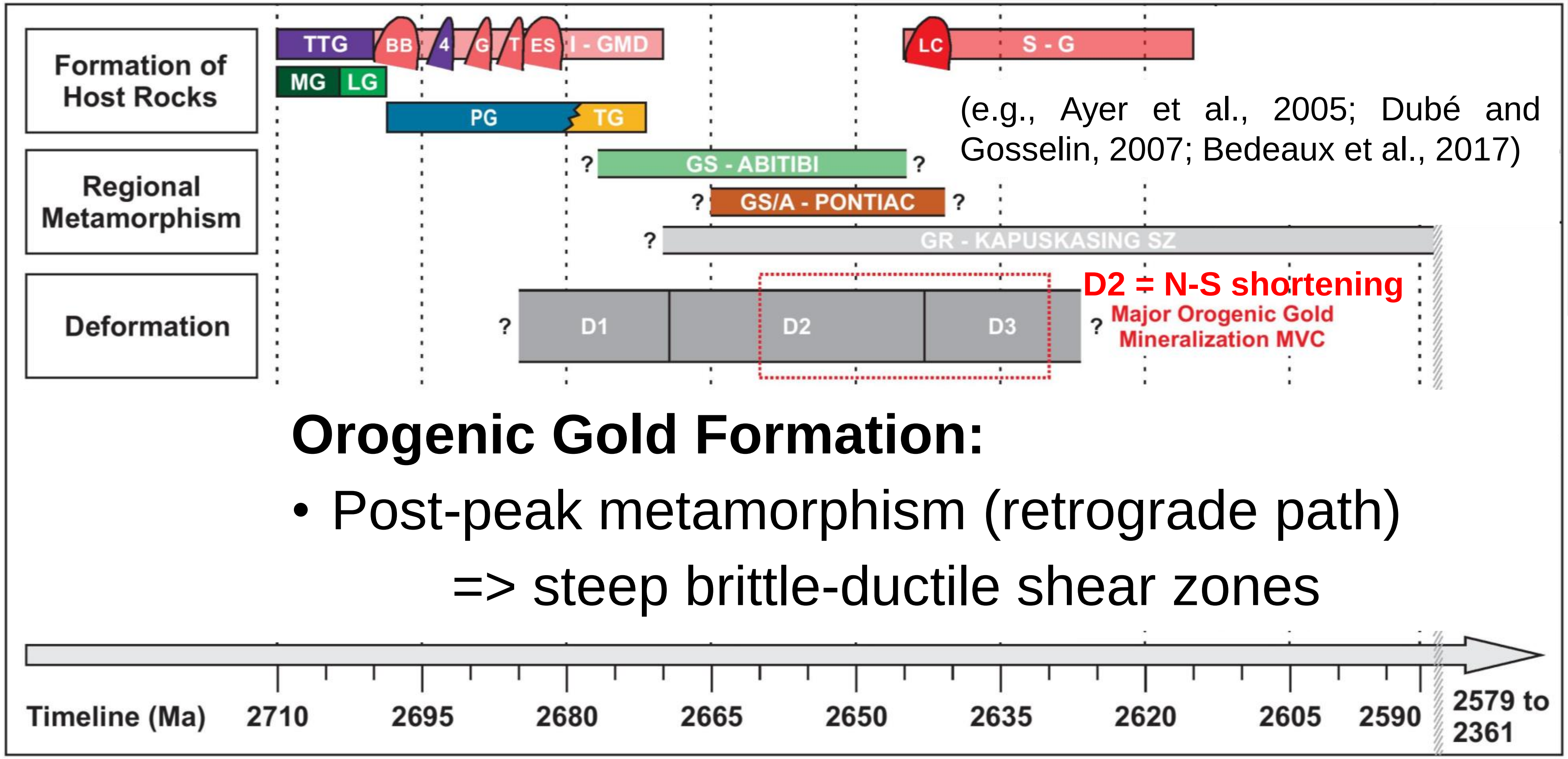
Malartic-Val-d'Or District



(e.g., Ayer et al., 2005; Dubé and Gosselin, 2007; Bedeaux et al., 2017)

Orogenic Gold Formation:

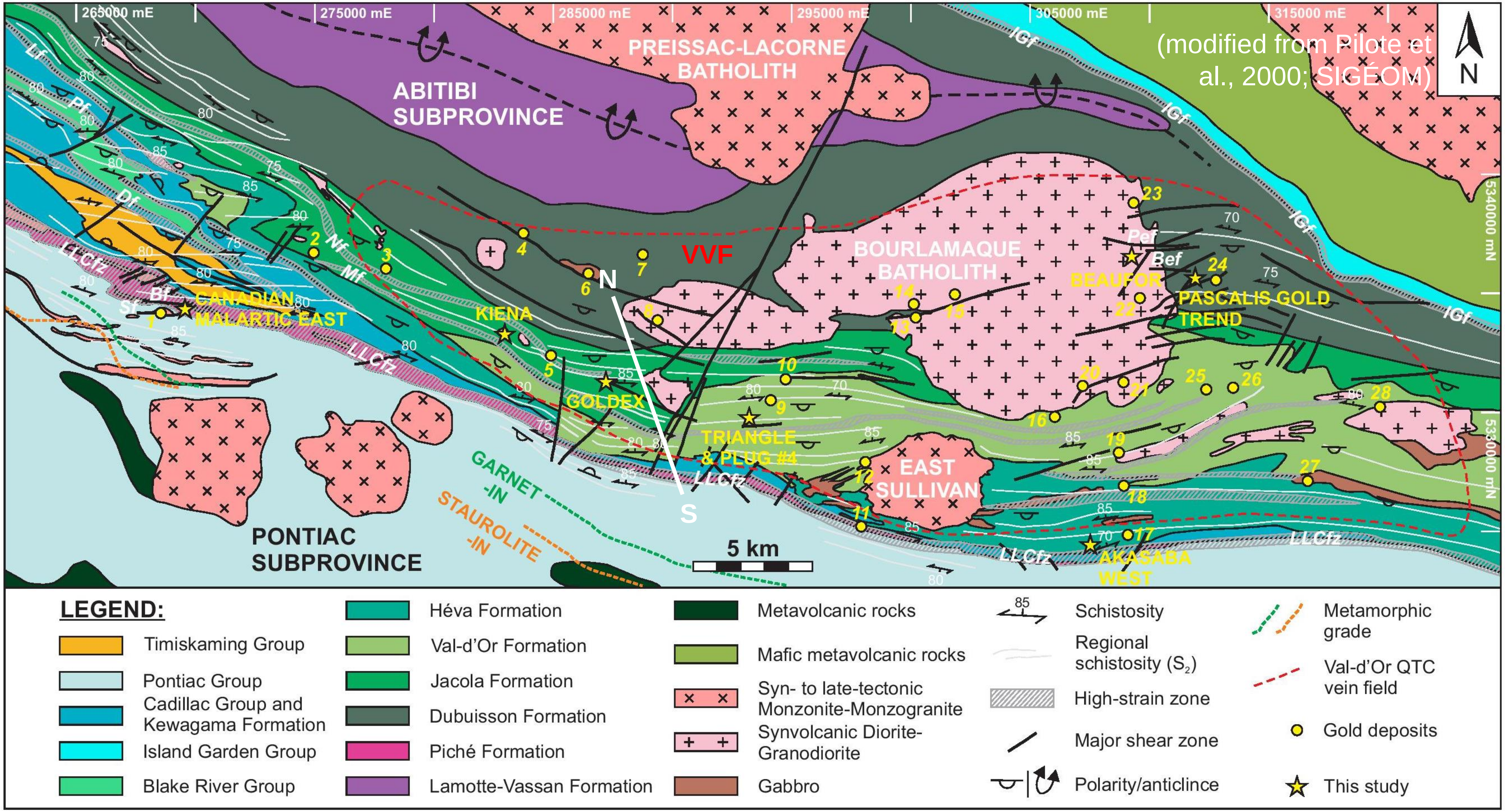
- Post-peak metamorphism (retrograde path)
  => steep brittle-ductile shear zones

Gold Mineralization:

- Deformed Qz-Cb veins (pre-D2)
- Qz-Tur-Cb veins (late- to syn-D2)

Major orogenic Au on retrograde path of Abitibi-Wawa Orogeny

Malartic-Val-d'Or District (2714-2685 Ma)

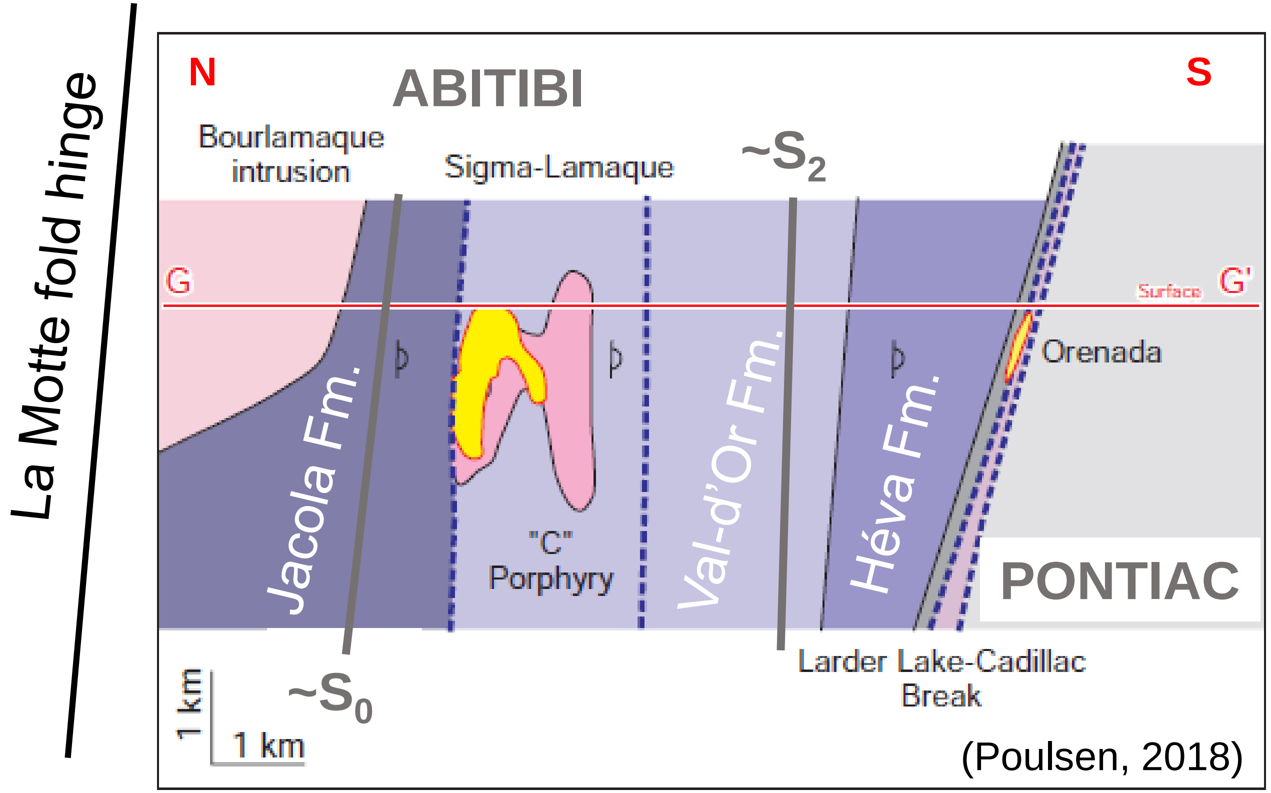


OVERALL DIP S(0)

YOUNGING

Malartic-Val-d'Or District – Structures

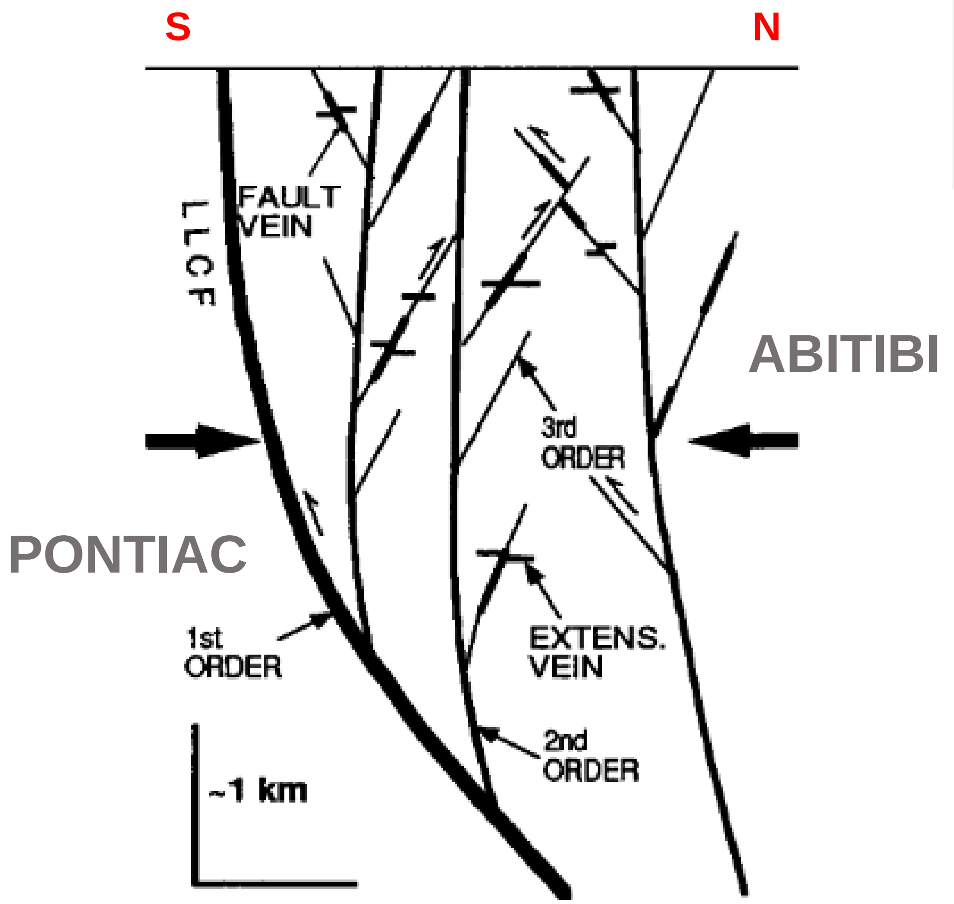
D1 – large-scale folding & tilting (QC?)



(Poulsen, 2018)

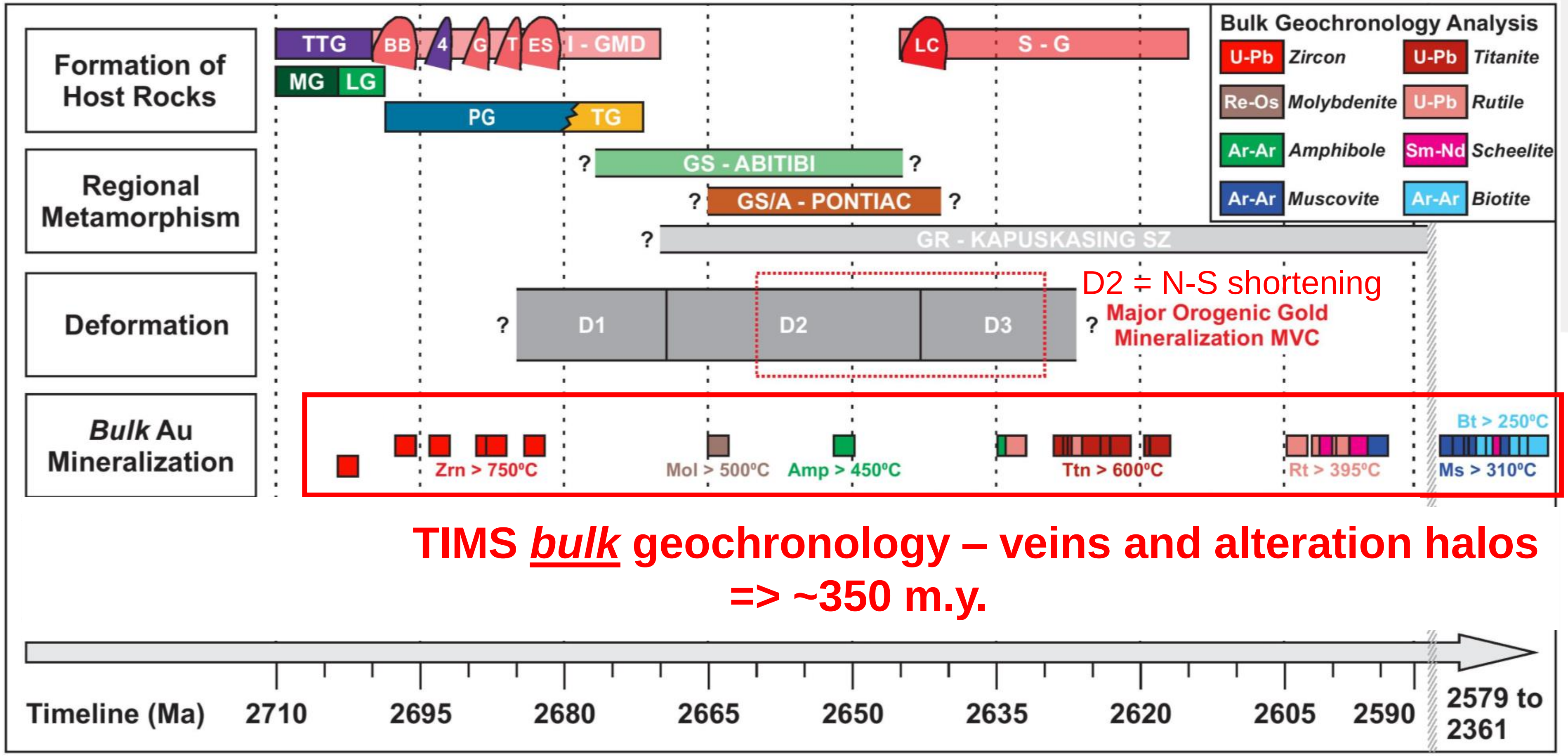
- southern limb of La Motte Anticline

D2 – steep reverse shear zones (QTC)
D3 – dextral reactivation



(Robert et al., 1995)

Timing of Gold Mineralization – MVD



Zircon > (Molybdenite) > Titanite > Rutile >> Muscovite > (Scheelite) > Biotite

>600°C

850°C → 250°C **decreasing T$_{CLOSURE}$**

U-Pb in xenotime & monazite

Regional cooling or different mineralization events? *U-Pb PHOSPHATES!*

Timing of Gold Mineralization

Mineralium Deposita (2023) 58:105–133
https://doi.org/10.1007/s00126-022-01131-1

ARTICLE

Check for updates

U–Pb vein xenotime geochronology constraints on timing and longevity of orogenic gold mineralization in the Malartic-Val-d'Or Camp, Abitibi Subprovince, Canada

M. Herzog[1] · C. LaFlamme[1] · G. Beaudoin[1] · J. Marsh[2] · C. Guilmette[1]

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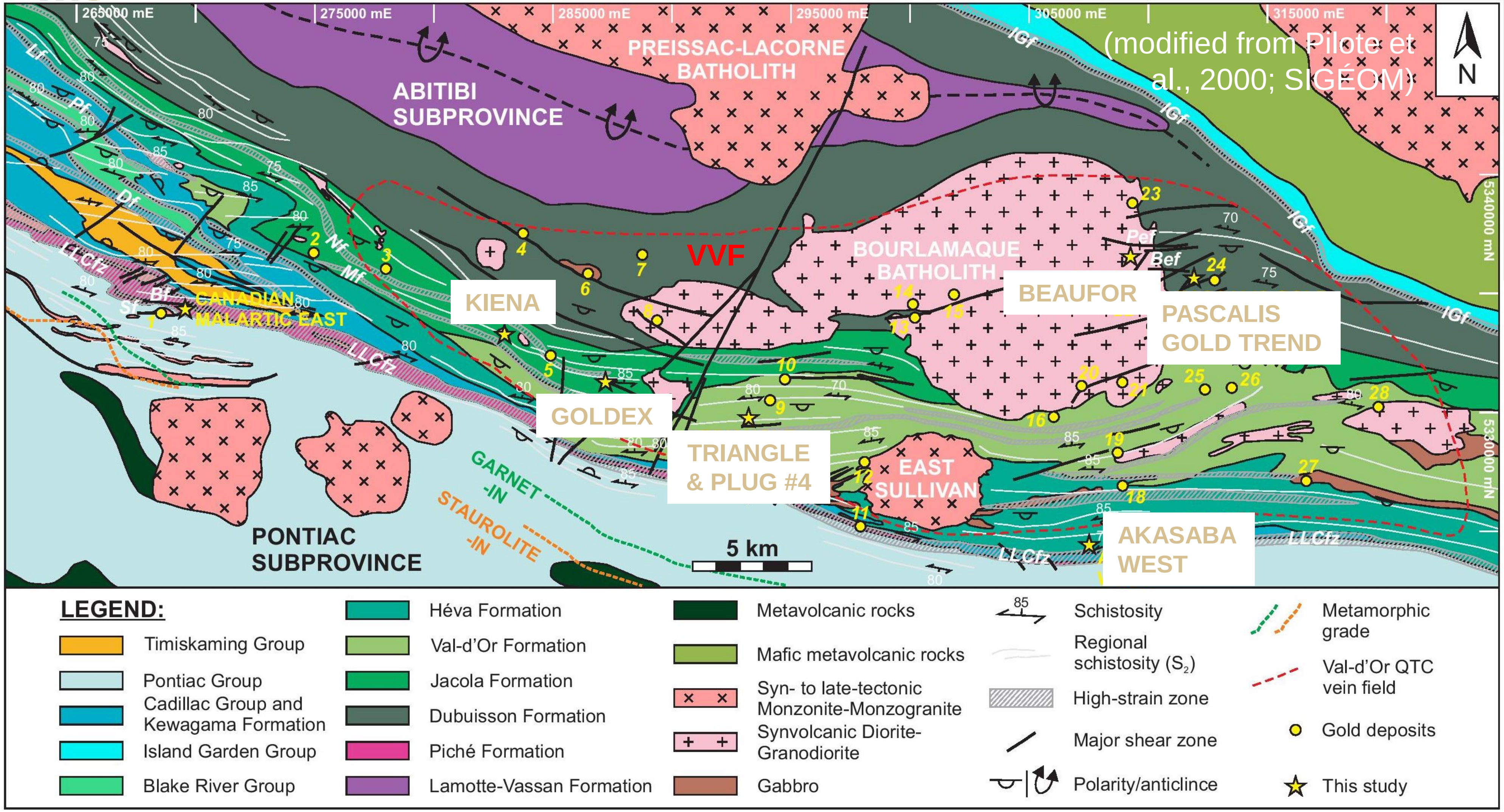
- **Geochronology**
  - => QC & QTC veins
  - => In-situ U-Pb vein xenotime
    - => LA-MC-ICPMS

Structural Framework & Mineralzation



QC (pre-D2)

- Kiena (S50)

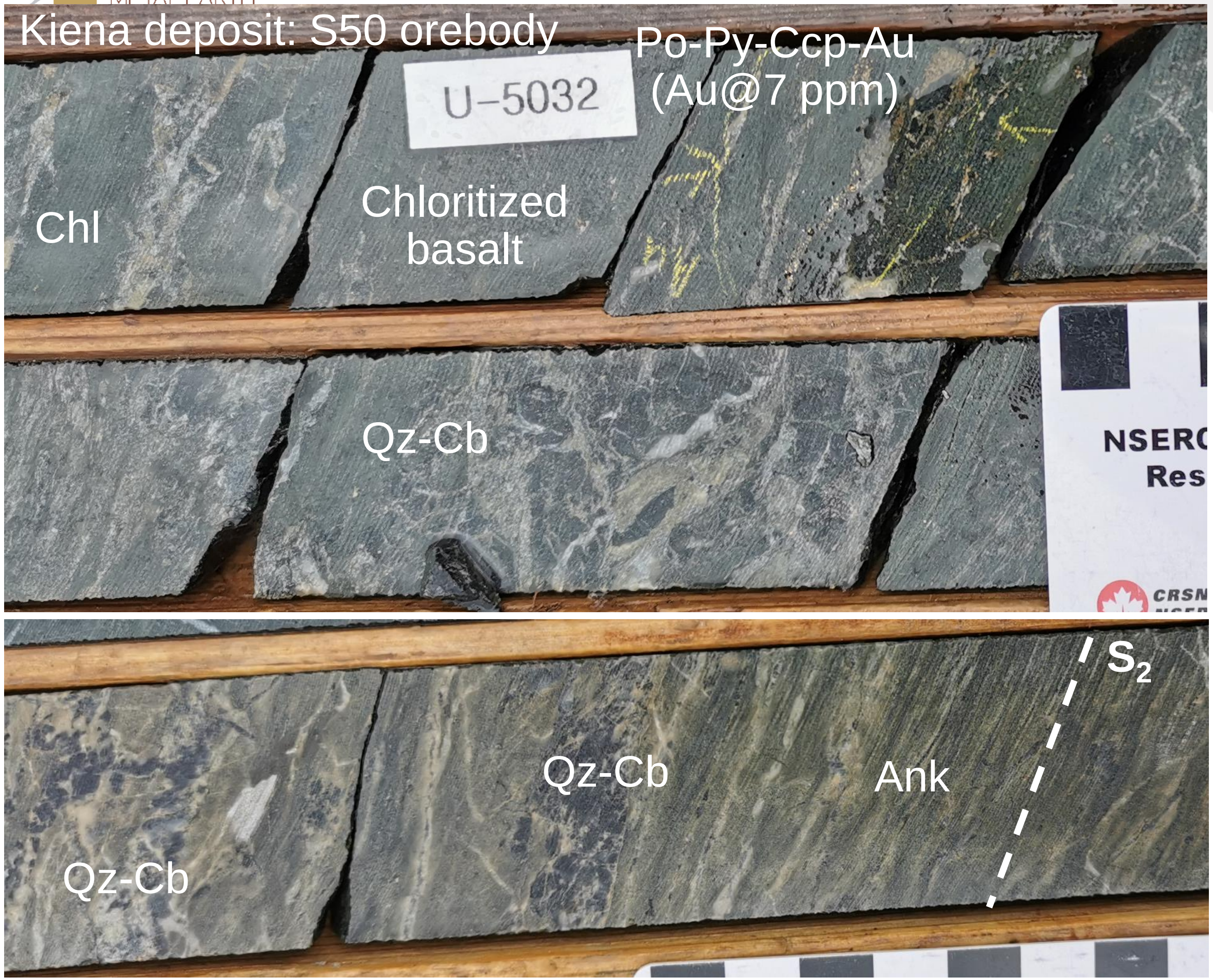
QTC (syn-D2)

- Kiena (Deep)
- Goldex
- Triangle
- Plug #4
- Beaufor
- Pascalis Gold Trend
- Akasaba West

D1: Ferguson et al. (1968), Imreh (1984), Davis (2002), Bleeker (2015)

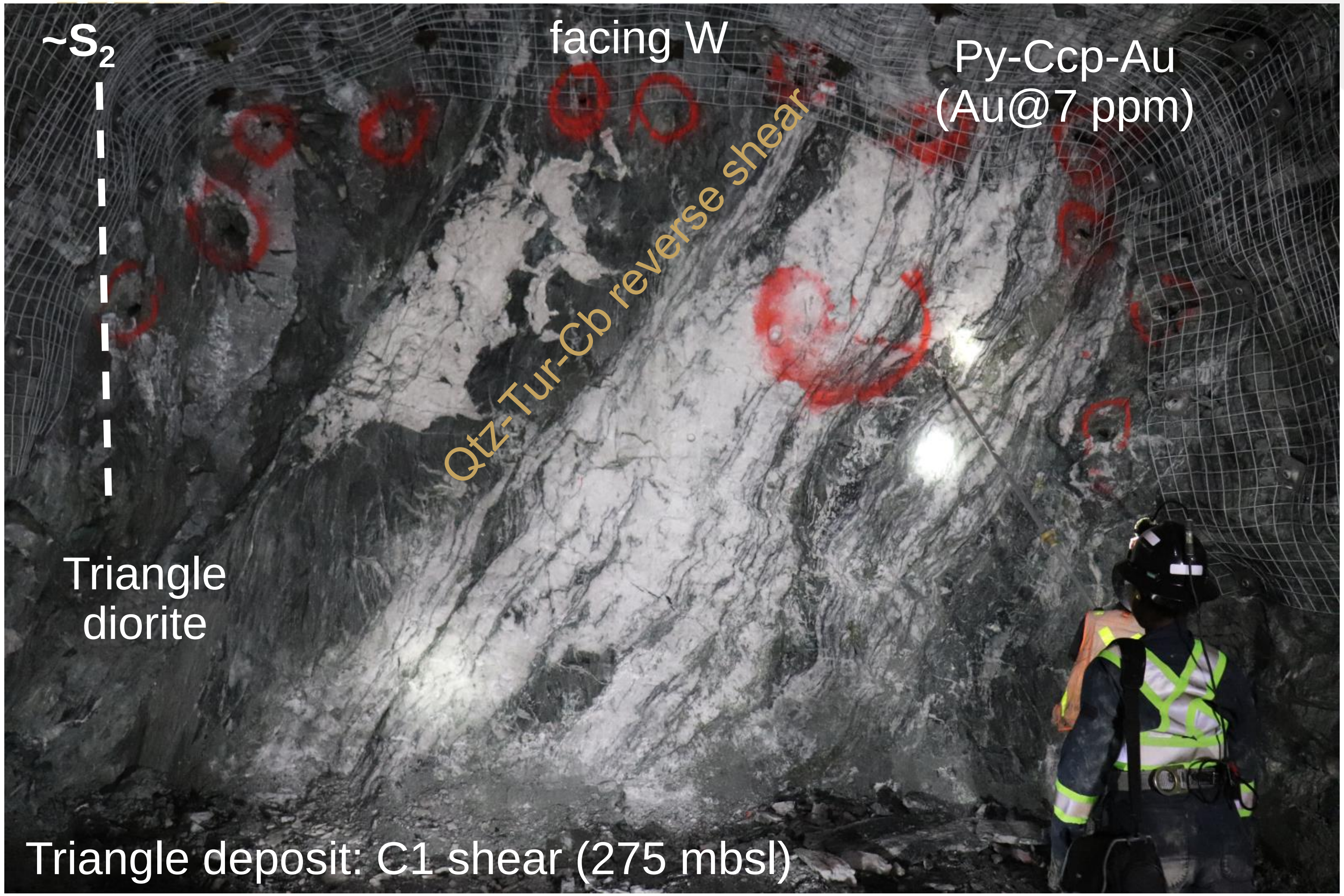
D2: Corfu et al. (1991), Feng and Kerrich (1991), Robert (1994), Couture et al. (1994), Daigneault et al. (2002), Bleeker (2015) Bedeaux et al. (2017), De Souza et al. (2017)

Mineralization – Pre-D2 QC Veins



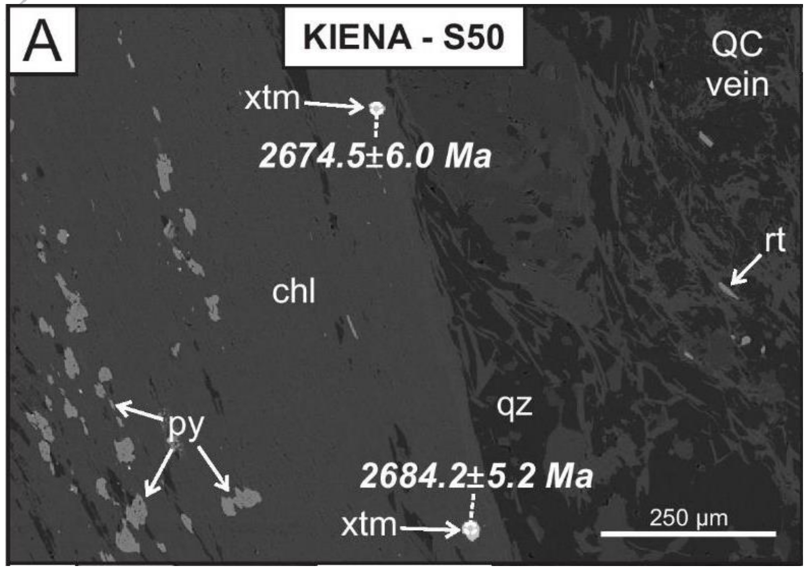
- Quartz-carbonate
  - => po-py-ccp-Au
  - => chl-ank-ab halo
- Marban-Norlartic Tectonic Zone
  - => NW-trending
  - => sub-vertical
- Magmatic-hydrothermal origin
  - => brittle texture
  - => breccia
- Strongly folded
  - => ductile texture
  - => boudinage

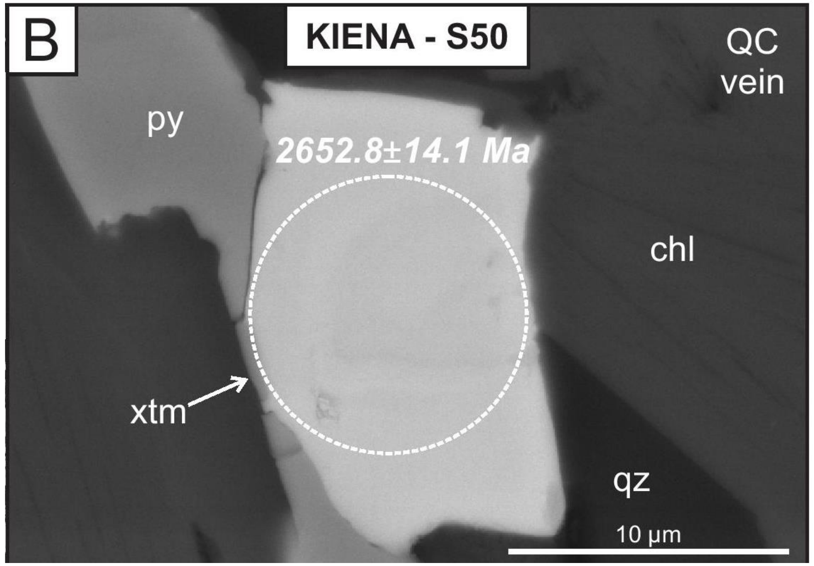
Mineralization – Syn-D2 QTC Veins



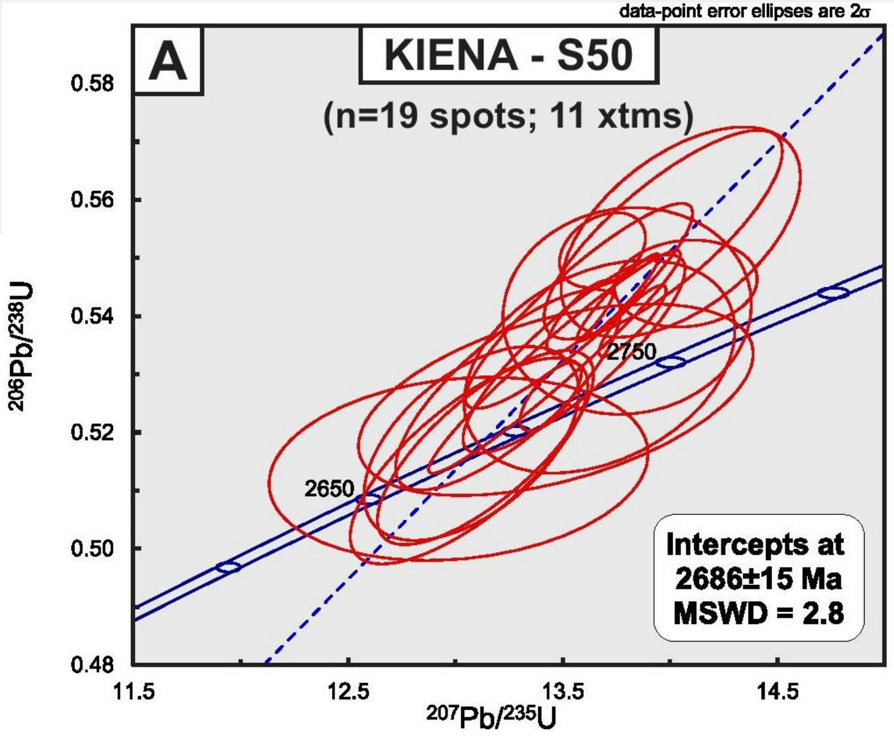
- Quartz-tourmaline-carbonate
  - => py-Au-po
  - => chl-ser-cal-ank-ab halo
- 2nd to 3rd order structures
  - => brittle-ductile texture
- Sub-parallel to S2 fabric
- Reverse shear zones
- Moderate to steep dip to south
  - => 35° to 70°
  - => conjugate vein sets

Timing of Au Mineralization – Pre-D2 QC





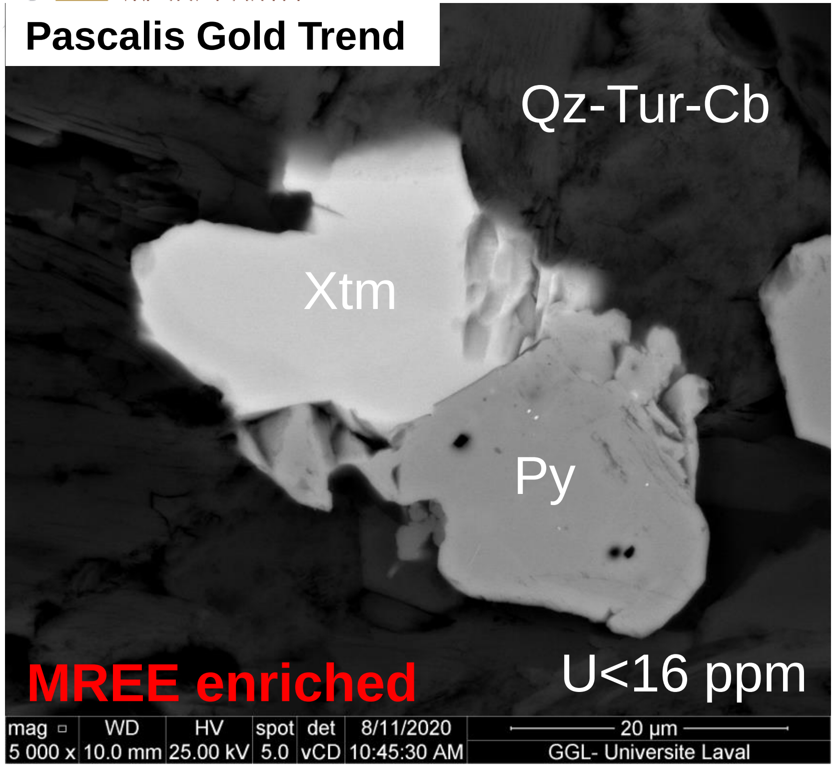
Mean $^{207}Pb/^{206}Pb$ = ca. 2688 Ma
(MSWD = 8.9)

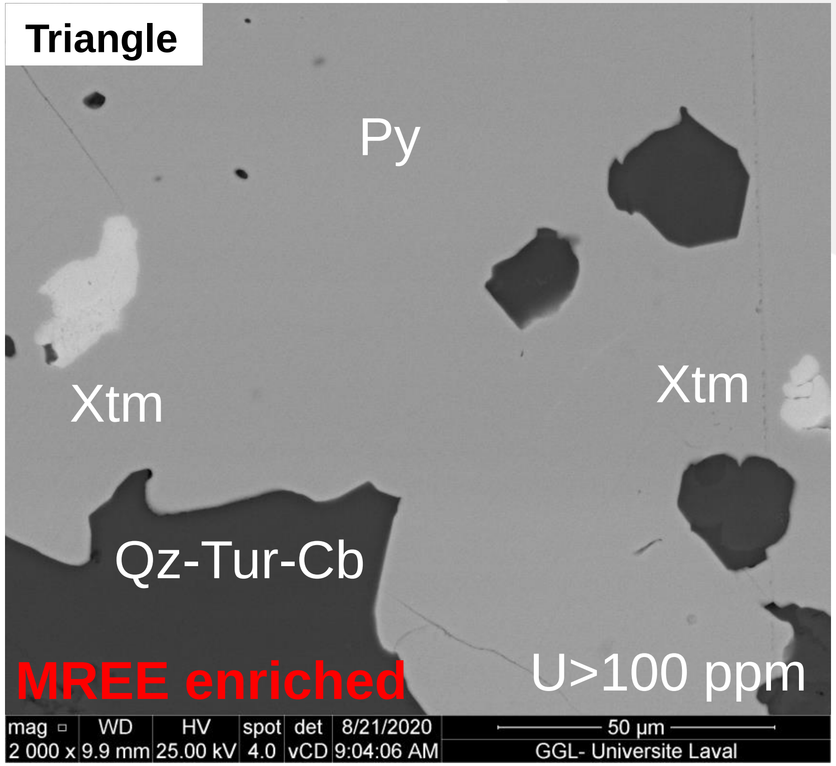


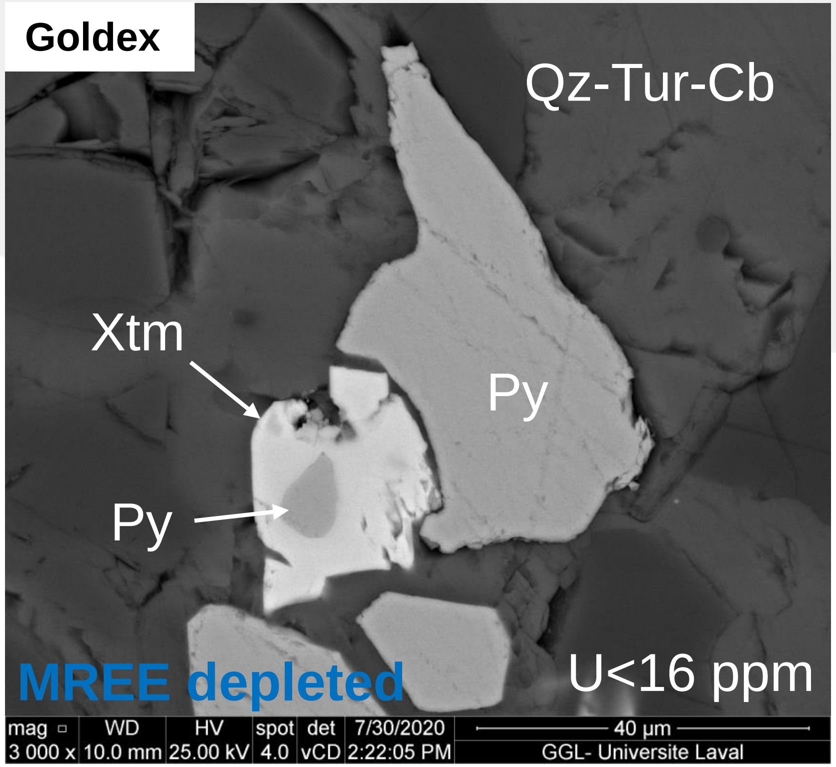
- In-situ LA-MC-ICPMS

- Xtm in equilibrium with Au-hosting py
- Xtm in equilibrium with hydrothermal vein assemblage
- **Timing of QC Au mineralization: ca. 2686 Ma**

Hydrothermal Xenotime Textures – QTC





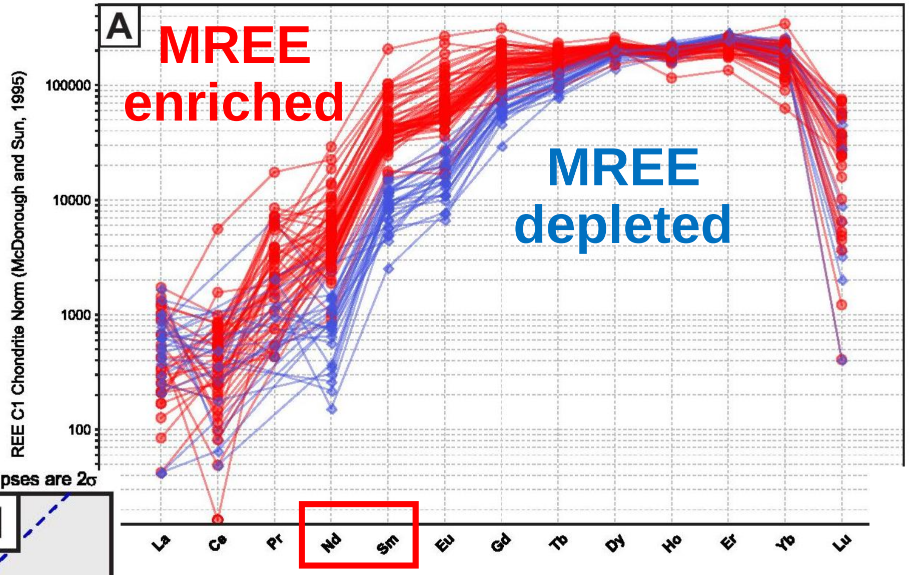


- In textural equilibrium with auriferous sulfides
- Sulfide mineral inclusions (Au-Te in py rim domain)
- Sulfide mineral overgrowth and replacement

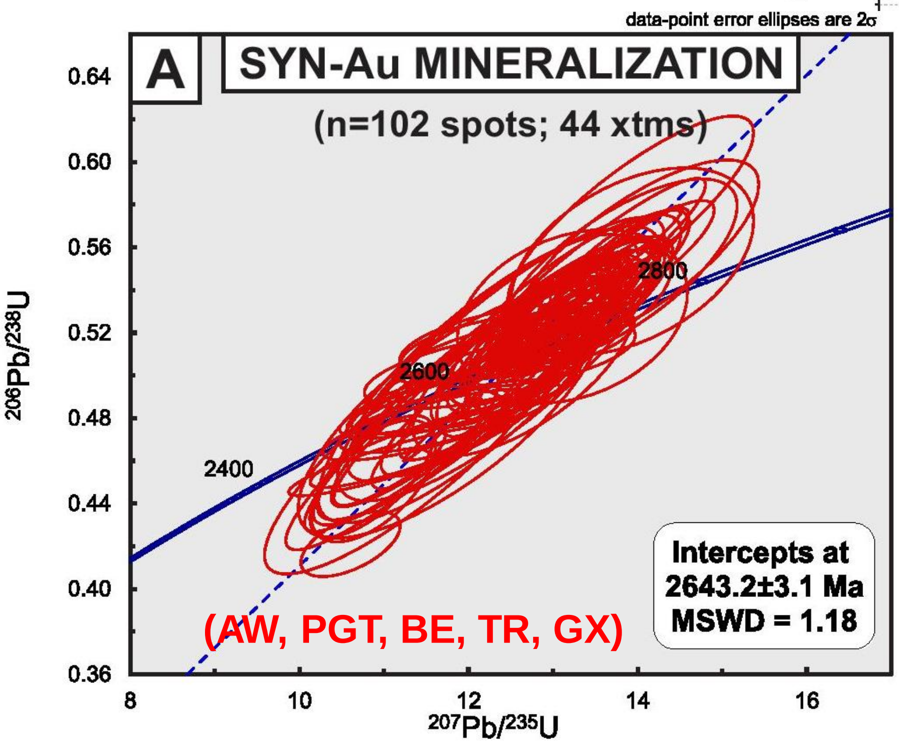
Different textures = different MREE contents

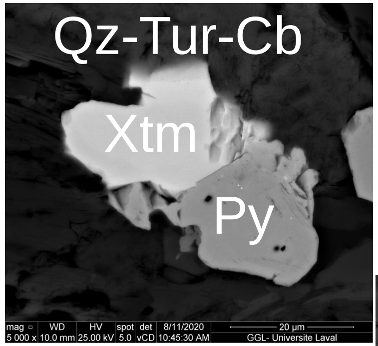
Timing of Au Mineralization – Syn-D2 QTC

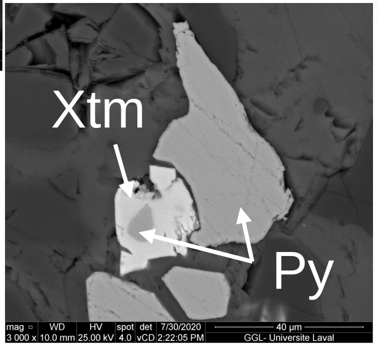
- **Au mineralization:** **ca. 2643 Ma**

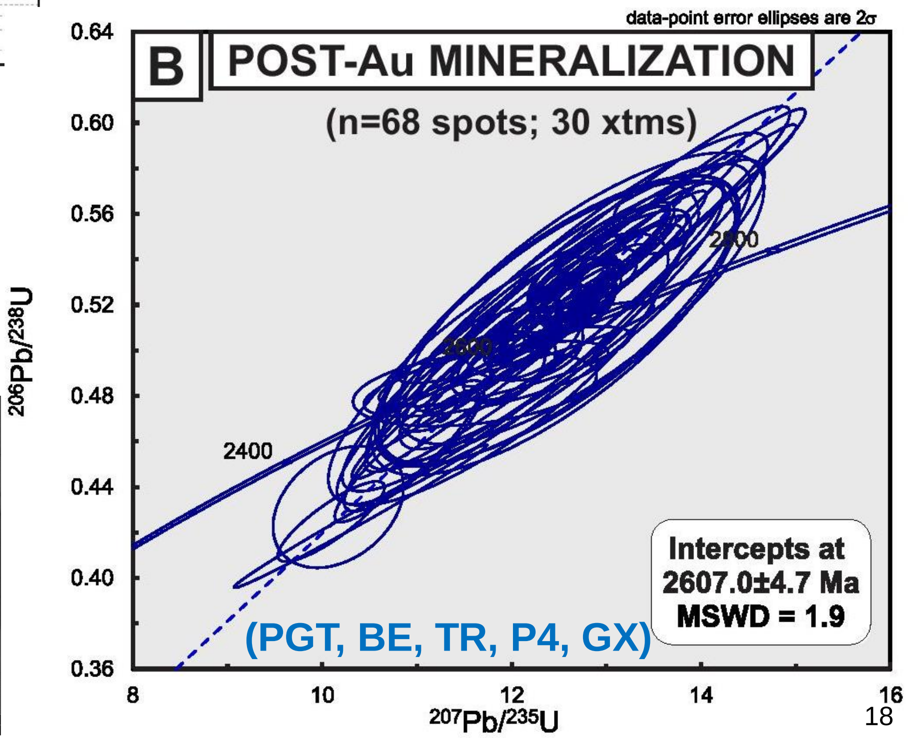


- **Au remobilization:** **ca. 2607 Ma**

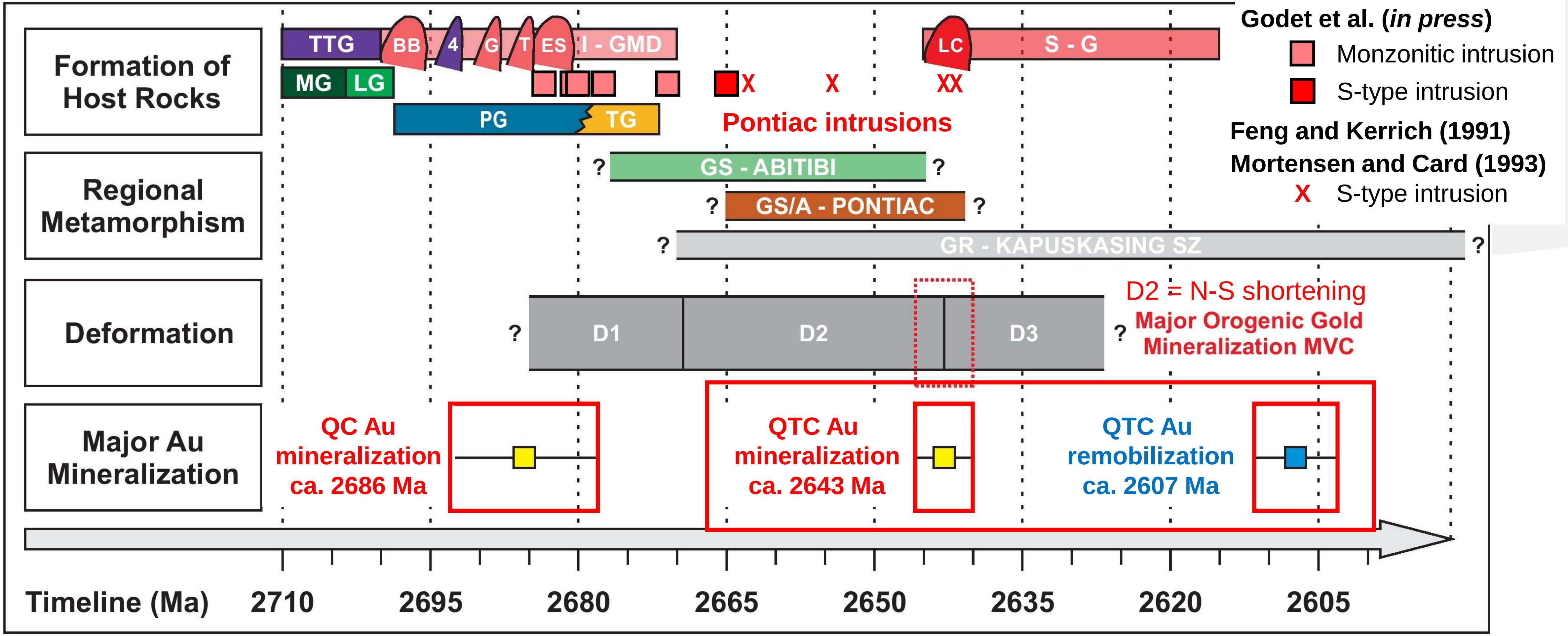




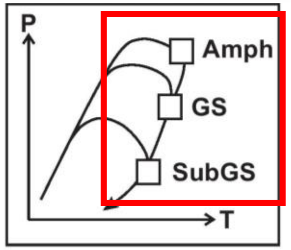




“The Golden Periods” of the MVD



Late S-type magmatic-pegmatitic activity by Preissac-Lacorne batholith (2645-2613 Ma)



Orogenic Au Fluid Mechanisms

- **Pyrite isotopic and chemical compositions**
  - => QTC veins (ca. 2643 Ma)
  - => Pyrite multiple S isotopes and trace elements
    - => in-situ LA-ICPMS & LA-TOF-ICPMS
    - => in-situ SIMS
- ***In peer review – Mineralium Deposita***
  - => *LaFlamme C, Beaudoin G, Barré G, Martin L, Savard D*

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Orogenic Au Precipitation Mechanisms

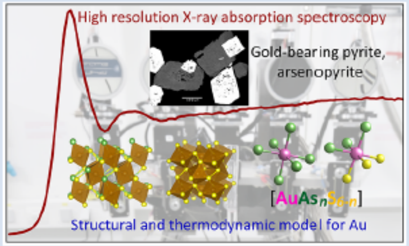
An arsenic-driven pump for invisible gold in hydrothermal systems

G.S. Pokrovski[1*], C. Escoda[1], M. Blanchard[1], D. Testemale[2], J.-L. Hazemann[2], S. Gouy[1], M.A. Kokh[1,8], M.-C. Boiron[3], F. de Parseval[1], T. Aigouy[1], L. Menjot[1], P. de Parseval[1], O. Proux[4], M. Rovezzi[4], D. Béziat[1], S. Salvi[1], K. Kouzmanov[5], T. Bartsch[6], R. Pöttgen[6], T. Doert[7]

OPEN ACCESS

doi: 10.7185/geochemlet.2112

Abstract



Pyrite (FeS_2), arsenopyrite (FeAsS) and löllingite ($FeAs_2$) are exceptional gold concentrators on Earth; yet the exact redox and structural state of this "invisible" gold and the forces driving its intake and release by these minerals remain highly controversial. Here we applied high resolution X-ray absorption spectroscopy to Au-bearing pyrite and iron sulfarsenides from hydrothermal deposits and their synthetic analogues. We show that Au preferentially enters octahedral Fe structural sites [$Au(As,S)_6$] enriched in As, by forming respectively [$AuAs_{1-3}S_{5-3}$], [$AuAs_3S_3$···$AuAs_6$] and [$AuAs_6$] atomic units in arsenian pyrite (>0.1–1.0 wt. % As), arsenopyrite and löllingite, implying a formal oxidation state of Au^{II} in the minerals. In contrast, in As-poor pyrite, Au is dominantly chemisorbed as [$Au^{I}S_2$] moieties in much lower concentrations. Combined with experimental data on Au mineral-fluid partitioning, our findings imply a universal control exerted by arsenic on gold incorporation in iron sulfides and sulfarsenides *via* coupled Au-As redox reactions. These reactions account for the observed variations in invisible gold contents in the minerals from different hydrothermal deposit types and enable quantitative prediction of iron sulfarsenide ability in controlling gold concentration and distribution in hydrothermal systems.

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- **Orogenic gold systems in As-rich districts**
- => coupled Au-As redox reactions
- => "invisible gold"

What about fluid processes in As-poor districts?
=> *in-situ* sulfide mineral record

In-Situ Mineral Grain-Scale Analyses

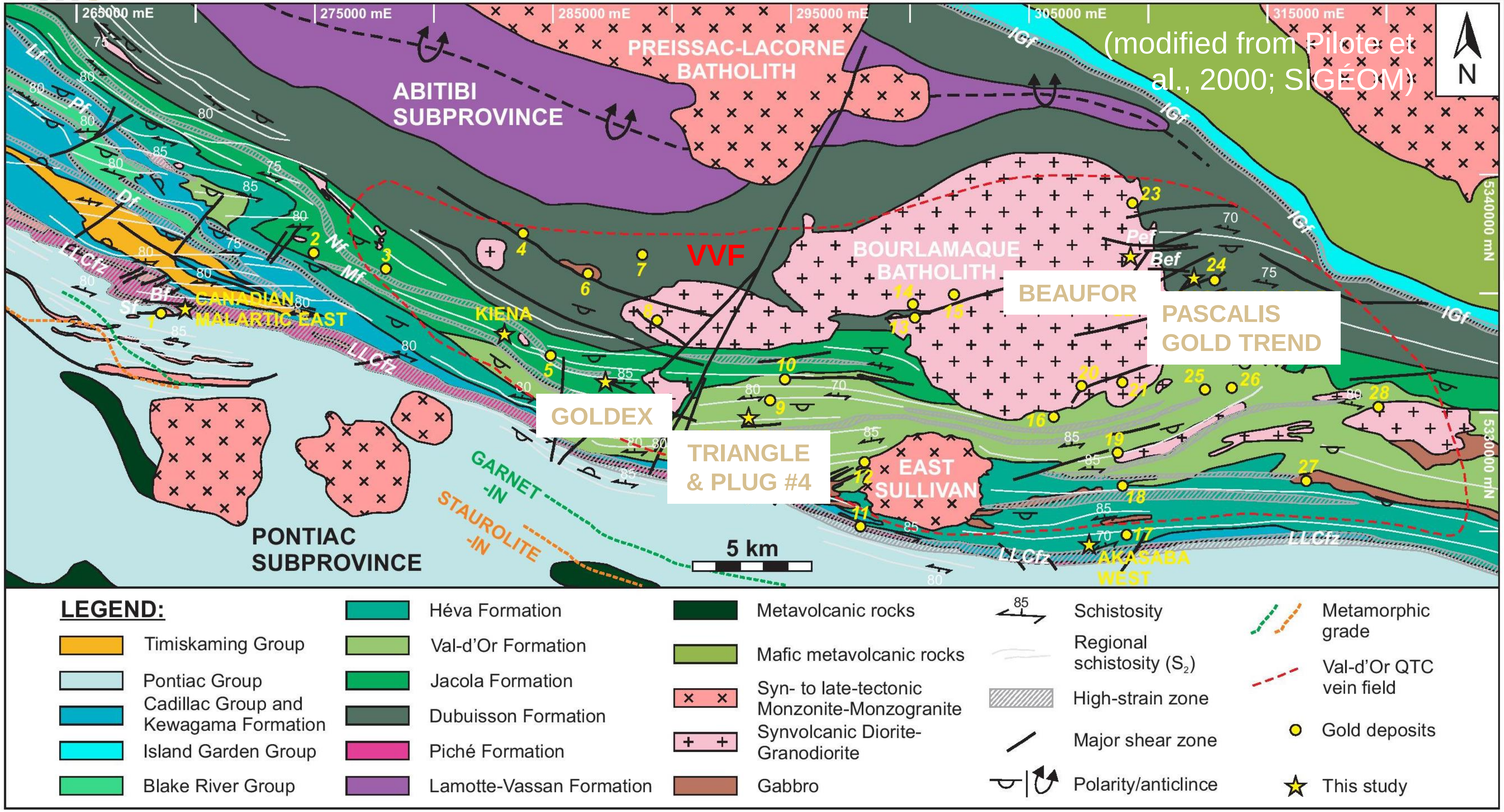
- Changes in **$\delta^{34}S$** at the mineral grain scale
- Changes in **trace element composition** at the mineral grain scale

→ **Physico-chemical fluid processes & gold precipitation mechanisms**

- Archean **$\Delta^{33}S$ & $\Delta^{36}S$** composition can help to decipher the source of sulfur in auriferous fluid

→ **Sulfur source (igneous or sedimentary)**

QTC – Investigated Orebodies



QTC (syn-D2)

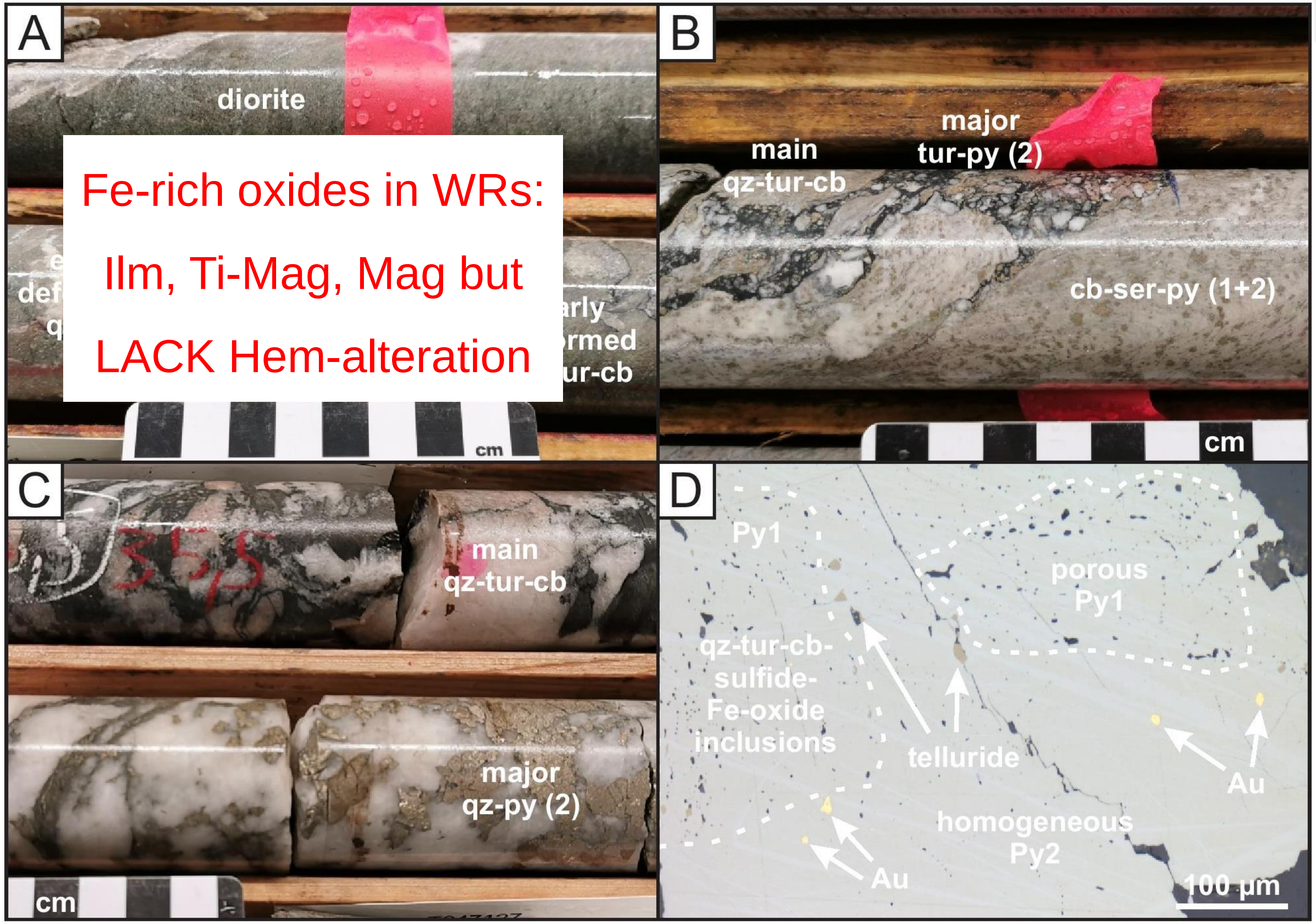
- Goldex
- Triangle
- Plug #4
- Beaufor
- Pascalis Gold Trend

D1: Ferguson et al. (1968), Imreh (1984), Davis (2002), Bleeker (2015)

D2: Corfu et al. (1991), Feng and Kerrich (1991), Robert (1994), Couture et al. (1994), Daigneault et al. (2002), Bleeker (2015) Bedeaux et al. (2017), De Souza et al. (2017)

QTC – Major Sulfide Paragenesis

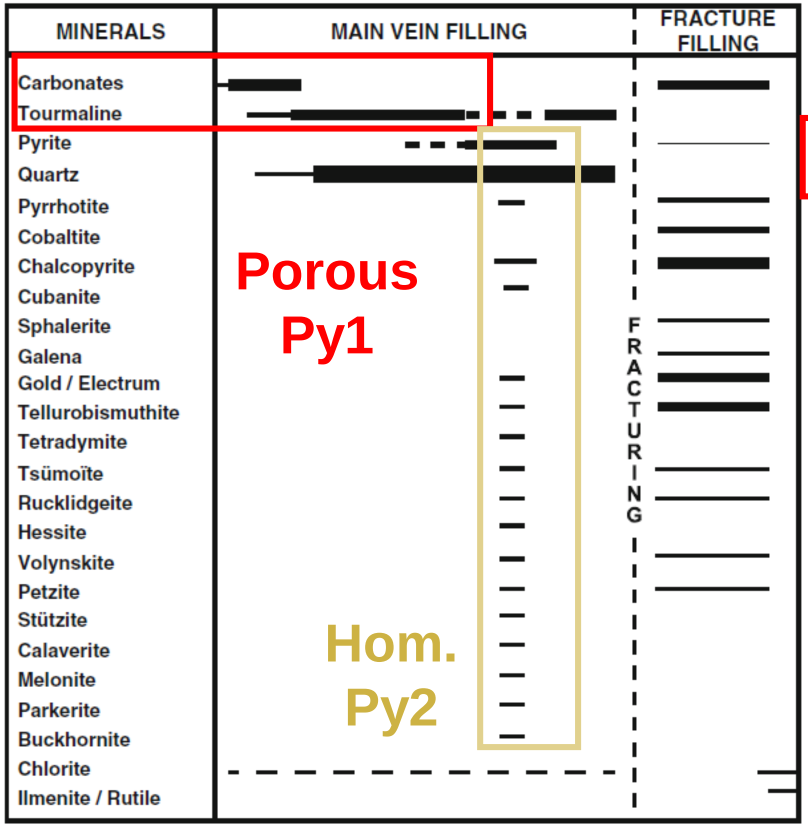
Goldex, Plug #4, Triangle, Pascalis Gold Trend, Beaufor orebodies



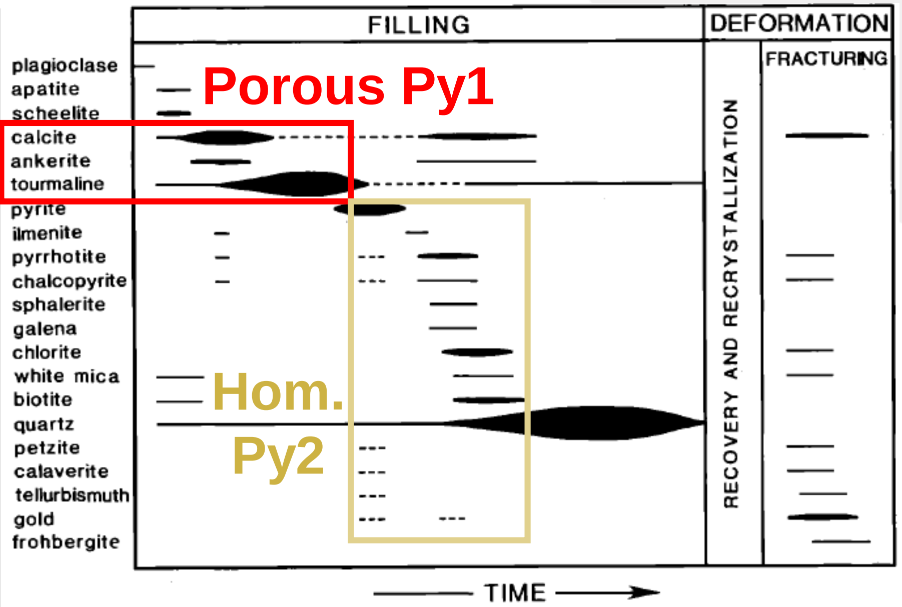
Similar sulfide characteristics

- Pyrite-rich sulfide aggregates
  - => py > 95 vol%
  - => sub- to euhedral
  - => vein- & wallrock-hosted
- Porous pyrite core (Py1)
  - => cb & silicate inclusions
  - => Fe-oxide inclusions
- Homogeneous pyrite rim (Py2)
  - => bulk of Au & tellurides

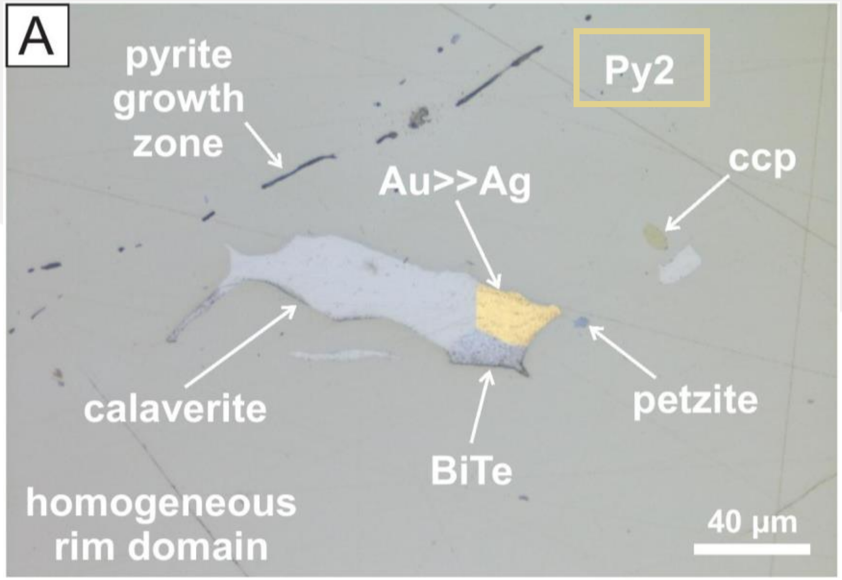
QTC – Major Sulfide Paragenesis II



(Rezeau et al., 2017)



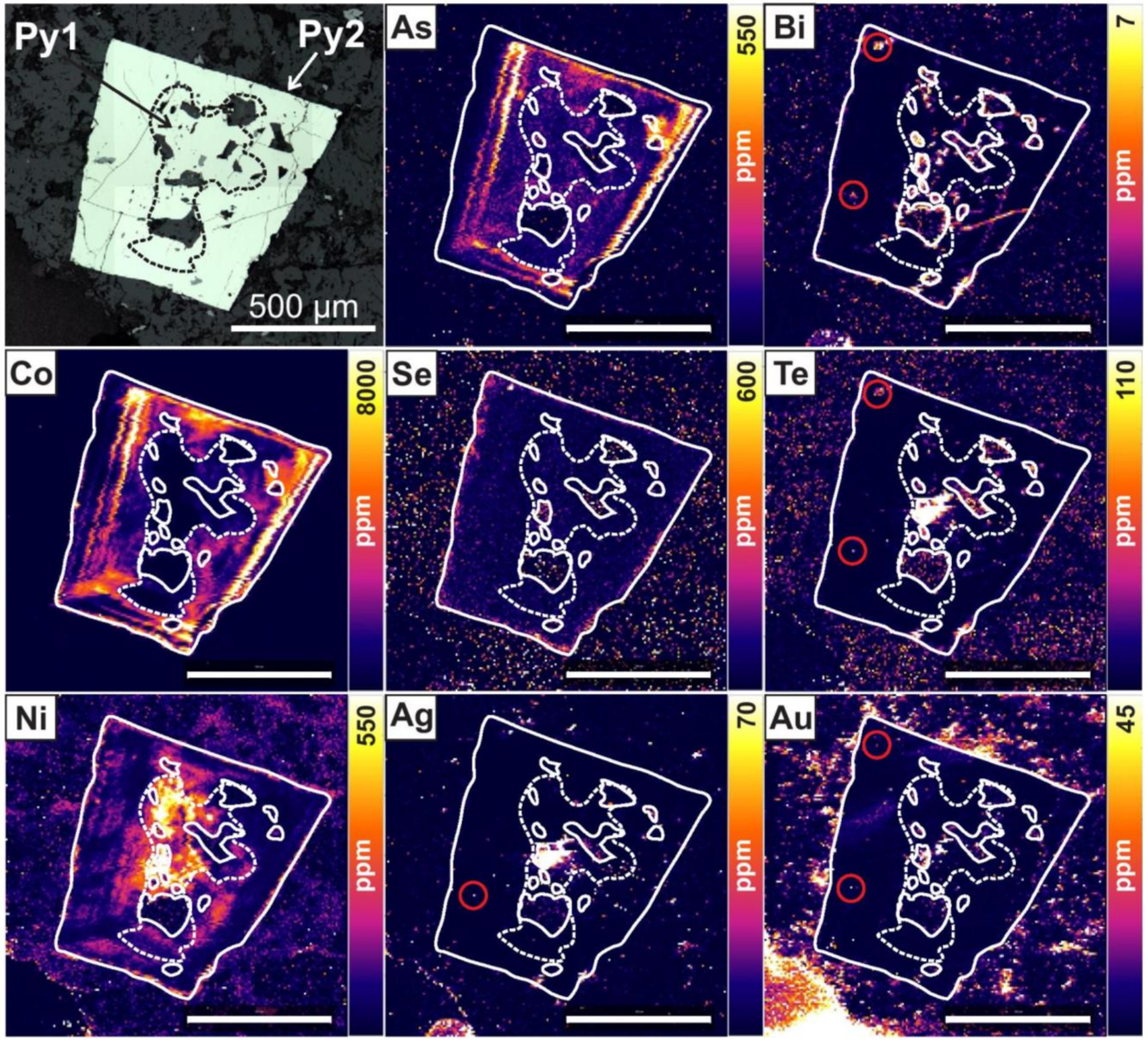
(Robert and Brown, 1986)



- Polymetallic inclusions
  - => in Py2 rims
  - => Au-Ag-Te-Bi
  - => ++calaverite ($AuTe_2$)
  - => ~petzite (Ag_3AuTe_2)
  - => ~hessite (Ag_2Te)

Similar sulfide textures and assemblages

Pyrite Trace Elements



- In-situ LA-ICPMS/LA-TOF-ICPMS
  => lines, spots, maps (Py1 & Py2)
  => minor Au Py1 & bulk Au Py2
- Only Co, Ni, As, Se, Sb detected
  => <<1 wt% (TE poor)
- Py1 core (localized concentrations)
  => Co < 4500 ppm
  => Ni < 635 ppm
- Py2 rim (weak oscillatory-zoning)
  => Co < 2200 ppm
  => Ni < 550 ppm

Py1 < 30 ppm Au ~ lattice-bound

Supports fluid fO_2 decrease

Pascalis Gold Trend

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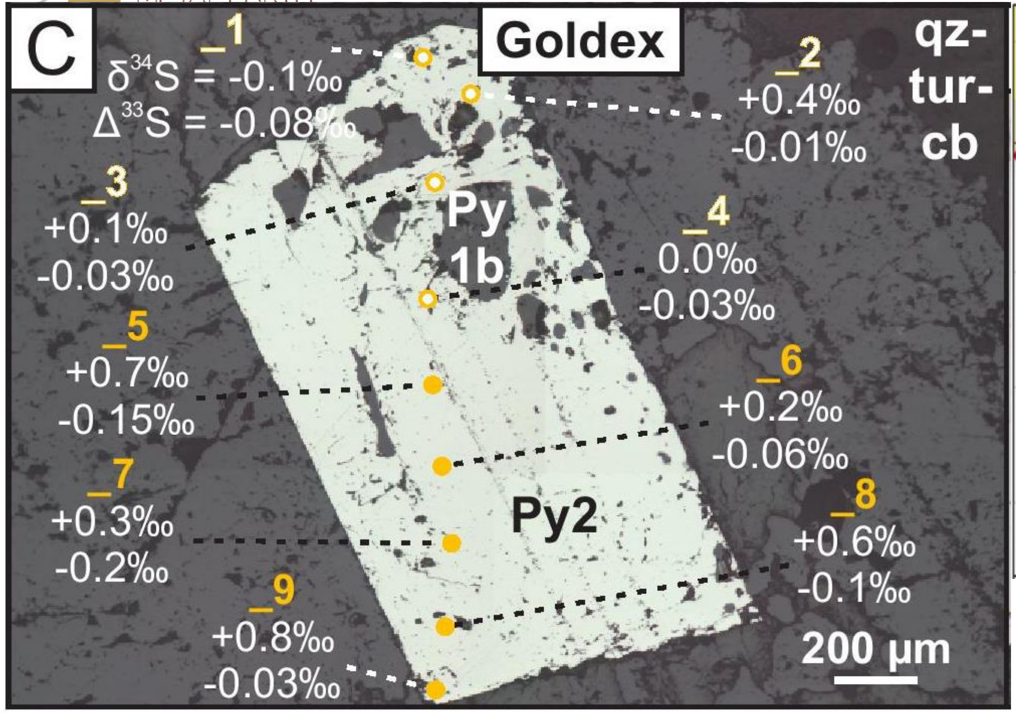
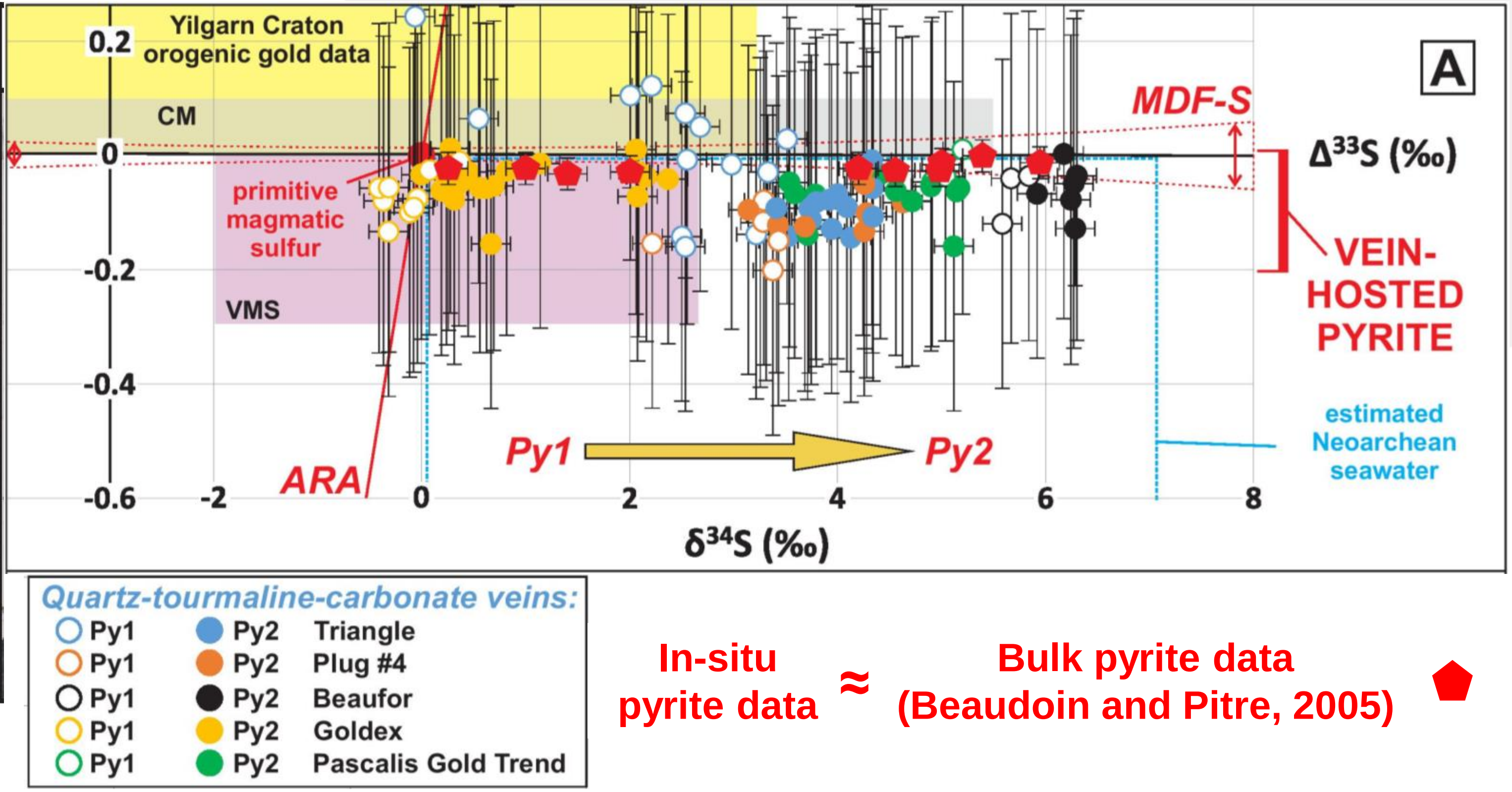
Multiple Sulfur Isotopes – $\delta^{34}S$ and $\Delta^{33}S$



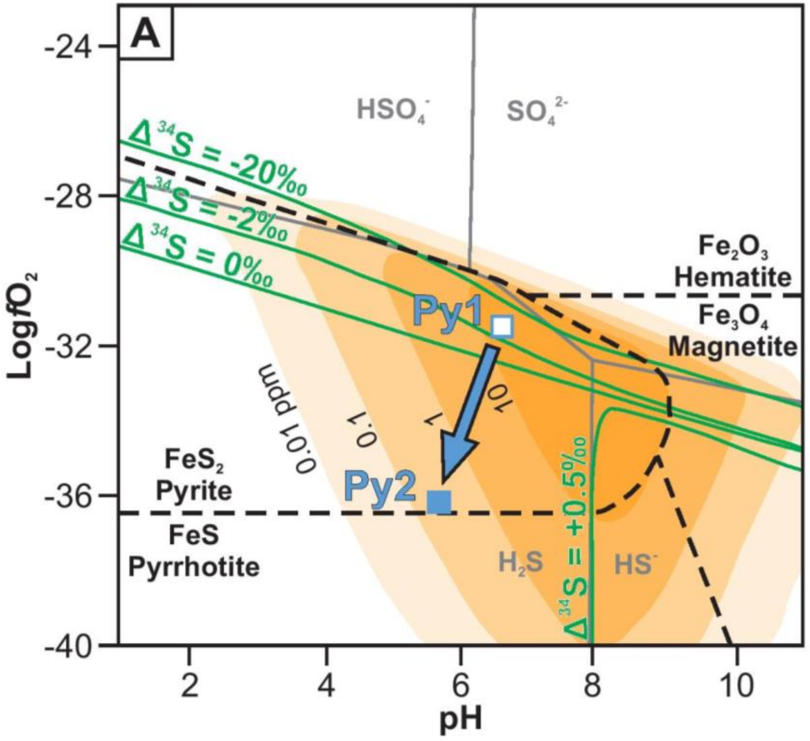


In-situ pyrite data ≈ Bulk pyrite data (Beaudoin and Pitre, 2005)

- In-situ SIMS analyses
  - => porous Py1 cores (±Au)
  - => homogeneous Py2 rims (Au)
- Consistent isotopic signature
  - => positive shift in $\delta^{34}S$ (+3.0‰)
  - => negative $\Delta^{33}S$

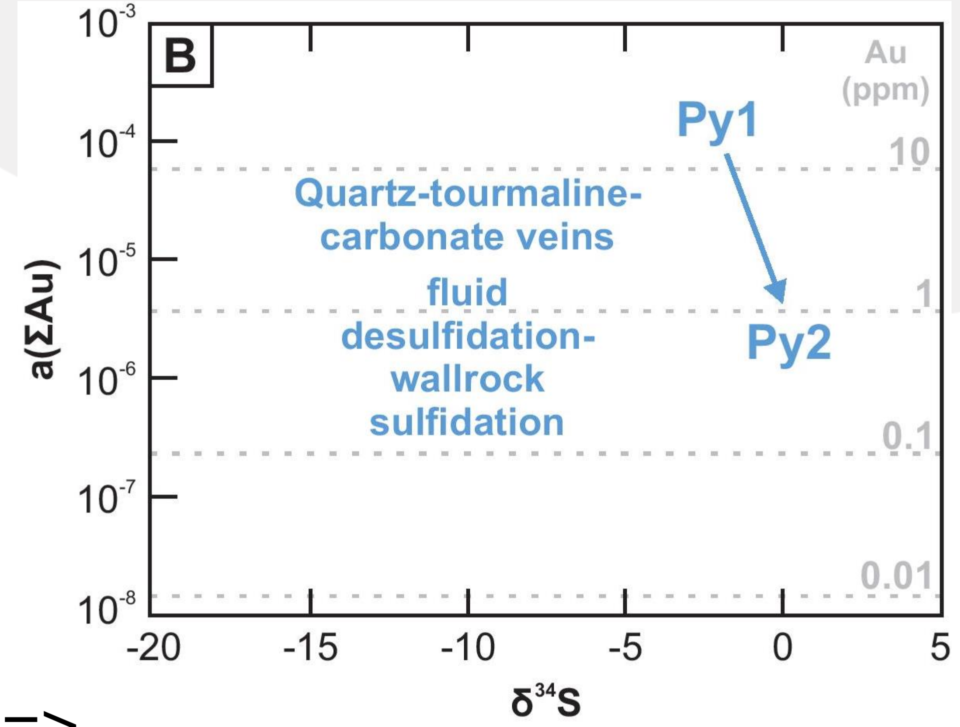
➡ Decrease in fluid fS_2 by removal of H_2S-complexes (e.g., $(AuHS)^-$)

Fluid Desulfidation-Wallrock Sulfidation I



QTC sulfide formation

- Replacement of Fe-oxides in WRs & entrained WR slivers
- Ilm, Ti-Mag, Mag

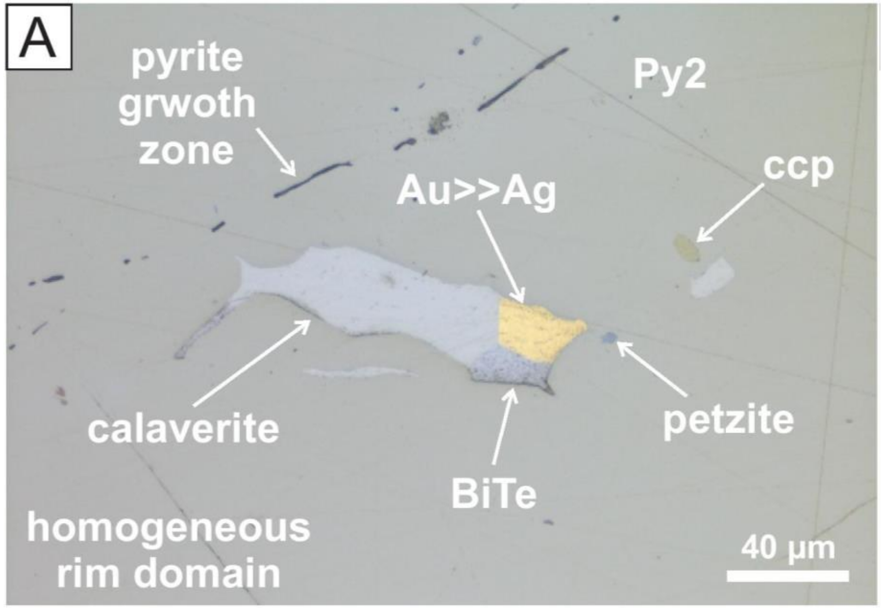


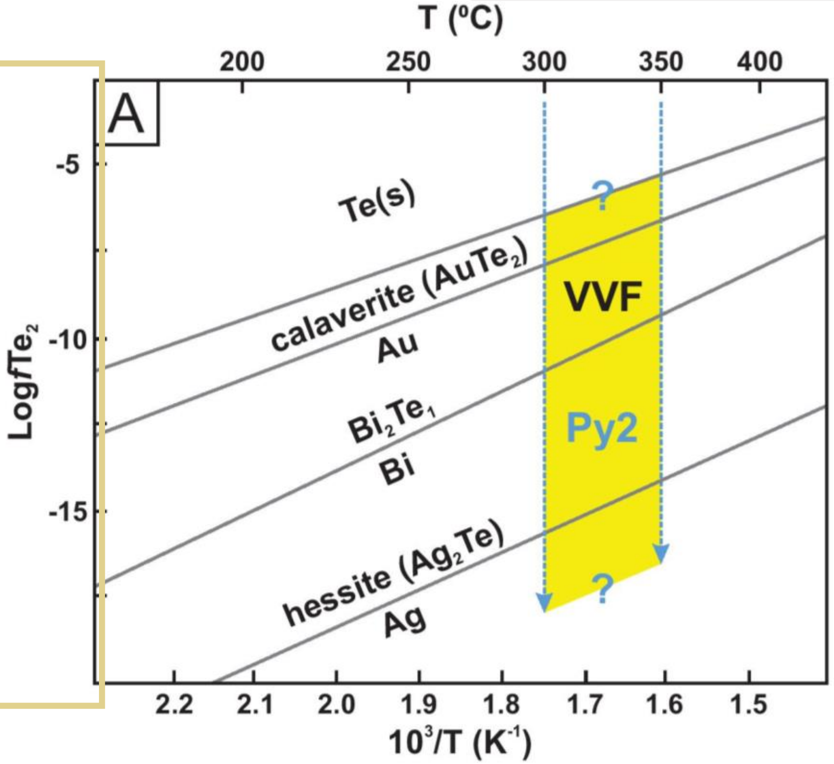
Fluid/Wallrock reactions =>

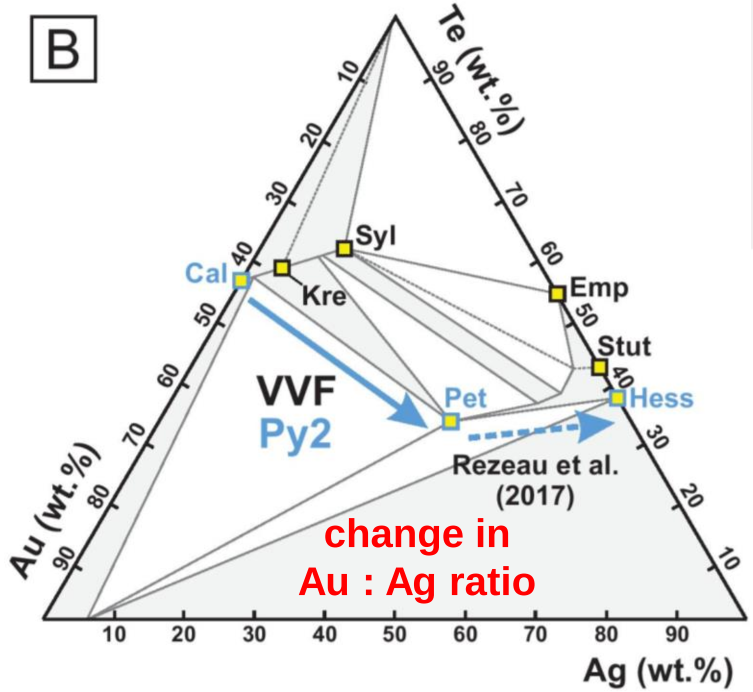
Decrease in fluid fO_2, fS_2 => removal of $Au(HS)^-$ => decrease in Au solubility

Major contrast to OGS mechanisms by fluid immiscibility or coupled As-Au redox reactions => Dependent on As content (<<1wt%)

Fluid Desulfidation-Wallrock Sulfidation II







Fluid/Wallrock reactions =>

Decrease in fluid fO_2, fS_2 => removal of $Au(HS)^-$ => decrease in Au solubility

Decrease in fluid fO_2 & fS_2 => Decrease in fluid fTe_2
=> As < 550 ppm => Inclusion-hosted Au (!)

Amorphous Carbon and Nanoparticle Formation

- **BiTe assemblages and textures**
  => QTC veins (ca. 2607 Ma)
  => Transmission Electron Microscopy
- ***Submitted – Geology***
  => *LaFlamme C, Petrella L, Rottier B, Beaudoin G*

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The Role of Nanoparticles in Orogenic Au

nature
COMMUNICATIONS

Fluid boiling and immiscibility

ARTICLE

Check for updates

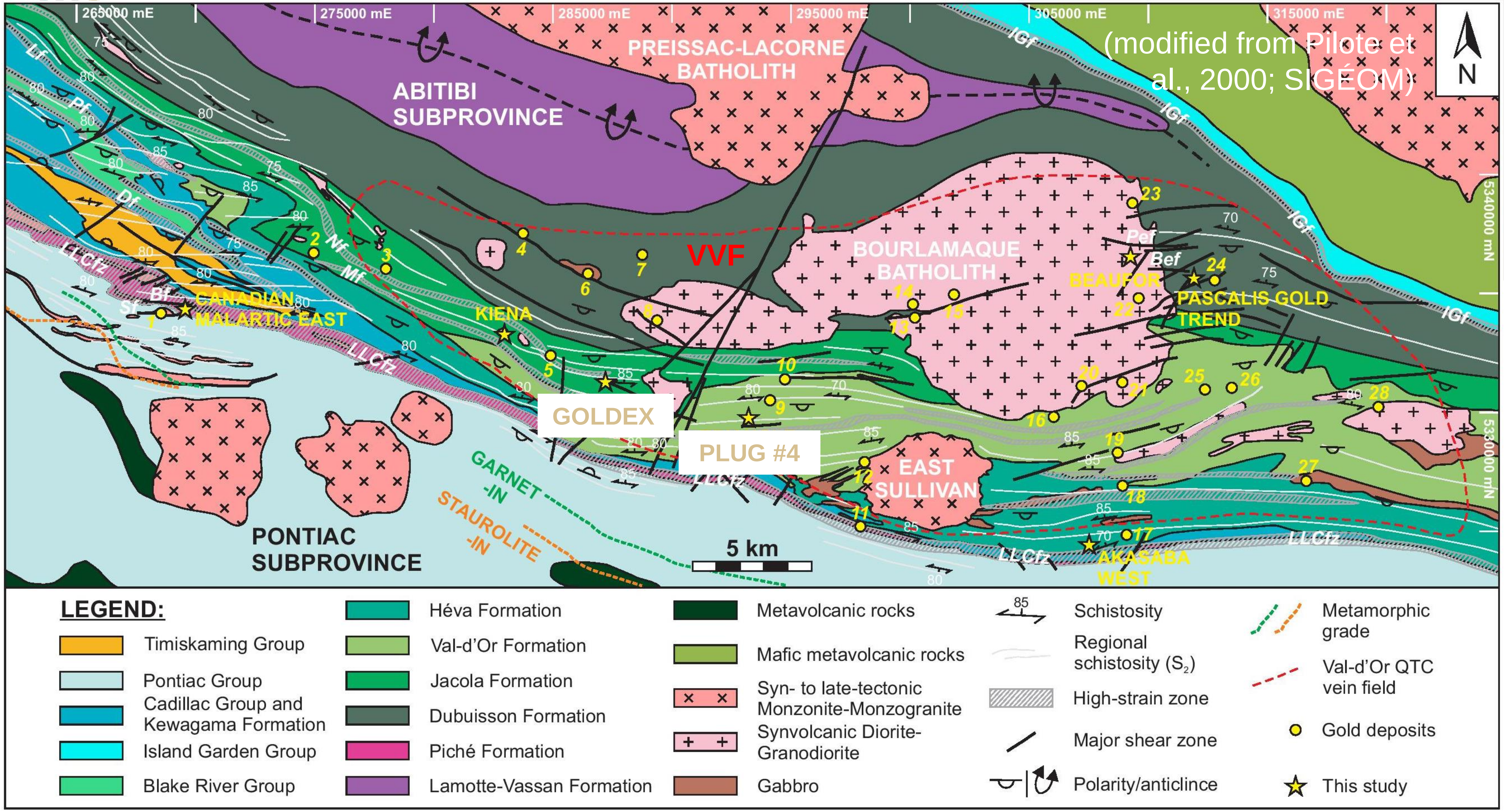
https://doi.org/10.1038/s41467-022-31447-5 OPEN

Nanoparticle suspensions from carbon-rich fluid make high-grade gold deposits

Laura Petrella[1✉], Nicolas Thébaud[1], Denis Fougerouse[2], Brian Tattitch[1], Laure Martin[3], Stephen Turner[4], Alexandra Suvorova[3] & Sarah Gain[5]

What about NPs associated with low- and medium-grade orogenic Au mineralization?

QTC – Investigated Orebodies



(modified from Pilote et al., 2000; SIGÉOM)

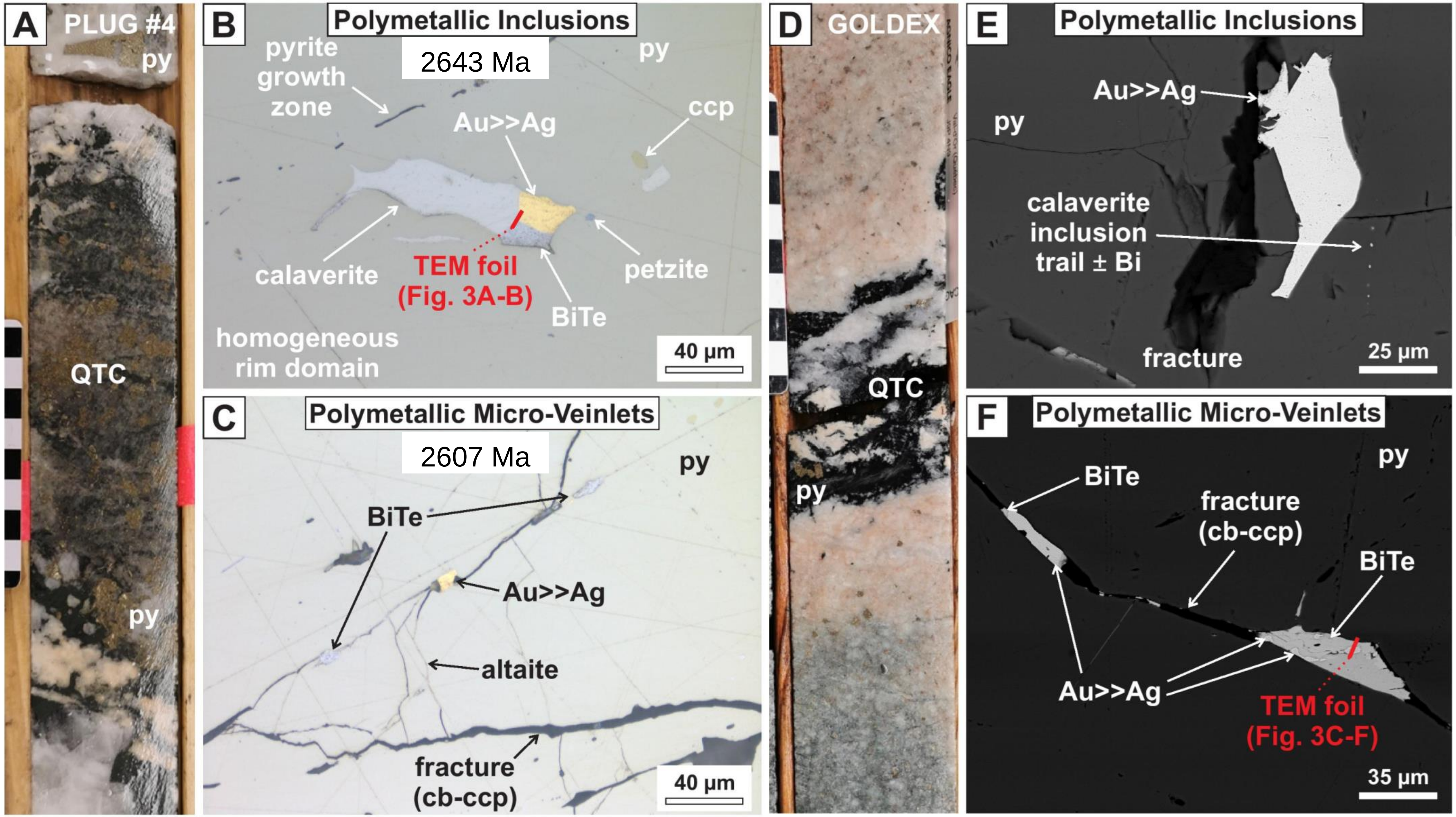
QTC (syn-D2)

- Goldex
- Plug #4

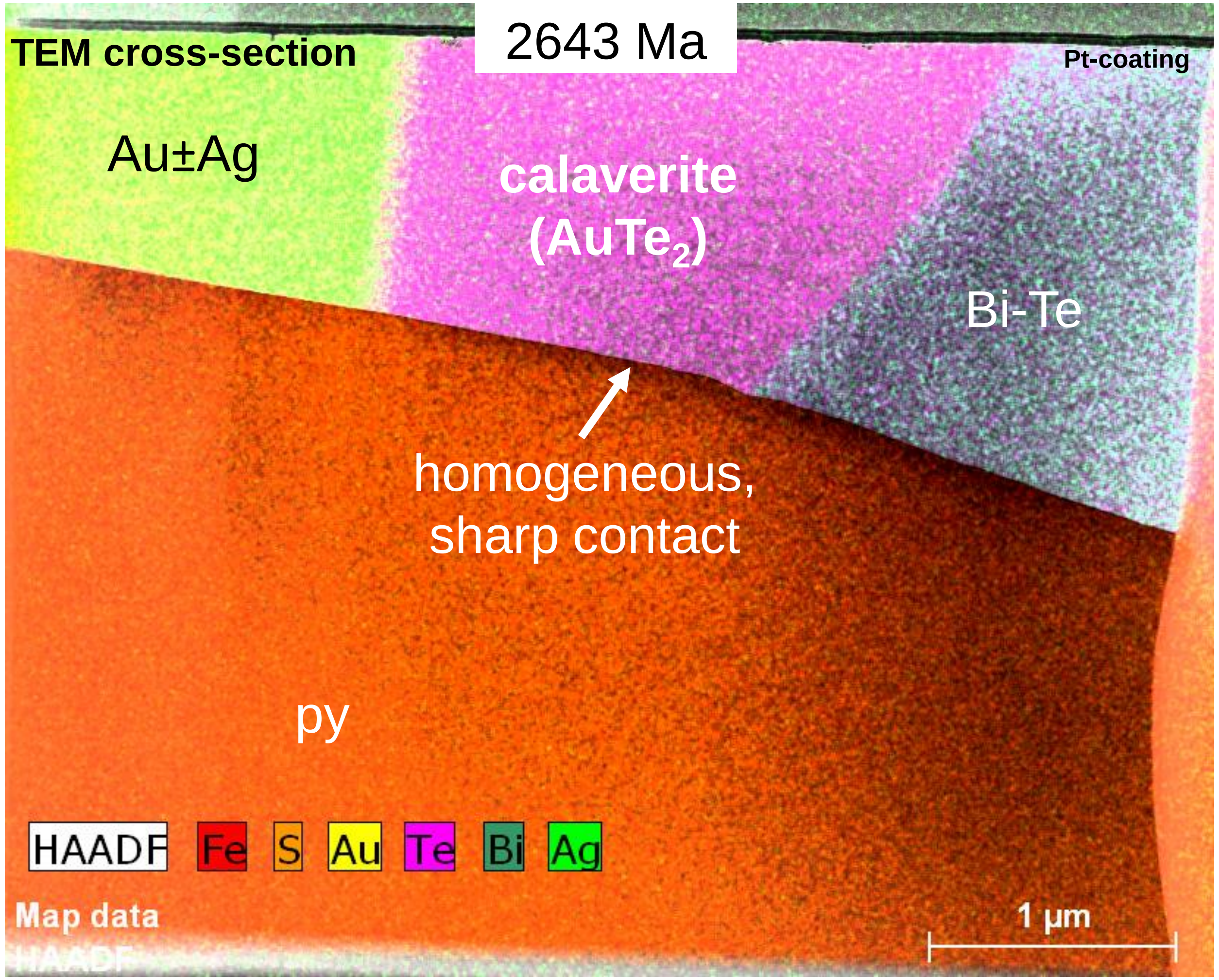
D1: Ferguson et al. (1968), Imreh (1984), Davis (2002), Bleeker (2015)

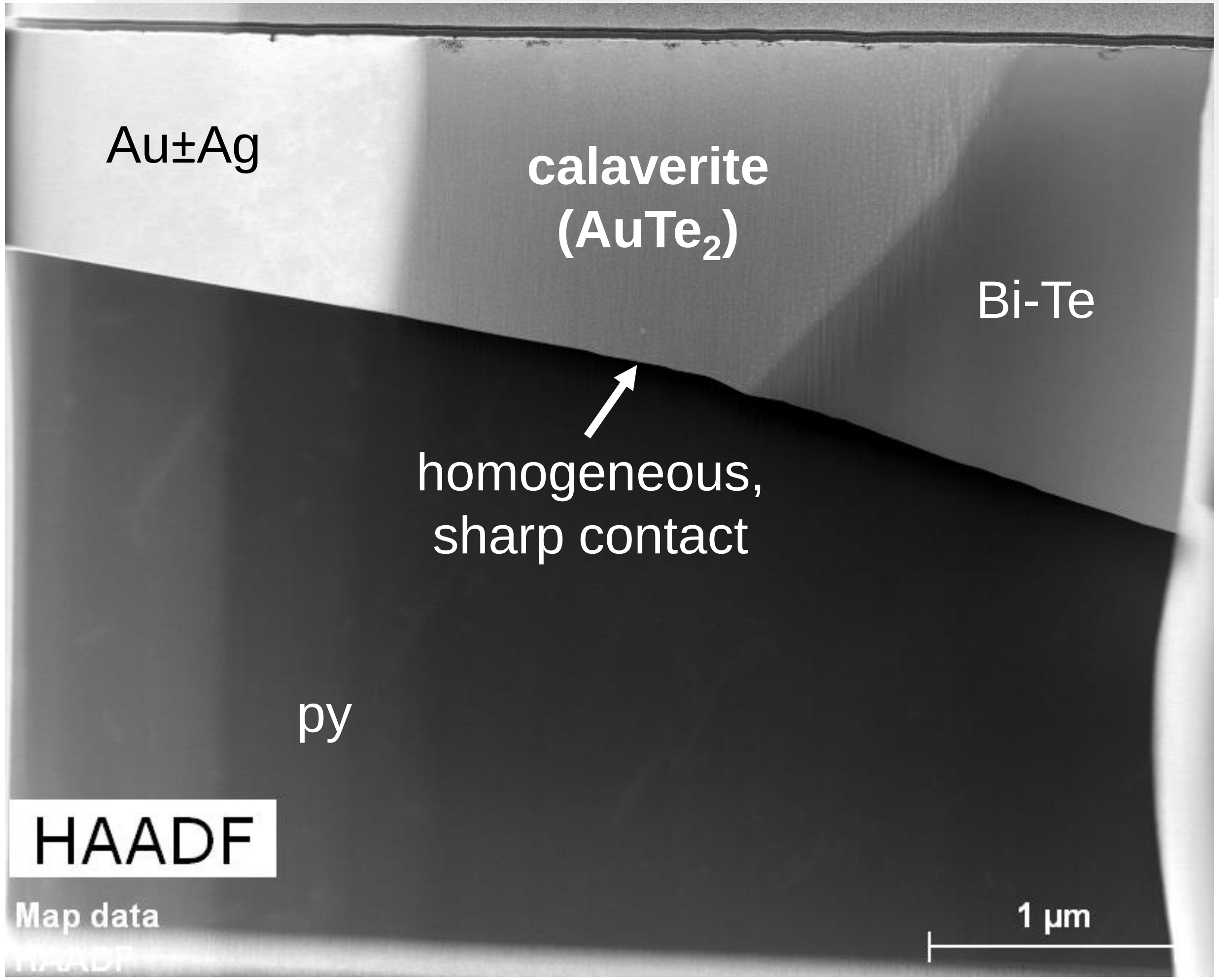
D2: Corfu et al. (1991), Feng and Kerrich (1991), Robert (1994), Couture et al. (1994), Daigneault et al. (2002), Bleeker (2015) Bedeaux et al. (2017), De Souza et al. (2017)

Polymetallic Inclusions & Veins in VVF



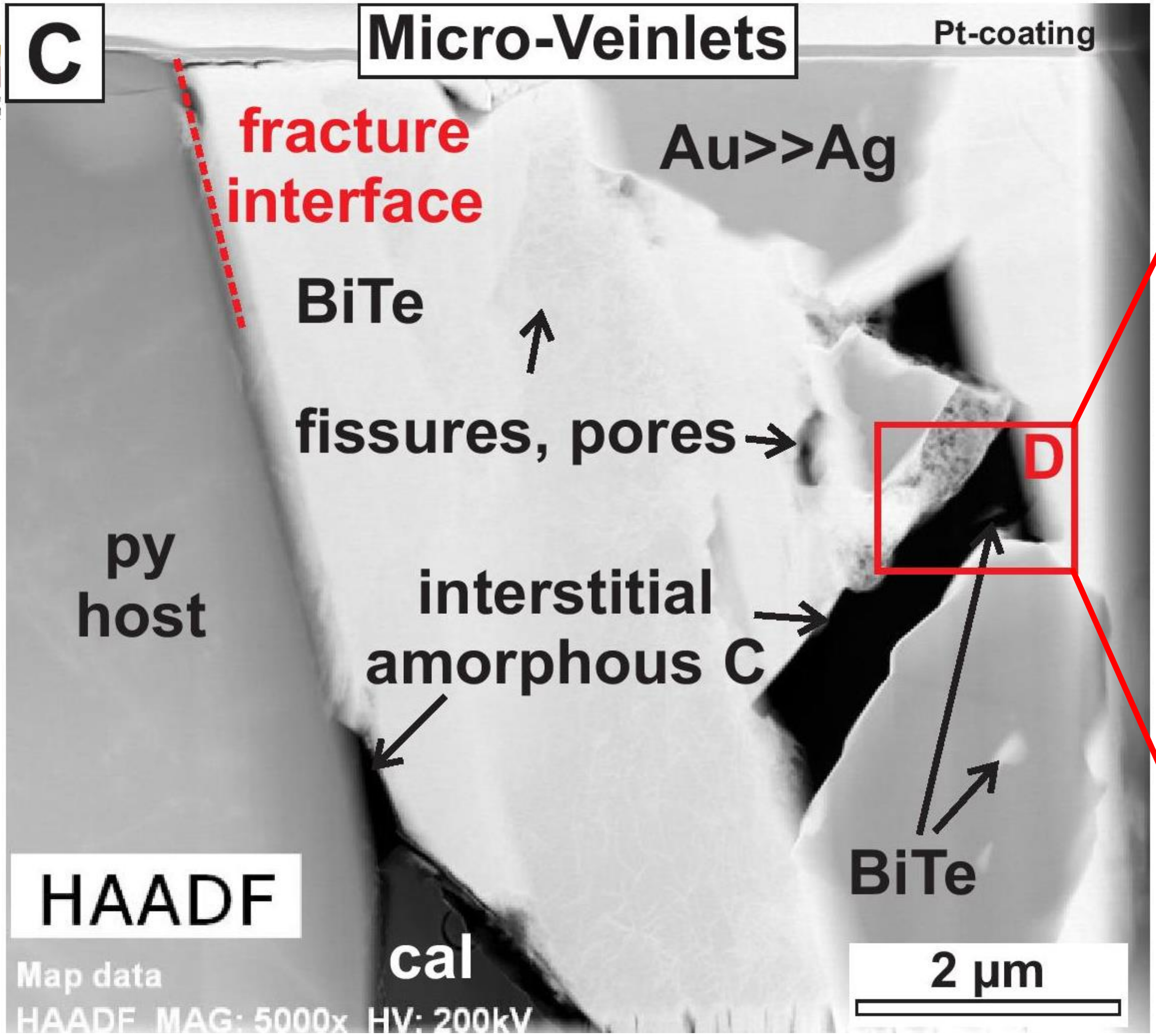
Pyrite-Hosted Au-Ag-Te-Bi Inclusions

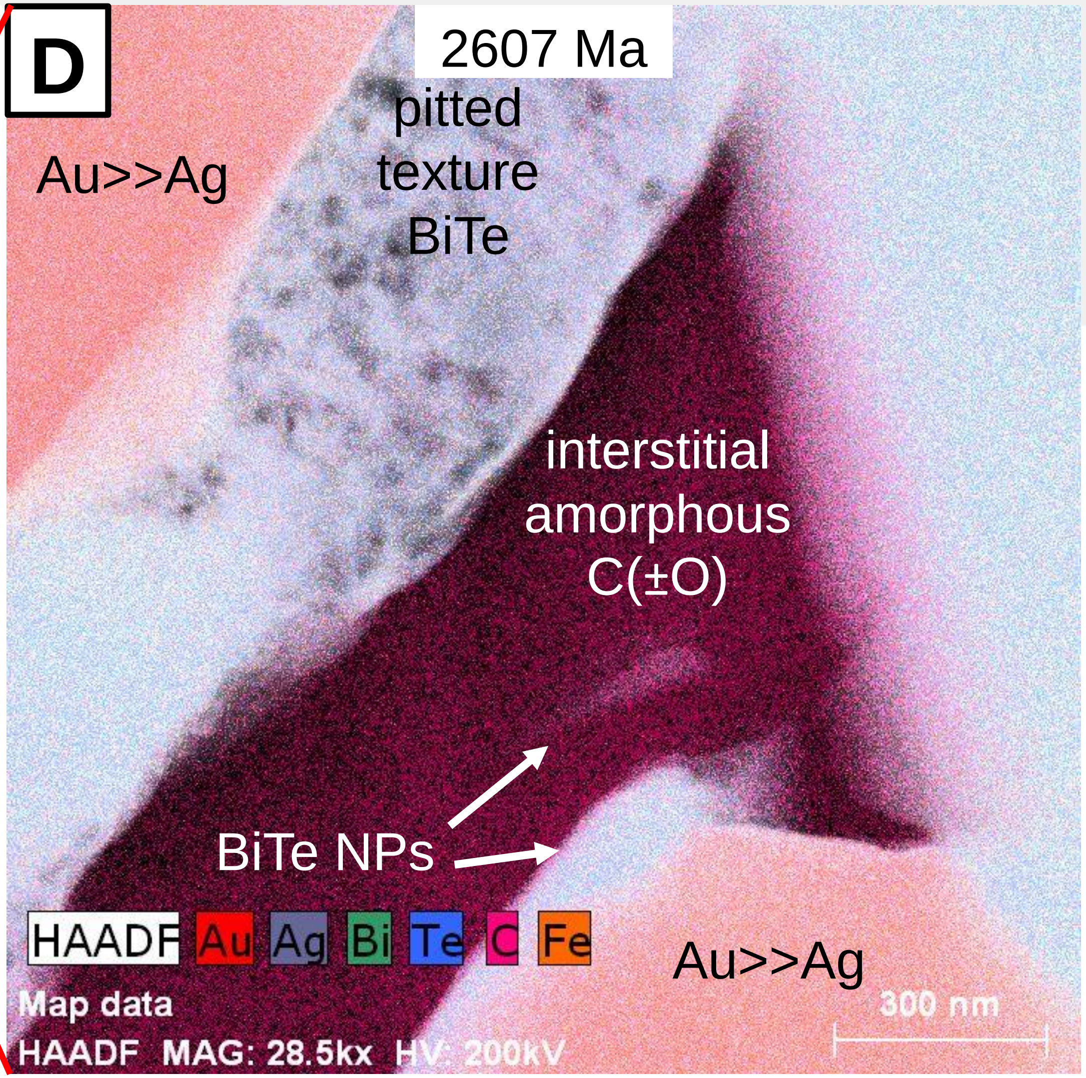




Undisturbed PM assemblages, not lattice bound => **calaverite-rich**

Au-Ag-Te-Bi Veinlets in Pyrite Fractures





Disturbed, pitted texture (Au>>Ag & BiTe) => **interstitial phases**

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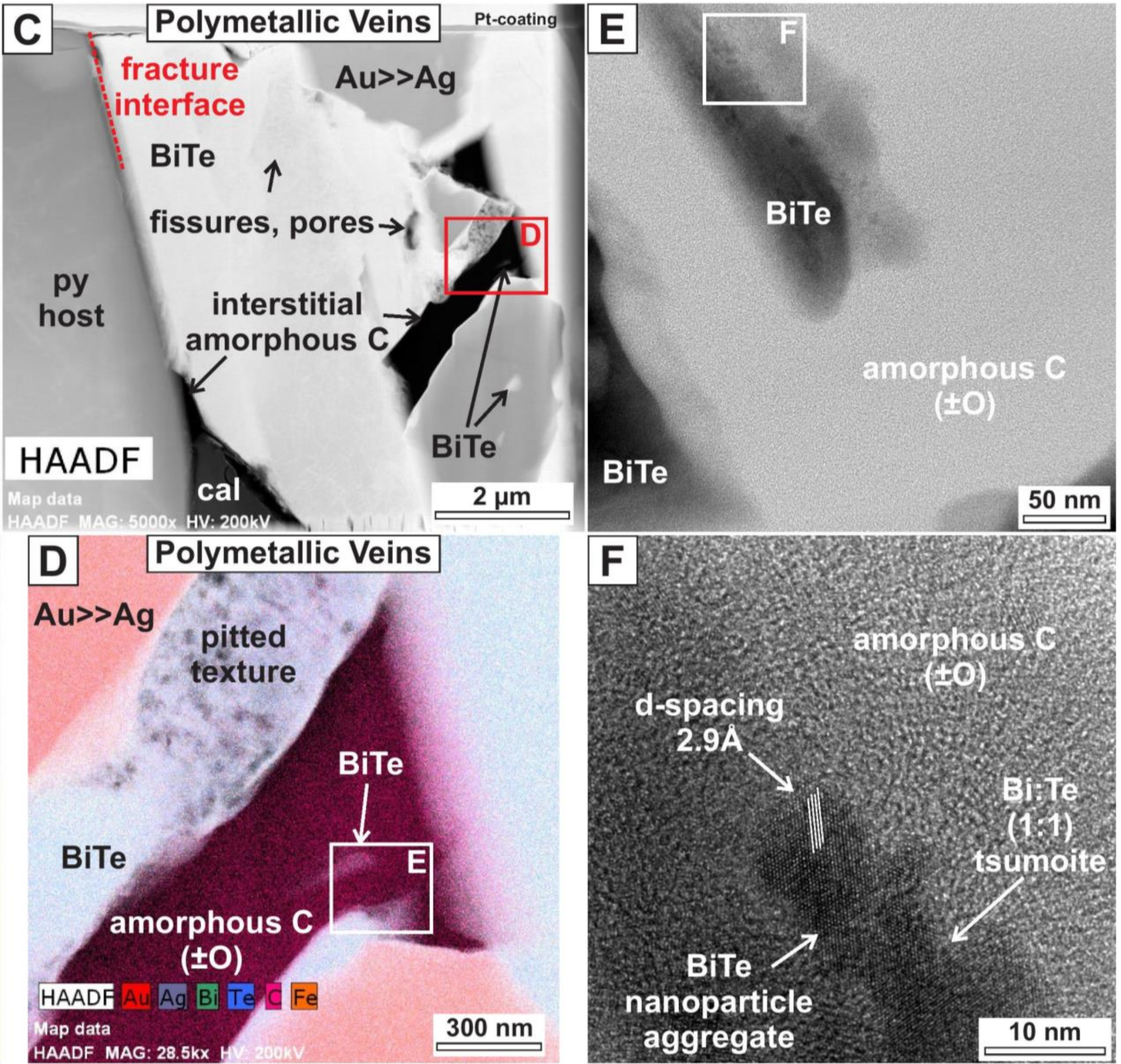
Redox Reactions Form BiTe NPs in amC



Low- and medium-grade orogenic Au

- PM veinlet assemblage, amC & BiTe NPs
- Hydrothermal activity at 2607 Ma

=> no pressure fluctuation

Oxidized $H_2Te^{IV}O_{3(aq)}$ and $Bi^{III}(OH)_{3(aq)}$

Te^{IV} and Bi^{III} reduction => $O_{2(aq)}$ removal

rapid calcite formation => amorphous C & BiTe NP

$$\mathbf{H_2Te^{IV}O_{3(aq)}} + \mathbf{Bi^{III}(OH)_{3(aq)}} + Au(HS)^-_{(aq)} + Ca^{2+}_{(aq)} + H_2CO_{3(aq)}$$
$$=$$
$$Au_{(s)} + \mathbf{BiTe_{(NP)}} + \mathbf{amC_{(s)}} + CaCO3_{(s)} + H_2S^{-II}_{(aq)} + 3H_2O_{(aq)}$$

Liu et al. (2016) => Te-NP synthesis from $Na_2Te^{IV}O_{3(aq)}$ at elevated T (180°C) <5h

Multi-Scale Controls Lead to Orogenic Au Formation in the MVD

- **Multiple hydrothermal events form bulk gold mineralization**

  => QC: 2686 Ma (Au)

  => QTC: 2643 Ma (Au) & 2607 Ma (remobilization?)

- **Fluid desulfidation-wallrock sulfidation (QTC)**

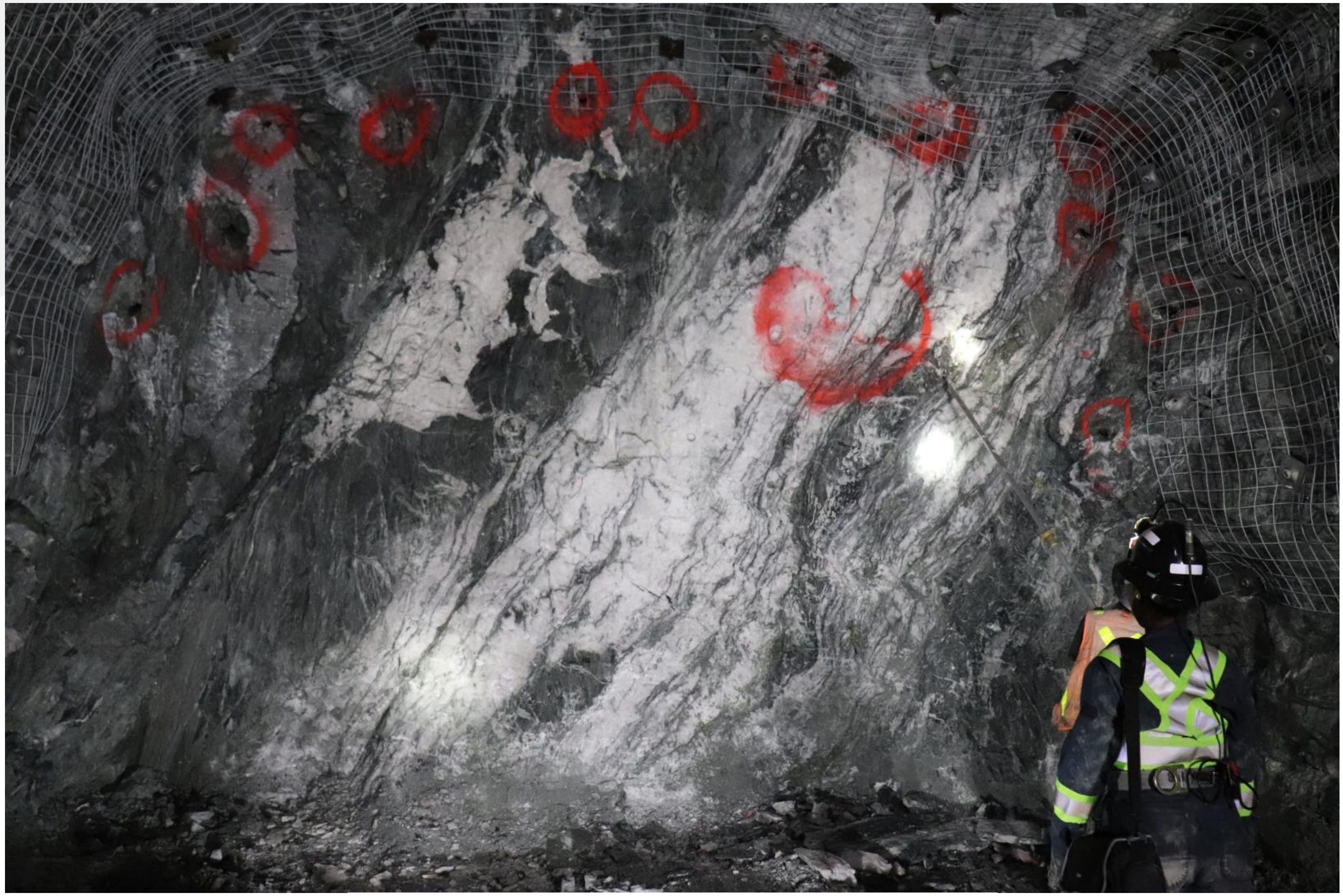
  => coupled decrease in fluid fO_2, fS_2 and fTe_2 deposit pyrite & precipitate Au and tellurides

  => regional mechanism in As-poor (<0.1 wt%) districts with Fe-rich oxides in intrusions?

- **Fluid-mediated redox reactions potential to form NPs**

  => during hydrothermal activity in lower grade OGS

  => may explain ubiquity of metallic NPs in OGS and present additional mechanism to form NPs?



Val-d'Or Vein Field (QTC)

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