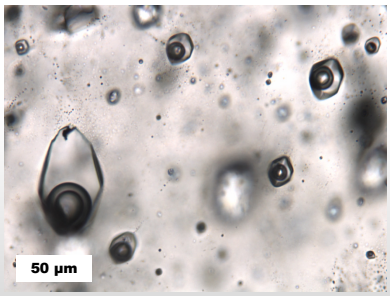
An Assessment of Gold Deposit Models from a Fluid-Chemistry Perspective



Daniel J. Kontak (and many collaborators)
Harquail School of Earth Sciences
(dkontak@laurentian.ca)

PDAC March 3, 2018

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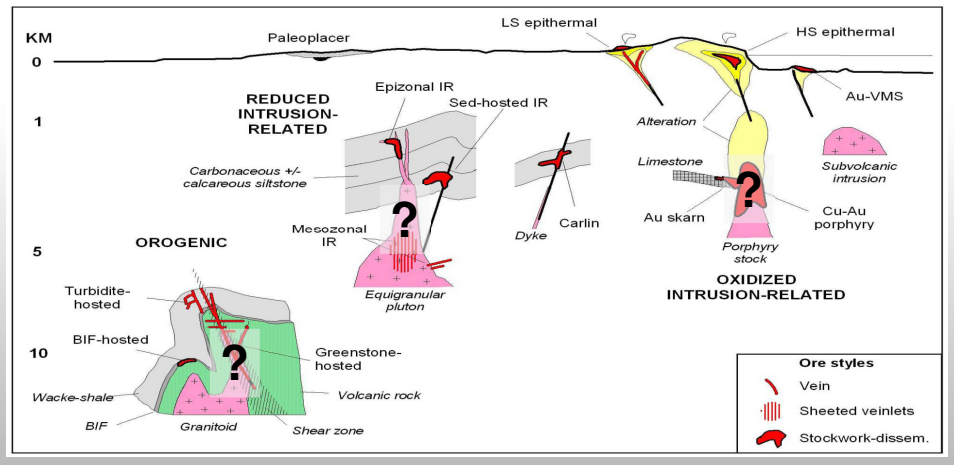
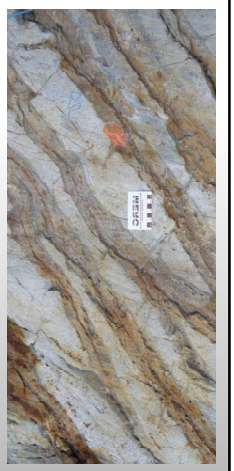
Can different Au systems be recognized? If so what are the discriminating features?





Robert et al. 2007

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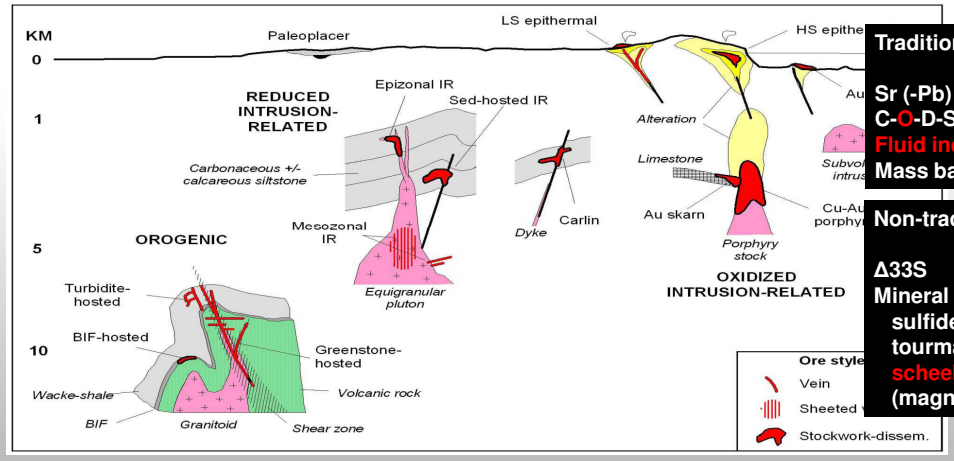


Traditional discriminators:

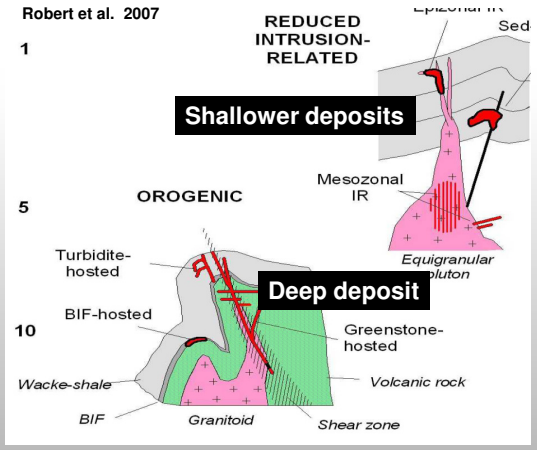
Sr (-Pb) isotopes
C-O-D-S isotopes
Fluid inclusions
Mass balance

Non-traditional methods:

Δ33S
Mineral chemistry
sulfides (aspy, py, cpy)
tourmaline
scheelite
(magnetite)

Robert et al. 2007

Address gold models (e.g., orogenic) from fluid-chemical perspective. What can we learn and apply to the models?



What is the "Global Gold Fluid"?

Is this fluid discriminatory?

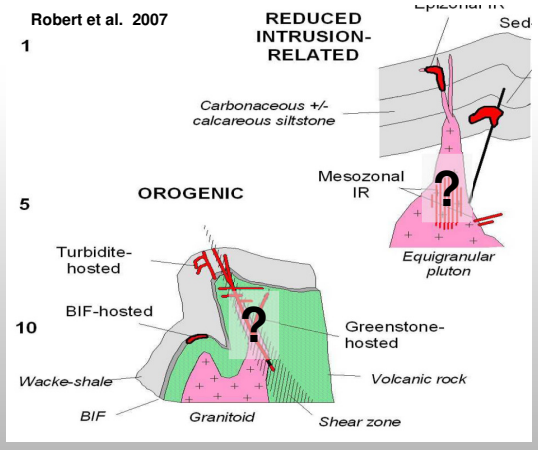
Examine processes (e.g., ΔP_{H2O})?

Nature/source of fluid(s).

Elemental associations - what do they mean?

= Deposit type discrimination (?)

Addressing Au deposit models from fluid-chemical perspective.
What is timing of Au versus vein formation and alteration?



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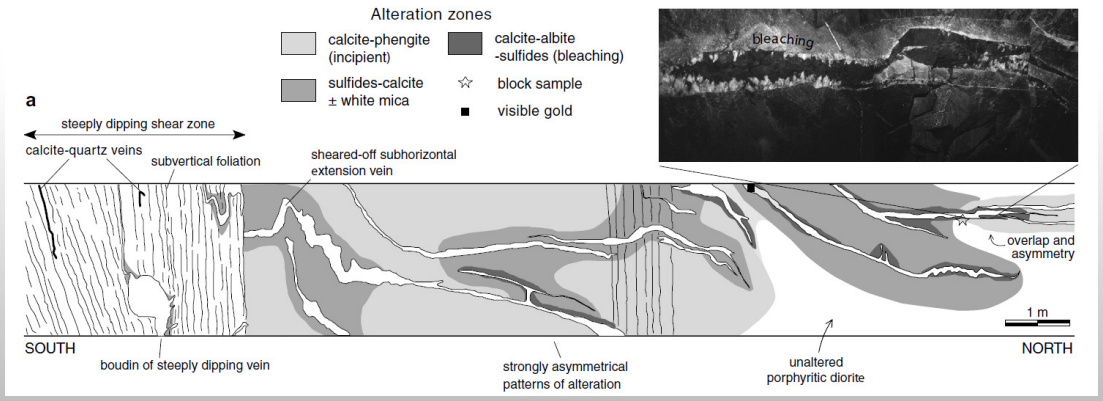
Addressing Au deposit models from fluid-chemical perspective.
What is timing of Au versus vein formation and alteration?

Garofalo 2004, Eur. J. Mineral.



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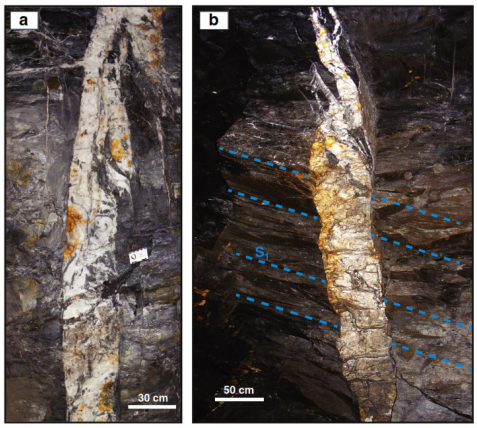
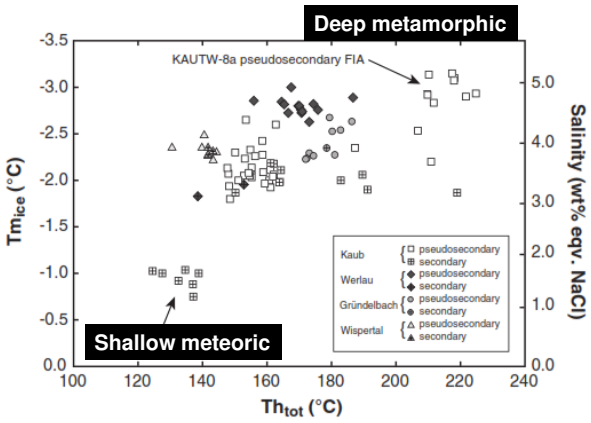
Addressing Au deposit models from fluid-chemical perspective.
Source of mineralizing fluid(s) and how long does a system last?

Marasala et al. 2013 Chem Geol.





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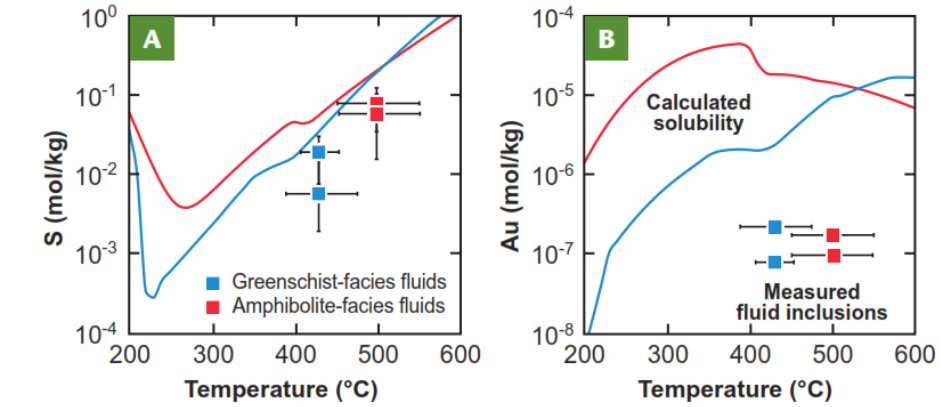
Addressing Au deposit models from fluid-chemical perspective.
What is the Au content of the mineralizing fluids?

Wagner et al 2016 Elements



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Addressing Au deposit models from fluid-chemical perspective.
Why is Au distribution so heterogeneous?

Dufferin deposit, NS (Nov 2017)

Typical slate-belt type bedding parallel or saddle vein showing multiple opening events

Does the fluid change episodically and are Au and fluids sourced differently

Is there an issue of Au precipitation (i.e., mechanism)?

Is quartz all the same event – deep vs. shallow?

Can these issues be addressed?

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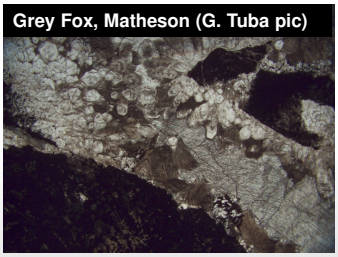
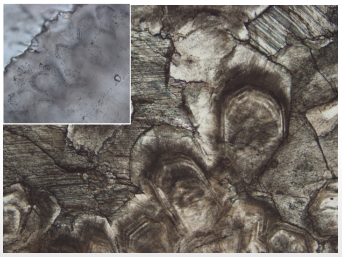
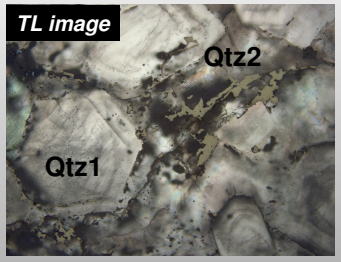
Addressing Au deposit models from fluid-chemical perspective.
What controls the sudden appearance of Au?

Grey Fox, Matheson (G. Tuba pic)

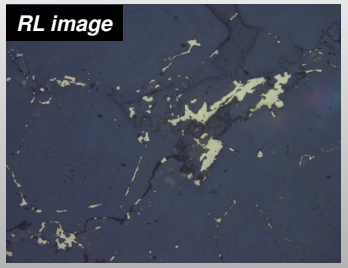




TL image



RL image



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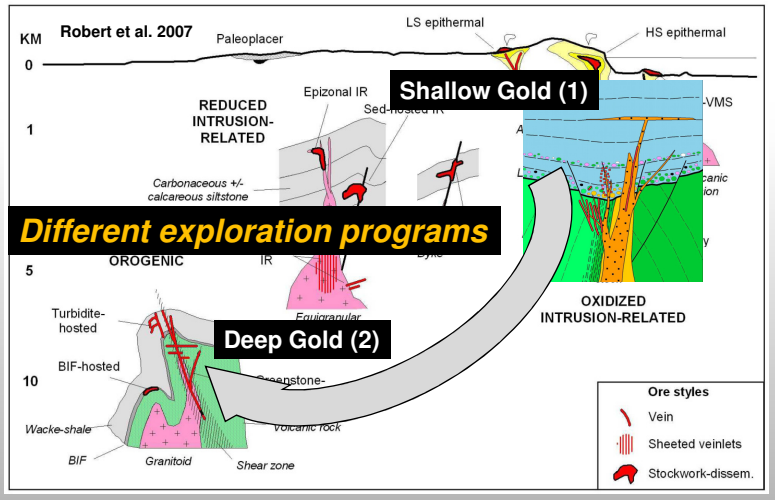
Can different Au systems: 1) be recognized, & 2) discriminated? What are the implications?

Croesus, ON (E. Hastie pic, OGS); ROM sample

Hoyle Pond, ON (Kontak pic)



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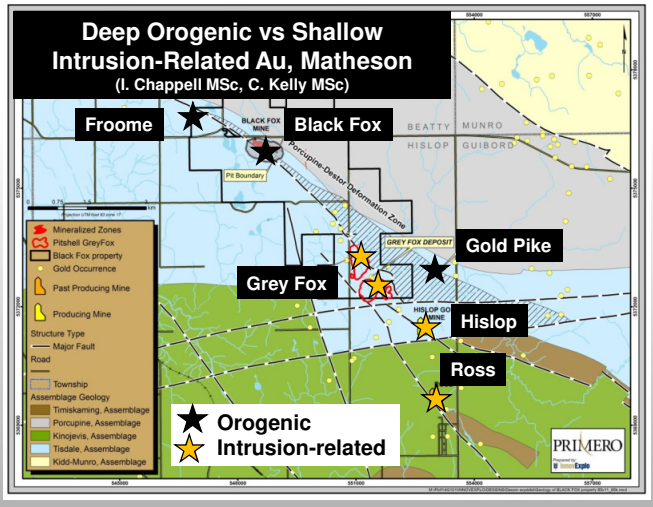

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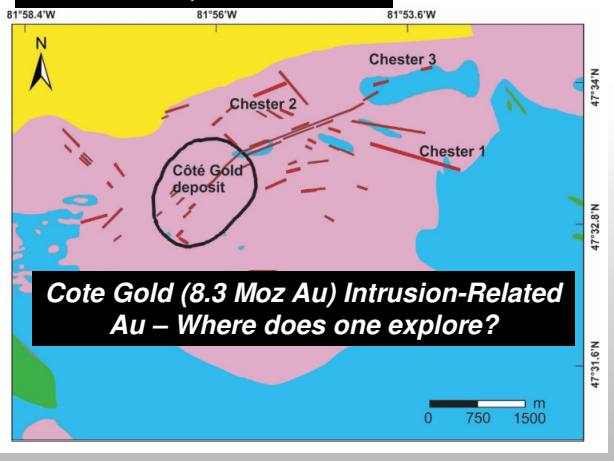
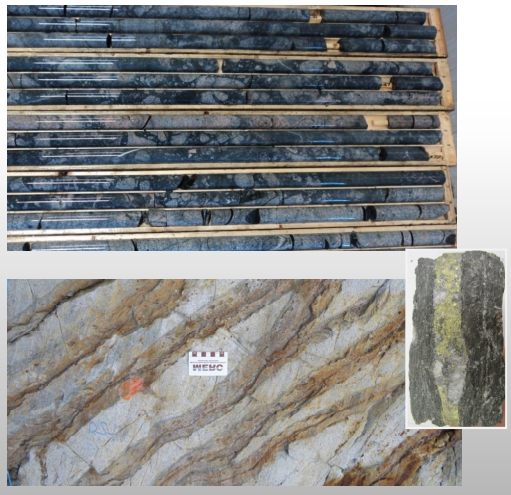
Can different Au systems: 1) be recognized, & 2) discriminated? What are the implications?

L. Katz PhD; J. Smith MSc



Cote Gold (8.3 Moz Au) Intrusion-Related Au – Where does one explore?



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Outline:

1. Fluid inclusions
2. LA-ICP-MS
   - *mineral discriminators*
   - *sulfide mapping*
3. O isotopes
4. An application

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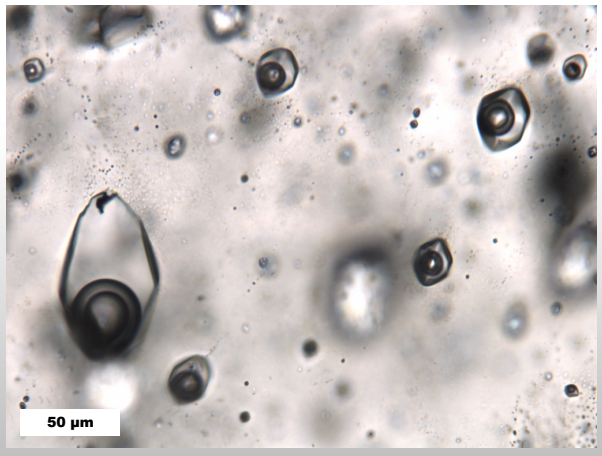
1. Fluid Inclusions – Why Study?



Only means to sample the ore fluids in mineralized system:

1. Define PTX conditions.

2. Characterize fluid chemistry and possible reservoirs.

3. Assess processes:
- **fluid mixing, unmixing**
- **changing fluid chemistry**
- **pressure cycling (ΔP_{H2O})**

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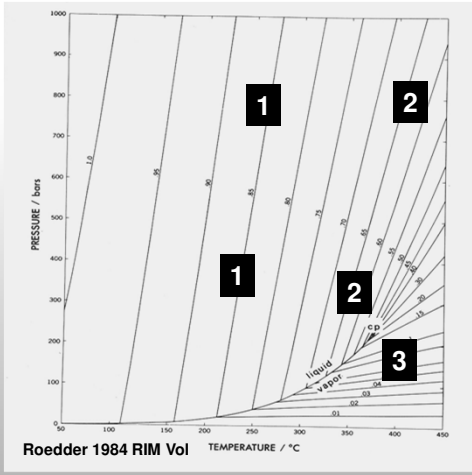
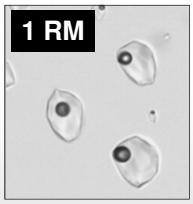
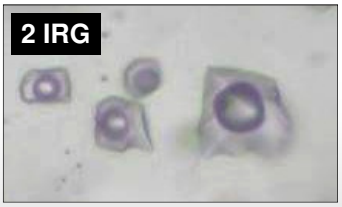
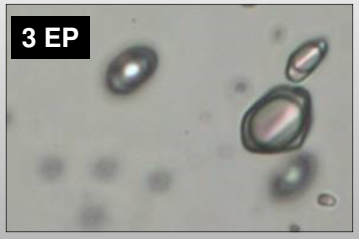
Fluid Inclusions – The Basics
Assess Deep vs Shallow and Affinity









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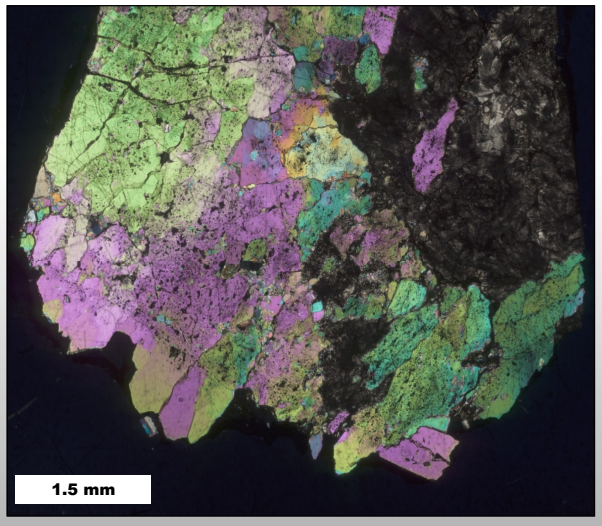
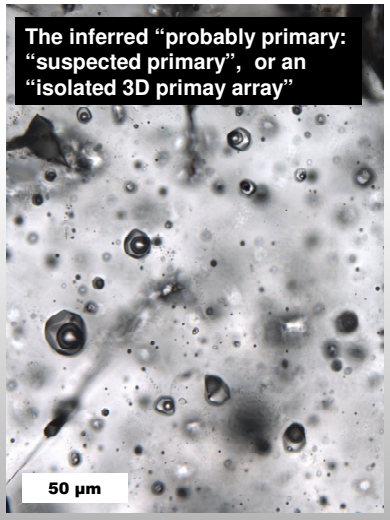
Fluid Inclusions: I. *Timing of fluid entrapment*





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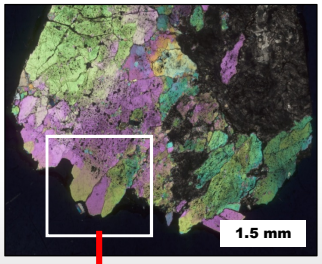

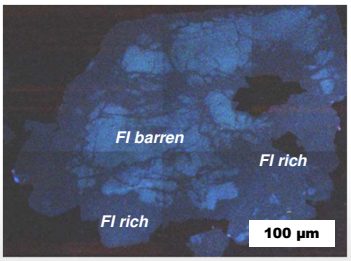

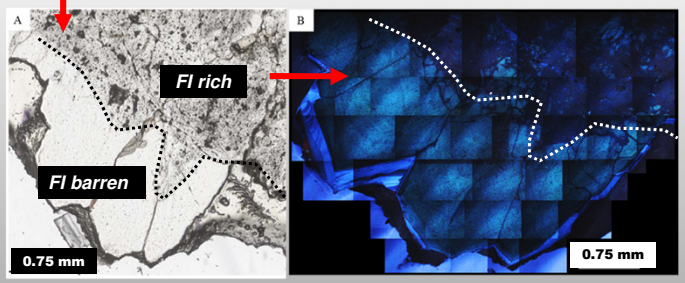

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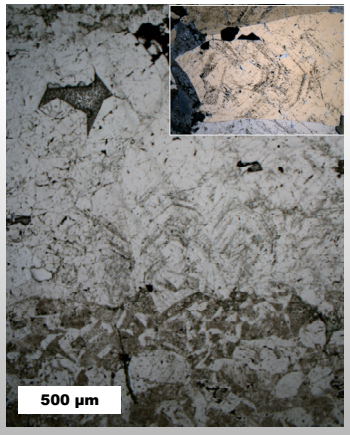
Fluid Inclusions: *Timing of fluid entrapment and quartz textures (deep vs shallow settings)*

Grey Fox, Matheson, ON

Boston Creek, Kirkland Lk, ON



A Generalization (!):

Episonal or inferred intrusion-related settings have preserved zoned quartz with primary inclusions.

Some quartz textures suggests original gels!

Fluids both H_2O and H_2O-CO_2.

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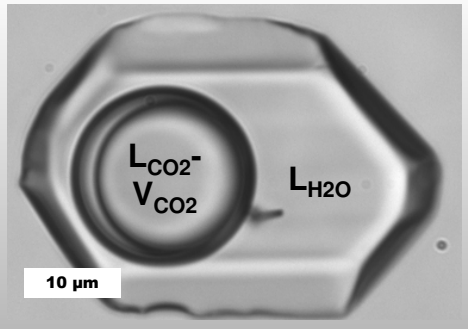
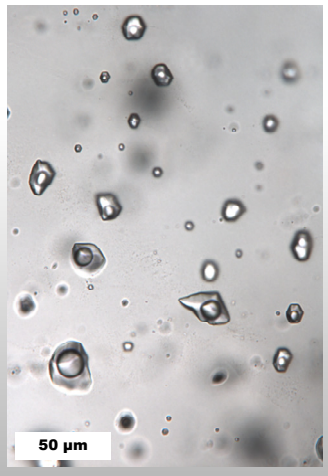
Fluid Inclusions: II. What is The "Global Gold Fluid"?

Room T view of a H_2O-CO_2 fluid common in gold systems (OR, IRG) through time and space!



Meguma, NS: H_2O-CO_2 fluid

Gap 144, ON: H_2O-CO_2 fluid



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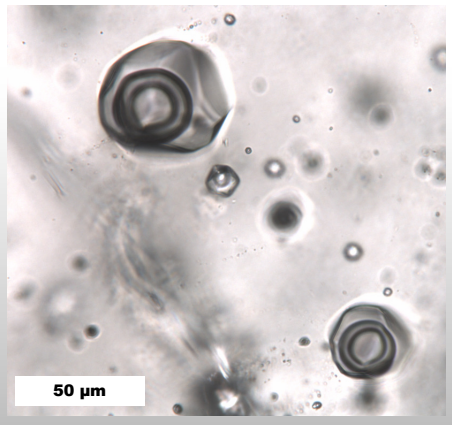
What is the "Global Gold Fluid"?

Meguma Gold Vein: H_2O-CO_2 fluid



Measurements of the phases proportions and and chemical properties indicates :

- **X_{CO2} ~ 0.10-0.20 ± CH_4, N_2, , <5-10 wt. % equiv. NaCl**
- **Trapped as either one- or two-phase fluid at ca. 1.5-2.5 kbars (5-8 km)**

Questions:

1. How unique is this fluid?
2. Is it actually Au-rich?

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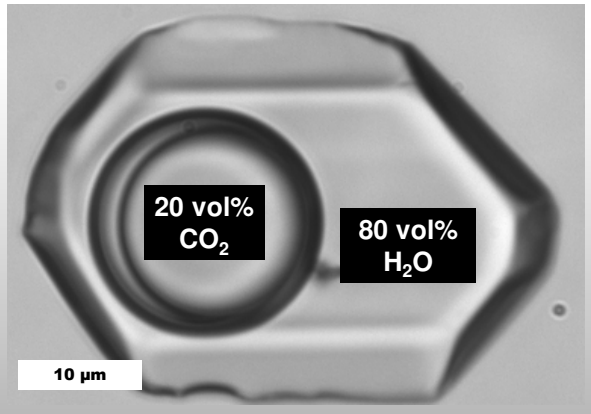
What is "The Gold Fluid"?
What is 10-20 mol% CO_2 (X_{CO2} = 0.1-0.2)

Meguma Gold Vein: X_{CO2} = 0.07



Determining mole % of phases:

1. Assume volume of 1 cm^3.
2. Estimate the volume % of phases.
3. Use ρ H_2O = 1 g/cm^3 and determine ρ CO_2 with the CO_2 phase diagram and thermometry.
4. No. Moles = wt. / # gms in 1 mole. For this inclusion have 80% L (H_2O) & 20% V (CO_2).
5. **For H_2O**:
   (0.8 cc * 1 g/cc)/18 g = 0.0444 moles
   For CO_2:
   (0.2 cc * 0.65 g/cc)/44 g = 0.00295 moles
6. Mole % H_2O [X_{H2O}] = $M_{H2O}/(M_{H2O}+M_{CO2})$ = **0.93**
   Mole % CO2 [X_{CO2}] = 1- X_{H2O} = **0.07**

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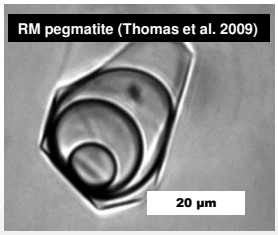
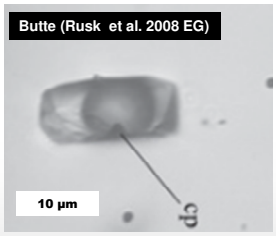
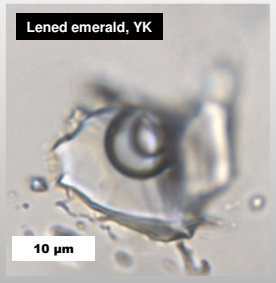
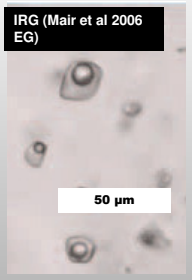
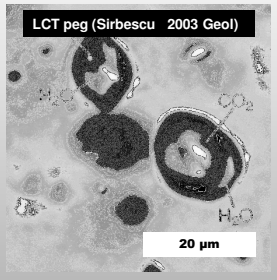
How Unique is the "Global Gold Fluid"?











Typical H_2O-CO_2 Fluids:

- Barren metamorphic quartz veins
- LCT/RM pegmatites
- Sn-W-Sb vein systems
- REE carbonatites/alkaline settings
- Eemerald) deposits
- IR gold deposits
- Deep porphyries (e.g., Butte)

Thus a common fluid!

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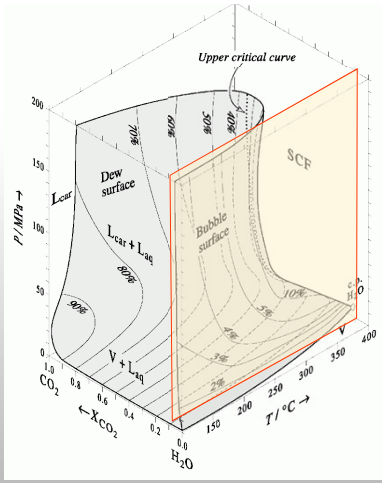
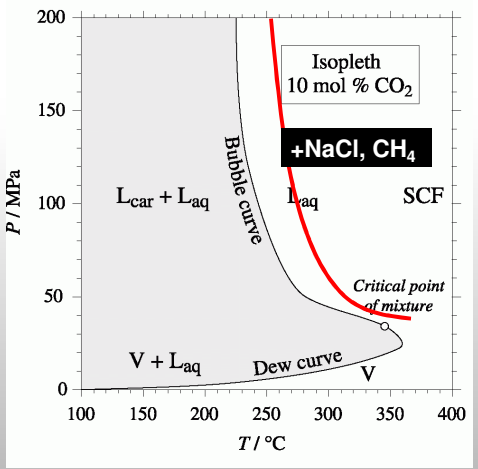
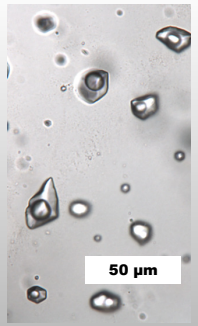
Fluid Inclusions: III. Proxy for Processes Why, How and Why Important



Diamond 2003 MAC SC Vol



SCF trapped in one phase field – uniform density



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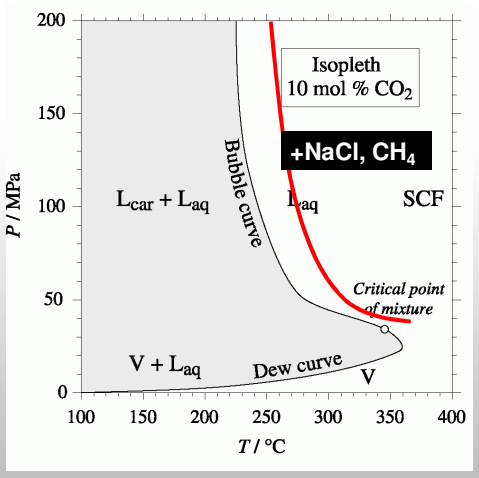
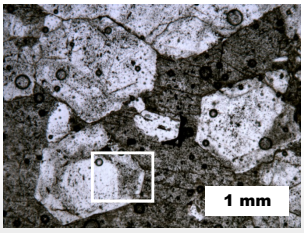
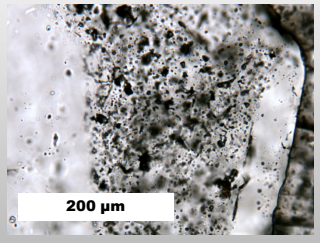
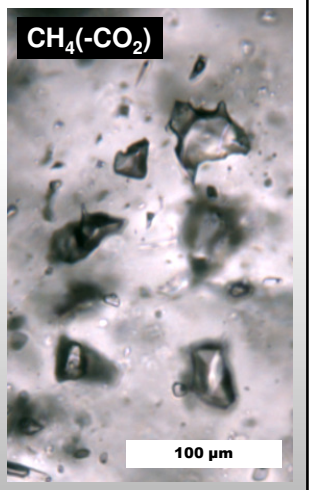
Fluid Unmixing: Does this lead to gold formation?



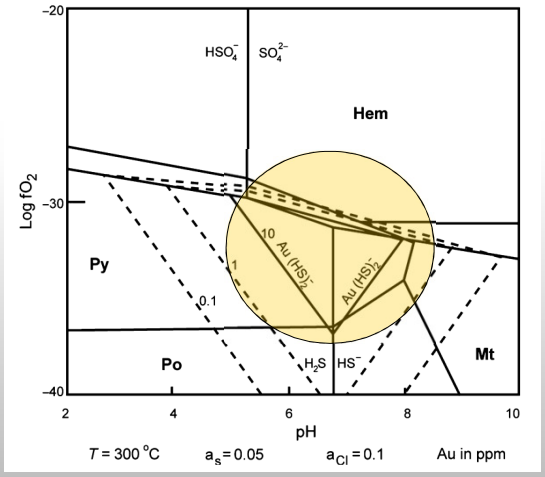






Diamond 2003 MAC SC Vol

Fluid Unmixing: Does this lead to gold formation?



Destabilizing fluid chemistry may lead to gold precipitation as modeled for system shown

Suggest that fluid unmixing is an important process in gold systems.

Phillips and Powell 2010 Earth Sci Rev

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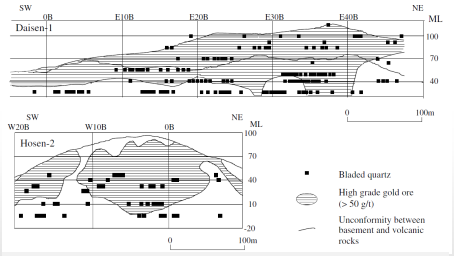
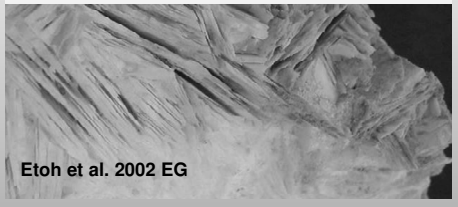
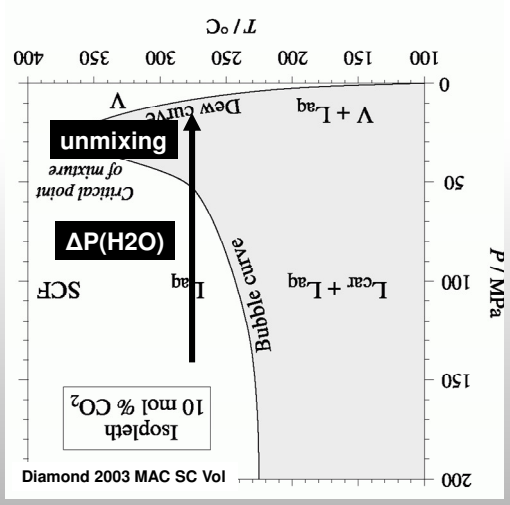
Fluid Unmixing: Pressure (i.e., depth) dependence



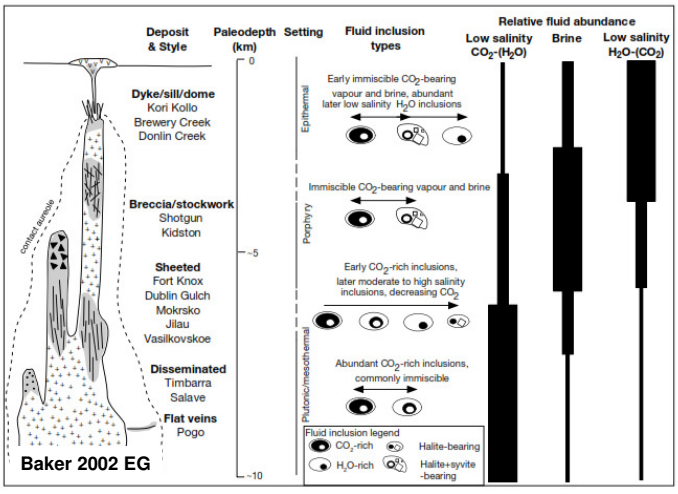
Hishikari low-sulphidization Au deposit – bladed quartz – 50 g/t Au



Etoh et al. 2002 EG



Fluid Unmixing: Pressure (i.e., depth) dependence Applied to Intrusion-Related Au deposits



Baker 2002 EG

Fluid inclusions reflect depth and fluid evolution of the ore system…..

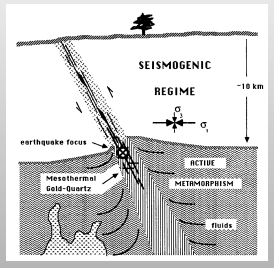
But similar to orogenic fluids and evolution!

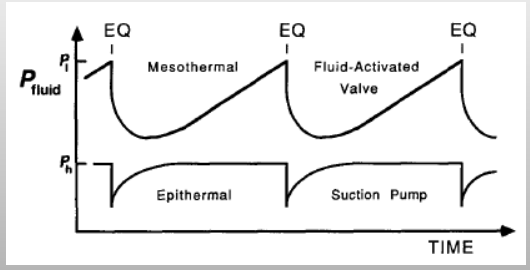
Fluid Pressure Cycling: Can this be detected?

High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits

Richard H. Sibson
Department of Geological Sciences, University of California, Santa Barbara, California 93106

Francois Robert, K. Howard Poulsen
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada





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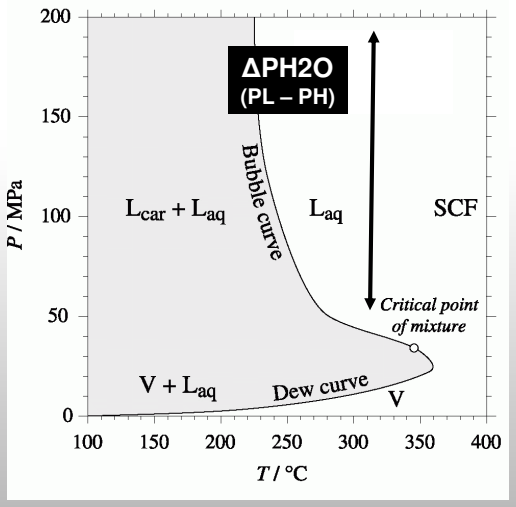
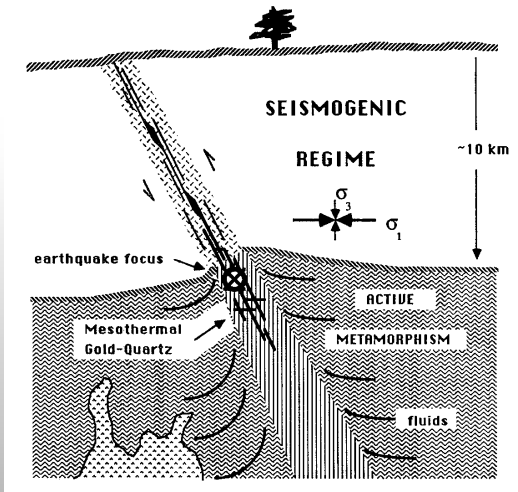
Fluid Pressure Cycling: Can this be detected?





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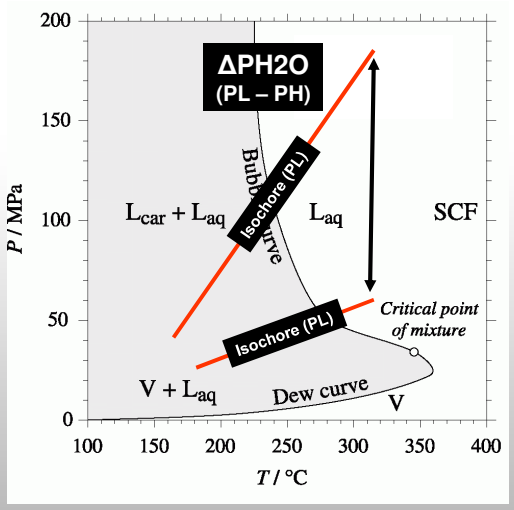
Seismic Pumping: Can this be detected?



Fluid Pressure and Vein Formation:

Over-pressured fluids sourced from below exceed confining pressure (lithostatic load) and initiate vein formation.

~1/3P_L = P_H

What if the fluid pressure exceeds $P_{lithostatic}$? = supralithostatic pressure

Does this happen and can it be detected using fluid inclusions?

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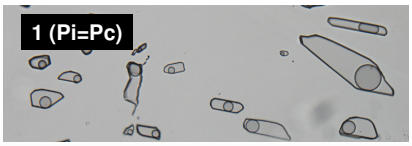
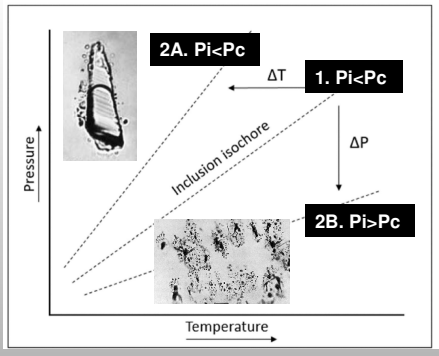
Seismic Pumping: Detected with FI Textures





J. metamorphic Geol, 1989, **7**, 243–260

Synthetic fluid inclusions – VII. Re-equilibration of fluid inclusions in quartz during laboratory-simulated metamorphic burial and uplift

S. M. STERNER AND R. J. BODNAR
Department of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Contrib Mineral Petrol (2010) 160:825–843
DOI 10.1007/s00410-010-0509-z

ORIGINAL PAPER

Modification of fluid inclusions in quartz by deviatoric stress I: experimentally induced changes in inclusion shapes and microstructures

Alexandre Tarantola · Larryn W. Diamond · Holger Stünitz

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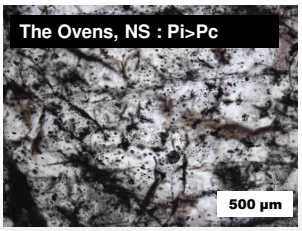
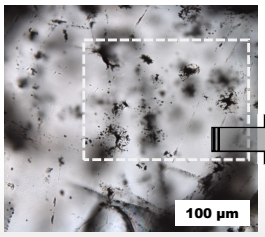
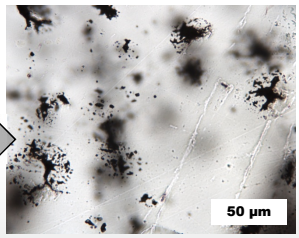
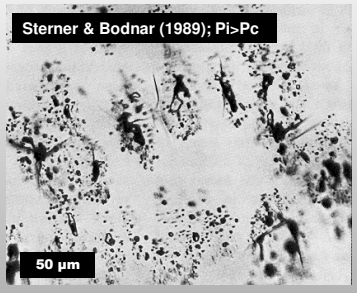
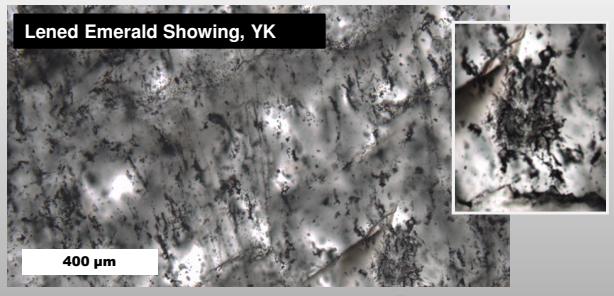
Seismic Pumping: Detected with FI Textures











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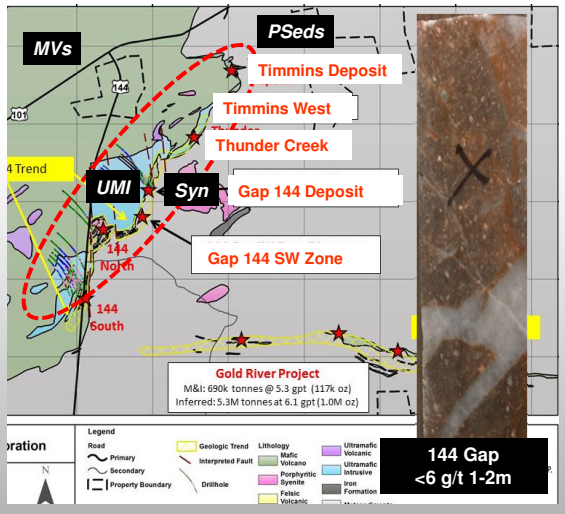
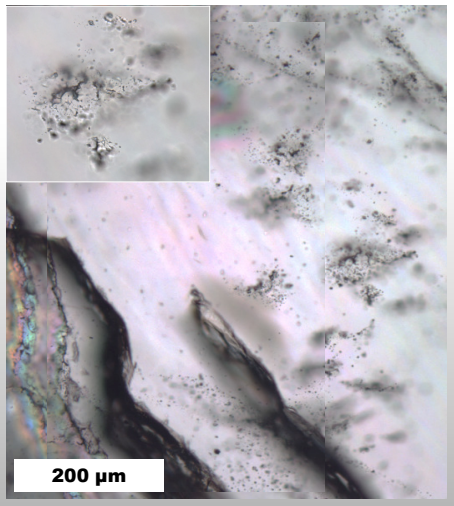
Seismic Pumping: Detected with FI Textures

Gap 144 Zone, West Timmins





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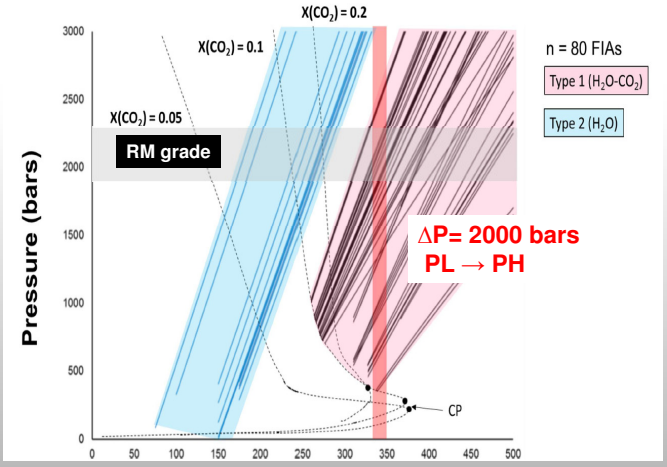
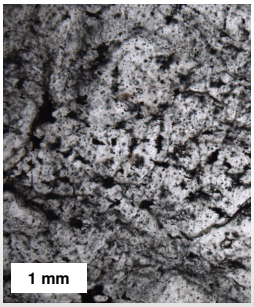
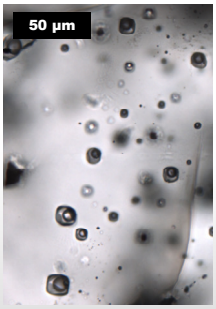
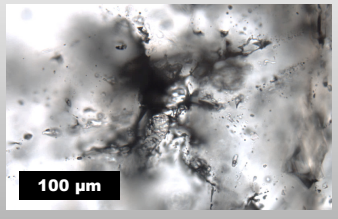
Seismic Pumping: Detected with FI Isochores

Caribou Deposit, NS (Choquette BSc 2017)









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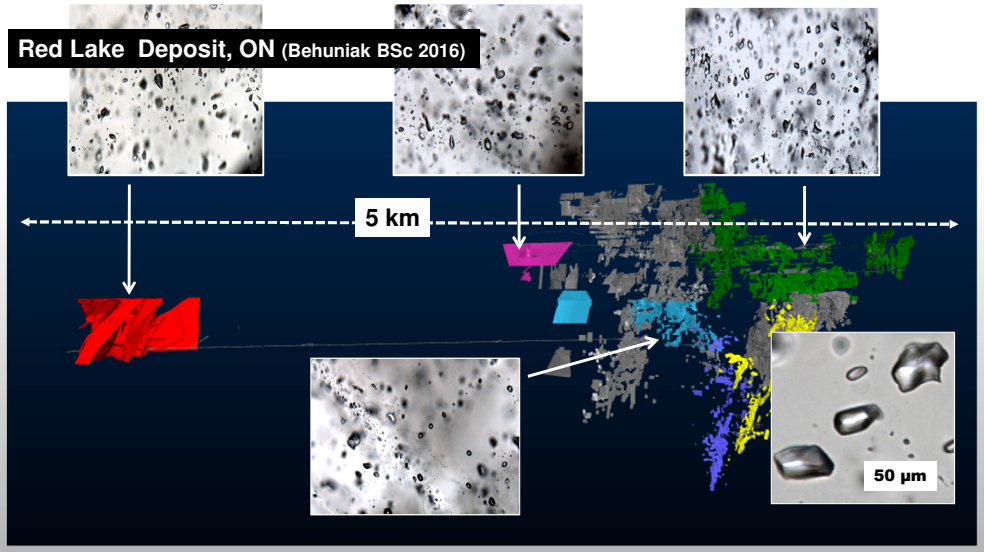
Seismic Pumping: Detected with FI Isochores

Red Lake Deposit, ON (Behuniak BSc 2016)



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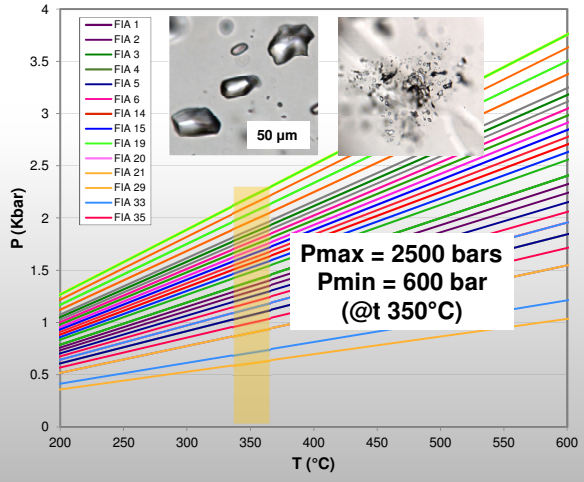
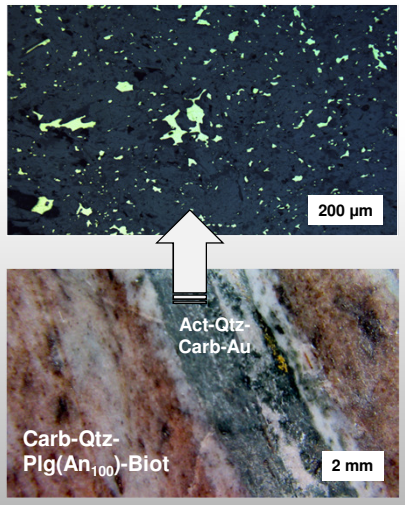
Seismic Pumping: Detected with FI Isochores





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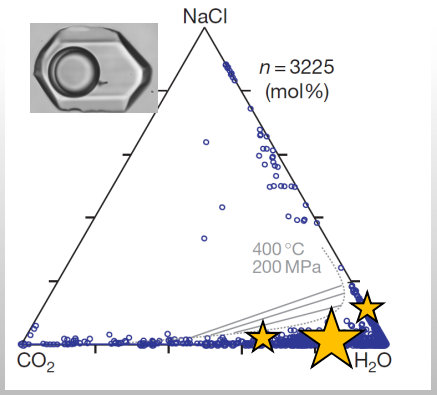
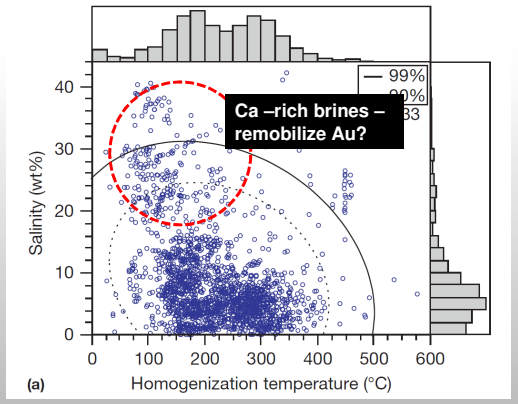
Fluid Inclusions: IV Composition of the Orogenic "Global Gold Fluid"

Bodnar et al 2014 (Treastise on Geochem)





Processes:

1. Fluid unmixing
2. Fluid mixing
3. Later fluid(s)

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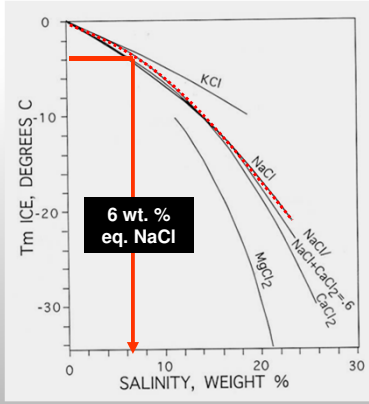
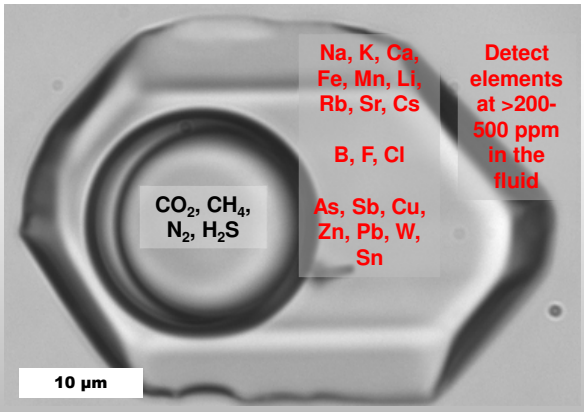
What is the Composition of the "Global Gold Fluid"?

X_{CO2} = 0.1-0.2; 5-10 wt. % equiv. NaCl (?)

What is done



What is possible: SEM-EDS, LA-ICP-MS



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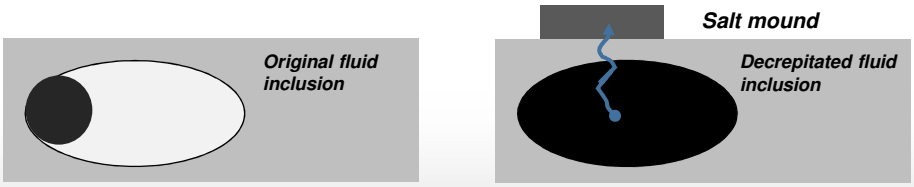
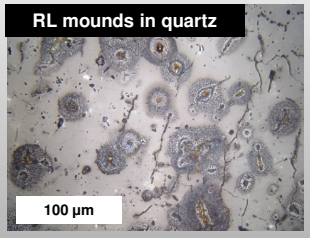
What is the "Global Gold Fluid"?

More that wt. % equiv. NaCl!

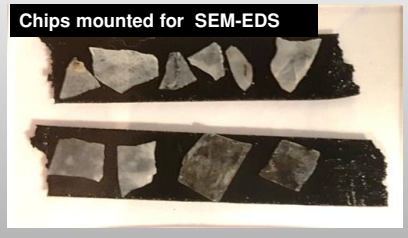


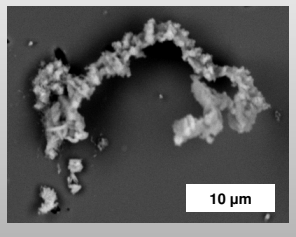
Heating @ 50-100ºC/min to 450-500°C

RL mounds in quartz



Chips mounted for SEM-EDS





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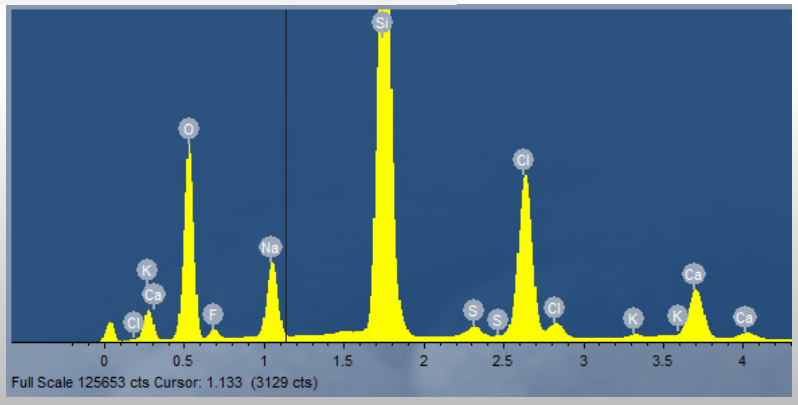
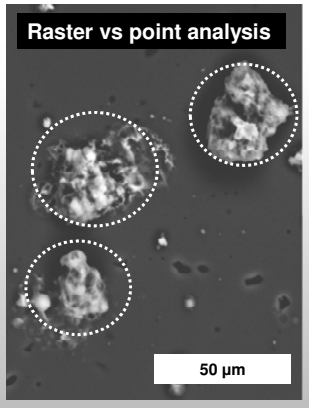
What is the "Global Gold Fluid"?

More that wt. % equiv. NaCl!

SEM-BSE image and EDS spectra:
(Na(24), Ca(18), K(1), Cl(45), F(5), S(5.4)





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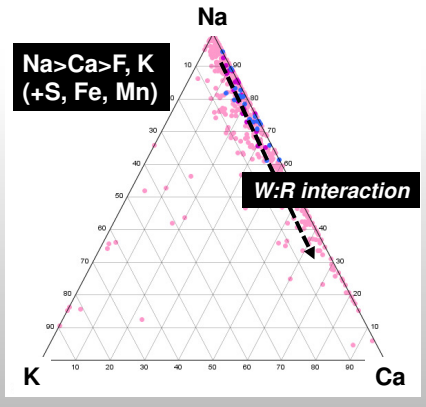
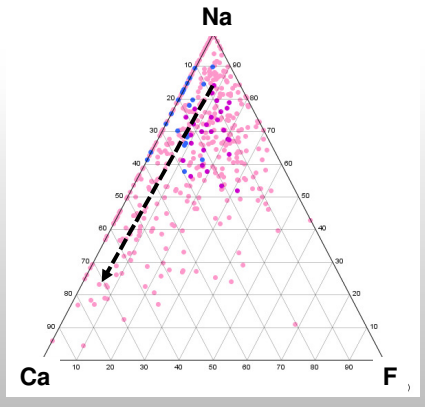
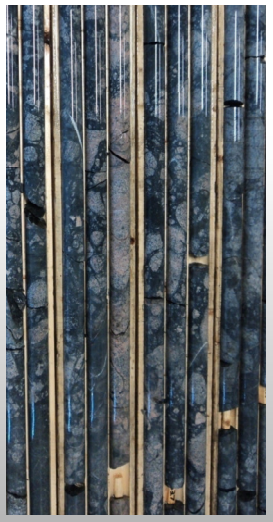
What is the "Global Gold Fluid"?

Côté Gold Au(-Cu) Deposit, ON







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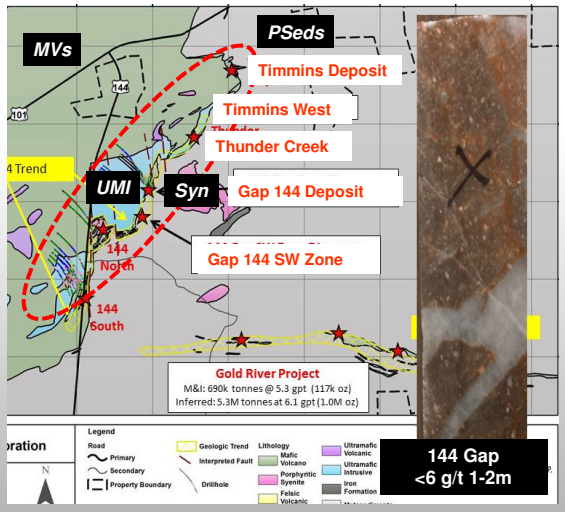
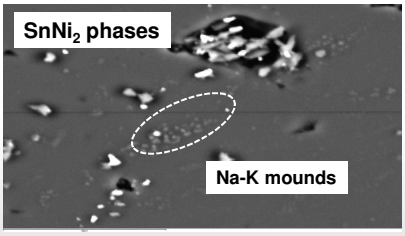
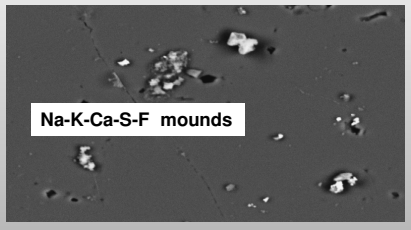
What is the "Global Gold Fluid"?

Gap 144 Zone, Timmins, ON







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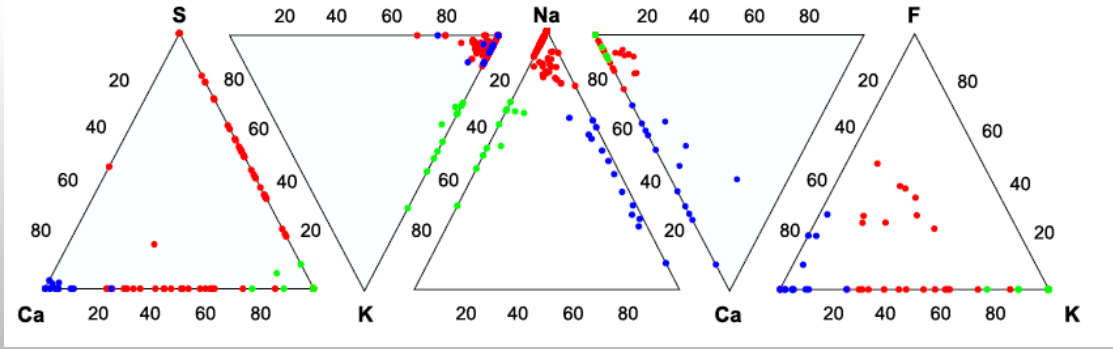
What is the "Global Gold Fluid"?

Gap 144 Zone, Timmins, ON

3 fluids identified: Na(K, F, S) Na-K Na-Ca(F)



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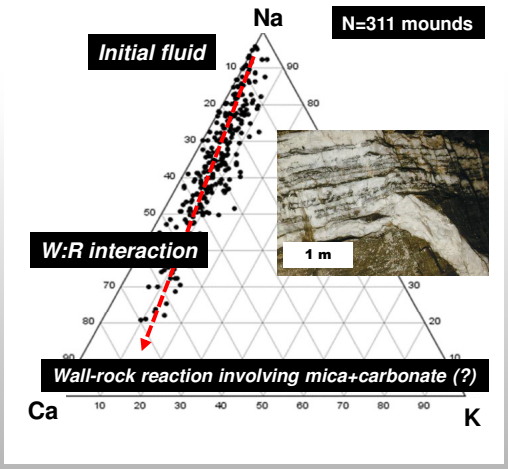
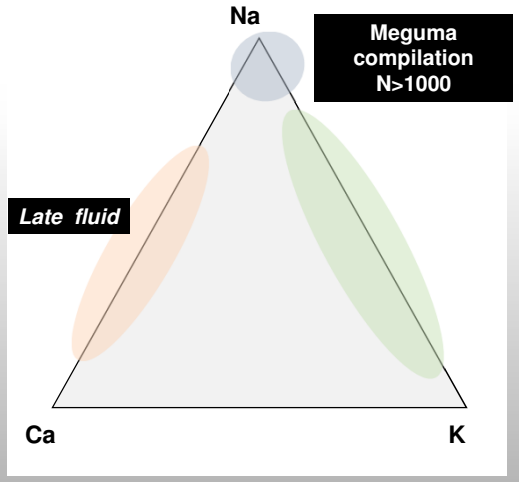
What is the "Global Gold Fluid"?

Caribou Deposit, Meguma terrane, NS





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What About the "Global Gold Fluid"

- **The global gold fluid in NOT unique.**
- **Fluid unmixing common (e.g., Abitibi), but not universal (e.g., Meguma, NS).**
- **P_{fluid} cycling is common (Seismic pump model validated); supralithostatic conditions possible.**
- **Characterizing fluid chemistry necessary in order to discriminate - fluids are NOT simple NaCl brines; F inferred to align with intrusion-related settings vs deeper orogenic settings.**
- **What is the geochemical signature of the Au fluid?**

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2. LA-ICP-MS: Mineral Discrimination

I. **Mineral discriminators**
(e.g., scheelite)

II. **LA sulfide mapping**
(arsenopyrite, pyrite)

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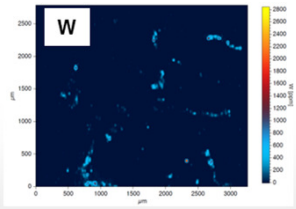
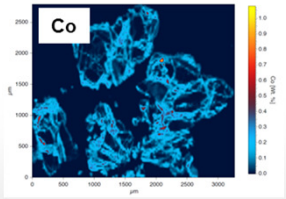
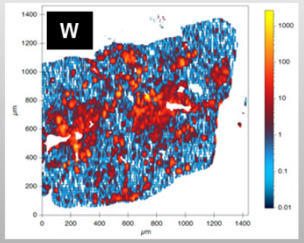
I. Scheelite as an Ore Deposit Discriminator

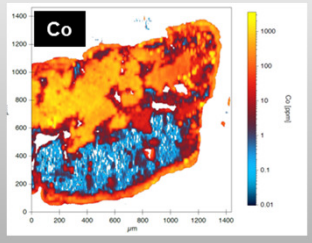
Bisset Au deposit, MB (Neyedley et al. 2017 EG)





Vickers Au deposit, NUN (S. Tokayrk MSc in prep.)





- **Is it valid to use scheelite as a proxy for Au?**
- **Was W sourced from another process or reservoir (Cave et al. 2017 Canadian Mineral)?**
- **Use scheelite with reservation!**

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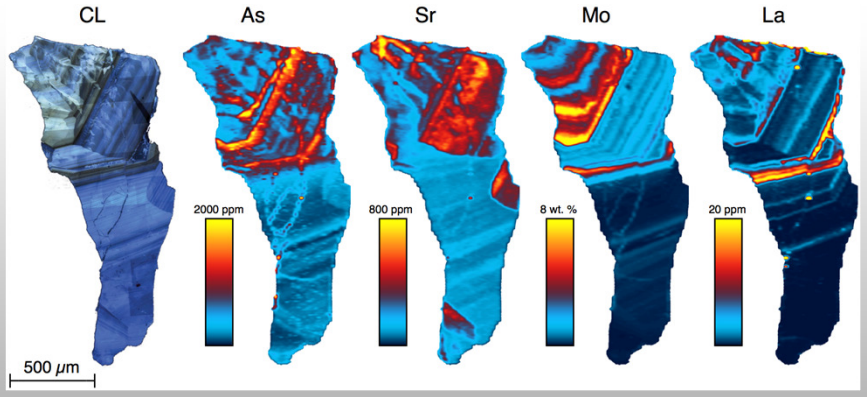
Scheelite as an Ore Deposit Discriminator

Poulin et al. 2016 Can Mineral, under review; Poulin 2016 MSc; Kontak et al. 2017 GSC OFR



CL shows complex grow history; more typical of shallow vs deep settings

Chemical changes due to pulsating fluids, co-temporal ppct of phases (e.g., monazite, apatite).

Redox sensitive elements (Eu, As, Mo) can be used to assess settings (orogenic vs intrusion related)

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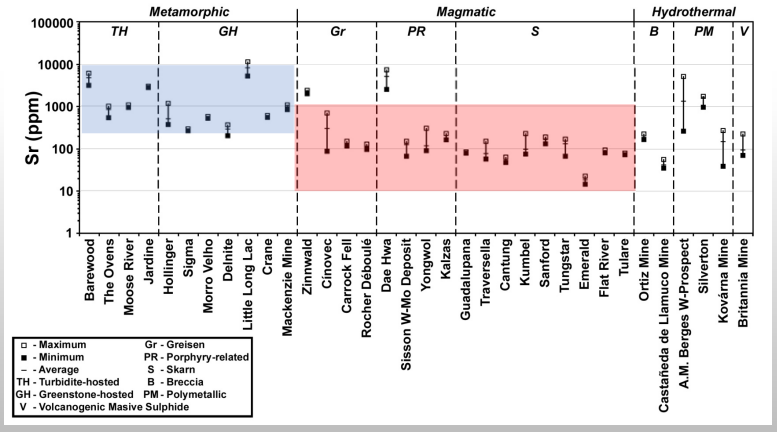
Scheelite as an Ore Deposit Discriminator: Sr Data



- **Enrichment reflects fluid chemistry as Sr ↔ Ca**
- **Enriched in metaseds/volcanic rocks vs. evolved granites**

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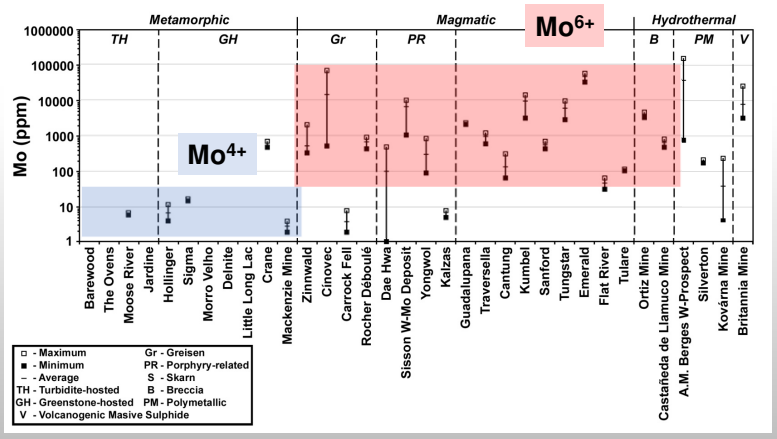
Scheelite as an Ore Deposit Discriminator: Mo data



- Multiple oxidation states (Mo^{4+} vs. Mo^{6+})
- Scheelite prefers Mo^{6+} in oxidized settings (i.e., porphyries)

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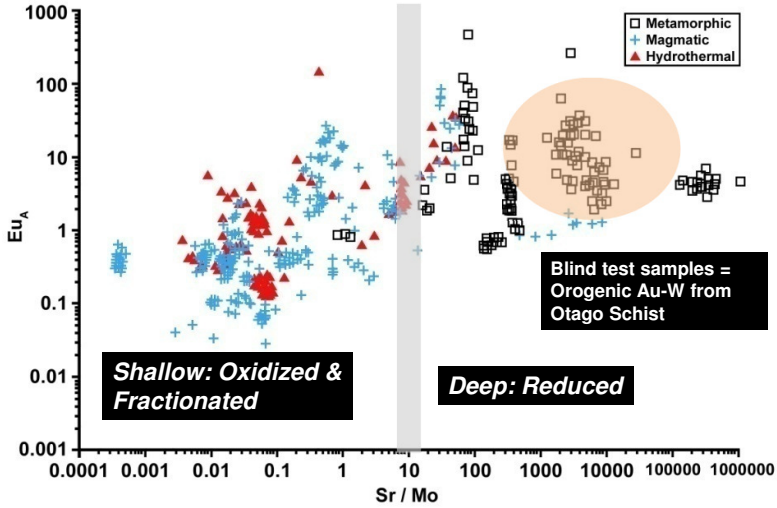
Scheelite as an Ore Deposit Discriminator



The scheelite message:

- An ore deposit discriminator
- Provides U-Pb age and time of Au (?)
- Rapid efficient, cost effective.

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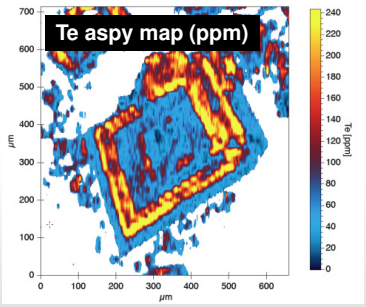
II. LA-ICP-MS Elemental Sulfide Mapping



Neyedley et al. (2016 EG), Gourcerol et al. (2018 Canadian Mineral; 2018 Mineral Deposita)

- Element distribution
- Element paragenesis
- Elemental associations
- Au:Ag ratios through sulfide paragenesis
- Identify Au events
- Age of Au event (Pb ages)

Traditional bulk rock analysis – what does it mean in terms of elemental associations?

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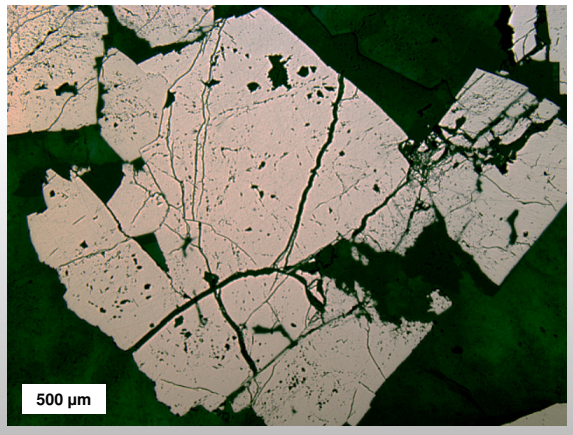
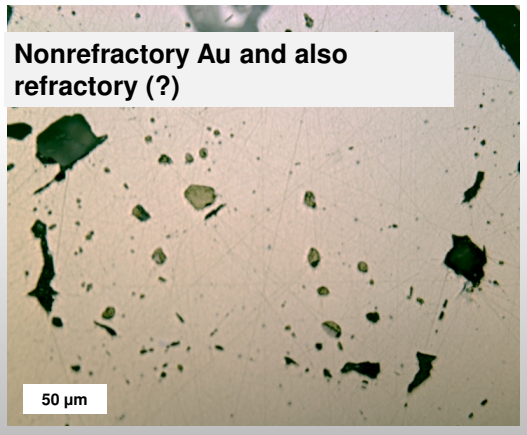
Elemental Sulfide Mapping: Identify Nature of Au





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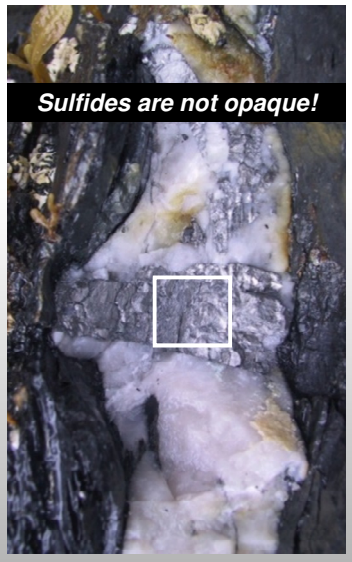
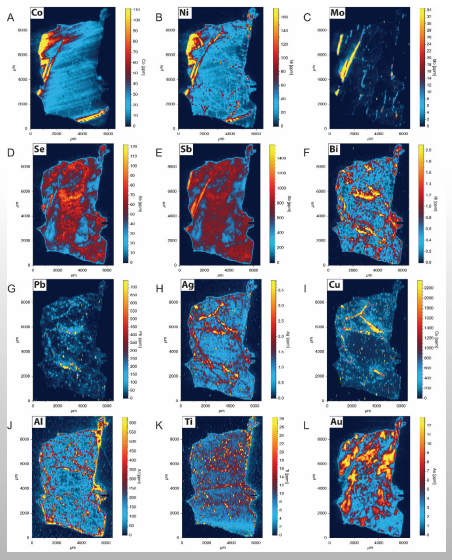
LA-ICP-MS: Elemental Distribution





Need a way to capture all this information.

Convert to individual elemental analysis.

~40,000 analyses represented here.

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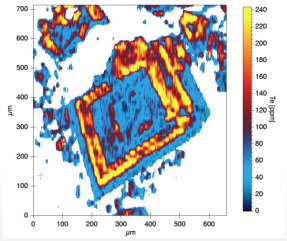
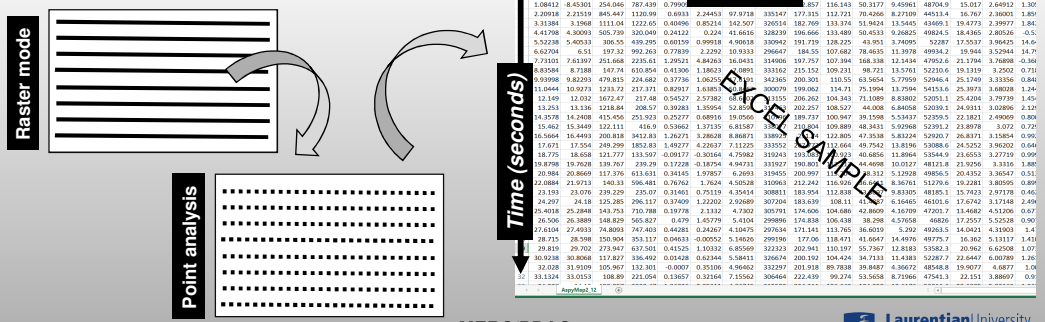
LA-ICP-MS: Generate Elemental Concentrations



Data converted into single point analyses using time for single scan in the MS detector (0.35 secs); typical map sample **15 000 to 40 000 individual analysis**;

Data organized in Excel and imported to *logas* for plotting.



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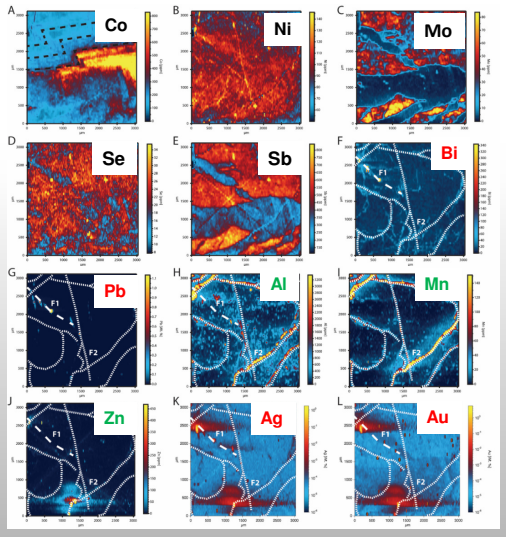
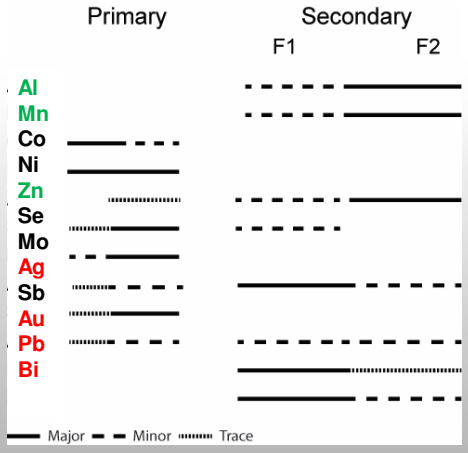
LA-ICP-MS: Elemental Paragenesis



E.g., Meguma Arsenopyrite (Orogenic setting)



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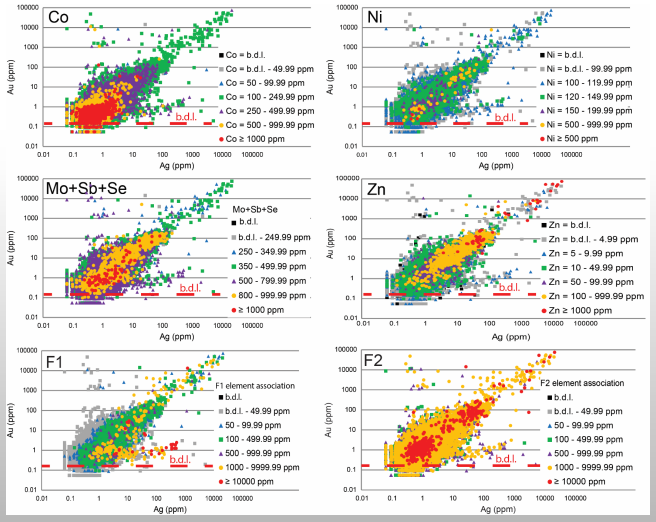
LA-ICP-MS: Elemental Concentrations/Associations



Meguma Arsenopyrite :

- **Early Au enrichment to 100 ppm**
- **Upgrading or new Au added**
- **Two stages of Au mineralization!**

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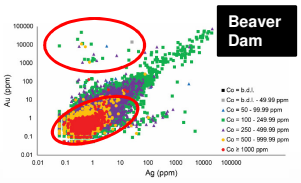
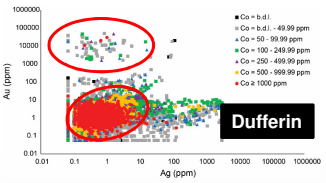
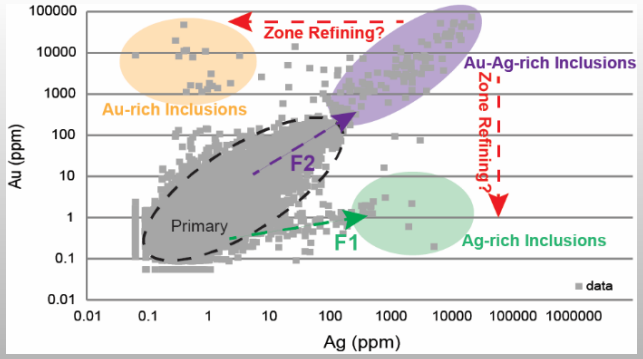
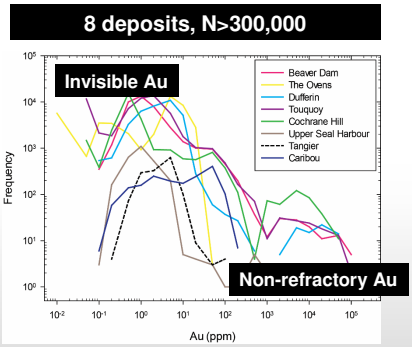
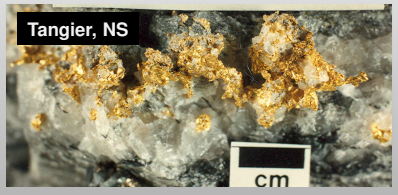
LA-ICP-MS: Elemental Concentrations/Associations











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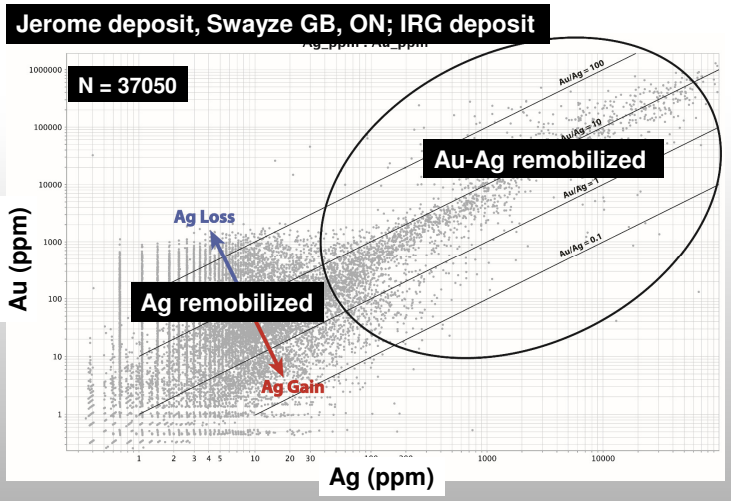
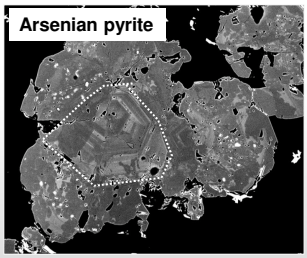
LA-ICP-MS: Elemental Concentrations/Associations

(E. Hastie PhD, LU; Hastie et al. 2017 GAC-MAC)





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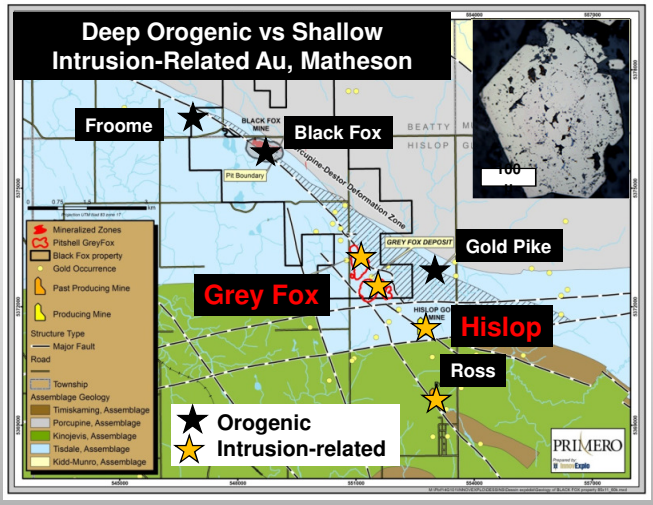
Can different Au systems be discriminated?
A Case study of the Matheson area (C. Kelly MSc)



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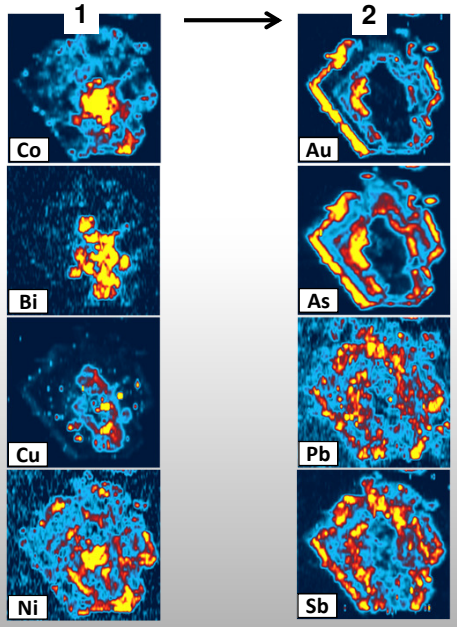

Grey Fox 147 Contact Zone

Inferred elemental paragenesis:

1 → 2 → 3 → 4

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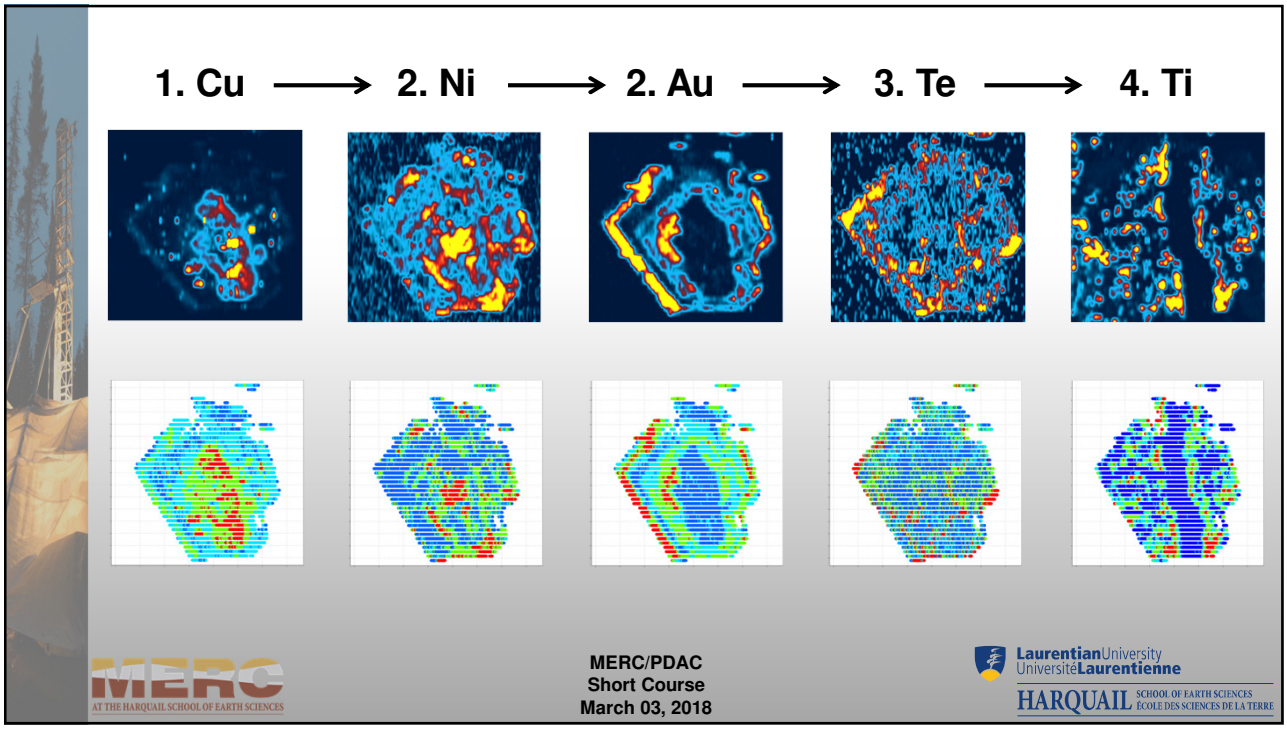
1. Cu
2. Ni
2. Au
3. Te
4. Ti
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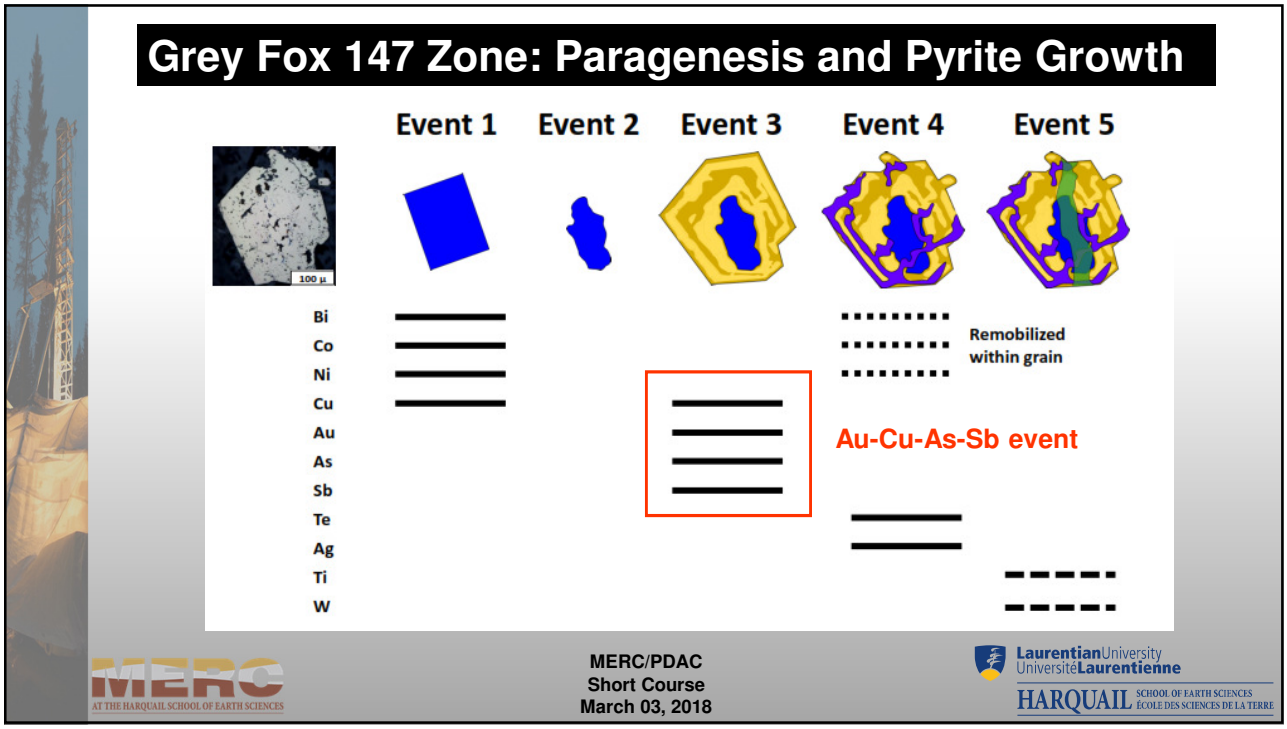
Grey Fox 147 Zone: Paragenesis and Pyrite Growth
Event 1
Event 2
Event 3
Event 4
Event 5
100 µ
Bi
Co
Ni
Cu
Au
As
Sb
Te
Ag
Ti
W
Remobilized
within grain
Au-Cu-As-Sb event
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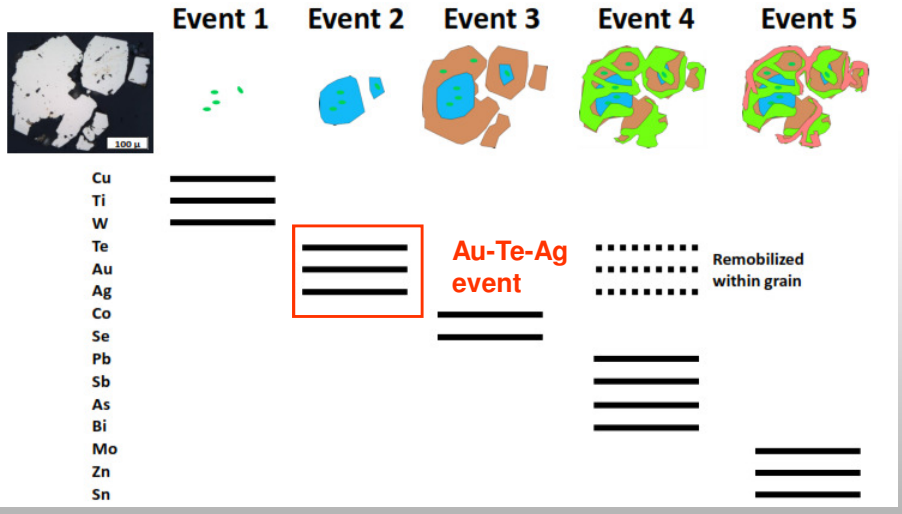
Hislop Zone: Paragenesis and Pyrite Growth



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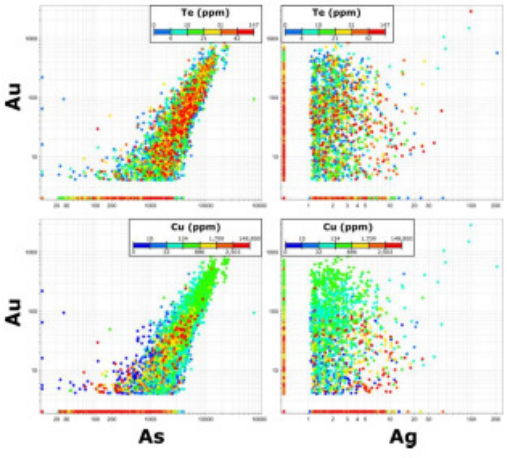
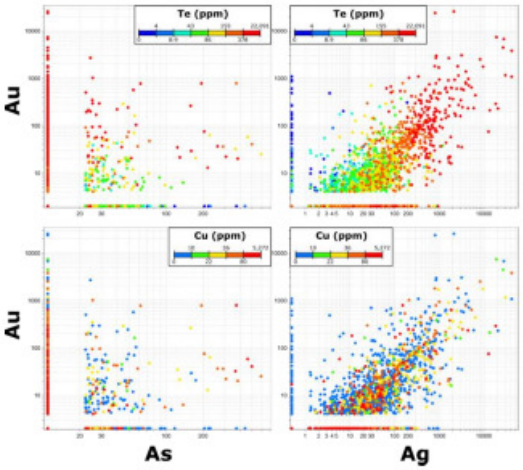
Comparison of Grey Fox and Hislop LA Pyrite Data

Grey Fox 147 Zone (Au-As-Te-Cu)



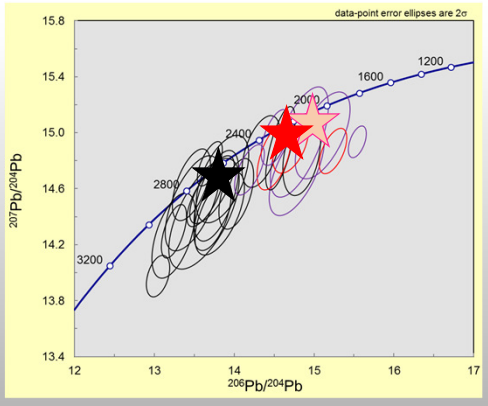
Hislop Zone (Au-Te-Ag)

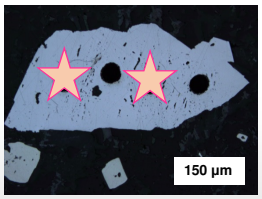


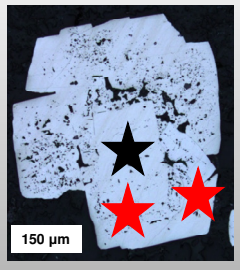
LA ICP-MS – In Situ Model Pb Dating

Vickers Zone, Pistol Bay Trend (S. Tokayrk MSc LU; C. Lawley GSC)

Different Au events with different chemical signatures (LA-ICP-MS); 3 events in region (Lawley et al. 2016)







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LA-ICP-MS Sulfide Mapping Summary

- Characterize style of Au mineralization (refractory, nonrefractory) – two or more Au stages
- Provides elemental associations and paragenesis – complicated and no simple story of deep (OR) vs shallow (IR)
- Possible model Pb ages and timing of Au – different gold events (?)
- Potential for vectoring and fertility as part of exploration projects (future work)

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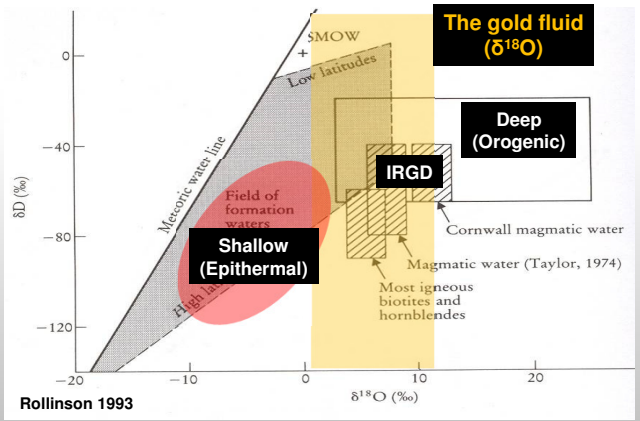
3. Stable Isotopes $\delta^{18}O_{quartz}$ and $\delta^{18}O_{H2O}$



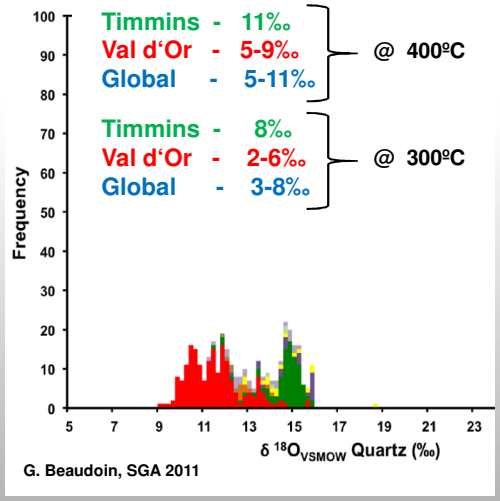
Rollinson 1993

$\Delta^{18}O_{quartz\text{-}H2O} = A * (10^6)/T^2 + B$

Or at 300°C (Matsuhisa et al. 1979)

$\Delta^{18}O_{H2O}$ (‰) = $\delta^{18}O_{quartz}$ - 7

Stable Isotopes $\delta^{18}O_{quartz}$ and $\delta^{18}O_{H2O}$



G. Beaudoin, SGA 2011

$\delta^{18}O_{quartz}$ vs $\delta^{18}O_{H2O}$

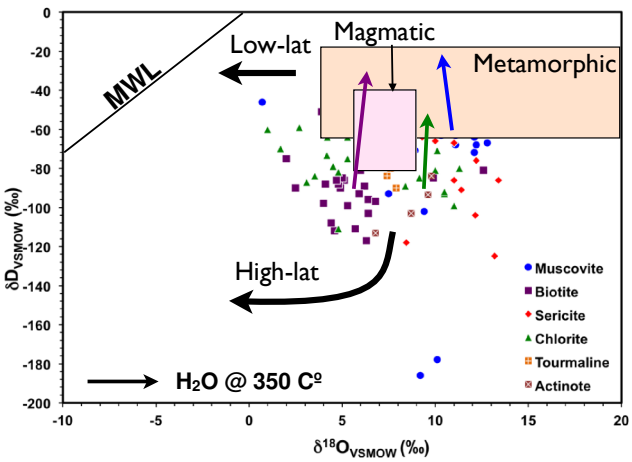
What is the reason for range in $\delta^{18}O_{quartz}$ for "orogenic" gold deposits in the Abitibi, ON?

1) fluid mixing (metamorphic-magmatic-meteoric)
2) multiple events
3) another process?

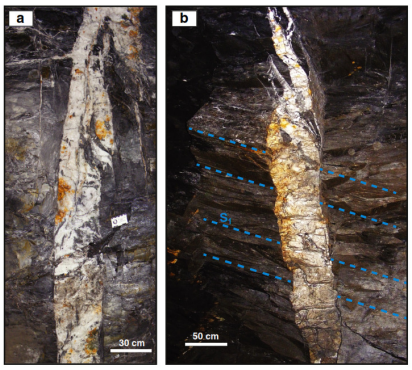
At what scale does the variation in $\delta^{18}O_{quartz}$ occur?

Stable Isotopes $\delta^{18}O_{quartz}$ and $\delta^{18}O_{H2O}$

Beaudoin SGA 2011



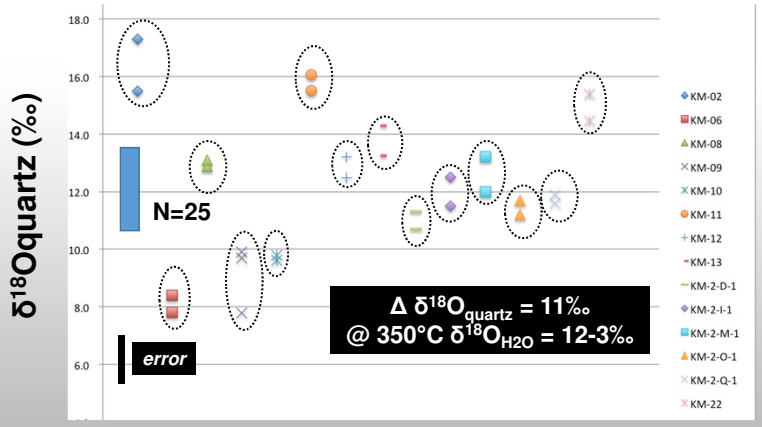
Marasala et al. 2013 Chem Geol.



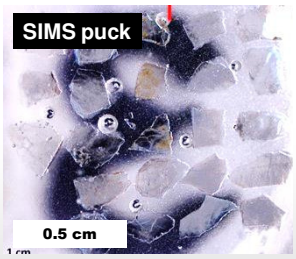
Alpine veins record mixing of metamorphic and meteoric waters

How reliable is conventional bulk $\delta^{18}O$quartz data?

Detour 58N Deposit (K. Malcolm MSc)



SIMS puck

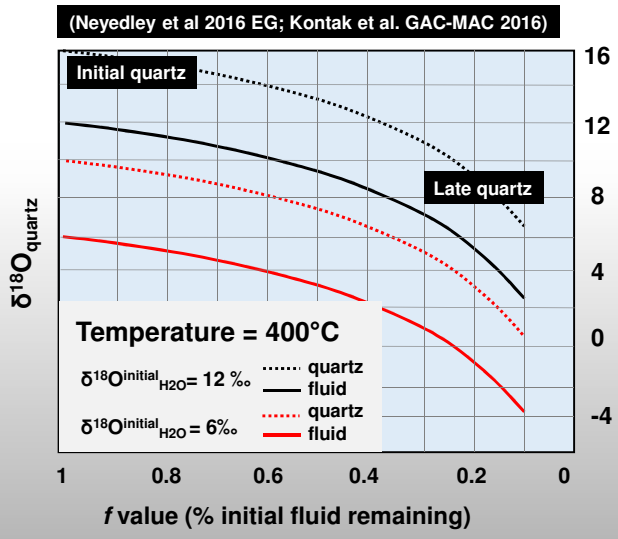


What is this range due to?

Is this the norm?

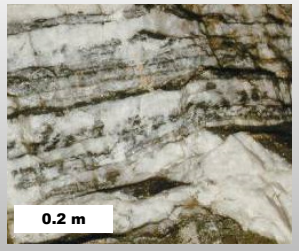
Implications for ore deposit studies?

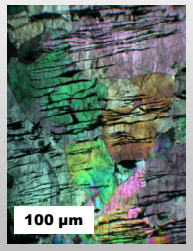
$\delta^{18}O_{quartz}$ Data: A Rayleigh Distillation Model



Where vein formation is NOT a flow-through system the fluid is distilled as quartz forms.

Conventional isotopic equilibrium invalidated - conventional bulk analysis not reliable (?)





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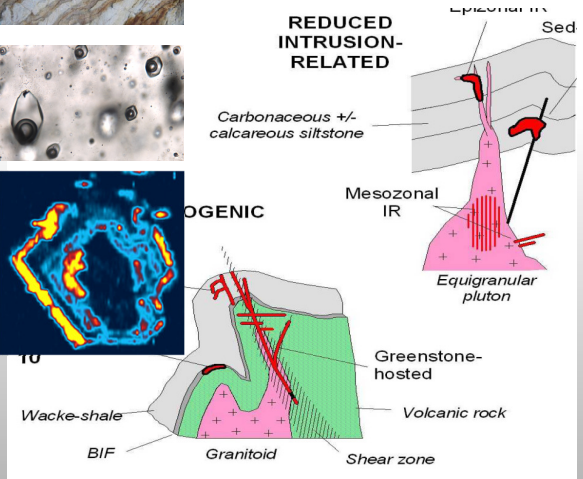
Assessing Gold Deposit Models from a Fluid-Chemistry Perspective



Field relationships define the general setting of deposits

Fluid-chemical data allows testing of models, e.g., depth of ore system

Processes can be detected (ΔP_{fluid}; fluid unmixing)

Multiple Au events (upgrading vs new Au)

Potential for using LA-ICP-MS to discriminate-vector

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