Sources of fluids, carbon and sulfur and fluid flow along the Cadillac-Larder Lake Deformation Zone

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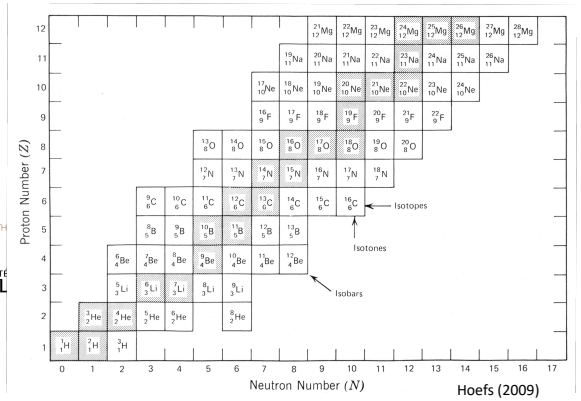
Presentation Outline

- Introduction to stable isotope geochemistry
- Stable isotope composition of orogenic gold deposits
- Sources of fluids along the Cadillac –Larder Lake Deformation Zone
- Fluid flow constraints along the Augmitto-Bouzan segment

Overview of Stable Isotope Geochemistry



Hoefs (2009)

- Stable atoms of chemical elements
- Isotopes have a different number of neutrons (N)

Overview of Stable Isotope Geochemistry

Symbol	Atomic Number Z	Neutron number N	Mass Number M	Abundance (per cent)	Atomic Weight (12C = 12.)
H	1	0	1	99.985	1.007825
D	1	1	2	0.015	2.0140
Li	3	3	6	7.42	6.01512
		4	7	92.58	7.01600
B	5	5	10	19.78	10.0129
		6	11	80.22	11.00931
C	6	6	12	98.89	≡12.
		7	13	1.11	13.00335
N	7	7	14	99.63	14.00307
		8	15	0.37	15.00011
O	8	8	16	99.759	15.99491
		9	17	0.037	16.99914
		10	18	0.204	17.99916
Si	14	14	28	92.21	27.97693
		15	29	4.70	28.97649
		16	30	3.09	29.97376
S	16	16	32	95.0	31.97207
		17	33	0.76	32.97146
		18	34	4.22	33.96786
		20	36	0.014	35.96709
Cl	17	18	35	75.53	34.96885
		20	37	24.47	36.96590

Sharp (2017)

- Several isotopes of one element
- Different abundance
- Several ratios heavy/light

Overview of Stable Isotope Geochemistry

δ value (per mil ‰); {low, high, but has no mass}

$$\delta = \left(\frac{R_x - R_{std}}{R_{std}} \right) \times 1000$$ where R is isotope ratio, e.g. $^{18}O/^{16}O$

Element	Standard	Standard
H	Standard Mean Ocean Water	V-SMOW
B	Boric acid (NBS)	SRM 951
C	Belemnitella americana from the Cretaceous Peedee formation, South Carolina	V-PDB
N	Air nitrogen	N2 (atm.)
O	Standard Mean Ocean Water	V-SMOW
Si	Quartz sand	NBS-28
S	Troilite (FeS) from the Canyon Diablo iron meteorite	V-CDT
Cl	Seawater chloride	SMOC

Hoefs (2009)

Overview of Stable Isotope Geochemistry

Mass dependent fractionation

Isotopic Equilibrium $H_2{}^{16}O + {}^{18}O = H_2{}^{18}O + {}^{16}O$

$\alpha \sim k = f$ (vibration energy)

- Temperature : $\alpha \sim 1/T2$
- Pressure : negligeable for crystals,
- Chemical composition : $SiO_2 > Fe_2O_3$ or $SO_4 > H_2S$
- Mass
- Ionic radius
- Charge
- Crystal structure : diamond > graphite

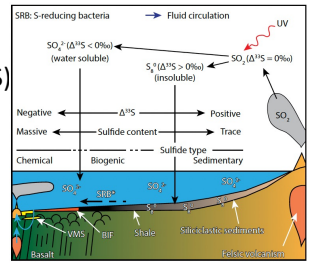
Overview of Stable Isotope Geochemistry

Kinetic Effects
- Disequilibrium
- Unidirectional
- Diffusion
- Biologic
  - Photosynthesis (e.g. C)
  - Bacterial reduction (e.g. S)

Mass Independent Fractionation (MIF)

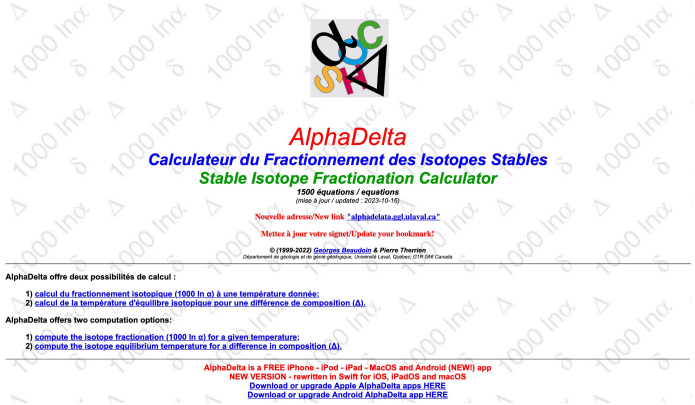
$\Delta^{17}O = \delta^{17}O - 0.53\ \delta^{18}O$ (ozone)

$\Delta^{33}S = \delta^{33}S - 0.515\ \delta^{34}S$ (UV light)



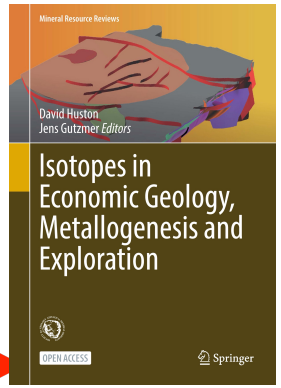
Virnes et al. (2024)

Overview of Stable Isotope Geochemistry



Stable Isotope Composition of Orogenic Gold Deposits

- 16 chapters
- Range of deposit types
- Dating
- Radiogenic isotopes
- Stable isotopes
- Metal stable isotopes




The Light Stable Isotope (Hydrogen, Boron, Carbon, Nitrogen, Oxygen, Silicon, Sulfur) Composition of Orogenic Gold Deposits

Benoît Quesnel, Christophe Scheffer, and Georges Beaudoin

Abstract

Orogenic gold deposits formed in various terranes of most ages since the Paleoarchean and generally consist of quartz veins hosted in shear zones formed at the ductile brittle transition under greenschist to lower amphibolite metamorphic conditions. Vein mineralogy is dominated by quartz with various amounts of silicates, carbonates, phyllosilicates, borates, tungstates, sulfides, and oxides. The isotopic composition of these minerals and fluid inclusions has been investigated since the 1960s to constrain the characteristics of orogenic fluid systems involved in the formation of gold deposits worldwide. This review is based on 8580 stable isotope analyses, including $\delta^{18}O$, δD, $\delta^{13}C$, $\delta^{34}S$, $\delta^{15}N$, $\delta^{11}B$, and $\delta^{30}Si$ values, from 5478 samples from 558 orogenic gold deposits reported in the literature from 1960 to 2010.

This contribution describes the variability of the light stable isotopic systems as function of the minerals, the age of the deposits, their regional setting, and their country rocks. The temperature of isotopic equilibrium of orogenic gold veins is estimated from mineral pairs for oxygen and sulfur isotopes. Based on these temperatures, and on fractionation between mineral and fluid components (H_2S, CO_2, and H_2S), the isotopic composition of fluids is estimated to better constrain the main parameters shared by most of auriferous orogenic fluid systems. Orogenic gold deposits display similar isotopic features through time, suggesting that fluid conditions and sources leading to the formation of orogenic gold deposits did not change significantly from the Archean to the Cenozoic. No consistent secular variations of mineral isotope compositions for oxygen ($-8.1‰ \leq \delta^{18}O \leq 33‰$, n = 4011), hydrogen ($-187‰ \leq \delta D \leq -45‰$, n = 246), carbon ($-26.7‰ \leq \delta^{13}C \leq 12.7‰$, n = 1179), boron ($-21.6‰ \leq \delta^{11}B \leq 9‰$, n = 119), and silicon ($-0.5‰ \leq \delta^{30}Si \leq 0.8‰$, n = 33) are documented. Only nitrogen ($1.6‰ \leq \delta^{15}N \leq 23.7‰$, n = 258) and sulfide sulfur from deposits hosted in sedimentary rocks ($-27.2‰ \leq \delta^{34}S \leq 25‰$, n = 717) display secular variations. For nitrogen, the change in composition is interpreted to record the variation of $\delta^{15}N$ values of sediments devolatilized during metamorphism. For sulfur, secular variations reflect

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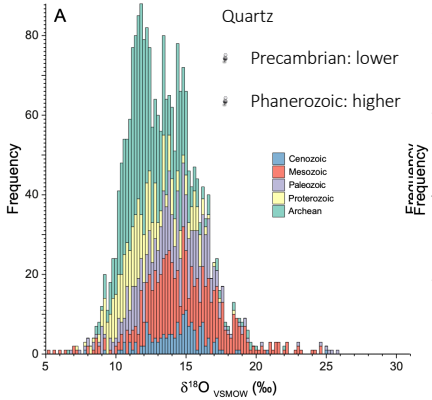
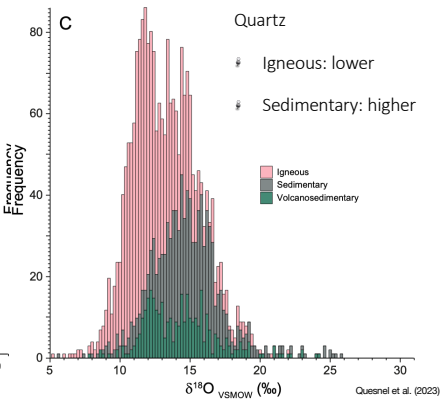
241

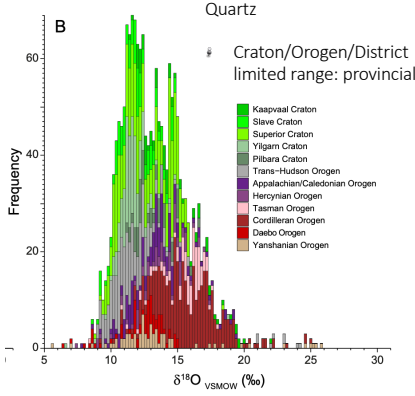
Stable Isotope Composition of Orogenic Gold Deposits

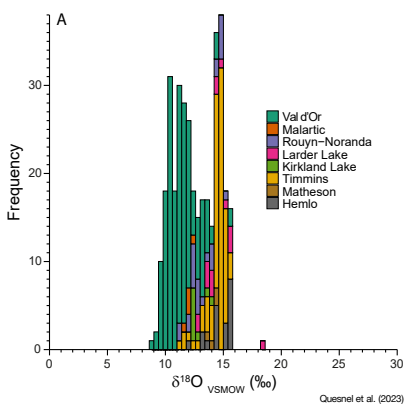




Quesnel et al. (2023)

Stable Isotope Composition of Orogenic Gold Deposits





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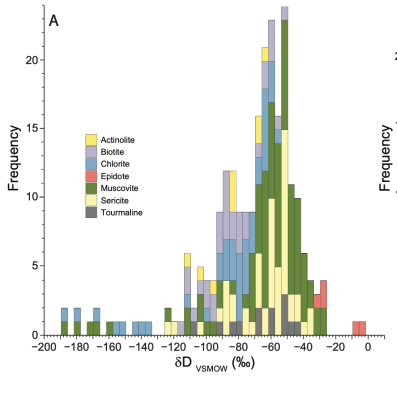
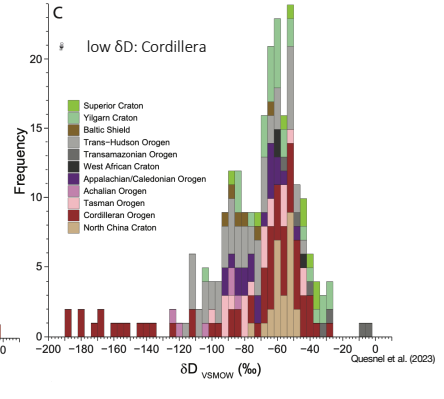
Stable Isotope Composition of Orogenic Gold Deposits





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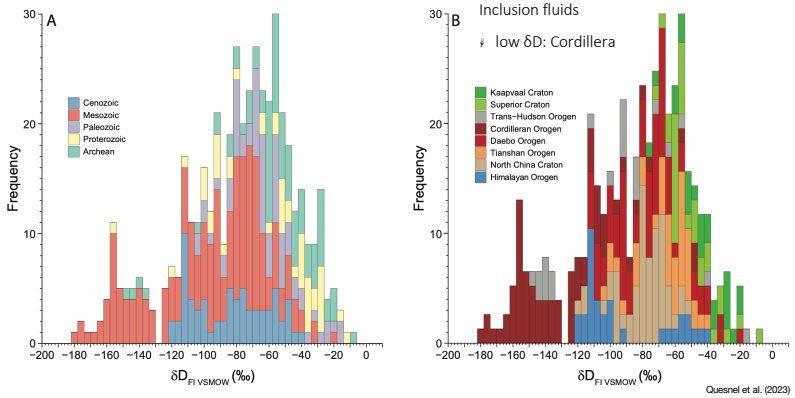
Stable Isotope Composition of Orogenic Gold Deposits

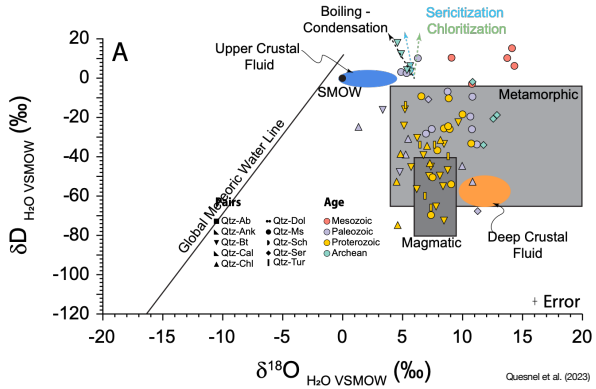


Inclusion fluids

- low δD: Cordillera

Quesnel et al. (2023)

Stable Isotope Composition of Orogenic Gold Deposits

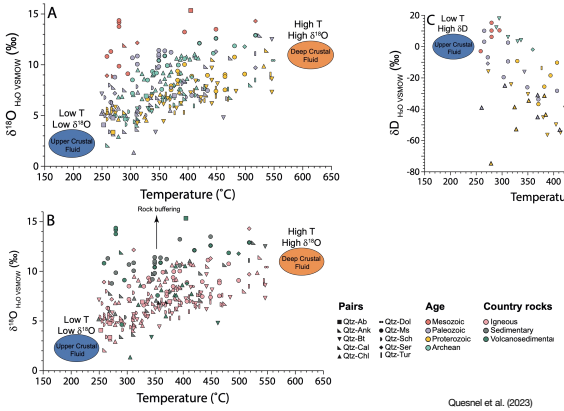


Water composition

- largely metamorphic
- magmatic permissible
- high δD: boiling or mica alteration

Quesnel et al. (2023)

Stable Isotope Composition of Orogenic Gold Deposits

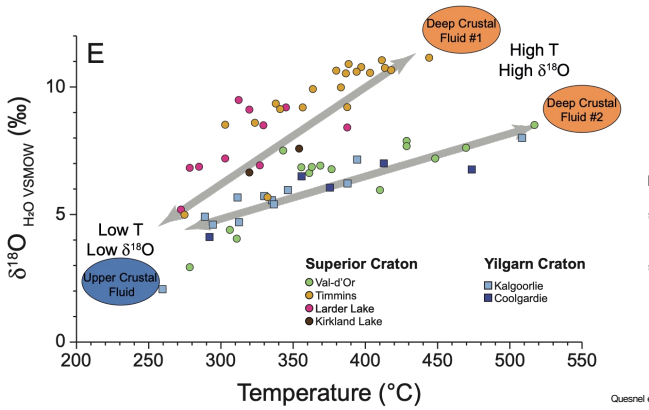


Mixing 2 common reservoirs

- deep-crustal metamorphic
- upper crustal, exchanged meteoric/sea water

Quesnel et al. (2023)

Stable Isotope Composition of Orogenic Gold Deposits

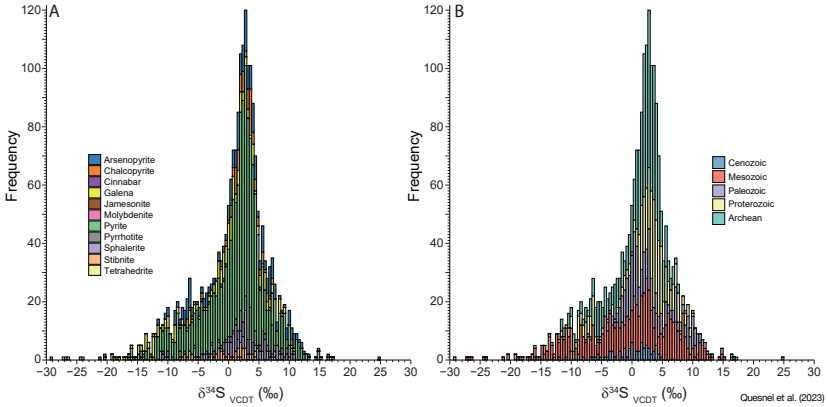


Mixing 2 reservoirs

- provinciality of deep-crustal metamorphic
- common upper crustal

Quesnel et al. (2023)

Stable Isotope Composition of Orogenic Gold Deposits



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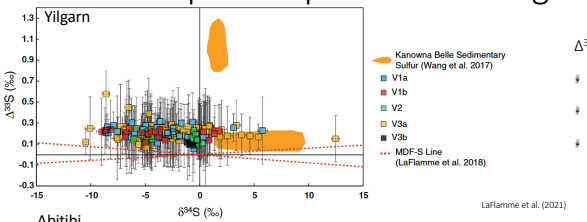
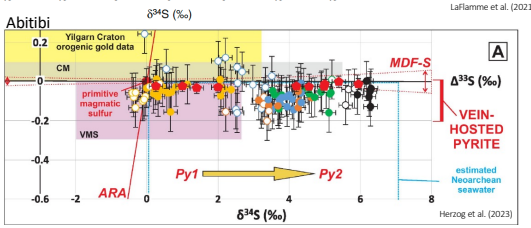
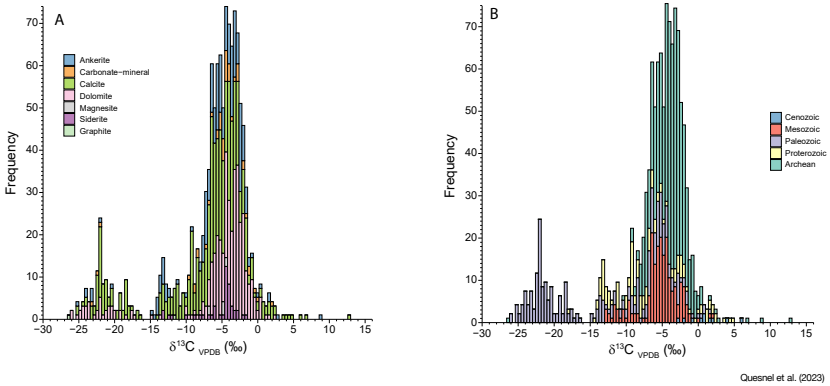




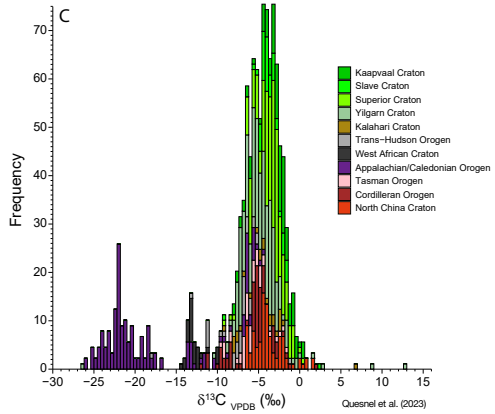
$\Delta^{33}S$

- Homogeneous S reservoir
- + $\Delta^{33}S$: S_8-sedimentary pyrite
- - $\Delta^{33}S$: seawater sulfate-volcanic sulfides

Stable Isotope Composition of Orogenic Gold Deposits



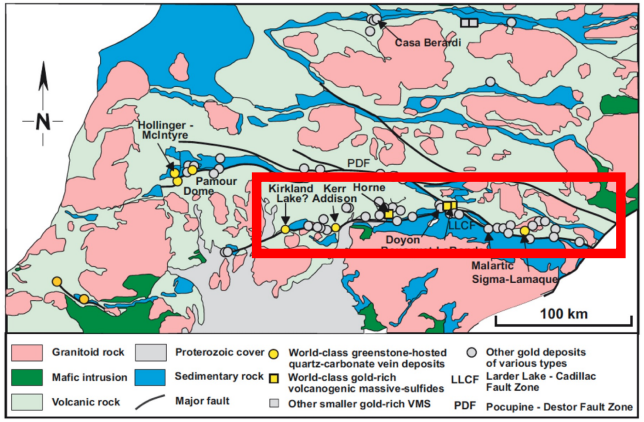
Stable Isotope Composition of Orogenic Gold Deposits



Low $\delta^{13}C$

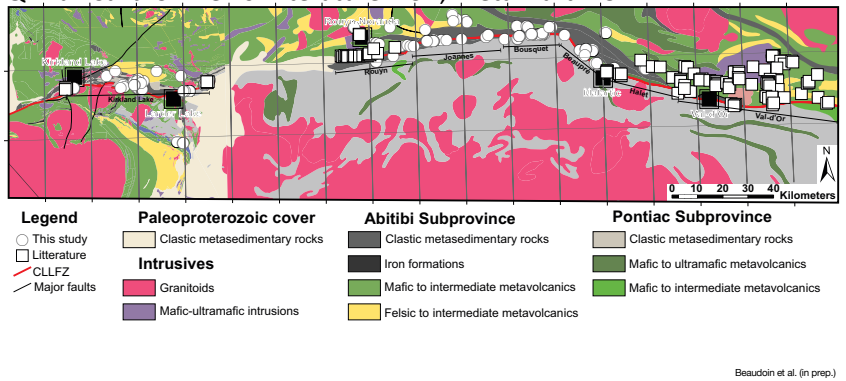
- Appalachian/Caledonian
- Corg-rich sedimentary rocks

Sources of fluids along the CLLDz



Sources of fluids along the CLLDz

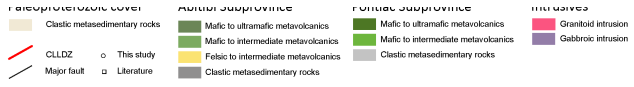
Qz-Tur-Carb-Chl veins. Literature: 291; Metal Earth: 317



Beaudoin et al. (in prep.)

Sources of fluids along the CLLDz

Données non-publiées



Beaudoin et al. (in prep.)

Change in fluid composition at inflexion in orientation of the CLLDz, west of Malartic

Sources of fluids along the CLLDz

N

Données non-publiées

No systematic temperature variation along strike

Beaudoin et al. (in prep.)

Sources of fluids along the CLLDz

Données non-publiées

Beaudoin et al. (in prep.)

Change in fluid composition at inflexion in orientation of the CLLDz, west of Malartic

Sources of fluids along the CLLDz

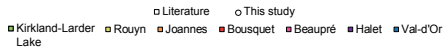
Metamorphic fluids
- Boiling
- Mica alteration

Données non-publiées

Beaudoin et al. (in prep.)

Sources of fluids along the CLLDz

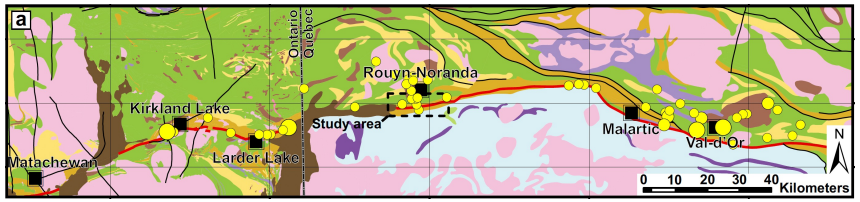
Données non-publiées



One common Upper Crustal fluid, 2 slightly different Metamorphic fluids, both auriferous

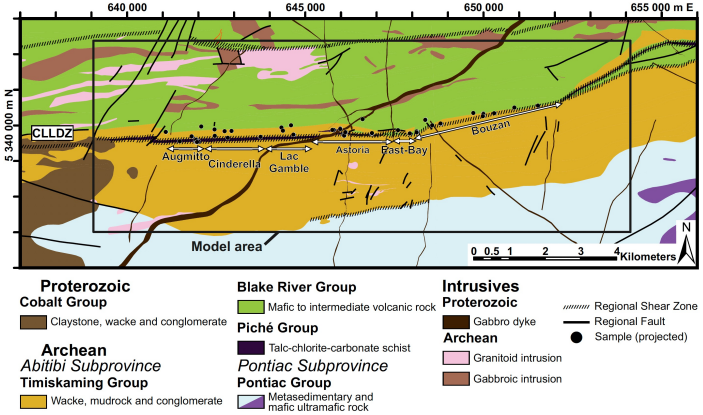
Beaudoin et al. (in prep.)

Fluid Flow Constraints, Augmitto-Bouzan



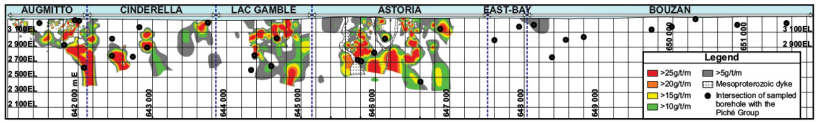
Raymond et al. (2024)

Fluid Flow Constraints, Augmitto-Bouzan



Raymond et al. (2024)

Fluid Flow Constraints, Augmitto-Bouzan



Raymond et al. (2024)

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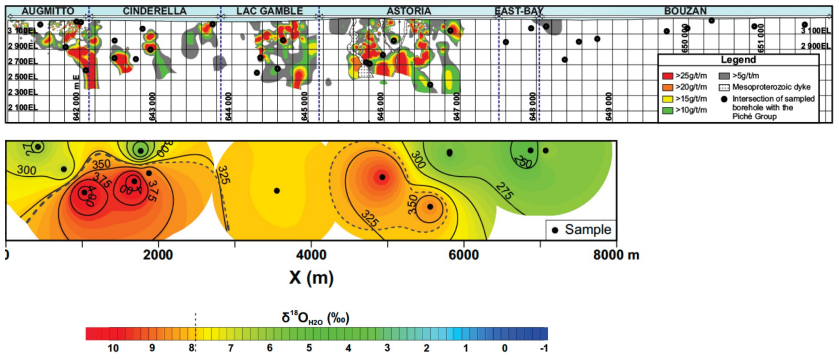
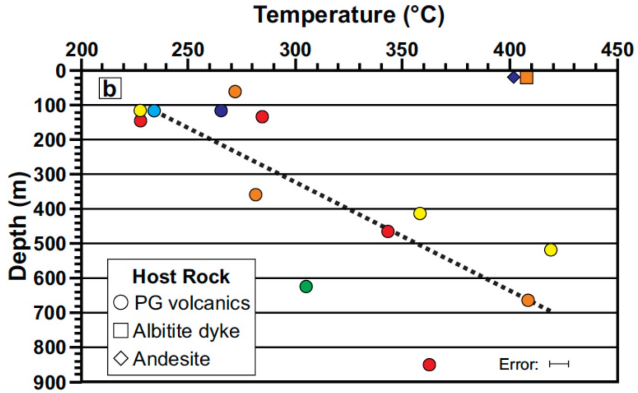


Raymond et al. (2024)

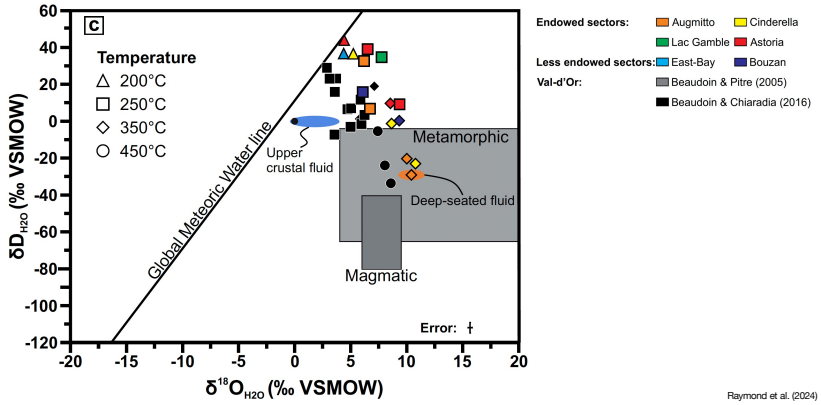
Fluid Flow Constraints, Augmitto-Bouzan



Temperature gradient: 30ºC/100 m

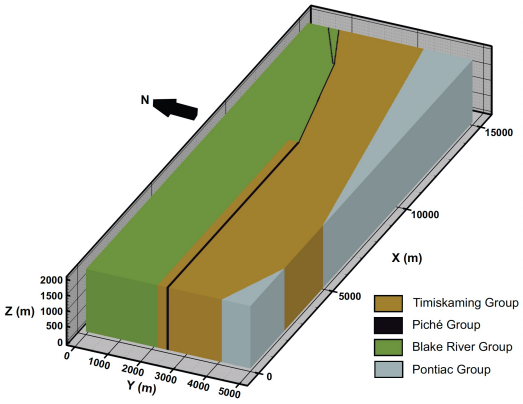
Raymond et al. (2024)

Fluid Flow Constraints, Augmitto-Bouzan



Raymond et al. (2024)

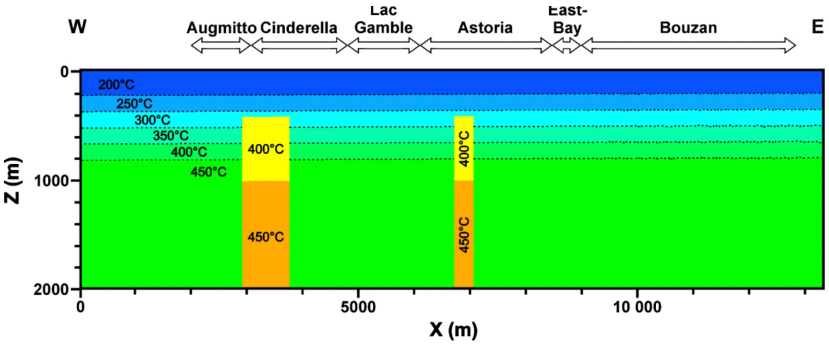
Fluid Flow Constraints, Augmitto-Bouzan



- 3D model, coupled advective-dispersive mass transport and oxygen isotope exchange (HydroGeoSphere)
- Each unit has representative hydraulic properties

Raymond et al. (2024)

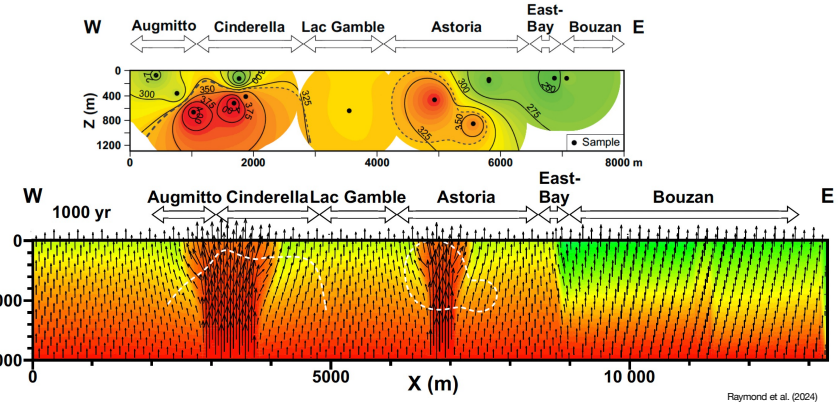
Fluid Flow Constraints, Augmitto-Bouzan



Temperature and permeability in plane of CLLDz

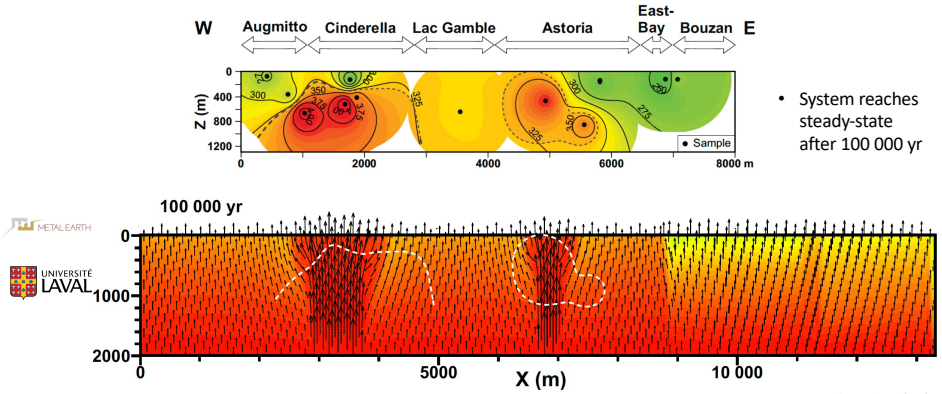
Raymond et al. (2024)

Fluid Flow Constraints, Augmitto-Bouzan



Raymond et al. (2024)

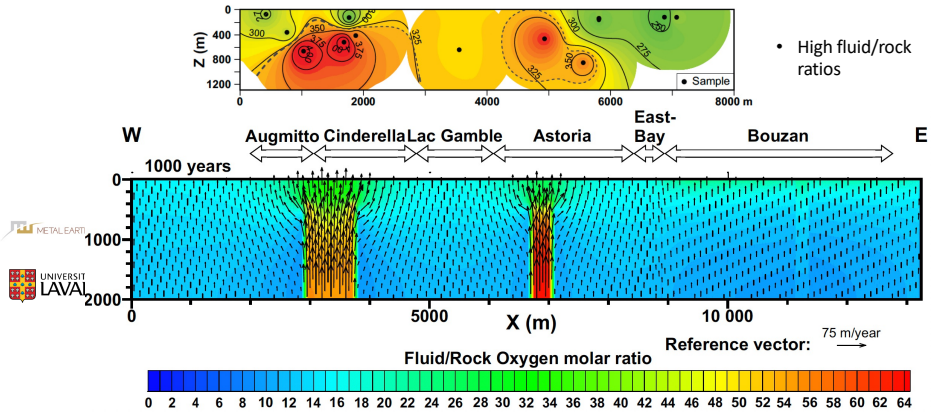
Fluid Flow Constraints, Augmitto-Bouzan



- System reaches steady-state after 100 000 yr

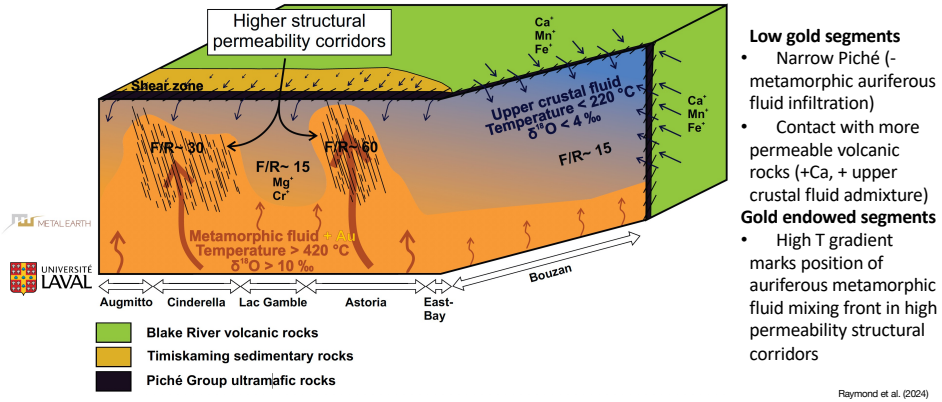
Raymond et al. (2024)

Fluid Flow Constraints, Augmitto-Bouzan



- High fluid/rock ratios

Fluid Flow Constraints, Augmitto-Bouzan



Low gold segments

- Narrow Piché (- metamorphic auriferous fluid infiltration)
- Contact with more permeable volcanic rocks (+Ca, + upper crustal fluid admixture)

Gold endowed segments

- High T gradient marks position of auriferous metamorphic fluid mixing front in high permeability structural corridors

Raymond et al. (2024)

Summary: Crustal-scale hydrogeology model

Données non-publiées

- Deep-seated auriferous metamorphic fluids mixing with poral upper crustal fluids
- Vertical advection of higher-temperature deep-seated fluids in the structural conduits
- Provinciality of auriferous metamorphic fluids, even along the same structural corridor