Genetic models of orogenic Au deposits depend on datasets collected at the large and small scales

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Toulouse, Ecole Thematique Ressources 2016

Talk objectives

1. **Show some relevant small- and large-scale characteristics of orogenic Au deposits;**
2. **Show how these characteristics constrain genetic models of orogenic deposits**

Collaborations

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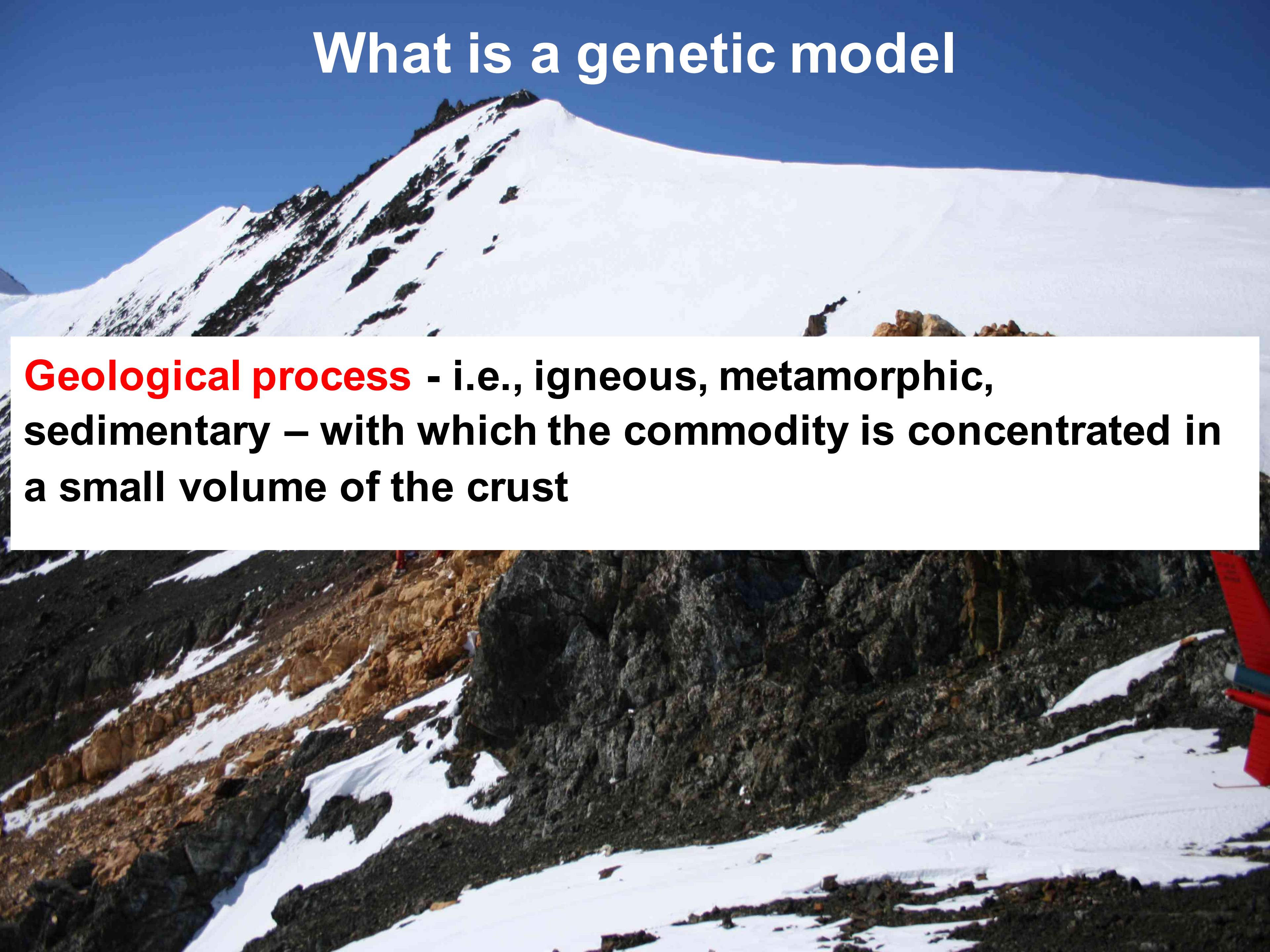
Unesco-IGCP Project No. 540

United Nations Educational, Scientific and Cultural Organization

What is a genetic model

Geological process - i.e., igneous, metamorphic, sedimentary – with which the commodity is concentrated in a small volume of the crust



Orogenic deposits

DEFINITION

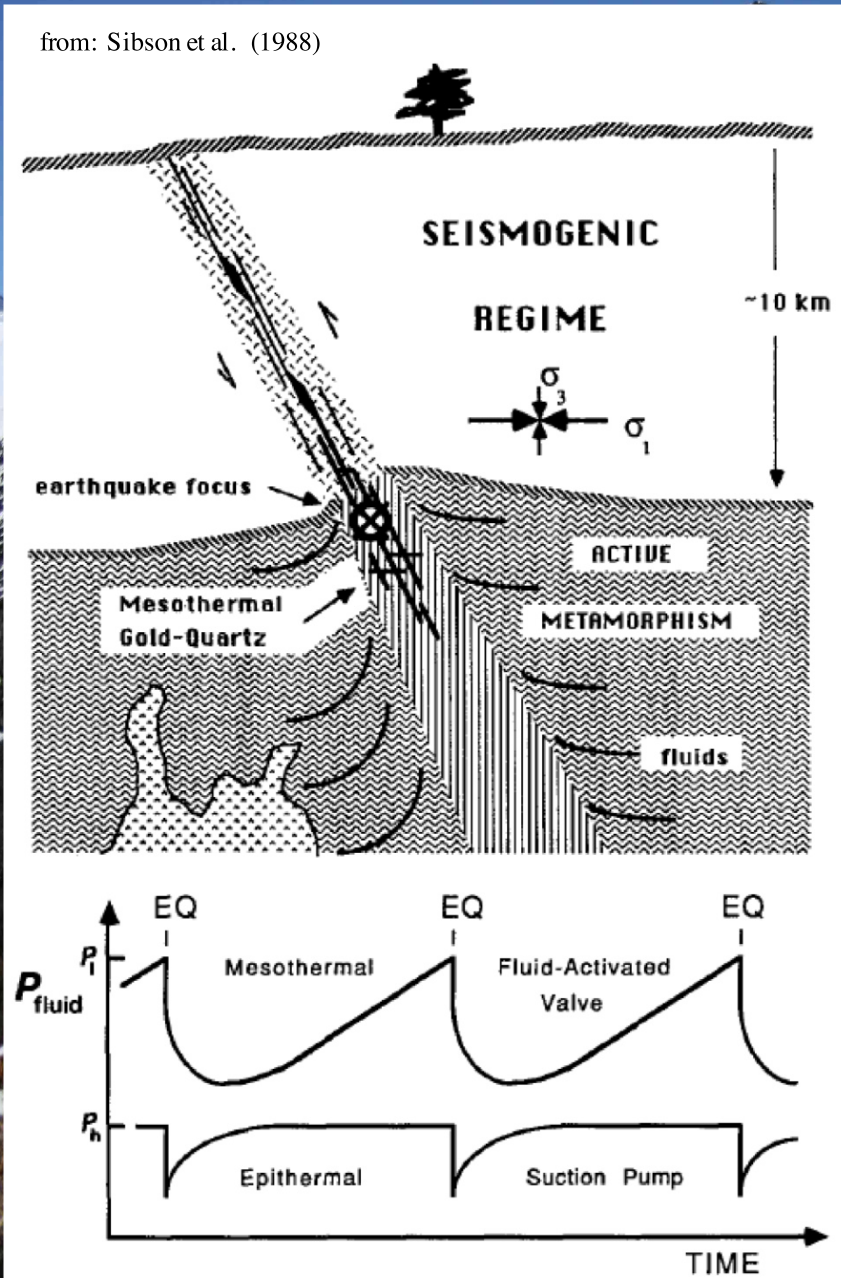
Fracture networks filled by quartz, carbonates, sulfides and variable quantities of Au (grade ~ 0-100 g/t) formed along convergent margins during terrane accretion, translation, or collision.

Orogenic deposits are peculiar fracture networks of orogenic belts ...

- **About 30% of global Au production**
- **Typical: <7.5 t Au; Large: 7.5-30 t; World class: >100 t; Giant: >250 t Au**

- **Orogenic = Mesothermal = Vein-hosted quartz-carbonate = Greenstone-hosted**

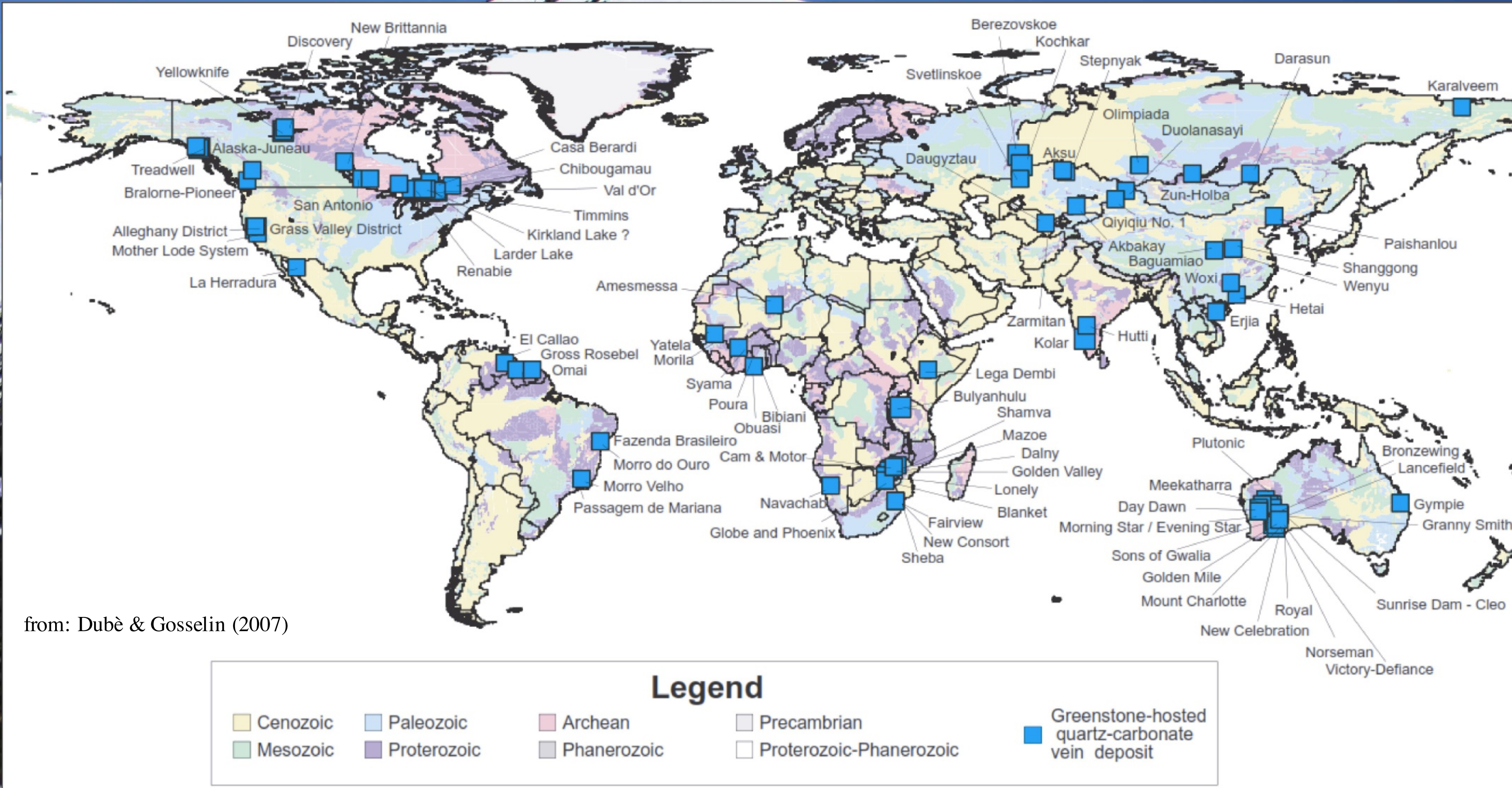
Accepted genetic model



Faults as "valves"

- Based on "friction theory" and field data;
- Fracture networks behave as "valves" that allow cyclic flux of (Au-bearing) geological fluids during EARTHQUAKES;
- Fracture networks record several seismic events

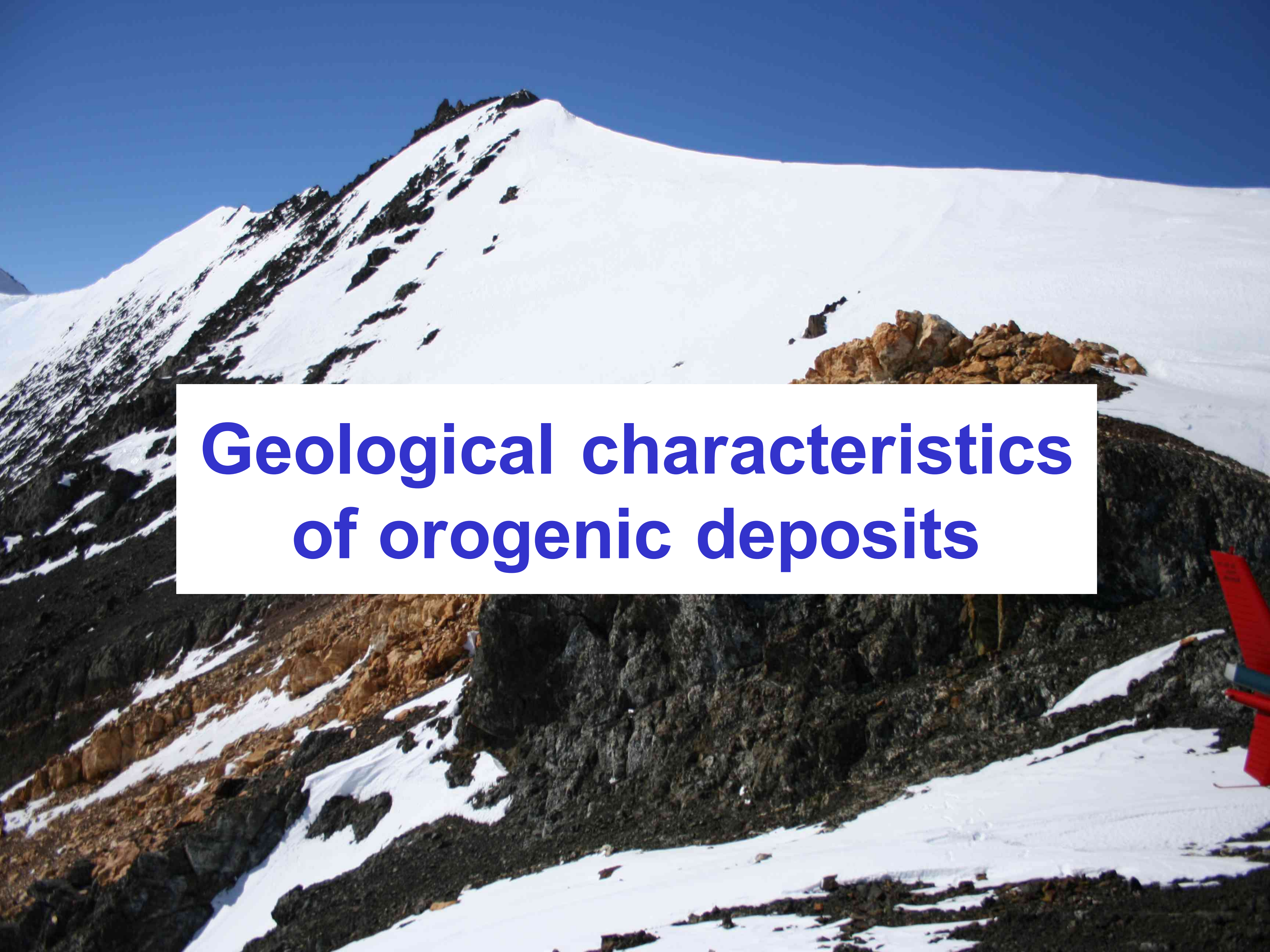
Where orogenic deposits are located



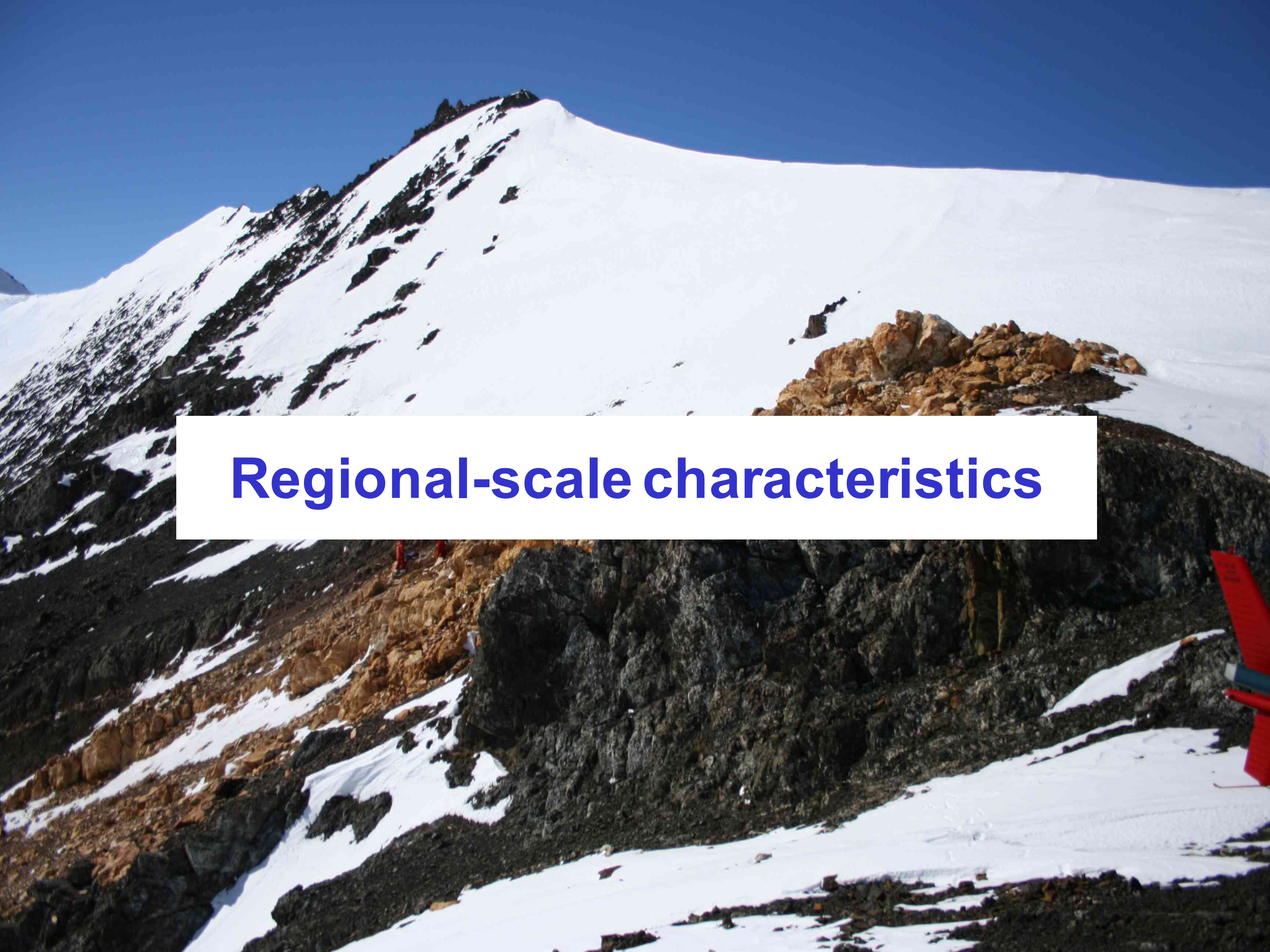
from: Dubè & Gosselin (2007)

Recent discovery: Dorn (N Victoria Land, Antartica)

Geological characteristics of orogenic deposits



Regional-scale characteristics

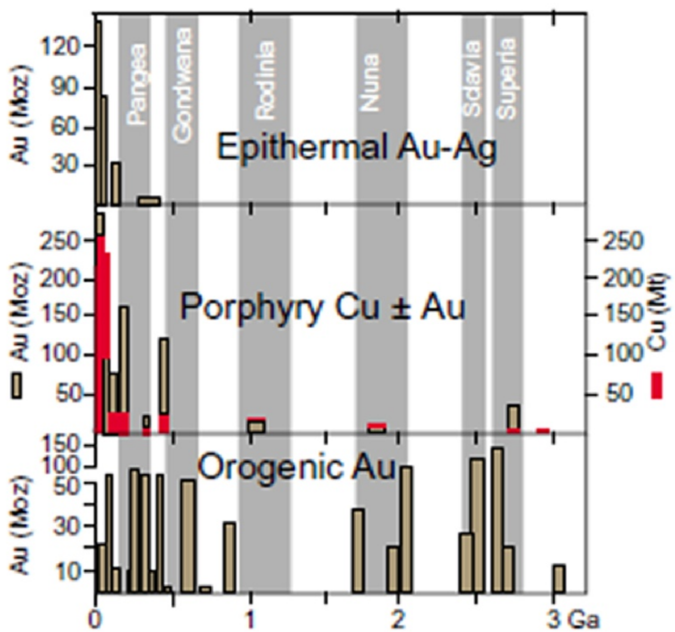


Main characteristics

1. Fracture networks whithin seismogenic regions of the crust and crosscuting all rock types (facies: greenschist – amphibolite)
2. Veins fill shear zones of ductile and brittle-ductile behaviour, and are locally associated with tectonic breccias and extensional open-space filling fractures*;*
3. Age of fractures: syn-deformation of host rocks, from syn- to late-metamorphic;
4. Gold mainly hosted within fractures (veins), in part also in the host rocks;
5. Hydrothermal alteration dominated by carbonate-sericite (sulf-turm-ap)

Age and production of largest deposits

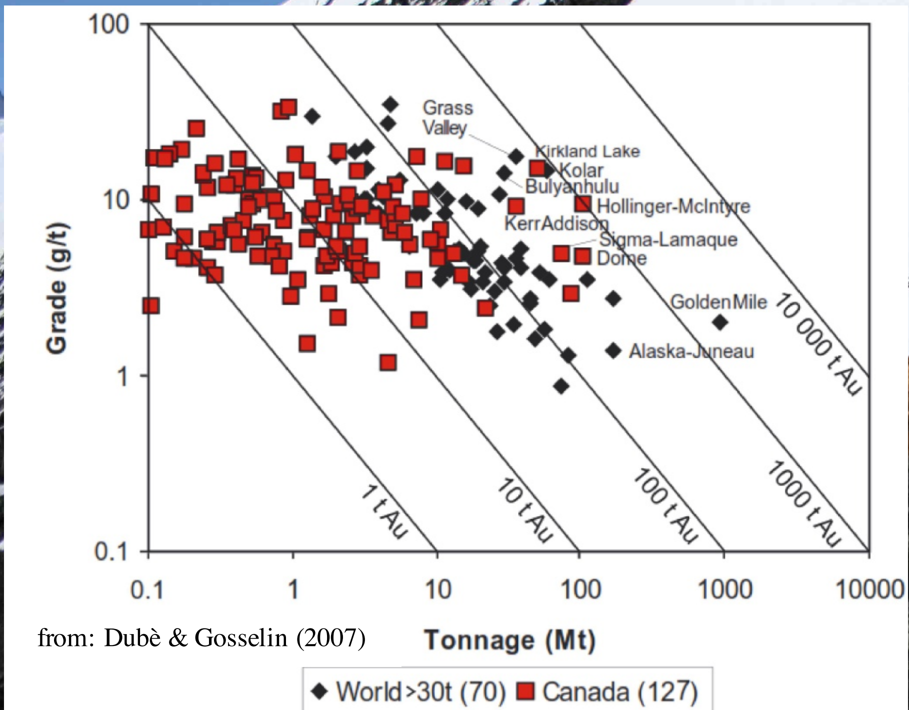
from: Cawood & Hawkesworth (2014)



- Age: from meso-Archean to Tertiary;
- Formation is episodic, in striking coincidence with formation of supercontinents (not evident for other deposit types);
- Distribution of mineral deposits would reflect balance between mineral deposits generated during established stages of convergence, collision and breakup of supercontinents (e.g., Pangea, Gondwana, Nuna) and the preservation potential of these stages;

- Depth of formation of deposits impact on their long-term survival within the rock record. High-level deposits have poor long-term survival record, especially in environments that undergo fast/active exhumation;

Typical grades and tonnage

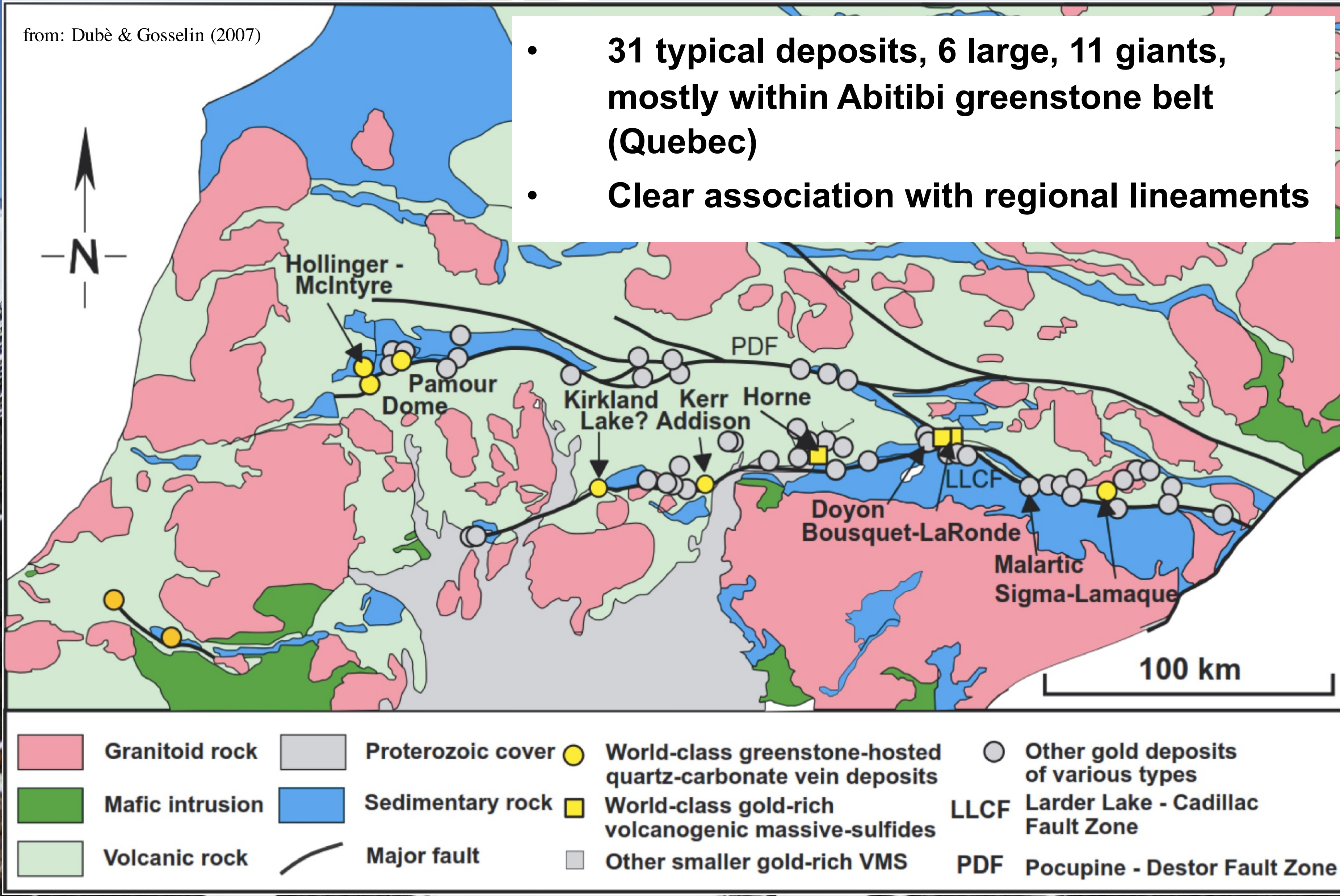


from: Dubè & Gosselin (2007)

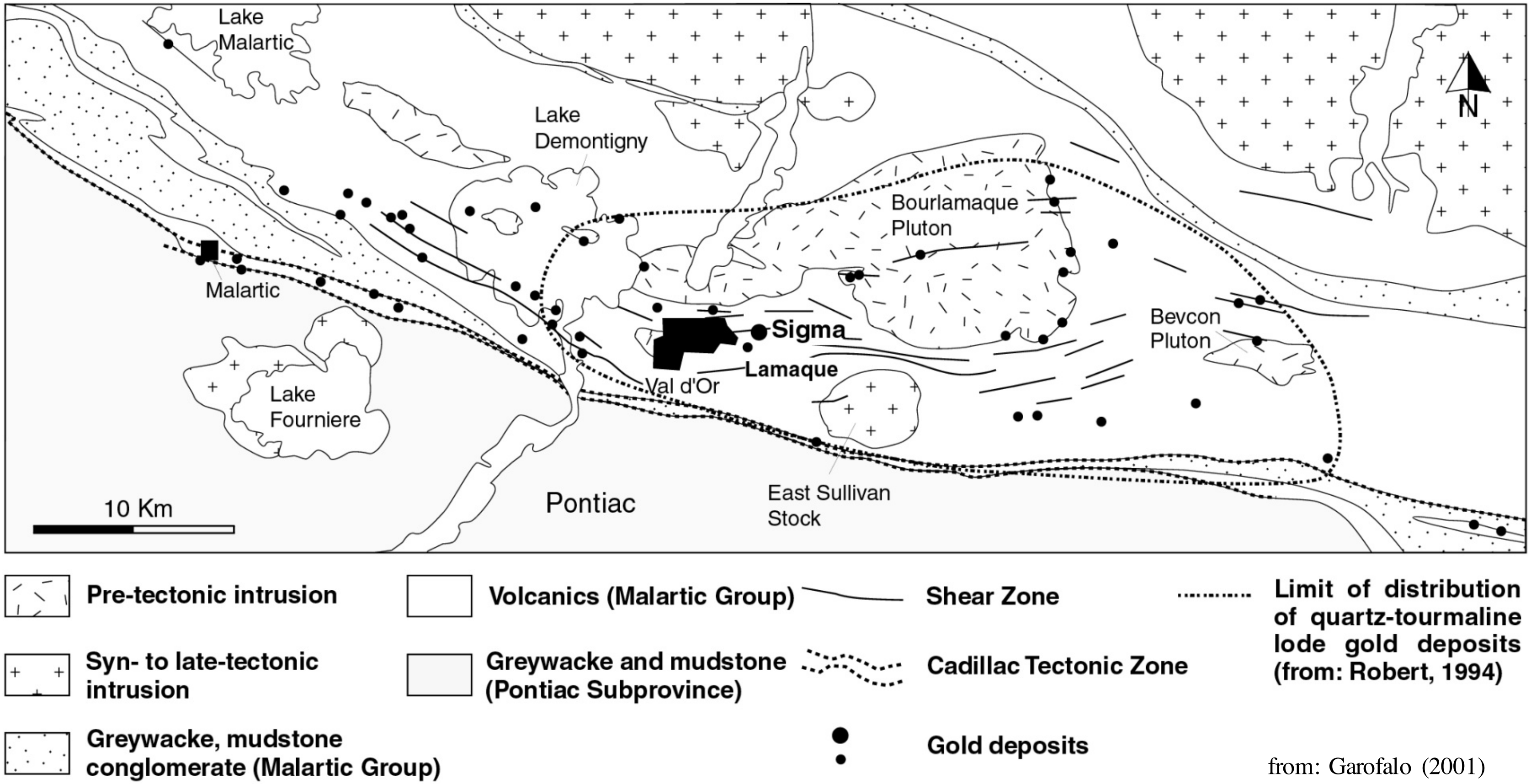
- Although most of the deposits have grades between 5 and 15 g/t Au, the tonnage of ore bodies vary between several orders of magnitude;
- Only few deposits have tonnage > 100t Au. The reasons for this “selection” is essentially unknown (particular fracture networks? host rocks? ...)

The Archean deposits of Canada

- 31 typical deposits, 6 large, 11 giants, mostly within Abitibi greenstone belt (Quebec)
- Clear association with regional lineaments



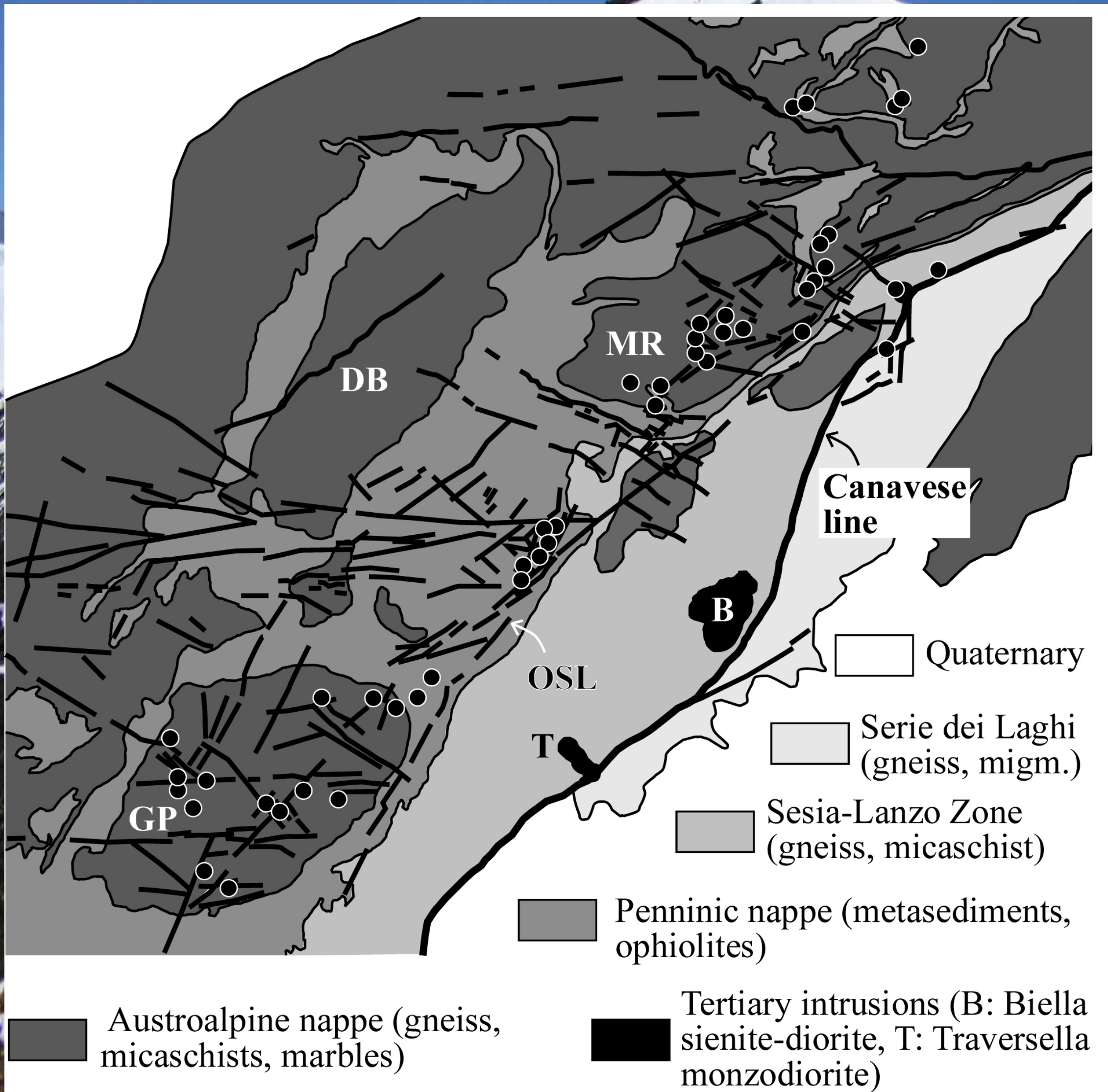
The Val d'Or district (Quebec)



from: Garofalo (2001)

- More than 20 Au-mineralized shear zones, 100 Moz Au extracted during last century (>8000 t Au), 360 deposits of various sizes
- Tourmaline main mineral in >40 deposits located around Bourlamaque pluton (diorite/qtz diorite; pre-mineralization in age)

Tertiary deposits of the W Alps



from: Garofalo (in prep.)

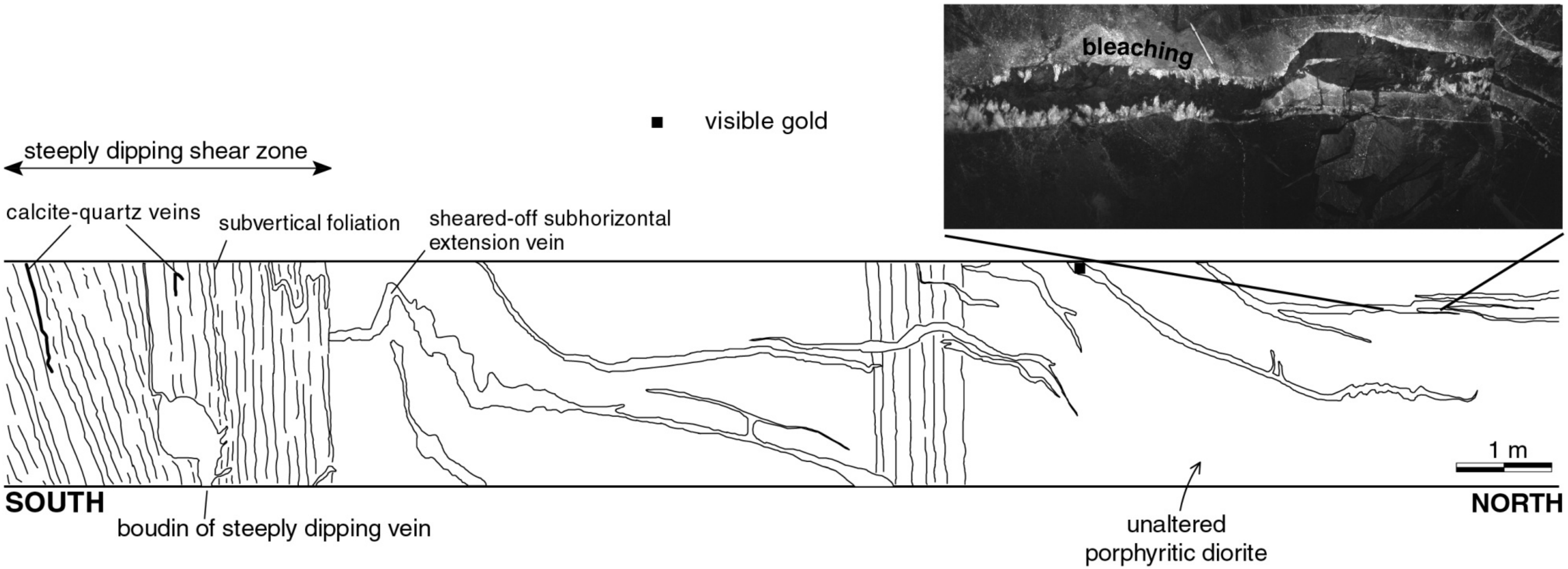
- **About 40 deposits, mostly located between the Gran Paradiso and M.te Rosa massives;**
- **Total documented production: ca. 31 t;**
- **Most important mine: Pestarena, M.te Rosa;**
- **Age: Tertiary – from c. 31.6 Ma to c. 10.6 Ma, with systematic younging from S to N**

Deposit scale characteristics

Typical orogenic fractures (veins)

Association between shear and extentional veins (Sigma, Quebec)

modified from: Garofalo (2004)



Data to consider

1. Network morphology (topology) and dimensions
2. Gold grade distribution within network
3. Vein textures
4. Mineralogy
5. Host rocks
6. Hydrothermal alteration

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2. **Gold grade distribution within network**
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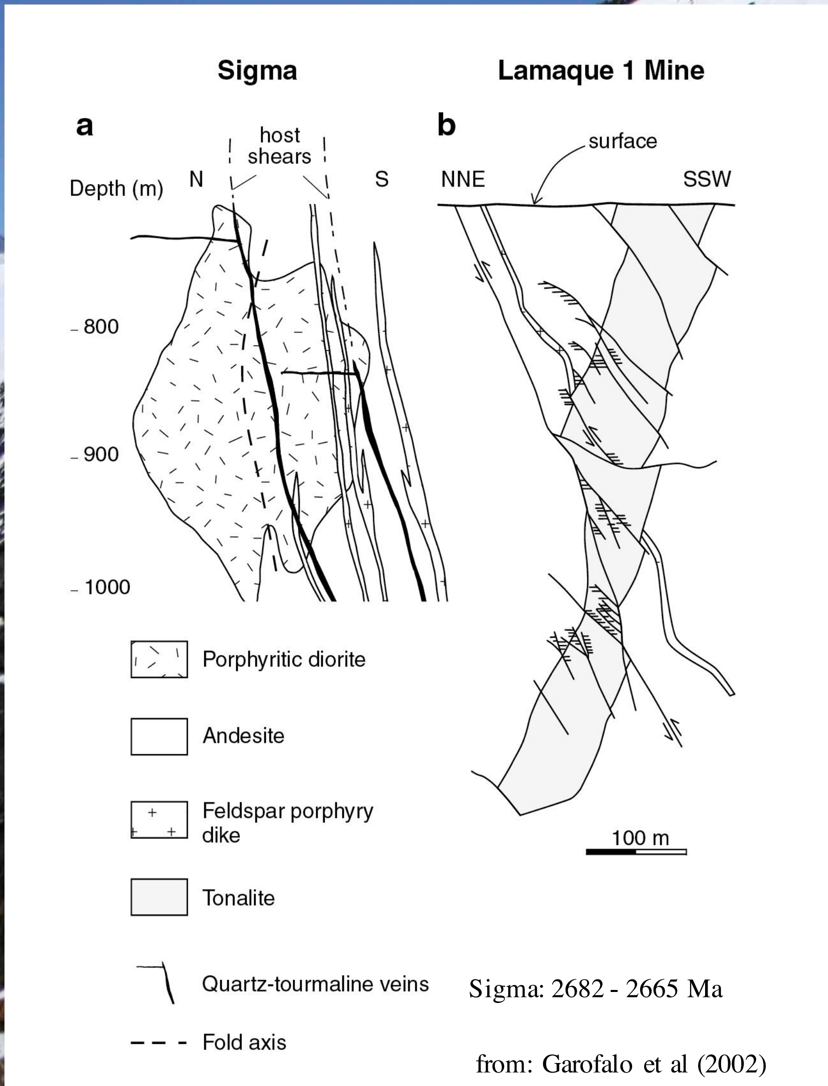
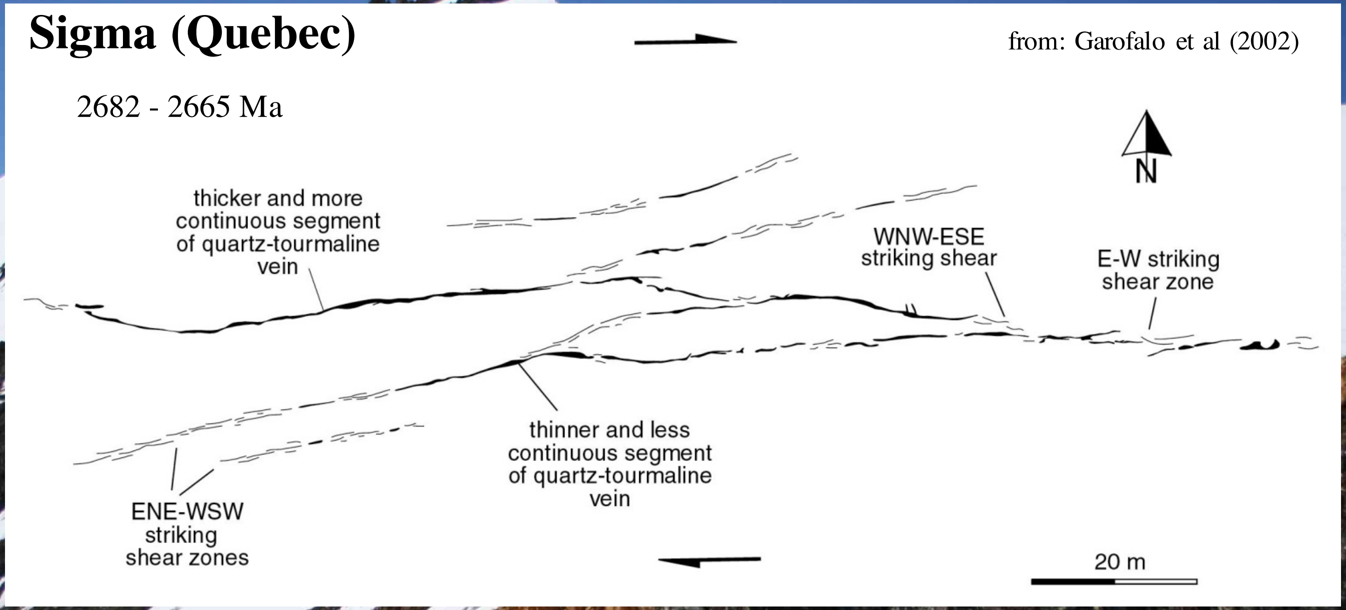
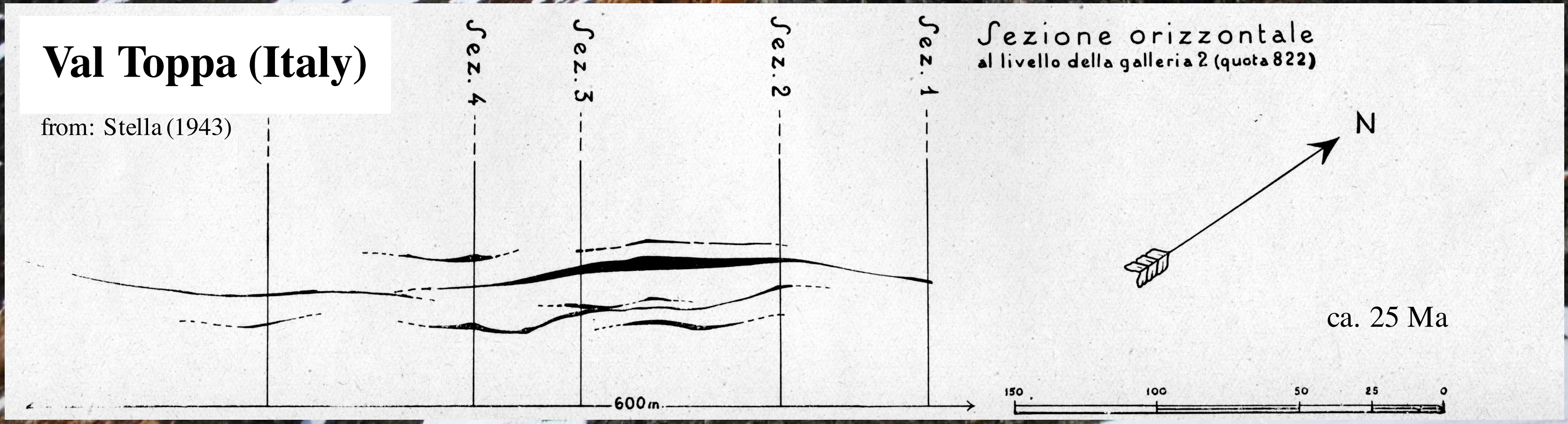
Vertical dimensions of shear zones



- **In large deposits, the continuity of fracture network at x00 m scale (*i.e.*, lateral extent, vertical dimension, thickness) determines ore body dimensions**
- **Sigma: ~2 km vertical, max 2 km horizontal. Thickness: max 4-5 m**
- **Network topology (*i.e.*, interconnections, concavities) controls Au grade distribution**
- **Anastomosed and discontinuous (segmented) shear veins and subhorizontal veins**

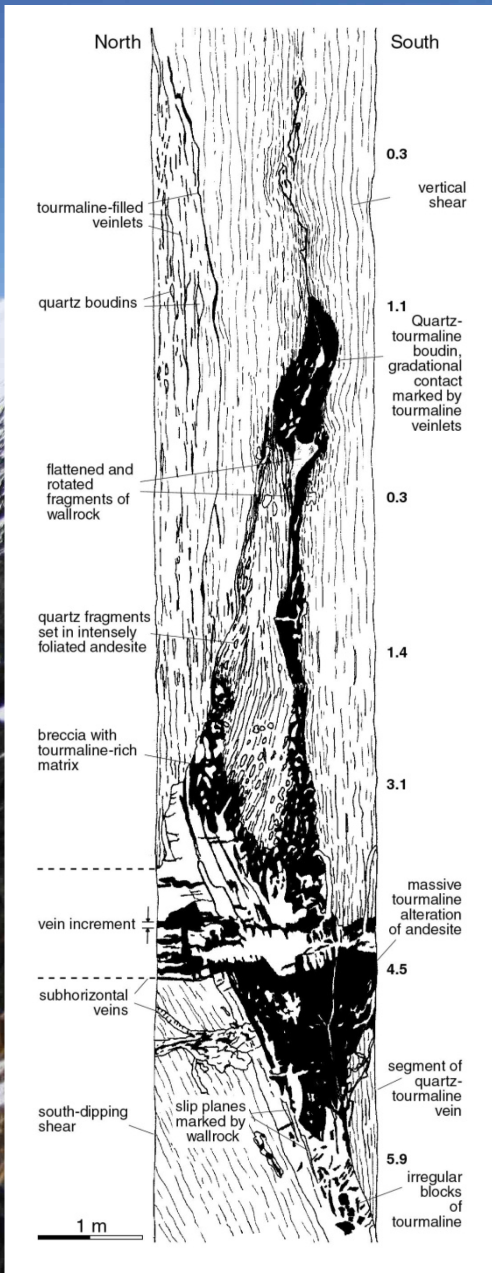
Horizontal dimensions of shear zones





- Characteristic and similar shear zone morphology in radically different deposits: common transpressive environment

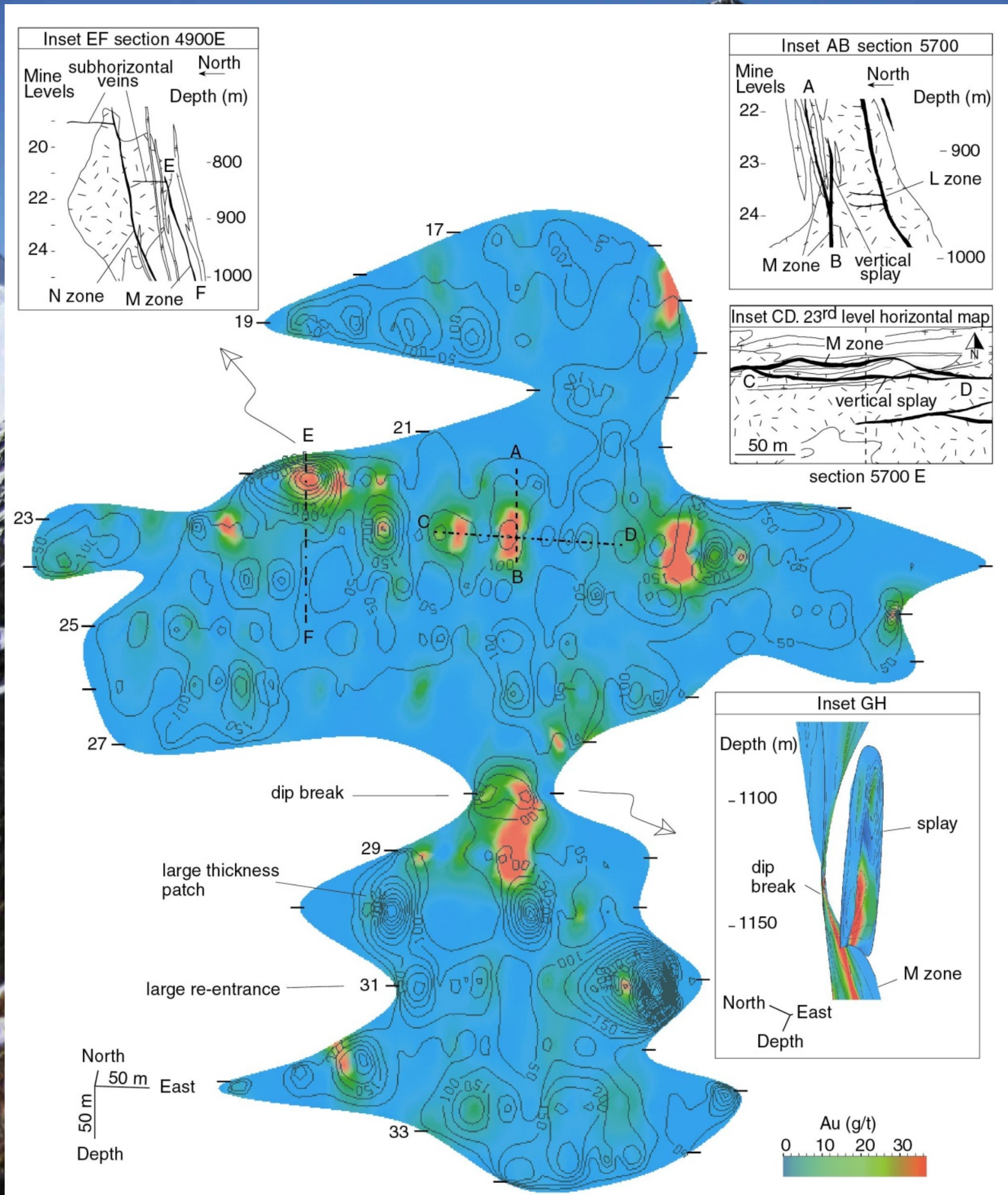
Morphology and dimensions of shear zones



from: Garofalo et al (2002)

- **Many shear zones are brittle-ductile and contain a network of subvertical shear veins, which show boudinage, drag folding, and brecciation**
- **Shear zones are much larger than shear veins, which occupy systematically the most dilated sections of the shear zones**
- **Several vein sets are <u>conjugated</u>. Extensional veins resolve stress occurring at tips of shear veins, and breccias mark terminations**
- **Sigma: the highest Au grades of the Au-mineralized qtz-turm-carb veins are found at the interconnection between distinct vein types**

The Sigma "M zone"

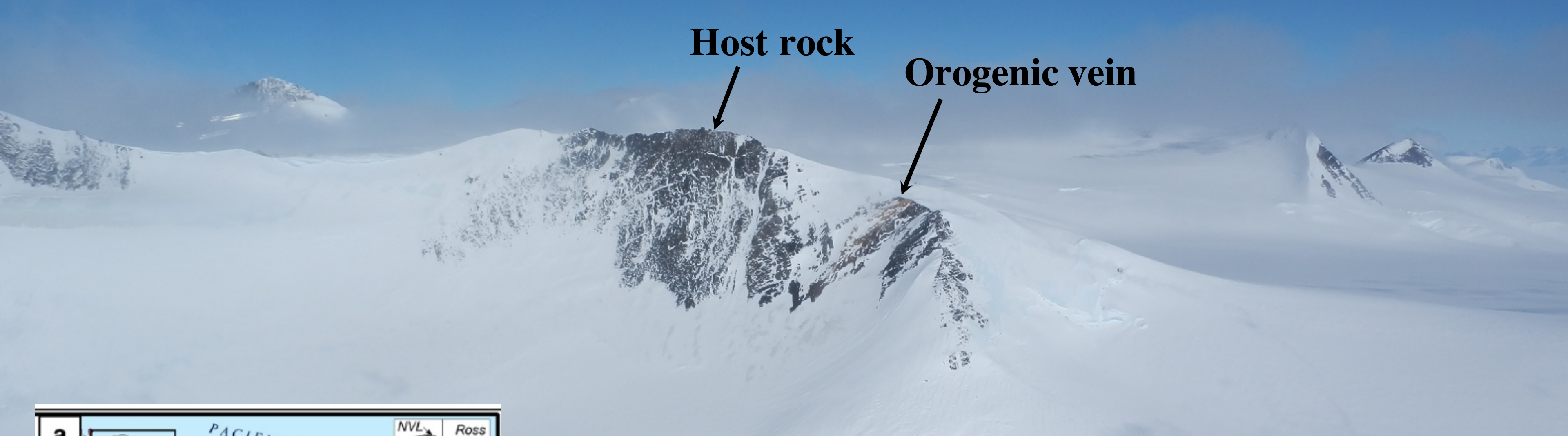


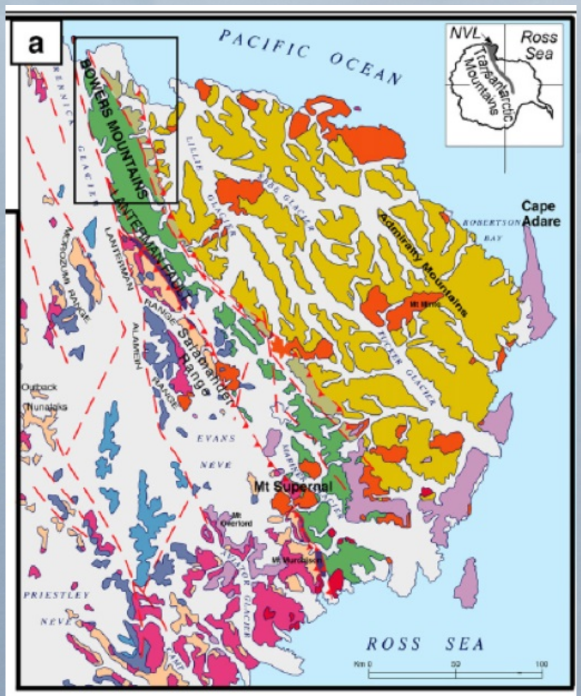
- Largest shear vein
- Dimensions: L_{oriz} max = 850 m; L_{vert} max = 914 m
- Strongly non-isometric and with clear *dip break*
- Characteristic elongate thicker zones (patches) interpreted as products of coalescence of isolated vein segments
- Segments with the highest Au grades are those in which distinct splays or veins interconnect

from: Garofalo et al (2002)

Dorn (Antarctica): extreme example

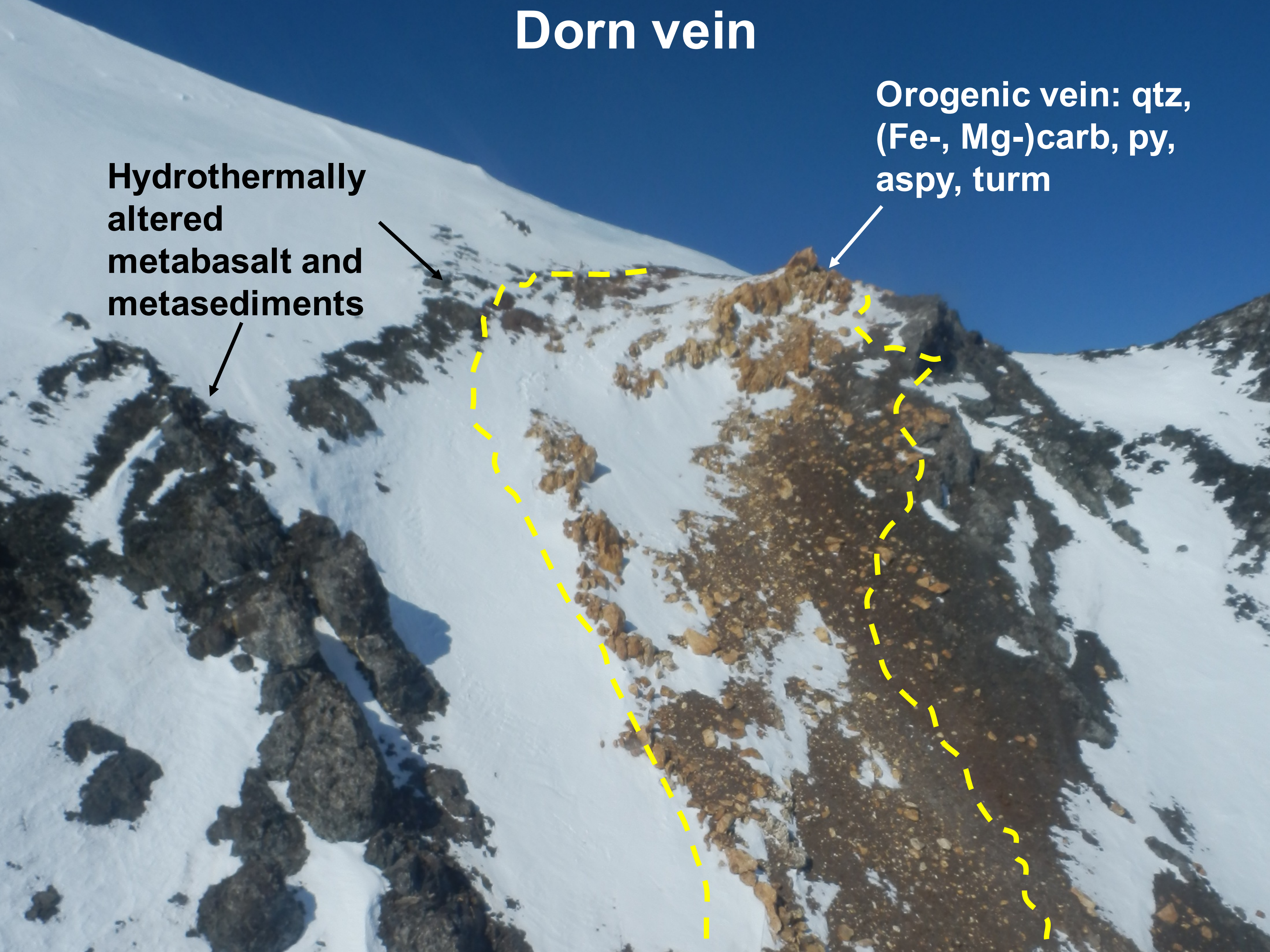
Dorn vein



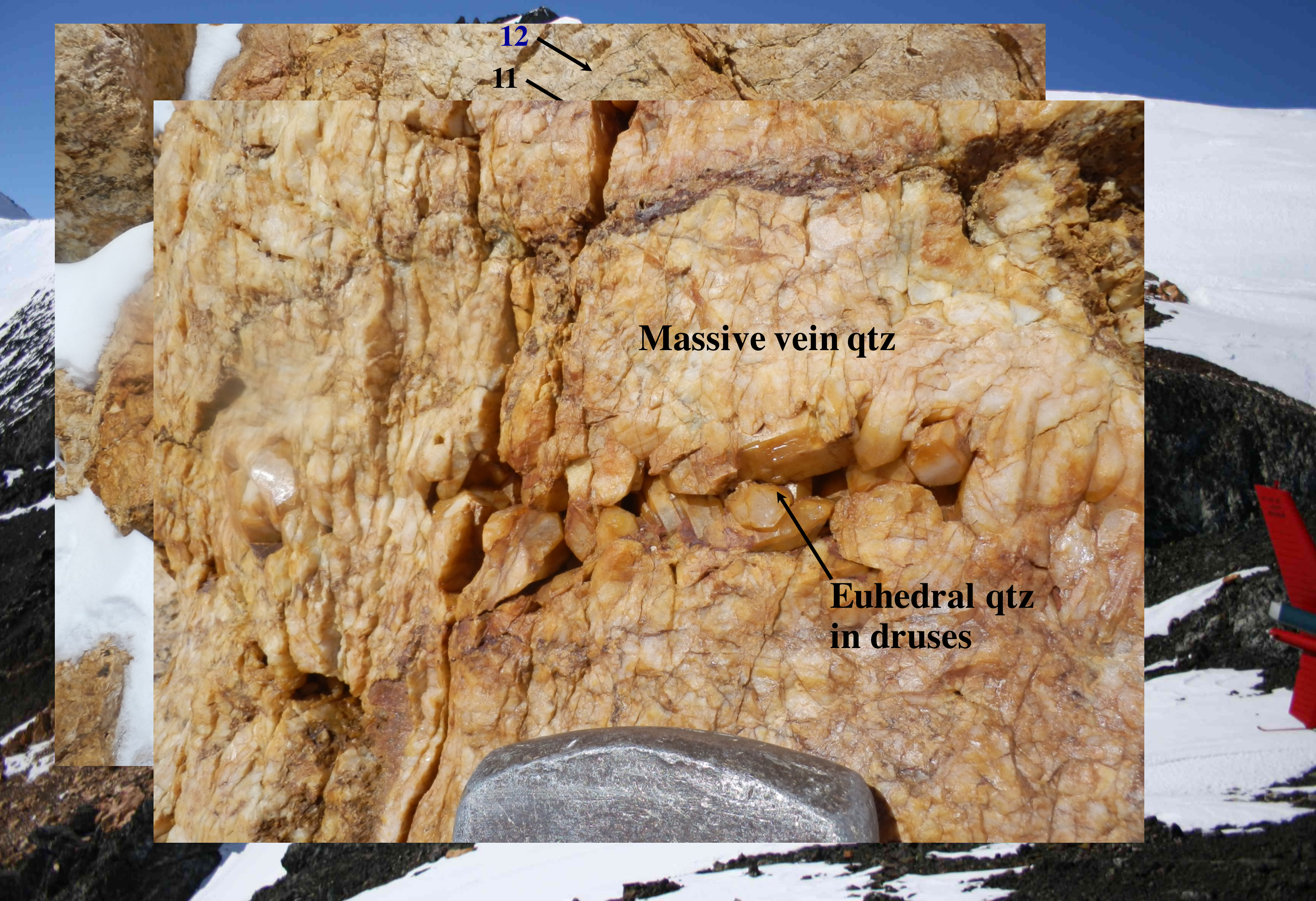


- Located in E sector of Bowers Mts. of the Paleozoic Ross orogen (N Victoria land);
- Close to NNW-trending fault of regional importance (Leap Year Fault);
- Host rocks: metavolcanics of the Glasgow Formation (Sledgers Group);
- Crispini et al. (2011): first report and description of this Au-mineralized vein

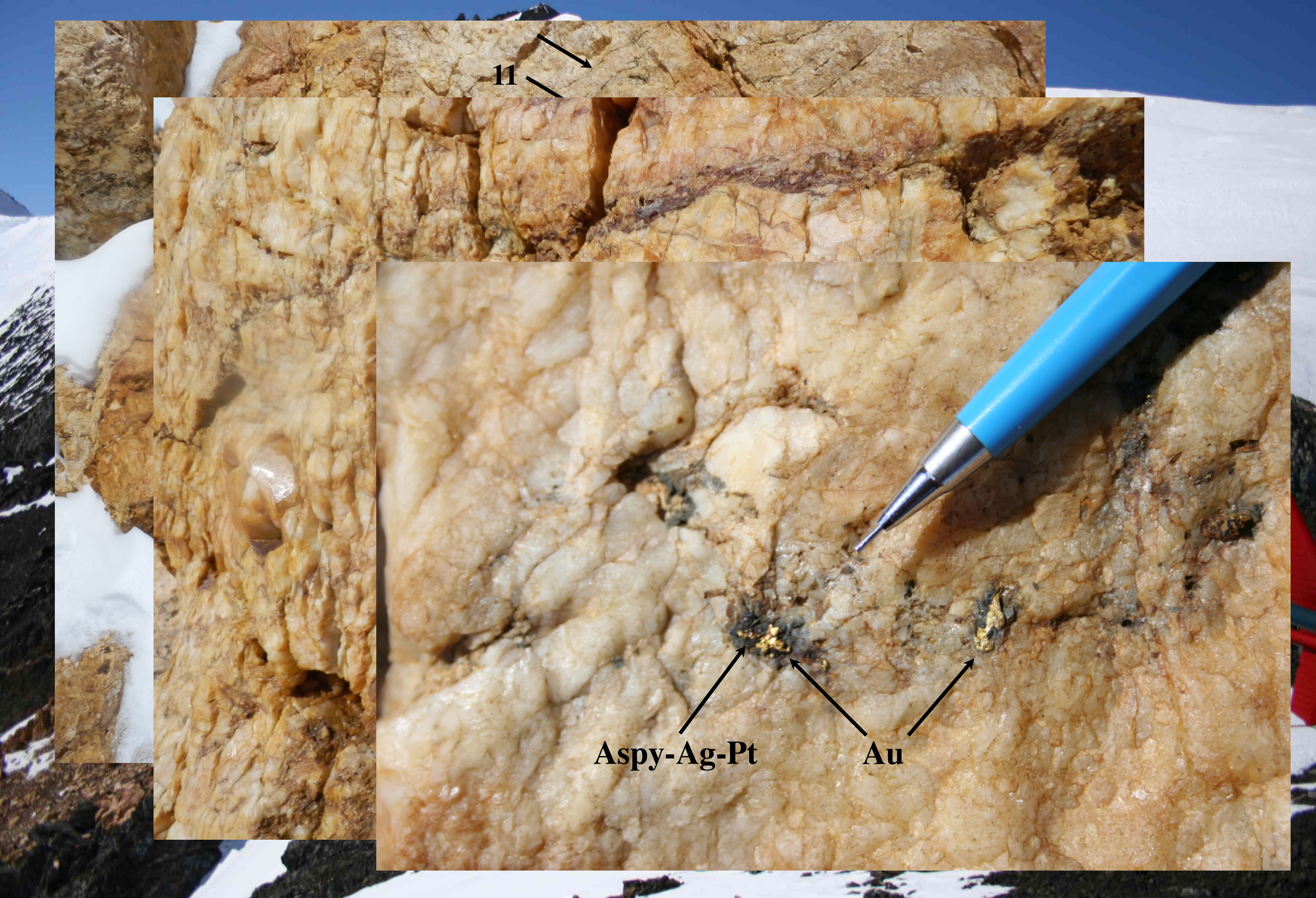
Dorn vein


Hydrothermally altered metabasalt and metasediments
Orogenic vein: qtz, (Fe-, Mg-)carb, py, aspy, turm

Dorn vein



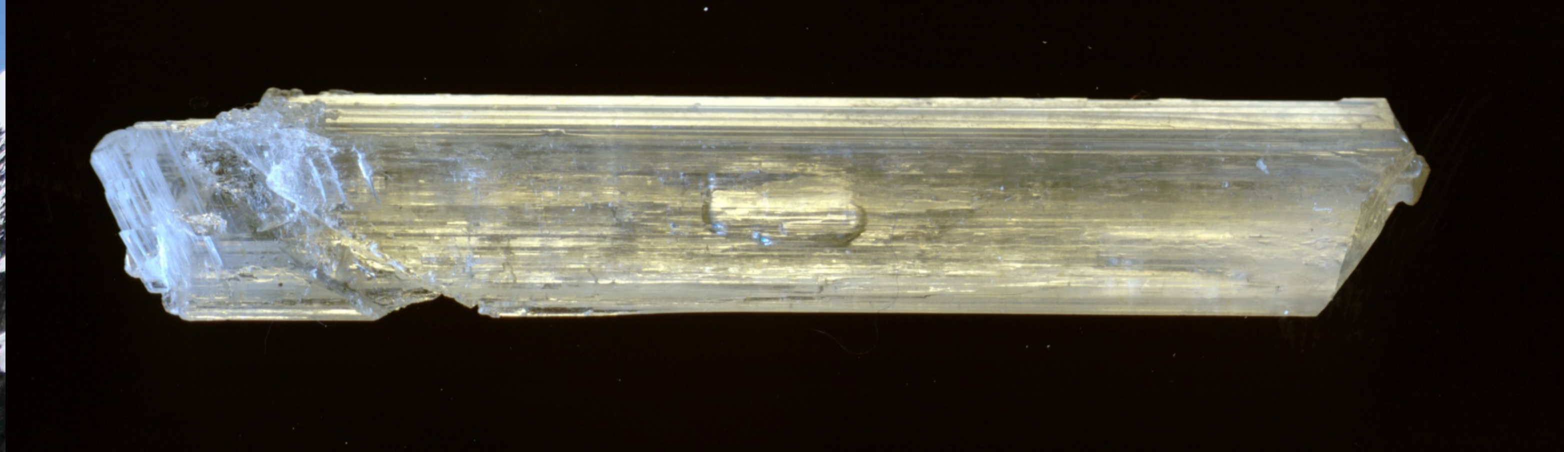
Dorn vein



Ore fluid properties

Fluid inclusion data

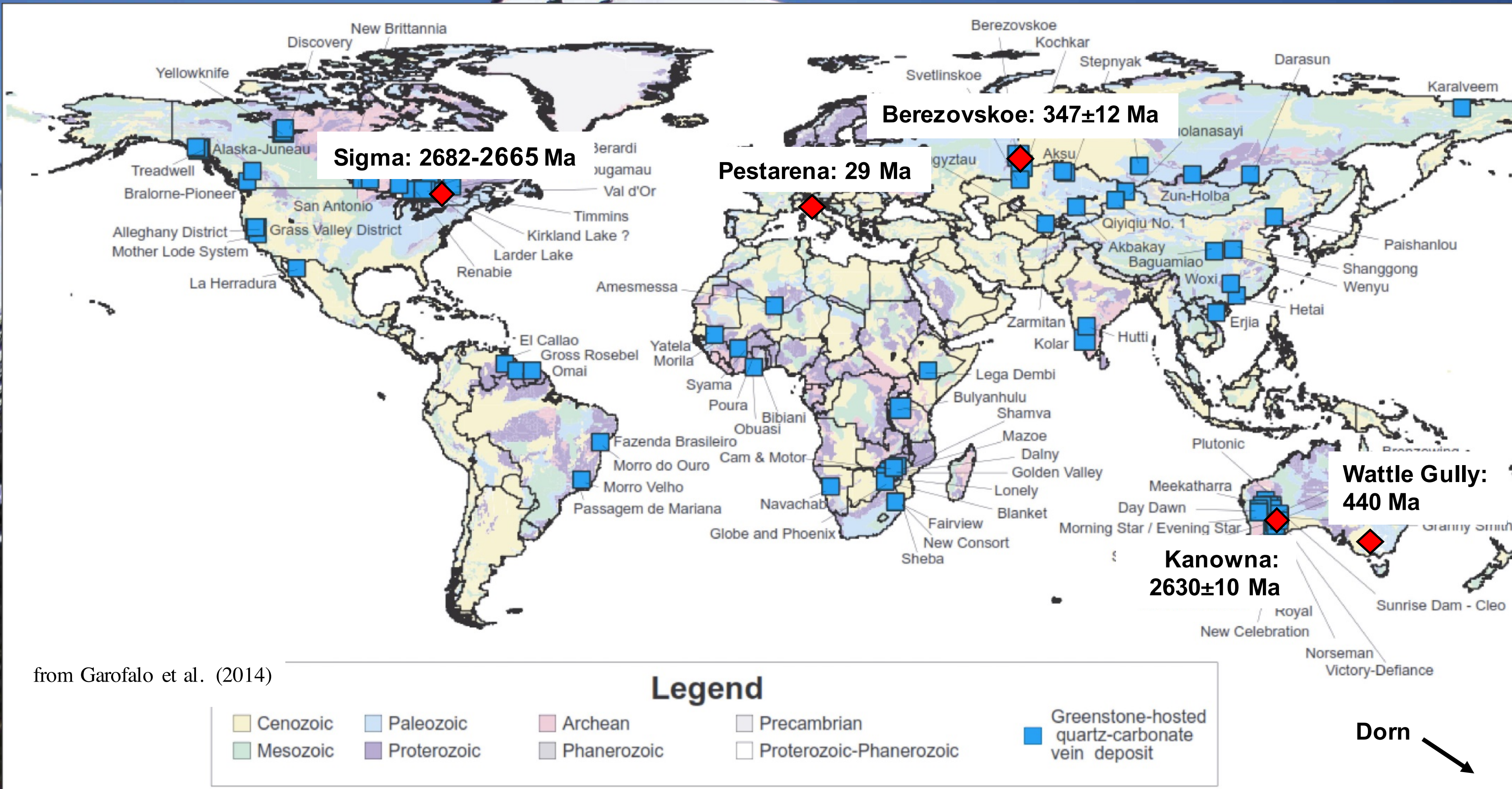
Fluid inclusions


FI in gypsum – Cueva de las Espadas, Naica (Mexico)

Definition: **micro-samples of geofluids entrapped within minerals during all stages of growth. Because these fluids are part of the rocks, they should be considered together with minerals**

Apart from few exceptions, all terrestrial minerals contain FIs

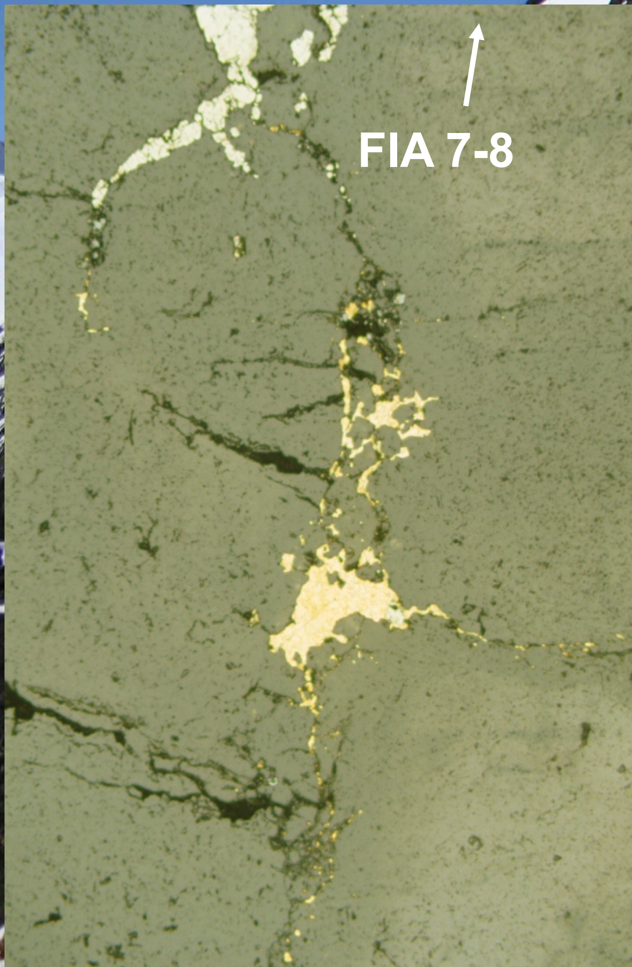
Four orogenic deposits studied in detail



from Garofalo et al. (2014)

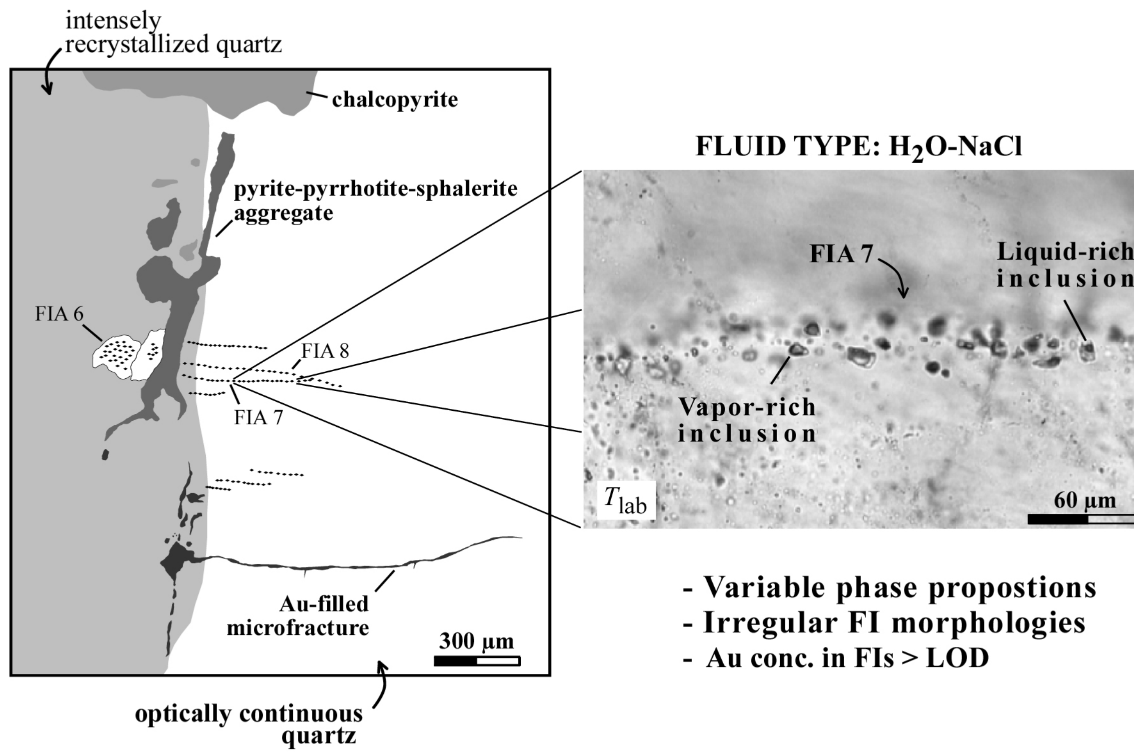
Deposits VERY different from one another in terms of economic relevance, age, 3D geometry, host rocks, hydrothermal alteration, etc.

Petrographic constraints



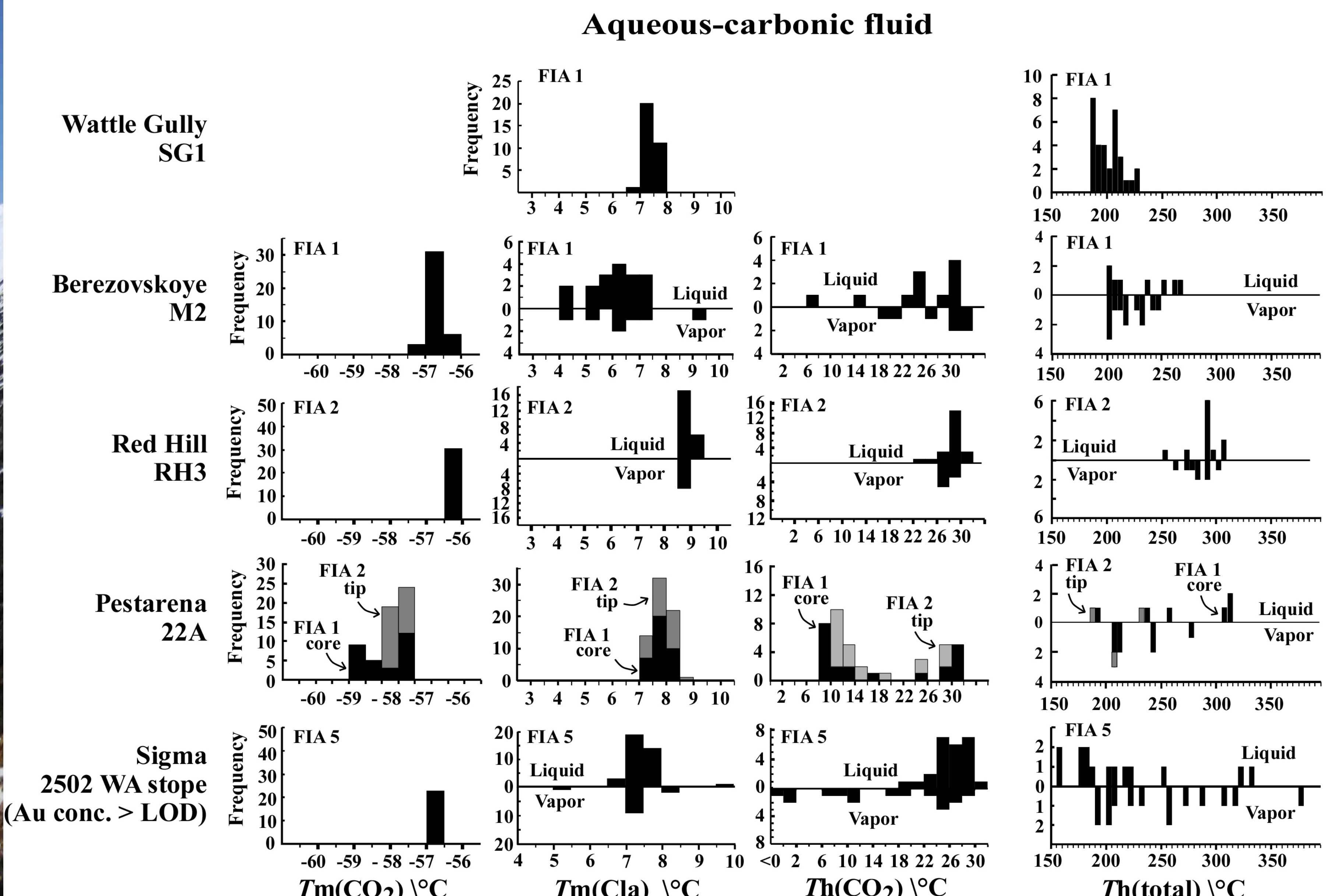
Sigma deposit

Sample DH 16280: FIAs parallel to Au-filled microfracture



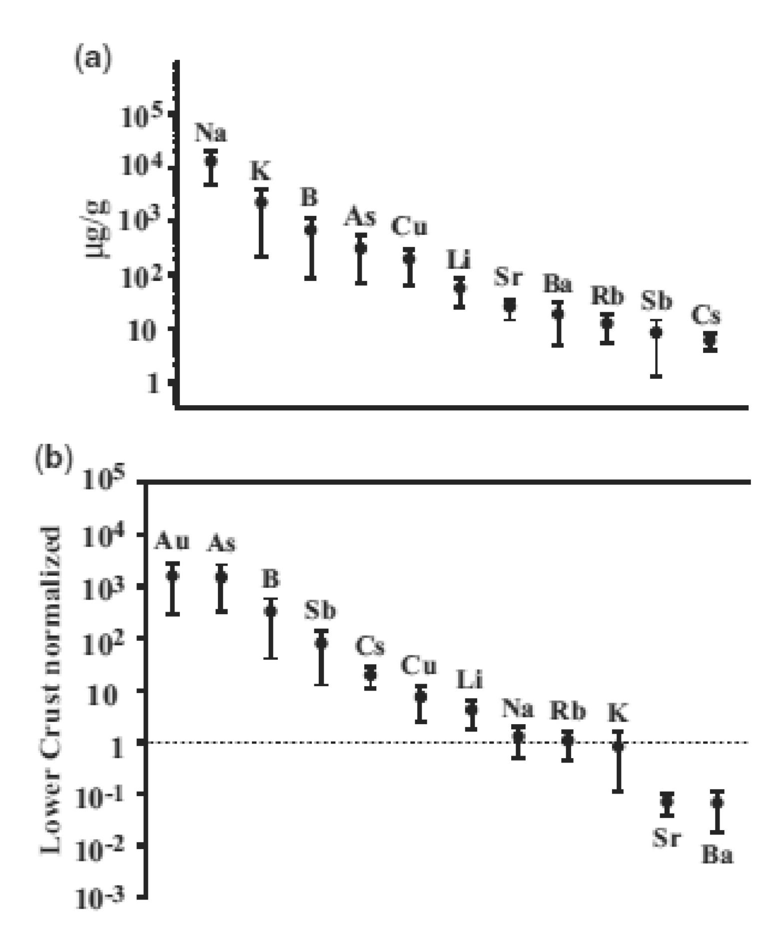
- Variable phase propostions
- Irregular FI morphologies
- Au conc. in FIs > LOD

Microthermometric data



from: Garofalo et al (2014)

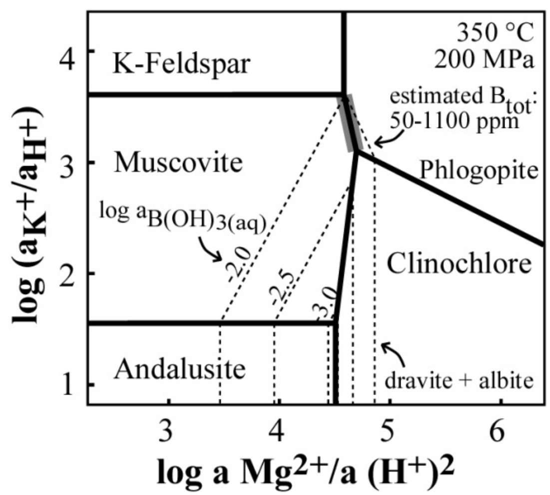
Properties of ore fluid

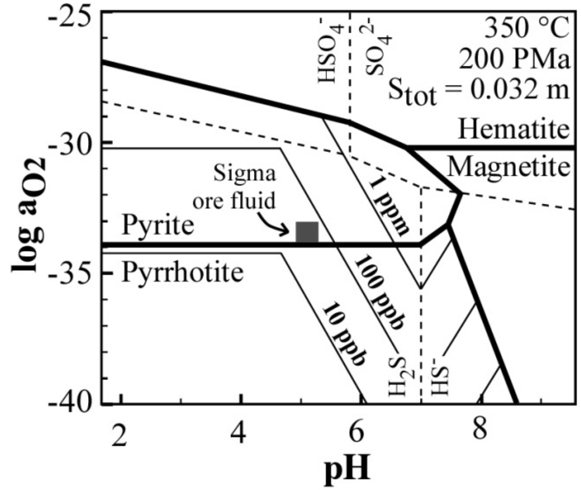


Summary of results

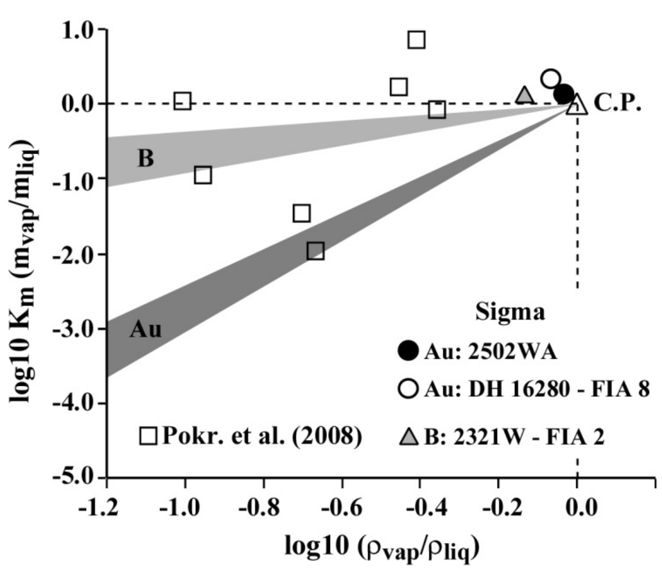
- Heterogeneous/homogeneous H_2O-NaCl-CO_2 (± H_2O-NaCl) fluid
- Low bulk salinity: 0.4-6.5 wt% $NaCl_{eq}$
- T_{trap}: c. 350 °C; P_{trap}: 200 MPa;
- XCO_2: from 0.03 (L) to 0.25 (V);
- Tot S: 4500-6400 μg/g;
- Au: 0.5-5 μg/g; B: 80-2200 μg/g;
- Uniform chemical composition, which implies SAME genetic process repeating in all orogenic belts;
- The ore fluid is enriched in components (Au, As, B, Sb) that are volatile at the ore forming conditions;
- Evidence for heterogeneous entrapment (boiling);

Transport and deposition





- Predicted B solubility (50-1100 µg/g) similar to B concentration in ore fluid (80-2200 µg/g) = equil. transport;
- Predicted Au solubility from aqueous complexes (0.02–0.1 µg/g) different from measured Au conc. (0.5-5 µg/g)



Modif. after from: Garofalo et al (2014)

OROGENIC FLUID IS VOLATILE

- Fluid volatility increases when the density difference between vapor and liquid phase decreases;
- Orogenic fluid: S-bearing, acidic, and >250 °C, therefore distinctly volatile due to the presence of stable Au-sulfide species in the vapor phase (e.g., $Au(HS)H_2S^0$; AuS_3^0);
- Boiling and fluid decompression causes Au deposition;
- These processes explain strong structural control on Au grade distribution

Volume of hydrothermal fluid

Fundamental constraints on Sigma

1. Total volume quartz-tourmaline network: $5.5\ 10^6\ m^3$
2. Volume of tourmaline precipitated within network: $2.1\ 10^6\ m^3$
3. Total mass of B within network: 71500 t
4. Total mass of Au within network: ~440 t
5. Concentration of B in ore fluid: 20-1300 g/t
6. Concentration of Au in ore fluid: 0.5-5 g/t

Fluid volume at Sigma

The total volume of the hydrothermal fluid is constrained by (3)-(6):

100% efficiency of tourm. and Au precipitation: $0.1\ km^3$

50% efficiency of tourm. and Au precipitation: $0.3\ km^3$

This is a SMALL FLUID VOLUME for a geological process

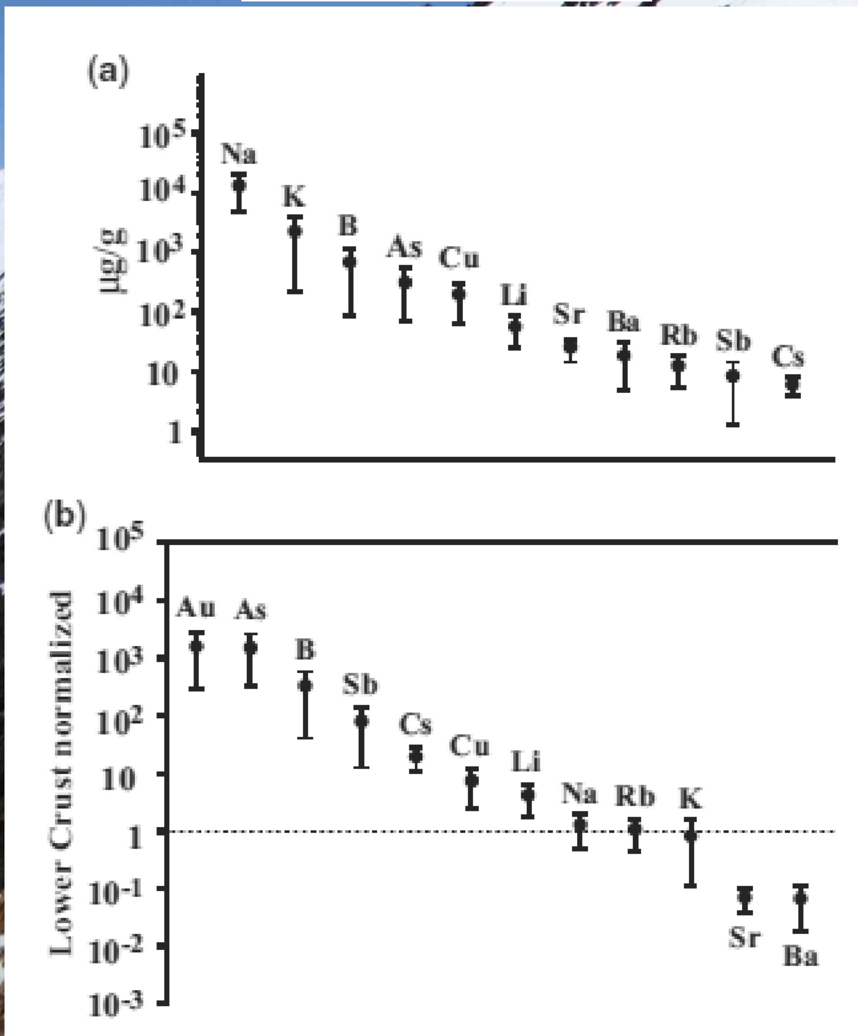
Conclusions

1. **Regional constraints identify fundamental structural controls on orogenic deposits and timing of events;**
2. **Regional constraints may identify relationships between orogenic deposits and earthquakes;**
3. **District scale constraints help identifing 1st and 2nd order fractures, which have distinct relations with Au deposition;**
4. **Deposit scale constraints identify fundamental relations between geometric properties of fracture network (metric vs. topologic) and Au grade distribution;**
5. **Outcrop constraints guide sampling and subsequent lab work;**
6. **FI constraints determine fundamental ore fluid properties, all of which are necessary for genetic model**
7. **To be robust, models on orogenic deposits need all points 1-6**

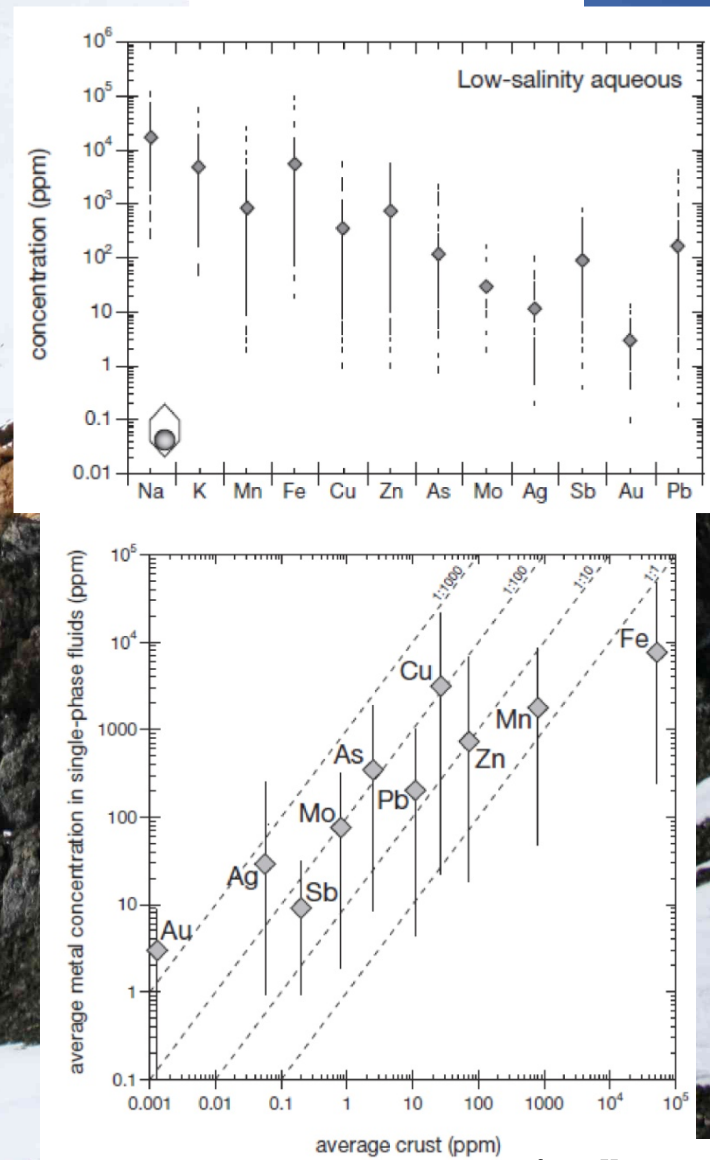
Thanks for your attention !!

CONSISTENT composition

OROGENIC

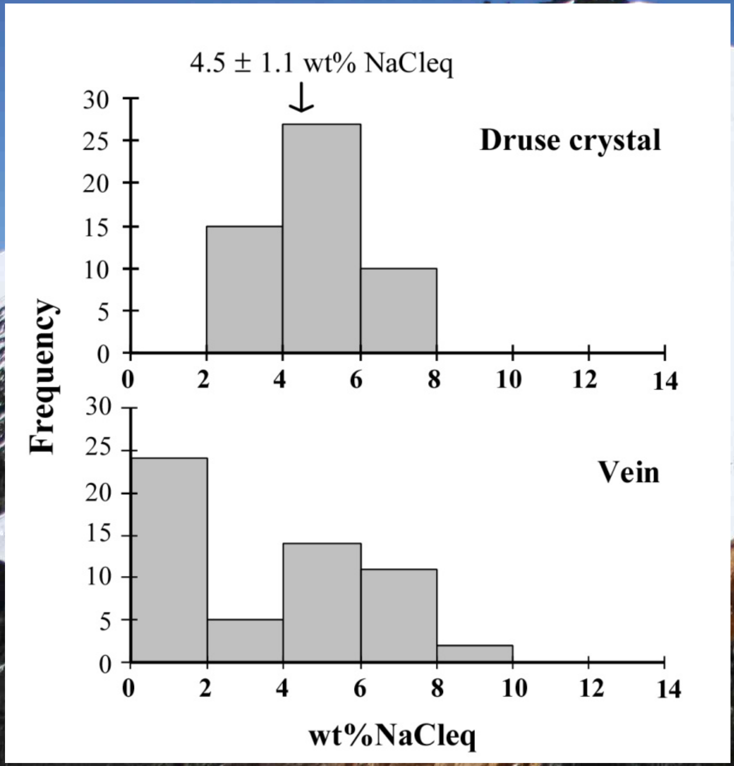


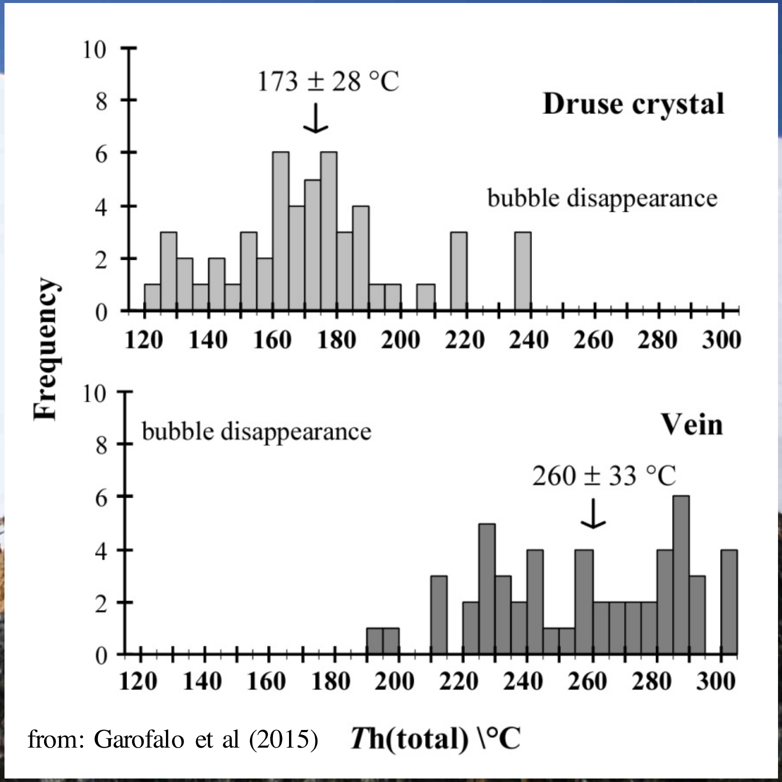
PORPHYRY



from: Kouzmanov et al (2014)

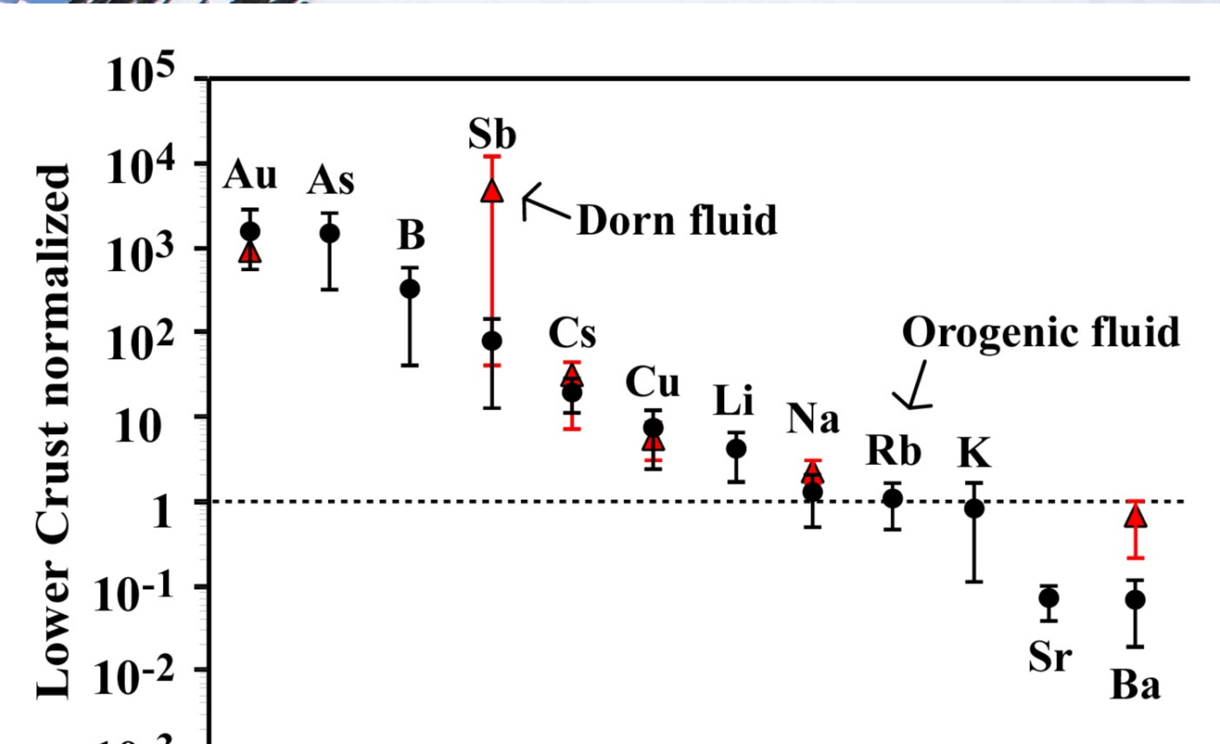
Dorn: microthermometry





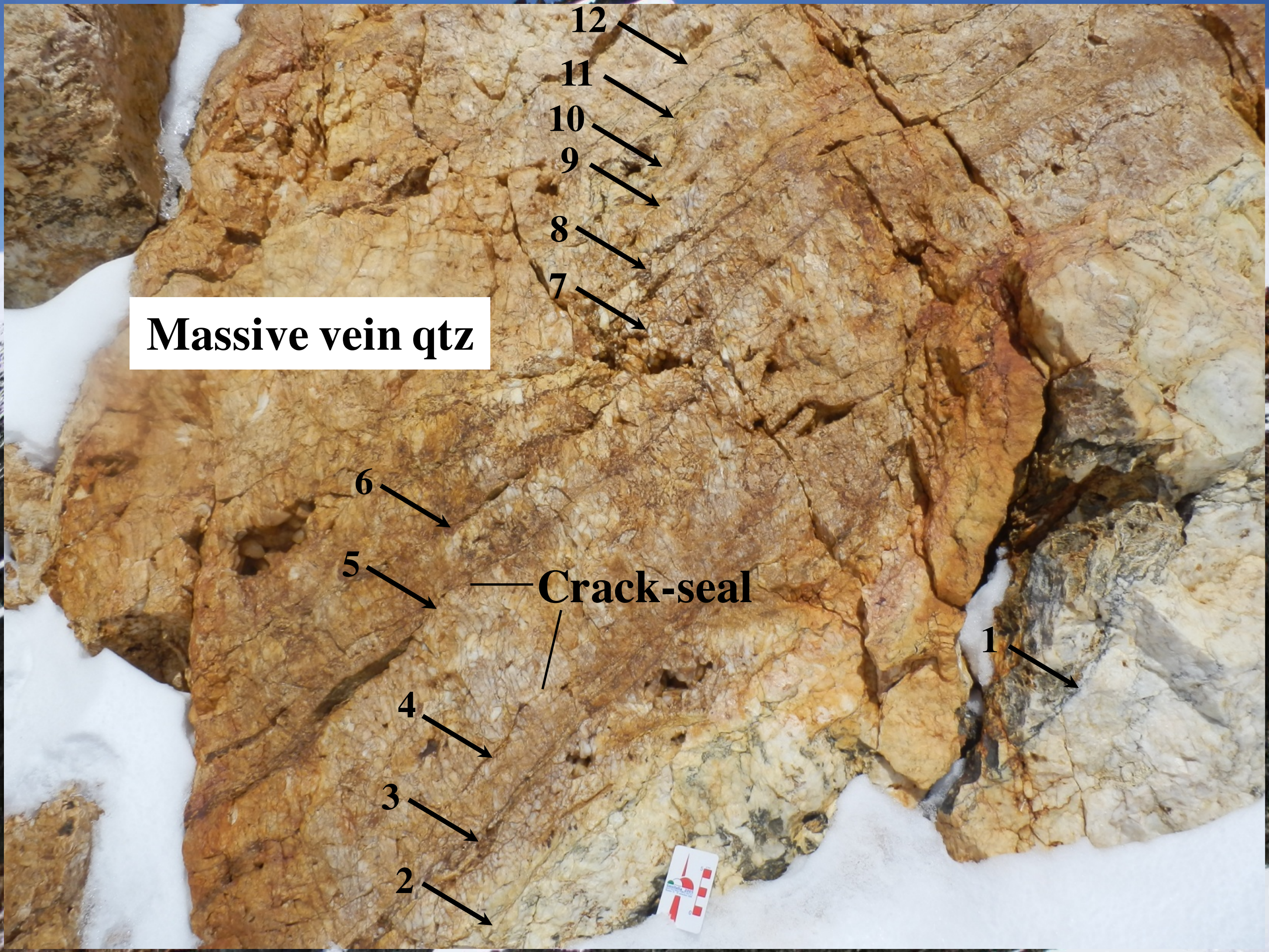
- Druse quartz: H_2O-NaCl model fluid; Massive vein: H_2O-NaCl-CO_2 model fluid;
- Bulk salinity of FIs in druses (average: 4.5 wt%$NaCl_{eq}$) more consistent than that of massive vein (range: 0-8.5 wt%NaCleq);
- *T*htot of FIs from massive vein are higher (260±33 °C) than those of FIs from druse crystals (173±28 °C)

The Dorn fluid (druse quartz)

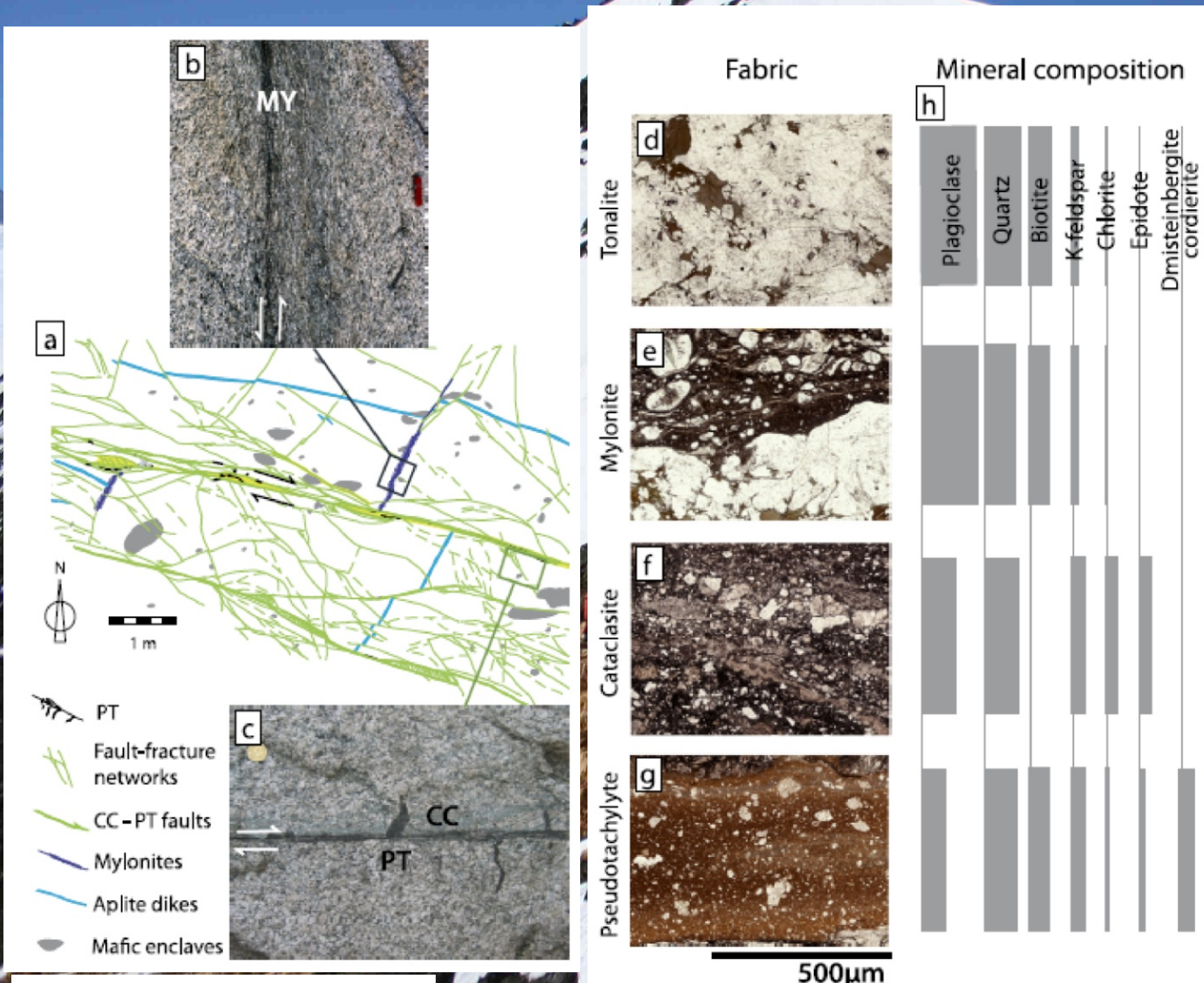


from: Garofalo et al (2015)

Dorn vein



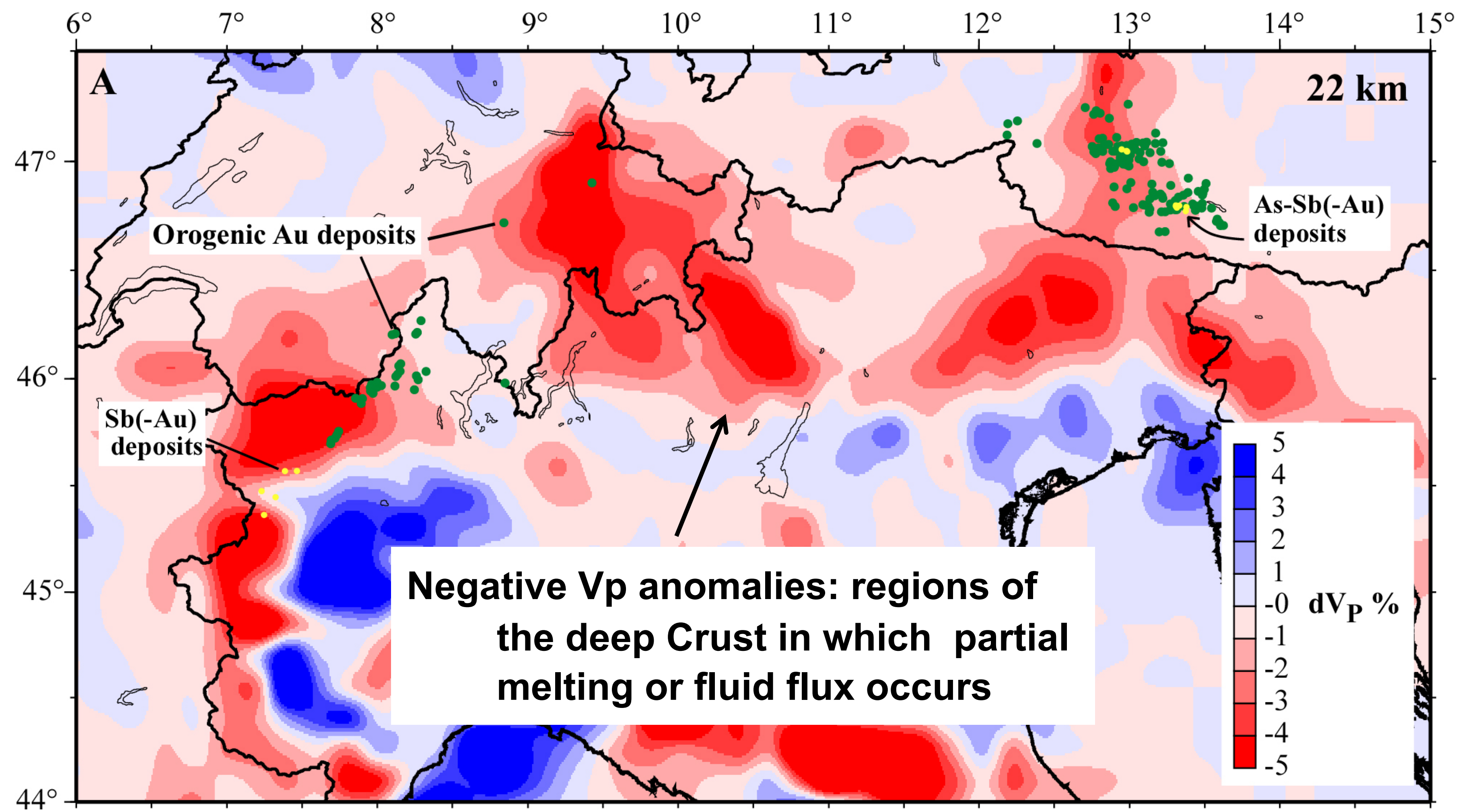
Earthquakes and orogenic deposits



from: Mittempergher et al (2014)

Regional faults associated to orogenic deposits contain "pseudotachilites" (PT), i.e. fault rocks formed by partial melting of *gouge* due to earthquakes and containing particular minerals (e.g. dmisteinbergite)

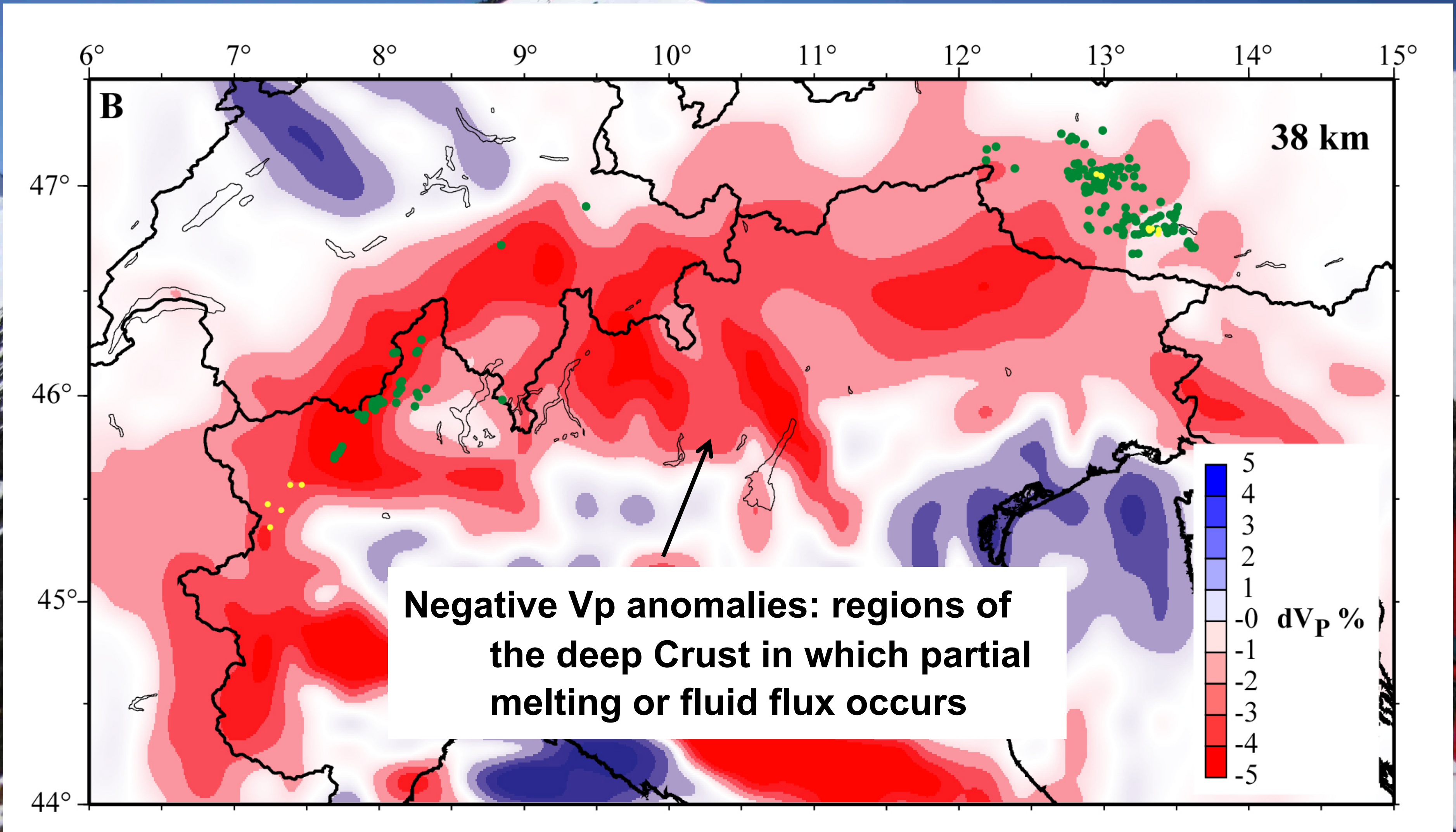
Orogenic deposits and earthquakes



Negative Vp anomalies: regions of the deep Crust in which partial melting or fluid flux occurs

from: Garofalo et al. (in prep)

Orogenic deposits and earthquakes



from: Garofalo et al. (in prep)