SKARNS: ZONING PATTERNS AND CONTROLLING FACTORS

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SEG Traveling Lecturer Webinars

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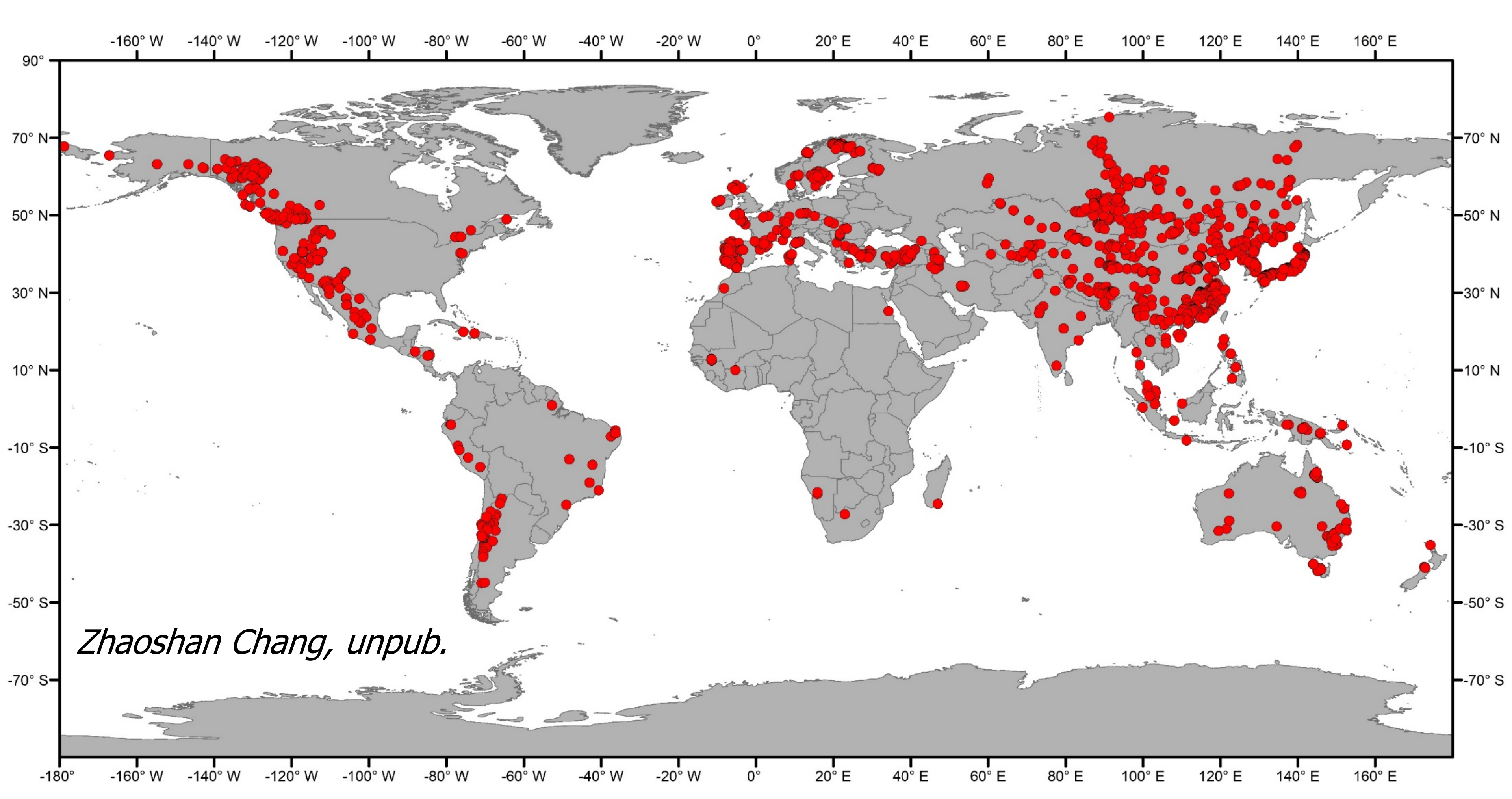
WHY SKARNS?

- Au, Cu, Sn, W, Pb, Zn, Mo, Fe, minor Ag, B, Be, Bi, Co, F, REE and U
- Common: *>1630* skarn deposits described in literatures



WHY SKARNS?

- Major source of W and Sn
- Significant source of base metals and Au, e.g., Antamina, Peru (2,968 Mt @ 0.89% Cu, 0.77% Zn, 11 g/t Ag and 0.02% Mo; 2015)

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WHY SKARNS?

Ertsberg-Grasberg district, Indonesia (0.5% Cu cut-off)

-Skarn: 2.8 Gt @ 1.12% Cu, 0.78 g/t Au

-Porphyry: 2.3 Gt @ 1.14% Cu, 1.09 g/t Au

OK Tedi, PNG

Cananea, Mexico

Bingham, Utah, US

Mission, Arizona, US

...

Einaudi, 1982; Meinert et al., 1997; 2005; Leys et al., 2012

- **High grade "sweetener" in porphyry deposits**

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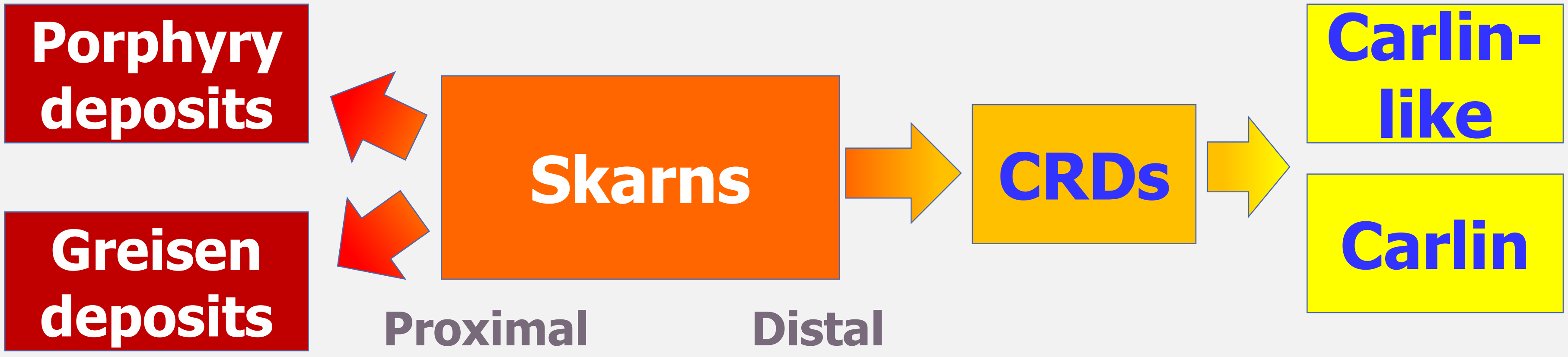
SKARN AND RELATED DEPOSITS

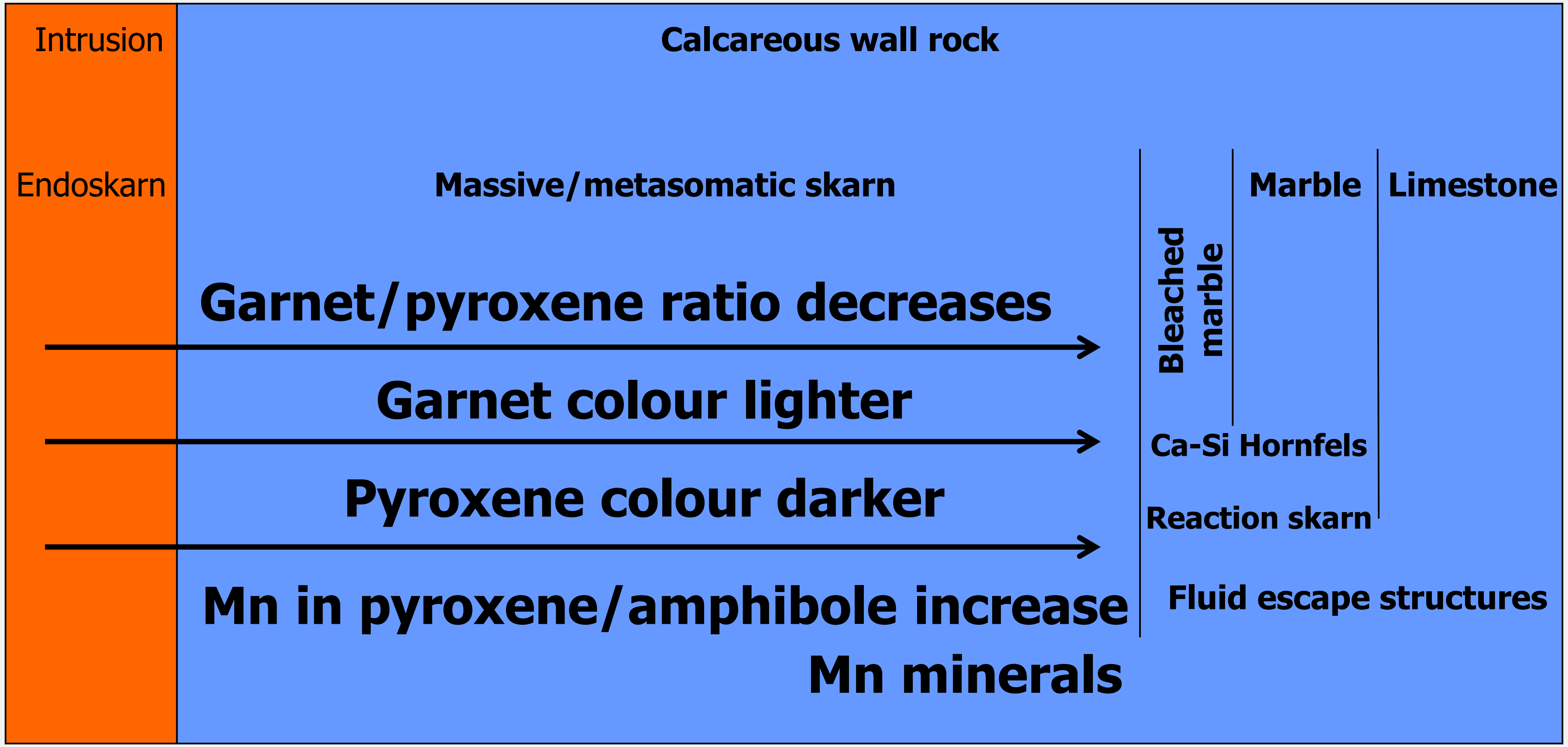


Zoning pattern:

1. Find out where you are and vector towards other parts of the system
2. Determine the causative intrusion

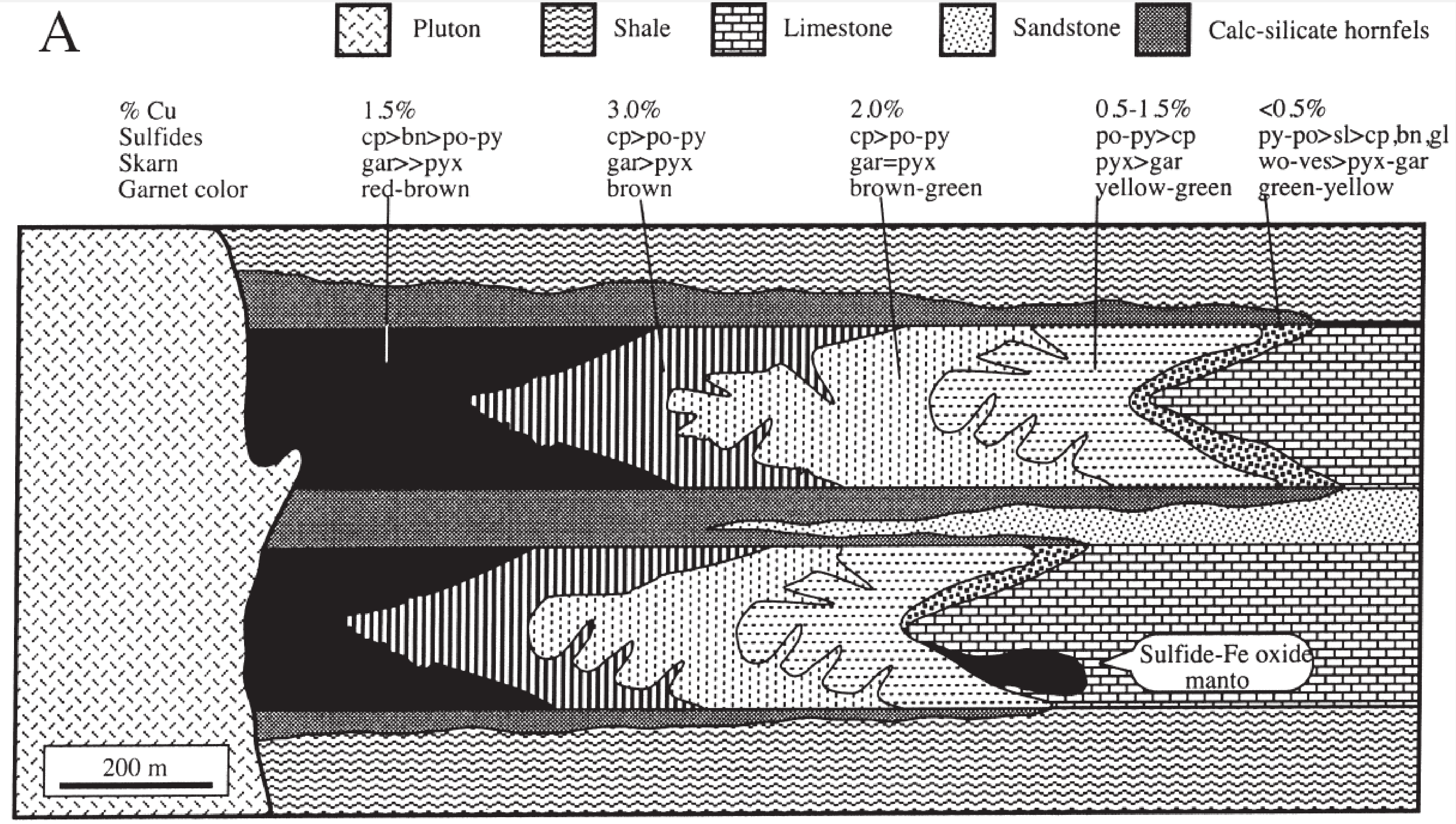
SKARNS ARE TYPICALLY ZONED

Transfer of heat and mass from intrusions or fluid conduits



ZONATION IN A CU SKARN

Carr Fork, Bingham, USA



gar: garnet; pyx: pyroxene; cp: chalcopyrite; wo: wollastonite; ves: vesuvianite; bn: bornite; po: pyrrhotite; py: pyrite

Meinert, 1997; based on Atkinson and Einaudi, 1978

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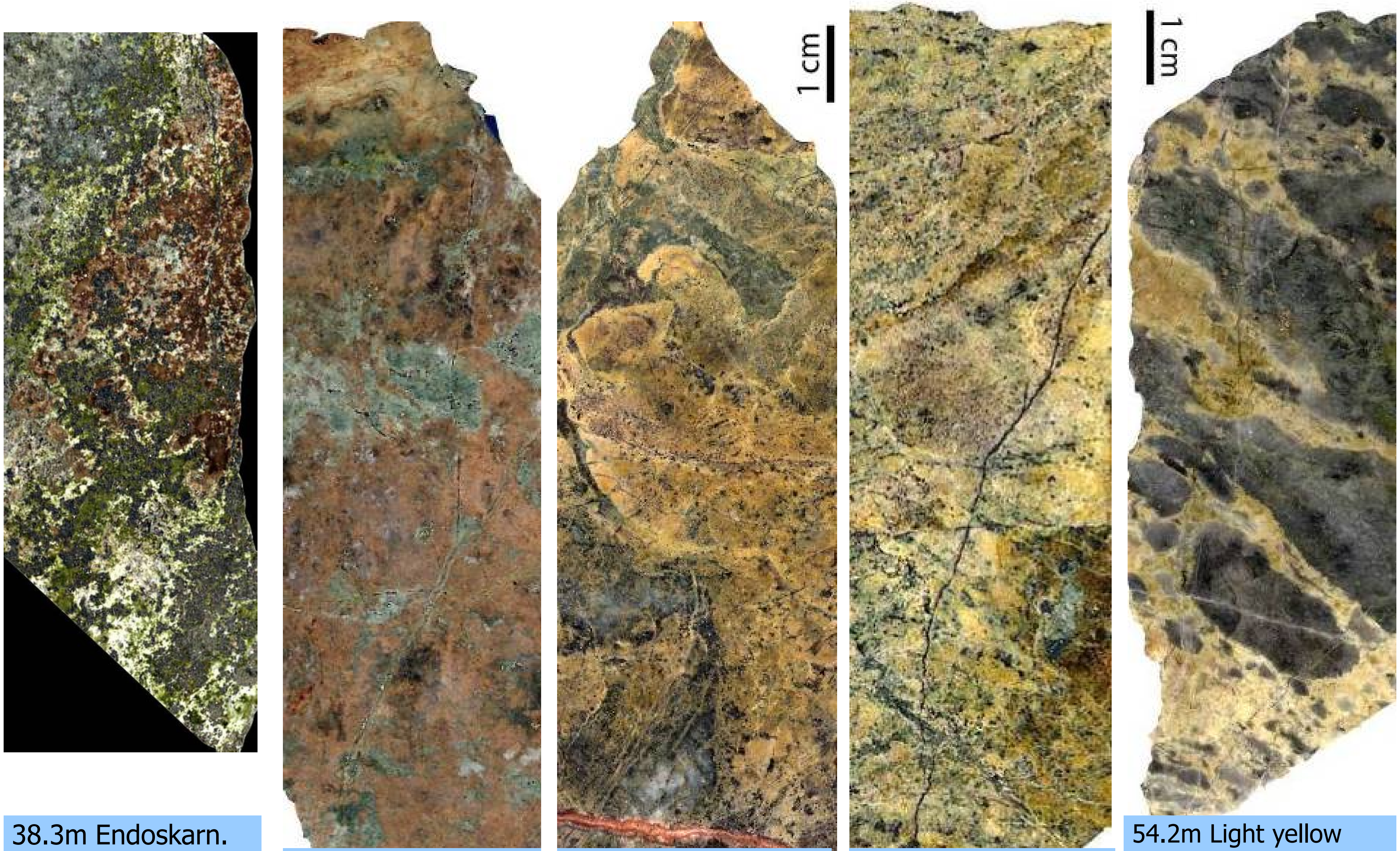
Zoning away from intrusion in a Cu skarn



38.3m Endoskarn. Dark red garnet

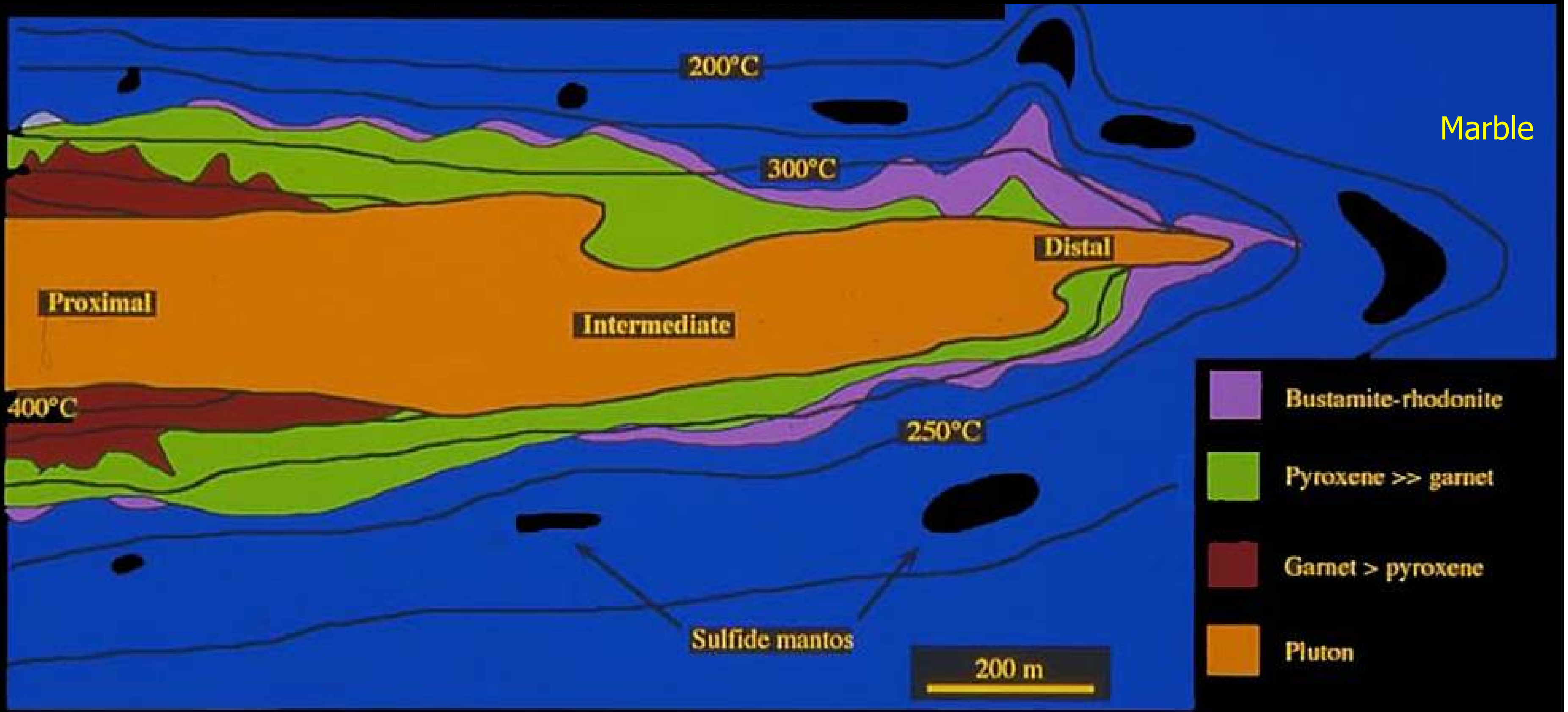
45.2m Red garnet

46.3m Brown garnet

48.2m Yellow garnet

54.2m Light yellow garnet

Zonation in a Zn skarn

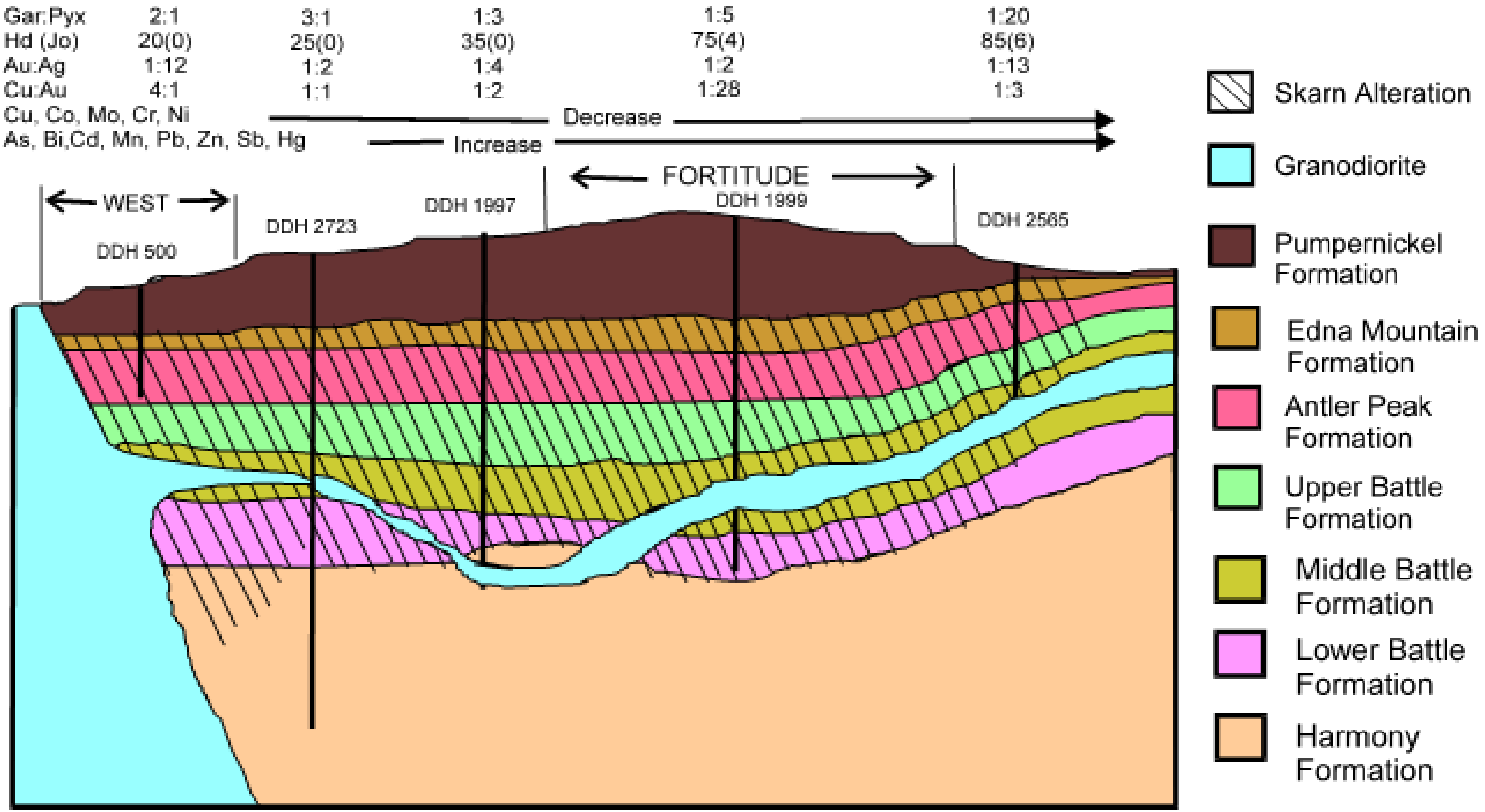


Feature	Proximal	Intermediate	Distal
Garnet:pyroxene	> 1:1	1:20	No garnet
Max Jo in pyroxene	< 25%	25-50%	> 50%
Fe oxides	mt > hm	hm ~ mt	hm > mt
Ore sulfides	sl > gl ~ cp	sl > gl > cp	sl ~ gl > cp
Skarn:manto ore	> 10	1-10	< 1
Temperature	> 400°C	320° - 400°C	< 320°C
Salinity (NaCl eq. wt.%)	> 15 %	7.5-15%	< 7.5%
Zn/Cu	< 10	10-20	> 20
Zn/Pb	> 5	2-5	< 2
Pb/Cu	< 5	5-10	> 10

Groundhog, USA;

Meinert, 1987

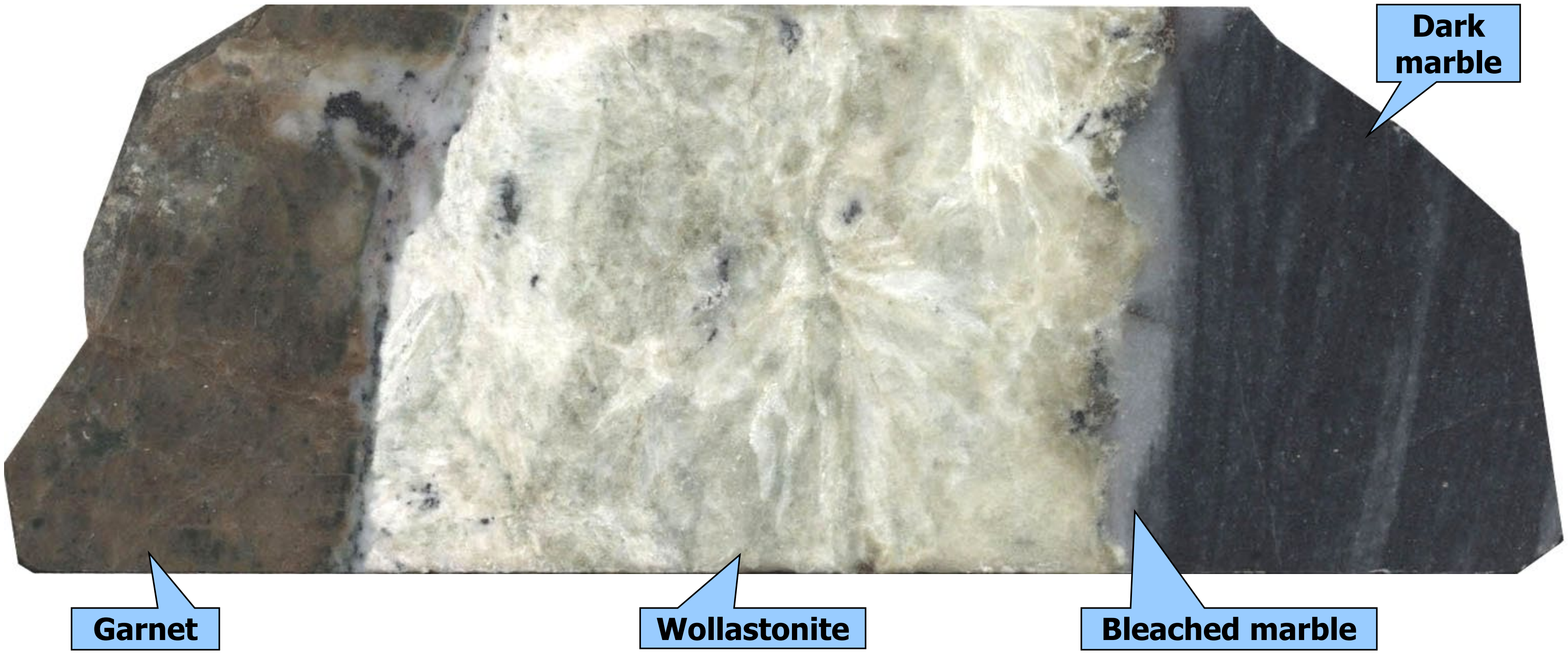
Zonation in a Au skarn – Fortitude, USA



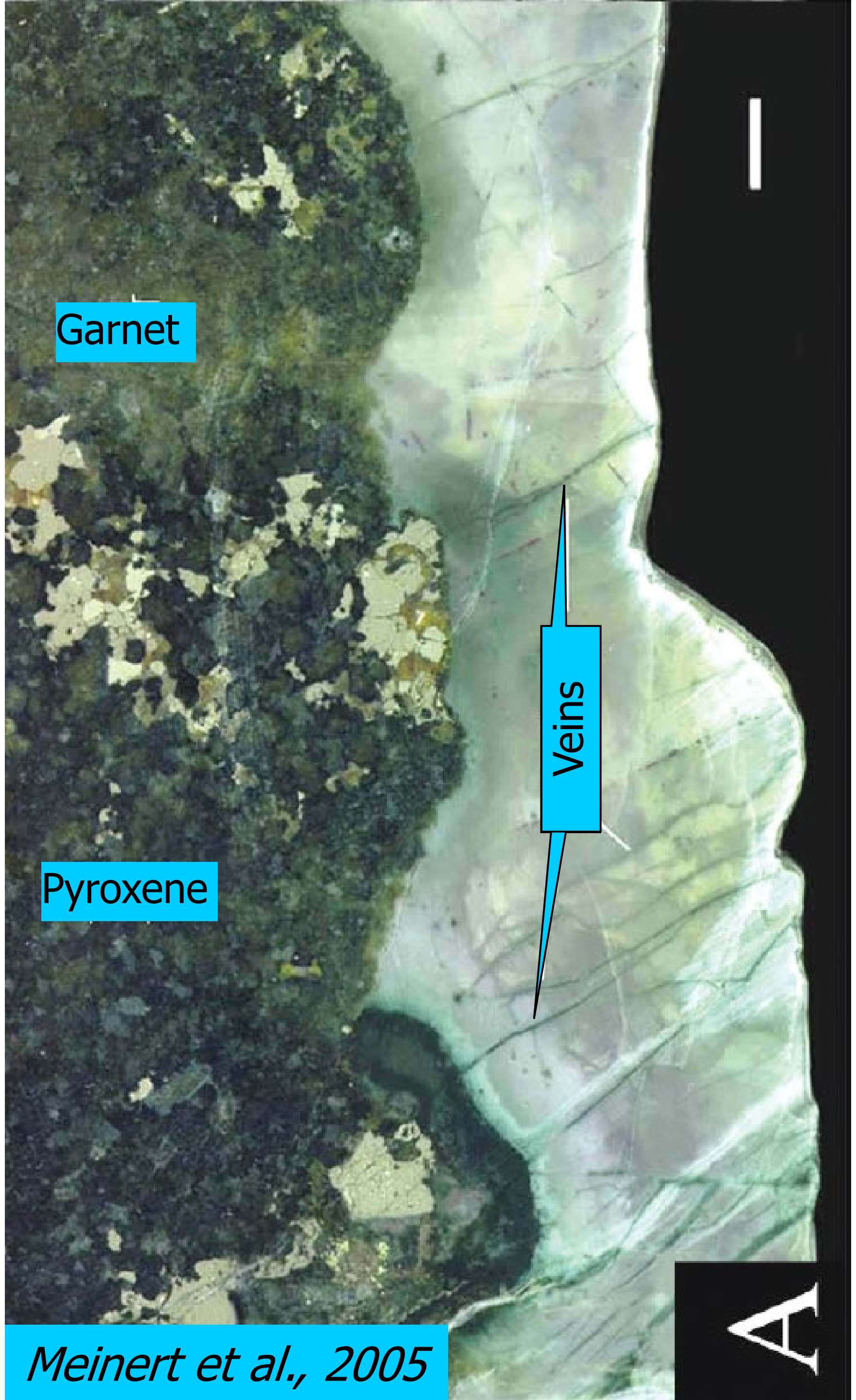
Gar: garnet; Pyx: pyroxene; Hd: hedenbergite; Jo: Johannsenite

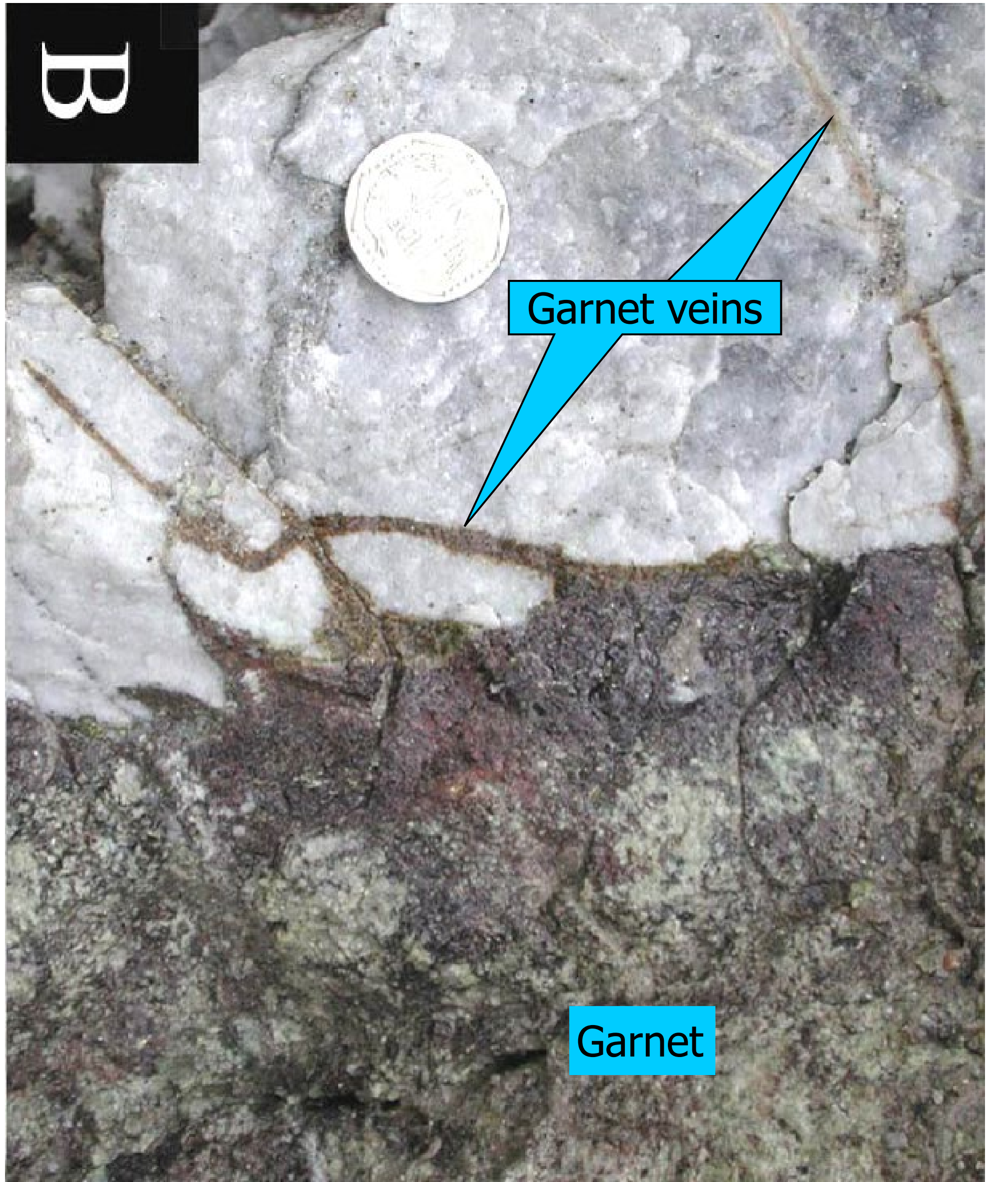
Meyer and Meinert, 1991

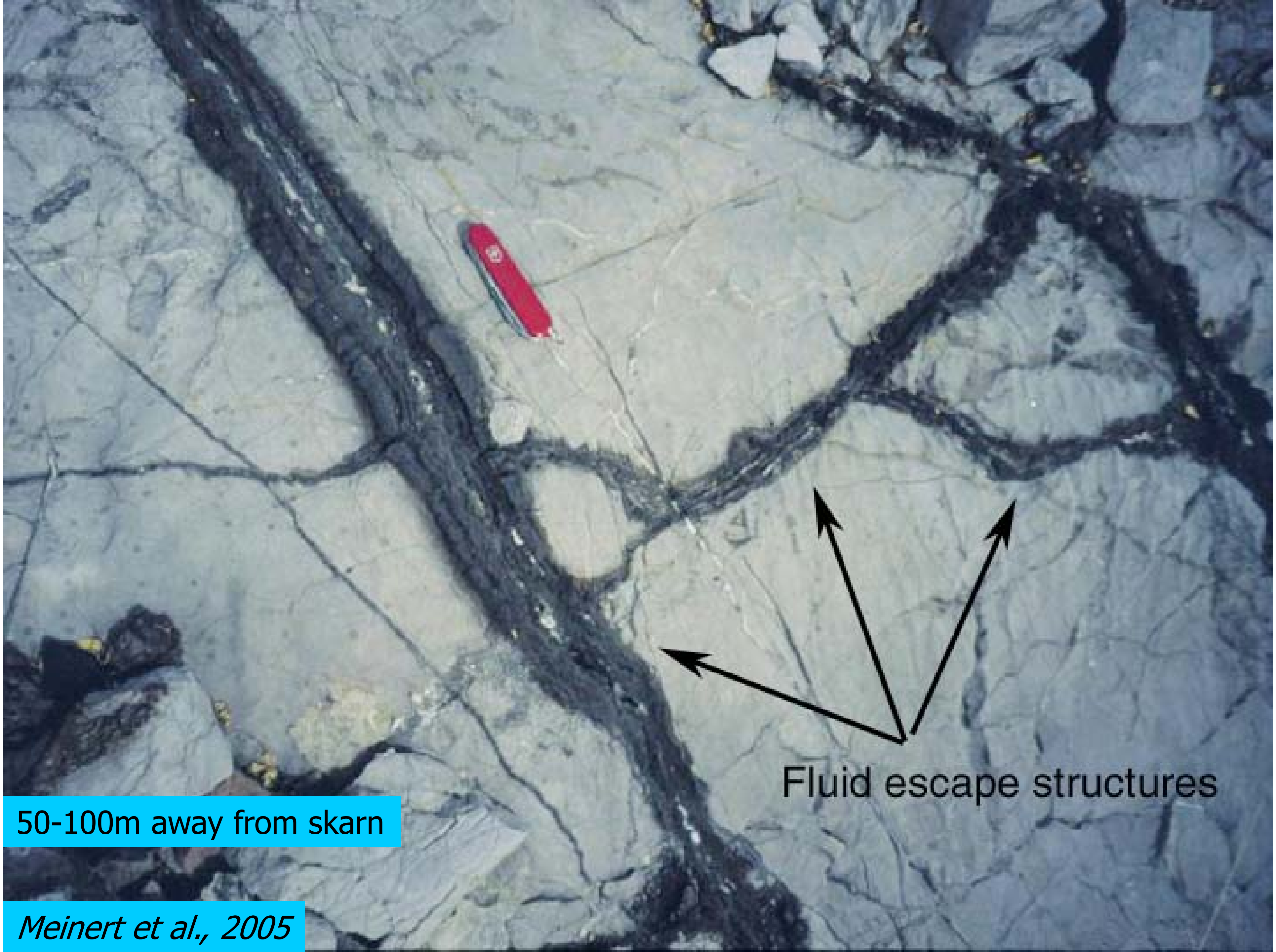
Zonation at marble front in a Au skarn, Mexico



Fluid escape structures – distal features beyond skarn

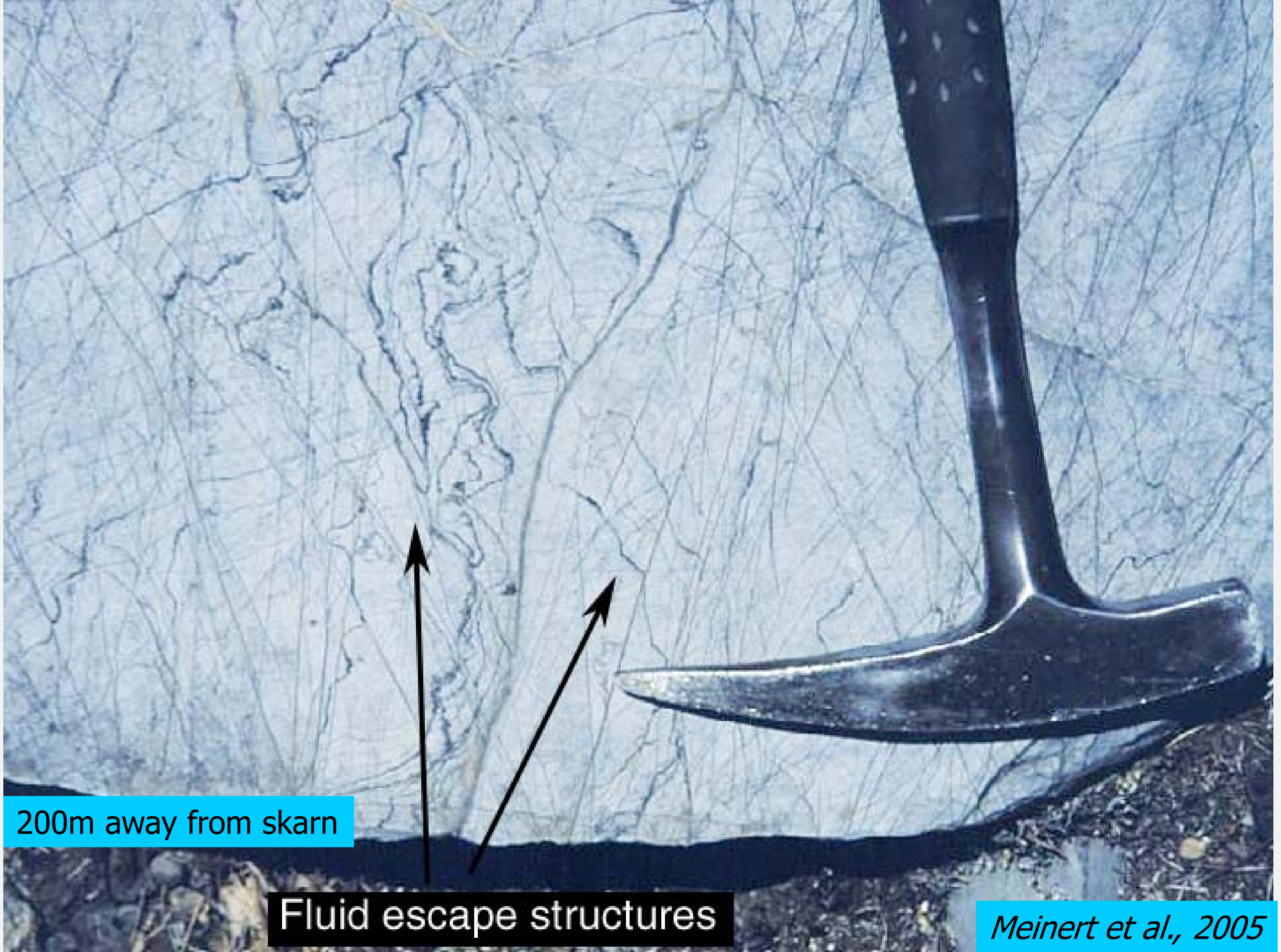






50-100m away from skarn

Meinert et al., 2005


200m away from skarn
Fluid escape structures
Meinert et al., 2005

FLUID ESCAPE STRUCTURES – DISTAL FEATURES BEYOND SKARN

Yaojialing Zn-Au skarn, China

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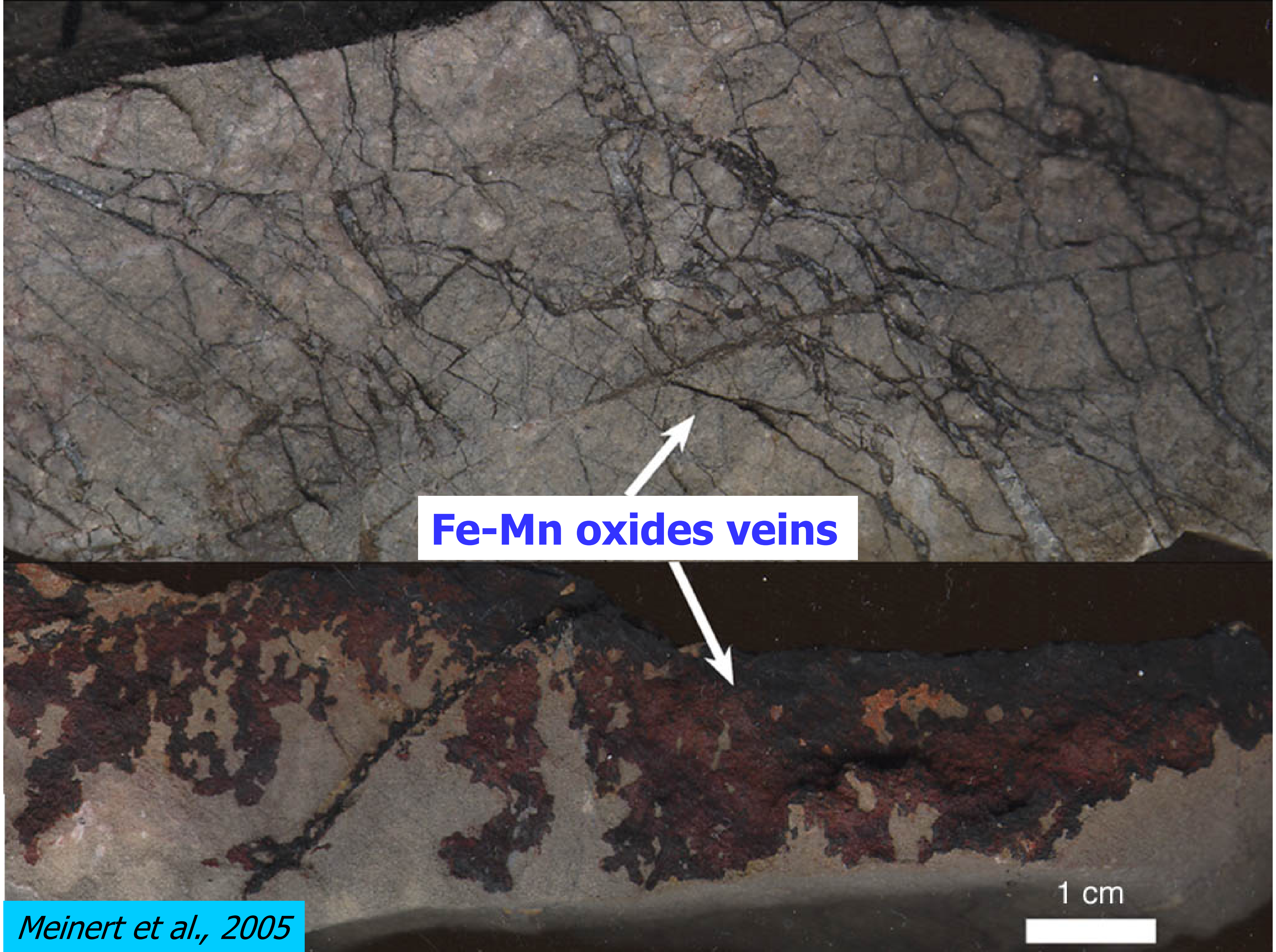
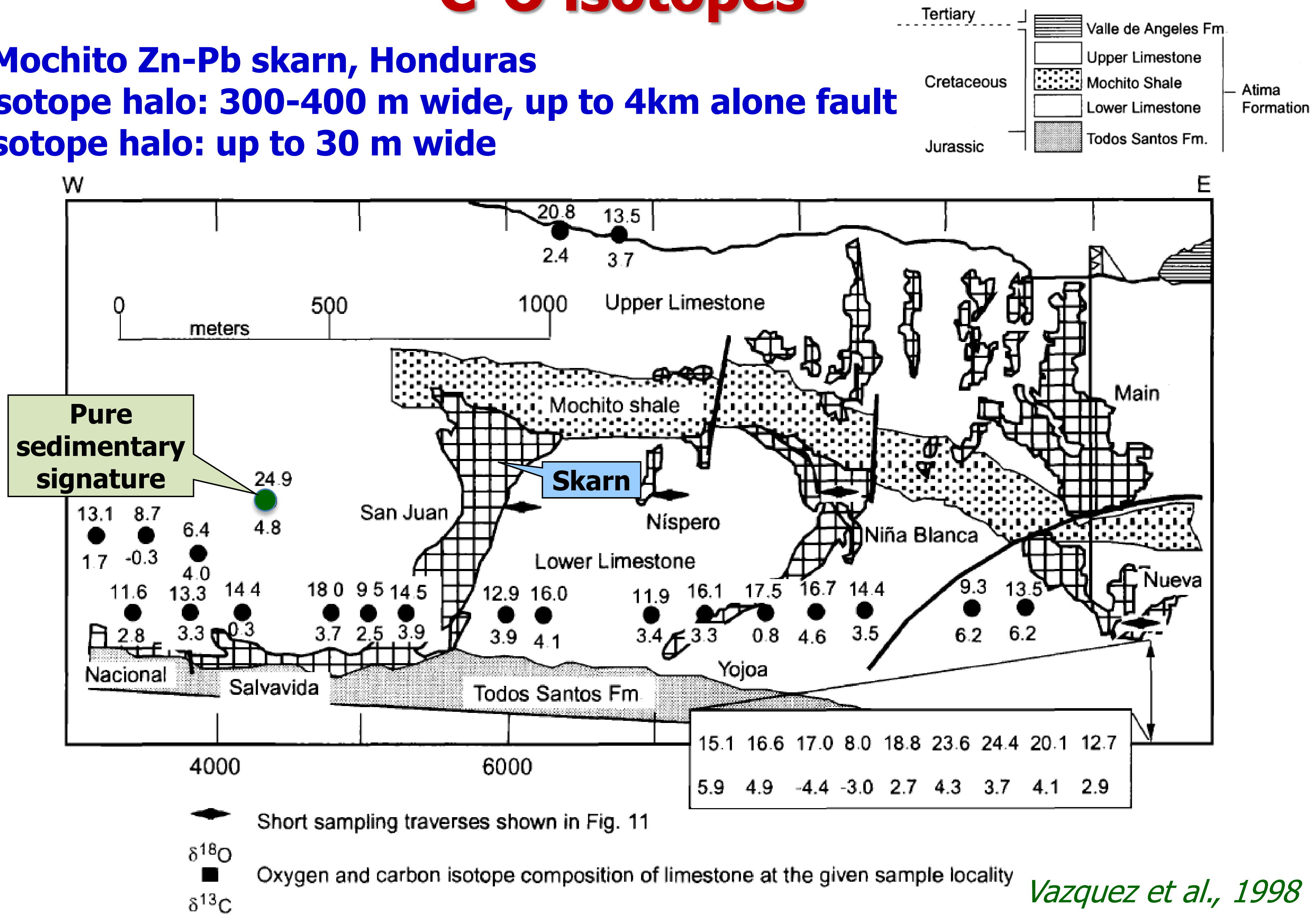


Meinert et al., 2005

Cryptic hydrothermal signals in marble: C-O isotopes

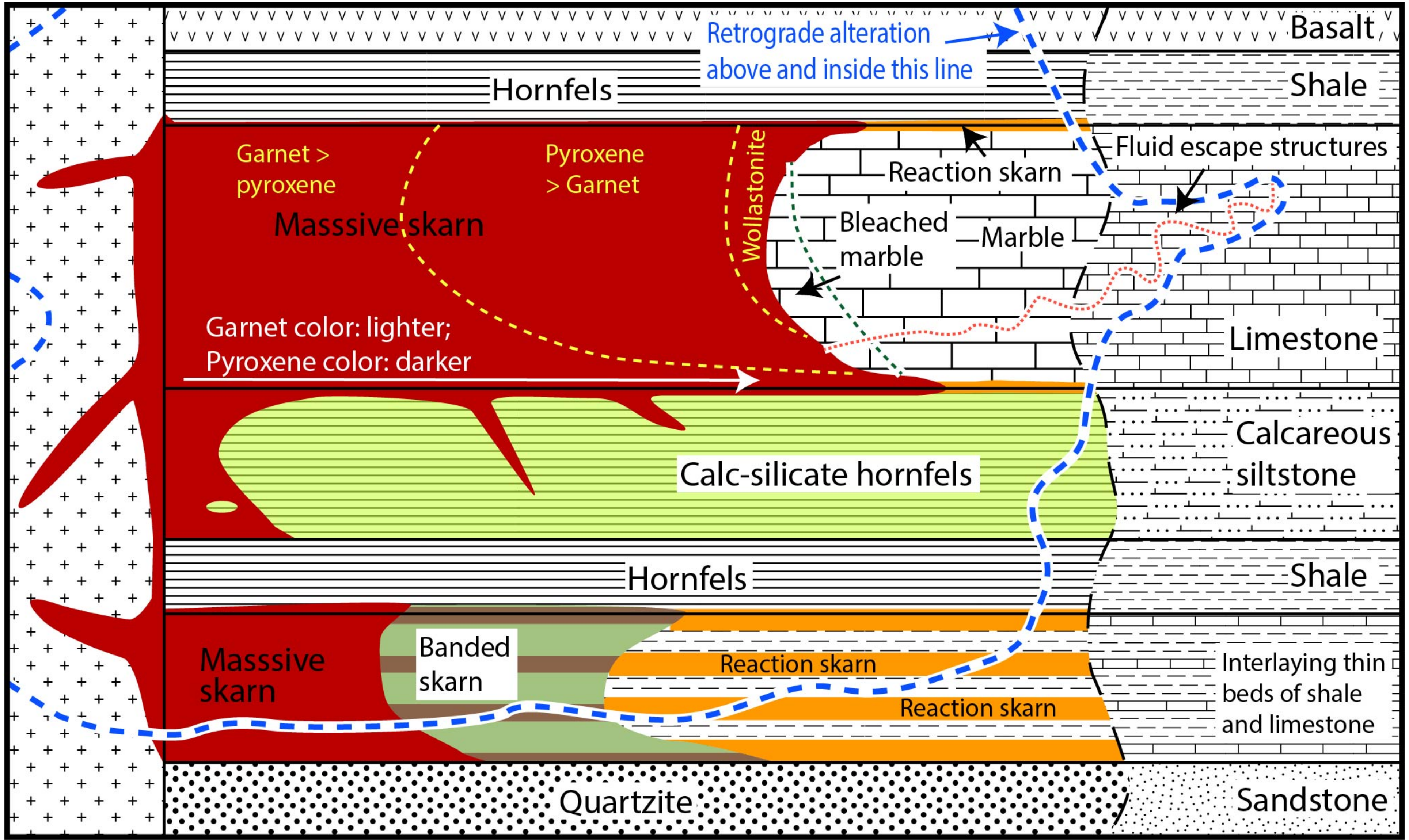
El Mochito Zn-Pb skarn, Honduras
O isotope halo: 300-400 m wide, up to 4km alone fault
C isotope halo: up to 30 m wide



Vazquez et al., 1998

Summary – skarn zonation

Chang et al., 2019



Factors affecting the formation of skarns

Redox state gradient between magma and wall rock

Causative magma

Volatiles
*Degree of fractionation**
*Redox state**

Wall rock

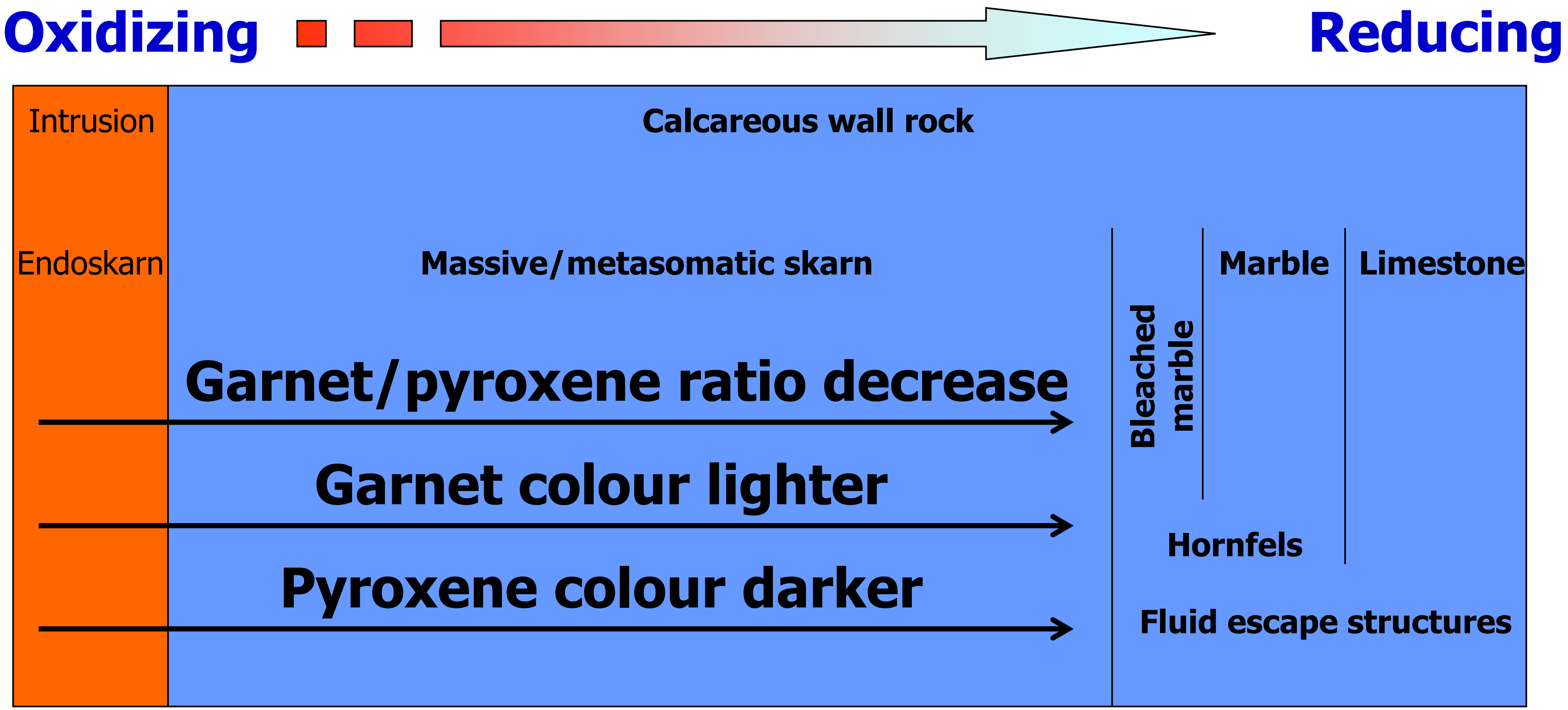
Composition
Redox state
Permeability

Depth of formation

Distance from magma

Redox state gradient

The zoning pattern is based on:



Fe^{3+} → garnet

Grossular $Ca_3Al_2(SiO_4)_3$

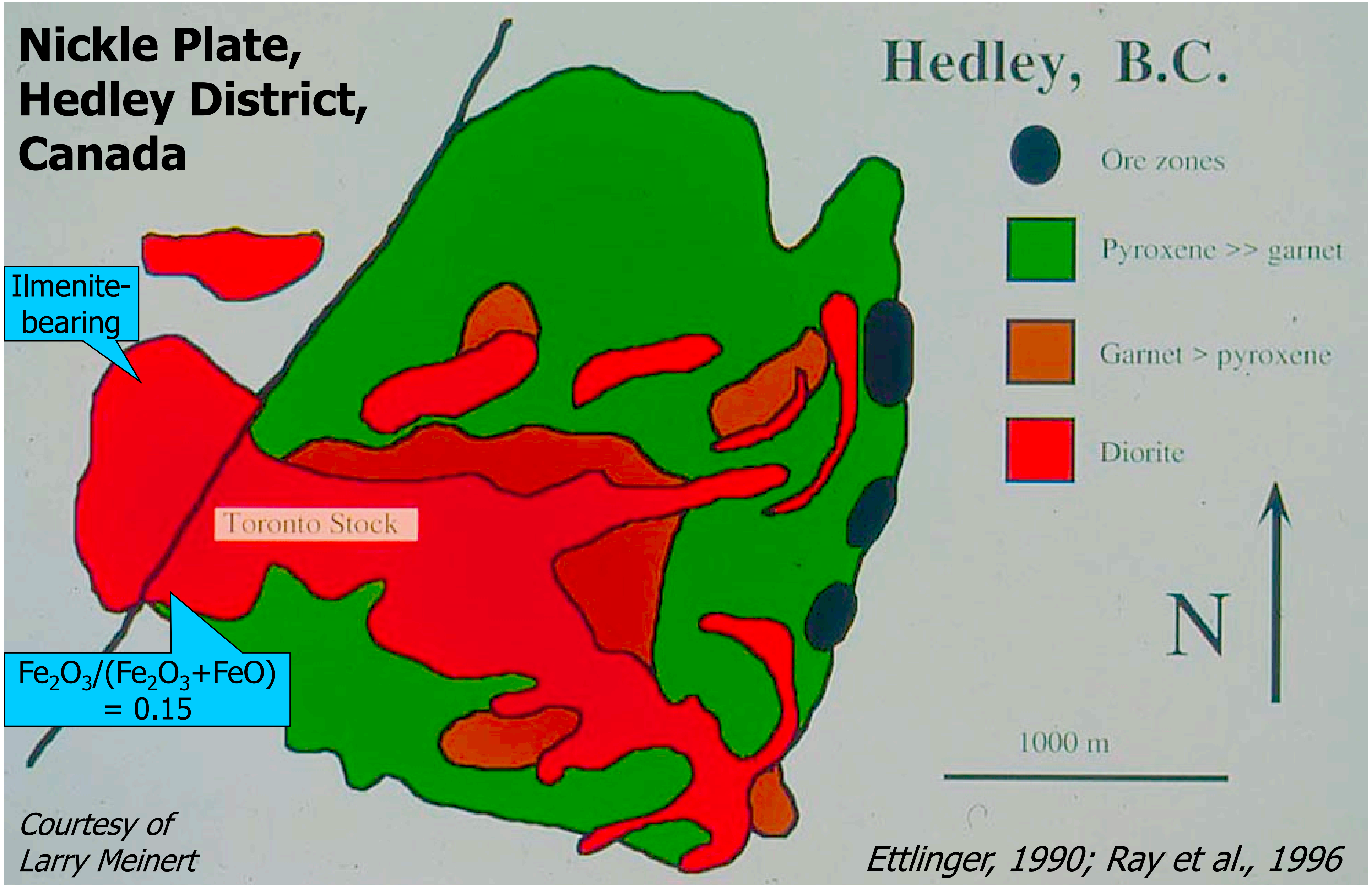
Andradite $Ca_3Fe^{3+}{}_2(SiO_4)_3$

Fe^{2+} → pyroxene

Diopside $CaMgSi_2O_6$

Hedenbergite $CaFe^{2+}Si_2O_6$

If both the magma and the wall rocks are reducing …



If both the magma and the wall rocks are oxidizing …

A Cu skarn prospect, Philippines

If both the magma and the wall rocks are oxidizing …

38.3m Endoskarn. Dark red garnet

45.2m Red garnet

46.3m Brown garnet

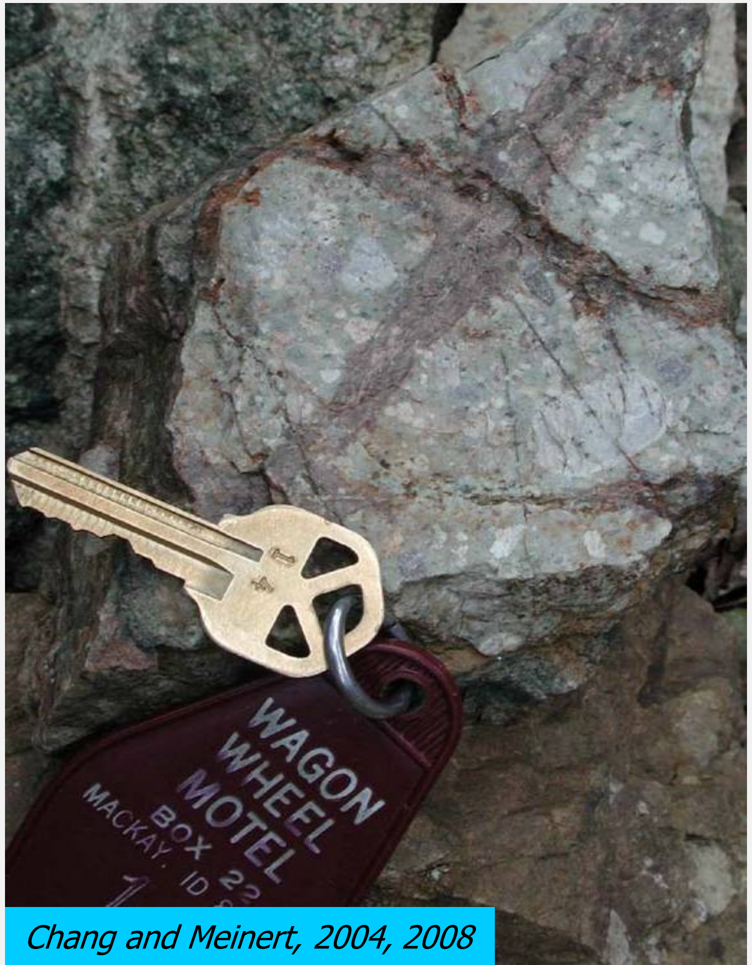
48.2m Yellow garnet

54.2m Light yellow garnet

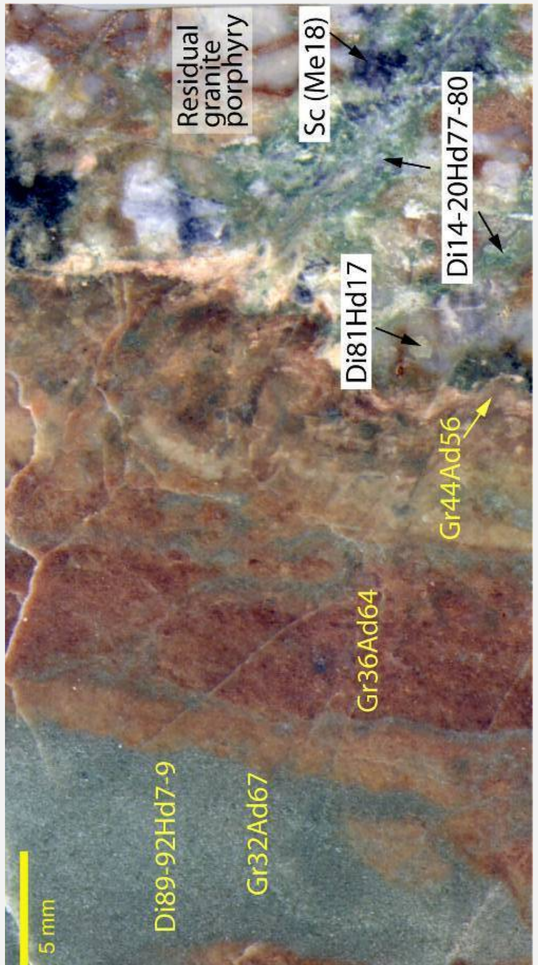
Effect of magmatic volatiles - F

Empire Cu-Zn skarn, USA

Unusual features: 1) Abundant endoskarn, > exoskarn
2) Proximal Zn minearlisation



Chang and Meinert, 2004, 2008

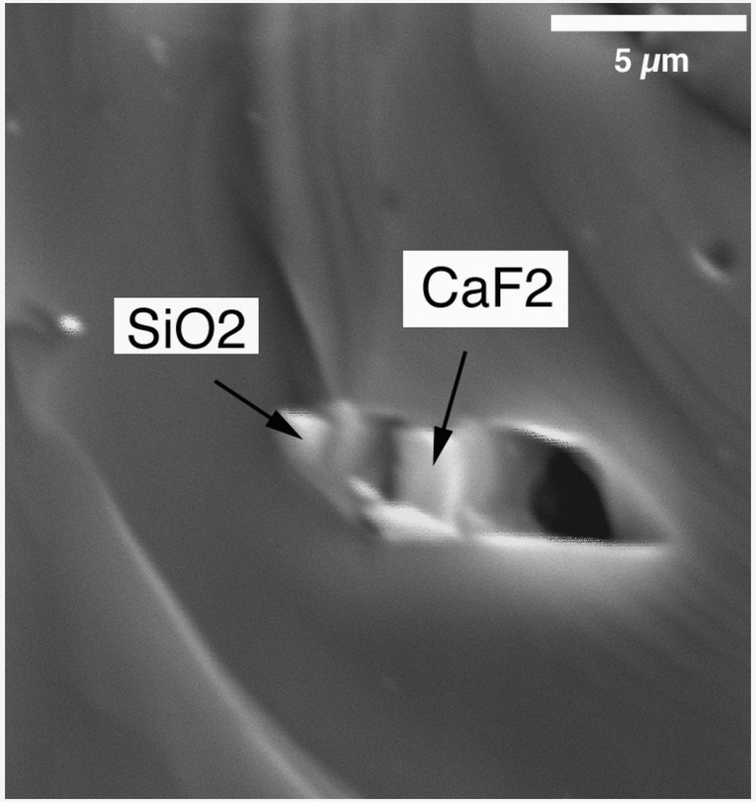


Effect of magmatic volatiles - F

Empire Cu-Zn skarn mine, USA

High F content in the magmatic-hydrothermal system as indicated by:

- **1.53-2.46 wt% F in magmatic hornblende**
- **1.43-3.87 wt% F in magmatic biotite**
- **Fluorite as igneous accessory mineral**
- **Fluorite as daughter mineral in fluid inclusions**
- **1.29-2.42 wt% F in hydrothermal vesuvianite**
- **Fluorite in skarns**



Chang and Meinert, 2004, 2008

Effect of magmatic volatiles - F

Empire Cu-Zn skarn mine, USA

Reasons for these unusual features:

- **F greatly facilitates the dissolution of silicates**
- **F decreases the solidus temperatures of magmas. When the late-stage fluids exsolved from them, the fluids were already at low temperatures, therefore only short transportation distance was needed for the fluids to be cool enough to deposit sphalerite**

Chang and Meinert, 2004, 2008

Textures indicating high F

Chang and Meinert, 2004, 2008

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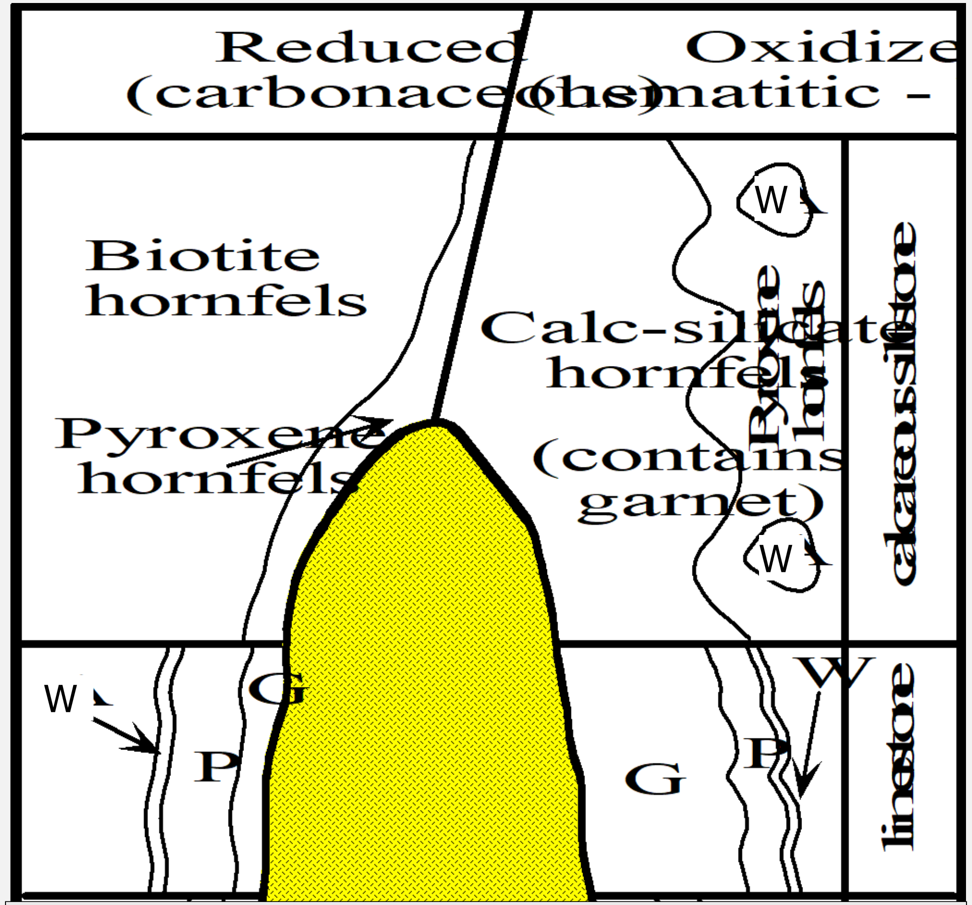
Effect of wall rocks

Composition – Ca skarn vs. Mg skarn

Redox

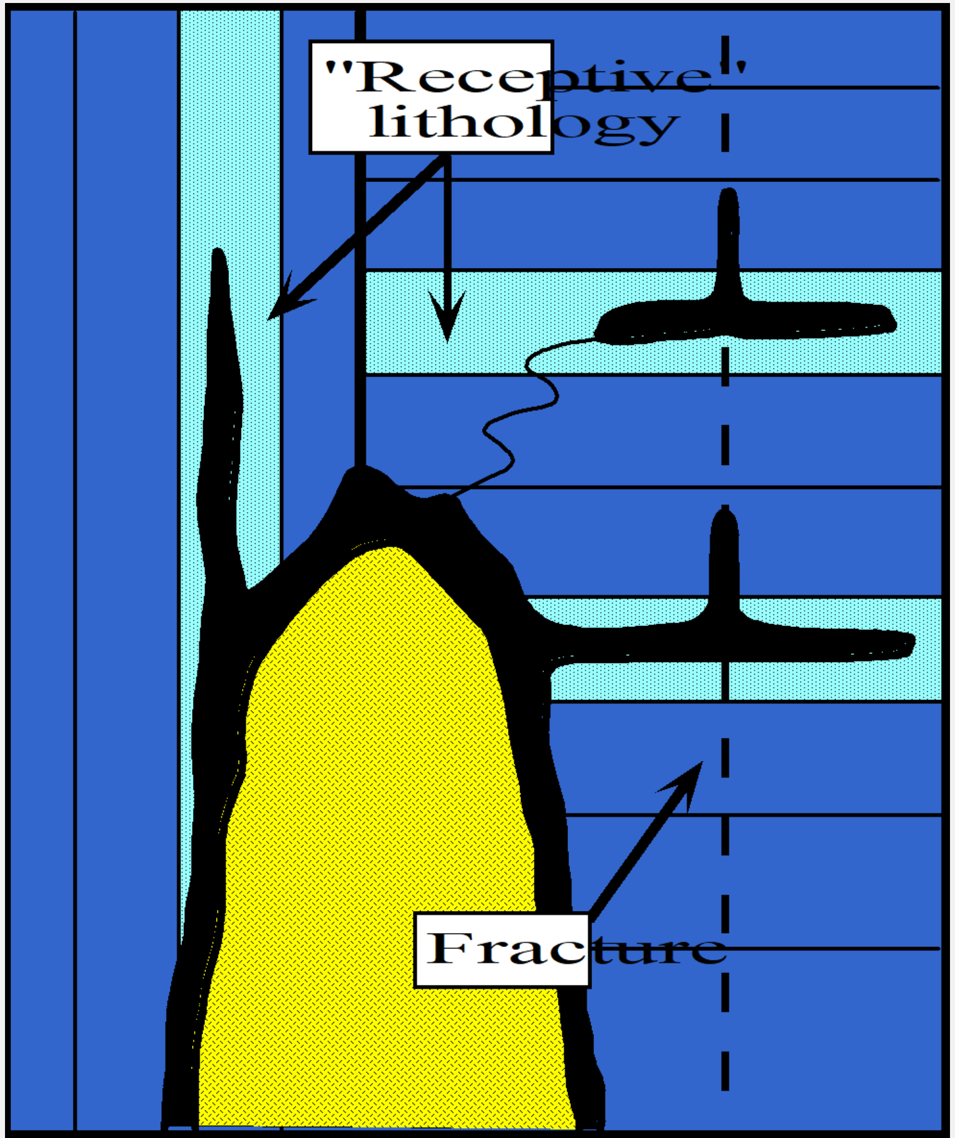


$CaCO_3 + SiO_{2(aq)} = CaSiO_3 + CO_2$

$C + O_2 = CO_2$

W: wollastonite; P: pyroxene; G: garnet

Porosity, composition

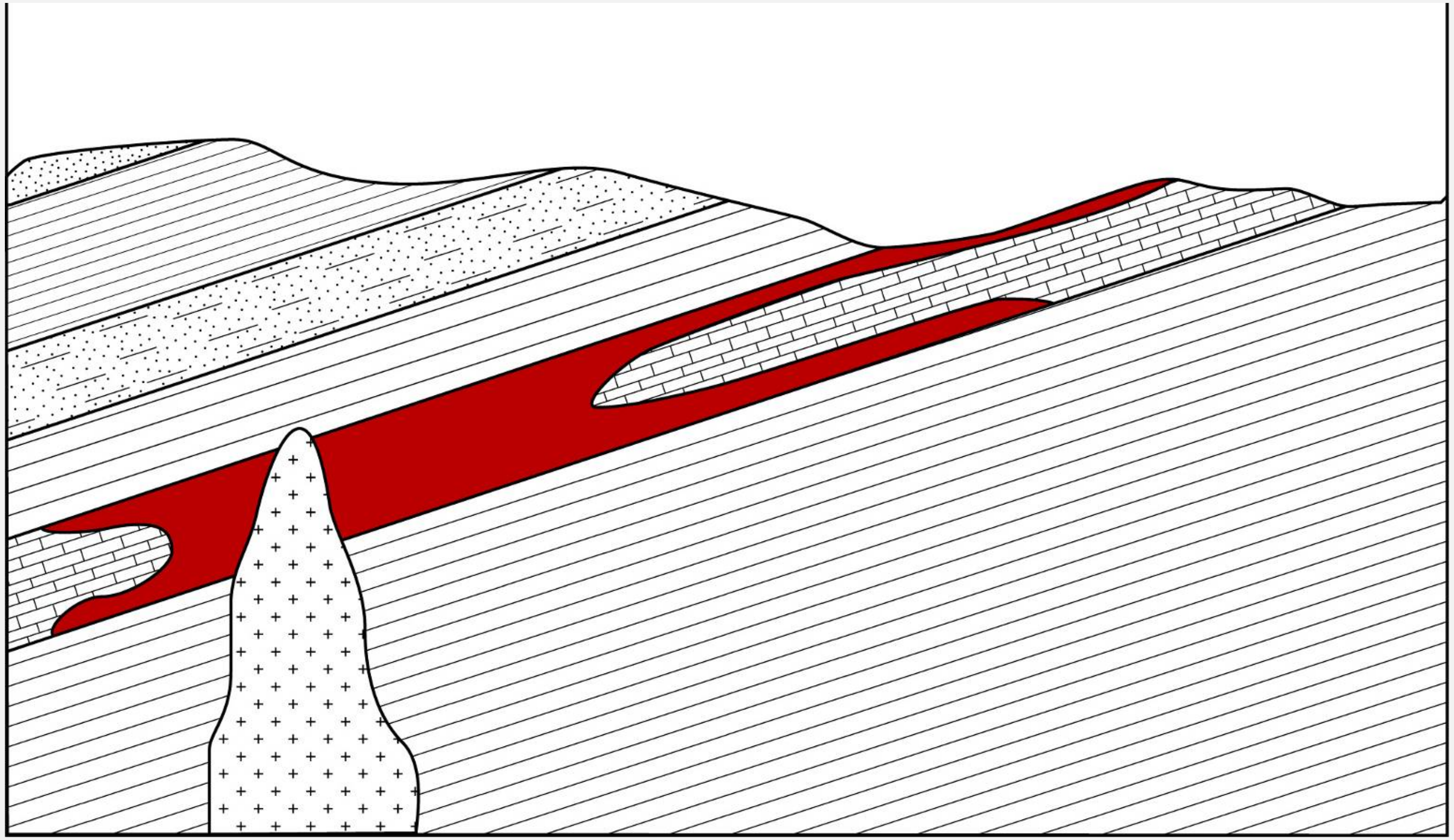


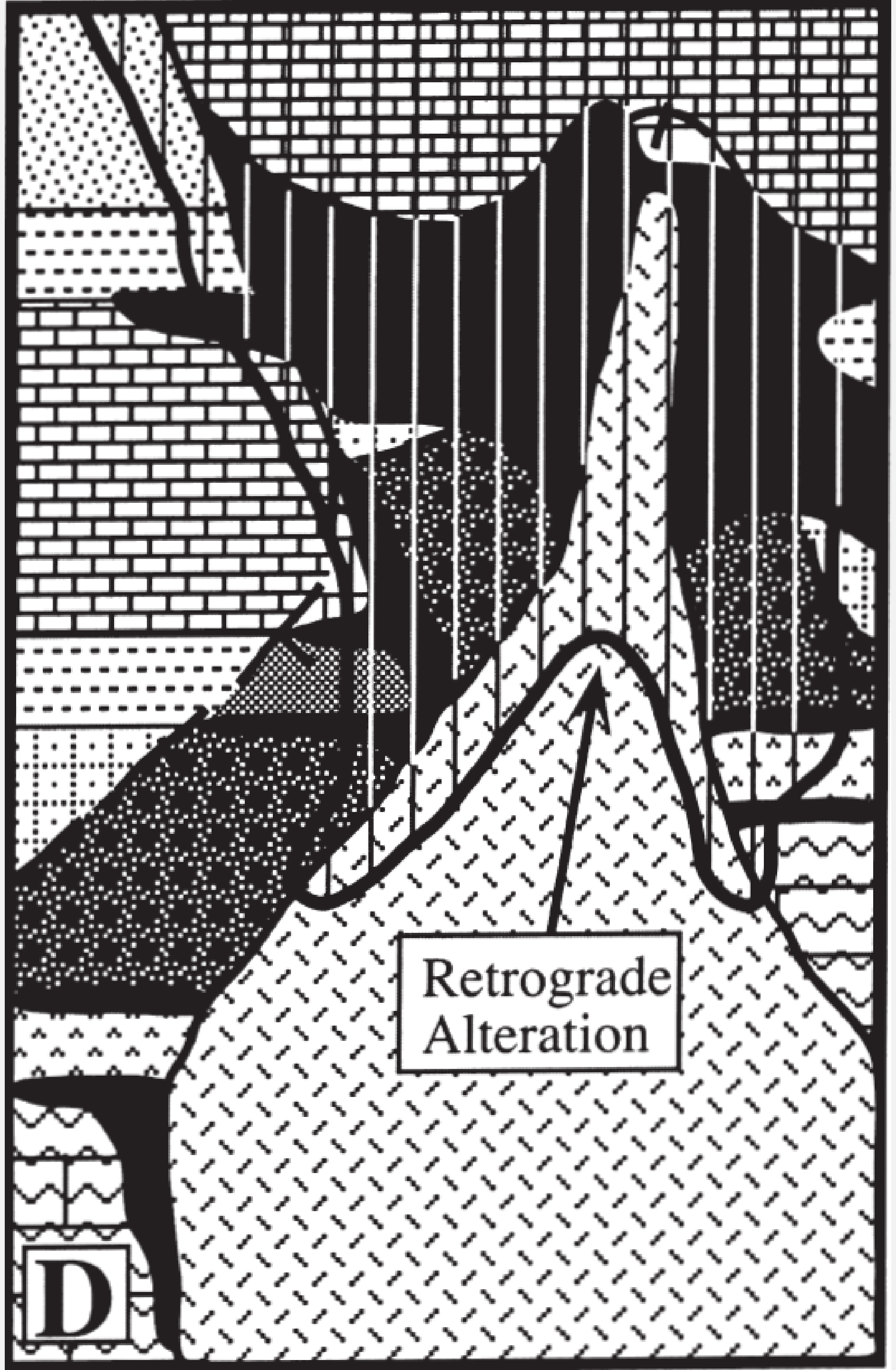
Courtesy of Larry Meinert

Effect of wall rocks

Geometry

- Massive/irregular vs. stratabound





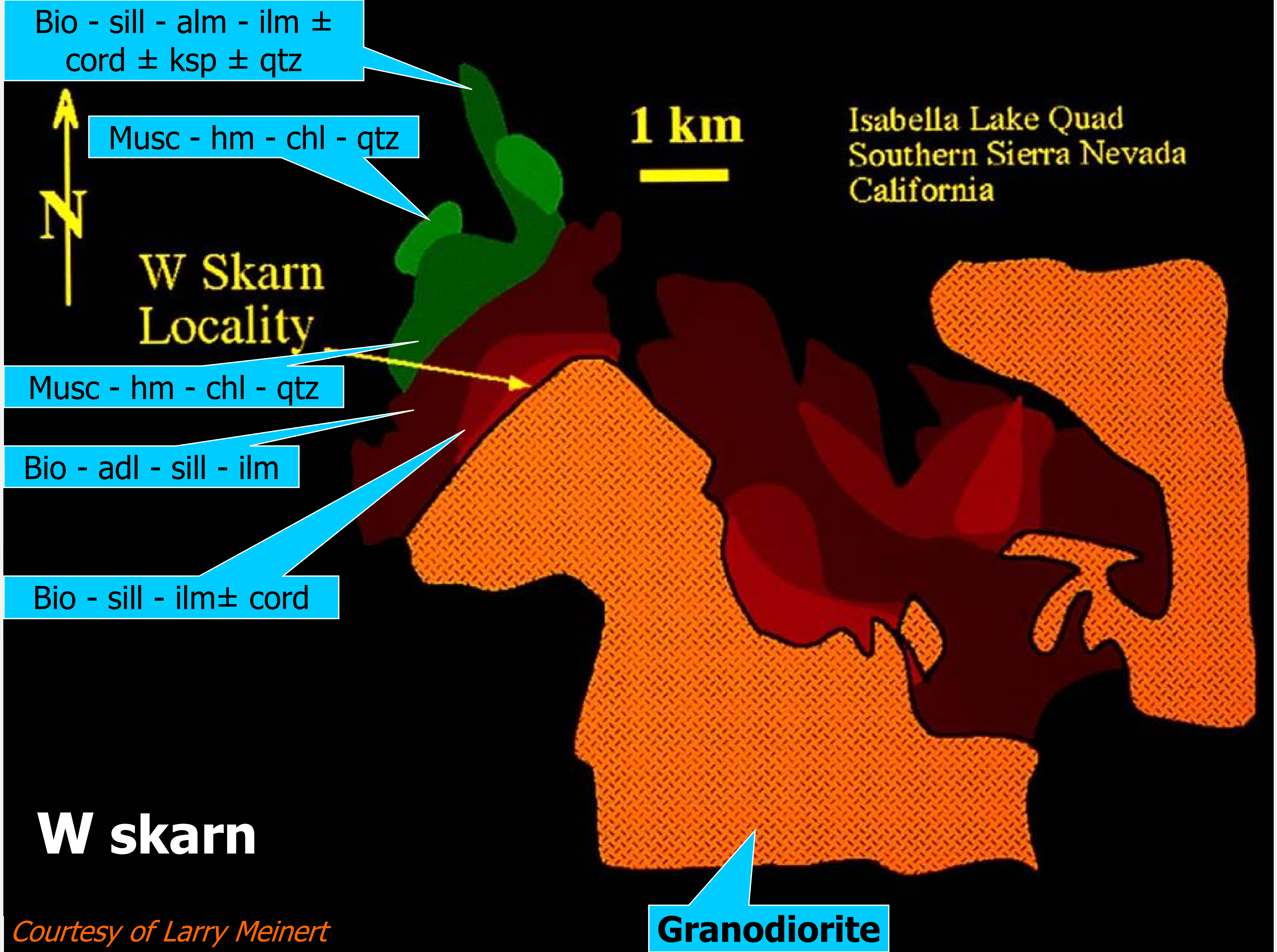
DEPTH OF FORMATION

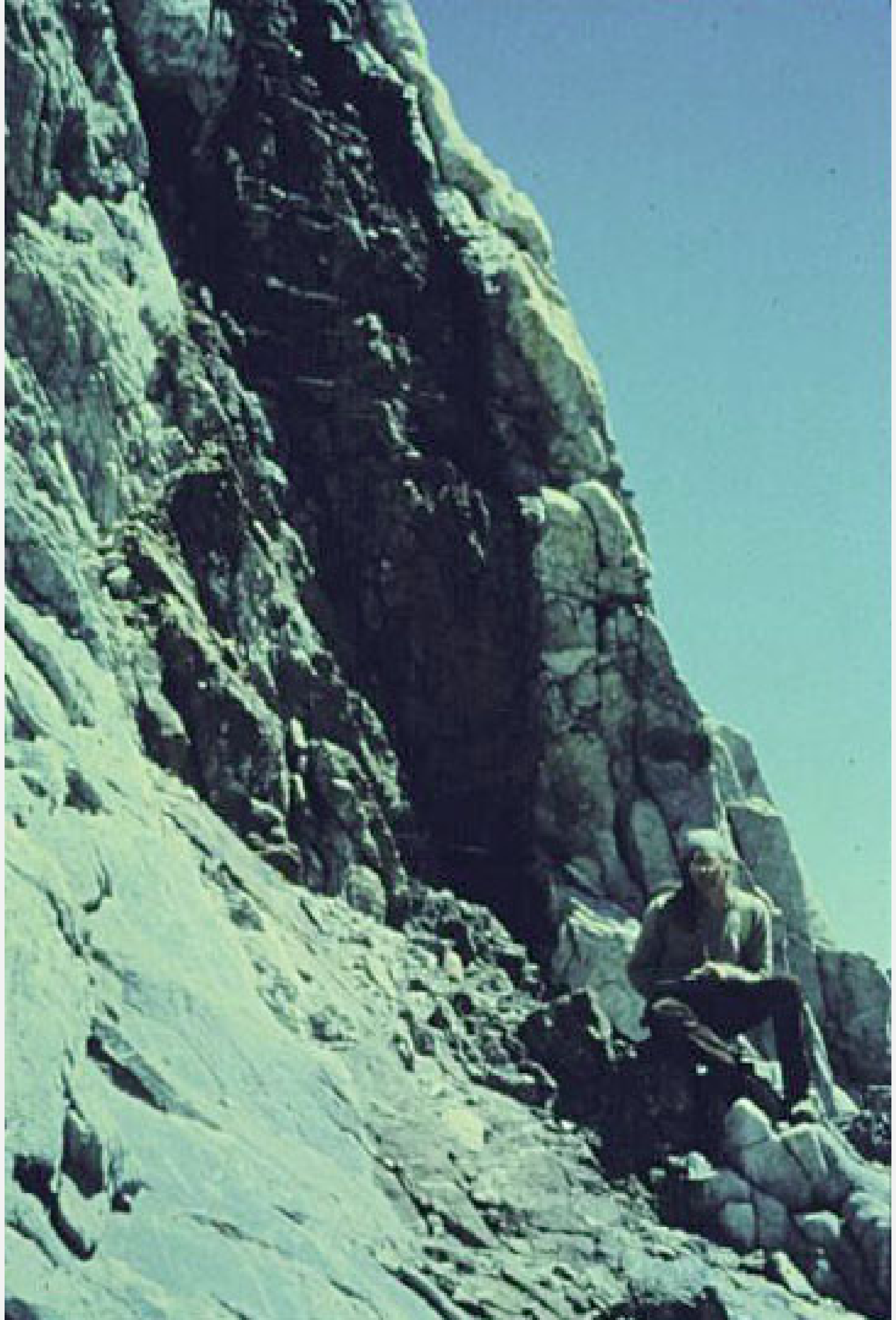
- **Ambient temperature**
  - **Metamorphism**
  - **Retrograde alteration**

- **Permeability**

W skarn vs. Cu skarn

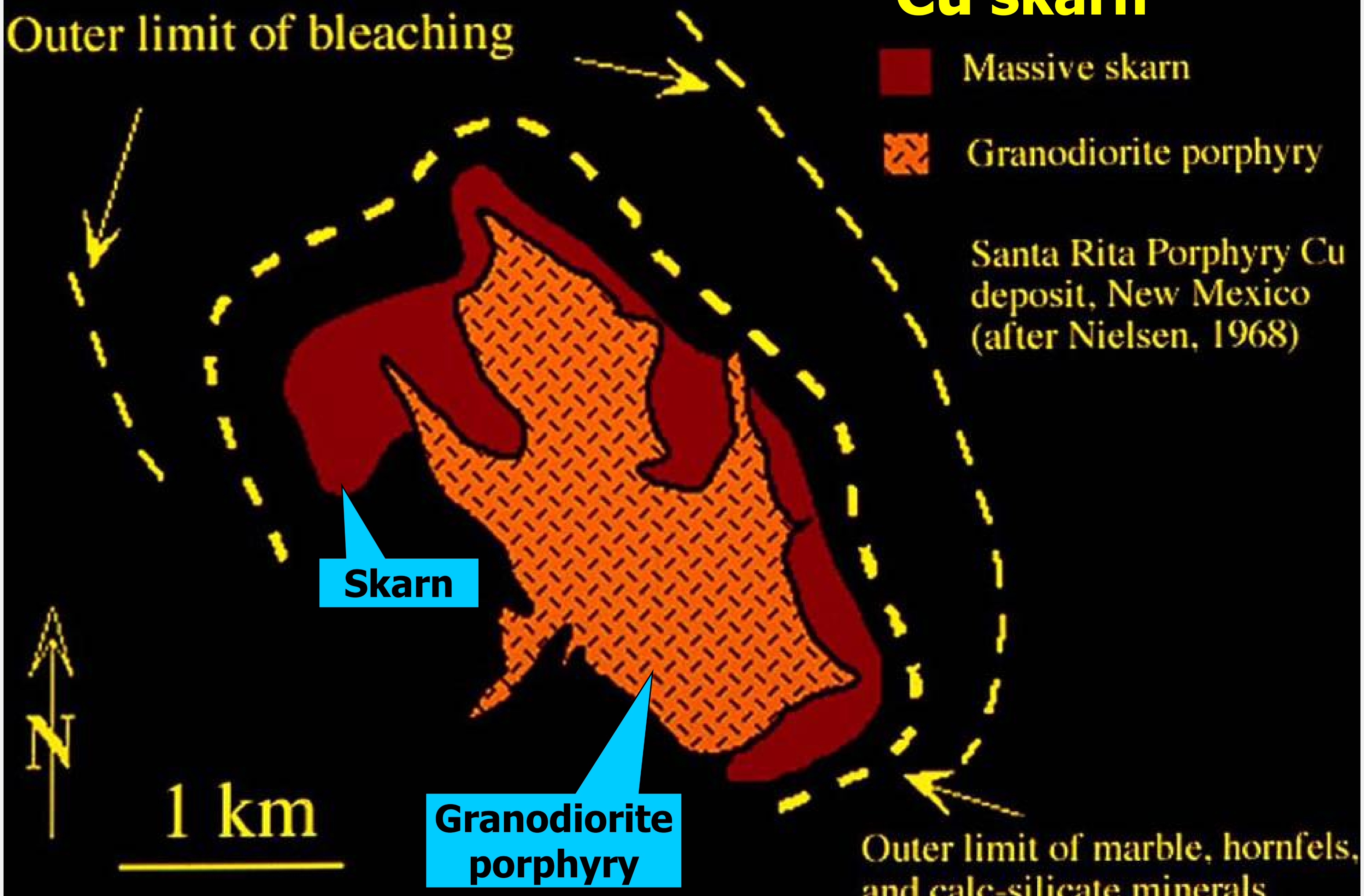
Meinert, 1992


Bio - sill - alm - ilm ± cord ± ksp ± qtz
Musc - hm - chl - qtz
N
W Skarn Locality
1 km
Isabella Lake Quad
Southern Sierra Nevada
California
Musc - hm - chl - qtz
Bio - adl - sill - ilm
Bio - sill - ilm± cord
W skarn
Granodiorite
Courtesy of Larry Meinert



Courtesy of
Larry Meinert

Cu skarn



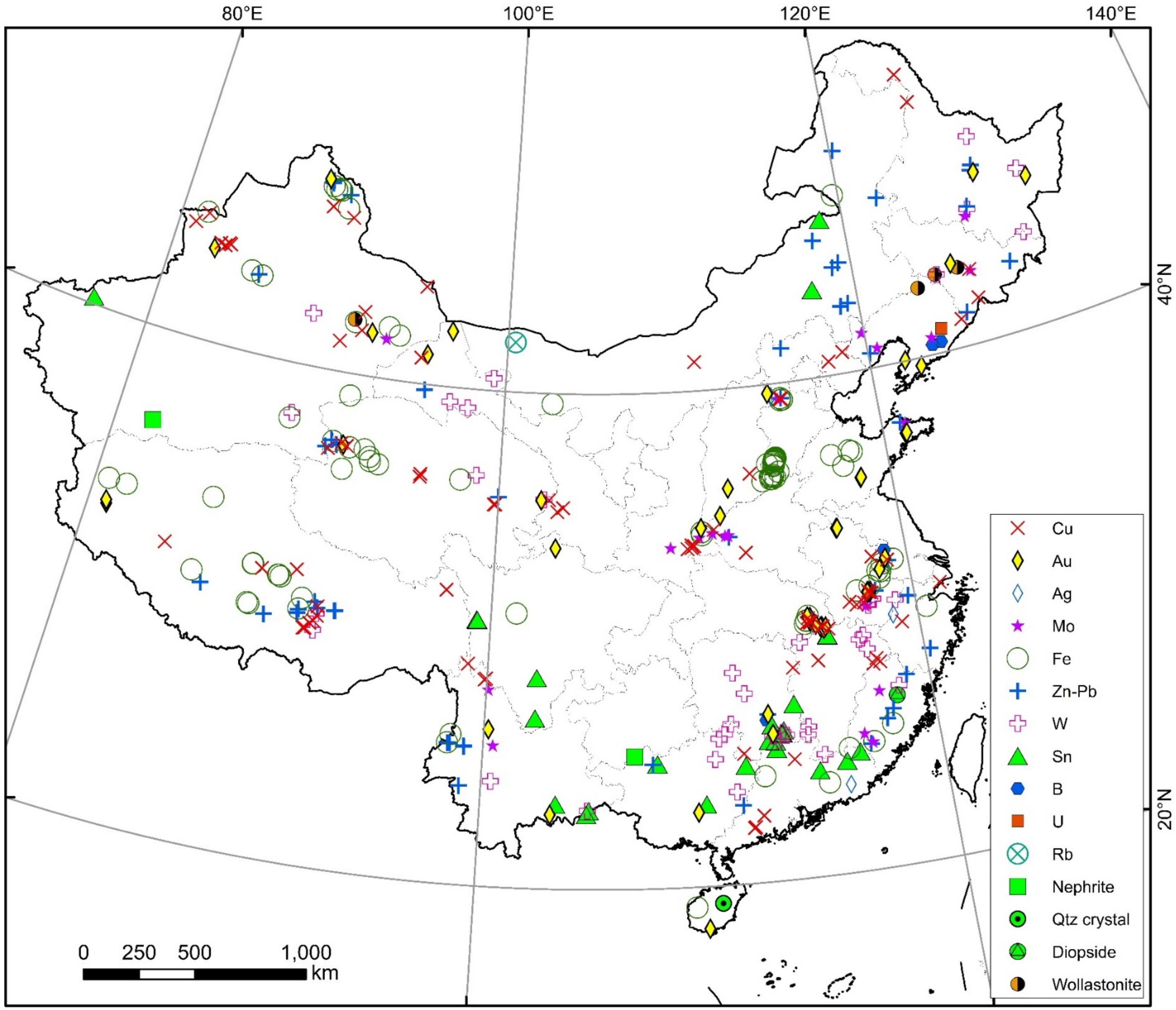
Courtesy of Larry Meinert


Courtesy of Larry Meinert

Metal association based on skarns in China

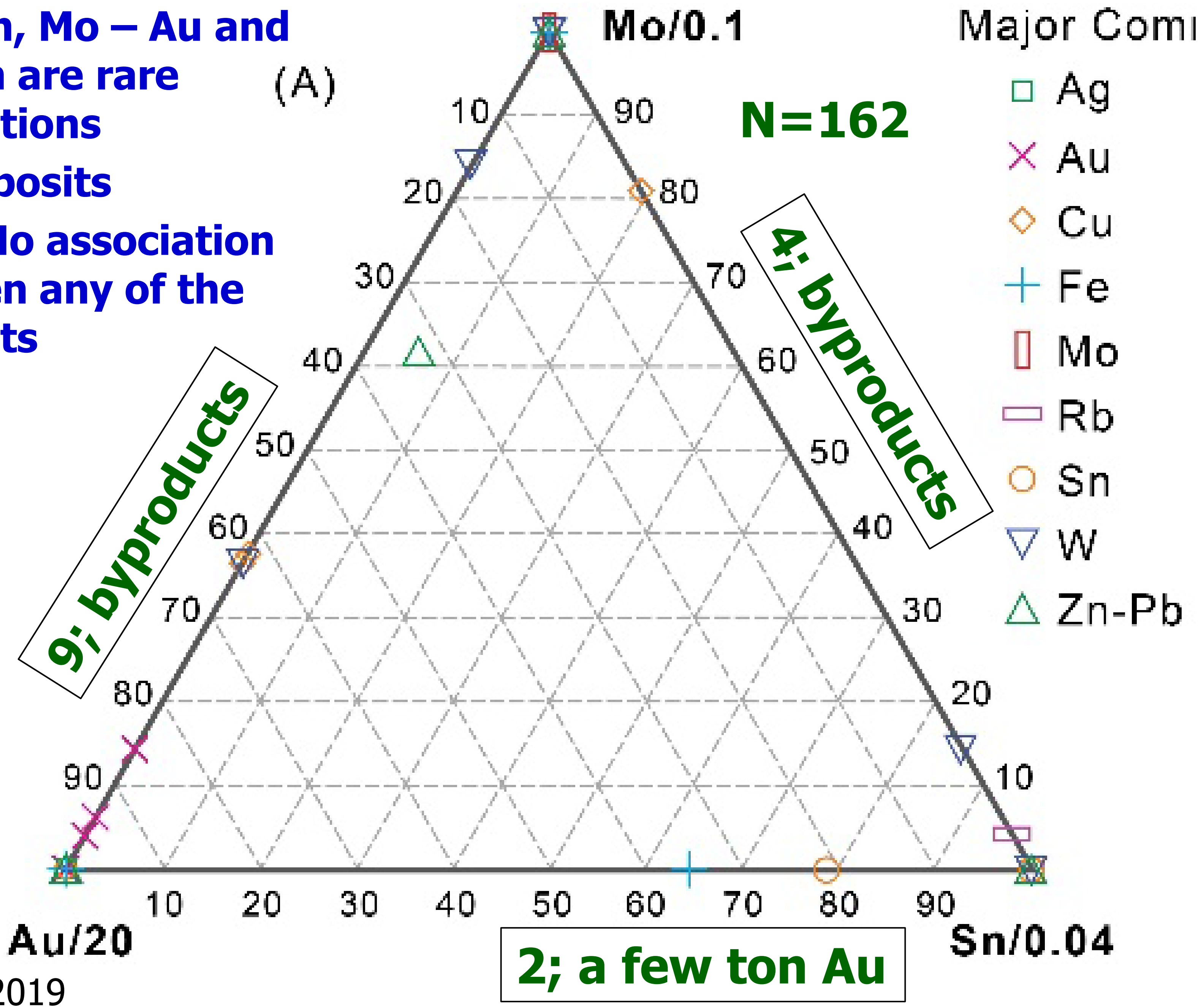
- **386 deposits reported, 24% of world skarns (1627)**
  - **Traditionally resources of all metals calculated under planned economy**

→ good for metal association studies



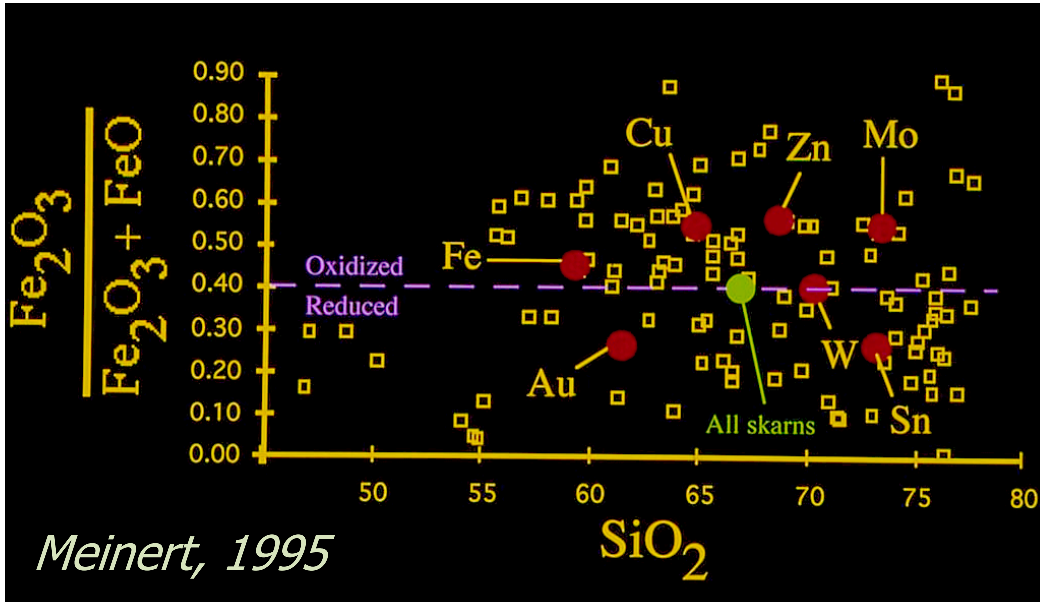
Chang et al., 2019

- **Mo – Sn, Mo – Au and Au – Sn are rare associations**
- **162 deposits**
- **90%: No association between any of the elements**



Chang et al., 2019

Redox and fractionation of causative magmas



Both Au-only skarn and Sn skarn are related to reduced magmas But Au is related to more mafic magmas whereas Sn & Mo related to felsic magmas

→ Mo-Au and Sn-Au associations rare

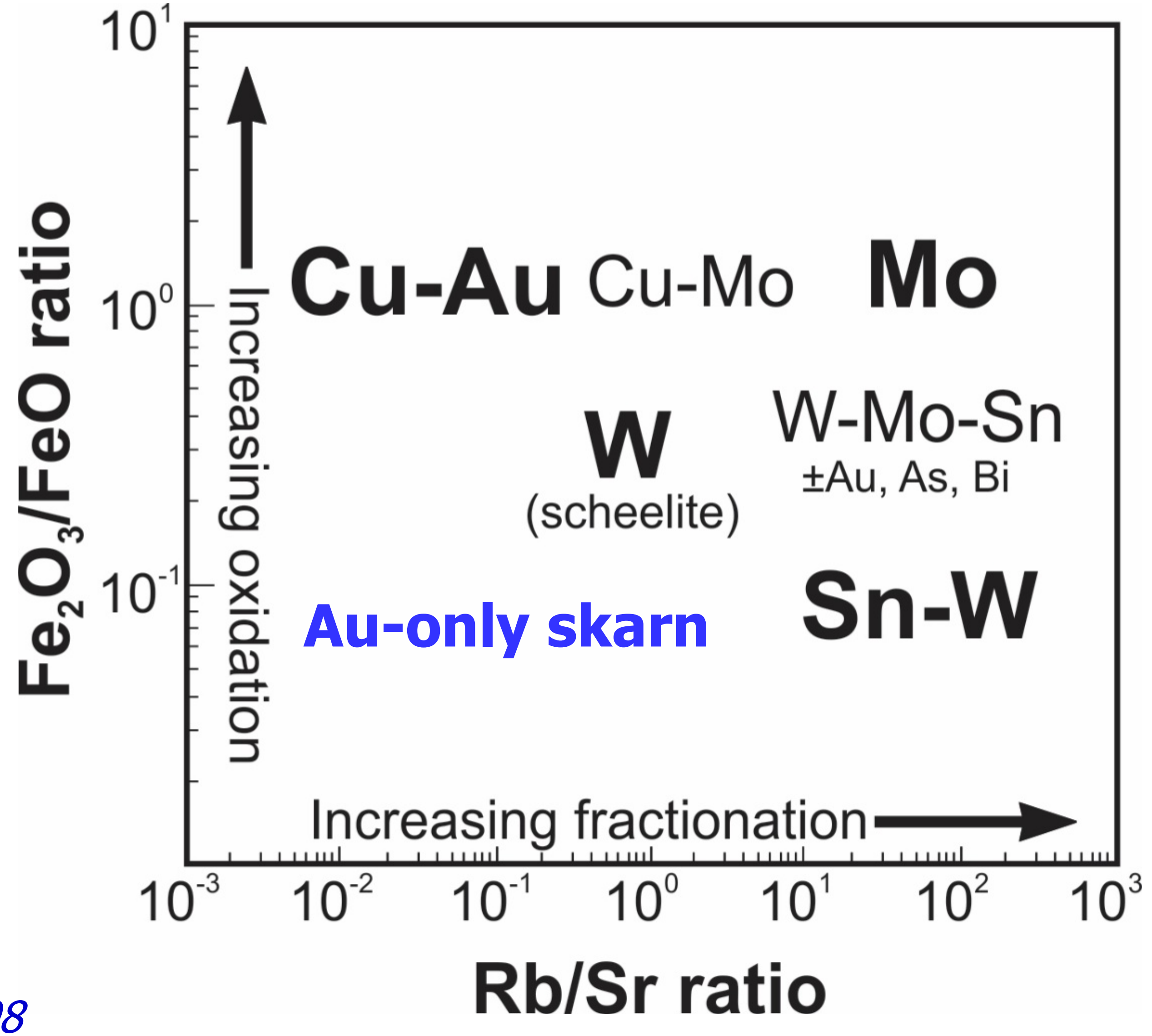
Chang et al., 2019

- Sn^{4+} : Ti^{4+} and Fe^{3+} in biotite, hornblende, titanite, ilmenite, and magnetite → Sn is dispersed in igneous rocks in oxidized environment
- Needs reduced environment so that Sn as Sn^{2+} is enriched in fractionated magmas

- Mo^{4+} can substitute for Ti^{4+}
- Mo^{6+} is incompatible

Lehmann, 1990

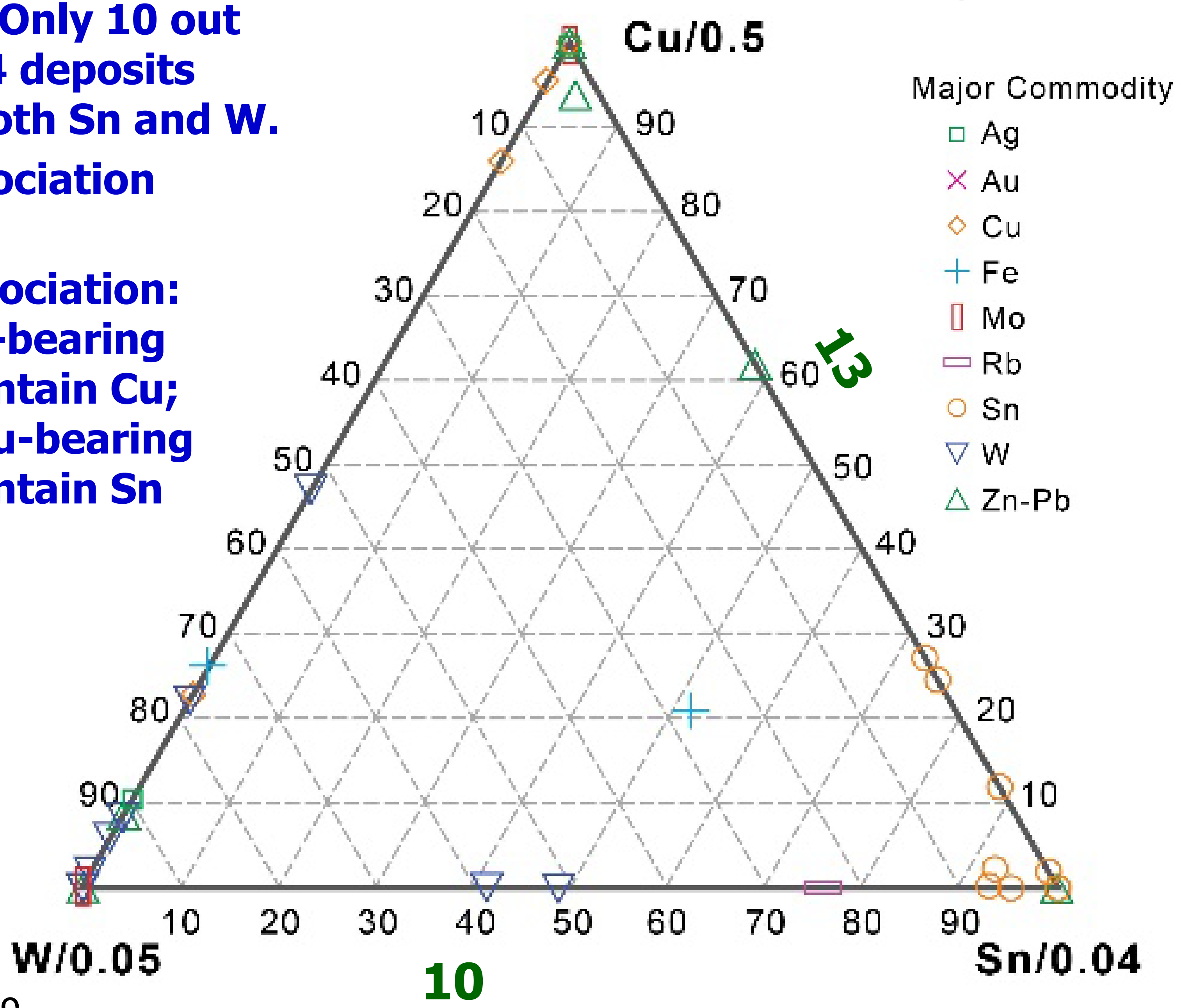
Redox and fractionation of causative magmas



Blevin, 1998

- W-Sn are not that common. Only 10 out of the 184 deposits contain both Sn and W.
- W-Cu association moderate
- Sn-Cu association: 13/33 Sn-bearing skarns contain Cu; 13/133 Cu-bearing skarns contain Sn

N=184



Chang et al., 2019

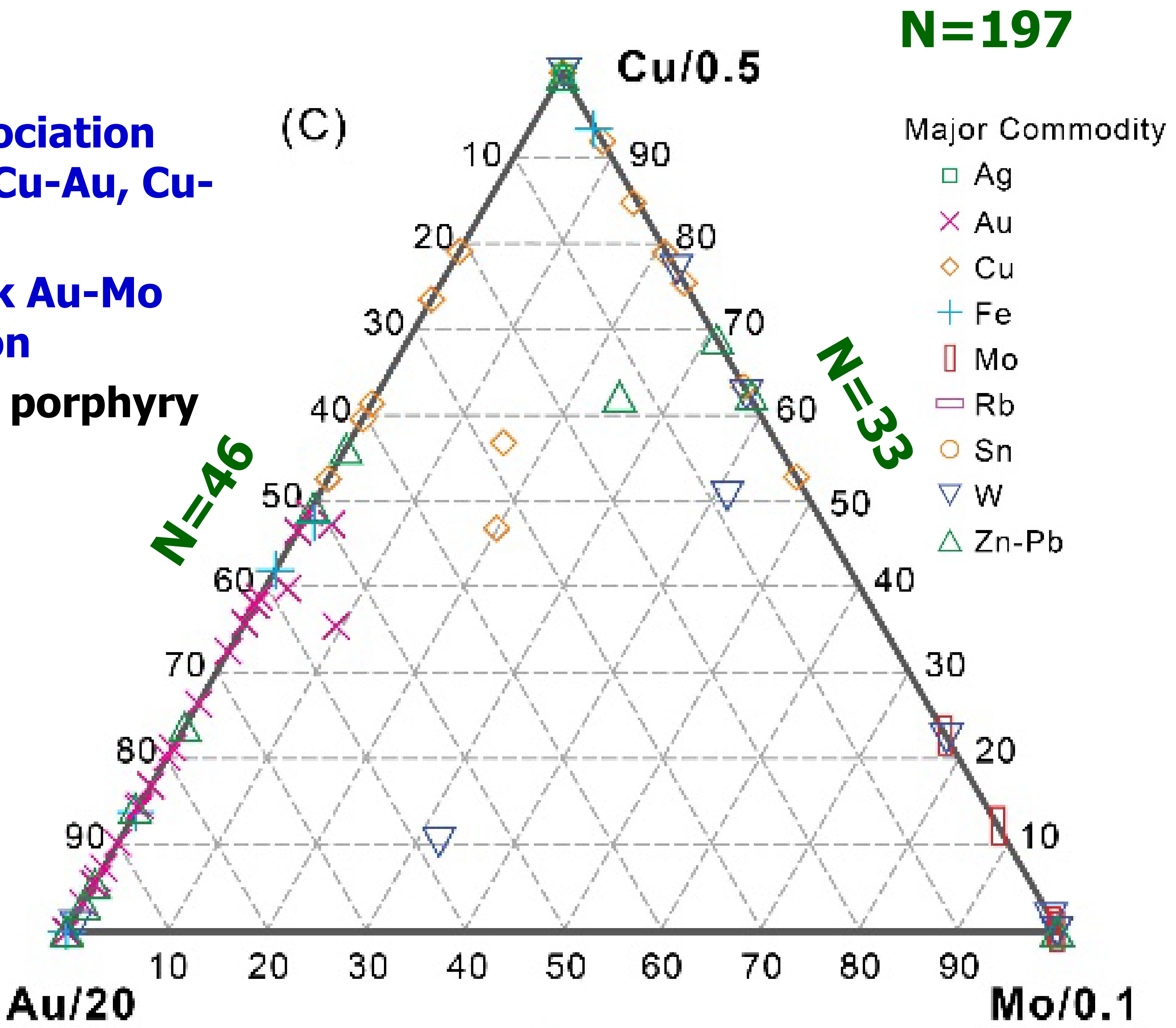
W VS. SN WORLD-WIDE

1. **Classic W skarns, even the reduced ones associated with S-type granite, contain little Sn and Sn-associated elements including Be, Li, Rb, F and Cs**

2. **Reduced W skarns and Sn skarns have low Mo (4-76ppm). Oxidized W skarns and W-F skarns have higher Mo (135-8400ppm)**

Newberry, 1998

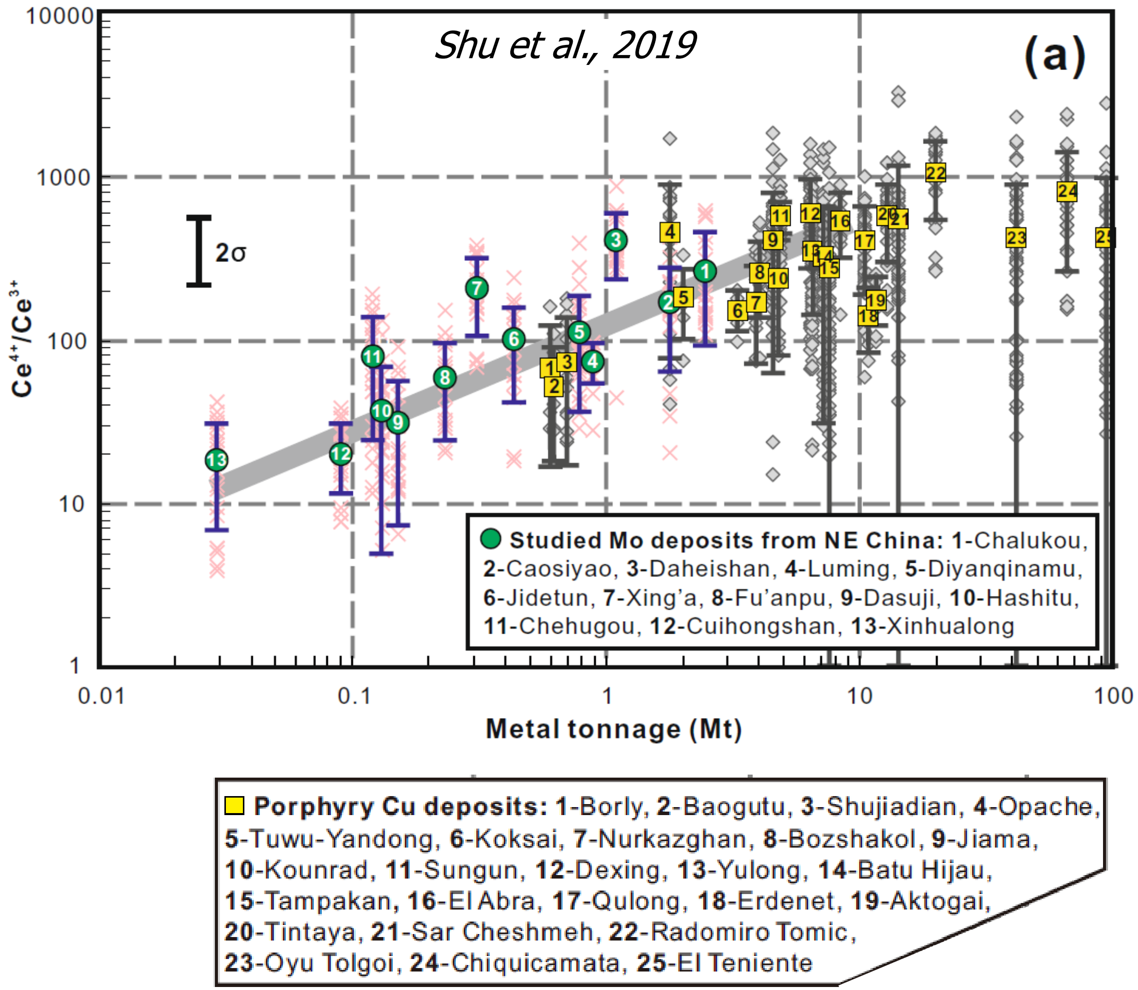
- **Close association between Cu-Au, Cu-Mo**
- **Very weak Au-Mo association**
  - **Similar to porphyry deposits**



Chang et al., 2019

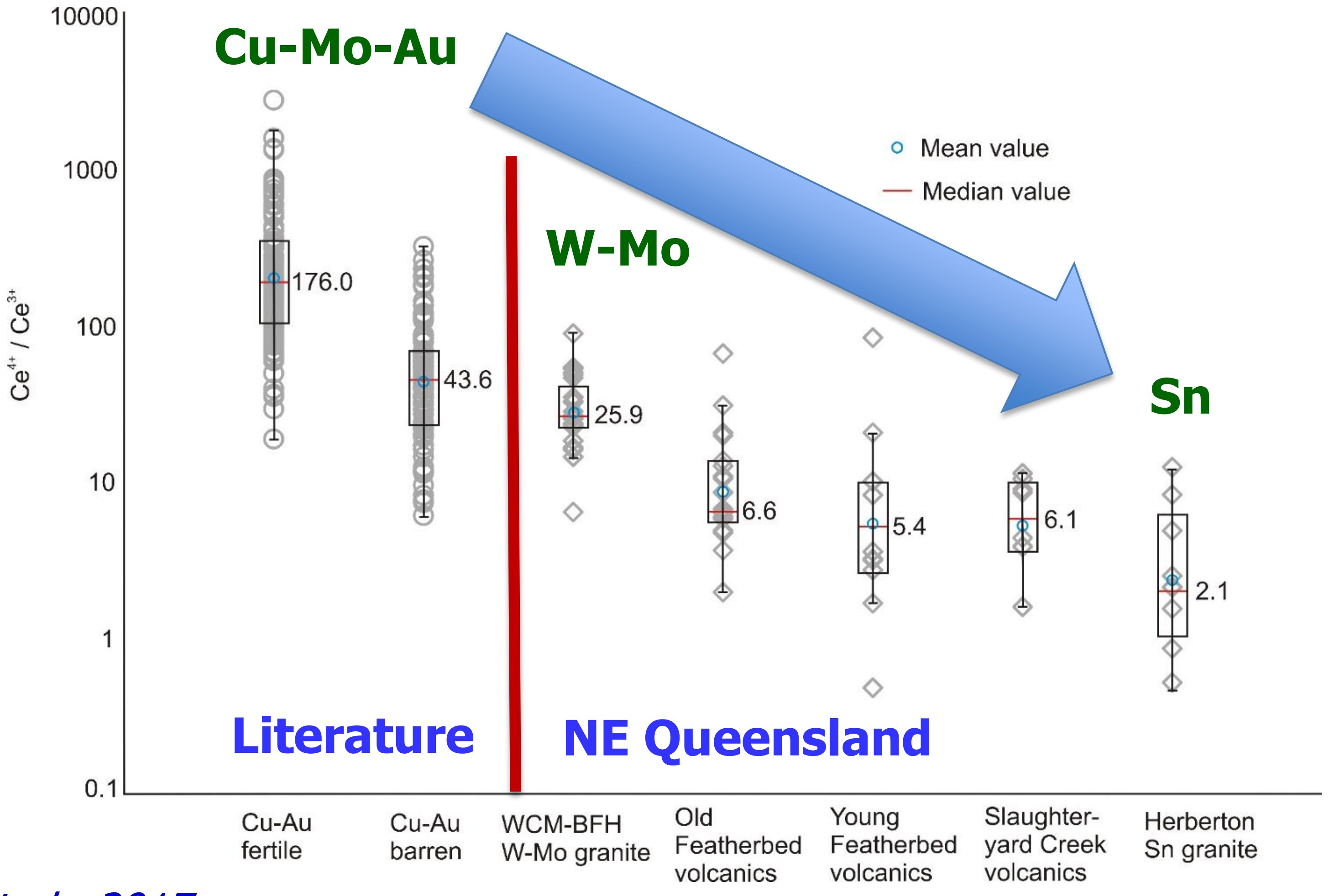
Cu-Mo:

- Both related to oxidized magmas; Cu magmas more oxidized
- Cu: less fractionated magmas; Mo: highly fractionated magmas



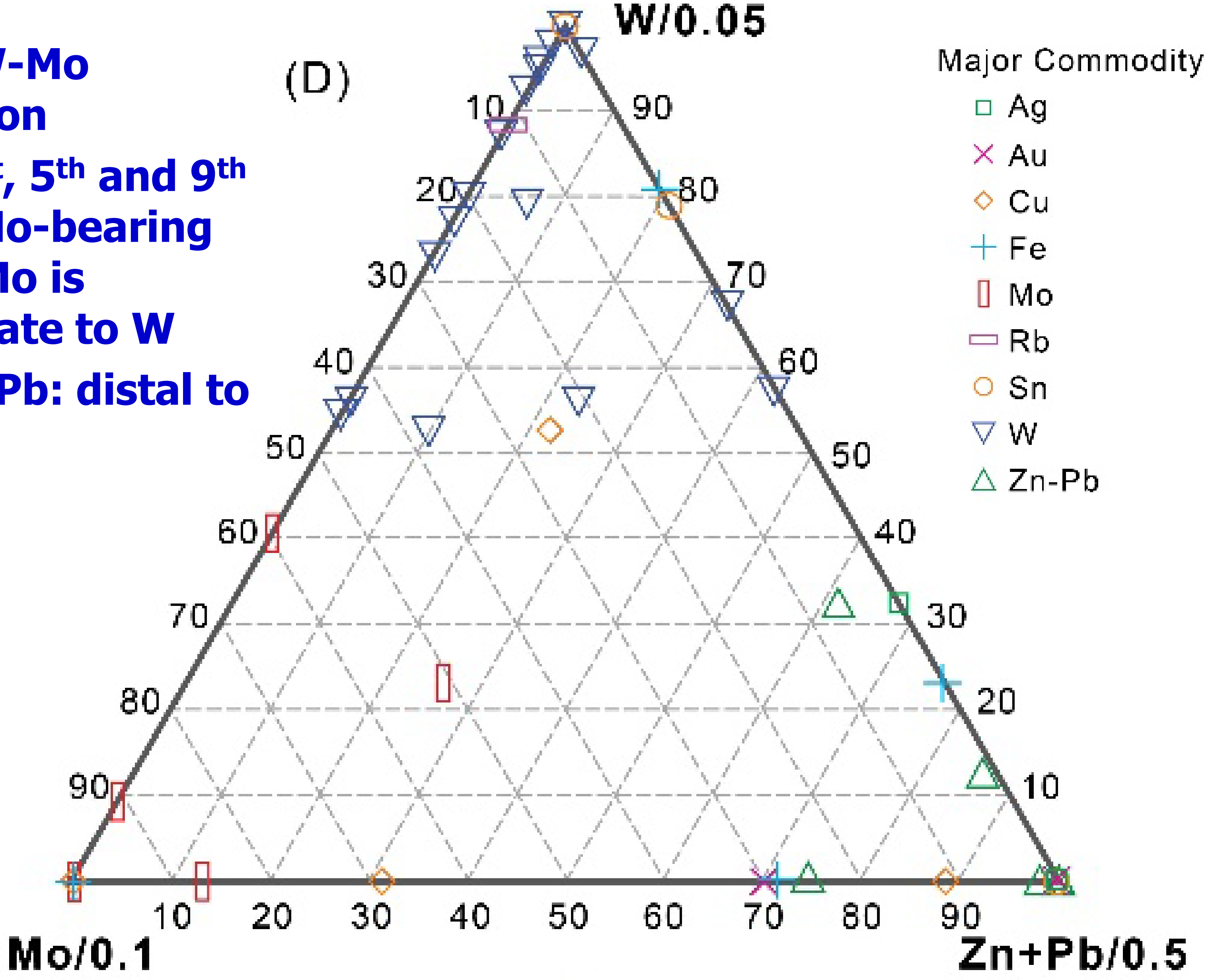
Chang et al., 2019

Redox indicated by zircon trace element



Cheng et al., 2017

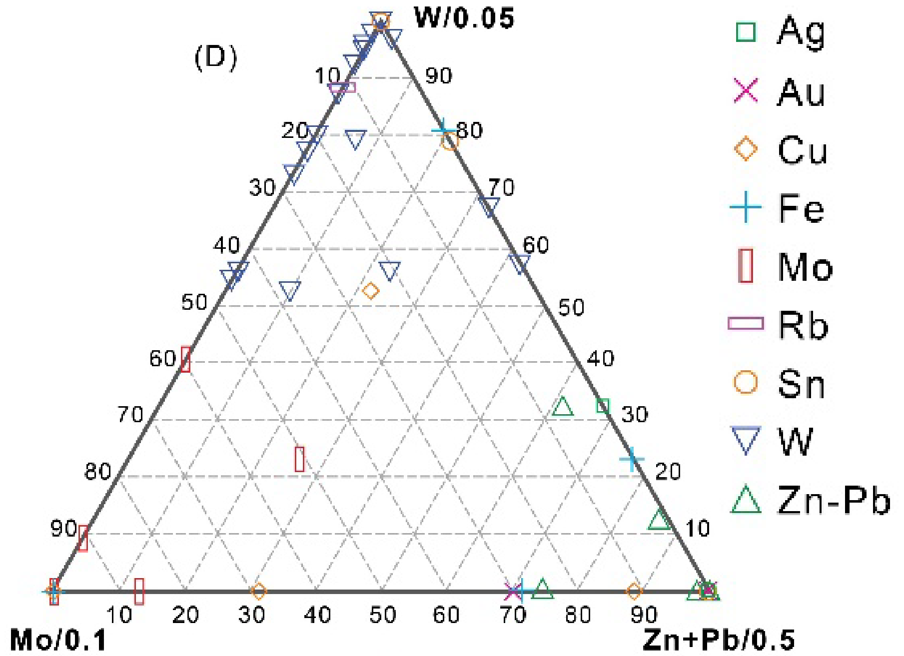
- **Strong W-Mo association**
- **In the 1st, 5th and 9th largest Mo-bearing skarns, Mo is subordinate to W**
- **Note Zn-Pb: distal to both**



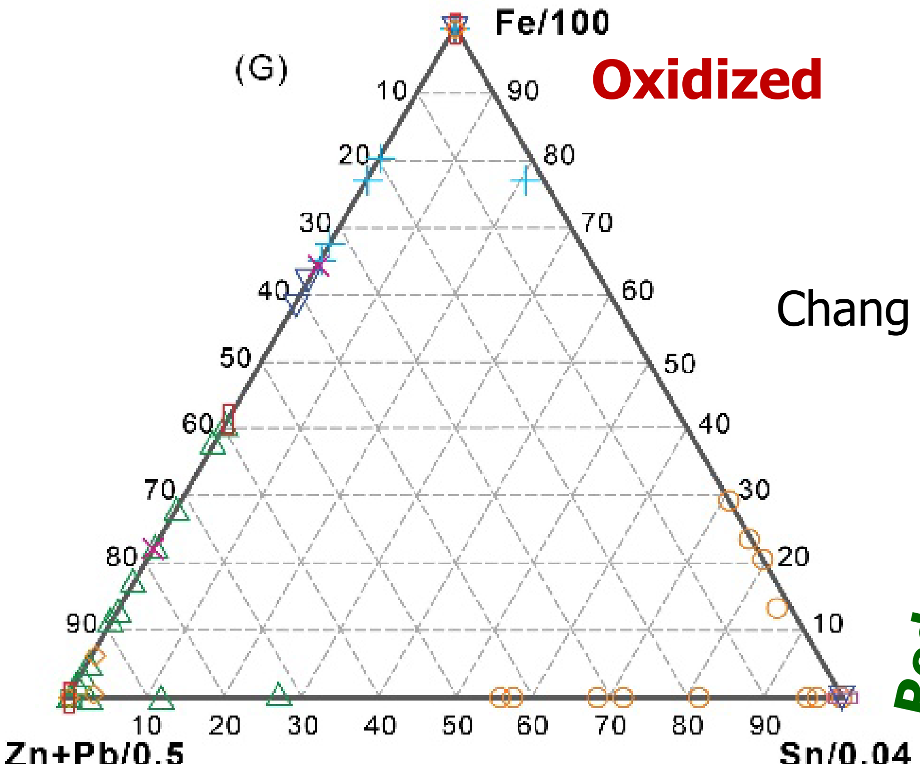
Chang et al., 2019

Zn-Pb:

- **Both oxidized and reduced magma**
- **Magmas of various degrees of fractionation**
- **Association with Au: Not commonly known; only a few deposits outside of China**



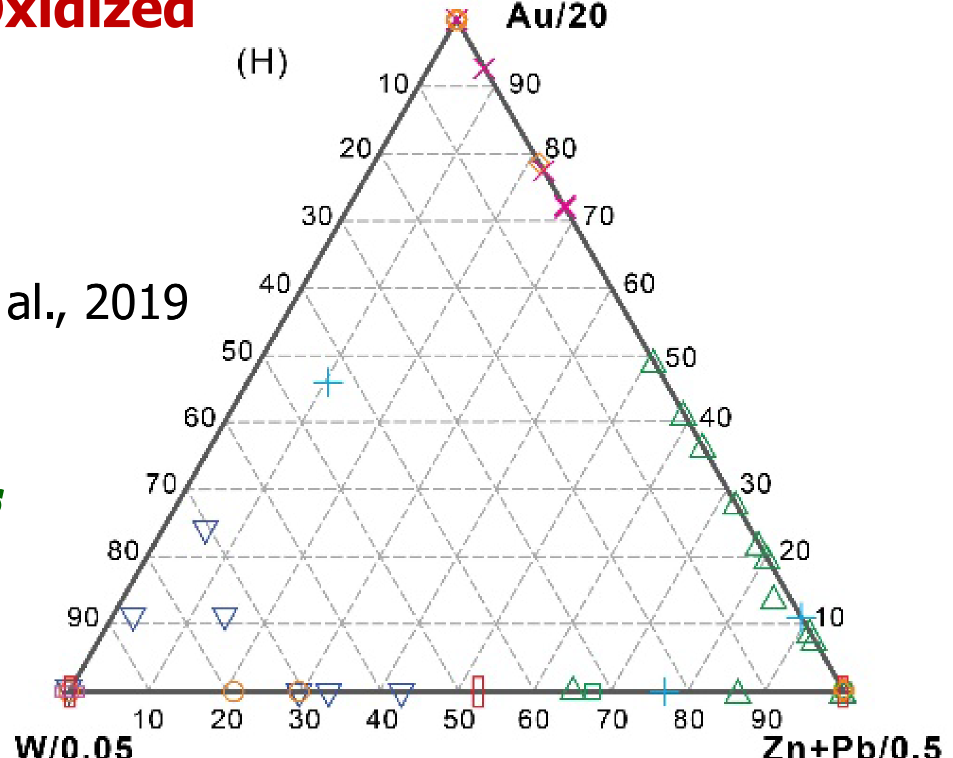
Oxidized



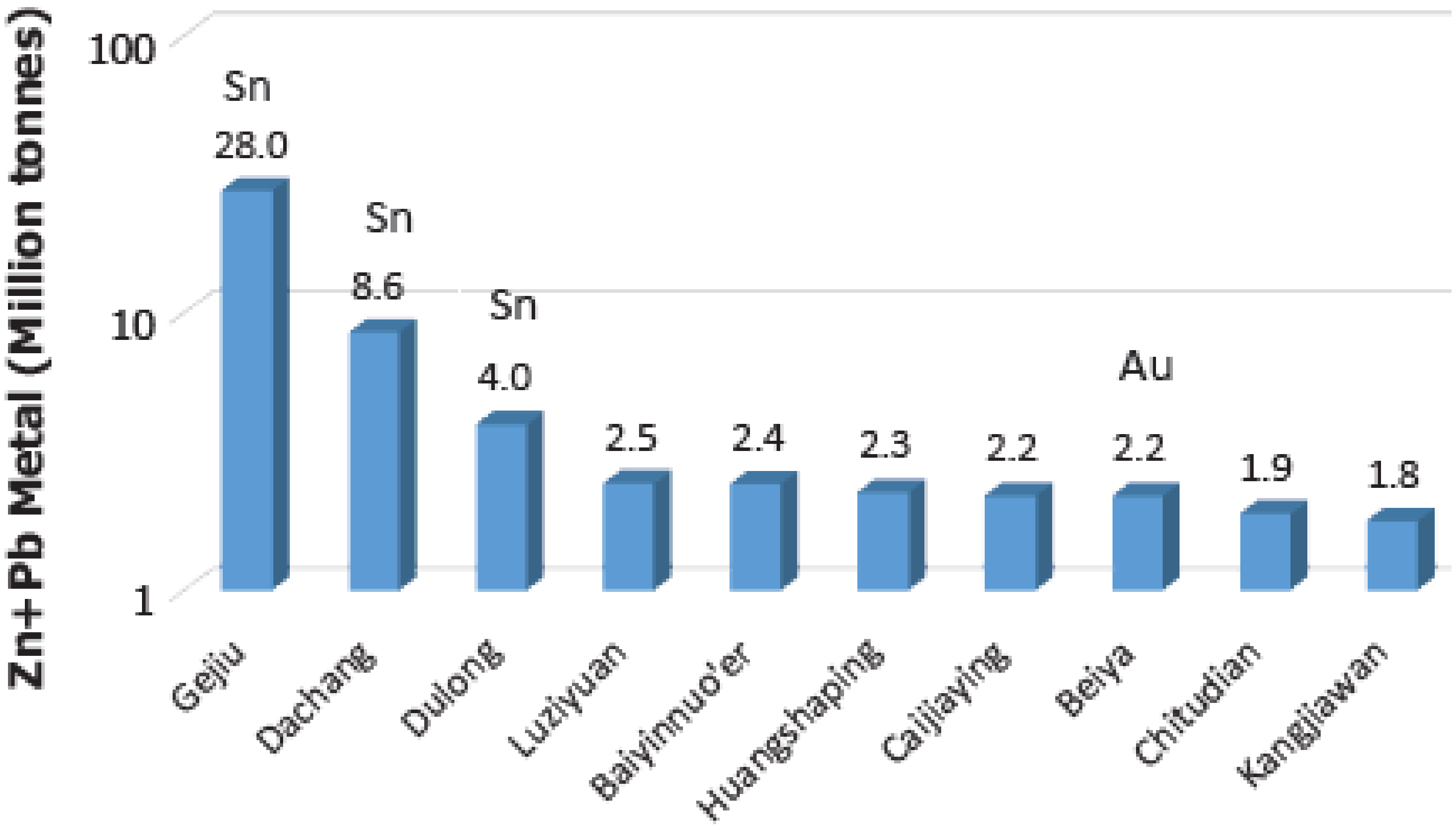
Oxidized

Chang et al., 2019

Reduced

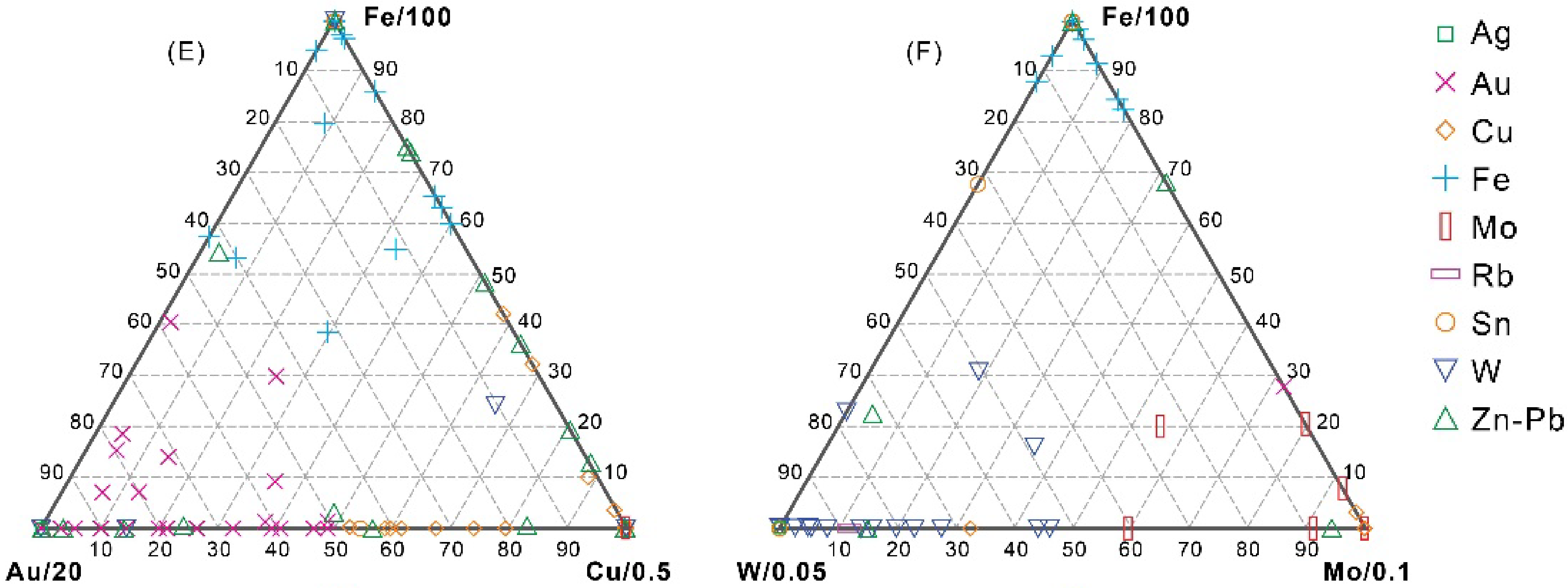


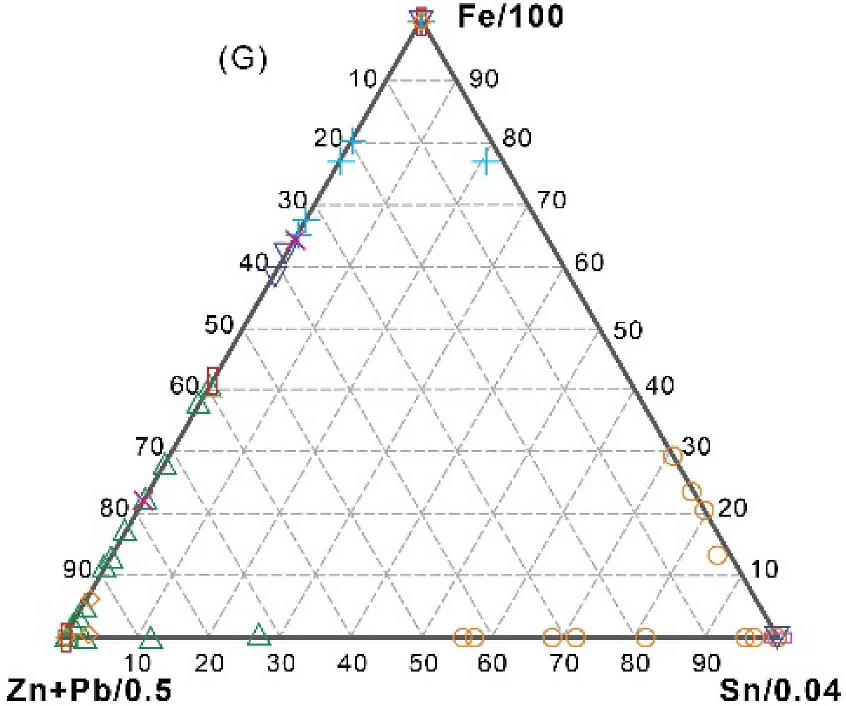
10 largest Zn-Pb skarns



Chang et al., 2019

- **May contain Ag, Au, Fe, Cu, Sn, Cd, As, Sb, Mo, Cr**
- **May be subordinate in Sn, W, Au, Fe, Cu, and Ag skarns. The largest ones mostly subordinate metal of Sn, W and Au deposits.**





Fe:

- **Moderate association with Cu, Au, Mo, Zn-Pb**
- **Weak association with W and Sn (e.g., Damoshan, Gejiu; Makeng; Xianghualing)**

Chang et al., 2019

METAL ASSOCIATIONS

4 sets:

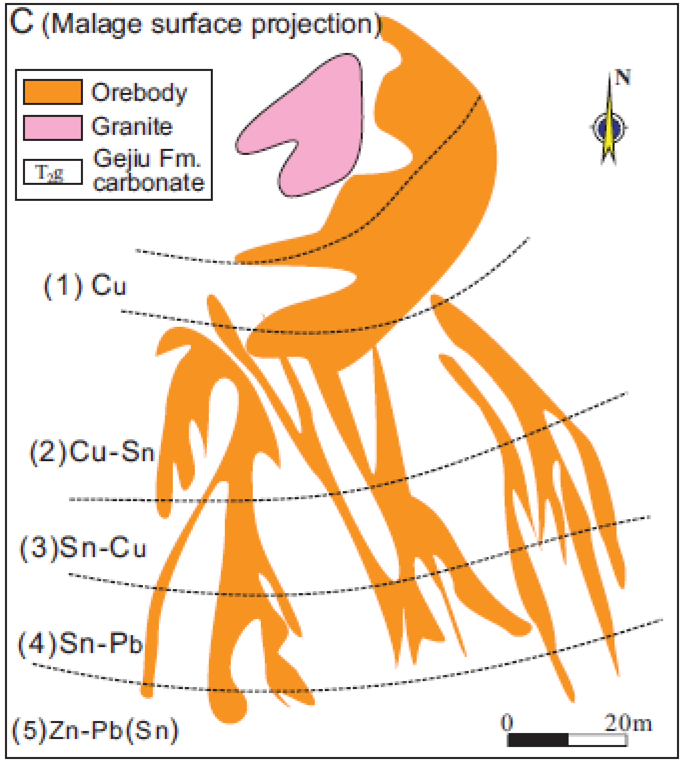
1. **Mo-W-Cu-Zn-Pb: oxidized; moderate to strong fractionation**
2. **Fe-Cu (±W)-Au-Zn-Pb: oxidized; weak to moderate fractiona.**
3. **Sn (±Fe, Cu?, W) – Zn-Pb: Reduced; strong fractionation**
4. **Au-Zn-Pb: Reduced; weak to moderate fractionation**

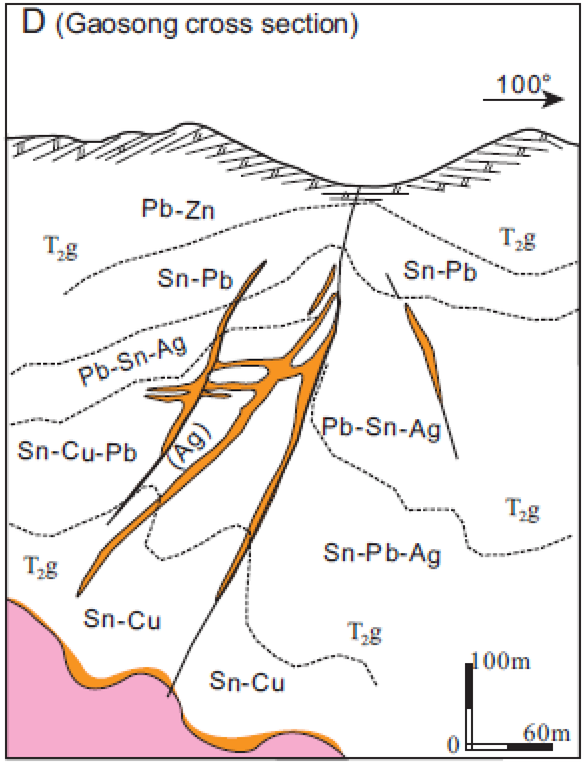
Chang et al., 2019

Metal Zoning

Zn-Pb being distal is well known.

What do you expect to find at the proximal locations of a Zn-Pb skarn? Cu?





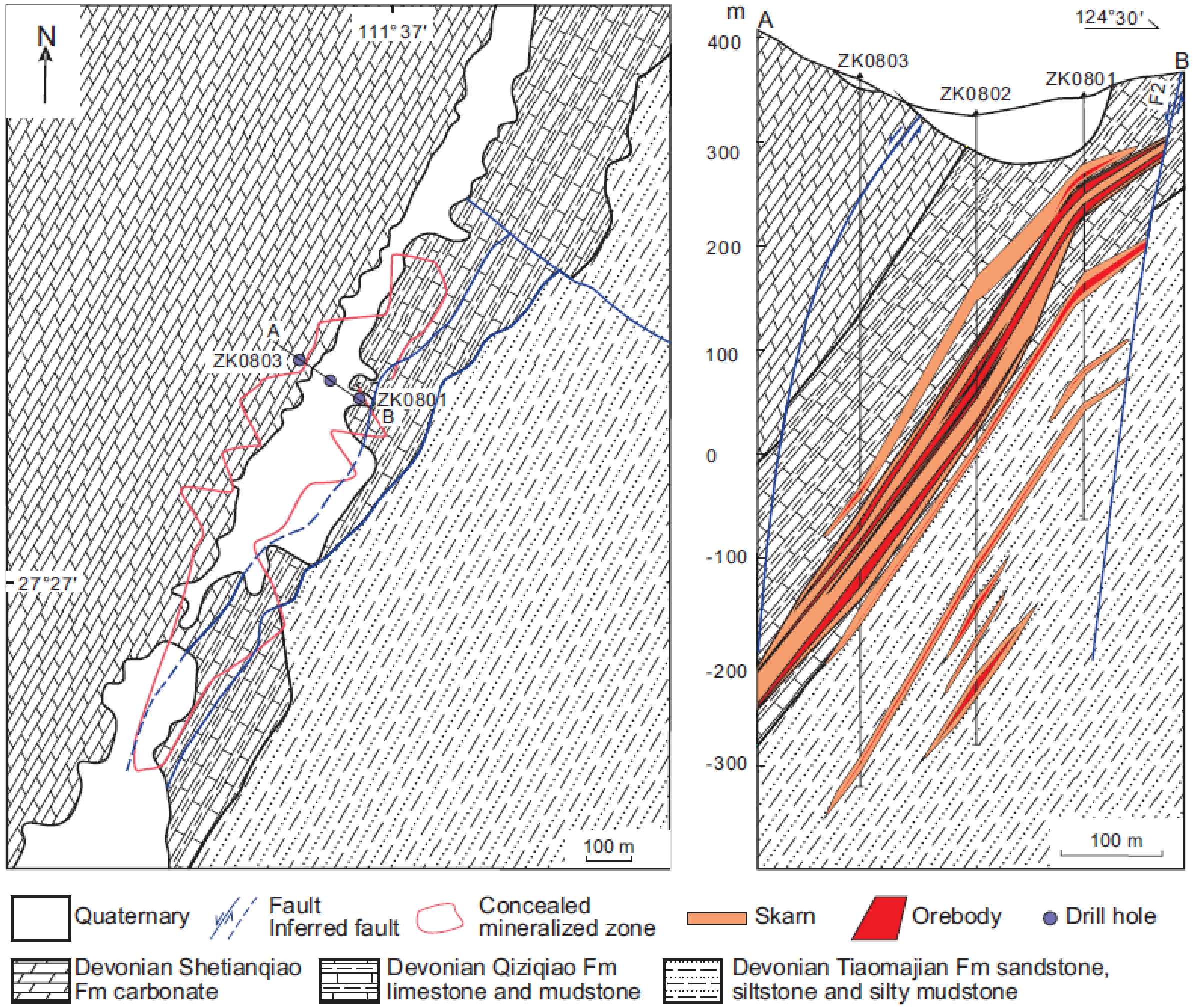
Gejiu:
3 Mt Sn
5 Mt Cu
28 Mt Zn-Pb

Cheng et al., 2013;
Chang et al., 2019

Metal Zoning

Zn-Pb being distal is well known.

But distal mineralization is not limited to Zn-Pb



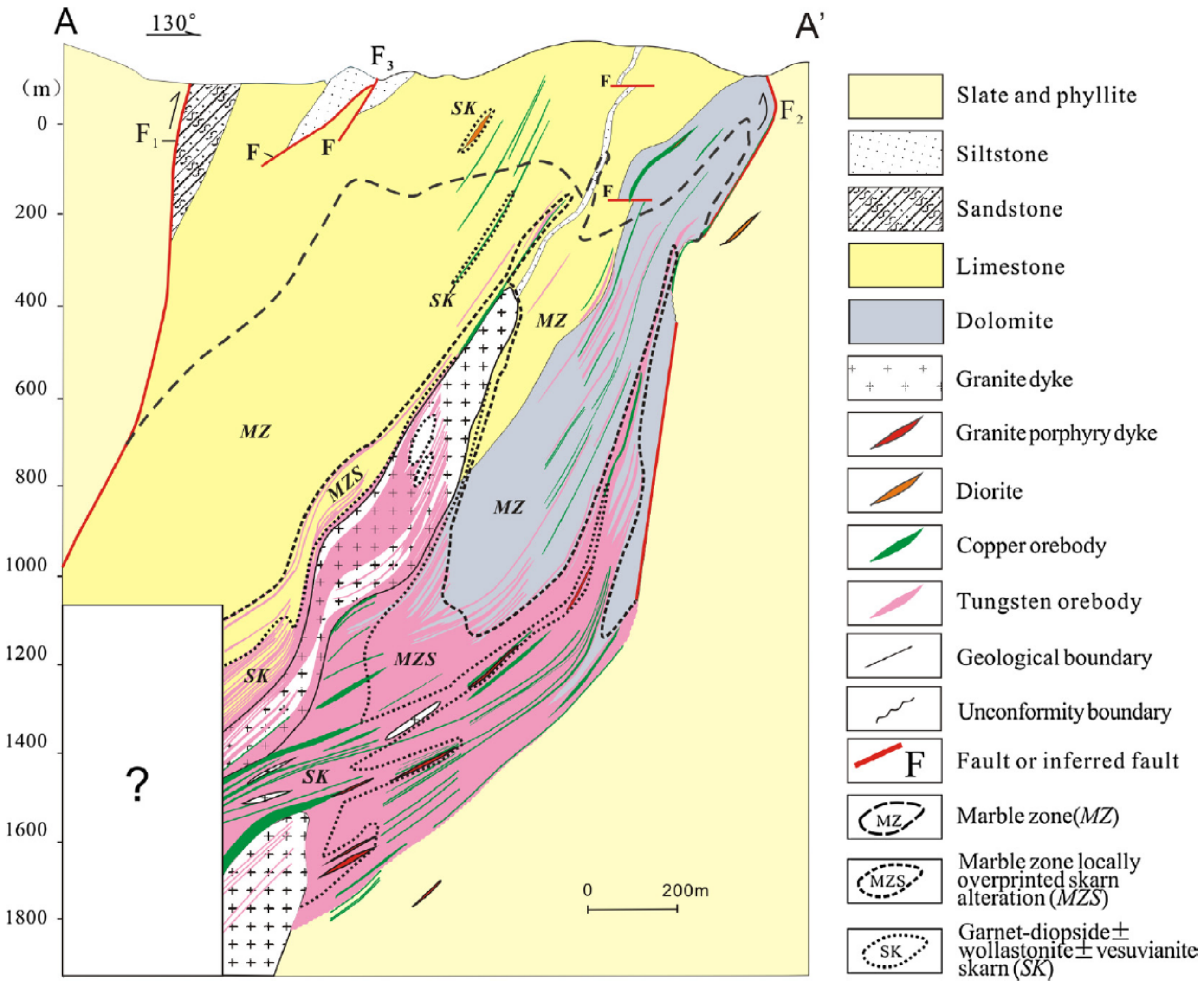
Distal W skarn

- **Caojiaba**

Xie et al., 2019;
Chang et al., 2019

Metal Zoning

Distal mineralization is not limited to Zn-Pb



Distal Cu in a W skarn

- **Zhuxi: 2.7 Mt W, 0.22 Mt Cu**

Other metals at distal locations: Sn, Mo, Au

No. 912 Team, 2013; Pan et al., 2017

Metal zonation

Chang et al., 2019

Table 5. Skarn Position and Metal Zonation of Selected Deposits

Deposit number	Deposit name	Resources	Rank[1]	Inside intrusion	At contact	Distal veins, mantos, and chimneys	References
27-15	Gejiu	3 Mt Sn, 28 Mt Zn + Pb, 5 Mt Cu	Sn1, Cu2, Zn-Pb1	Minor; W	Some; Cu (Sn)	Major; Sn-Cu, to Sn-Pb, to Pb-Zn in pipes; Cu at Kafang in mantos	Y.-M. Zhao et al. (1990); Cheng et al. (2012, 2013)
24-07	Dachang	1.5 Mt Sn, 8.6 Mt Zn-Pb, 0.37 Mt Cu	Sn2, Zn-Pb2	Little	Major; Cu, Zn	Major: Sn, Zn-Pb	Fu et al. (1991, 1993); W.-H. Huang et al. (2012)
23-20	Furong	0.7 Mt Sn	Sn3	Major	Major	Minor	Shuang et al. (2009)
23-04	Xitian	0.59 Mt Sn, 0.037 Mt W	Sn4	Some: Greisen W-Sn	Major: Sn- minor W	Some: vein Sn-Zn-Pb	Cai and Jia (2006)
23-10	Shizhuyuan	0.63 Mt W, 0.49 Mt Sn, 0.2 Mt Mo	W2, Sn5, Mo9	Some: W-Sn-Mo-Bi greisen	Major; W-Sn-Mo-Bi-F skarn and overprinting veins	Minor; Sn-Be veinlets	Lu et al. (2003)
05-08	Huanggang-liang	0.46 Mt Sn, 180 Mt Fe ore, 0.043 Mt W, 0.12 Mt Zn-Pb, 0.016 Mt Cu	Sn6	Little	Major; Sn, Fe	Major; Sn, Fe, + minor W	Z.-H. Zhou et al. (2010)
23-18	Bailashui	0.42 Mt Sn, 0.03 Mt W, 0.12 Mt Cu	Sn7	Major	Major	Minor	Shuang et al. (2009)
27-19	Dulong	0.4 Mt Sn, 4 Mt Zn-Pb, 4,000 t In	Sn8, Zn-Pb3	Little	Little	Major; Sn, Zn	B. Xu et al. (2015)
18-08	Pengshan	0.3 Mt Sn, 1.5 Mt Zn-Pb	Sn9	Minor; Sn	Minor; Sn	Major; Sn to Zn-Pb to Zn-Pb-F-Ba	B. Xu et al. (2017)
23-17	Xiang-hualing	0.17 Mt Sn, 0.095 Mt Zn-Pb	Sn10	Minor; greisen Nb, Ta, W, Sn	Minor; Be, W	Major; Sn to Zn-Pb	Du (1988)
22-06	Dading	0.17 Mt Sn, 128 Mt Fe ore, 0.014 Mt Zn-Pb	Sn10	No info	No info	No info	NA
28-28	Jiama	7.4 Mt Cu, 208 t Au, 0.62 Mt Mo, 1.4 Mt Zn-Pb	Cu1, Au2, Mo4	Some Mo, minor Cu	Major; Mo, Cu, Au	Major Zn-Pb, some Cu	W.-B. Zheng et al. (2010, 2016)
18-06	Cheng-menshan	3.1 Mt Cu, 44 t Au	Cu3	Major; porphyry and skarn Mo to Cu-Mo	Major; Cu-Fe	Major; Cu to Cu-Zn-Pb (No.1 orebody along quartzite-limestone boundary, ~2.4 km long)	Z.-L. Wang (1991)
18-02	Wushan	2.5 Mt Cu, 67 t Au	Cu4, Au7	Some; Mo-Cu	Major; Cu	Major; Cu to Zn-Pb (north zone)	J.-W. Li et al. (2007)
15-16	Shizishan-Donggua-shan	2 Mt Cu, 50 t Au	Cu5, Au8	Minor	Major: Cu, Au, minor Mo	Major: Cu	X.-C. Xu et al. (2011)
27-03	Hongniu-Hongshan	1.8 Mt Cu, 0.006 Mt W, 0.006 Mt Mo, 0.025 Mt Zn-Pb	Cu6	Minor; Mo-Cu	Minor; Mo, Cu	Major; Cu to Zn-Pb (up to 1.6 km long)	Peng et al. (2016)
27-01	Yangla	1.5 Mt Cu	Cu7	Minor	Minor	Major	Zhu et al. (2015)
18-14	Yongping	1.5 Mt Cu, 0.024 Mt W	Cu8	Little	Some	Major	Tian et al. (2014)
17-11	Tonglushan	69 Mt Au, 1.1 Mt Cu, 57 Mt Fe ores	Au6, Cu9	Major	Minor	Minor	Xie et al. (2011)
09-07	Xiaoligou	1.1 Mt Cu	Cu10	No info	No info	No info	NA
18-11	Zhuxi	2.7 Mt W, 0.22 Mt Cu	W1	Some; W	Major; W-Cu	Major; W-Cu to distal Cu-only	Pan et al. (2018)
14-14	Sandao-zhuang	0.44 Mt W, 0.75 Mt Mo	Mo1, W3	Major; porphyry	Some; Mo-W	Major; Mo-W	Xiang et al. (2012)

Metal zonation

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Deposit number	Deposit name	Resources	Rank[1]	Inside intrusion	At contact	Distal veins, mantos, and chimneys	References
02-01	Xiaoliugou	0.20 Mt W, 0.31 Mt Mo	Mo5, W8	Some; porphyry Mo	Some; Mo	Major; proximal Mo-W to distal W-Cu 600 m above intrusion contact	T.-G. Zhou et al. (2002); X.-M. Zhao et al. (2014)
15-23	Baizhang-yan	0.02 Mt W, 0.01 Mt Mo	Medium W	Little	Some	Major	G.-X. Song et al. (2012a)
14-13	Shang-fanggou	0.72 Mt Mo, 60 Mt Fe ore	Mo3	Major; porphyry style Mo	Major; Mo-Fe	Minor	Y. Yang et al. (2013)
08-03	Yangjia-zhangzi	0.26 Mt Mo	Mo6	Minor; porphyry-style Mo	Major; garnet-dominant, Mo	Some; garnet-dominant to distal pyroxene-dominant, Mo	Wu et al. (1990); X.-L. Liu et al. (2009)
27-11	Beiya	303 t Au, 4.4 Mt Zn-Pb, 125 Mt Fe ore, 0.6 Mt Cu	Au1, Zn-Pb8	Minor	Major; Fe-Cu-Au	Major; Cu-Au-Pb, to Au-Pb, to Pb	He et al. (2015); Mao et al. (2017)
12-04	Liaoshang	78 t Au	Au4	Not found yet	Not found yet	Major	Sun et al. (2011)
23-06	Kangjiawan	71 Mt Au, 1.8 Mt Zn-Pb	Au5, Zn-Pb10	Not found yet	Not found yet	Major; carbonate replacement deposit Zn-Pb-Au	Zuo et al. (2014)
27-13	Luziyuan	2.5 Mt Zn-Pb, 0.024 Mt Cu	Zn-Pb4	Not found yet	Not found yet	Major; deeper: Fe; shallower: Zn-Pb; orebodies up to 3 km long	Jiang et al. (2013)
05-07	Baiyinnuo'er	2.4 Mt Zn-Pb	Zn-Pb5	Minor; carbonate xenoliths	Major	Major	Shu et al. (2017)
23-14	Huang-shaping	2.3 Mt Zn-Pb, 0.12 Mt W, 0.043 Mt Mo	Zn-Pb6	Minor; Cu	Major; shallower: Fe-Sn-Zn-Pb; deeper: W-Mo-Cu-Zn-Pb	Major; Cu to Zn-Pb, up to 1.2 km away from intrusion contacts	Y.-M. Zhao et al. (1990); S.-F. Deng (1997)
09-01	Caijiaying	2.2 Mt Zn-Pb, 25 t Au	Zn-Pb7	Not found yet	Not found yet	Major; Zn-Pb-Au; in a belt ~2.3 km long	Chang et al. (2013)
14-15	Chitudian	1.9 Mt Zn-Pb	Zn-Pb9	None	Minor; Mo	Major; distal skarn: minor Mo, +Zn; to CRD Zn-Pb; up to 4.5 km long and away from the intrusion	Duan et al. (2011)
08-04	Bajiazi	0.37 Mt Zn-Pb, 0.012 Mt Cu	Medium-size Zn-Pb	None	Minor; Mg-skarn + Fe-Cu, 20–50 m wide	Major; along faults; up to ~4 km from contact; proximal Fe-Cu to distal Zn-Pb	Y.-M. Zhao et al. (1990)
15-20	Yaojialing	1.4 Mt Zn-Pb, 32 t Au, 0.13 Mt Cu, 382 t Ag	Large-size Zn-Pb and Au	Major: roof pendants Cu-Zn-Pb-Au	Some	Major	Zhong et al. (2015)
12-08	Laiwu	206 Mt Fe ore	Fe1	Minor	Major	Minor	C.-B. Yang et al. (2006)

Metal zoning patterns

Magma	Intrusion	Proximal	Distal
Reduced; strong fractionation	Greisen Sn±W	Sn±Cu±Fe	Sn: distal Zn-Pb: far distal
Oxidized; week to moderate fractionation	Porphyry and/or endoskarn Mo and/or Cu	Cu and/or Fe, ±Au, ±Mo	Cu: distal; locally Zn-Pb±Au: far distal
Oxidized; strong fractionation	Porphyry Mo, greisen W	Mo and/or W, ±Fe, ±Cu	Mo or W, ±Cu
Reduced; week to moderate fractionation	?	Au?	Zn-Pb-Au

Au:

Proximal to distal; Oxidized to reduced

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Mineral Deposits of China

Many deposits:

- **1303 deposits reported in public literature and summarized in SEG SP No. 22. + some new deposits with not publically described yet + some deposits not summarized**

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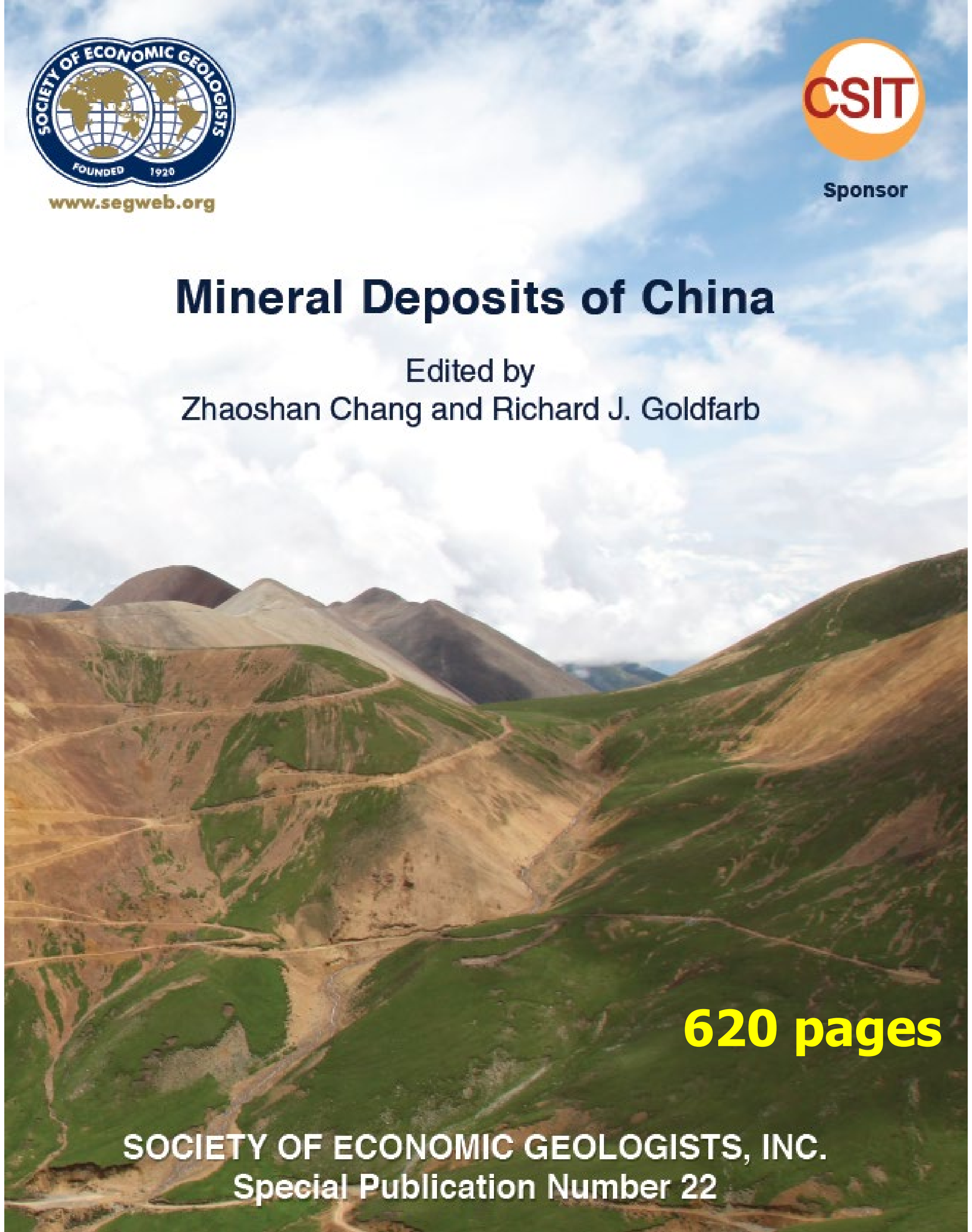

Final Remarks

- Not one metal zoning pattern can fit all skarns
- Many examples of continuous transition from distal to proximal skarn alteration and mineralization proves distal systems are part of a skarn (up to 4.5 km; Chitudian Zn-Pb skarn)
- Large deposits have all parts discovered
- Be aware of skarns replacing igneous rocks, particularly mafic-intermediate rocks
- Tectonic control at large scale; tectonic reconstruction important for older terranes

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Professional Master degree in Mineral Exploration at CSM

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- Enquiries: mineralexploration@mines.edu

Thanks!

Additional Questions

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