Mineralization related to magmatism: on example of copper-porphyry deposits in Mongolia

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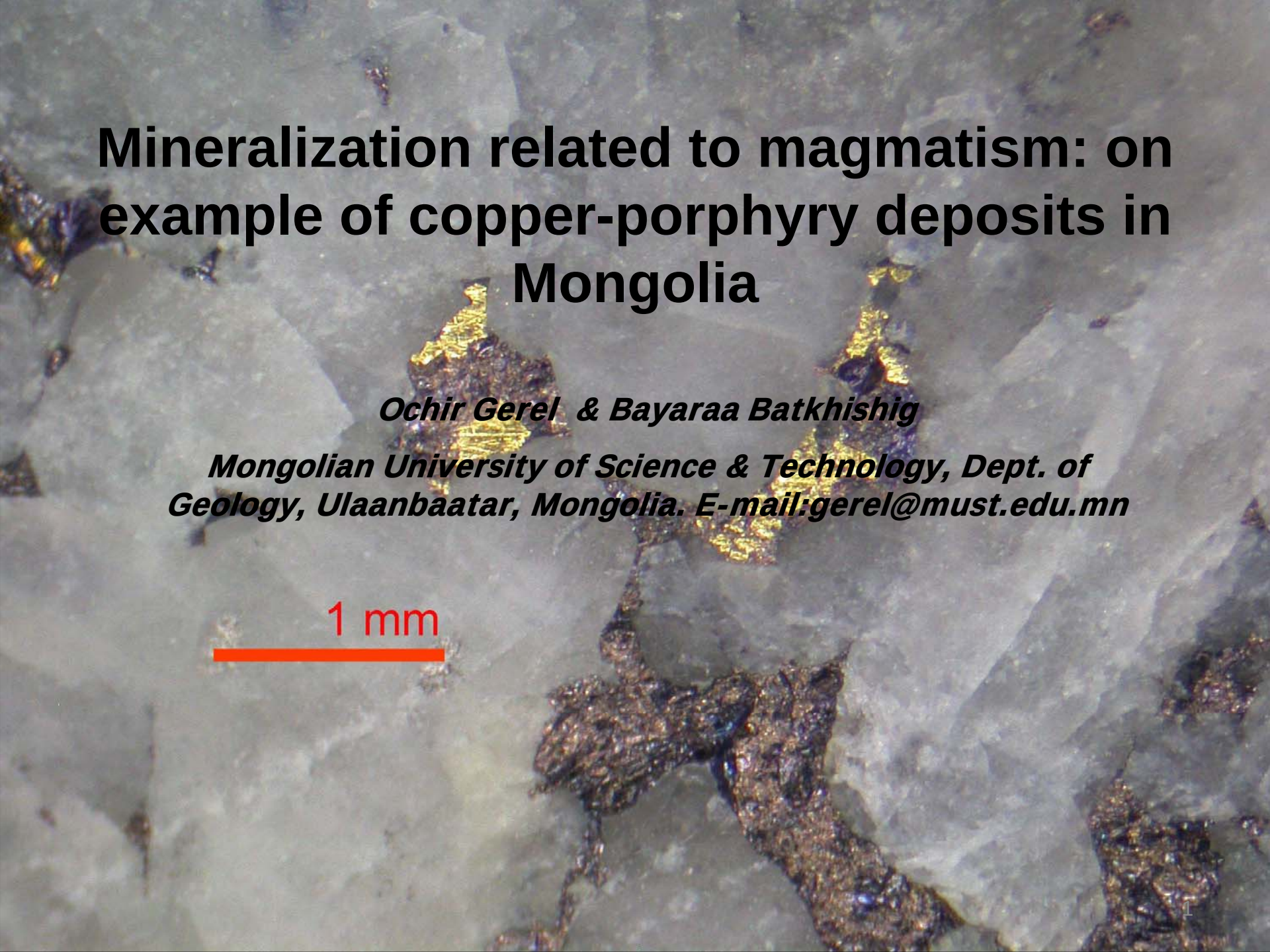
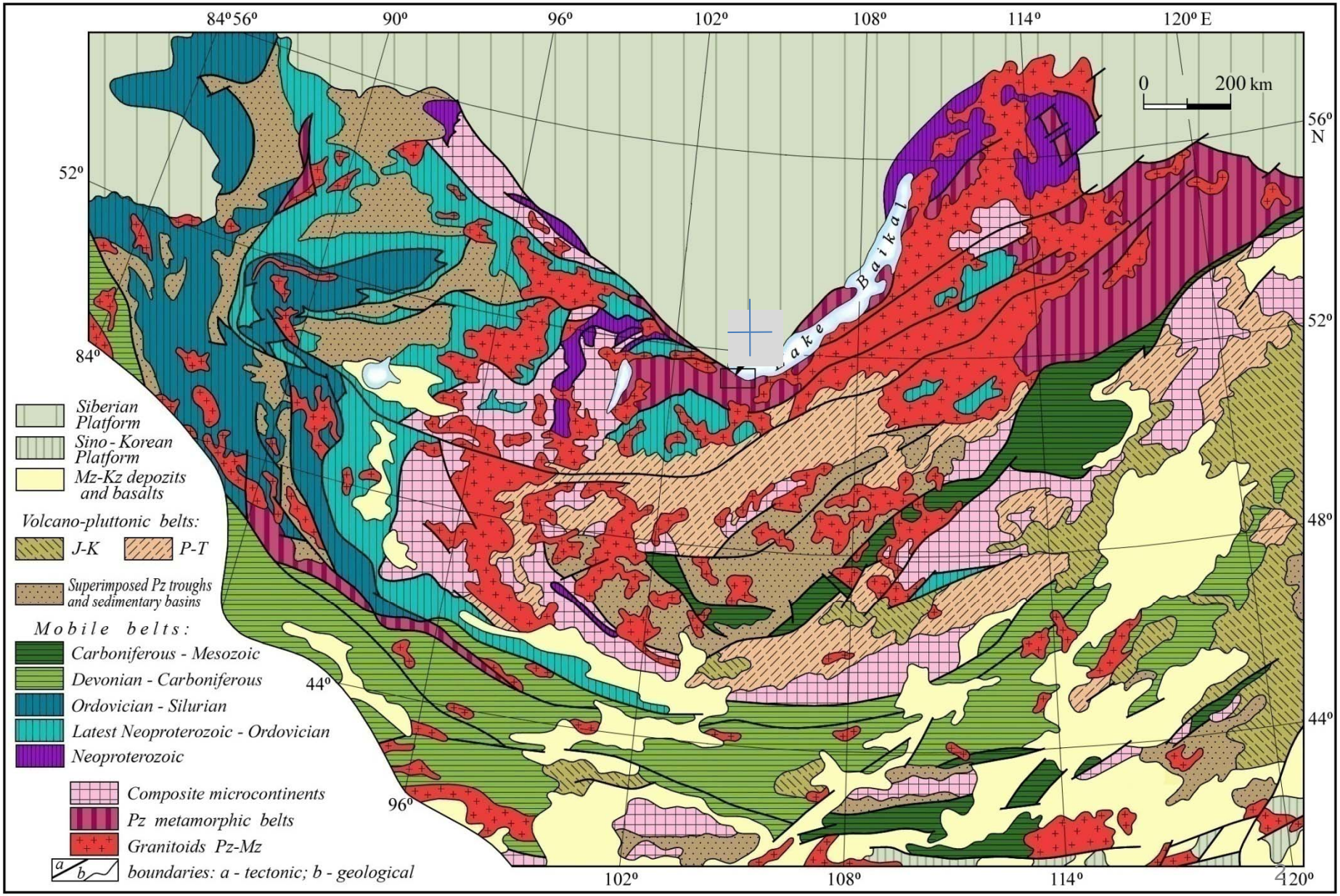
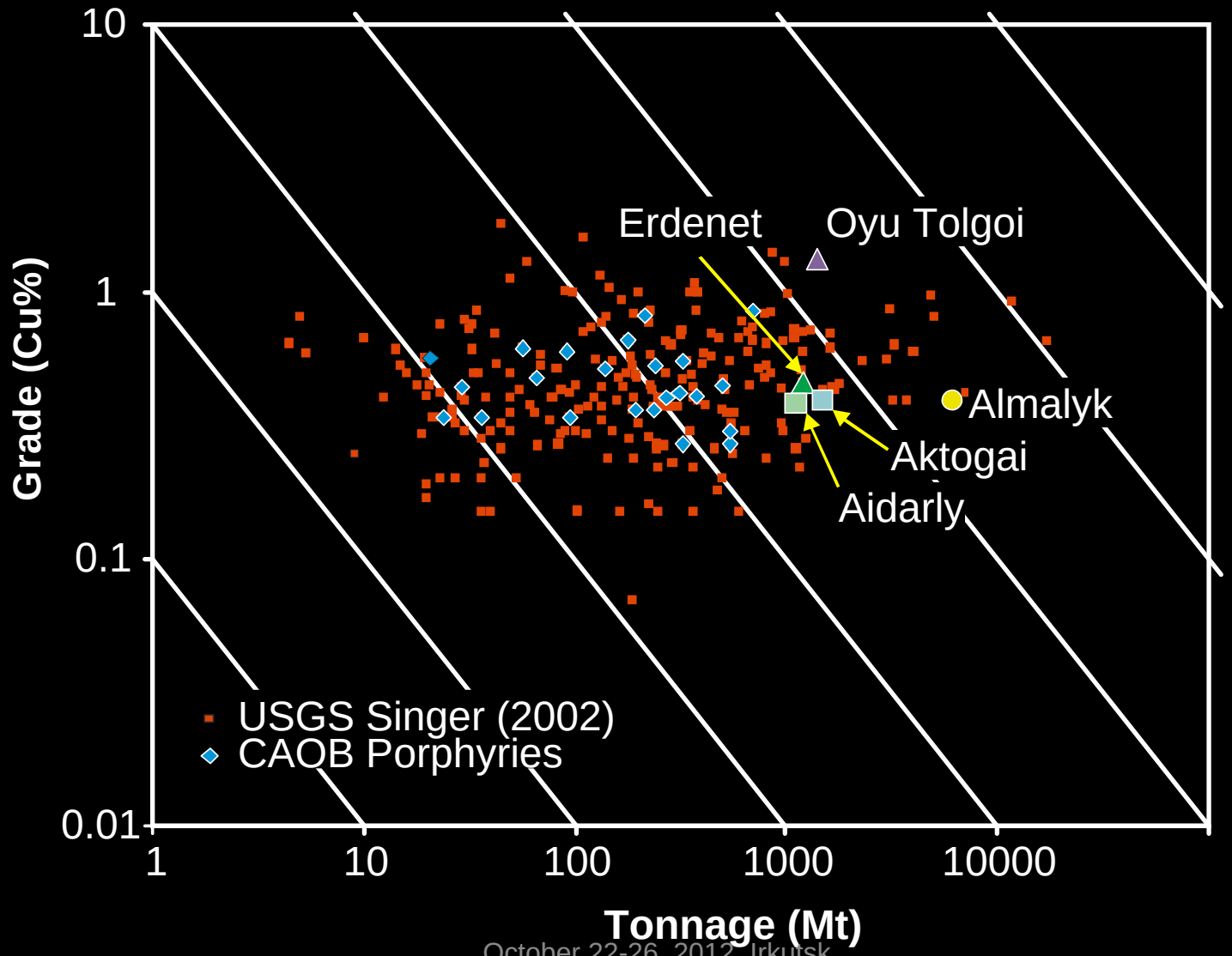


Geological scheme for the eastern segment of the Central Asian Orogenic Belt (Yarmolyuk et al., 2011)



Porphyry deposits



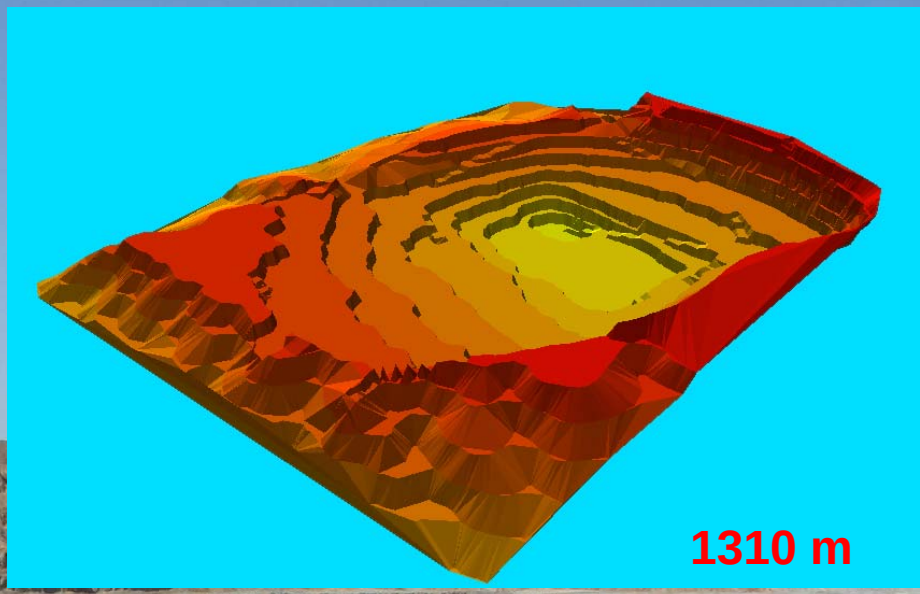
Porphyry deposits

Erdenet deposit

Discovered and explored by

E. Kominek, Czech Republic

L. Myagmar, Mongolia, et al,



Exploited since 1978

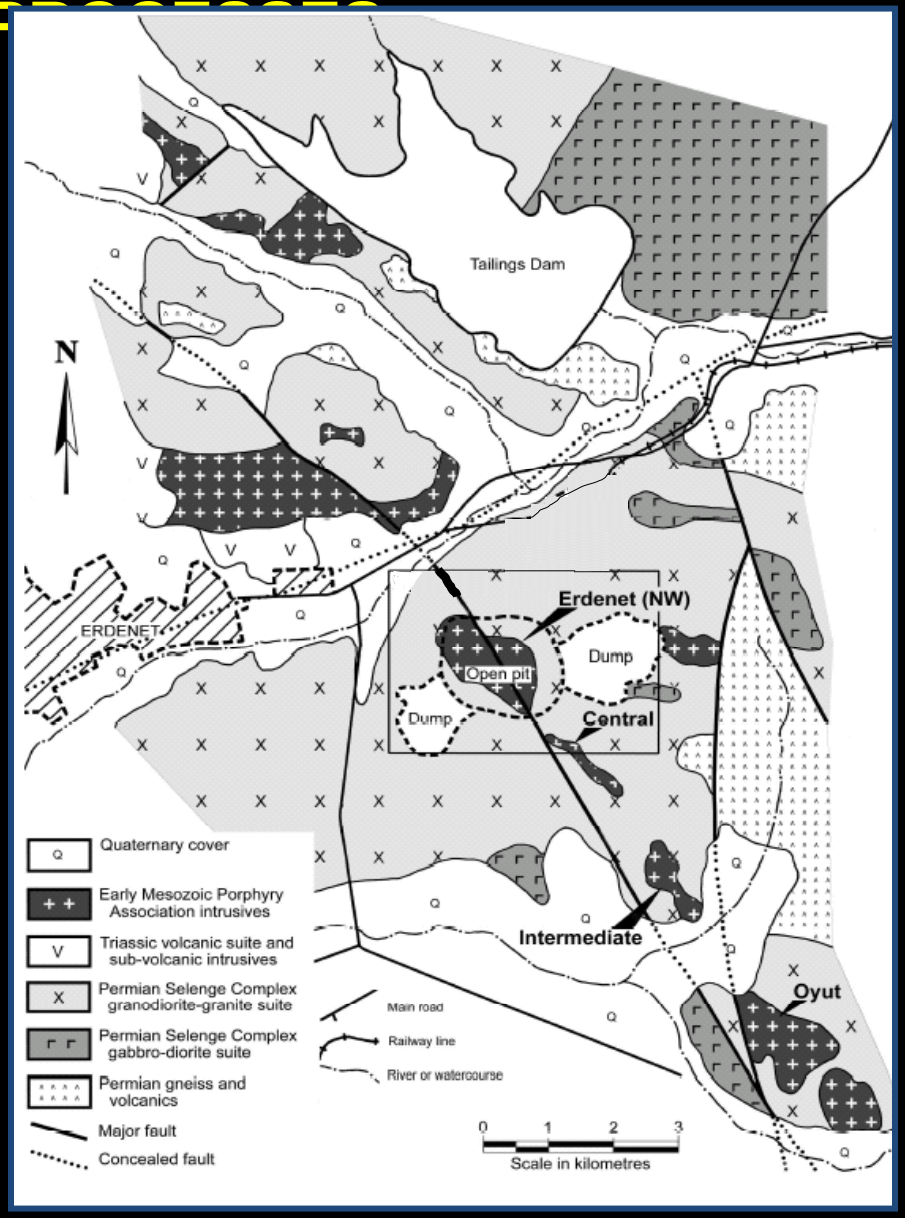
Reserves: 1.78 Gt @0.62% Cu 0.025% Mo

Annual production:

Ore: 25, 000 tons

Cu-Mo concentrate: 530, 000 tons

GEOLOGY AND MAGMATIC PROCESSES



Gerel & Munkhtsengel, 2005

Mogod Formation Volcanic (170-180 Ma) (Sotnikov et al., 1995)

(203 Ma, Lamb, Cox, 1998)

Porphyry Association (235-243 Ma)

Erdenet Porphyry Complex

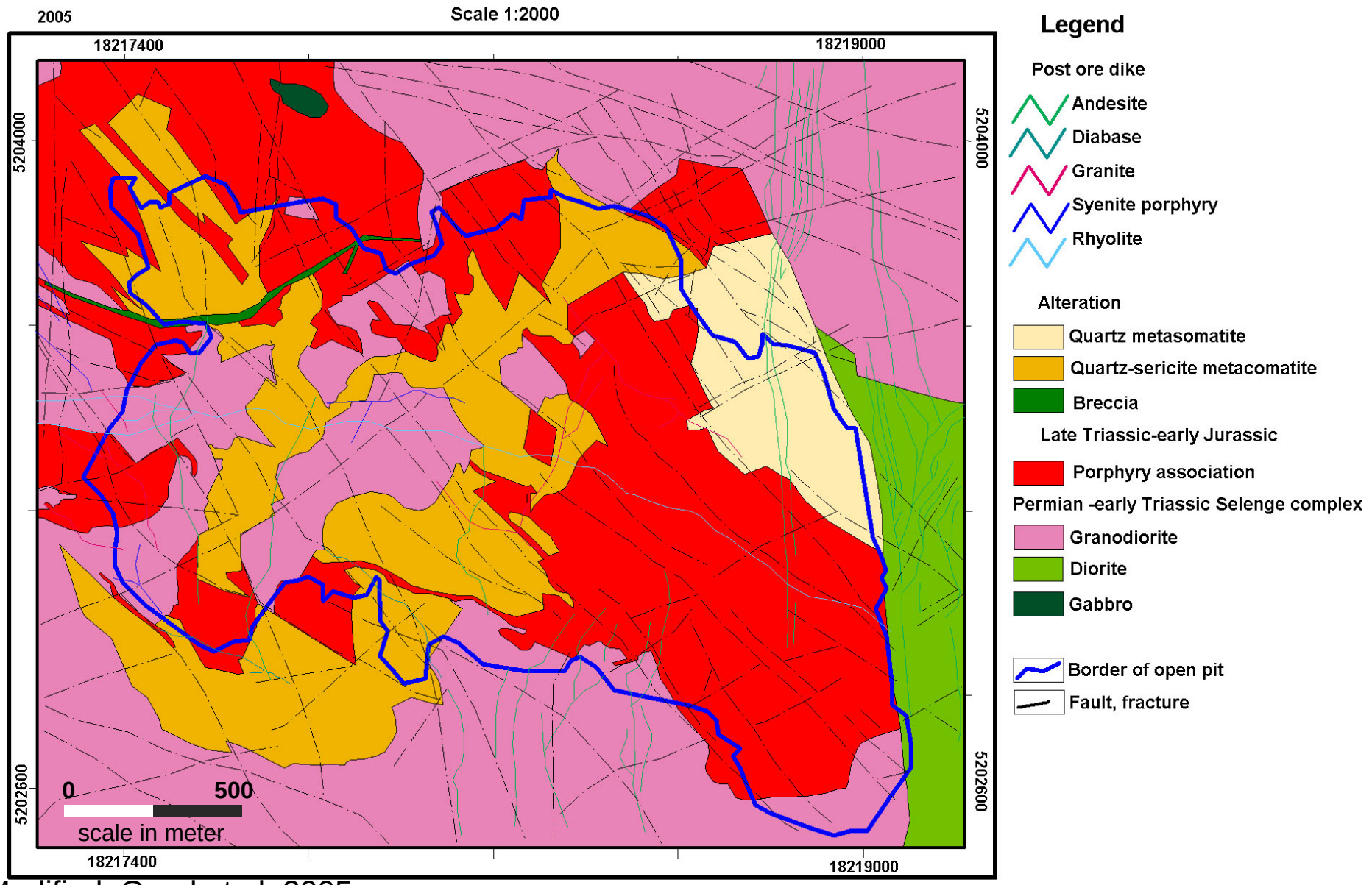
Mogod Formation

Selenge Intrusive Complex (241-248 Ma)

(Koval, Gerel, 1984, 1987)

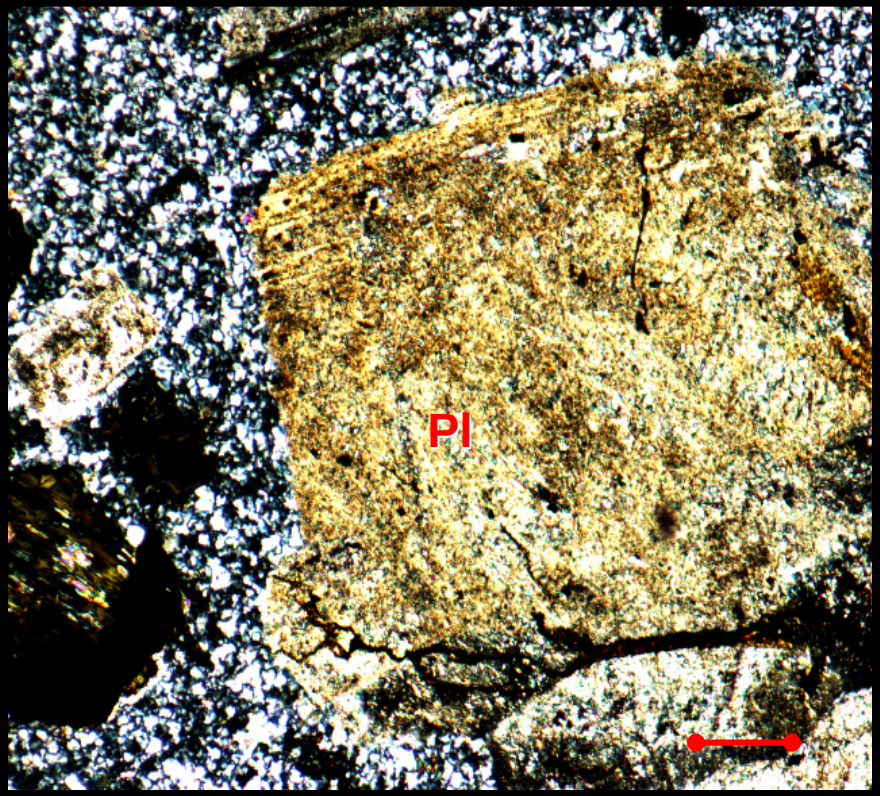
Khanui Group (Permian) Subalkalic, high K, bimodal (277-283 Ma, Munkhtsengel, 2007)

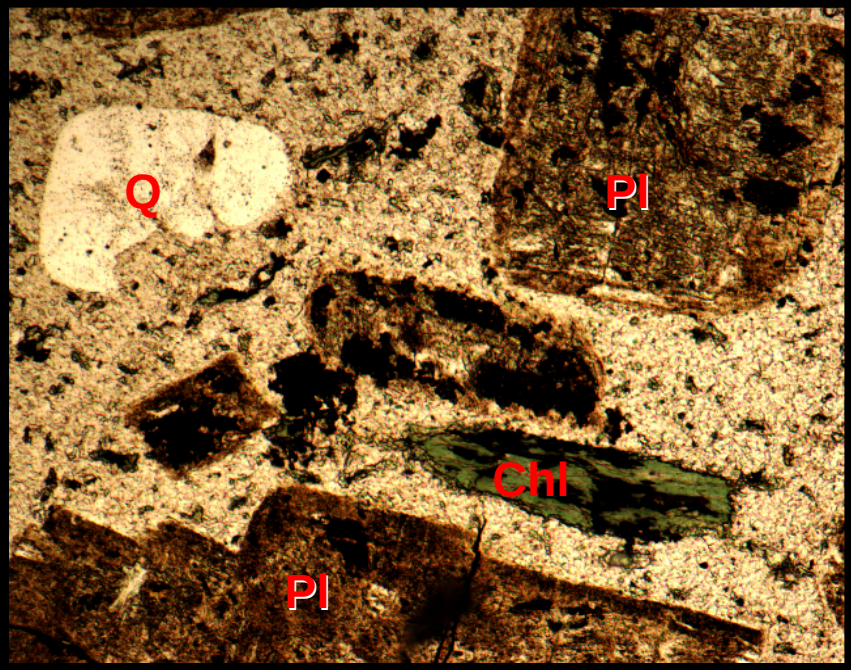
Geological map

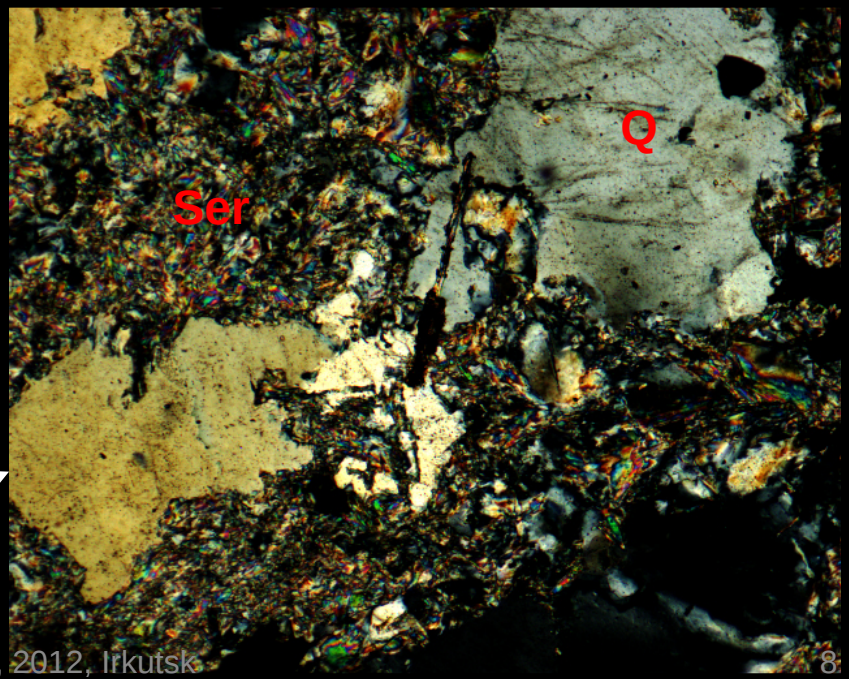


Modified, Gerel et al, 2005

Granodiorite porphyry



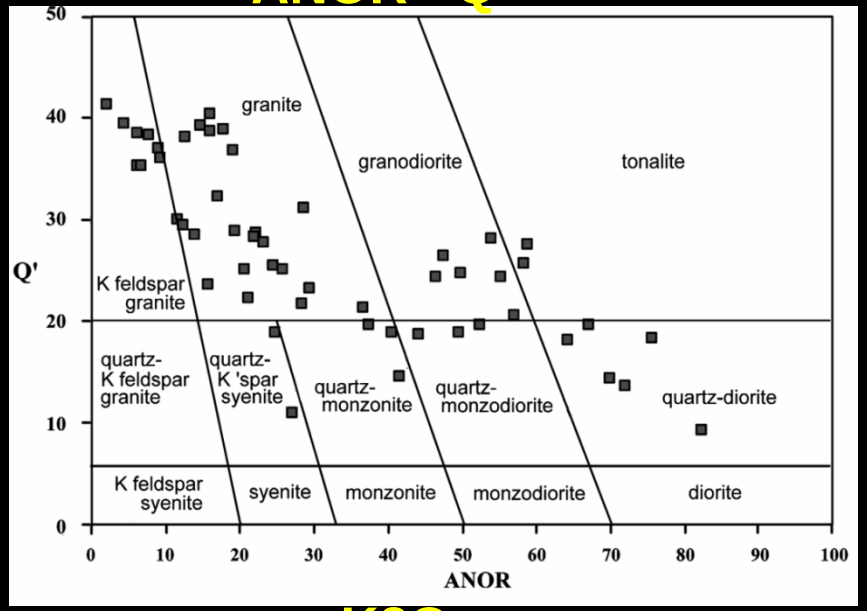


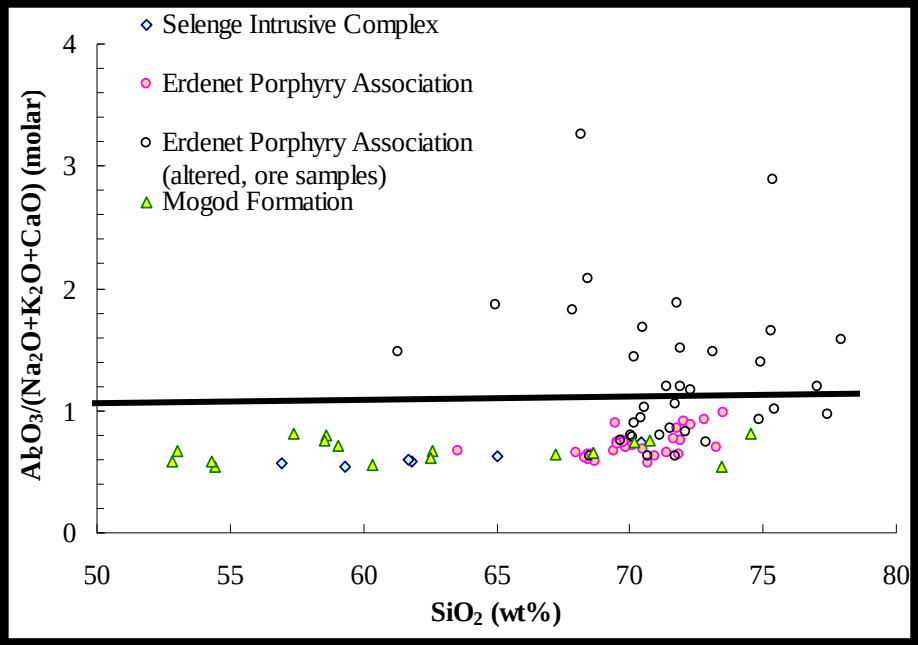


Quartz-sericite alteration

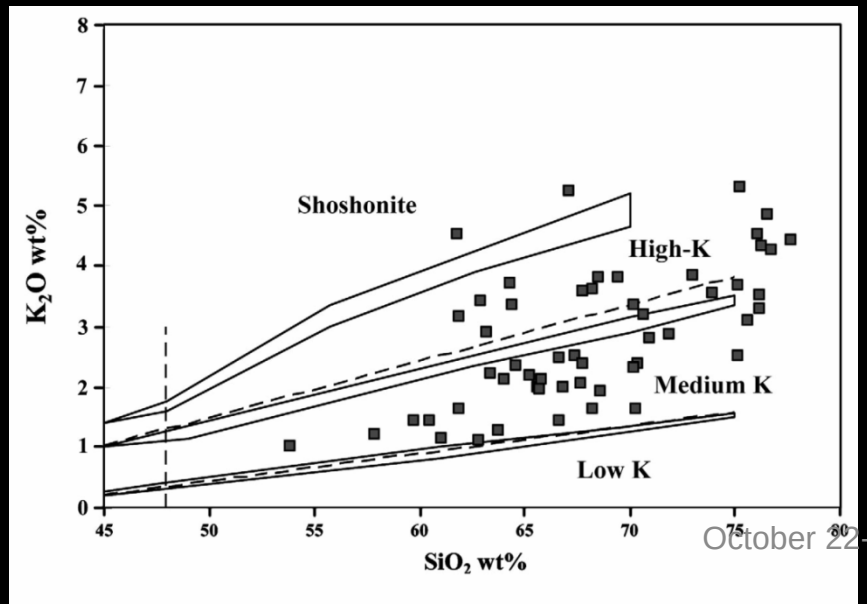
Erdenet Porphyry Association

ANOR - Q'





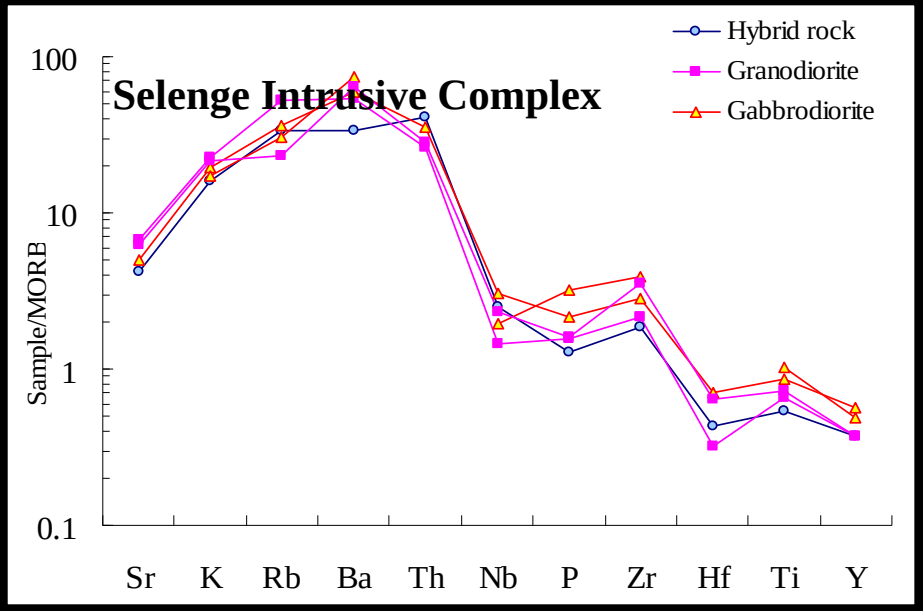
K2O –

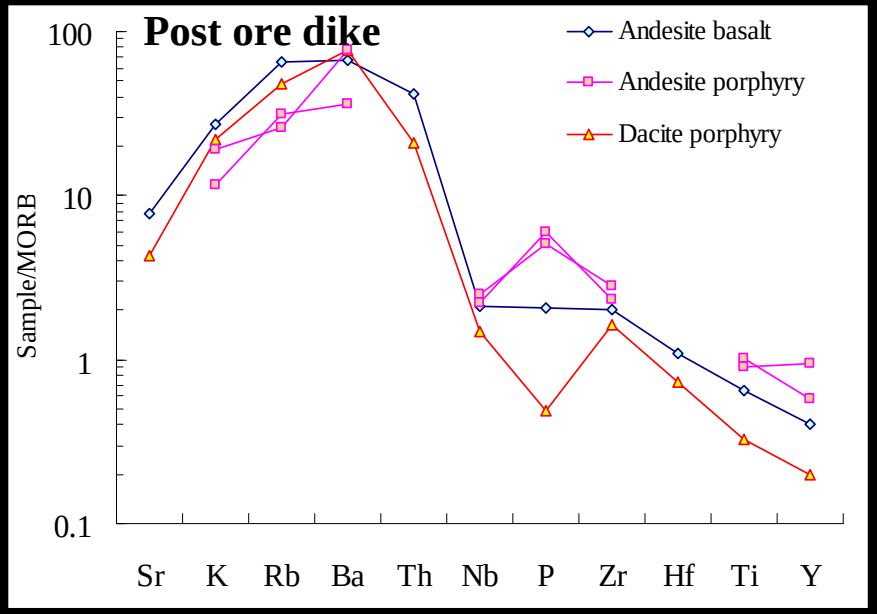


Metaluminous and altered rocks peraluminous

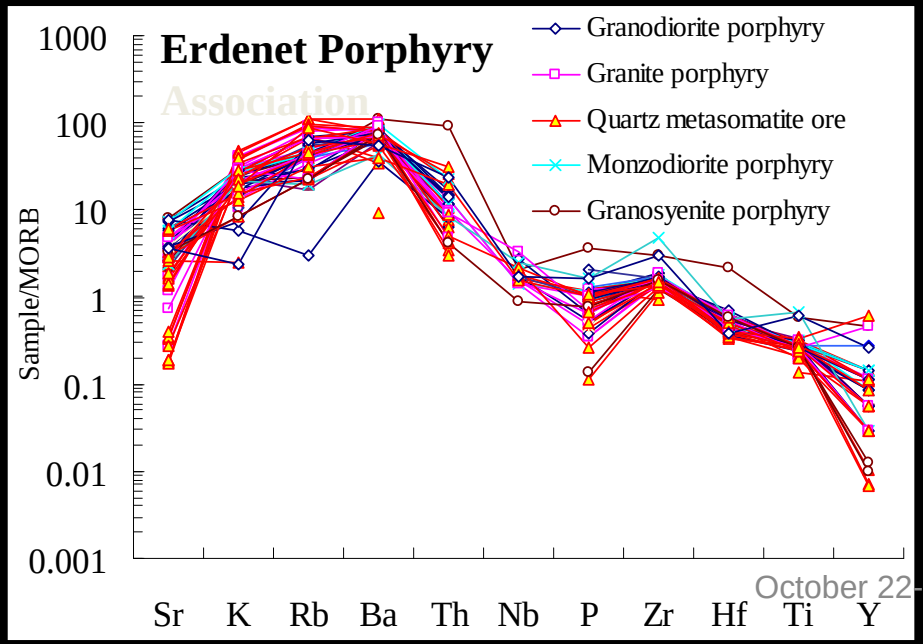
Calc-alkaline I-type
Medium to high potassic

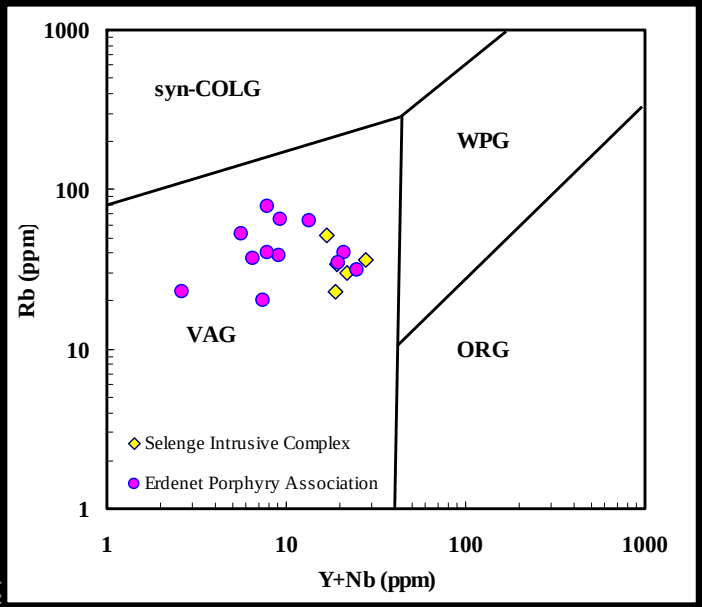
Geochemistry





Enriched in LIL: **K, Rb, Th** depleted in HFS: **Nb, Zr, Hf, Y, Ti and P**





Alteration

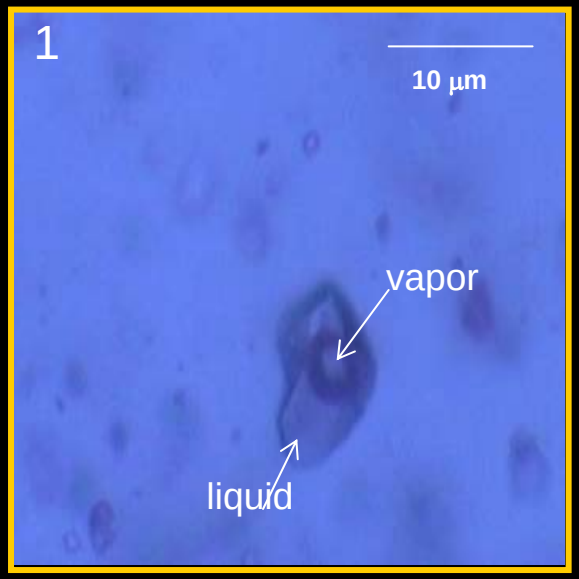
Three principal types are developed:

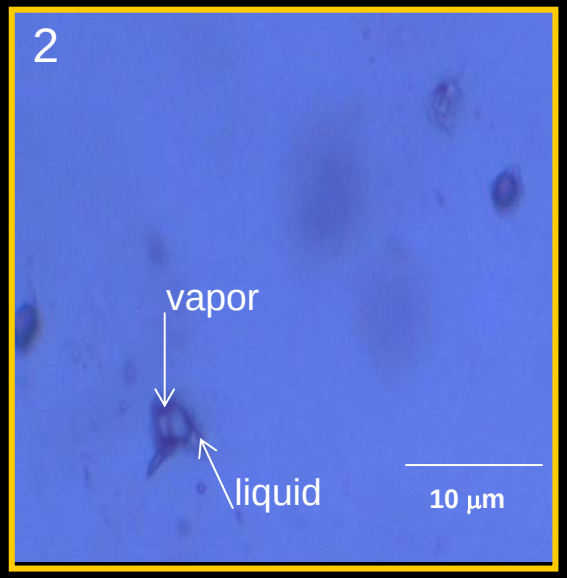
- sericitic (quartz-sericite)
- intermediate argillic (chlorite-sericite)
- propyllitic (chlorite and epidote-chlorite)

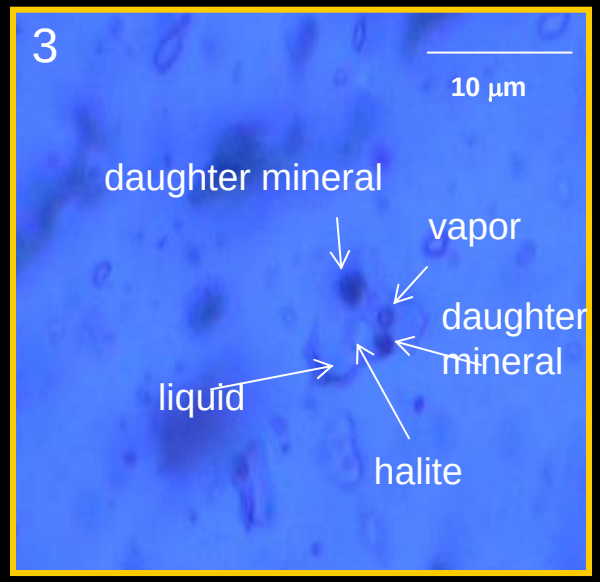
- The most common clay minerals: illite, smectite, montmorillonite, rarely kaolinite, also hematite and muscovite.

- Montmorillonite mainly associated with distribution of mafic dikes

Fluid inclusions







Three types of fluid inclusions are observed at room temperature :

1. Liquid rich inclusions L:V (70:30 – 90:10 volume %)
2. Vapor rich inclusions V:L (80:20 – 95:5 volume %)
3. Polyphase inclusions L:S:V (60:35:5-70:20:10 volume %)

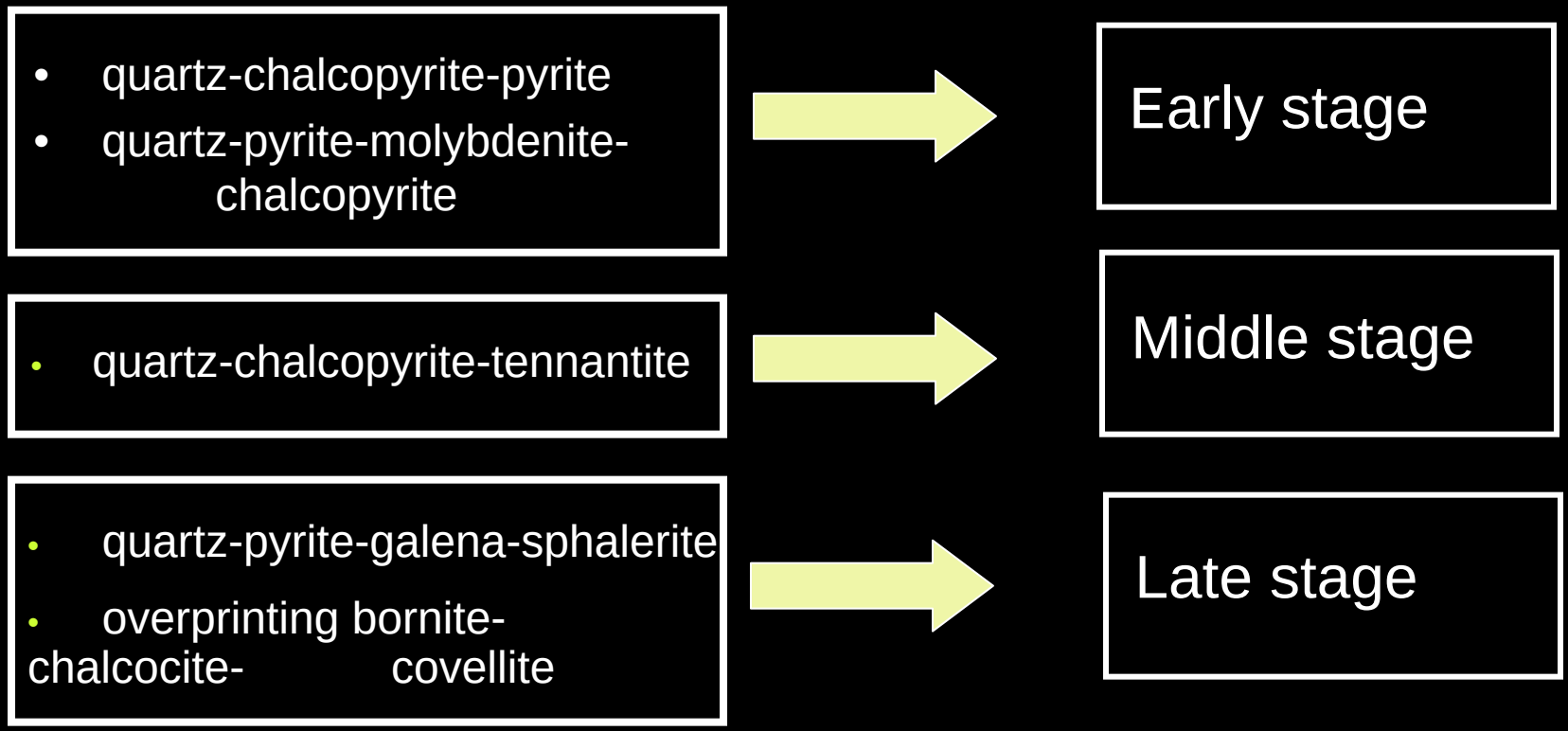
Solid phase daughter minerals are halite and unknown crystal.

Higher T up to 360°C, lower about 170°C, dominant average 200-250°C

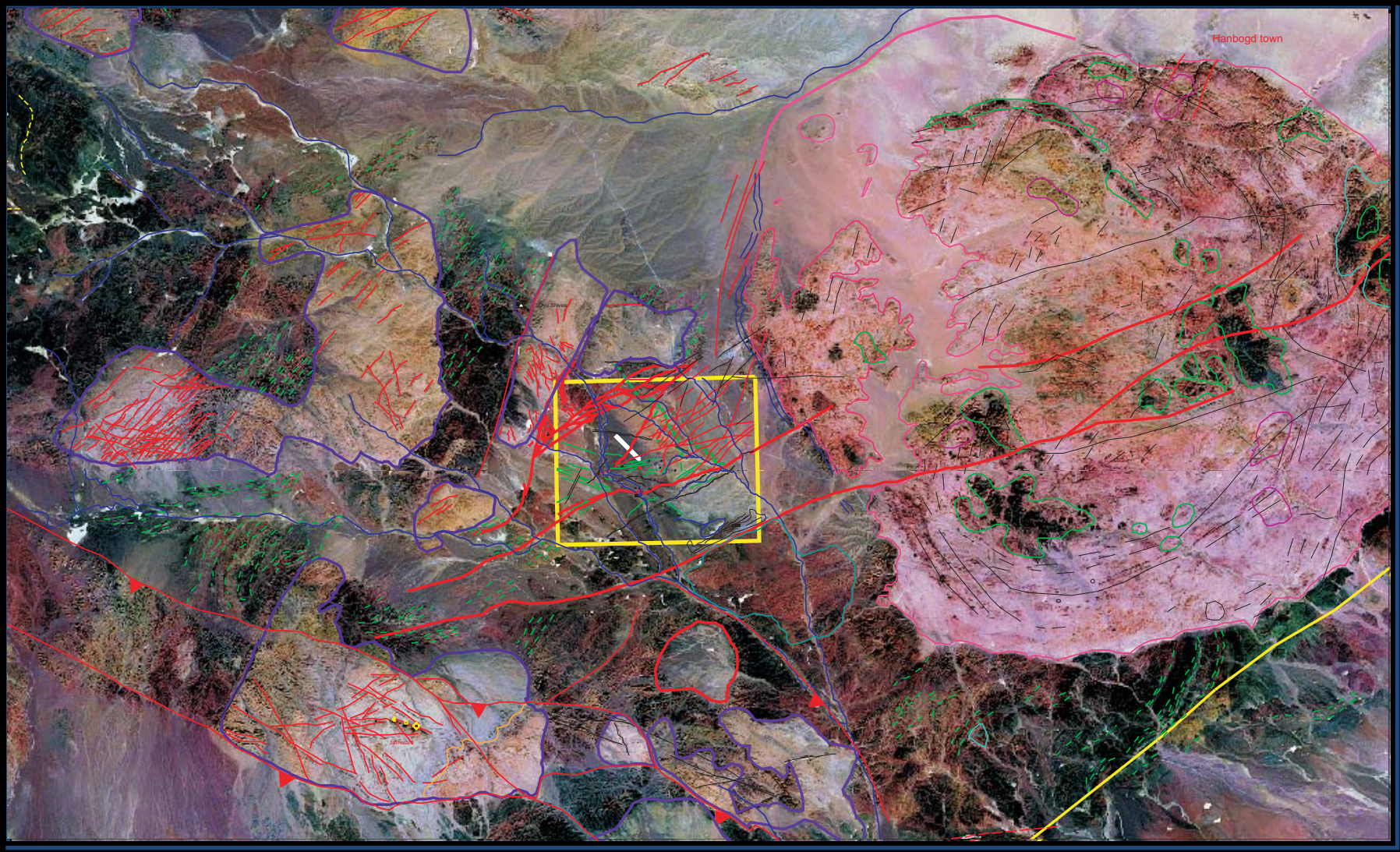
Munkhtsengel, 2007

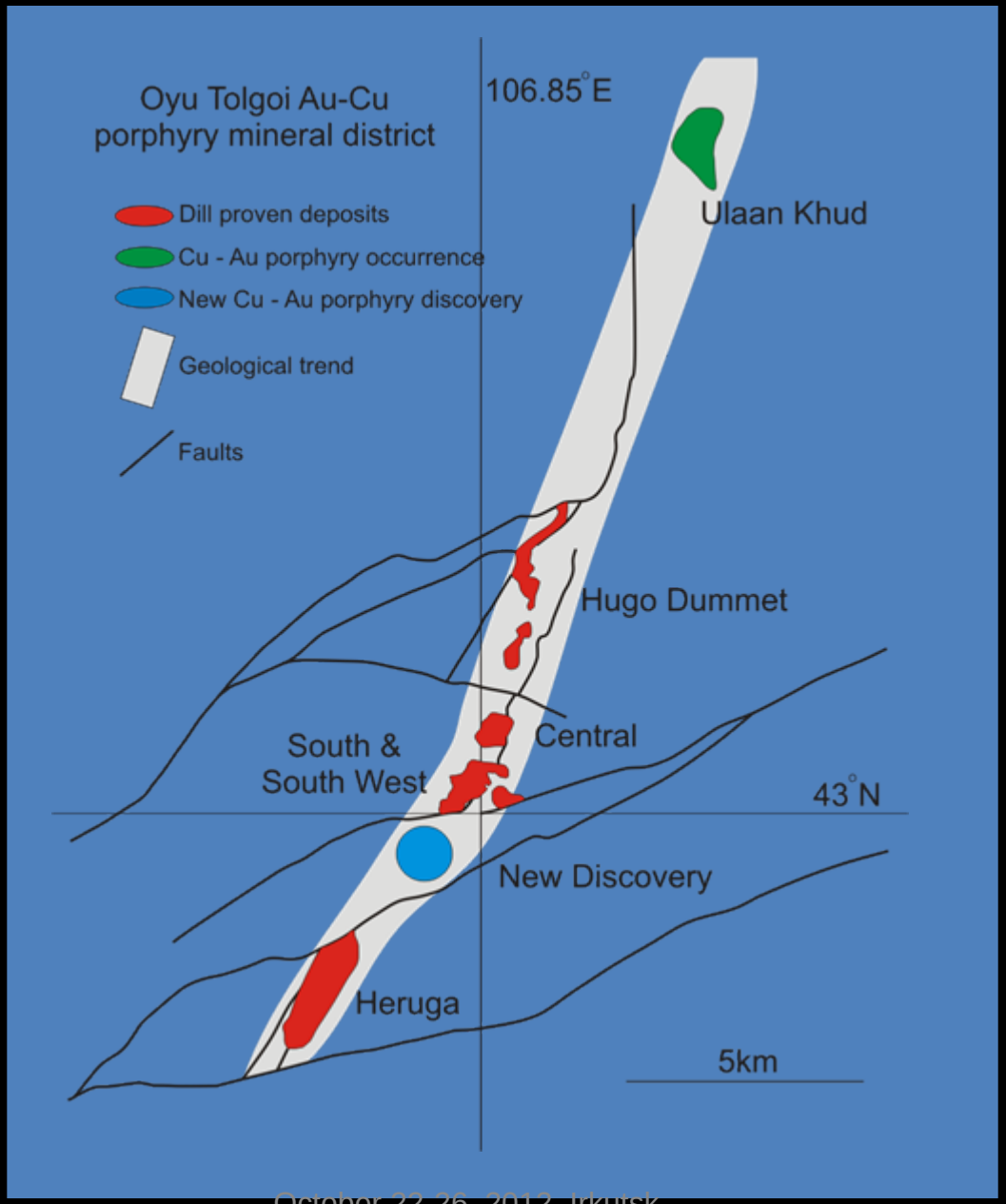
Results of SEM-CL study

Mineralization stages



Satellite image view of Oyu Tolgoi area

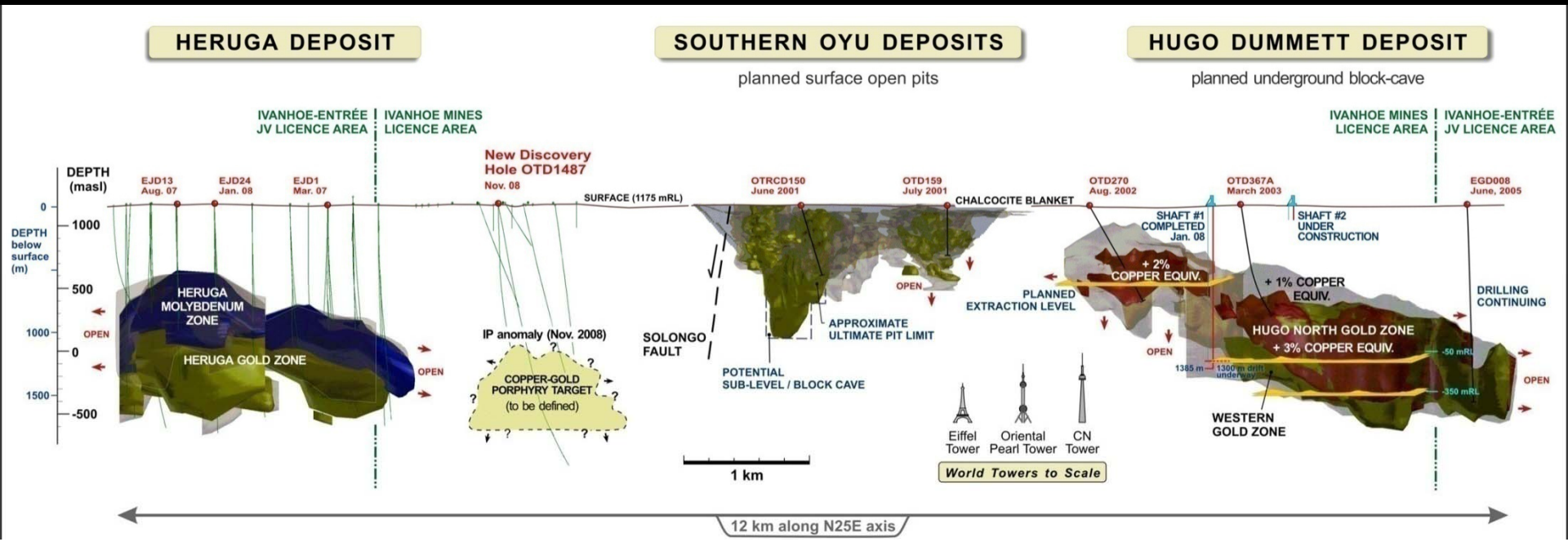



Oyu Tolgoi Au-Cu
porphyry mineral district
106.85°E
Dill proven deposits
Cu - Au porphyry occurrence
New Cu - Au porphyry discovery
Geological trend
Faults
Ulaan Khud
Hugo Dummet
Central
South &
South West
43°N
New Discovery
Heruga
5km

South
Oyu
Tolgoi

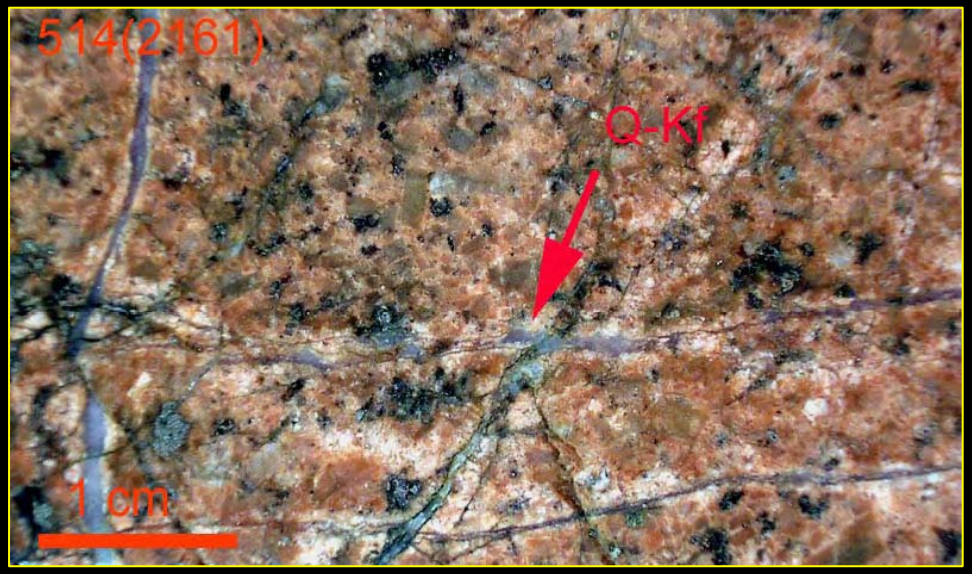
View to North
and Central
Oyu

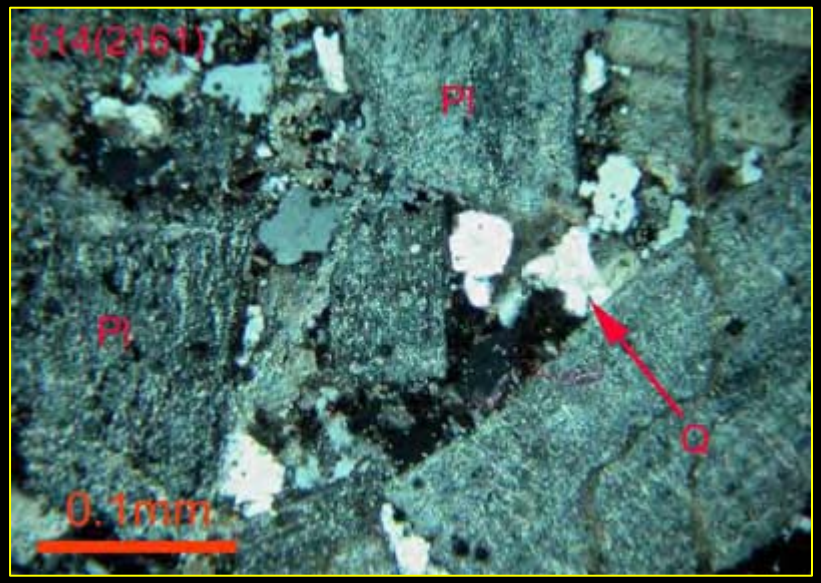
OT trend: long section



Measured and indicated resource of 1,390 Mt at 1.33 % Cu, 0.47 g/t Au, and an inferred resource of 2,200 Mt at 0.83 % Cu, 0.37 g/t Au (at 0.6% Cu equiv. cut-off)

Quartz monzodiorite (Lqmd)

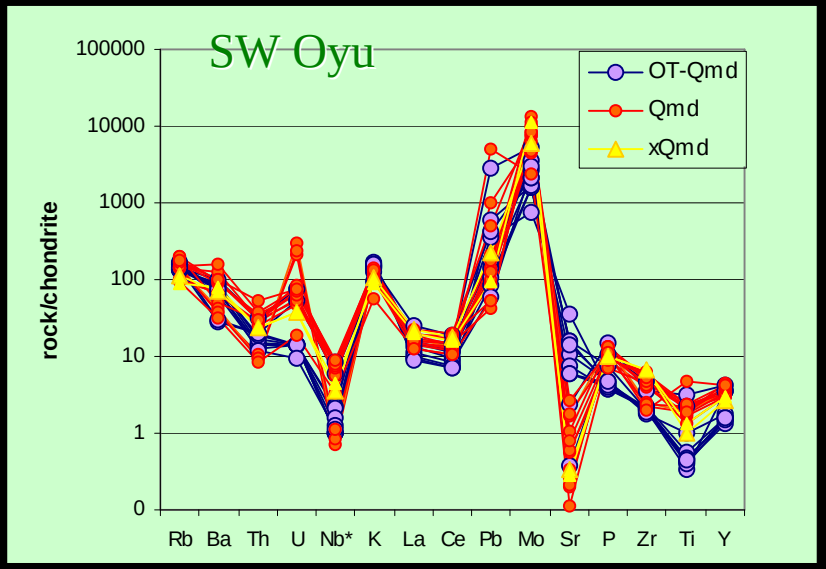


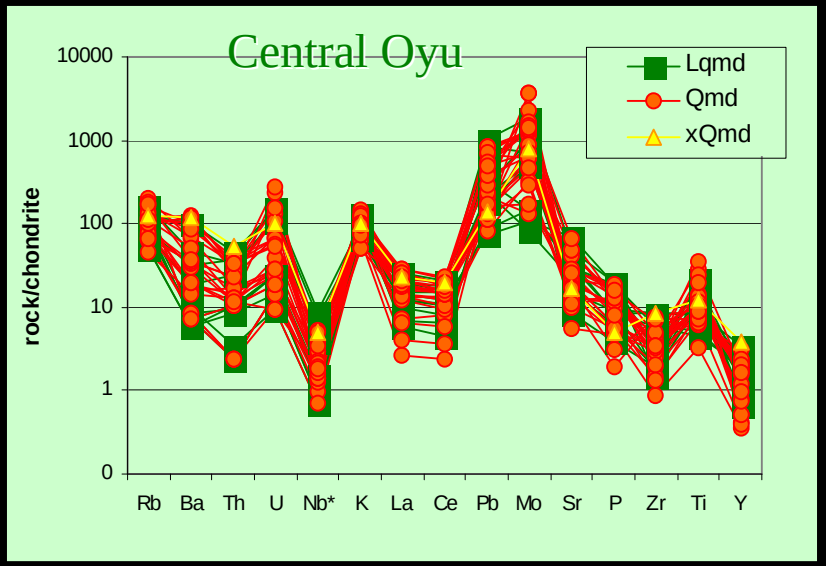


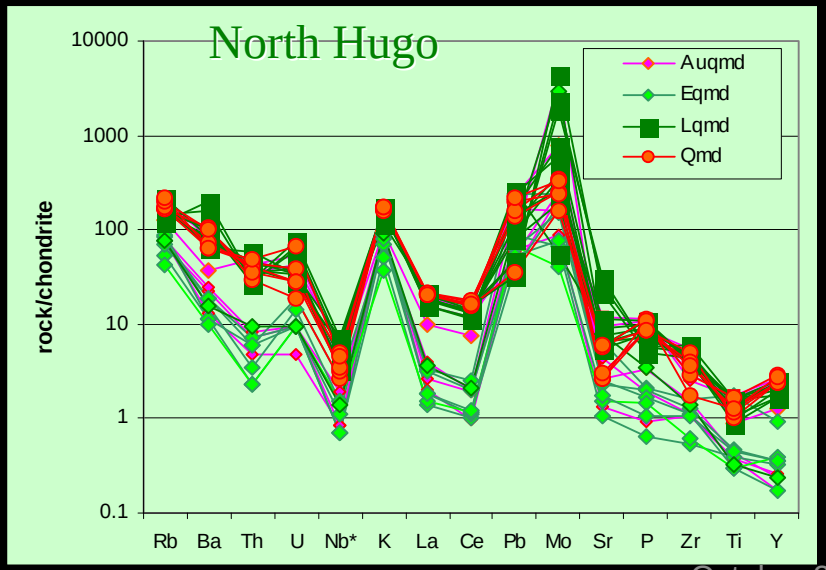
Composition:

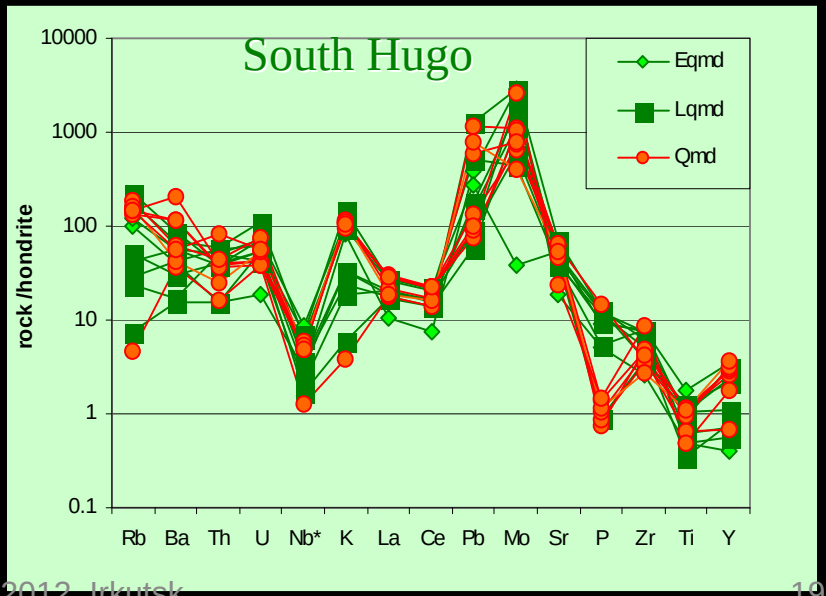
60% plagioclase
10% quartz, partly secondary
10% K-feldspar alteration intergrown with quartz
20% completely altered ferromagnesian minerals (chlorite, opaques)

Devonian Oyu Tolgoi porphyry Cu-Au system
Trace element distribution in monzodiorite



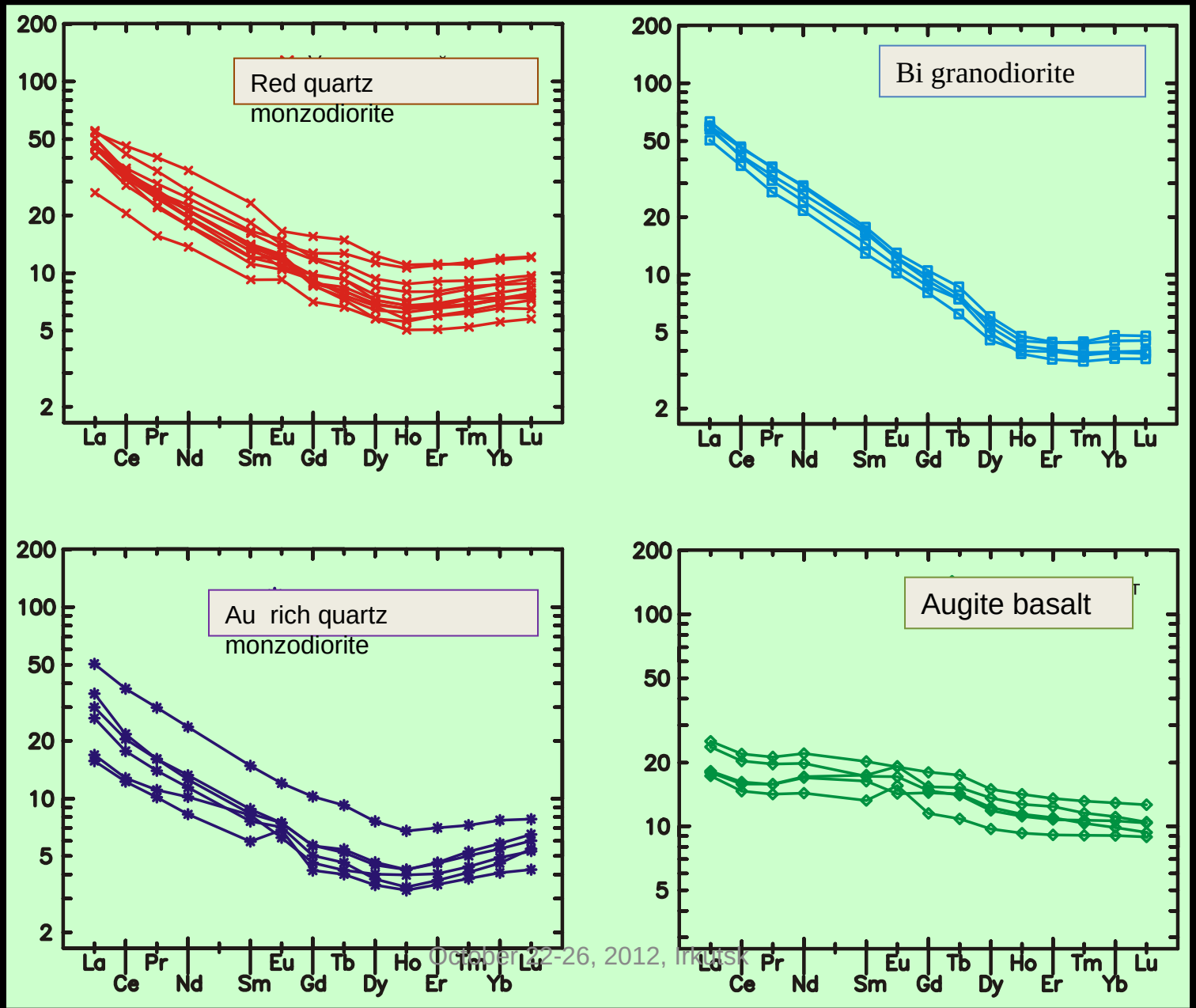




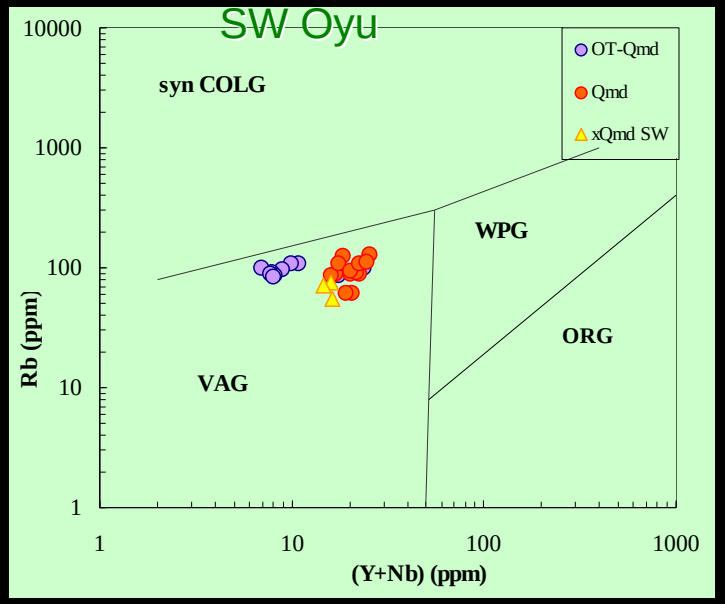


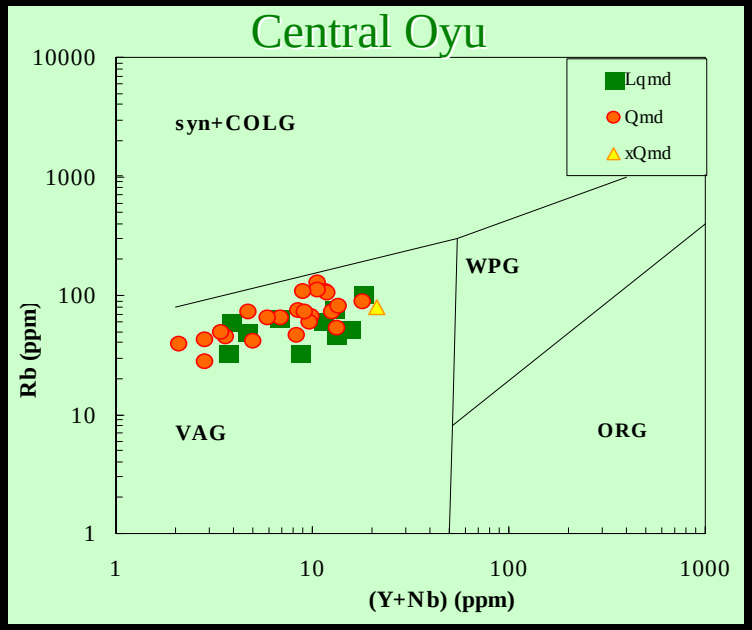
Data from Ivanhoe Mines

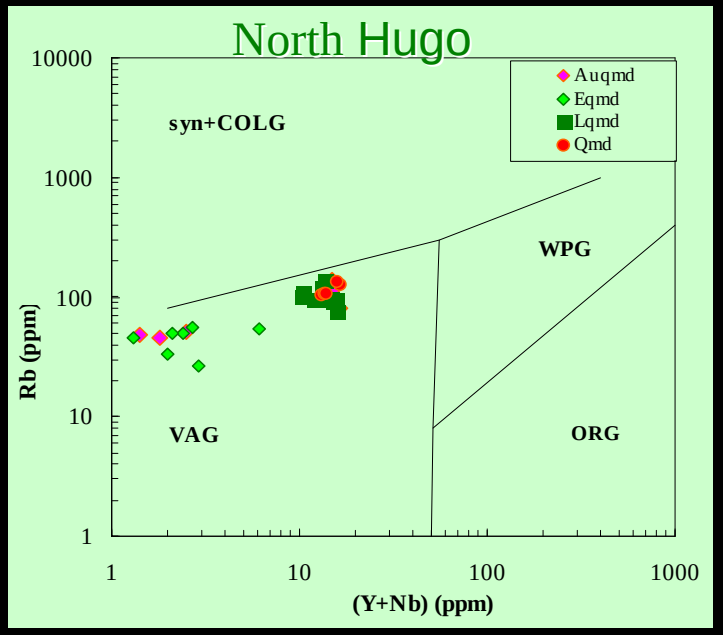
REE distribution

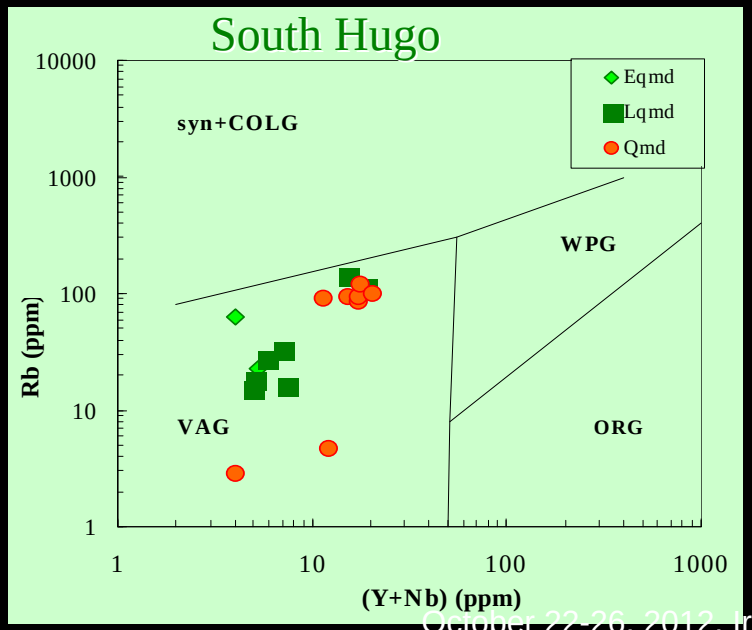


Rb versus Y+Nb diagrams



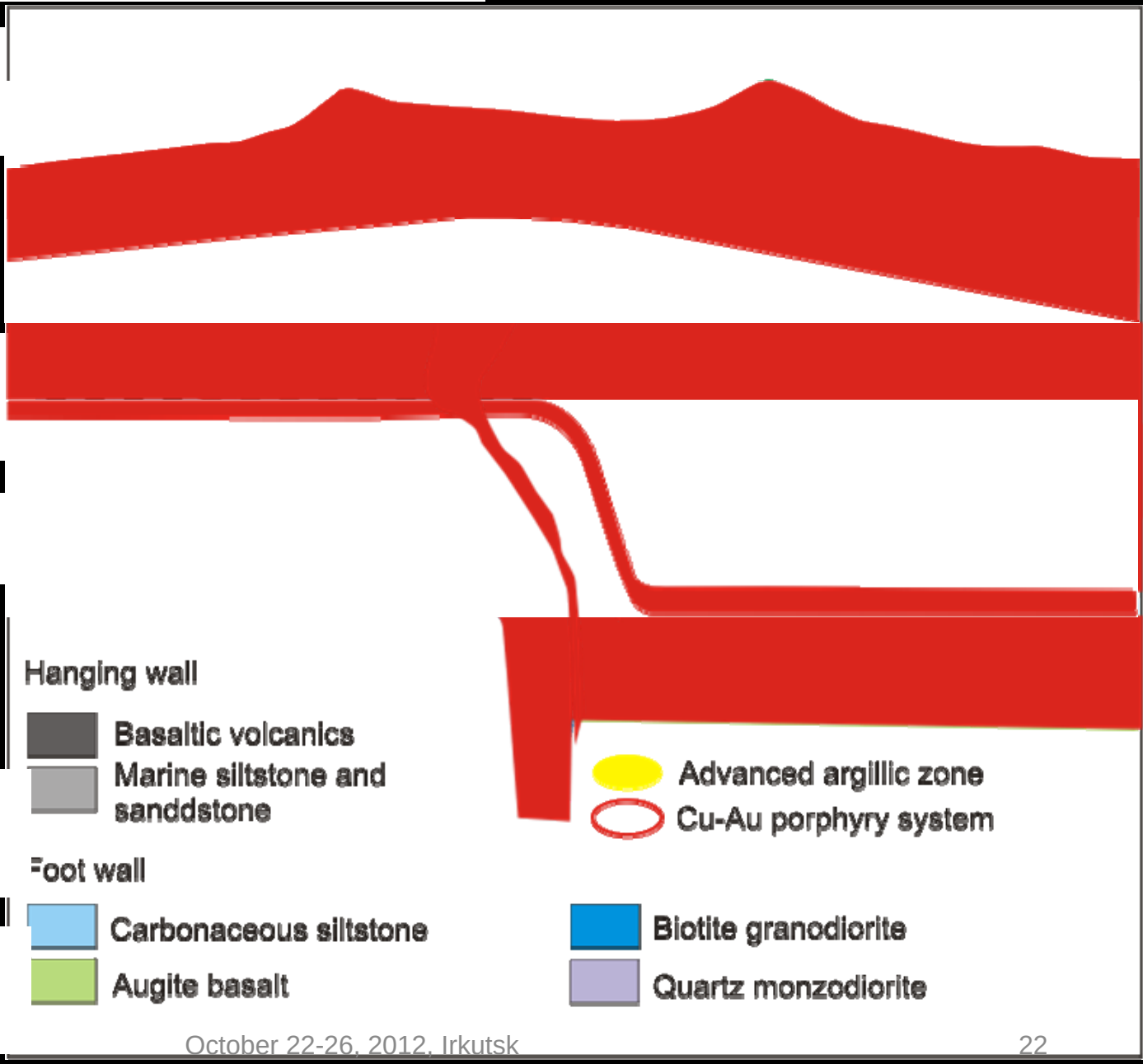




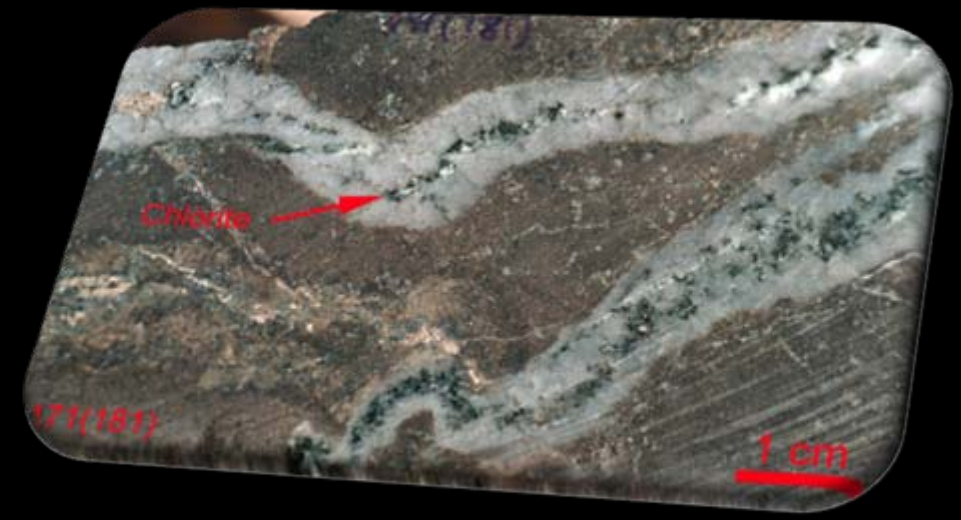


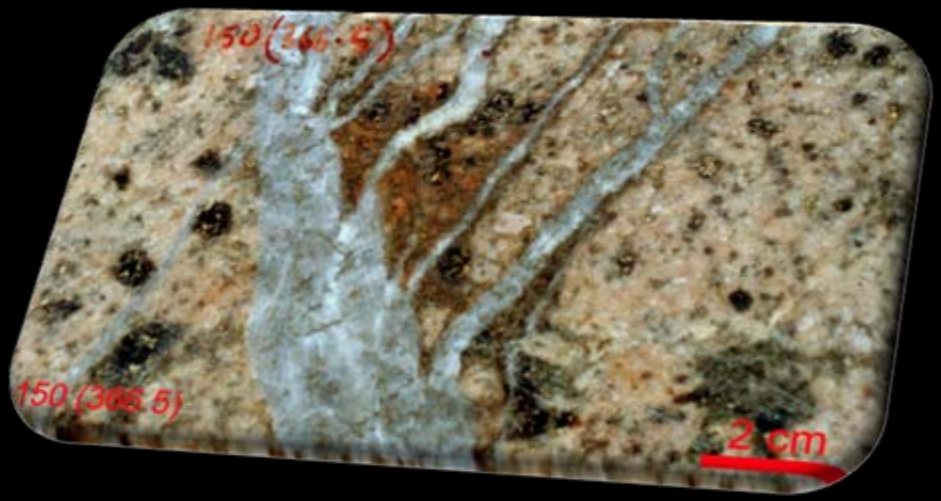
Oyu Tolgoi Geology mineralisation model

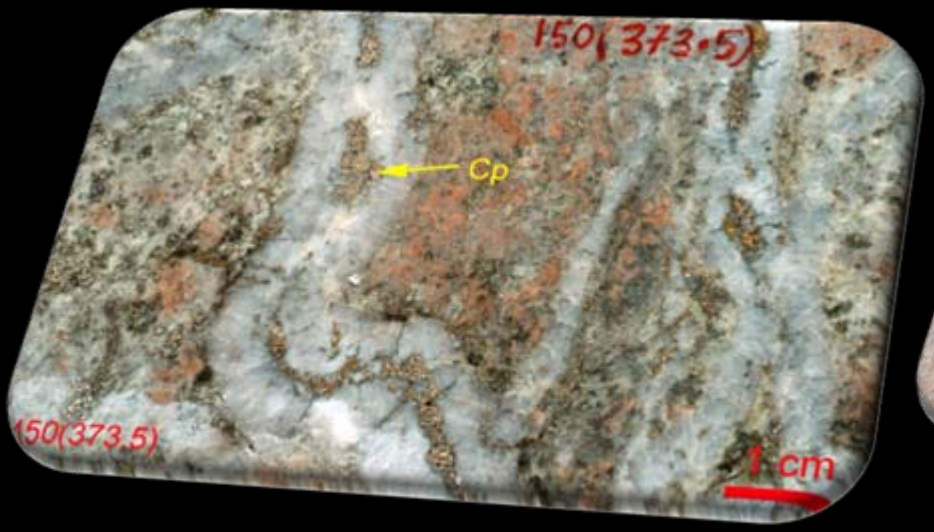
- Augite basalts below major thrust host late Devonian porphyry mineralisation
- Irregular porphyry's at centre of mineralising system
- Alteration extends up to carbonaceous siltstone below thrust
- Major thrust hosted in carbonaceous siltstone
- Basalts and sediments above thrust commonly overturned, exotic min.
- Biotite granodiorite intrudes overthrust sequence 10my younger than mineralisation
- All overlain unconformably by early carboniferous sediments, volcanics

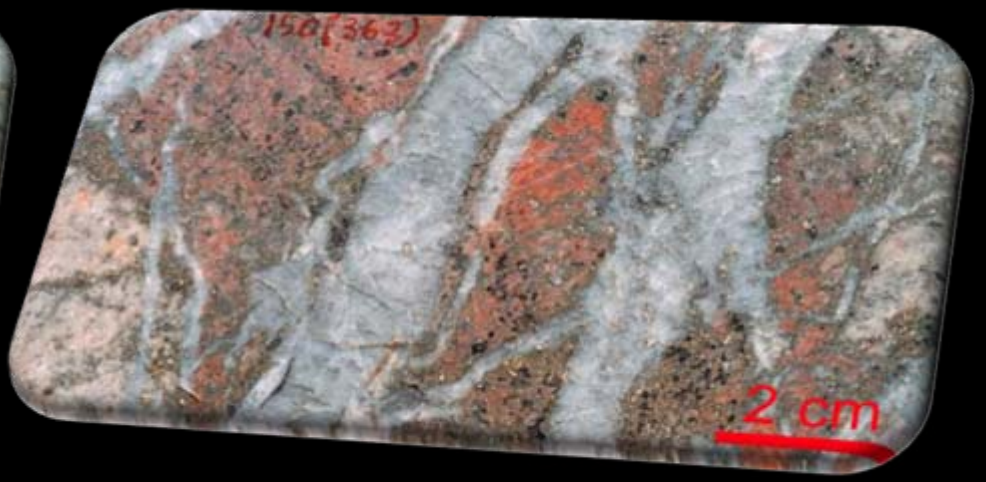


Veining


Chlorite
171(181)
1 cm

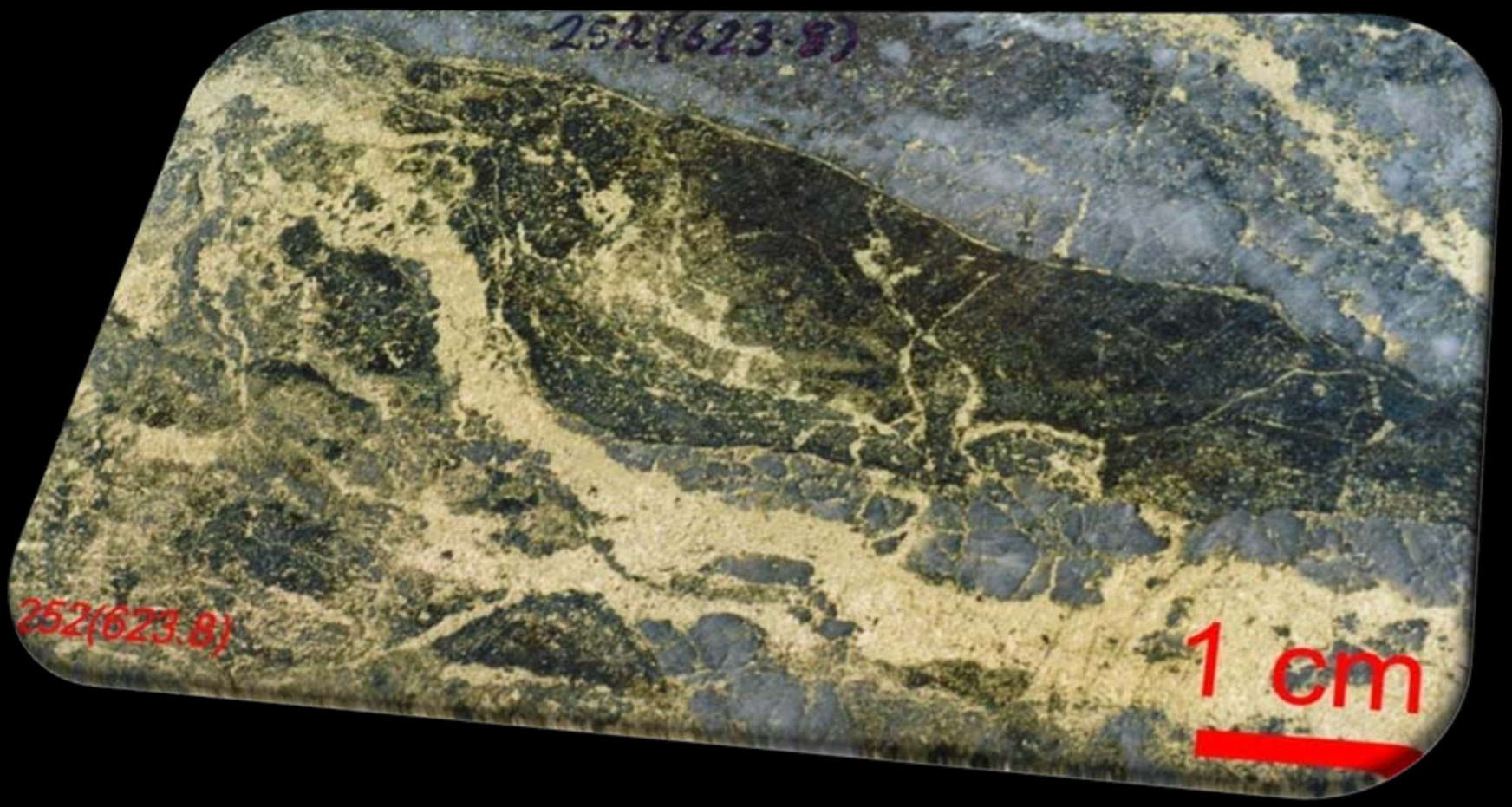

150(366.5)
2 cm


150(373.5)
Cp
150(373.5)
1 cm

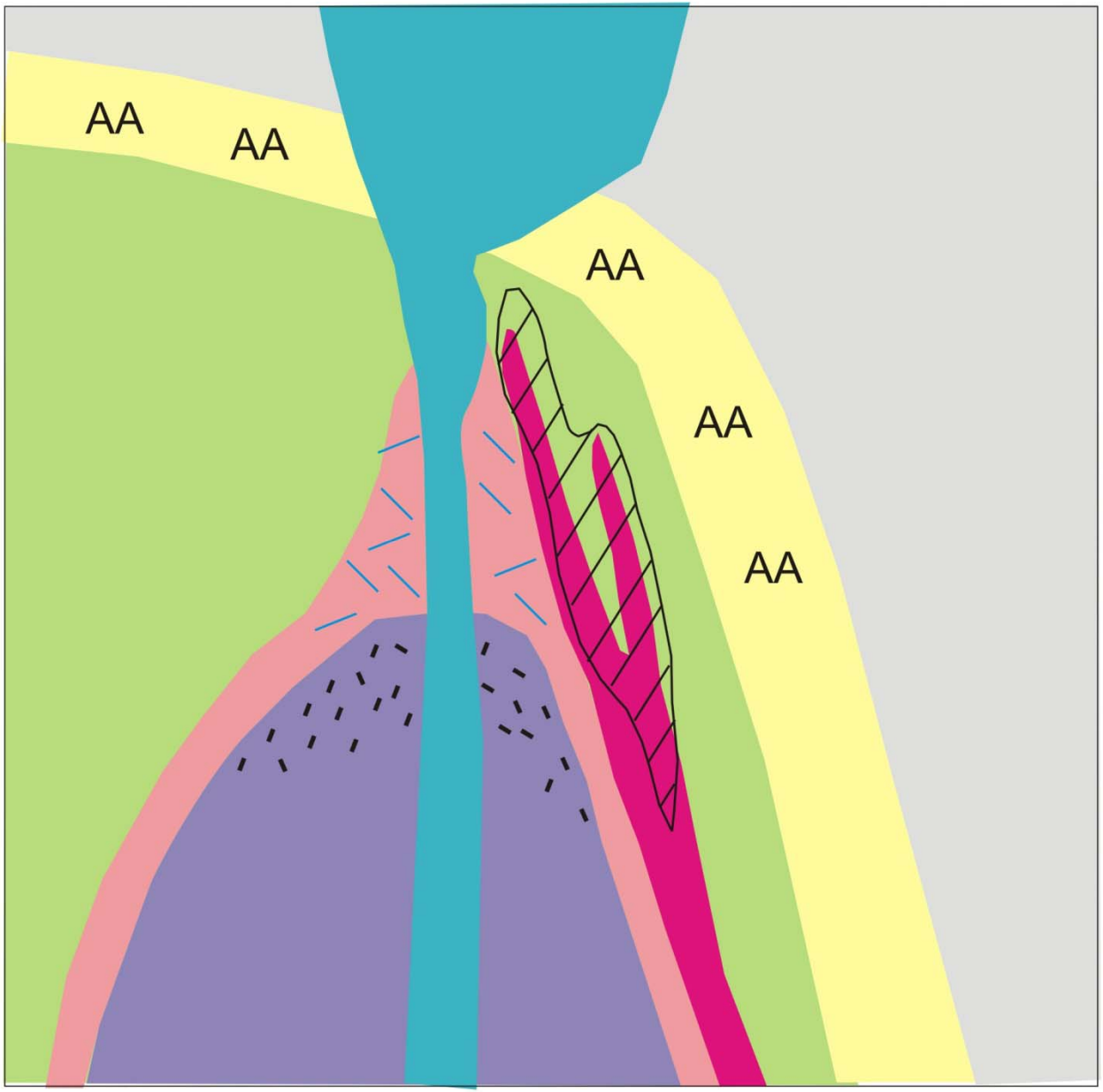

150(363)
2 cm

Southwest Oyu Tolgoi: high-grade Cu-Au mineralization in core

622-624m: 8.9g/tAu, 3.75% Cu



Hugo Dummet alteration and mineralization



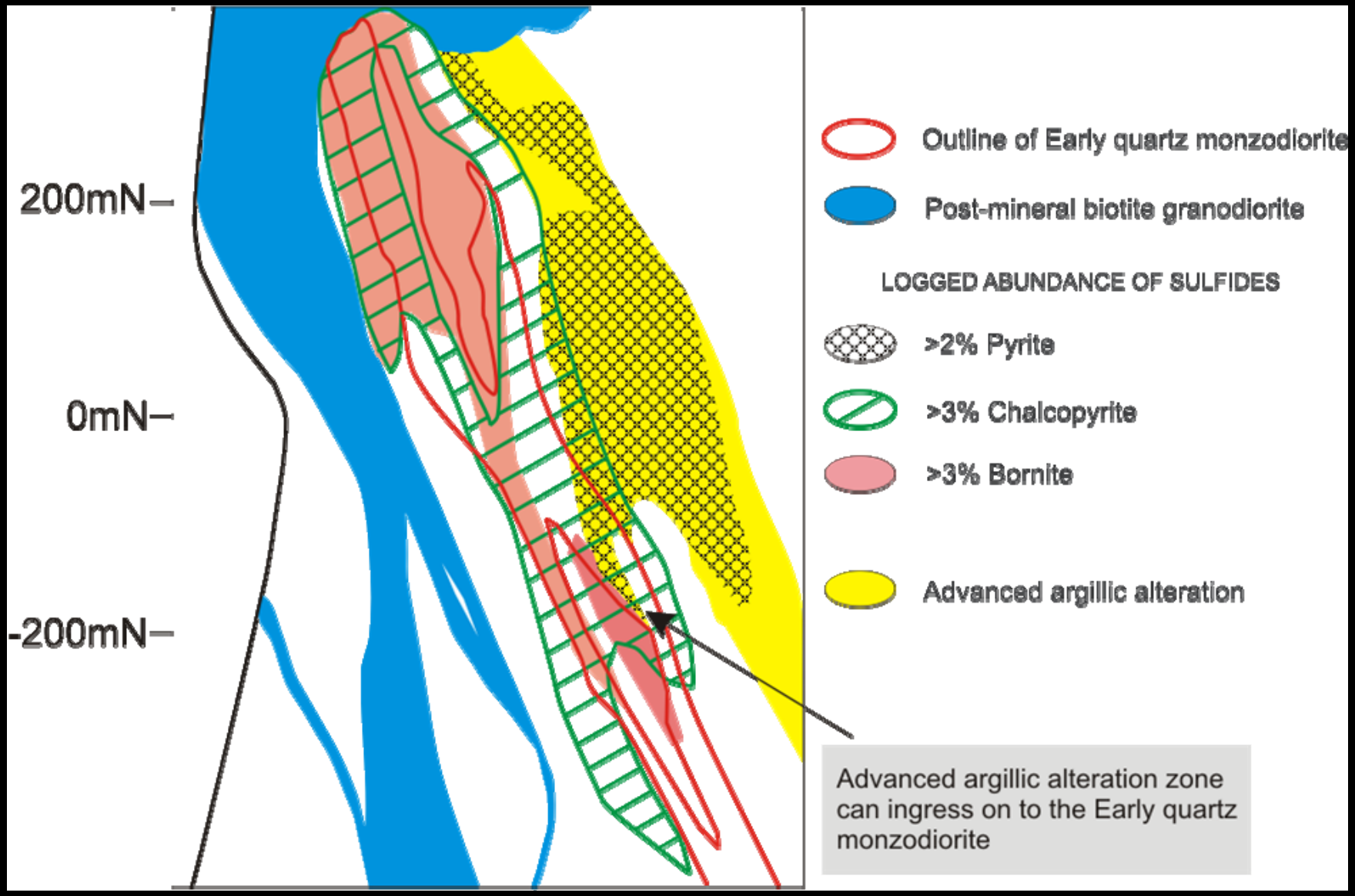
Late-mineral biotite granodiorite
Late inter-mineral Qmd
Early inter-mineral Qmd
Early Qmd

Sedimentary rocks
Dacitic ignimbrite
Basalt

AA Advanced argillic alteration
Dense A-veinlets:(Qv90) +Cu
A-veinlets + Cu-Au
Weak A-veinlets + fine bornite

0 500
Approximate scale

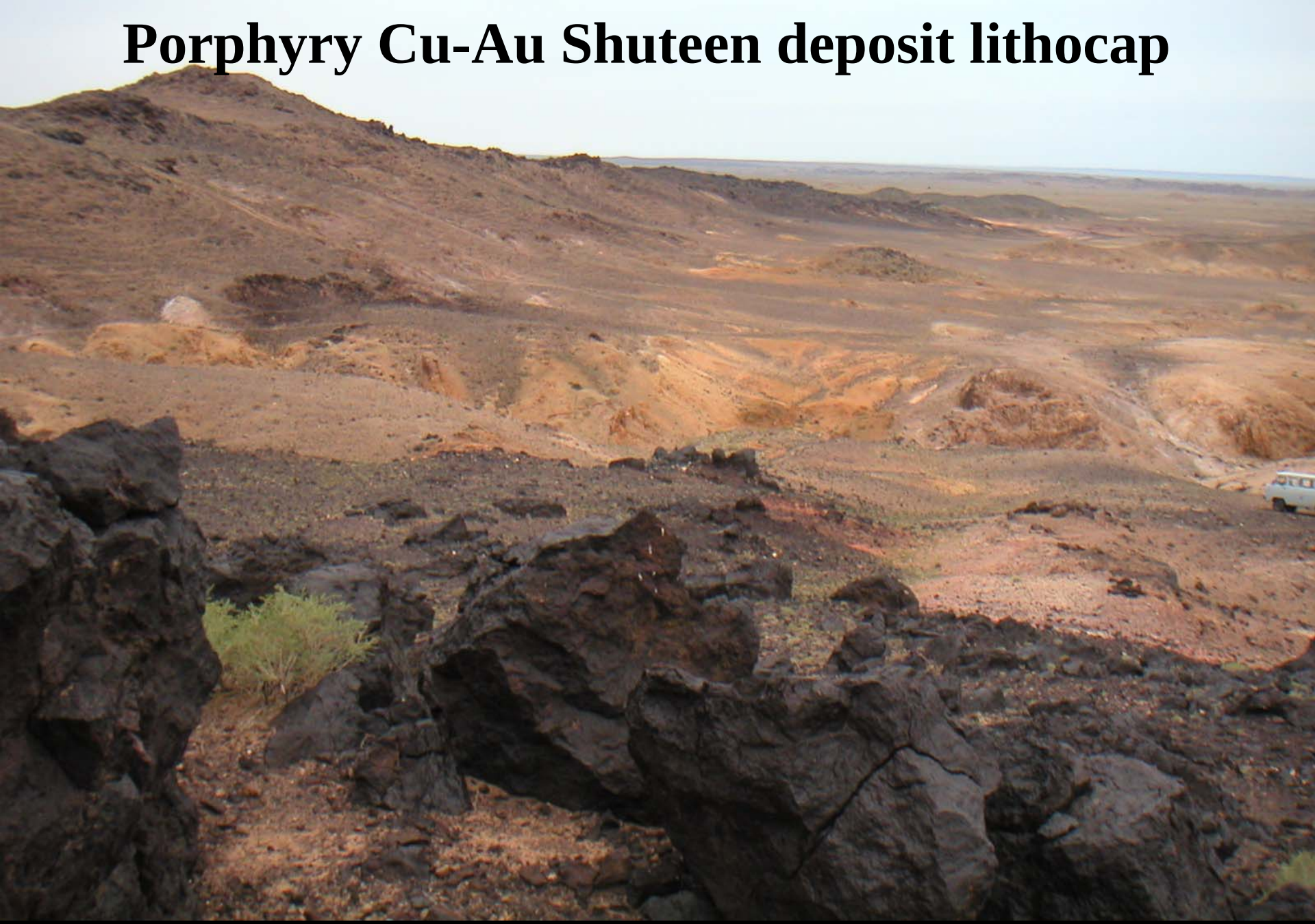
Hugo Dummet North alteration and mineralization



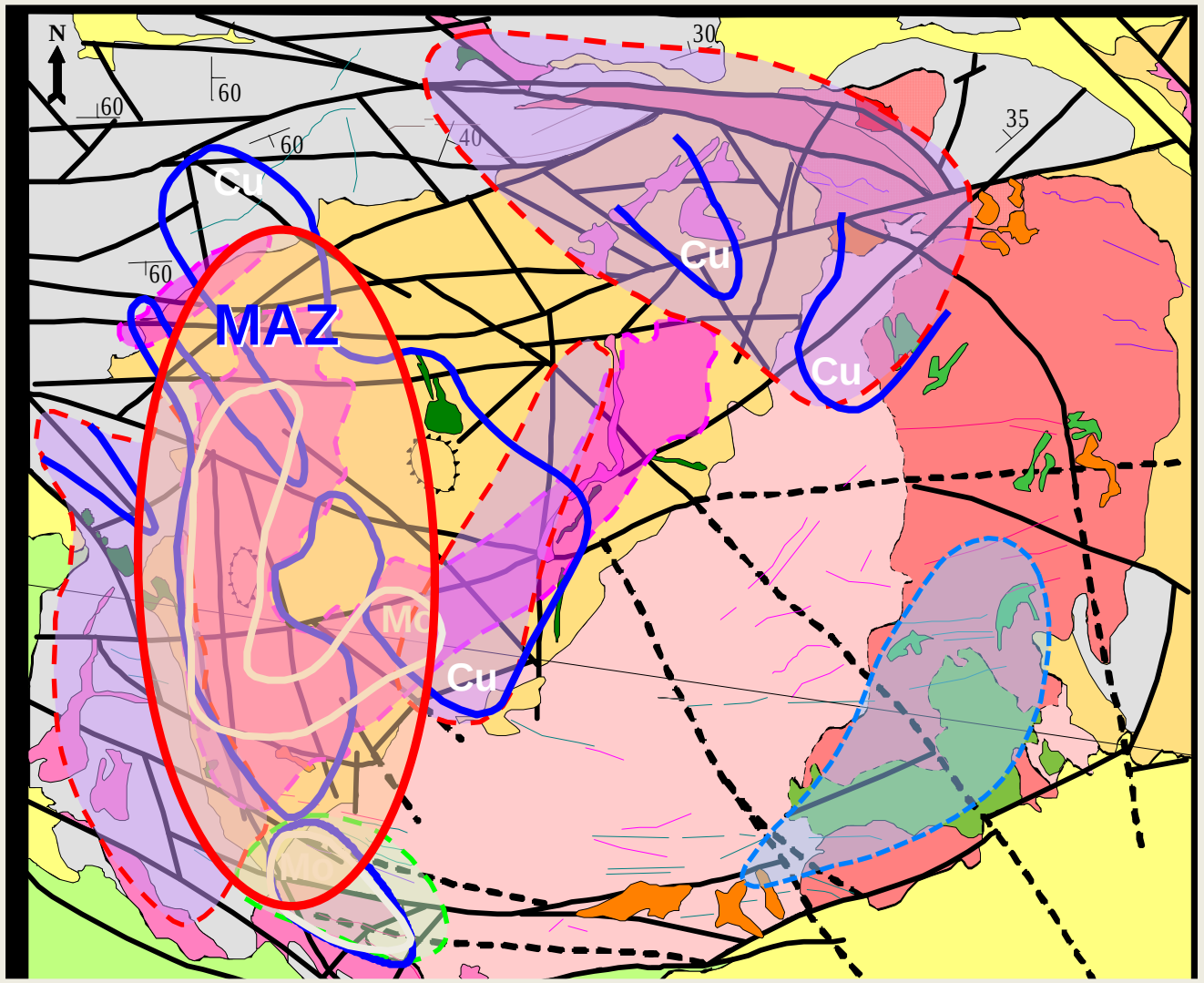
Characteristics of the advanced argillic zone

- Andalusite, corundum, diaspore, residual quartz, alunite, aluminum phosphate-sulfate (APS)
- **Minerals:** zunyite, topaz, pyrophyllite, kaolinite, dickite, gypsum, fluorite
- Developed in augite basalt, dacitic ash flow and quartz monzodiorite, controlled by the augite basalt-dacitic tuff contact, and the most extensive AA is after augite basalt
- **Cu minerals:** (enargite, tennantite, bornite, chalcopyrite, chalcocite, covellite), but no significant gold in the AA zone
- O, H and S isotope study shows that the alunite is derived from magmatic condensate, without a significant meteoric component

Porphyry Cu-Au Shuteen deposit lithocap



Geological map of the Shuteen area



SHUTEEN COMPLEX

Late stocks and dikes

SHUTEEN PLUTON

Third Stage
Bt granodiorite, granite

Second Stage
Granodiorite, Hb-Bt granite

First stage
Diorite, monzodiorite

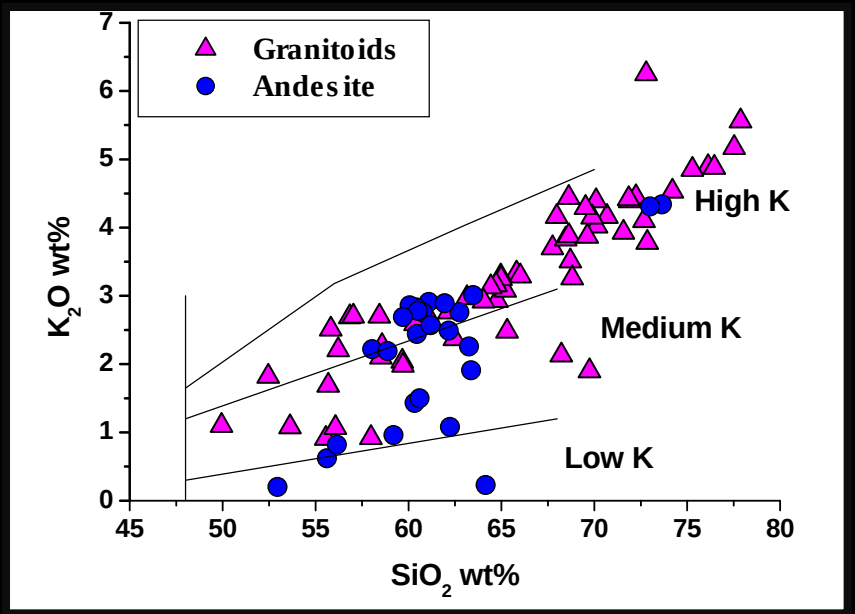
Early stocks and dikes

Dusiin Ovoo Formation
Andesite

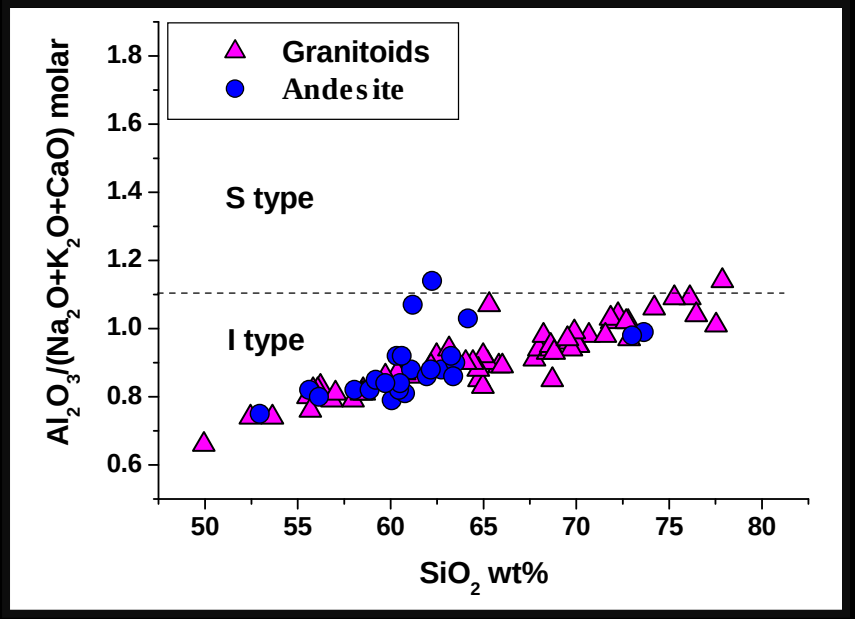
- High K series (Batkhishig, 2003, 2006).
- Metaluminous
- Na_2O in granite is >3.2%
- Accessory titanite

I type (igneous source)

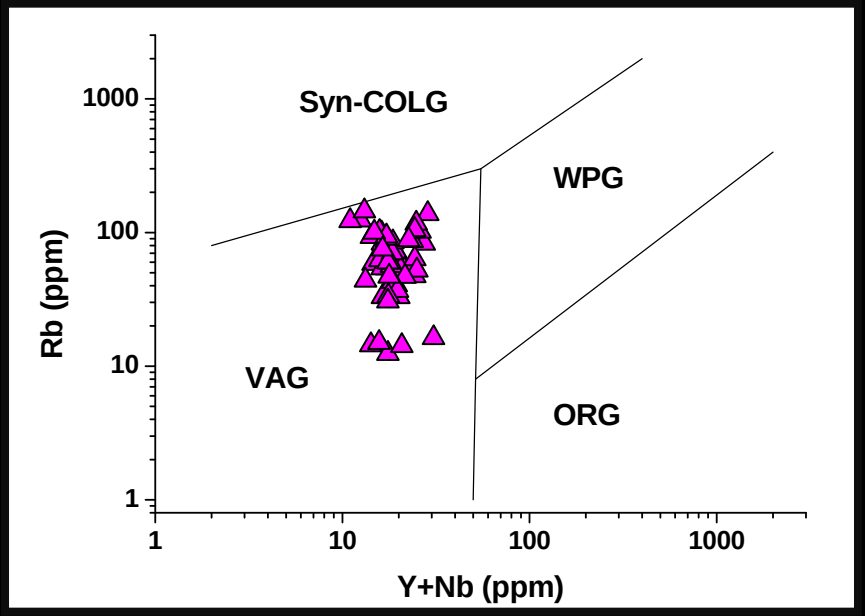
Volcanic arc setting



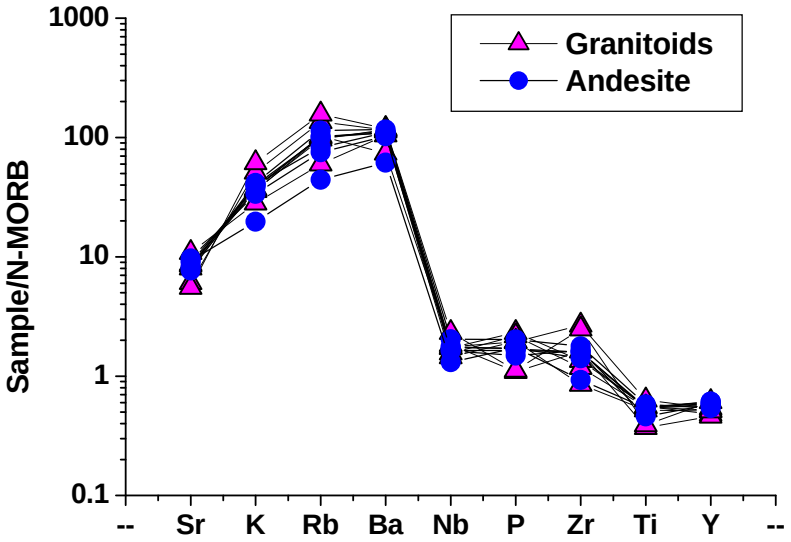
K_2O vs SiO_2 diagram after Le Maitre *et al.*, 1989.

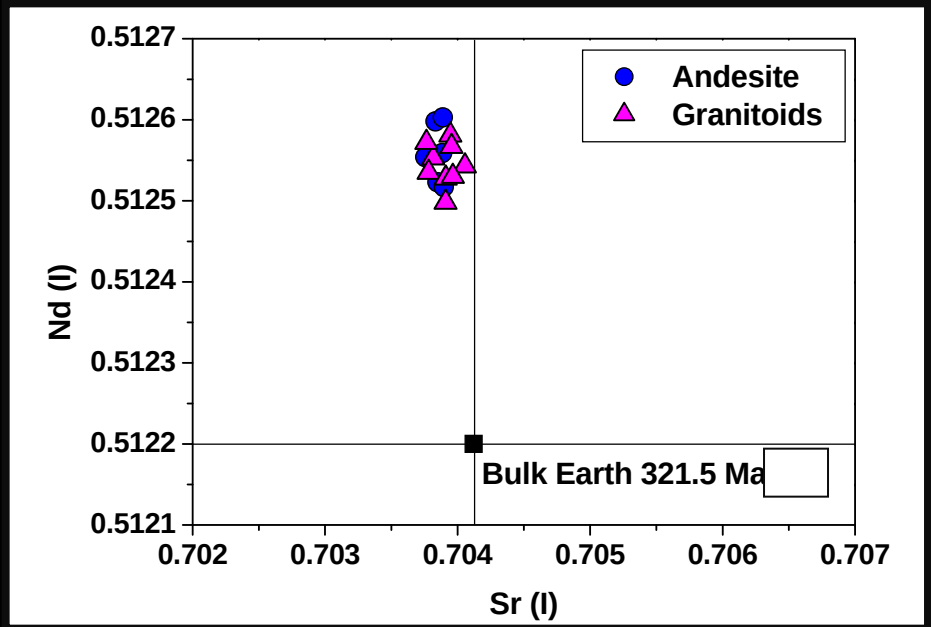


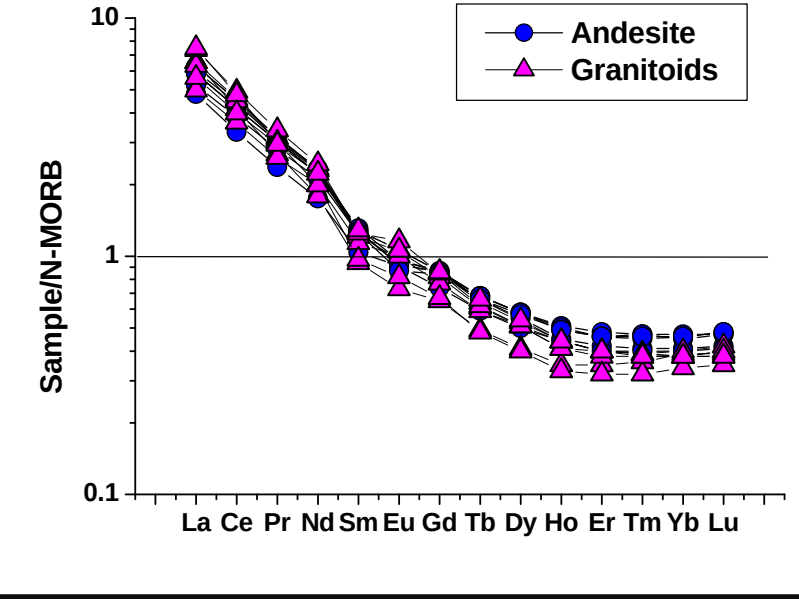
ASI vs SiO_2 diagram after Chappel and White, 1974.



Rb vs (Y+Nb) diagram after Le Pearce *et al.*, 1984







Andesite and granitoids have similar

- Whole rock chemistry
- Initial Sr and Nd isotope ratios

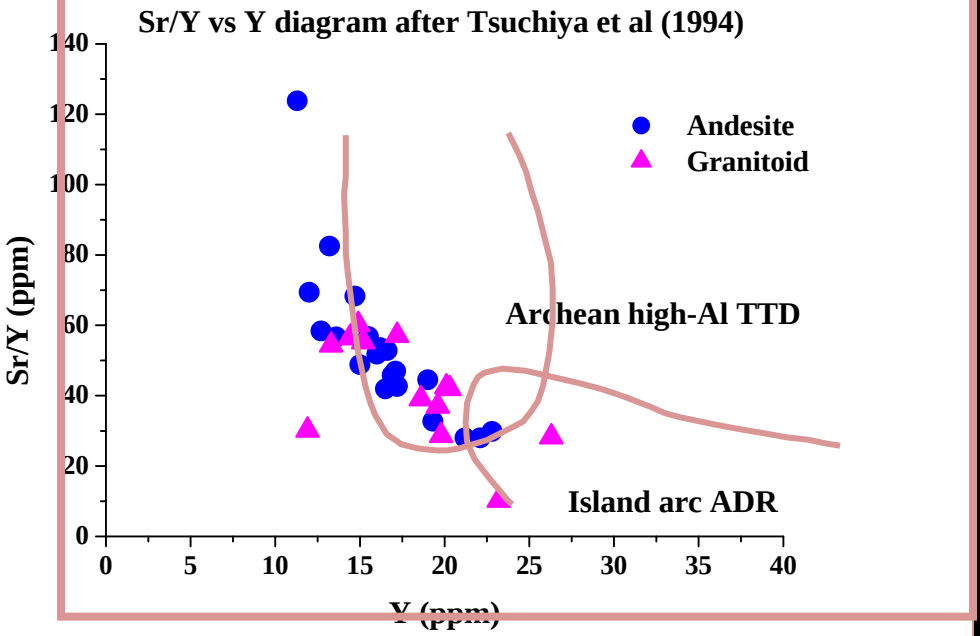
Geochemistry of the Shuteen complex

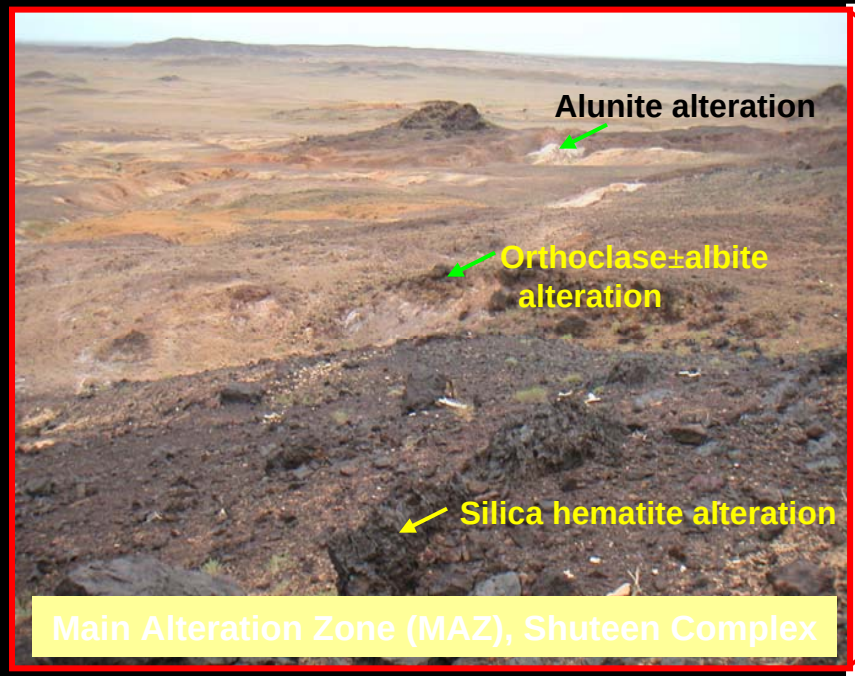
Characteristics of adakite/Archean high Al TTD*

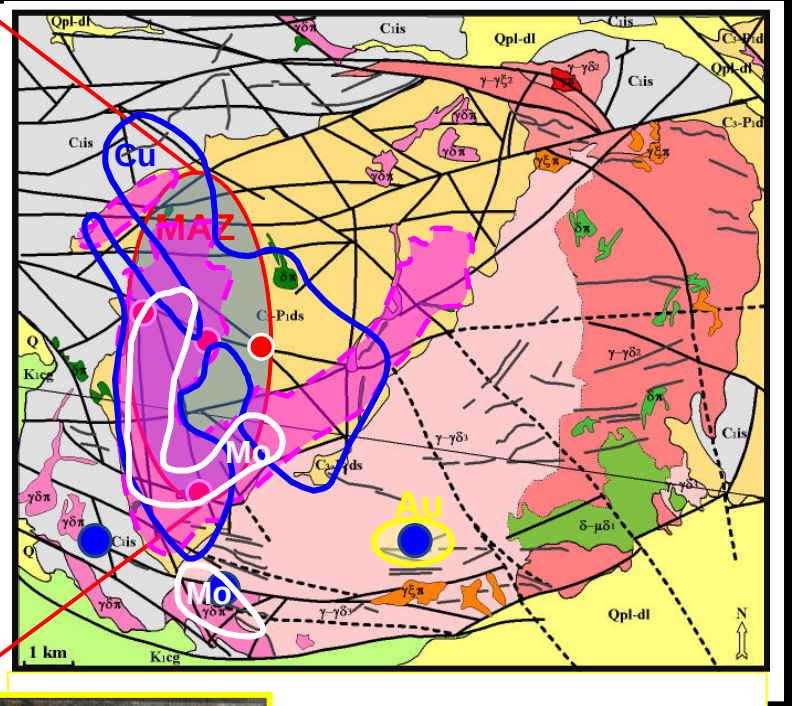
- **Silica over saturated**
- **High Al_2O_3 >15%**

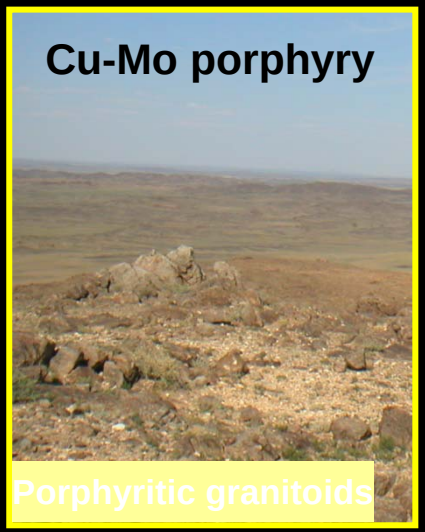
- **High Sr >400ppm**
- **Low Y<18ppm**
- **Yb <1.9ppm**
- **La/Yb >20**
- **Zr/Sm>50**

- **Depleted in HREE**
- **High Sr/Y >40**
- **Low initial $^{87}Sr/^{86}Sr$**
- **High initial $^{143}Nd/^{144}Nd$**



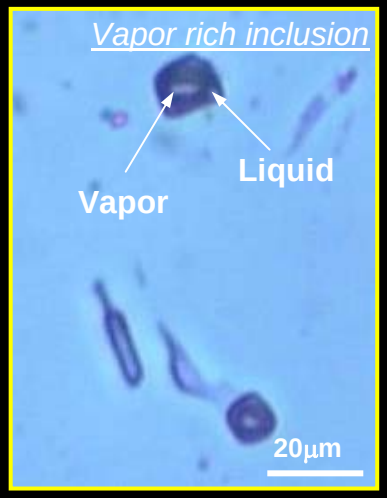


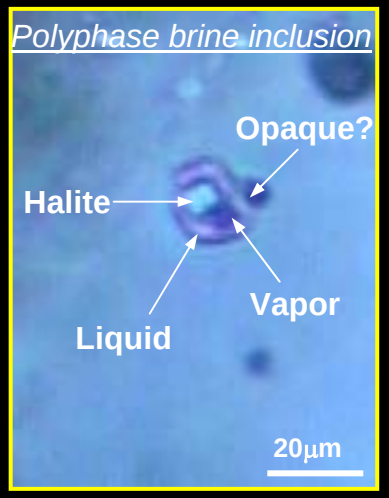


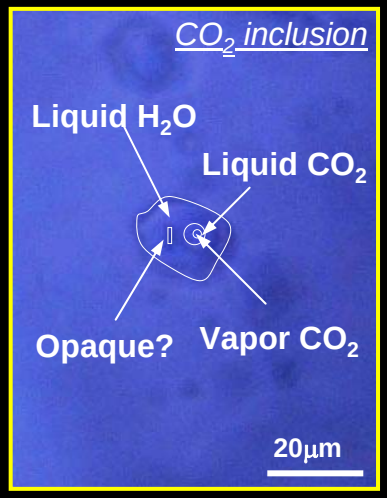


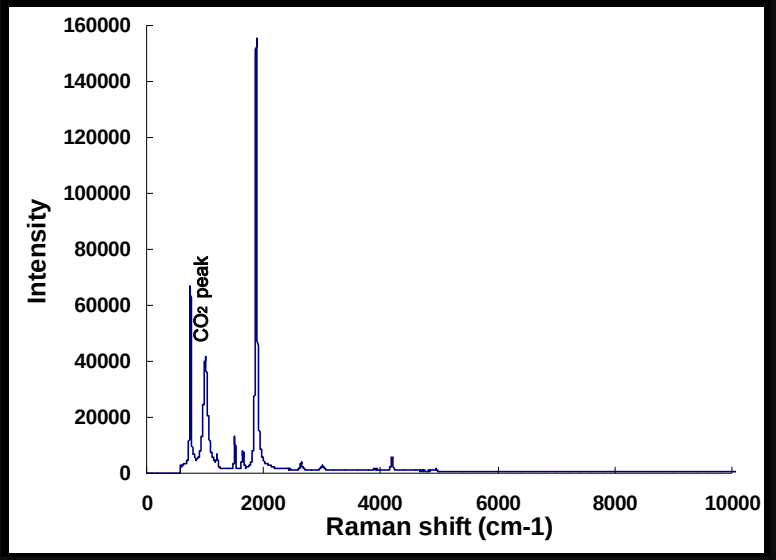
Hydrothermal quartz veins and breccias occurred at the southern margin of the MAZ and breccia vein samples from drillcores were used for the fluid inclusion microthermometry and SEM-CL study.

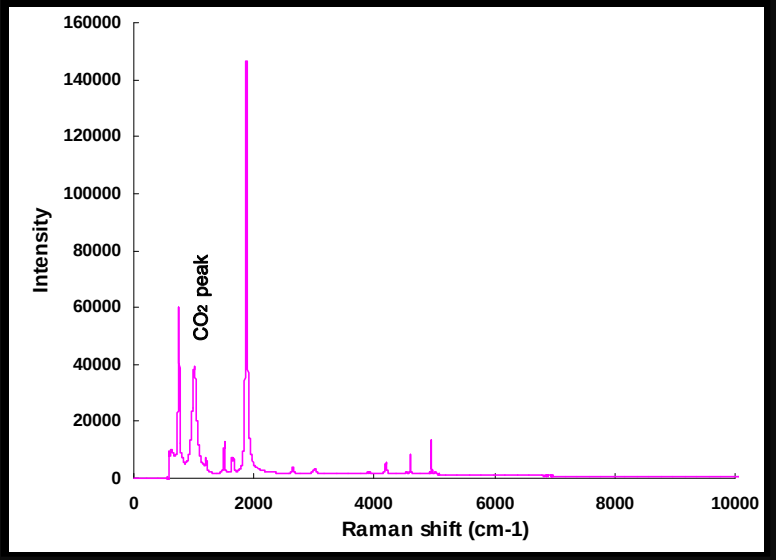
At room temperature 4 types of fluid inclusions observed in rocks from the Shuteen Complex





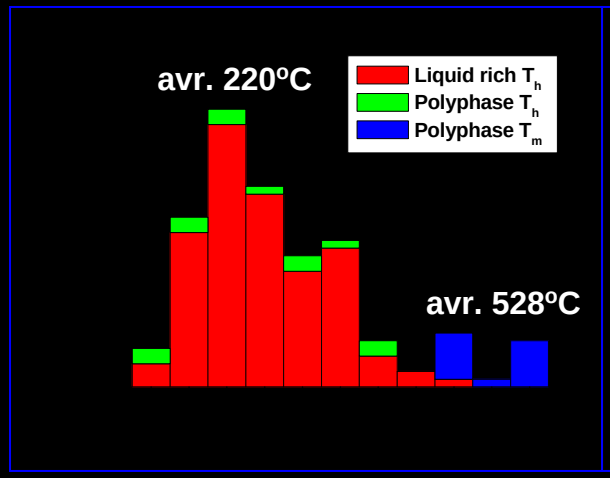




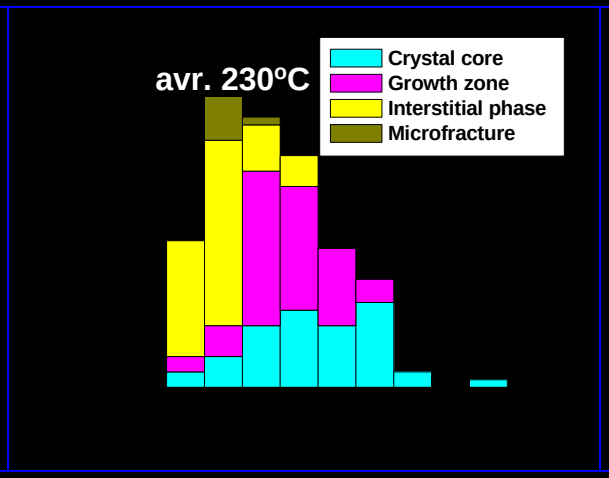


Homogenization T and salinity frequency diagrams (Batkhyshig, 2005)

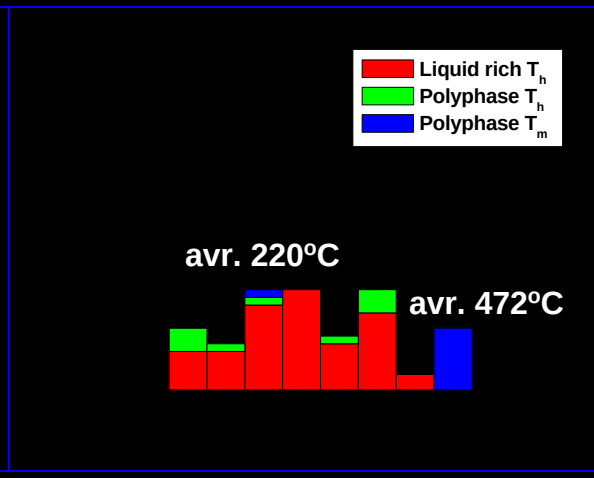
Porphyritic granodiorite

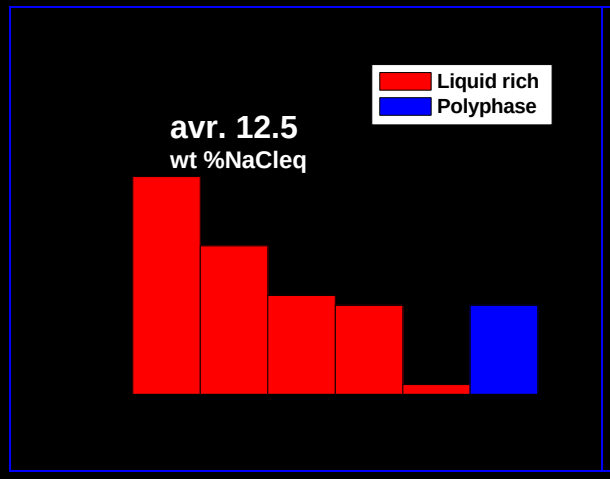


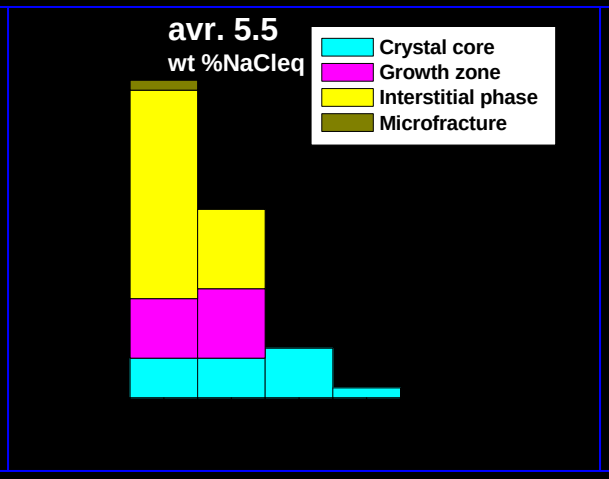
Quartz vein

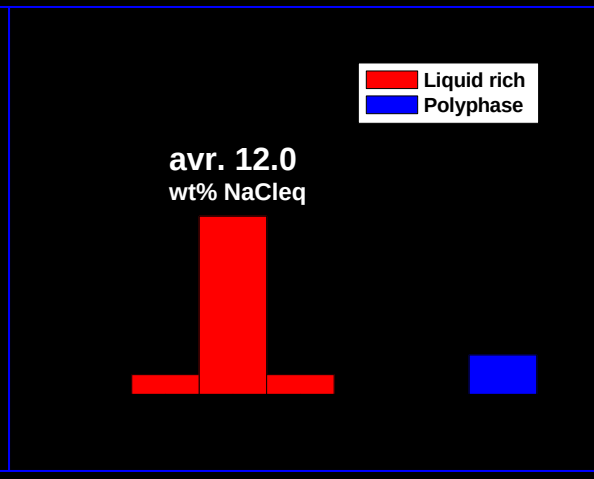


Quarz from Breccia

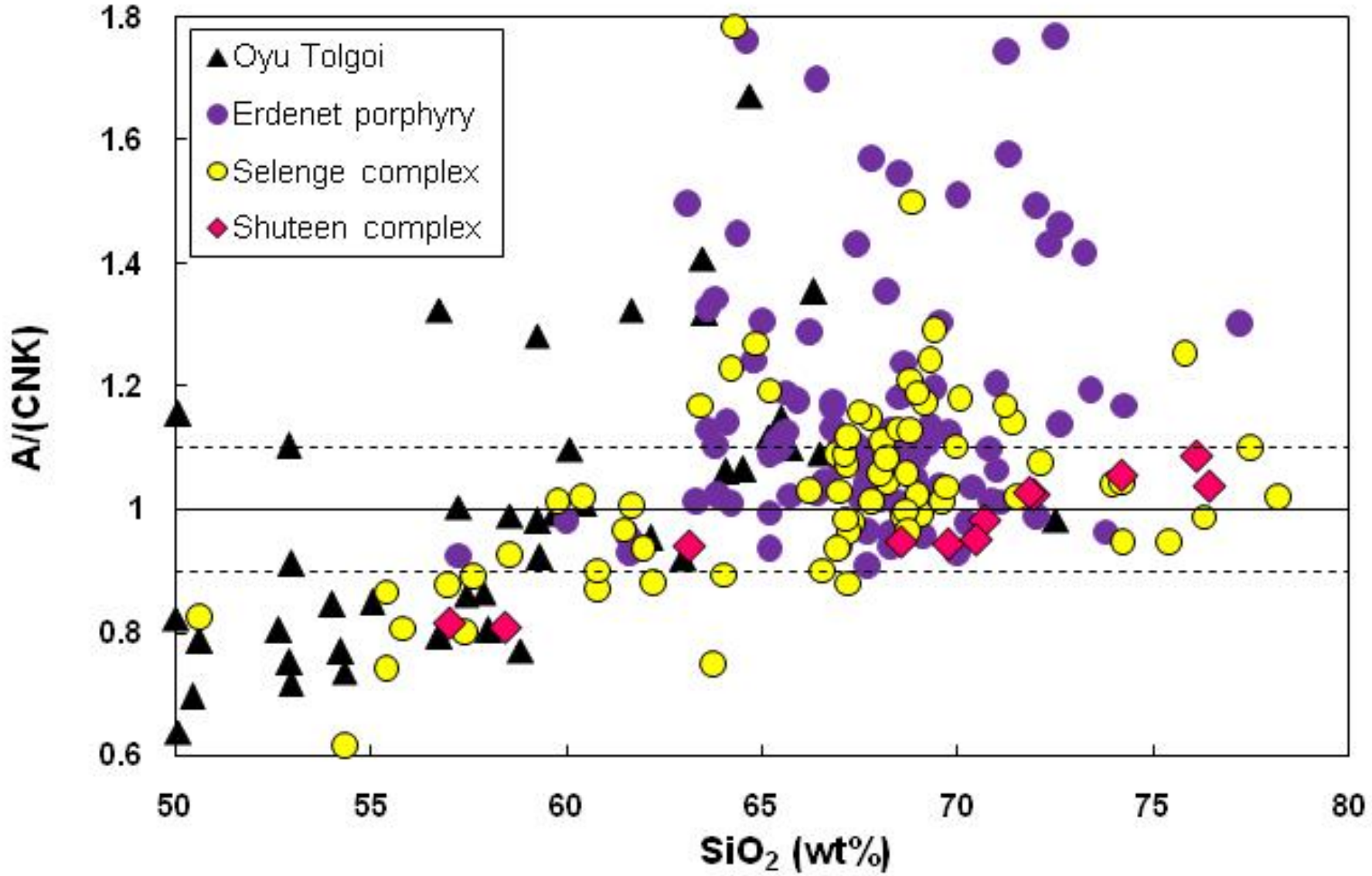




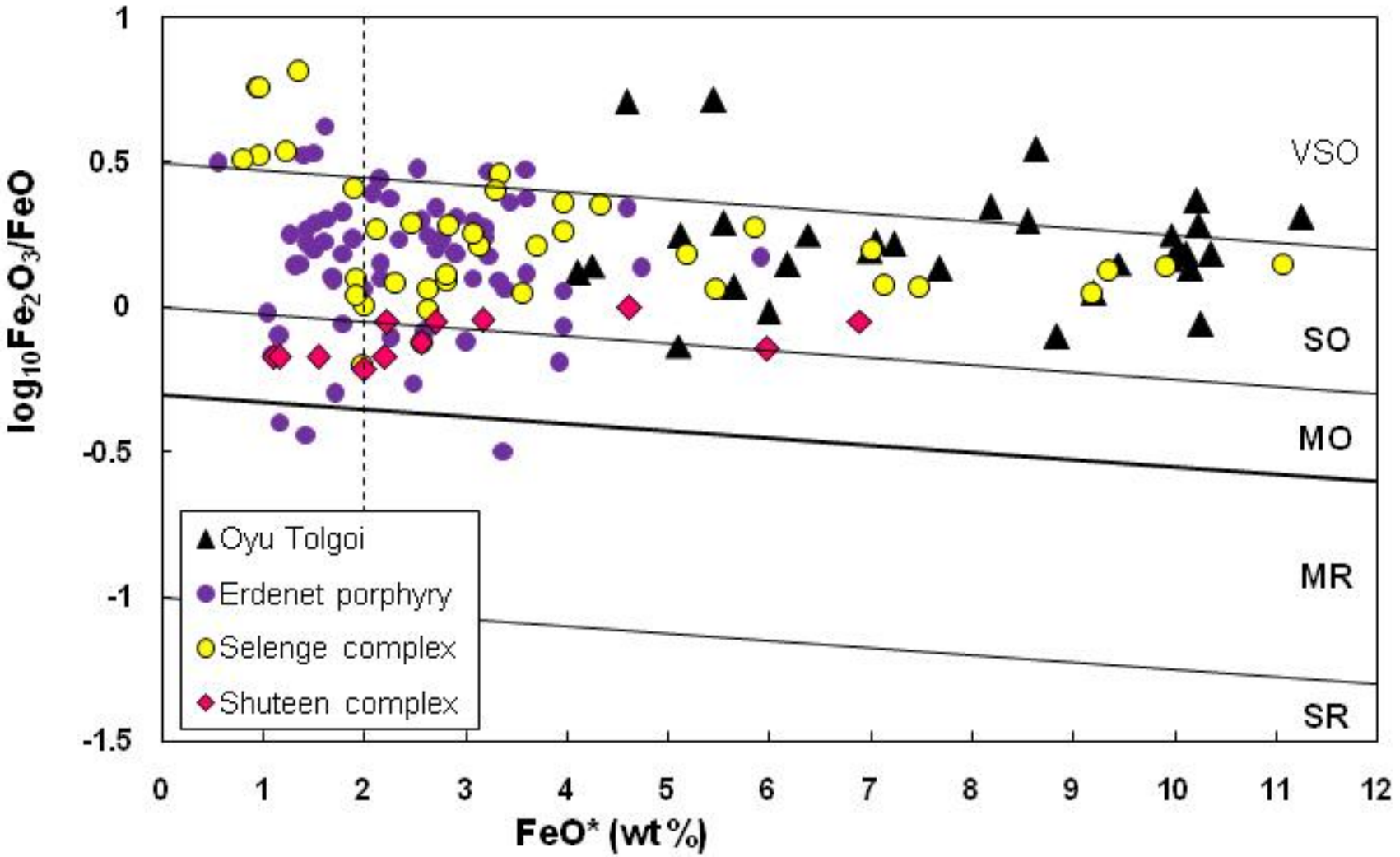




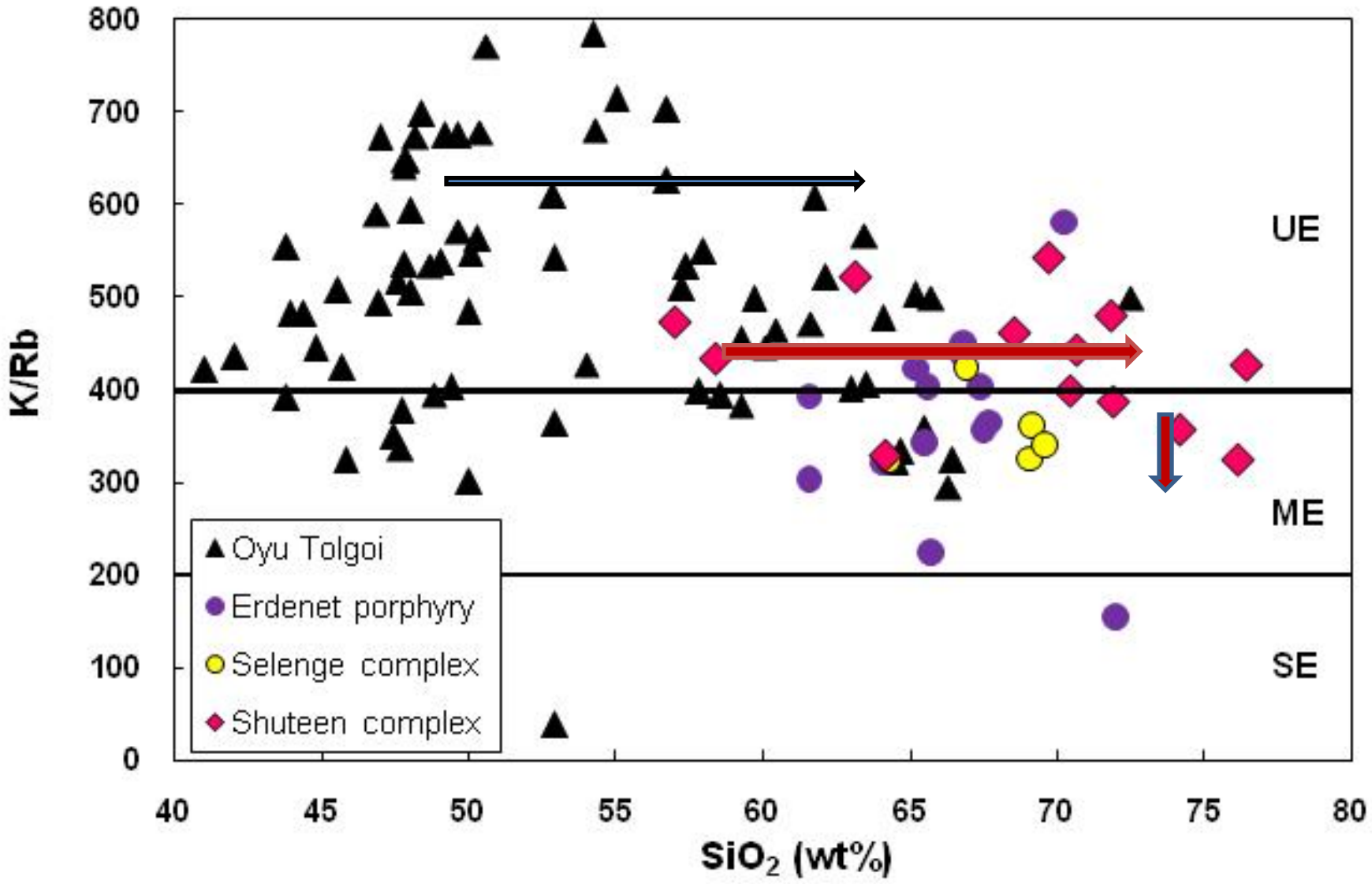
Compositional type: A/CNK vs. SiO_2



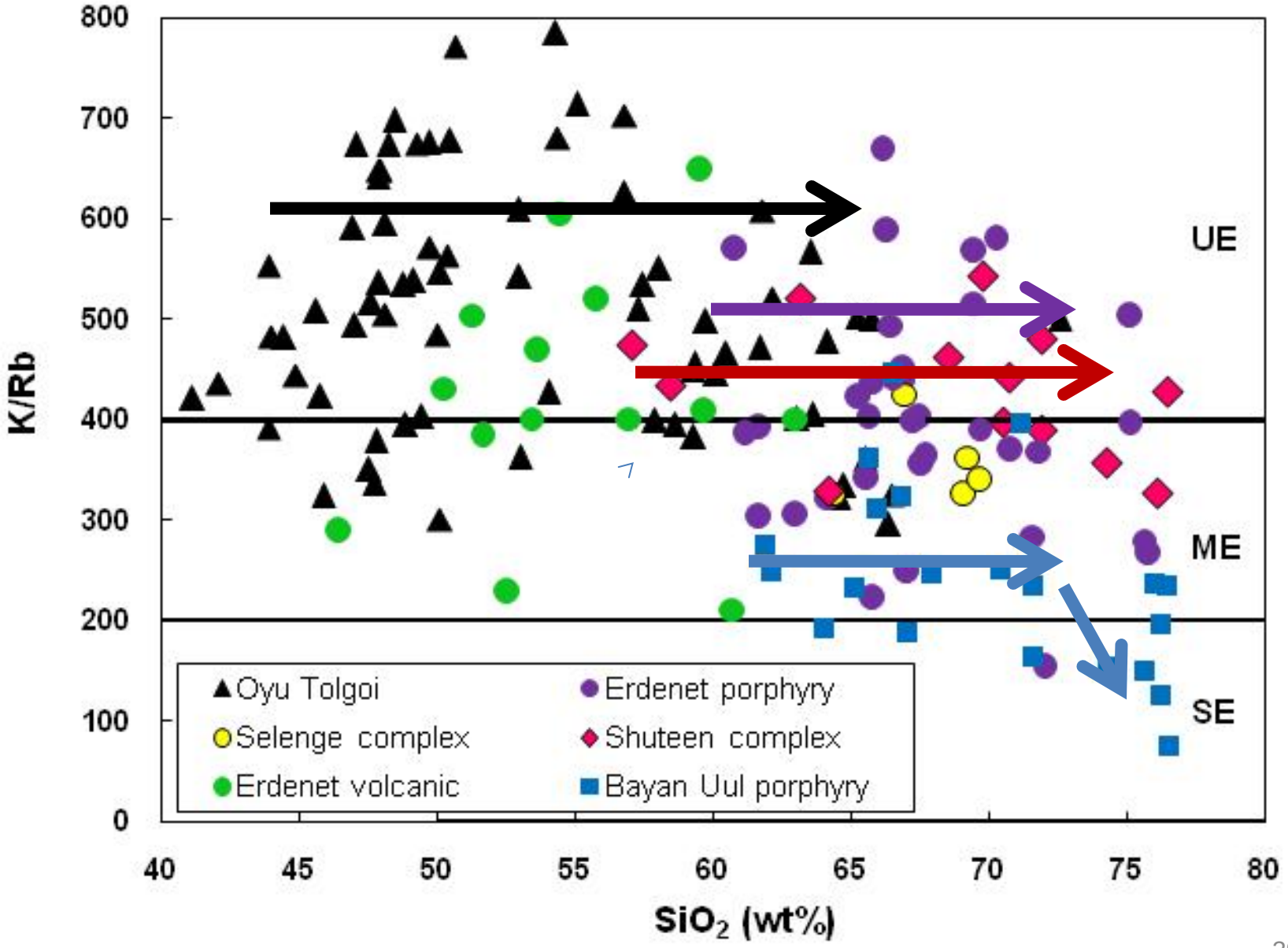
Oxidation state: Fe_2O_3/ FeO vs.FeO



Differentiation mechanism: K/Rb vs. SiO_2



K/Rb vs. SIO2


800
700
600
500
400
300
200
100
0
K/Rb
40
45
50
55
60
65
70
75
80
SiO2 (wt%)
UE
ME
SE
Oyu Tolgoi
Erdenet porphyry
Selenge complex
Shuteen complex
Erdenet volcanic
Bayan Uul porphyry

Metallogeny of granitoids with porphyry deposits

- Granitoids are calc-alkaline, medium to high K, metaluminous I type, altered porphyries are weakly to strongly peraluminous

- Granitoids are strongly oxidized (Oyu Tolgoi, Erdenet) to moderately oxidized (Shuteen Erdenet)

- Porphyries are unevolved (Oyu Tolgoi) or moderately evolved (Shuteen, Erdenet), rarely highly evolved (porphyry Cu-Mo)

- Granitoids are depleted in Nb, enriched in LILE, typical VAG , with adacitic signuture (High Sr/Y and La/Yb ratio, and low Y and Yb).

Hugo Dummet deposit: high grade Cu – Au ore

Thank you

OTD918C(1124): 15% Cu, 1.4g/t Au