Department of Geology & Geophysics, IIT Kharagpur

The Dharwar Gold: Current understanding and future Research

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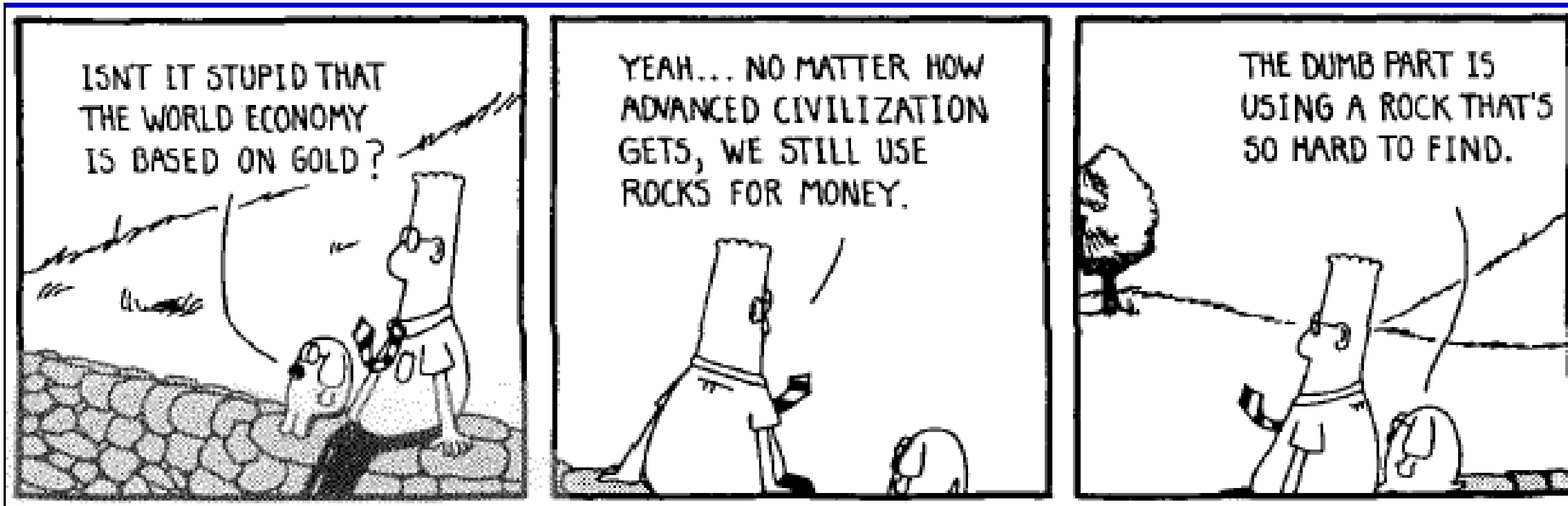
Genesis of metallic ore deposits

How and WHEN do/did ore deposits form? Philosophical
Why do they occur **where** they are? Exploration & Mining

Ore deposits are crustal segments, with minable positive anomalies of one or more metals by efficient/slow earth processes

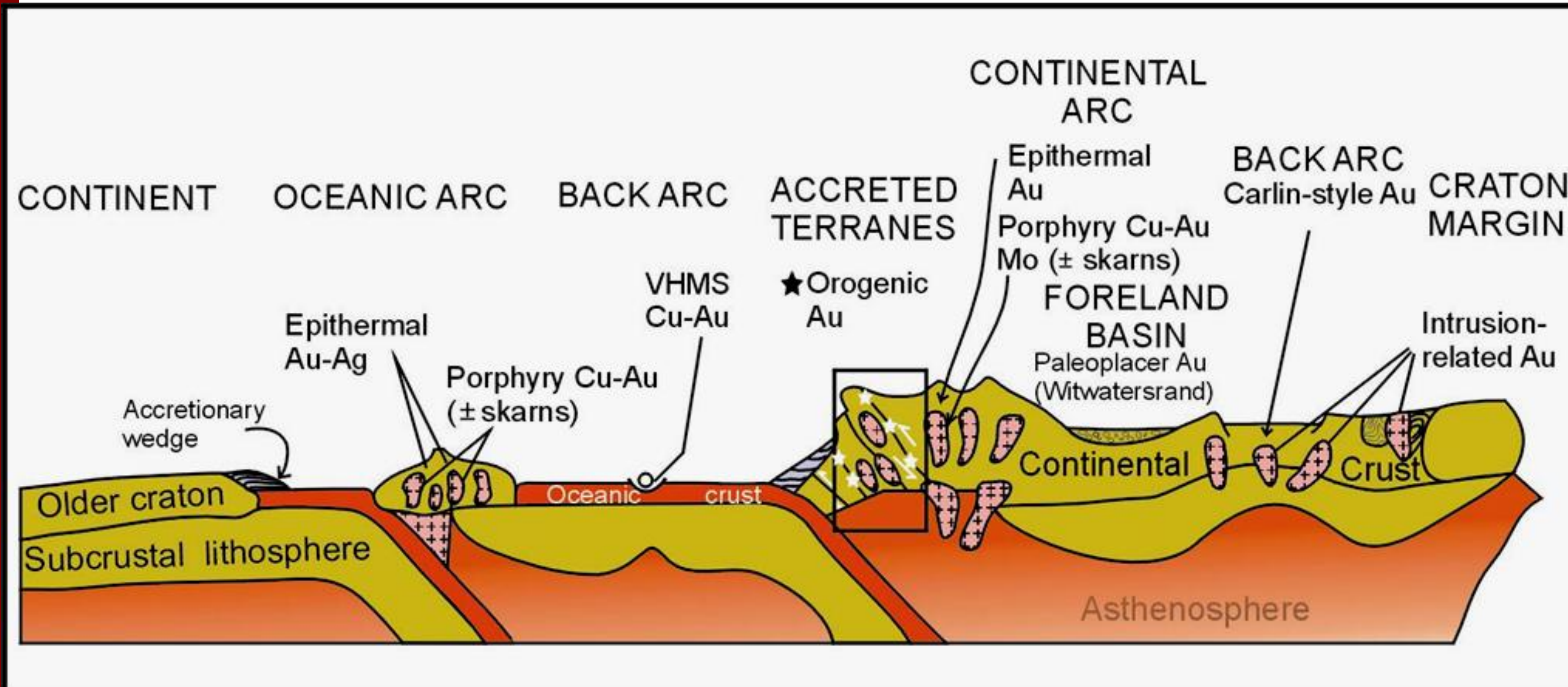
Geochemically abundant metals (> 100 ppm; Fe, Al and Cr) and scarce metals (< 100 ppm; many in Periodic table)



Ore-forming elements at a glance: how much to enrich?

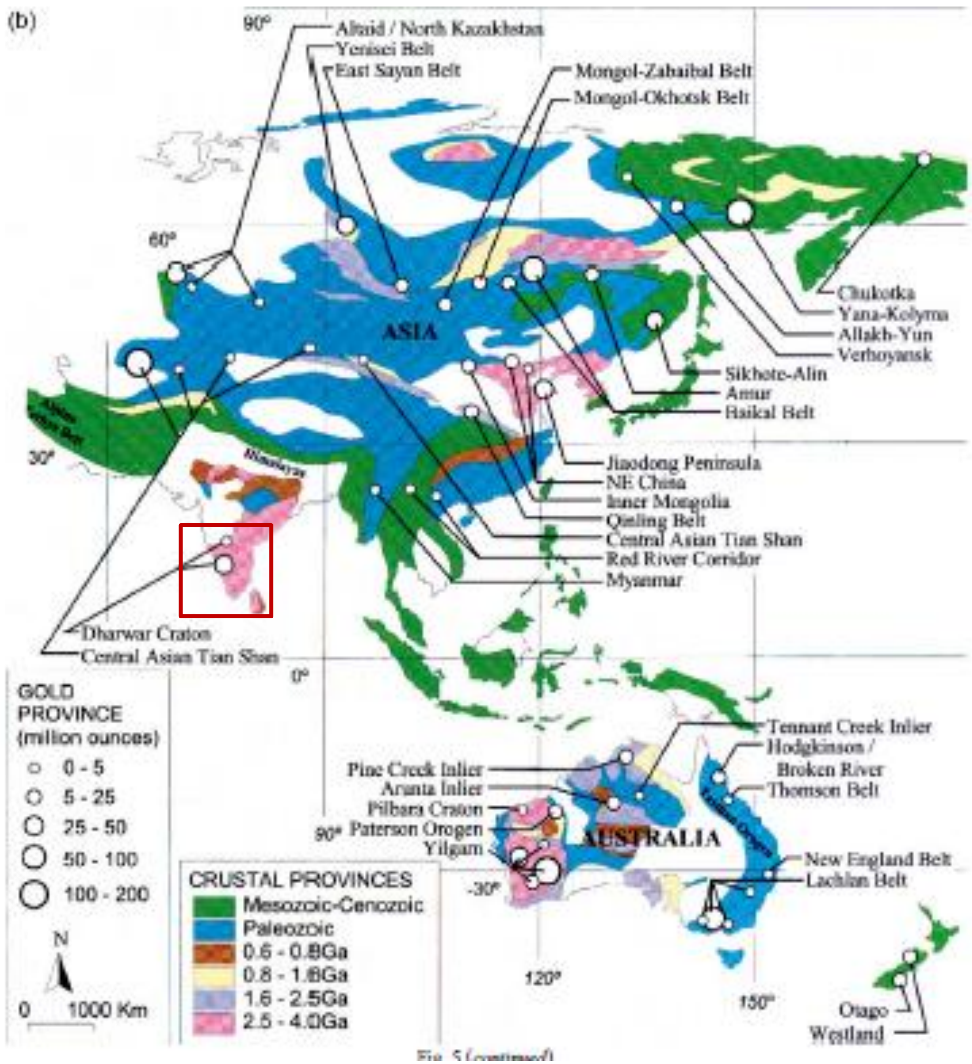
Element	Clarke Value in ppm (X)	Cut-off grade in ppm (Y)	Enrichment Factor (Y/X)
Al	81,300	300,000	4
Fe	50,000	280,000	6
Zr	165*	14,000	85
P	1065	100,000	95
V	135	14,000	104
Cu	55*	10,000	160
Nb	20	3,400	170
Ni	75*	1,500	188
Mn	950	350,000	350
Pt	0.01	4	400
U	1.8	0.1	500
Zn	70*	40,000	600
Mo	1.5	1,300	870
W	1.5	1,400	935
Au	**0.003**	**3**	**1,000**
Pb	13	40,000	3,000
Cr	100	300,000	3,000
Sn	2	10,000	5,000
Ag	0.07	500	7,150
Hg	0.08	3,000	37,500
Sb	0.2	10,000	50,000

Orogenic Au deposits: tectonic setting



Along convergent margins → terrain accretion or collision related to subduction late in the metamorphic-magmatic evolution of the orogen (Groves et al 2003, *Econ Geol*)

Orogenic Au deposits: Asia-Pacific



(Goldfarb et al, 2001, *OGR*)

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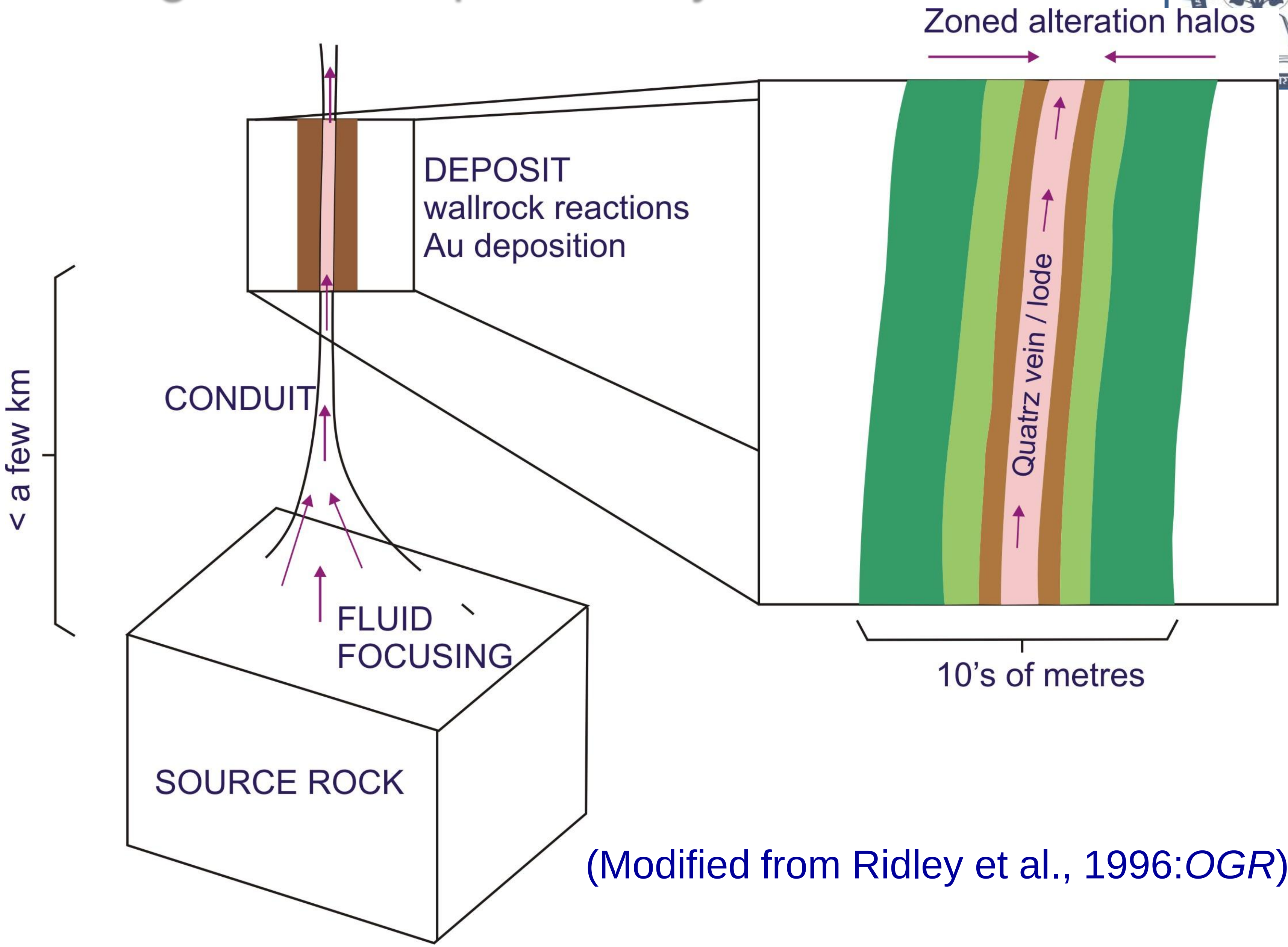
Orogenic Au deposits: key features



(Modified from Ridley et al., 1996:*OGR*)

Unresolved questions ?

- Relative timing of alteration/mineralization wrt greenstone volcanism/metamorphism and granitoid intrusion

- Precise architecture of the hydrothermal systems, particularly the relationship between first- and higher-order structures (splays)

- Sources of (i) ore fluid (low salinity H_2O+NaCl+ $AuHS_2^-$+ CO_2±CH_4), (ii) gold, (iii) sulfur

Metamorphic? Magmatic ? Both ???

- Specific depositional mechanisms for gold, particularly for high-grade deposits

Today's discussion

- Greenstone metamorphism: Uti, Kolar, Jonnagiri
- Geochronology (mostly of granitoids), Monazite dating
- Alteration geochemistry/ore mineralogy: Hutti, Jonnagiri
- Fluid inclusions: Kolar, Ramagiri, Hutti, Hira-Buddini, Ajjanahalli, Jonnagiri, Gadag
- C- and oxygen isotope Ajjanahalli/GR Halli/Gadag
- Sulfur isotope: Most camps
- Geochemistry of hydrothermal minerals (tourmaline, scheelite, pyrite and arsenopyrite)
- Synthesis
- Future research directions

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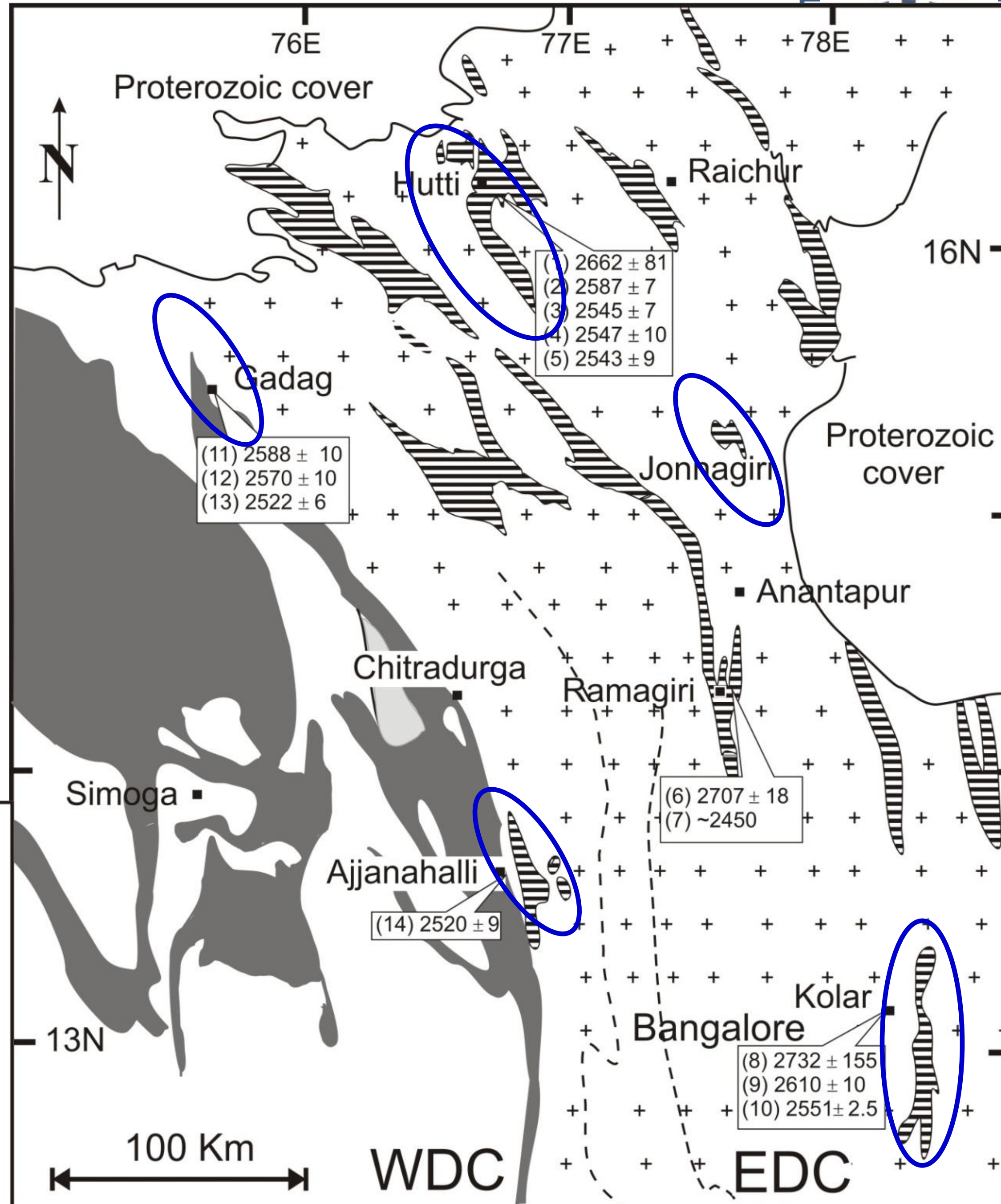
Study areas

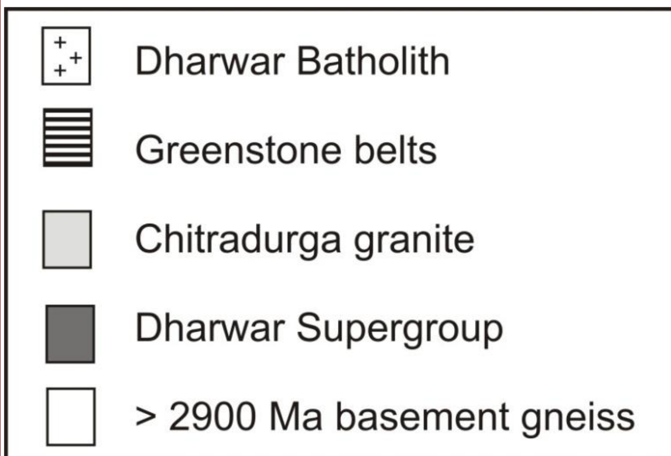
- ➢ Age of greenstone metamorphism ?
- ➢ Age of volcanism

Hutti: 2662±81Ma

Kolar: 2732±155 Ma

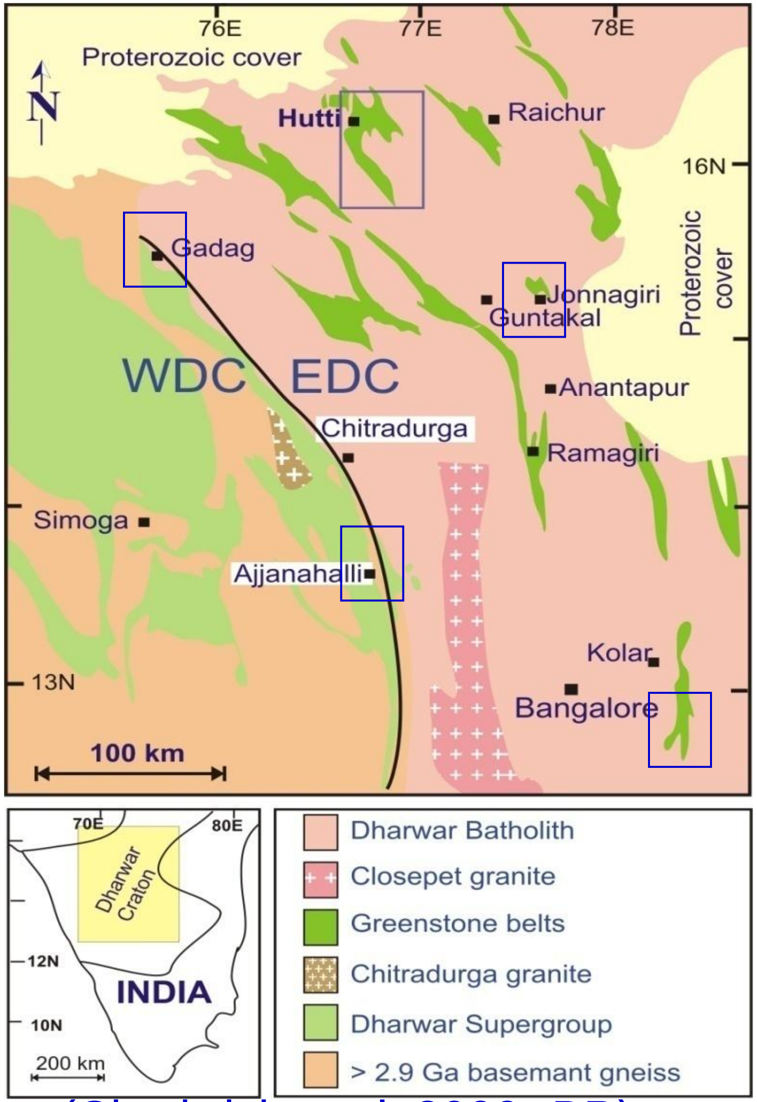
(Anand and Balakrishnan, 2010, JAES)
(Balakrishnan et al., 1990, CMP



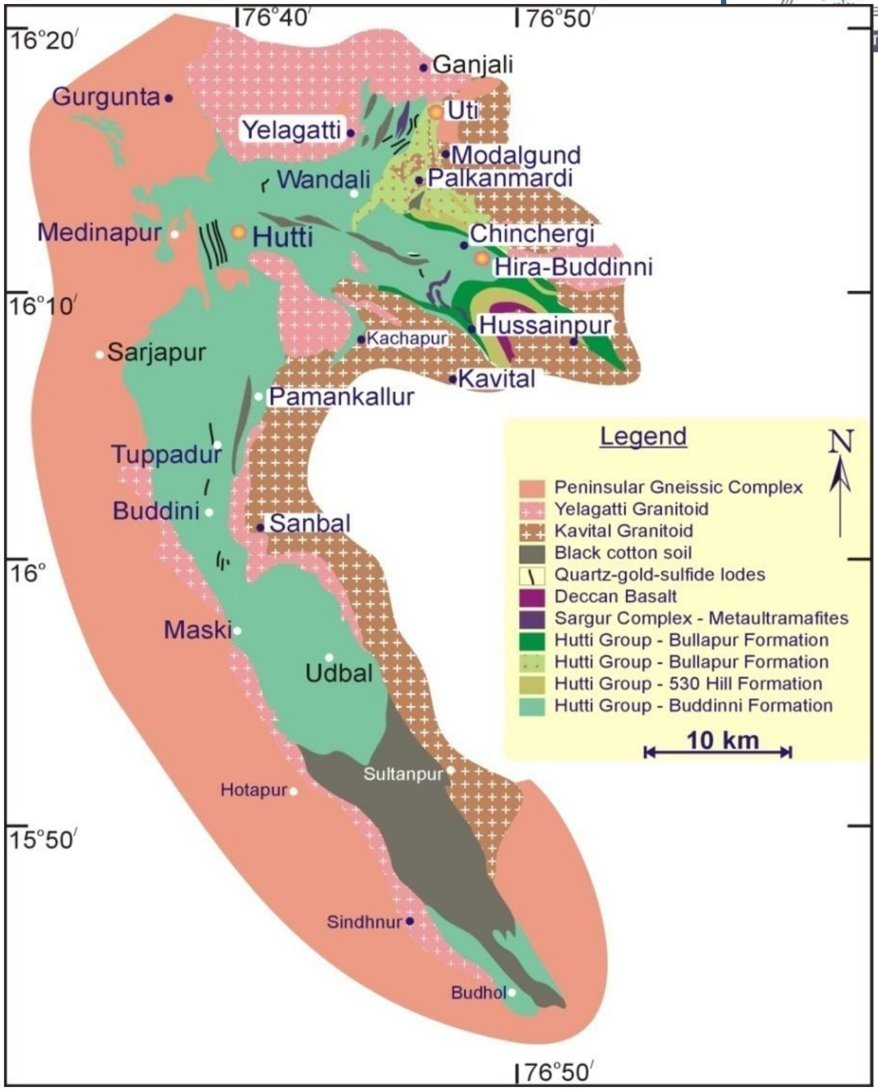


(Modified after Chadwick et al., 2000,*PR*)

Study areas (contd.)

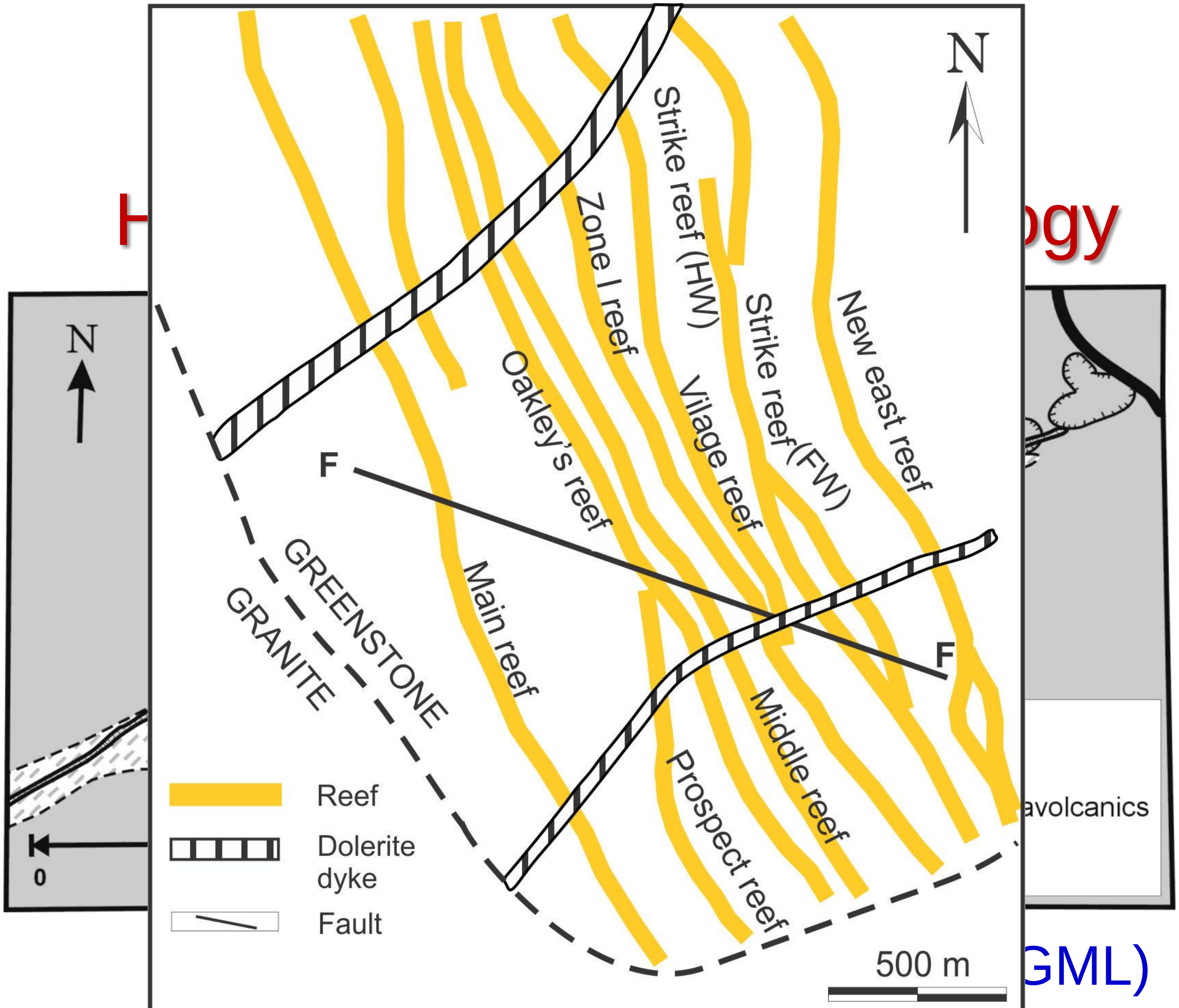


(Chadwick et al, 2000, *PR)*



(Srikantia 1995, *GSIM*)

Hutti: auriferous reefs



Curtis and Radhakrishna (1995)

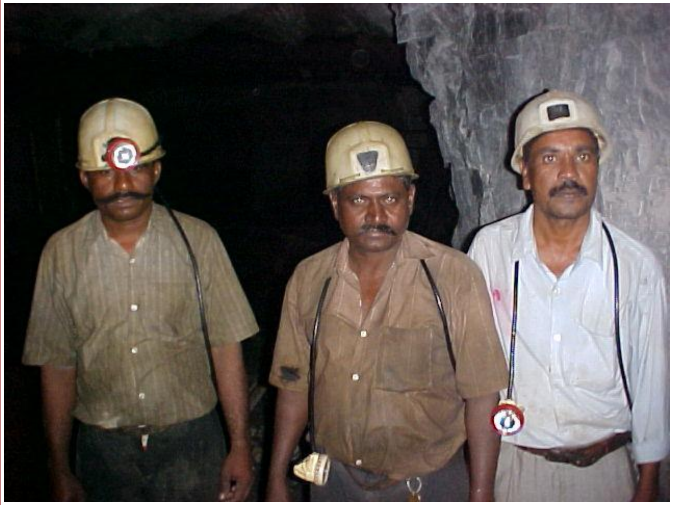
Hutti: world class deposit (>100 t Au)

Uti open pit

Central shaft

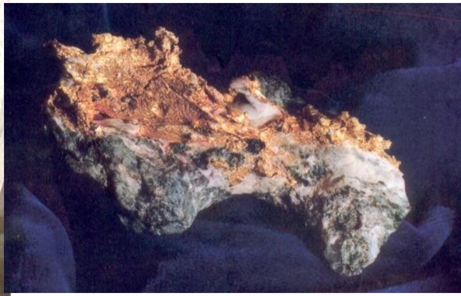
Drilling at depth

Friendly miners

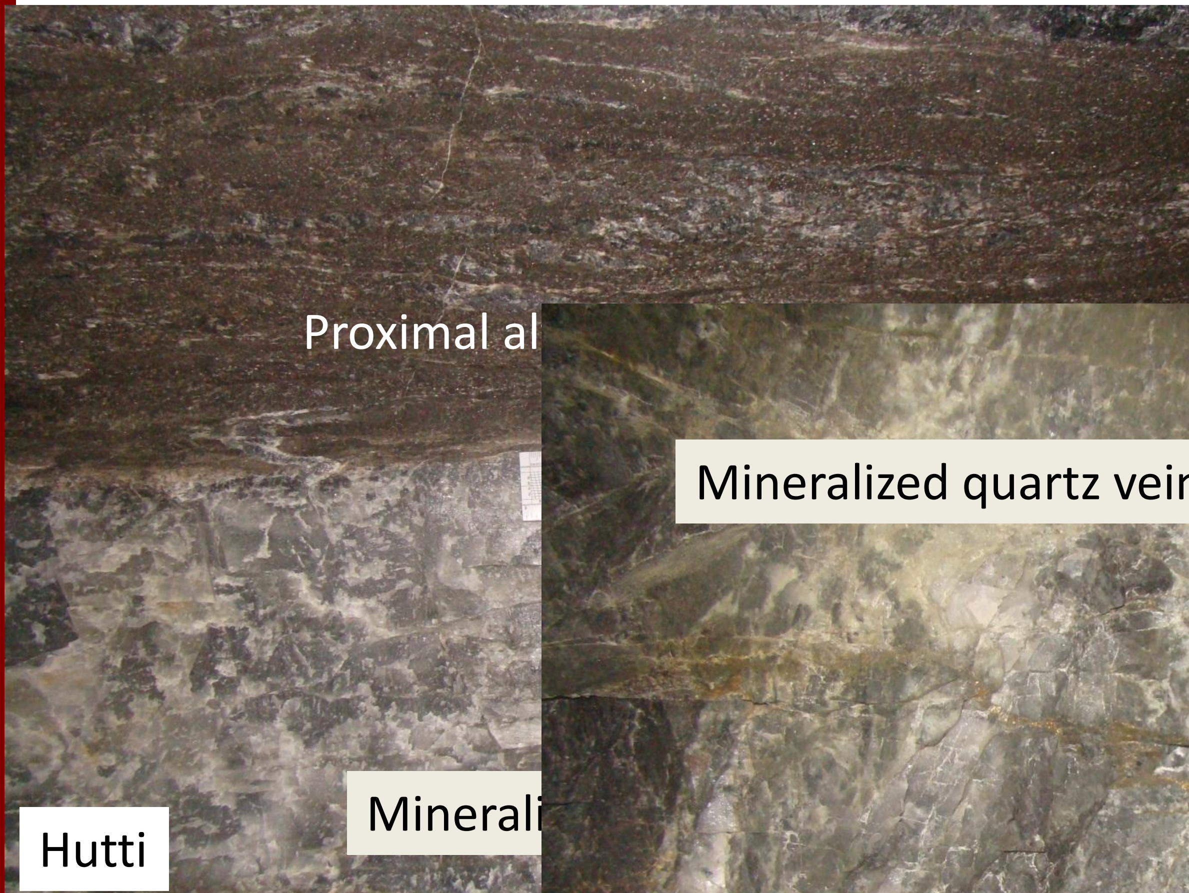


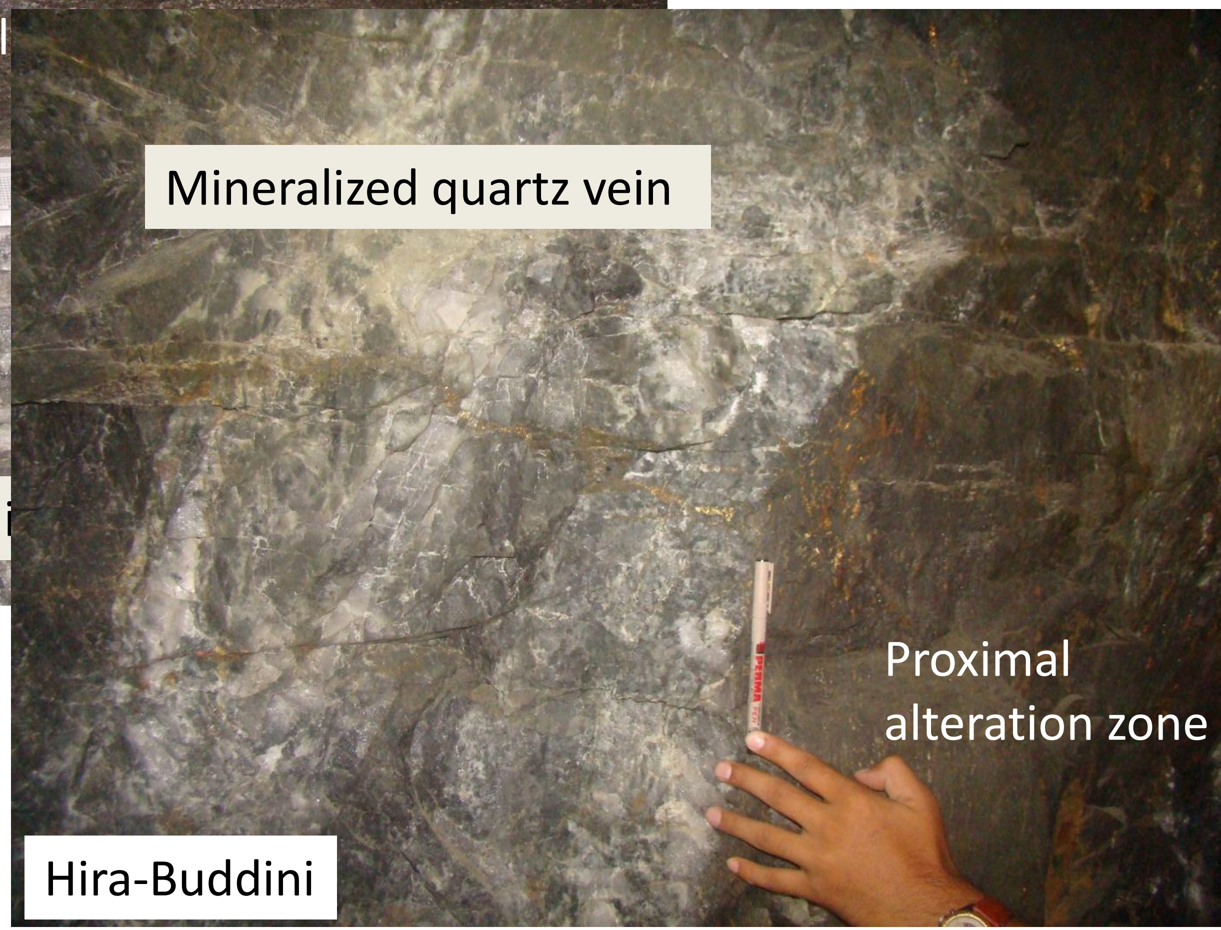
Security checking

Native gold



Hutti and Hira-Buddini:underground





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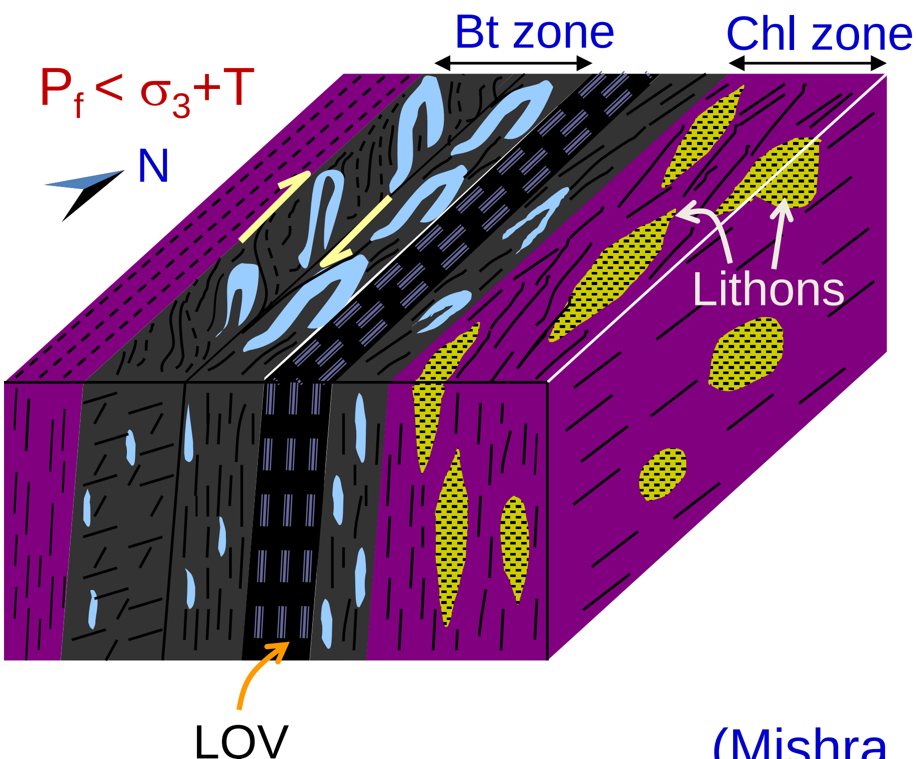
Hutti

D_2 and D_3 veins (LQV) are mineralized (D_1-D_5)

Absence of extension veins and extensional shear veins→

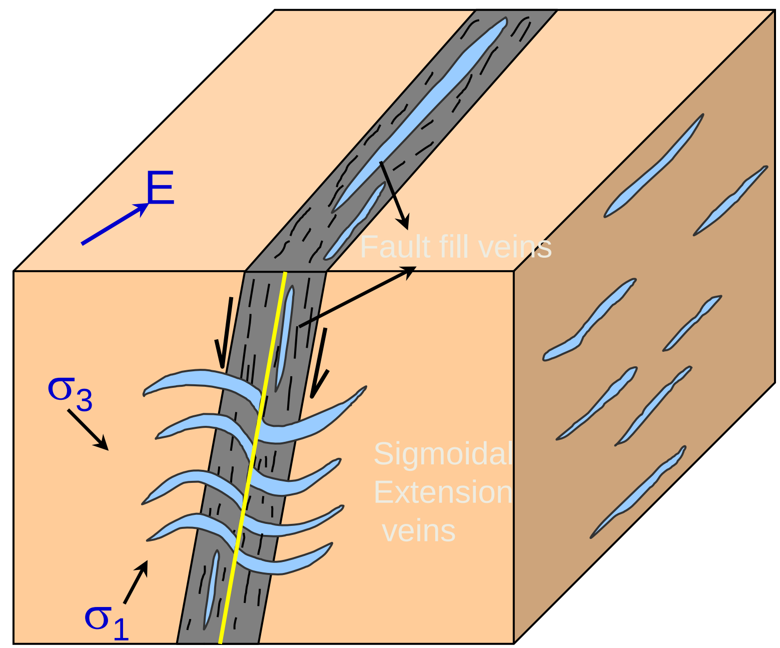
$P_f < \sigma_3 + T$



Hira-Buddini

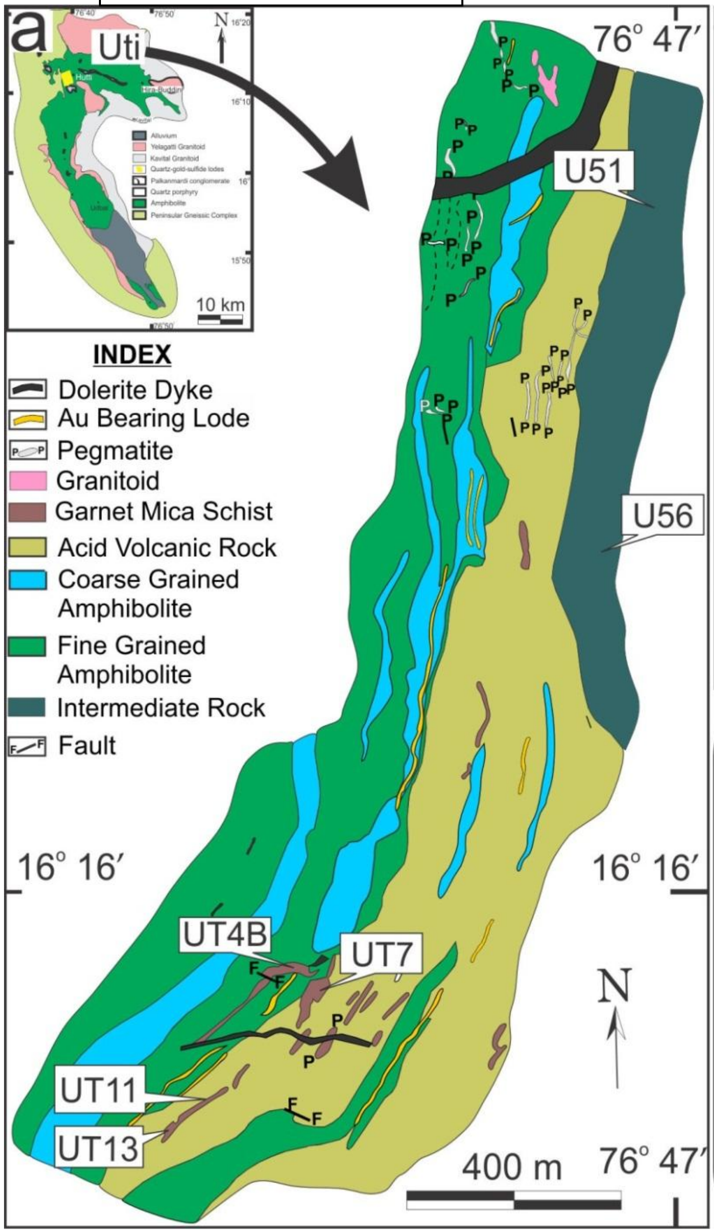
Presence of sigmoidal extension veins→

$P_f \geq \sigma_3 + T$

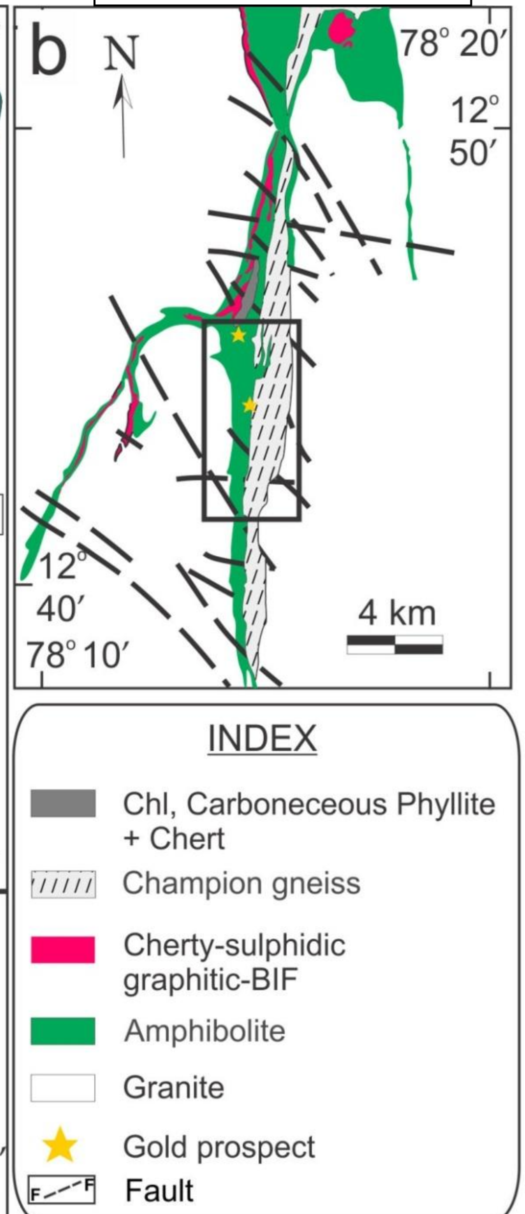


(Mishra & Pal, 2008, *Econ Geol*)

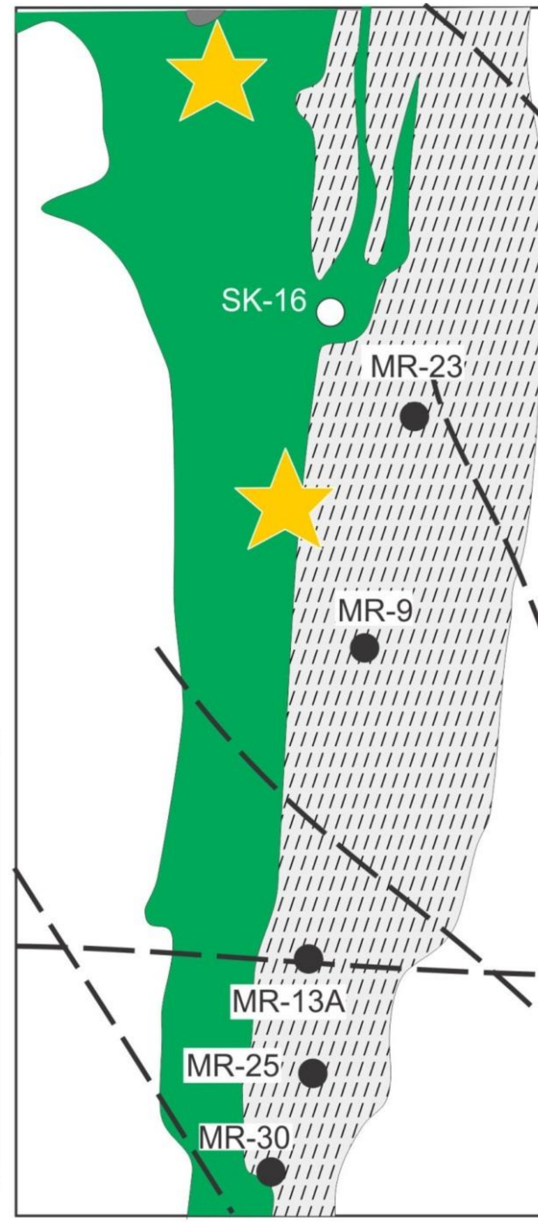
Hutti-Maski



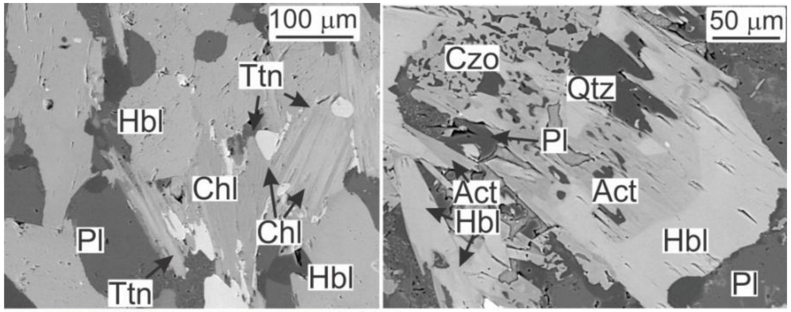
South Kolar

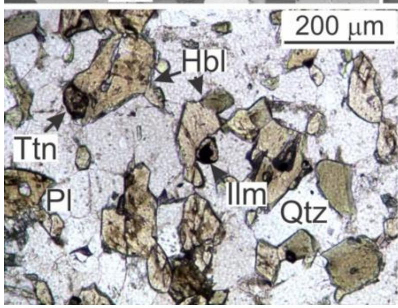


Sample Locations



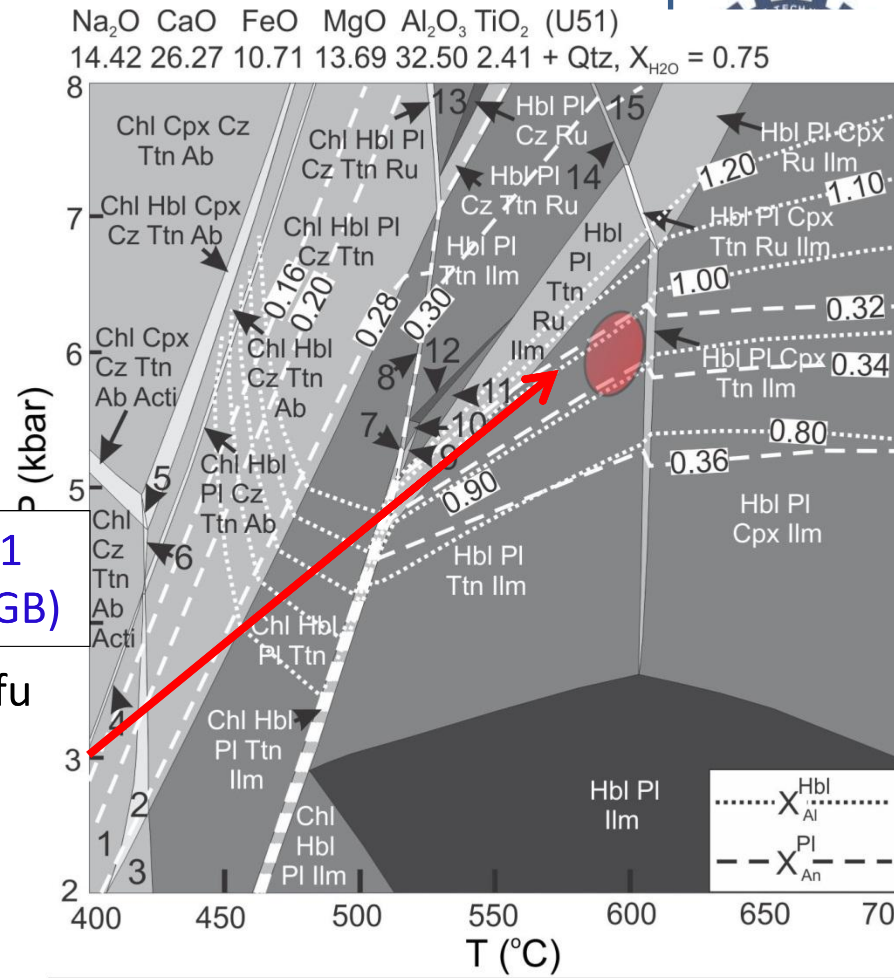
Uti (HMGB) metamorphism



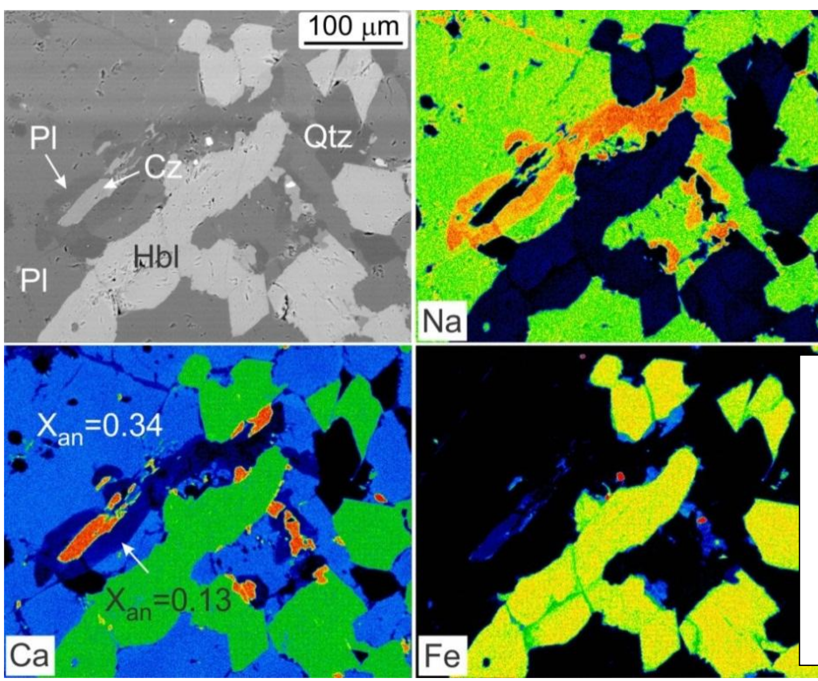


Hbl composition
Al(IV) 0.60→0.8
Na 0.14→0.24,
X_{Fe} 0.46→0.49,
Total Al 0.80→1.06 apfu

U51 (HMGB)



Legend
1 Chl Pl Cz Ttn Acti
11 Hbl Pl Ru Ilm

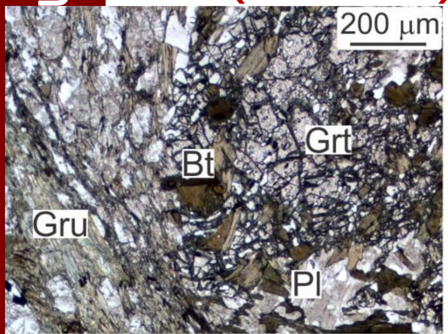


Mineral thermobarometry

P = 5.3–6.1 kbar (Hornblende-Plagioclase barometry, Bhadra and Bhattacharya, 2007, *AM*)

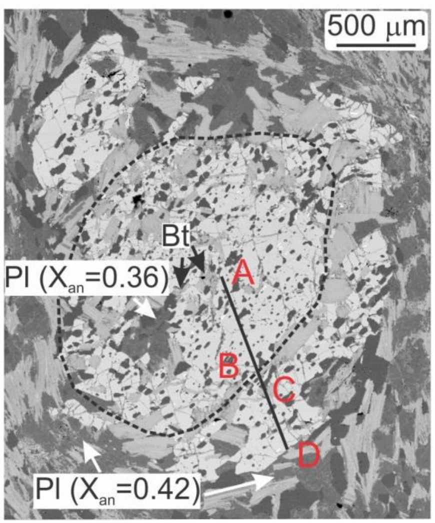
T = 586 – 617 °C (Hornblende-Plagioclase thermometry, Holland and Bludny, 1994, *CMP*)

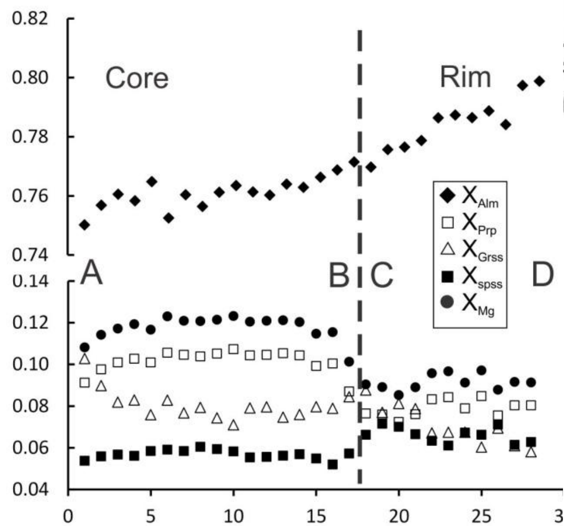
Uti (HMGB) metamorphism

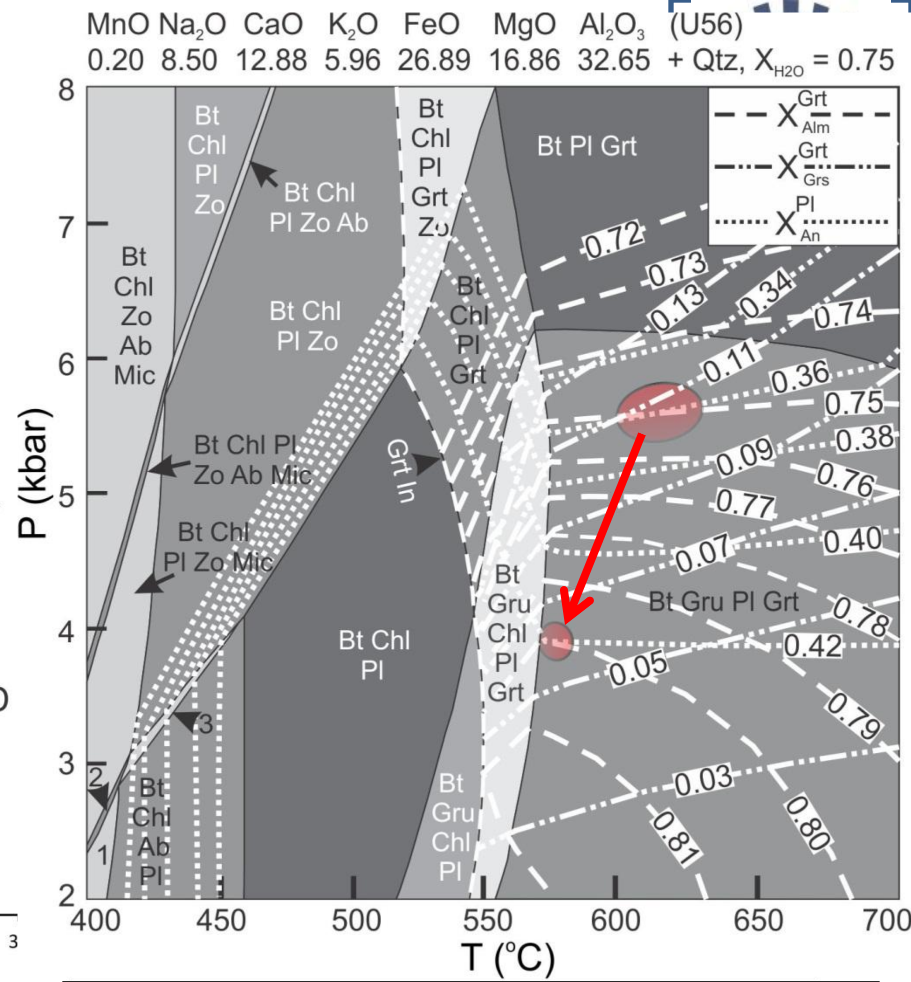


Sample U56 (HMGB)

Grt-Bt-Gru-Pl-Qtz







Mineral Thermobarometry

Garnet core-included Biotite-included Plagioclase

GBPQ barometry (Wu et al., 2004, *JP*)

P = 5.1–5.7 kbar

Garnet-Biotite thermometry (Ferry and Spear, 1978, *CMP*; Bhattacharya et al., 1992, *CMP*)

T = 620–645 °C

Mineral thermobarometry

Garnet rim-near neighbor Biotite-near neighbor Plagioclase

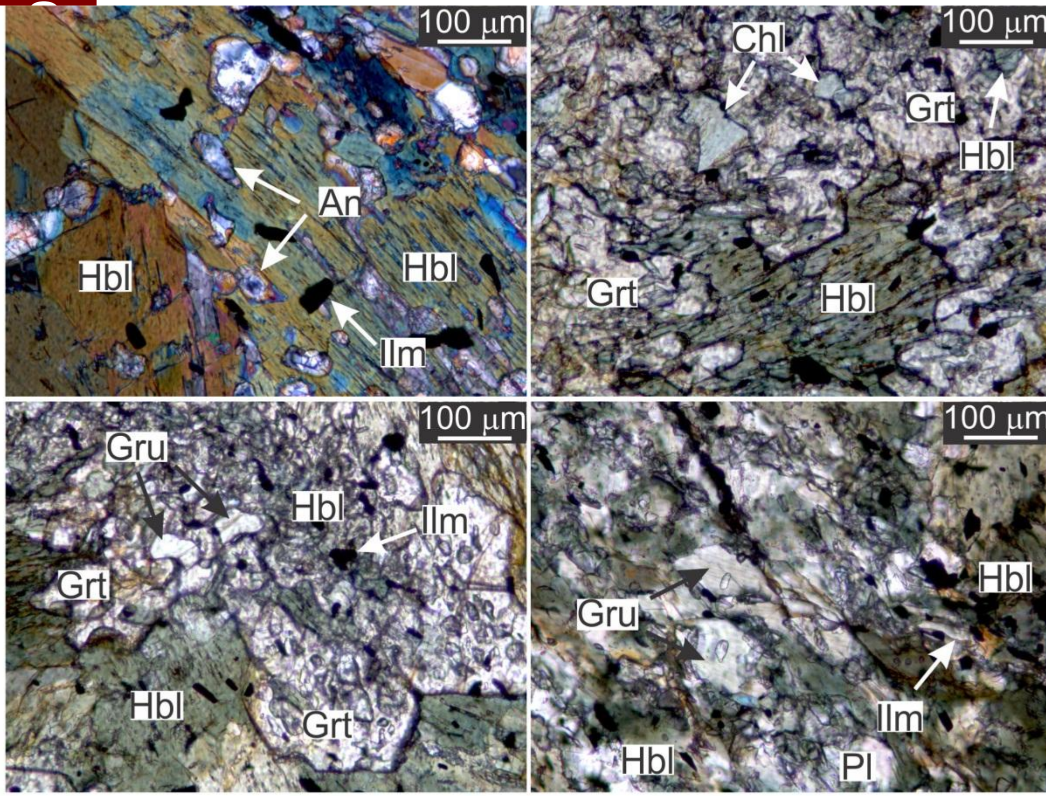
GBPQ barometry

P = 3.6–4.2 kbar

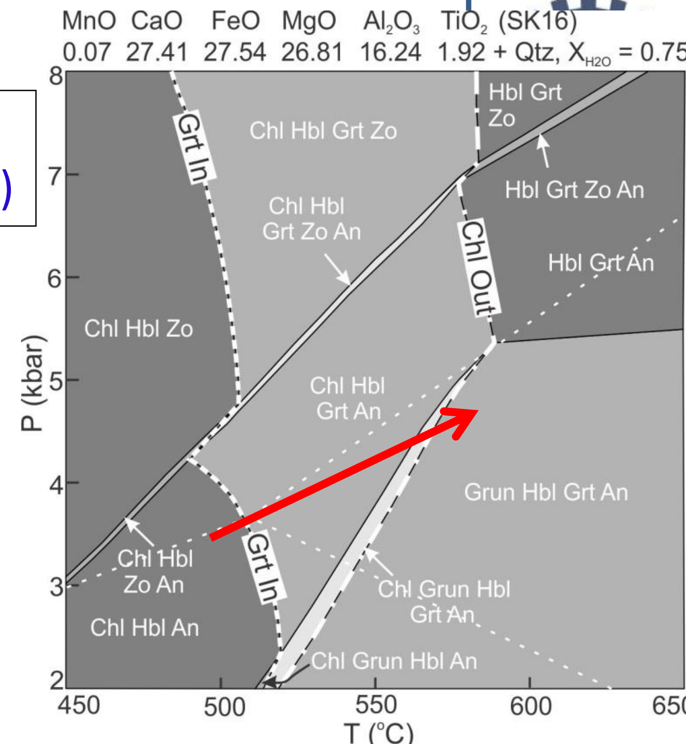
Garnet-Biotite thermometry

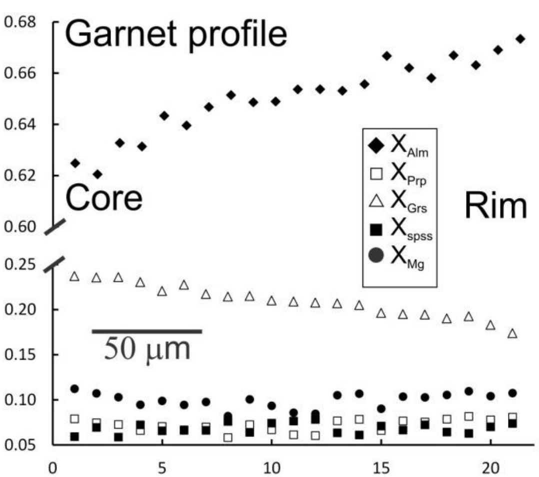
T = 617–632 °C

SKB metamorphism

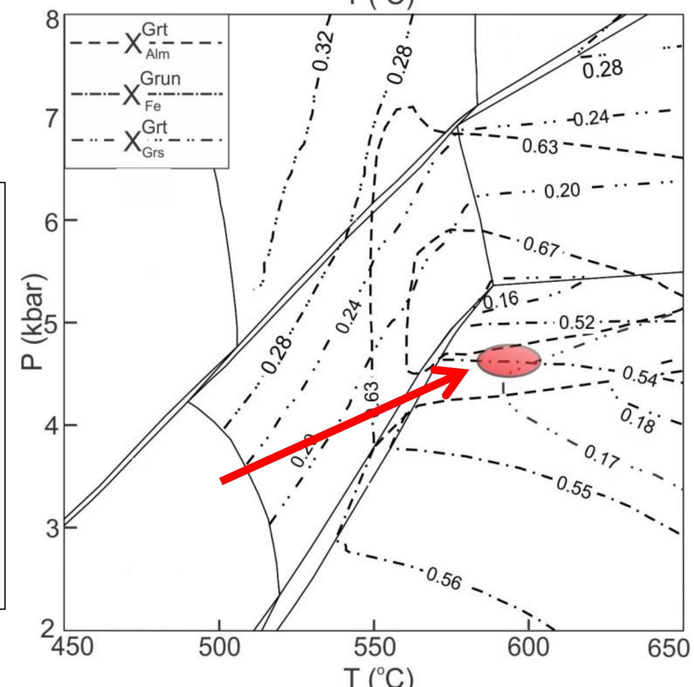


SK16
(SKGB)





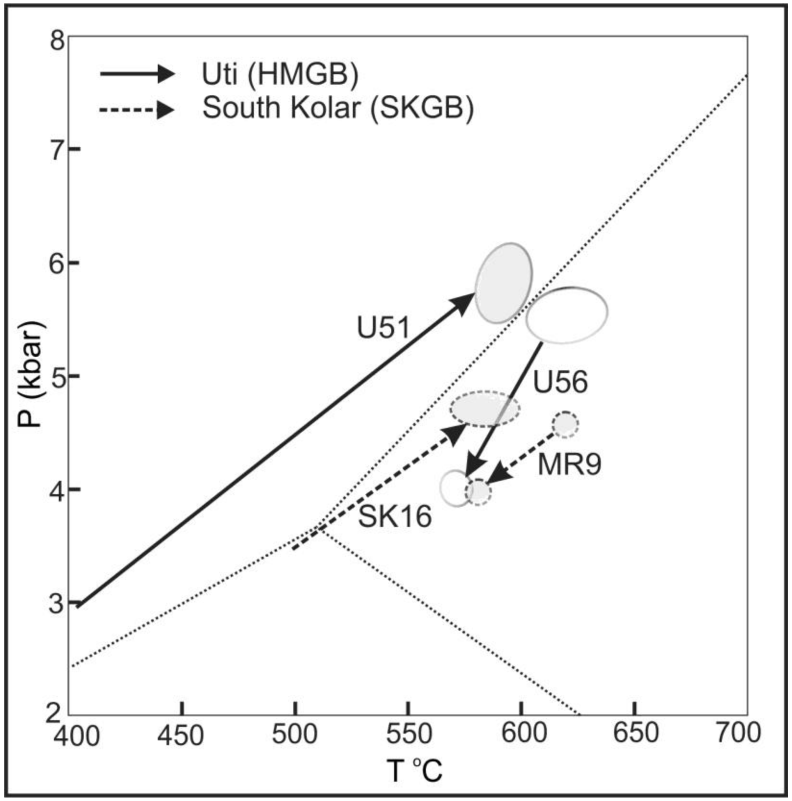
GPHQ barometry (Kohn and Spear, 1990, *AM*)
P = 3.99–4.21 kbar
Grt-Amph thermometry (Graham and Powell, 1984, *JMG*)
T = 580–590 °C



Greenstone metamorphism: summary

- HMGB underwent middle amphibolite facies metamorphism with concomitant increase in P and T on prograde path. Garnet retrograde zoning indicate near isothermal decompression

- SKGB underwent lower amphibolite facies metamorphism with synchronous increase in P and T in the prograde path followed by decompressional cooling retrogression



Hazarika et al (2015) *Journal of Geology*

Rationale behind monazite chemical dating
Poor man's tool

$Pb_m = Th\ (e^{\lambda 232t-1}) + 0.9928\ U\ (e^{\lambda 238t-1)} + 0.0072\ U\ (e^{\lambda 235t-1}) = Pb_e$

where Pb_m and Pb_e are measured and estimated Pb contents

$t \Rightarrow Pb_m - Pb_e \approx 10^{-4}$

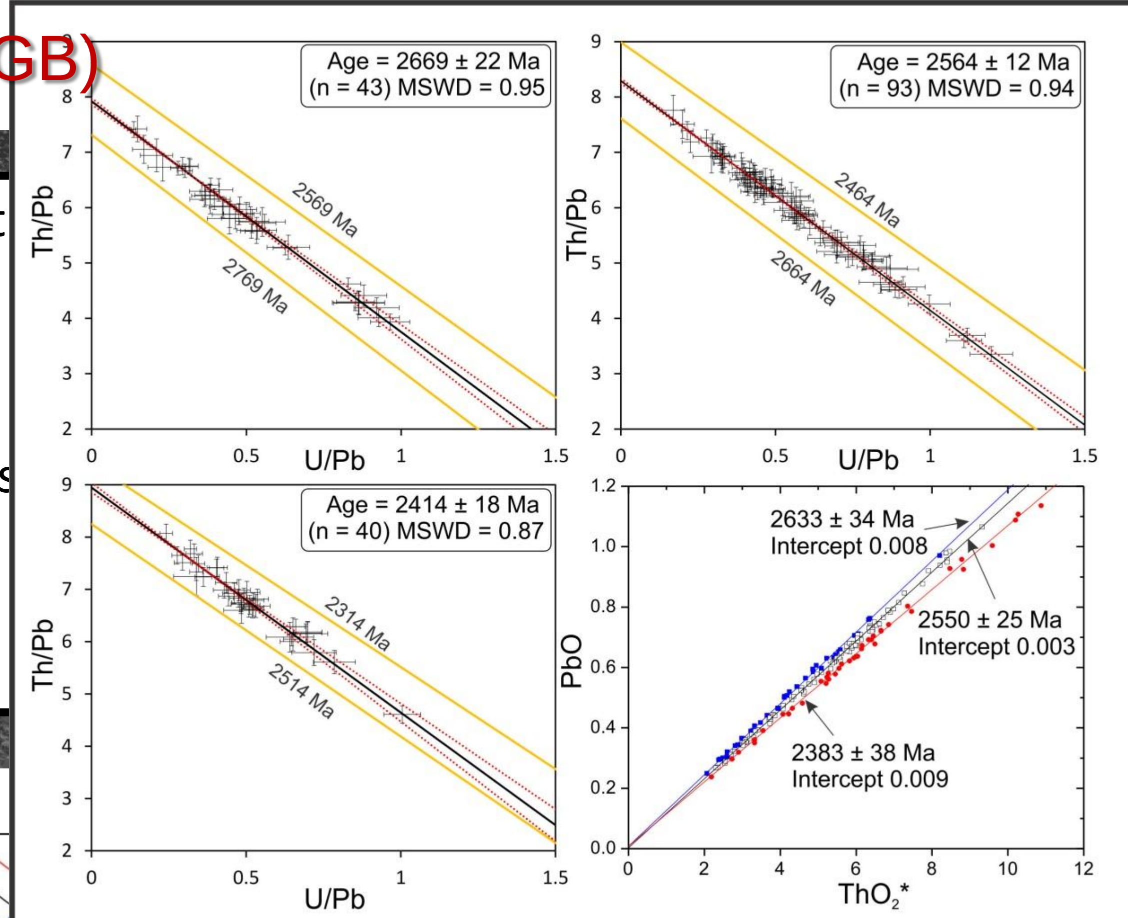
(Montel et al, 1996, *GCA*)

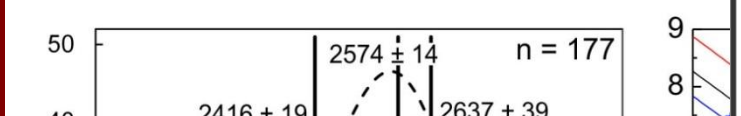
$^{238}U/(^{238}U+^{235}U) = 0.9928$, $^{235}U/(^{238}U+^{235}U) = 0.0072$

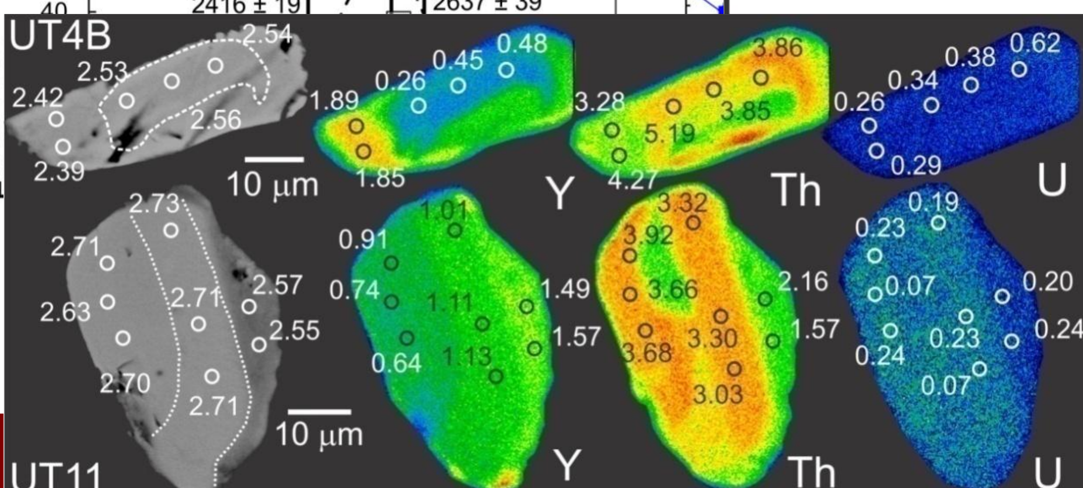
- Insignificant initial Pb
- High (>900 °C closure temperature)

Monazite dating (HMGB)

Age Domain A → within Grt
2743–2624 Ma (n = 43)
Age Domain B → Matrix
2618–2503 Ma (n = 93)
Age Domain C → Near Veins
2481–2352 Ma (n = 40)
Overlapping 2σ errors
(64–225 Ma)







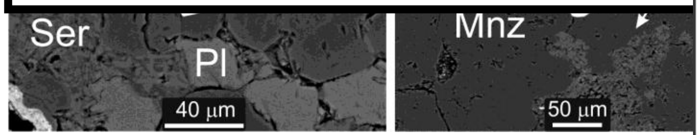
Cocherie and Albarede, 2001, *GCA*; Suzuki and Kato, 2008, *GR*

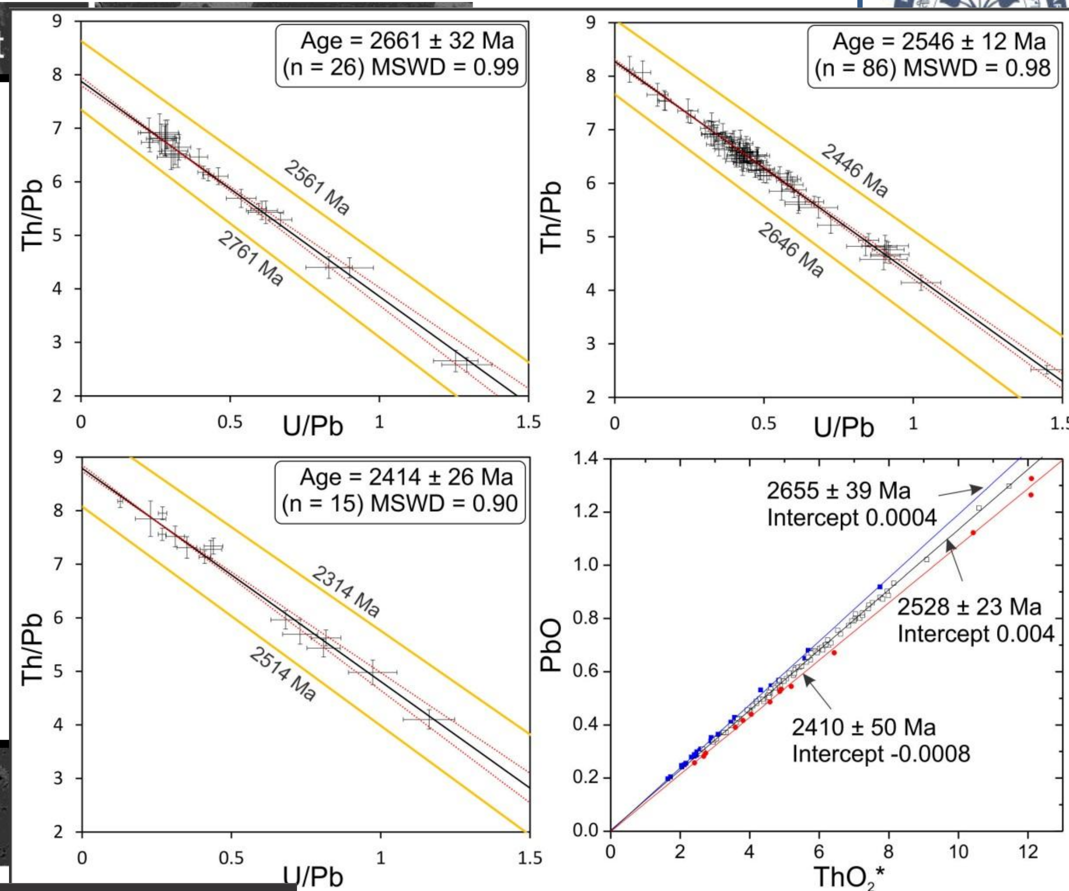
Y-content (oxide wt.%) in monazite

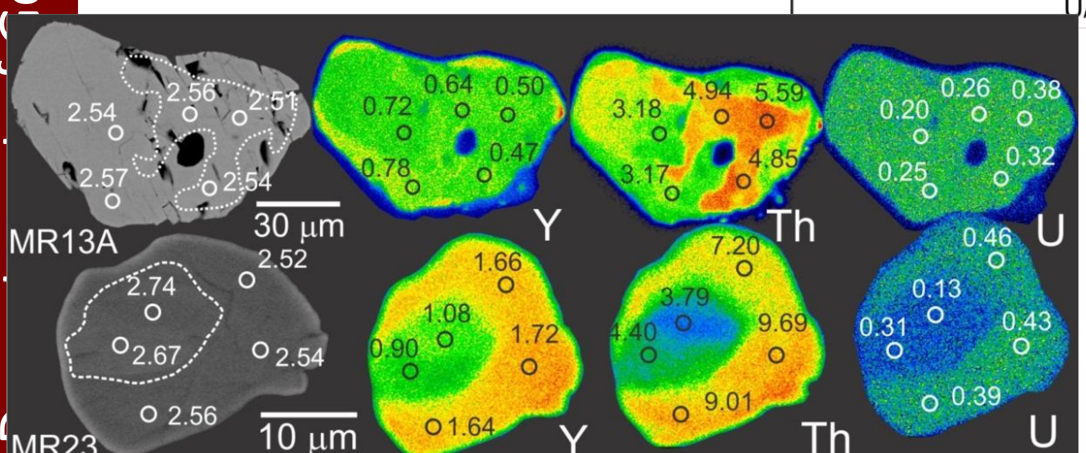
Population		B	C
Garnet Present	UT7	0.37	2.08
	UT4B	0.52	1.92
Garnet Absent	UT11	1.28	1.24
	UT13	1.19	1.18

Monazite dating (SKB)

Age Domain A → within Grt and Cores of zoned Mnz
2736–2612 Ma (n = 26)
Age Domain B → Matrix
2604–2488 Ma (n = 93)
Age Domain C → Near sericitization
2459–2343 Ma (n = 15)
Overlapping 2σ errors
(50–217 Ma)







Y-content (oxide wt.%) in monazite

Population		→ B
Garnet Present	MR13A	0.78
	MR25	0.32
Garnet Absent	MR23	1.71
	MR30	1.59

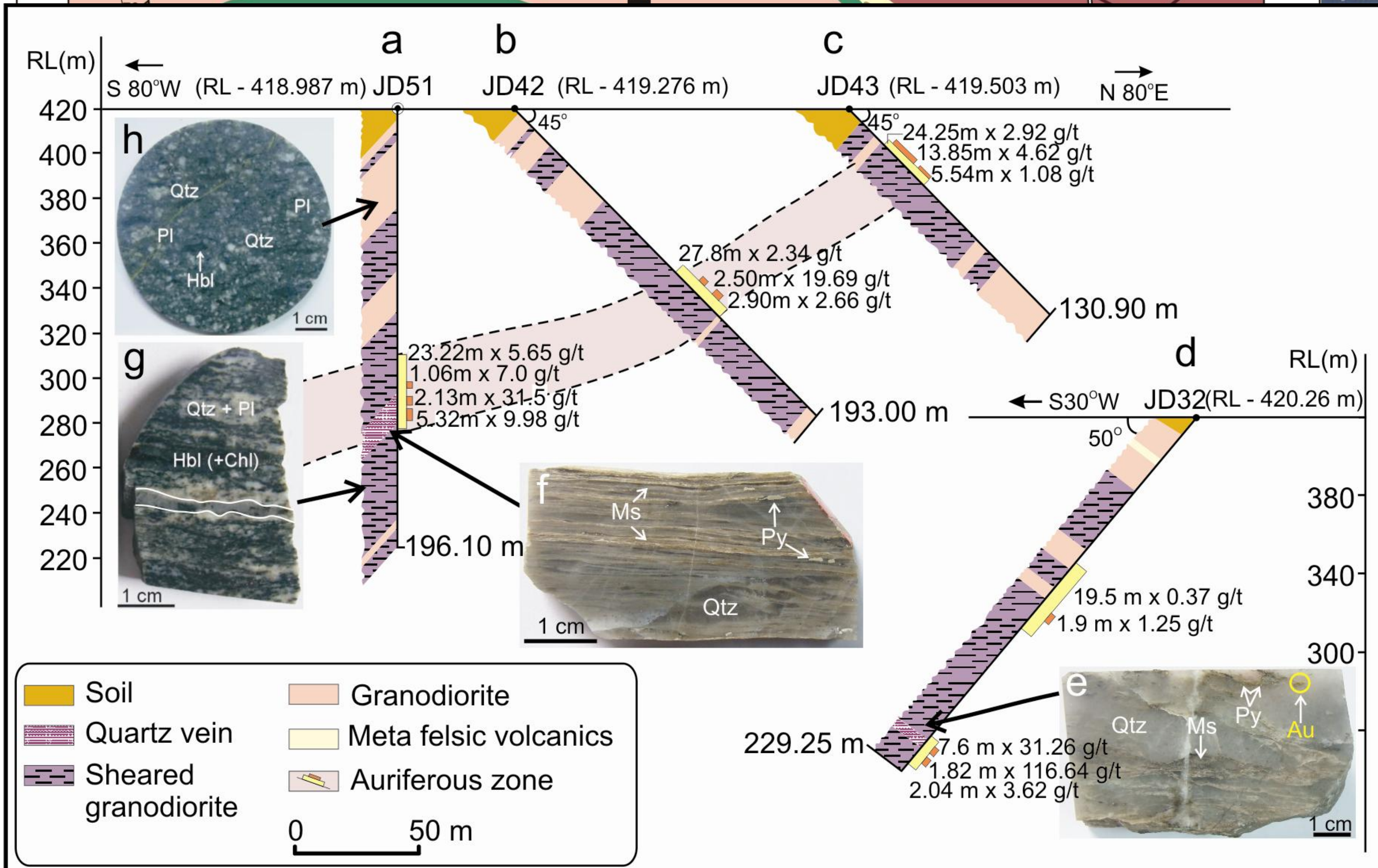
Summary: monazite ages

- Although ~400 km apart; HMGB and SKGB witnessed similar geochronological evolution
- Greenstone volcanism at ~2.67–2.66 Ga
- Greenstone metamorphism at ~2.56–2.55 Ga
- Hydrothermal alteration at ~2.41Ga

Hazarika et al (2015) *Journal of Geology*

Jonnagiri granitoid-hosted Au deposit

Bole hole logs (courtesy GSI)



(Redrawn from Jairam et al, 2001)

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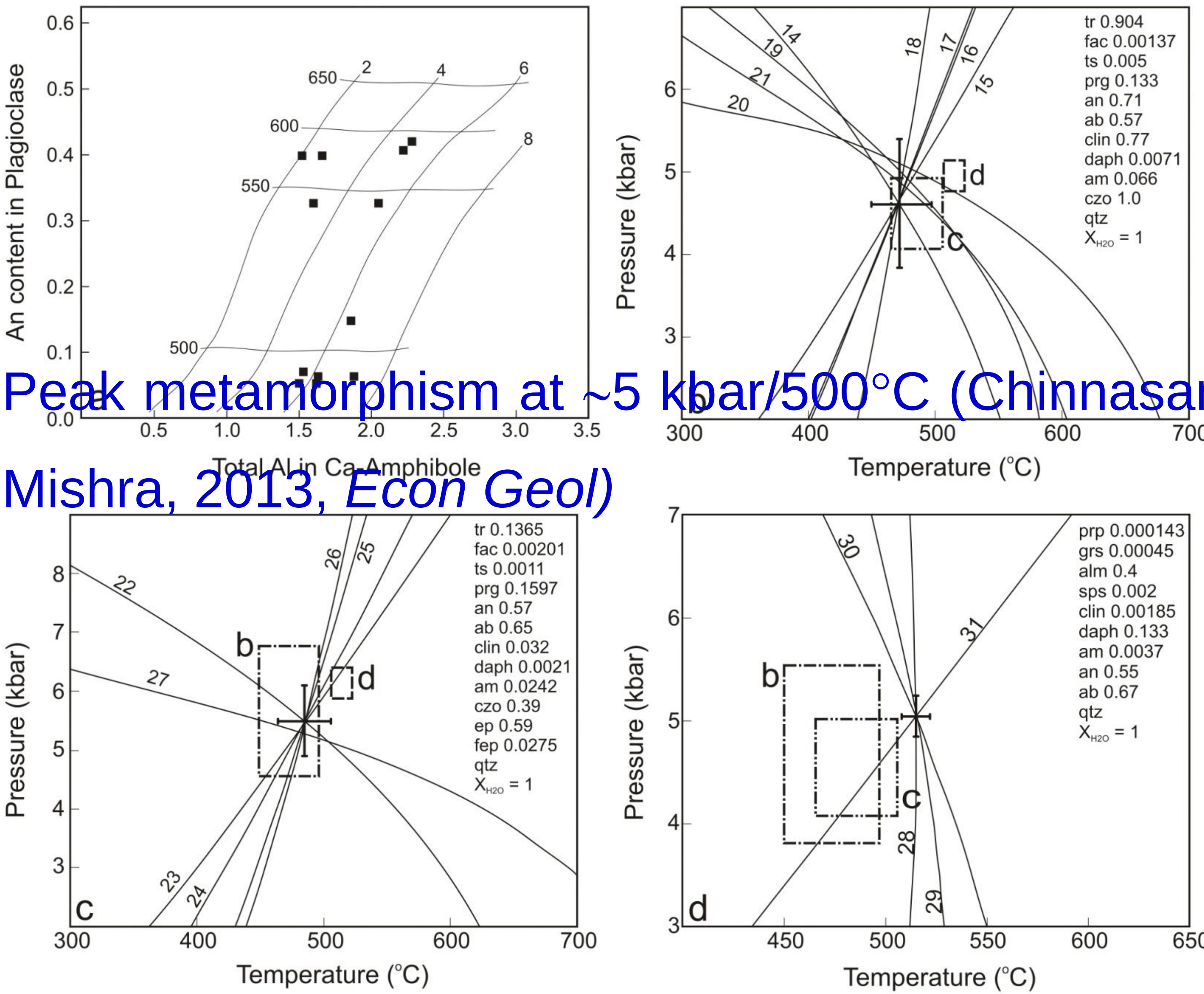
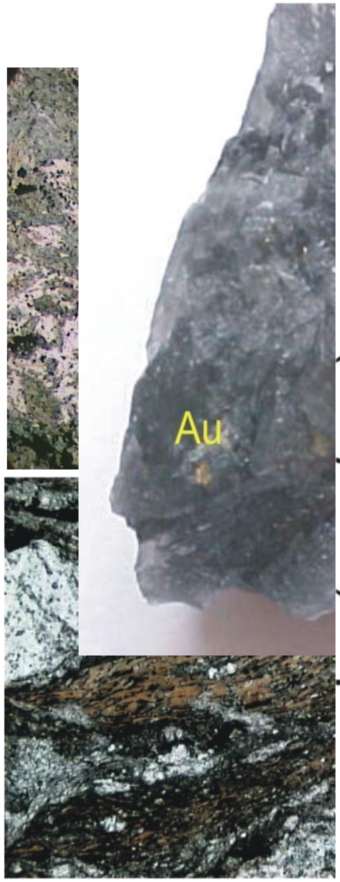
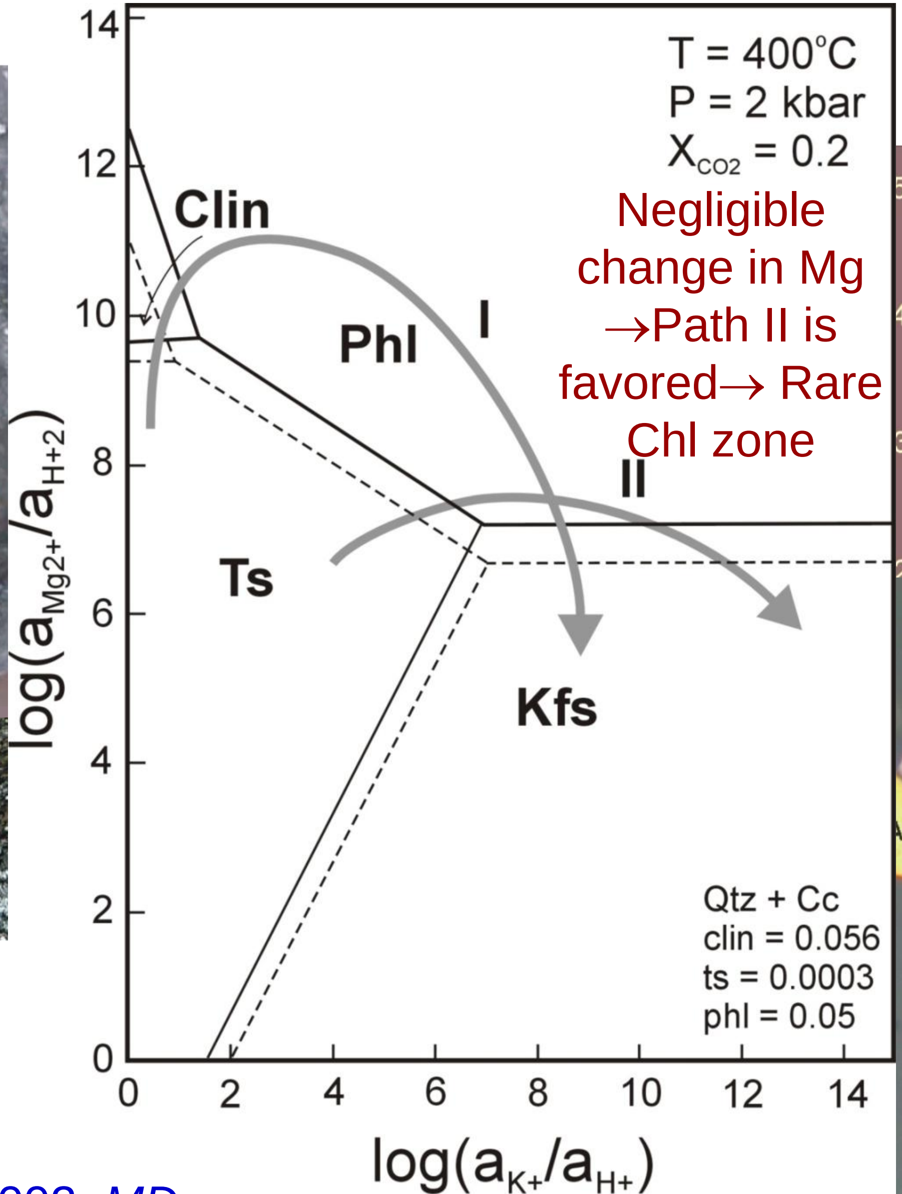
Thermobarometry of Jonnagiri greenstones



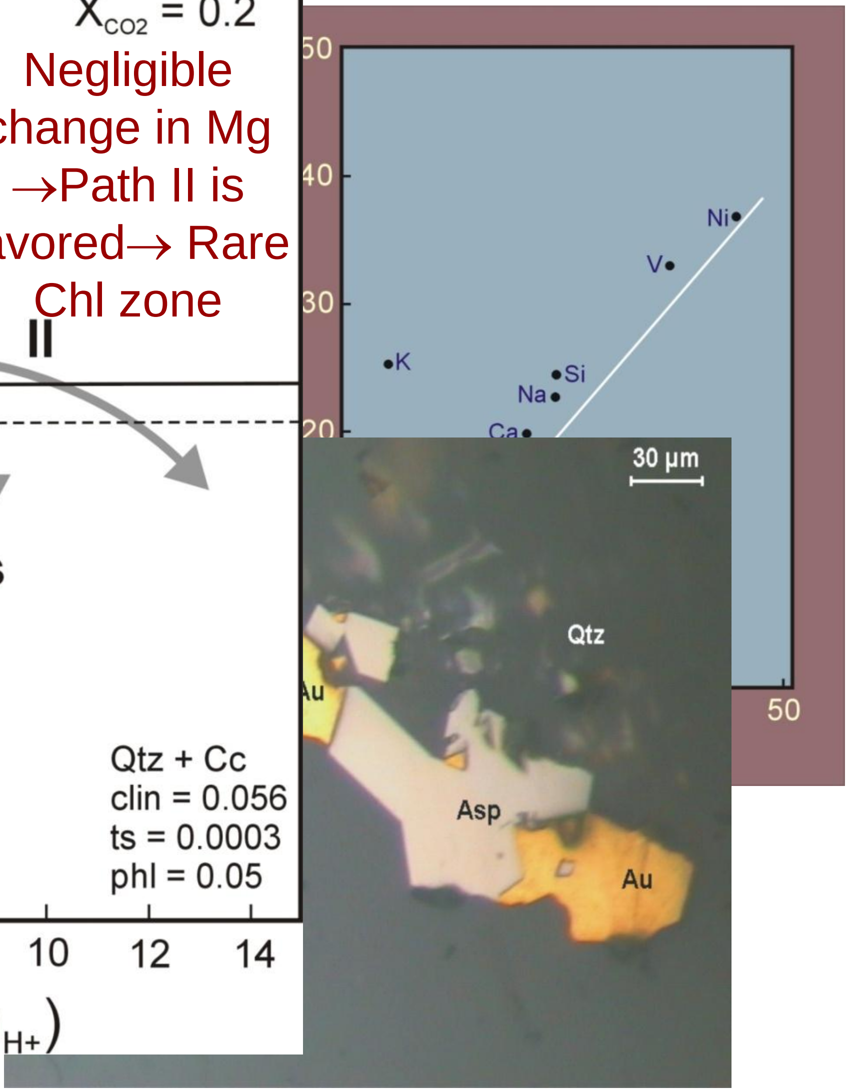
Peak metamorphism at ~5 kbar/500°C (Chinnasamy & Mishra, 2013, *Econ Geol)*

Hutti : alteration and mineralization



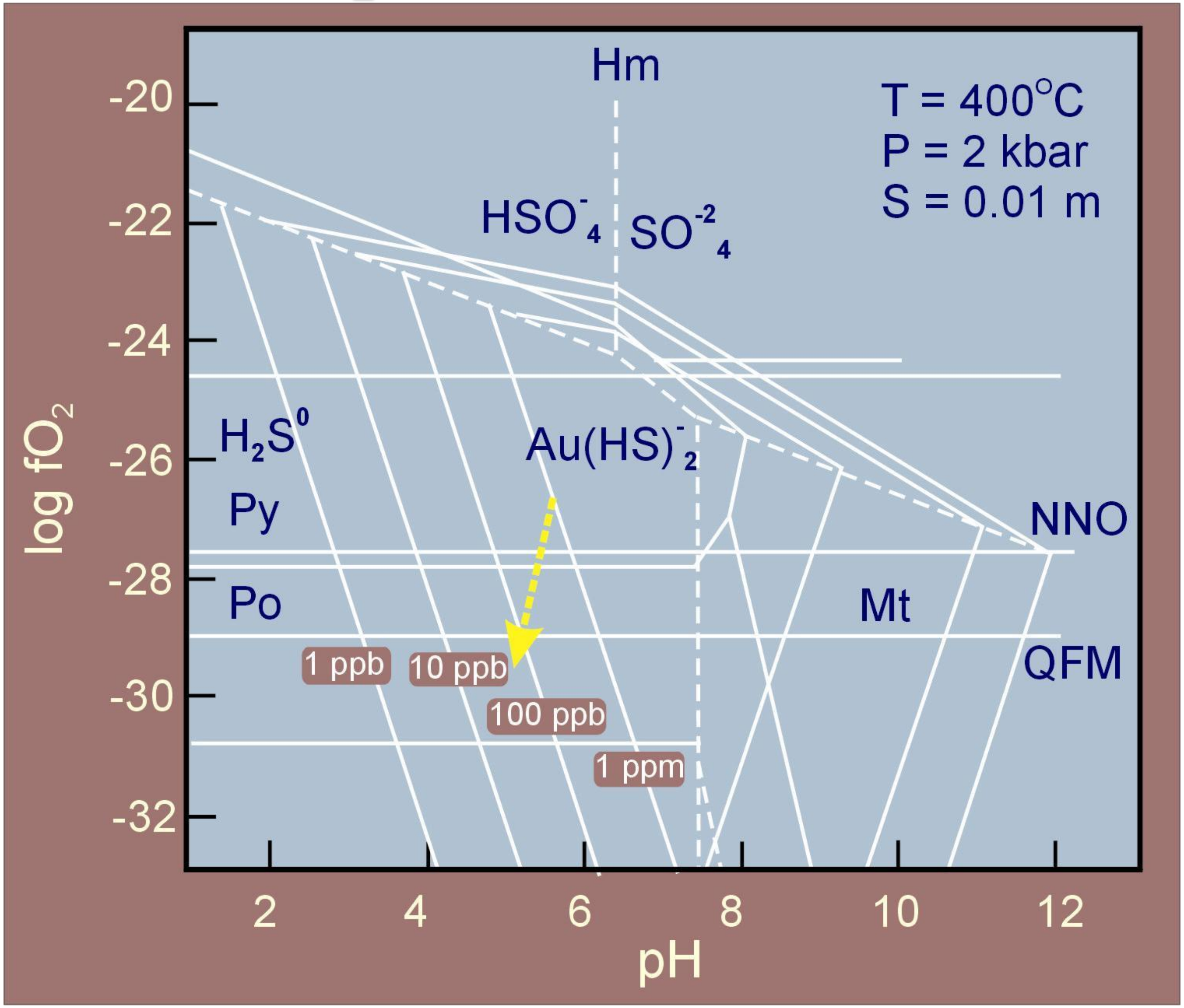


Negligible change in Mg →Path II is favored→ Rare Chl zone



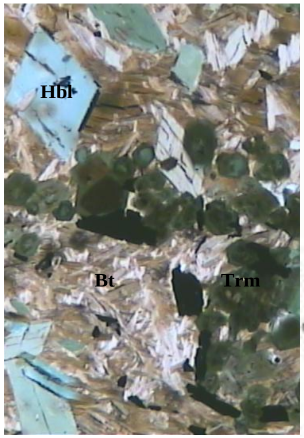
(Pal & Mishra, 2002, *MD*; Mishra & Pal, 2008, *EG*)

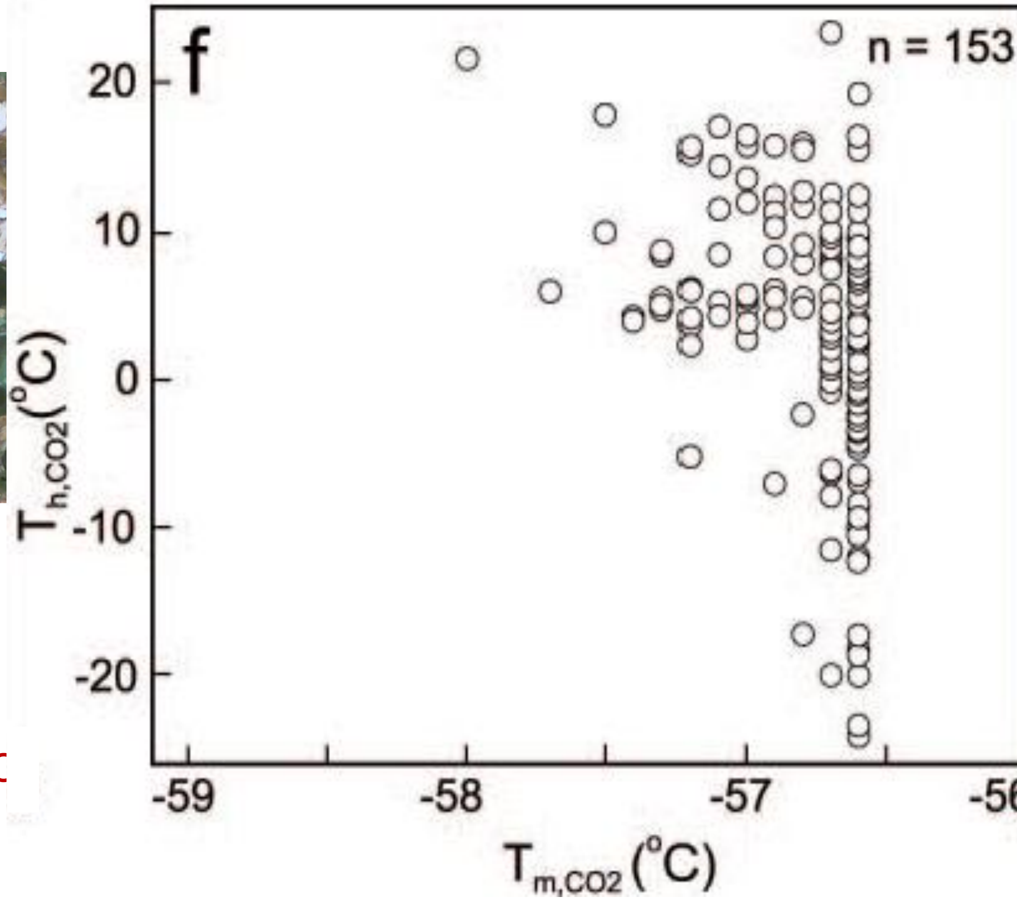
Hutti: fO_2-pH variation in D2 veins

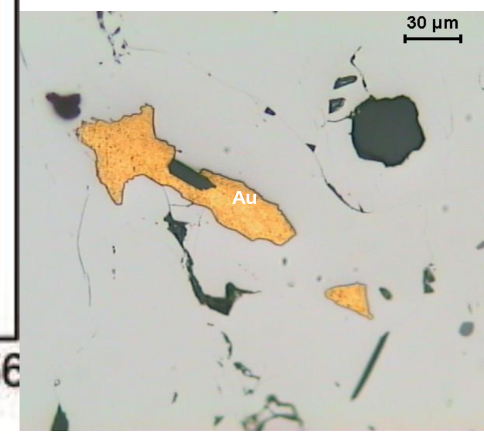


Solubility drop by decrease in f_{O2} and marginal fall in pH

Hira-Buddini: Alteration and Au occurrence



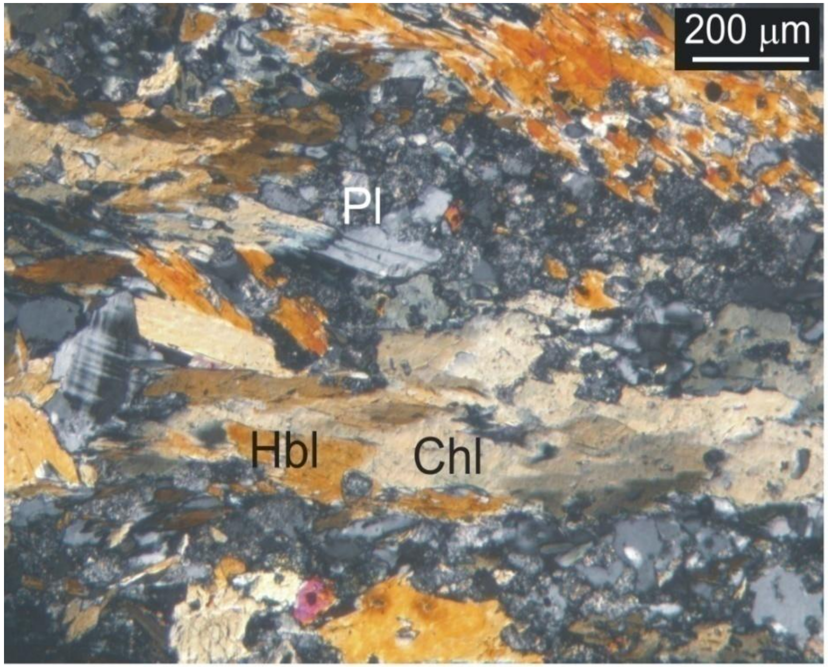


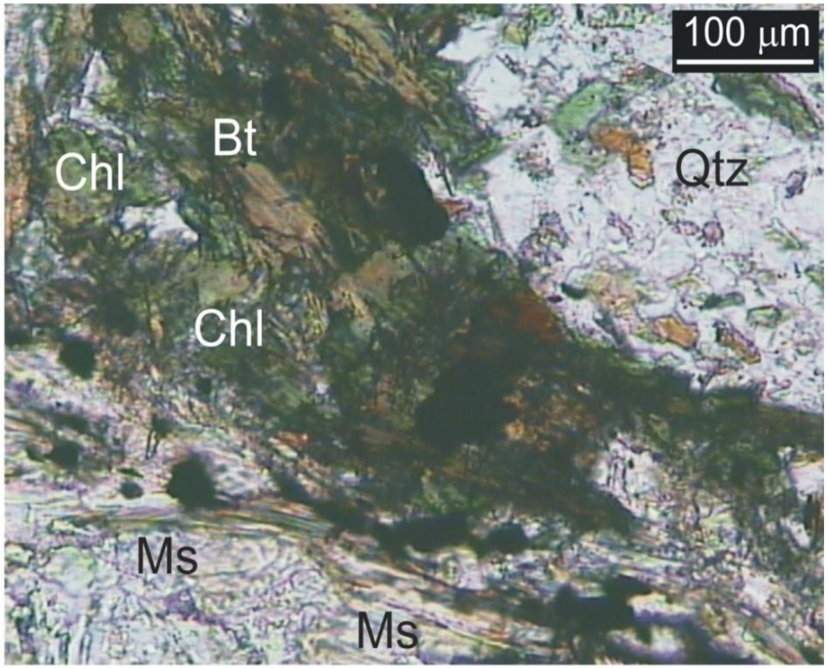


Distal: Chl +
and inner zc
2007, *MD*)

Pressure fluctuations (variation in $T_{h,CO2}$) aided fluid immiscibility (Fault valve/Sibson Cycle) → decrease in ΣS favoring gold precipitation

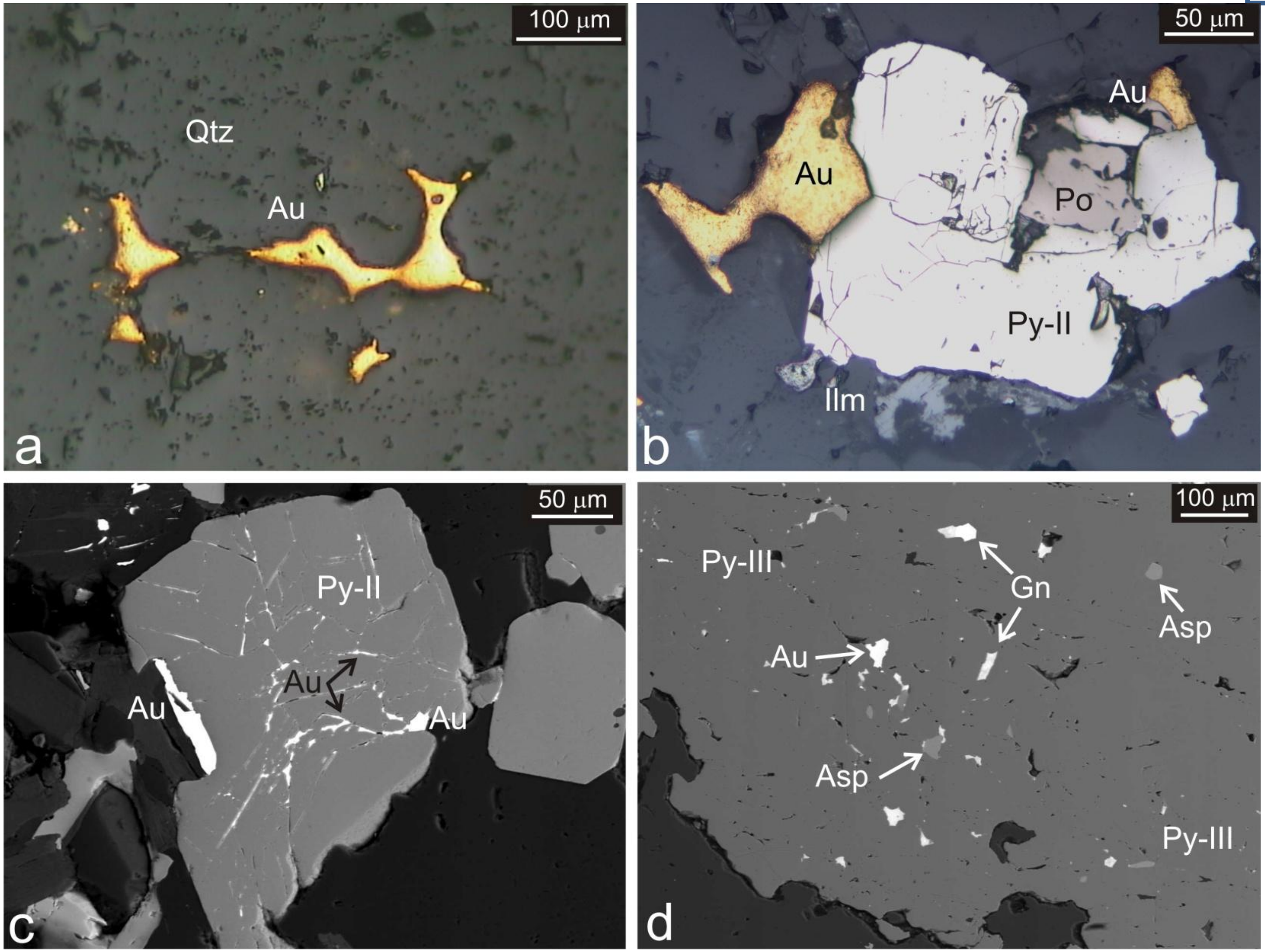
Jonnagiri: alteration



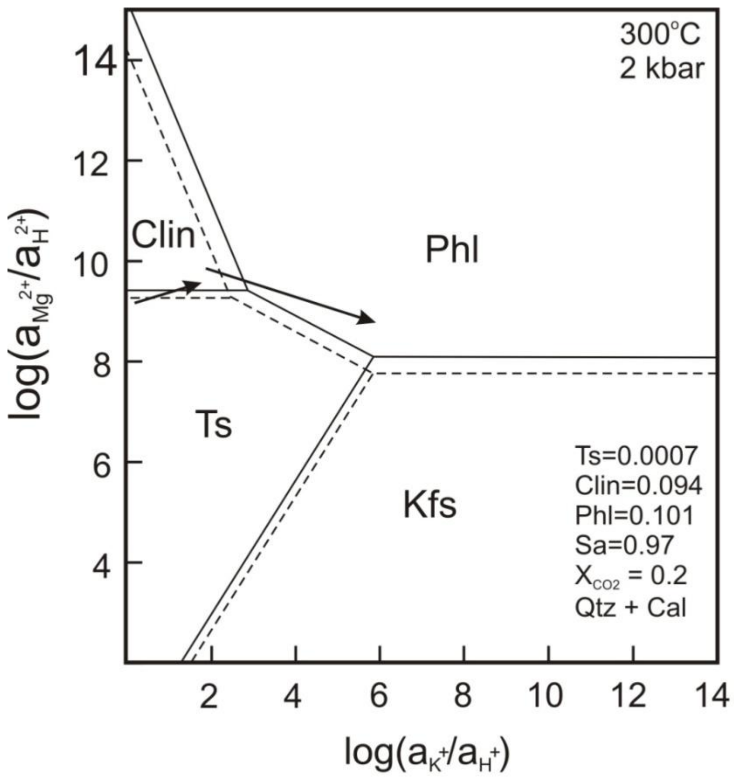


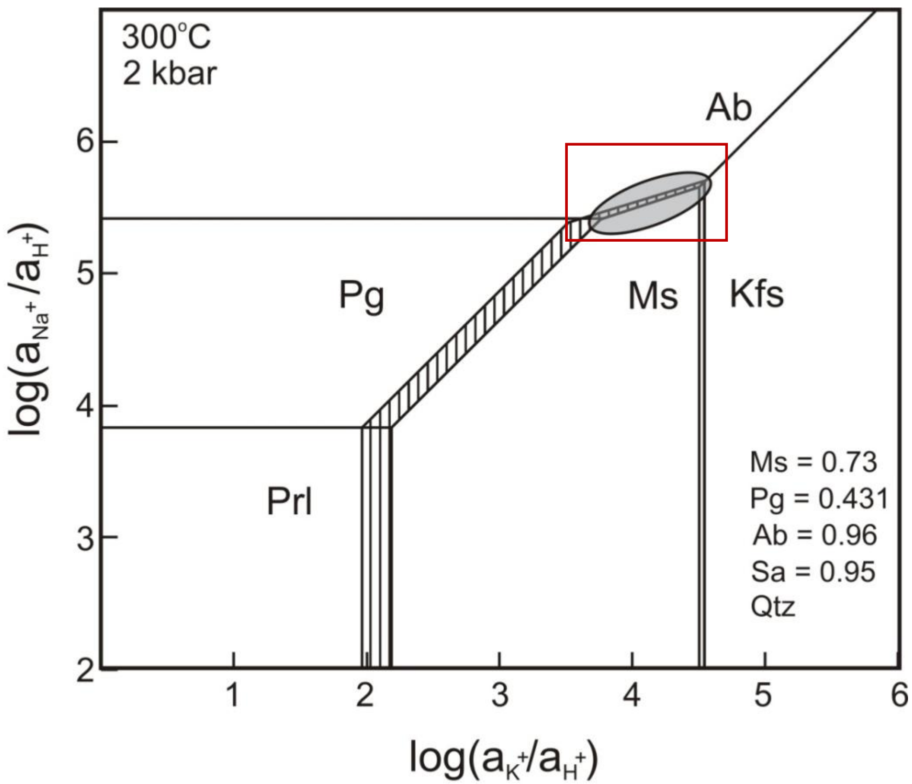
Proximal: Chl + Bt (+Ms)

Jonnagiri: Au-bearing inner zone



Jonnagiri: alteration

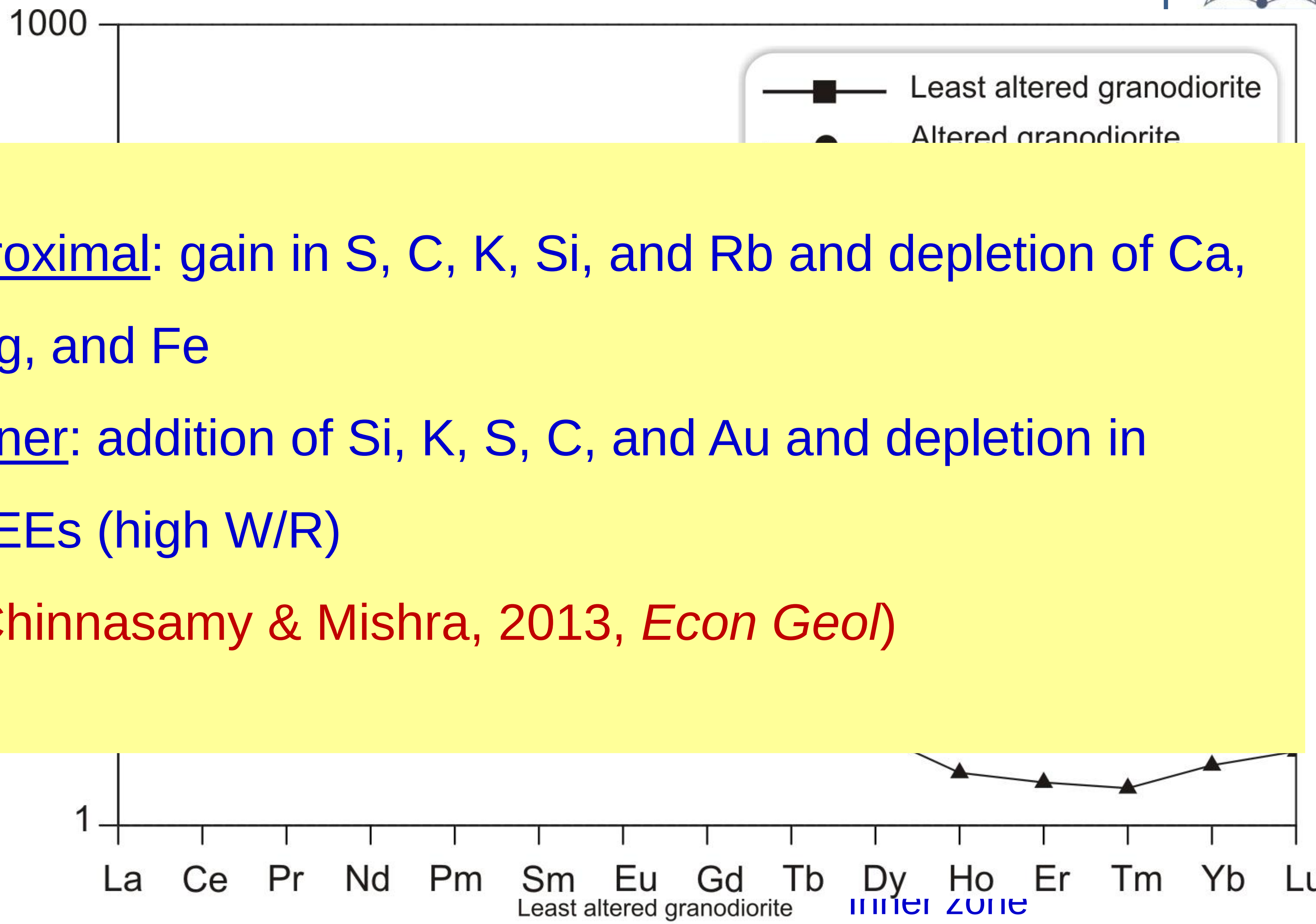




Proximal zone: Hbl $\rightarrow$ Chl $\rightarrow$ Bt

Inner zone: Ms + Kfs + Ab

Jonnagiri: alteration



<u>Proximal</u>: gain in S, C, K, Si, and Rb and depletion of Ca, Mg, and Fe

<u>Inner</u>: addition of Si, K, S, C, and Au and depletion in REEs (high W/R)

(Chinnasamy & Mishra, 2013, *Econ Geol*)

Craton scale ore fluid uniformity

Composition: Initial low saline (4 to 10 wt. % equivalent) H_2O-CO_2-CH_4-NaCl-$Au(HS)_2^-$ fluid ← phase separation by various means (NO MAGMATIC SIGNATURE) analogous to many in Yilgarn Craton/ Canadian Shield (Saravanan et al, 2009, *OGR*)

P-T of ore formation

Hutti: (i) D2: 2–3 kbar/ ≥400°C (Mishra and Pal, 2008 *EG*; Rogers et al, 2013, *MD*), (ii) D3: 1.0 –1.7 kbar/280° – 320°C (Pal and Mishra, 2002 *MD*)

Kolar: 1.80 kbar/280°C (Mishra and Panigrahi, 1999 *MD*)

Ramagiri: 1.45 –1.7 kbar / 240°–270°C (Mishra and Panigrahi, 1999 *MD*)

Ajjanahalli: 0.8 –1.15 kbar/265º – 310ºC (Pal and Mishra, 2003 *GR*)

Jonnagiri: 1.54 – 2.50 kbar/290 – 320°C (Saravanan et al, 2009 *OGR*)

Gadag: 1 kbar/ 216 °C to 321 °C (Swain et al., 2015 *OGR*)

Stable isotopes

Sulfur

$\delta^{34}S_{Sulfide}$(+1.1 to +7.1 ‰) $\delta^{34}S_{H2S}$ = +0.2 to +5.8 ‰
(Hutti, Hira- Buddini, Uti, Chigargunta, Ajjanahalli, Jonnagiri)
→ magmatic or average crustal source of sulfur
(Saravanan & Mishra, 2009, *MD*)

Carbon and oxygen

Carbonate $\delta^{13}C$ = 5.5±1.3‰, $\delta^{18}O$ = 4.1±2.7‰ (Ajjanahalli)
6.2 ± 1.9‰ 14.1 ± 0.5‰ (GR Halli)
−2.2‰ to −9.7‰ 12.0‰ to 30.5‰ (Gadag)

Average fluid $\delta^{13}C$ = 5.81 ± 1.14‰ $\delta^{18}O$ = 13.78 ± 5.1‰
4.64 ± 0.7‰, 6.50 ± 0.6‰
−2.1‰ to −9.6‰ 6.8‰ to 25.9‰

(Sarangi et al., 2012, *JAES*; Swain et al., 2015, *OGR*)

FI and stable isotope data: global synthesis

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- H_2O–NaCl–CO_2±CH_4 fluid (Na >K > Mg and Ca)
- Salinity = 3 to 7 wt. % NaCl equivalent
- $X(CO_2)$ = 0.1 to 0.25
- S = 57–1840 ppm (~0.006 to 0.18 mol%) mostly <200 ppm
- pH = ~5.5
- Au = 3–30 ppb Au (under saturated)
- P = 1 to 5 kbar
- T = 220 to 450 °C
- $\delta^{18}O$ = +6 to +11‰ (Precambrian) = +7 to +13‰ (Phanerozoic)
- δD = −20 to −80‰ (insignificant lighter meteoric H_2O)
- $\delta^{13}C_{fluid}$ = −11 and +2‰ (non-mantle source and insignificant fluid mixing)
- $\delta^{34}{}_{Sulphide}$ = −20 to +25 ‰

(Ridley & Diamond, 2000, Rev. Econ Geol.; Goldfarb & Groves, 2015, *Lithos*)

Some exceptions: possible non-metamorphic fluids?

Late … at Hira-Buddi … et al, 2007, …

Late … at Hutti from … MD)

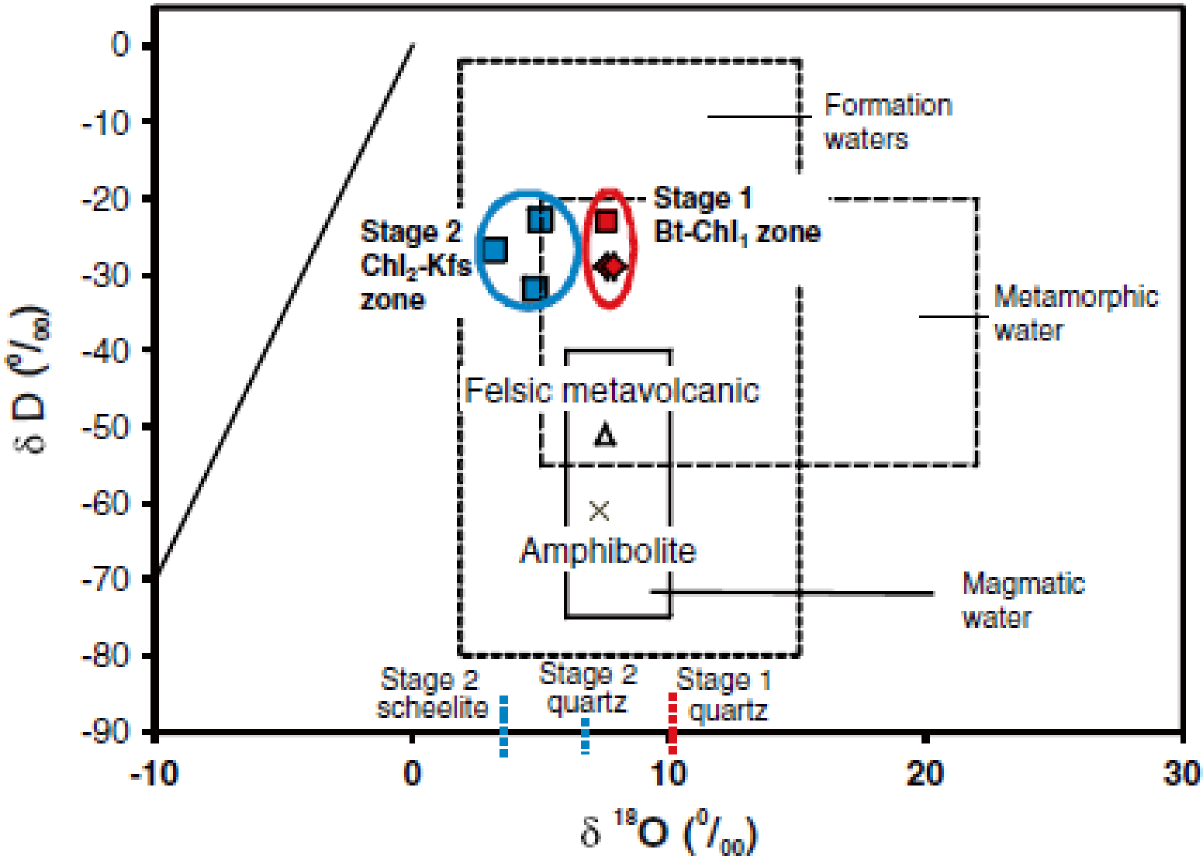

Fig.7 of Rogers et al (2013, *MD*): fields defined by data points for Hutti stage 1 and stage 2 mineralizations are much closer to each other, within fields of metamorphic and formation waters, away from the magmatic water field?

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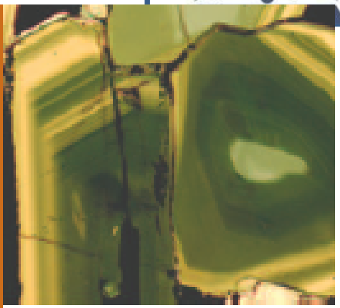
Geochemistry of hydrothermal minerals

Tourmaline as a Recorder of Ore-Forming Processes

John F. Slack[1] and Robert B. Trumbull[2]



Zoned tourmaline from the Ore Knob VMS deposit, North Carolina, USA. The matrix (black) is chalcopyrite.

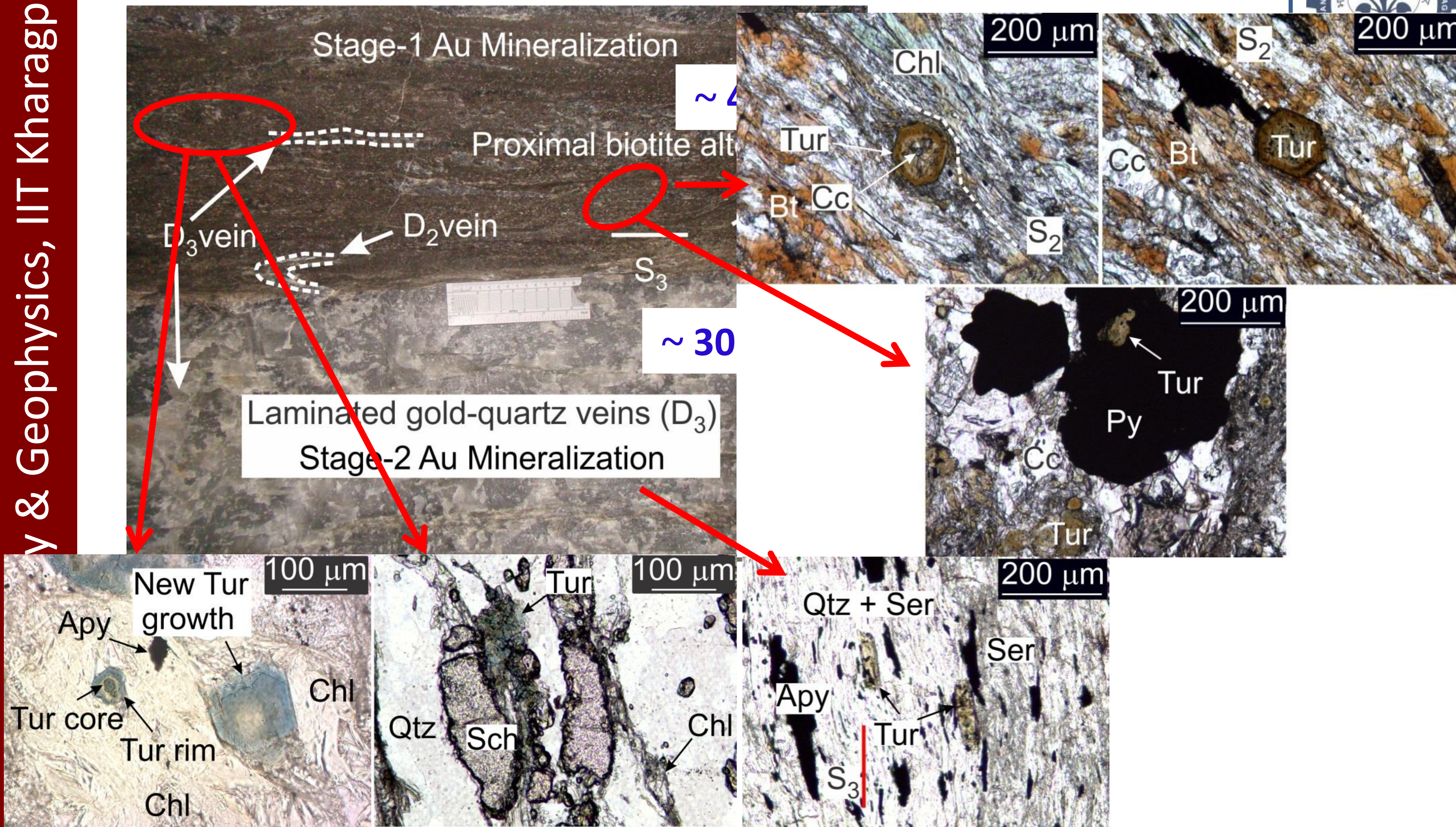
1811-5209/11/0007-0321$2.50 DOI: 10.2113/gselements.7.5.321

Tourmaline occurs in diverse types of hydrothermal mineral deposits and can be used to constrain the nature and evolution of ore-forming fluids. Because of its broad range in composition and retention of chemical and isotopic signatures, tourmaline may be the only robust recorder of original mineralizing processes in some deposits. Microtextures and in situ analysis of compositional and isotopic variations in ore-related tourmaline provide valuable insights into hydrothermal systems in seafloor, sedimentary, magmatic, and metamorphic environments. Deciphering the hydrothermal record in tourmaline also holds promise for aiding exploration programs in the search for new ore deposits.

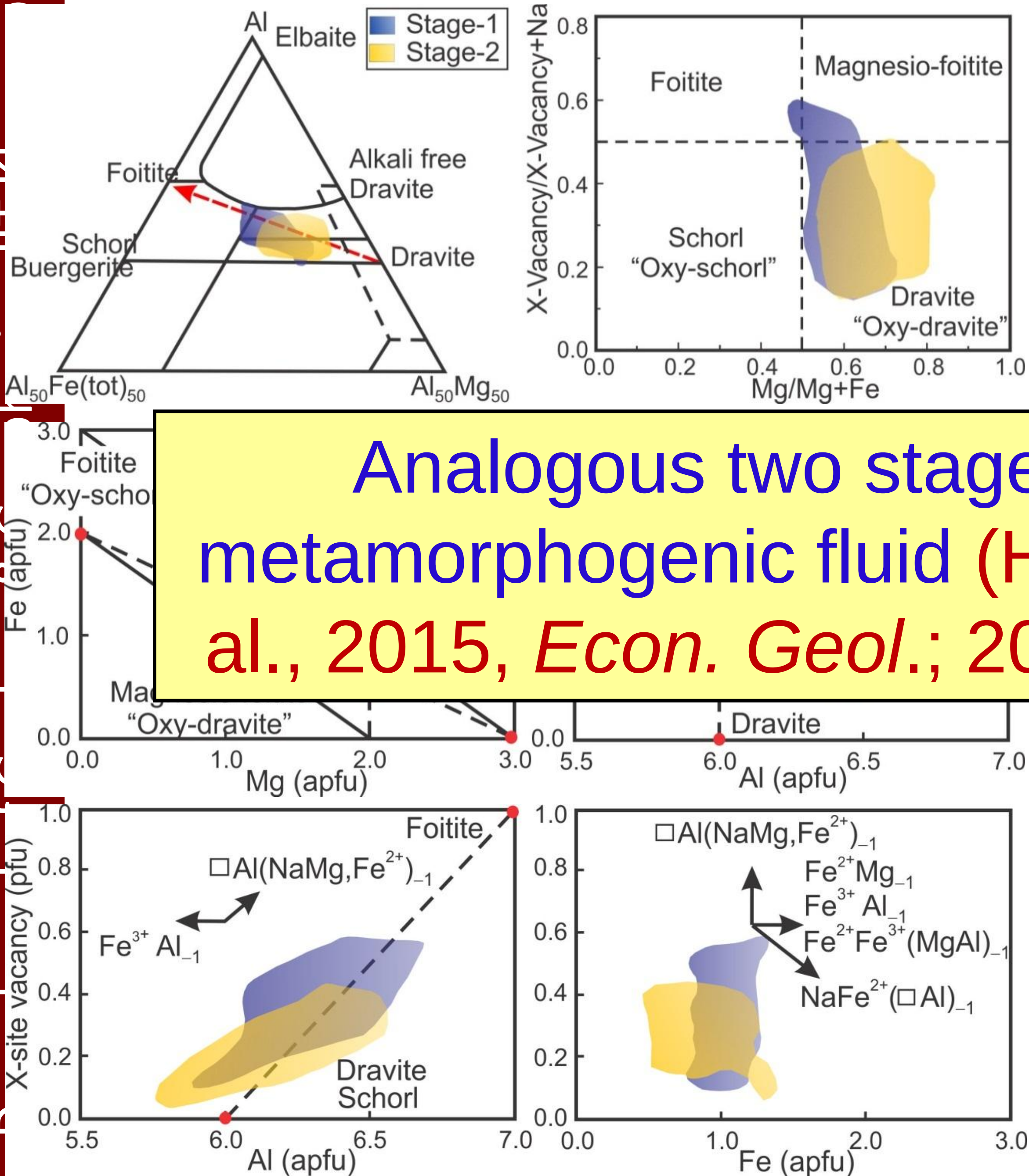
The formation of hydrothermal tourmaline requires the fortuitous convergence of complex processes: derivation of boron and other essential elements from one or more sources; transport in fluids of diverse provenance (magmatic-derived, metamorphic, basinal or evaporitic brines, heated meteoric water, evolved seawater); and finally precipitation in settings and conditions that may coincide with the deposition of economi-

Slack and Trumbull (2011) *Elements*

Fluid proxy: Hydrothermal mineral geochemistry Tourmaline



Fluid proxy: Hydrothermal mineral geochemistry   Tourmaline

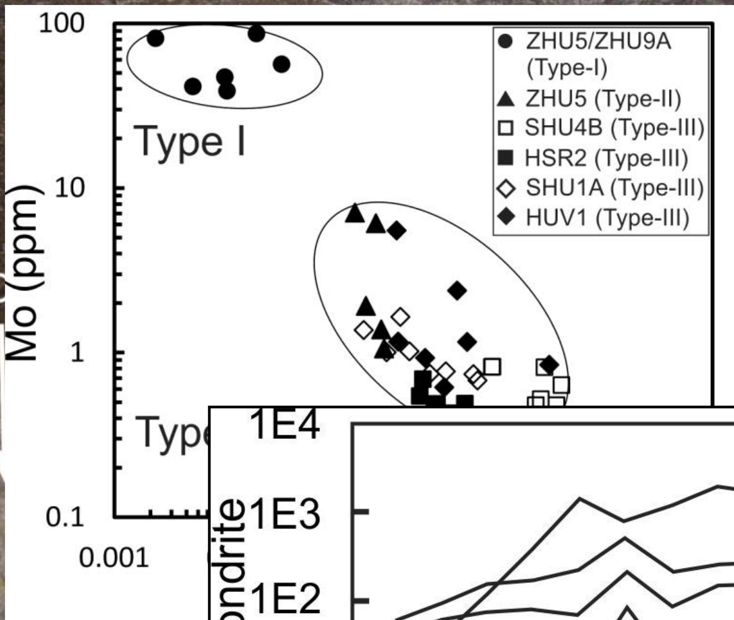


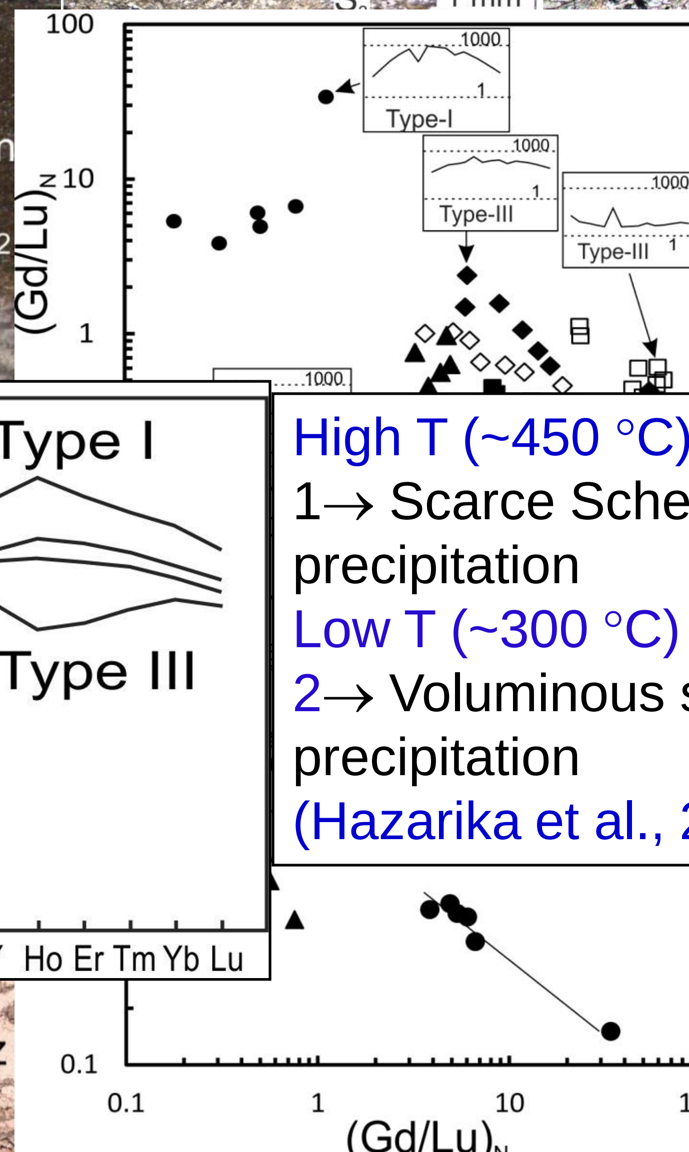
Analogous two stage Hutti metamorphogenic fluid (Hazarika et al., 2015, *Econ. Geol.*; 2016, *OGR*)

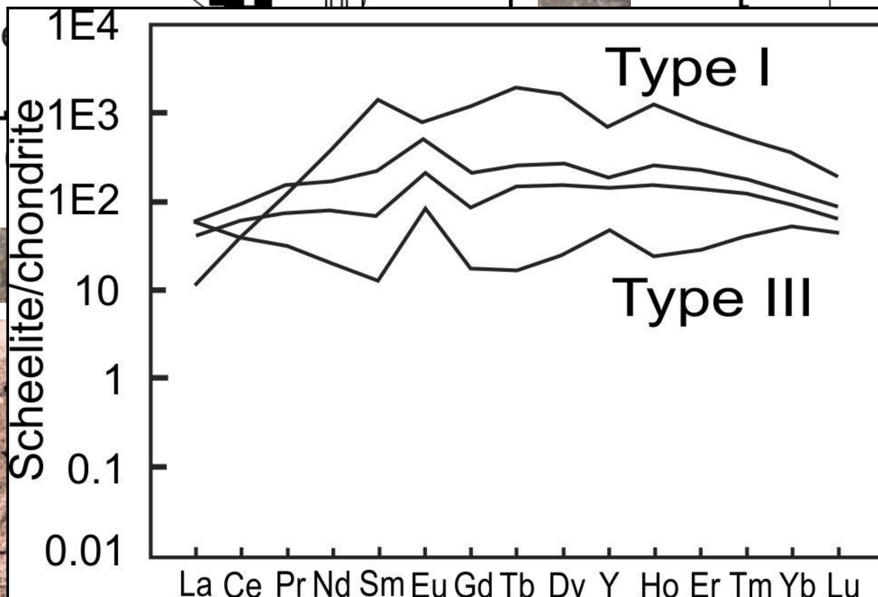
Characteristics

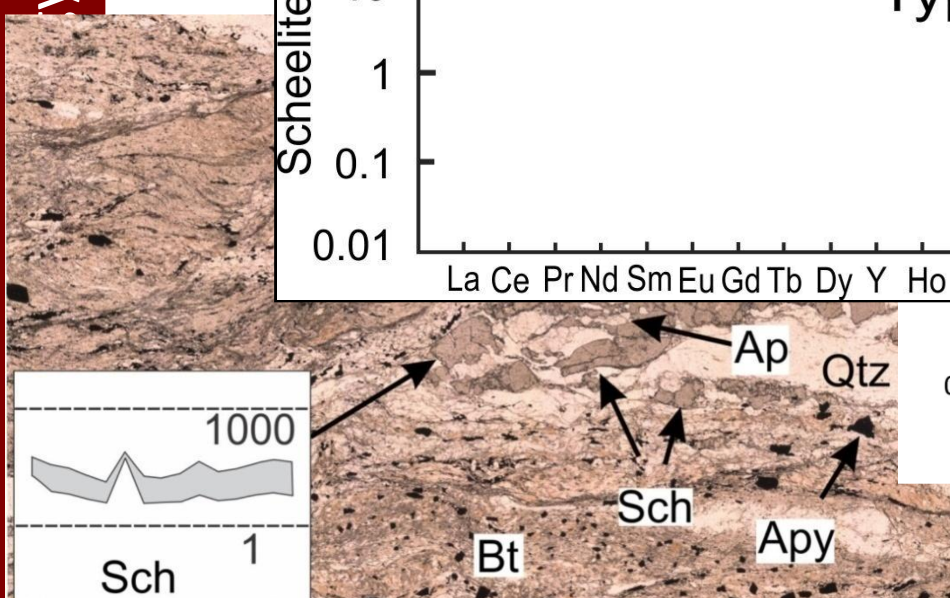
- Low Na contents (< 0.61 apfu) and high X-site vacancies (up to 0.53 pfu) → low salinity fluid
- Dravite-Foitite trend
- ... Fe^{3+} in Z-site
- ... □Al Na ... substitutions and insignificant $Fe^{3+}Al_{-1}$ substitution → Prevalent Fe^{2+}
- Low Fe^{3+}/Fe^{2+} → reducing fluid
- Low trace element contents (LILE and HFSE)

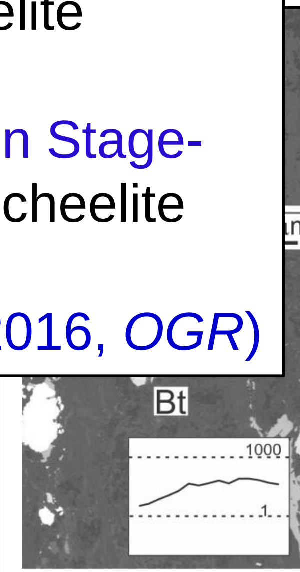
Fluid proxy: Hydrothermal mineral geochemistry Scheelite









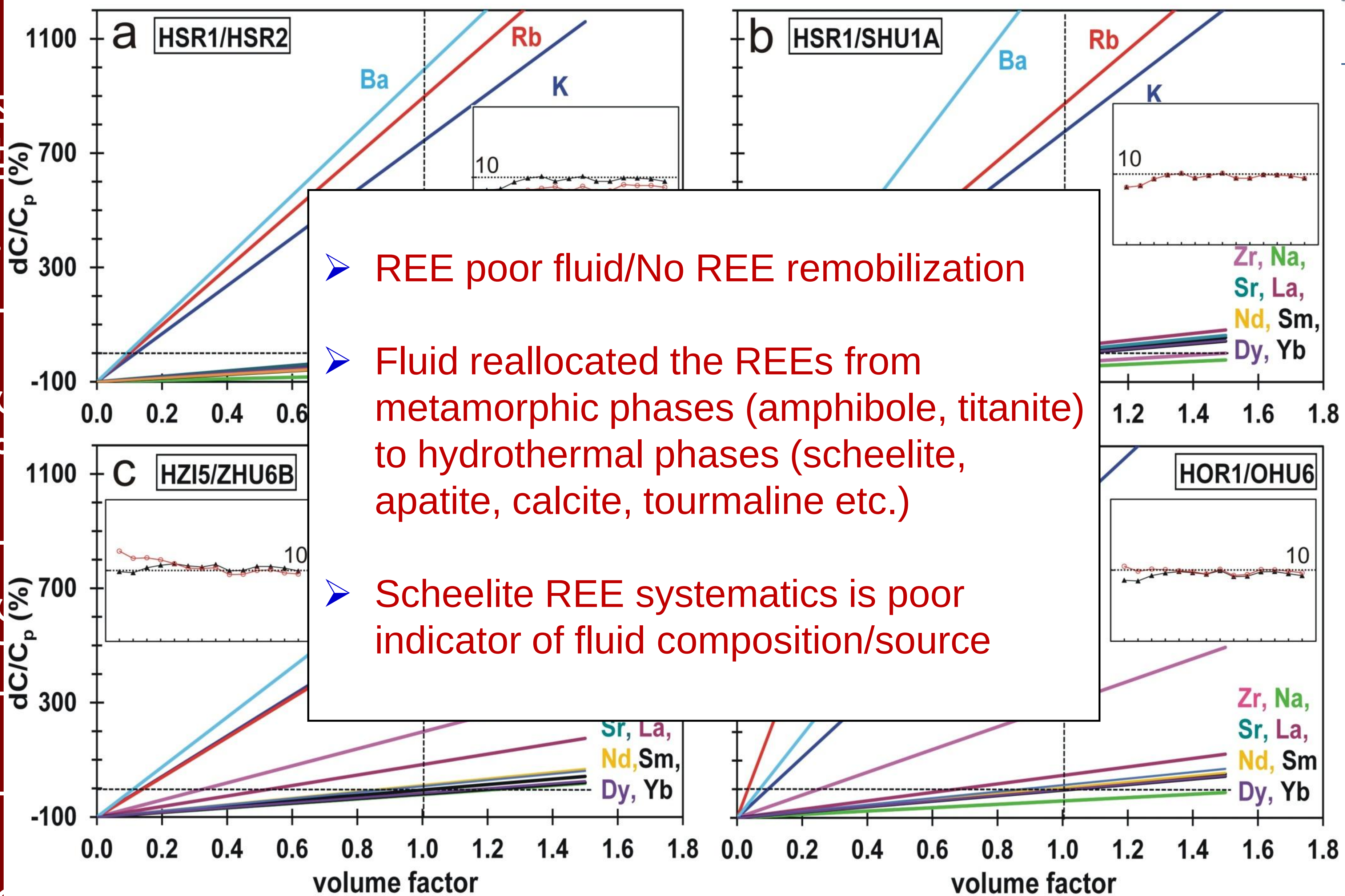


Negative Eu-anomaly in stage-1 scheelite→ Low

High T (~450 °C) in Stage-1→ Scarce Scheelite precipitation
Low T (~300 °C) in Stage-2→ Voluminous scheelite precipitation
(Hazarika et al., 2016, *OGR*)

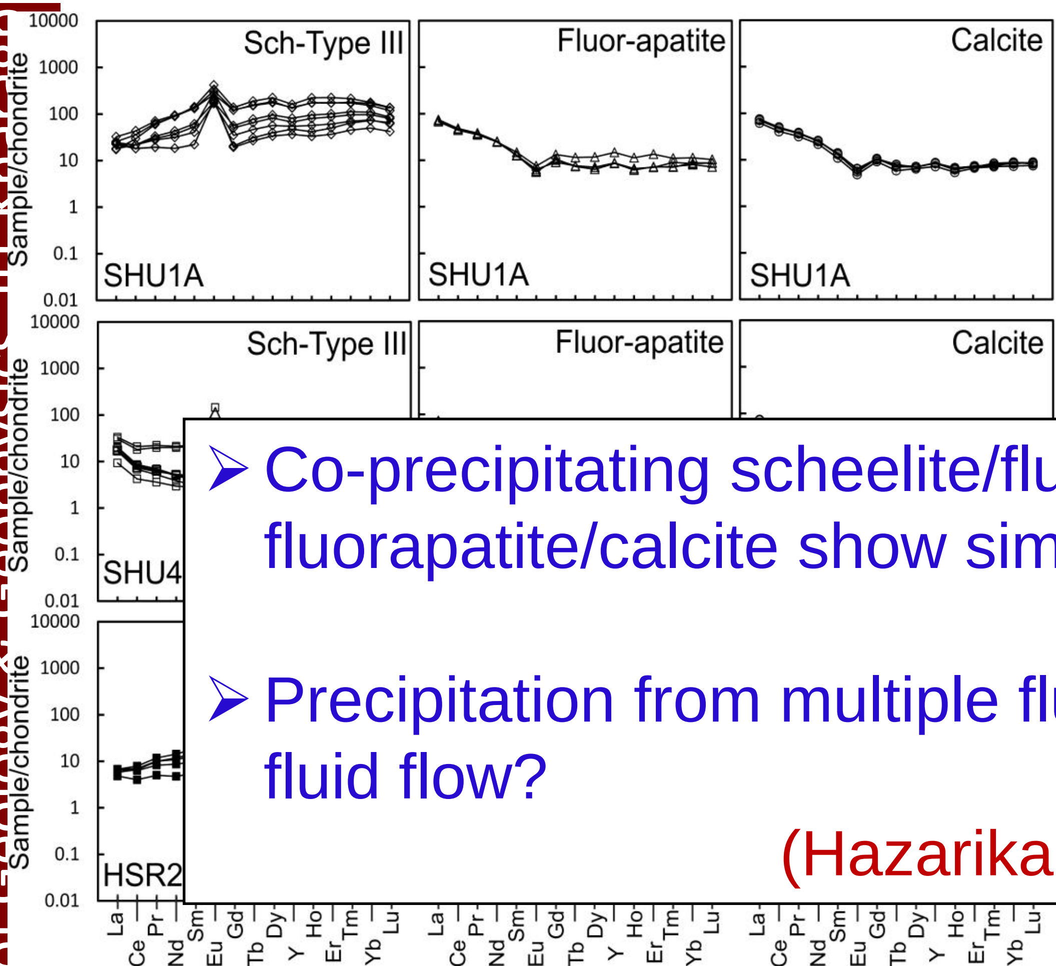
ar REE patterns ?

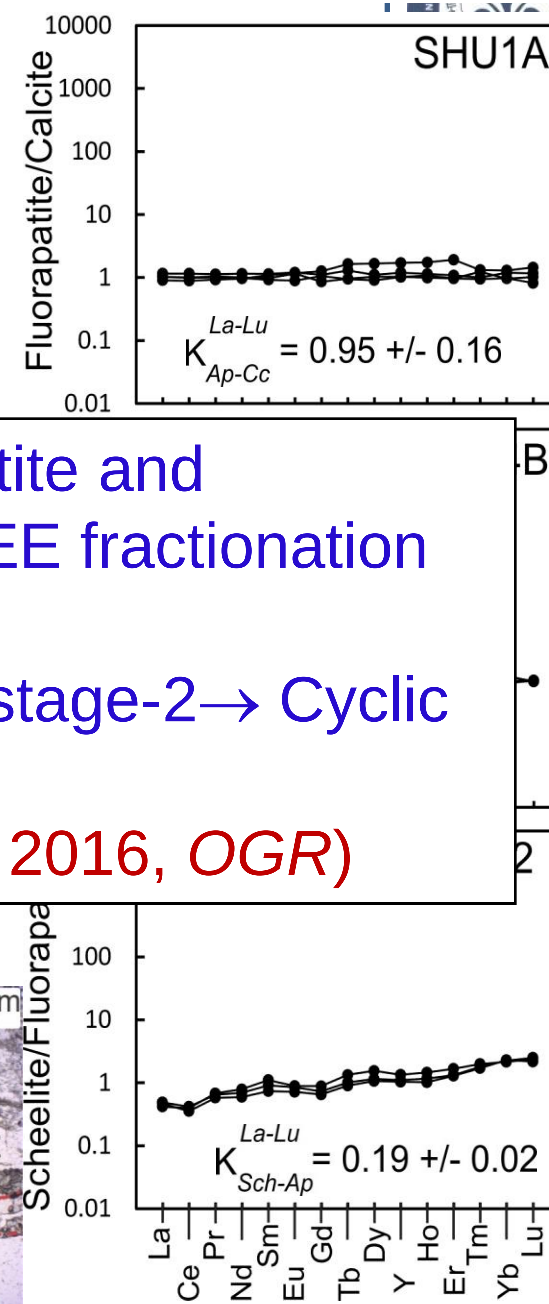
Hutti: Whole rock mass balance calculations



- REE poor fluid/No REE remobilization
- Fluid reallocated the REEs from metamorphic phases (amphibole, titanite) to hydrothermal phases (scheelite, apatite, calcite, tourmaline etc.)
- Scheelite REE systematics is poor indicator of fluid composition/source

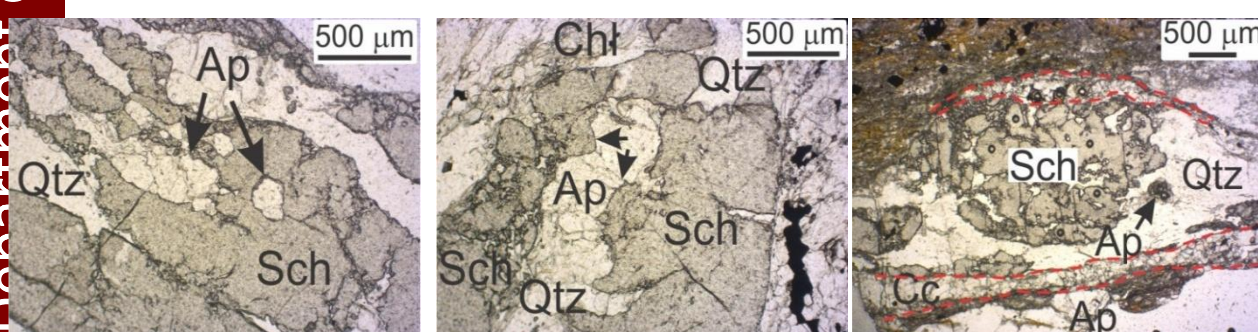
Fluid proxy: Hydrothermal mineral geochemistry Apatite/Calcite





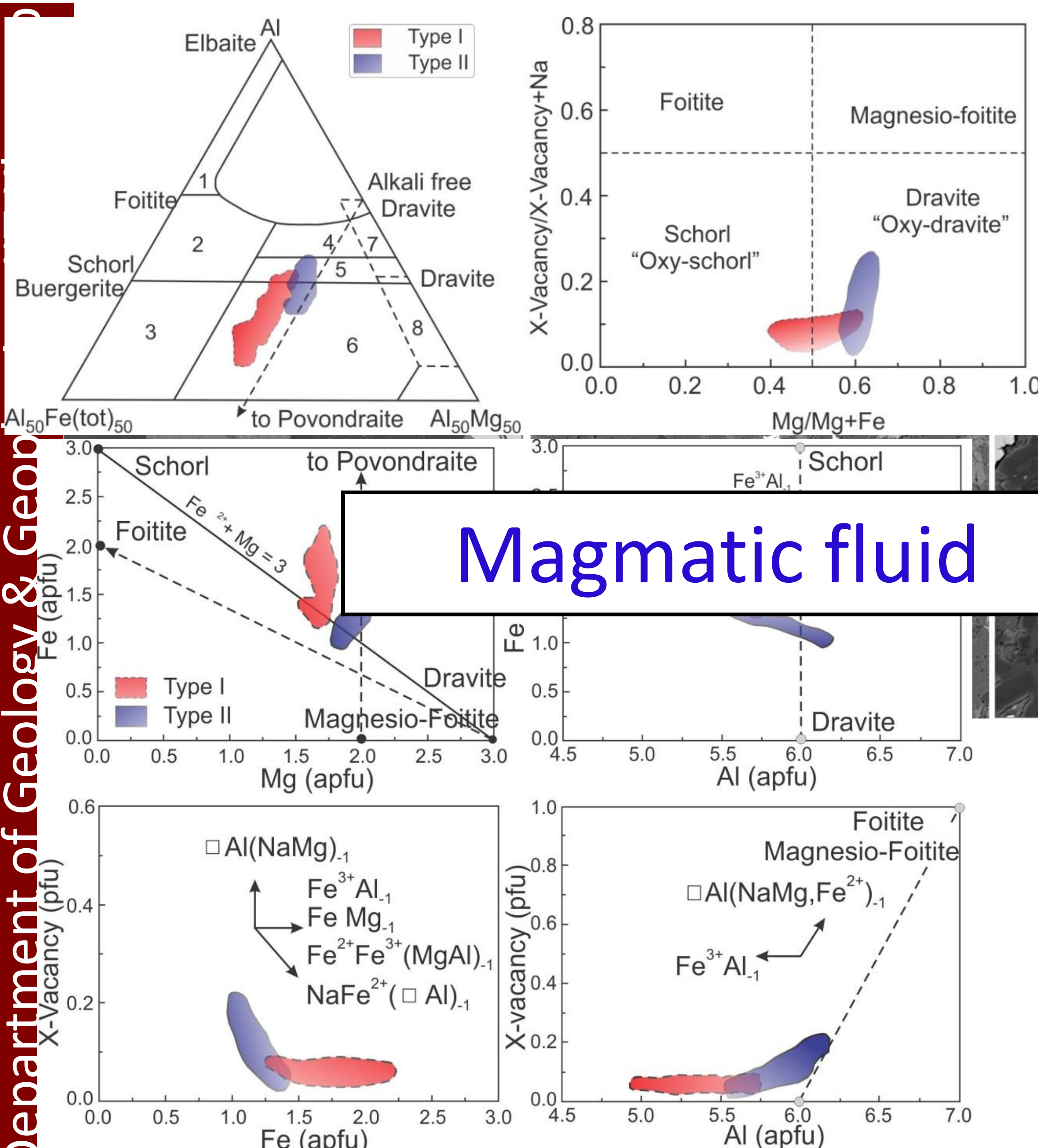
- ➢ Co-precipitating scheelite/fluorapatite and fluorapatite/calcite show similar REE fractionation
- ➢ Precipitation from multiple fluid in stage-2→ Cyclic fluid flow?

(Hazarika et al., 2016, *OGR*)



Fluid proxy: Hydrothermal mineral geochemistry

Hira-Buddini (Tur)



Magmatic fluid

Characteristics (Type I)

- High Na contents (up to 0.84 apfu) and low X-site vacancies (< 0.14 pfu) → High salinity of the fluid
- Oxy-dravite-Povondraite trend

  Al < 6 apfu → Fe^{3+} in Z-site
- Dominant $Fe^{3+}Al_{-1}$ substitution → Prevalent Fe^{3+}
- High Fe^{3+}/Fe^{2+} → oxidizing fluid
- High contents of Pb, Sr and REE

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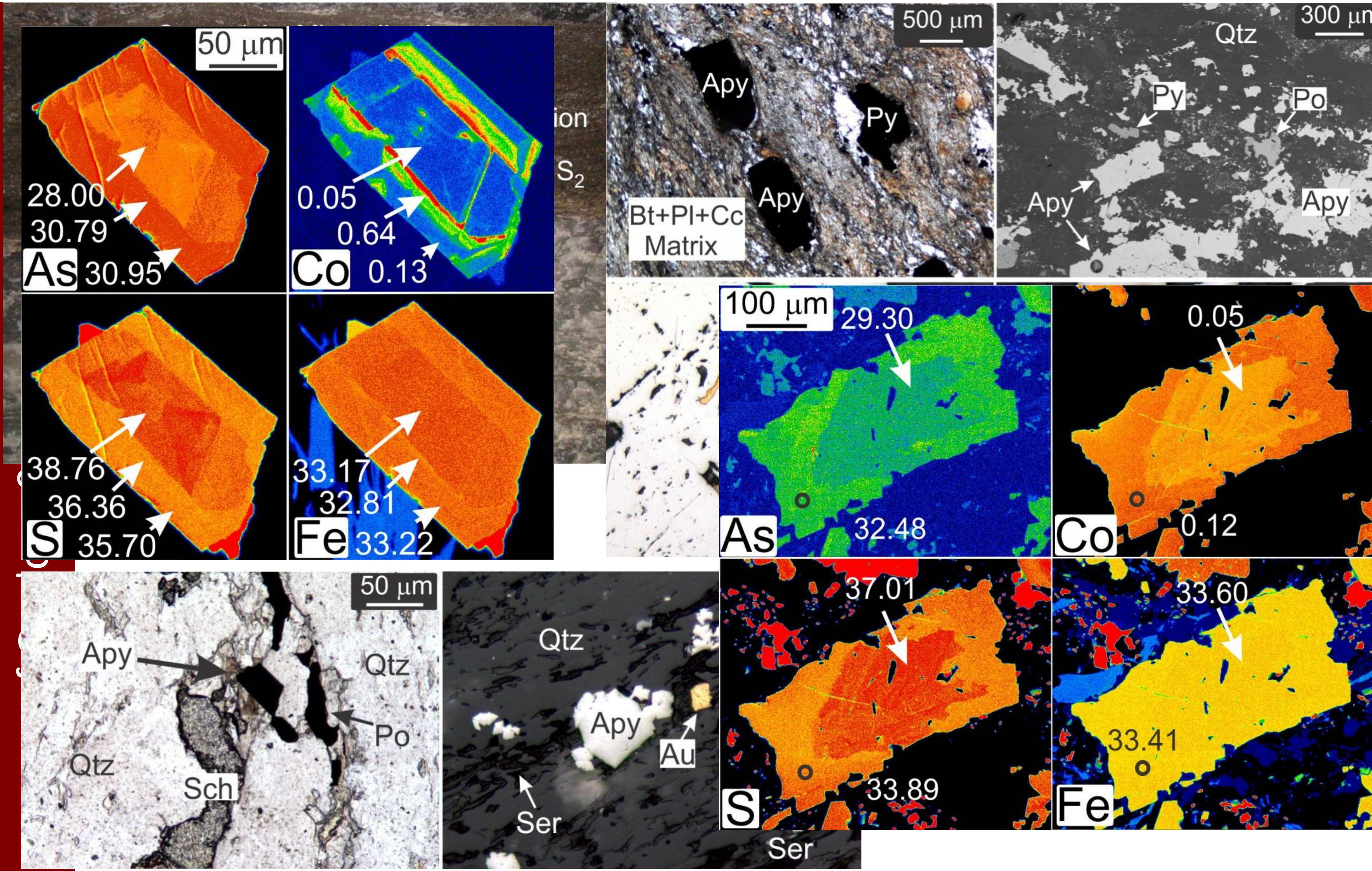
Arsenopyrite/pyrite compositions

Hutti

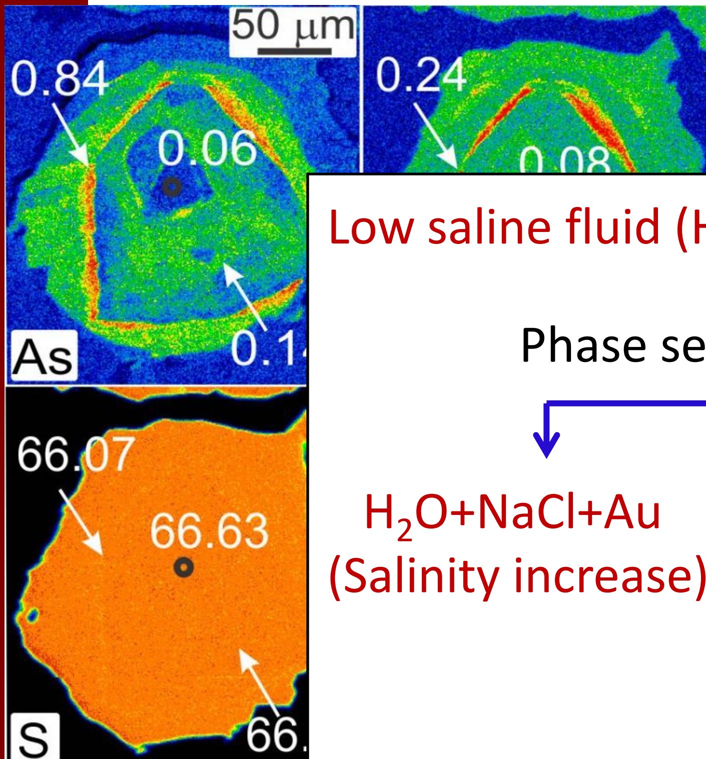


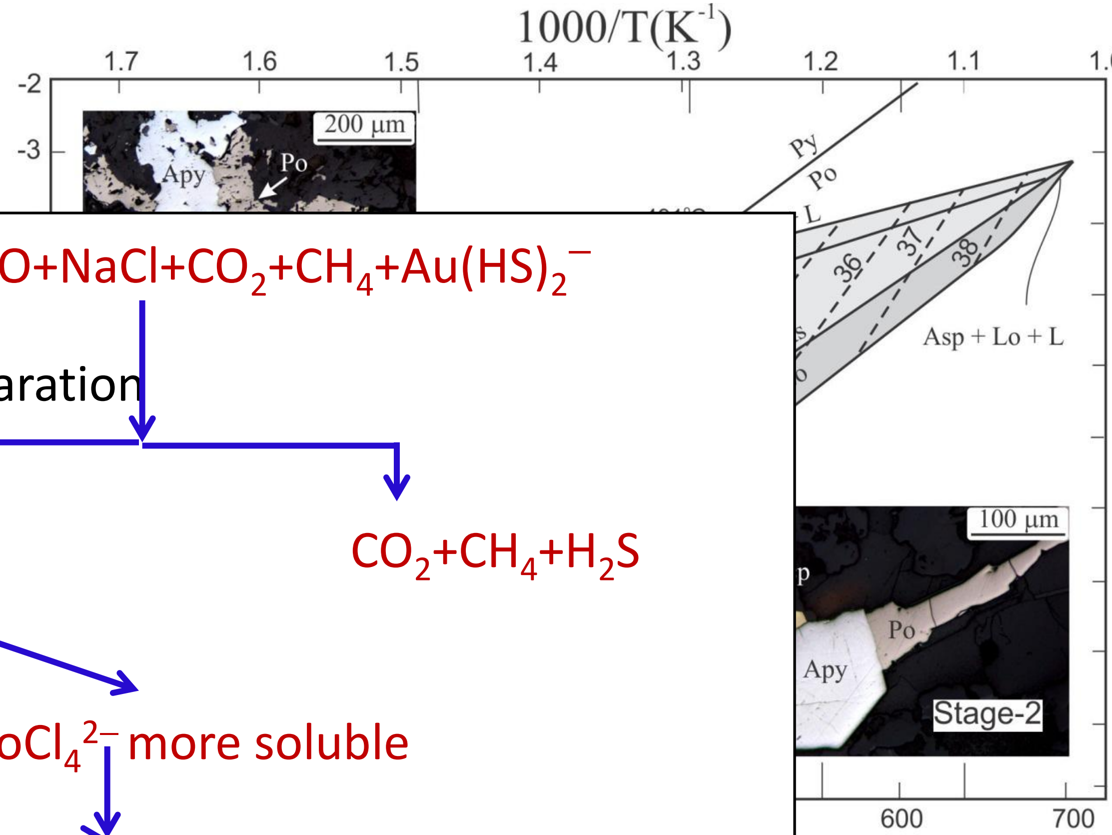
Stage-1: Py + Apy + Po; Stage-2:Apy + Po

Arsenopyrite/pyrite compositions

Hutti

Department of Geo





Low saline fluid (H_2O+NaCl+CO_2+CH_4+$Au(HS)_2^-$)

Phase separation

H_2O+NaCl+Au
(Salinity increase)

CO_2+CH_4+H_2S

$CoCl_4^{2-}$ more soluble

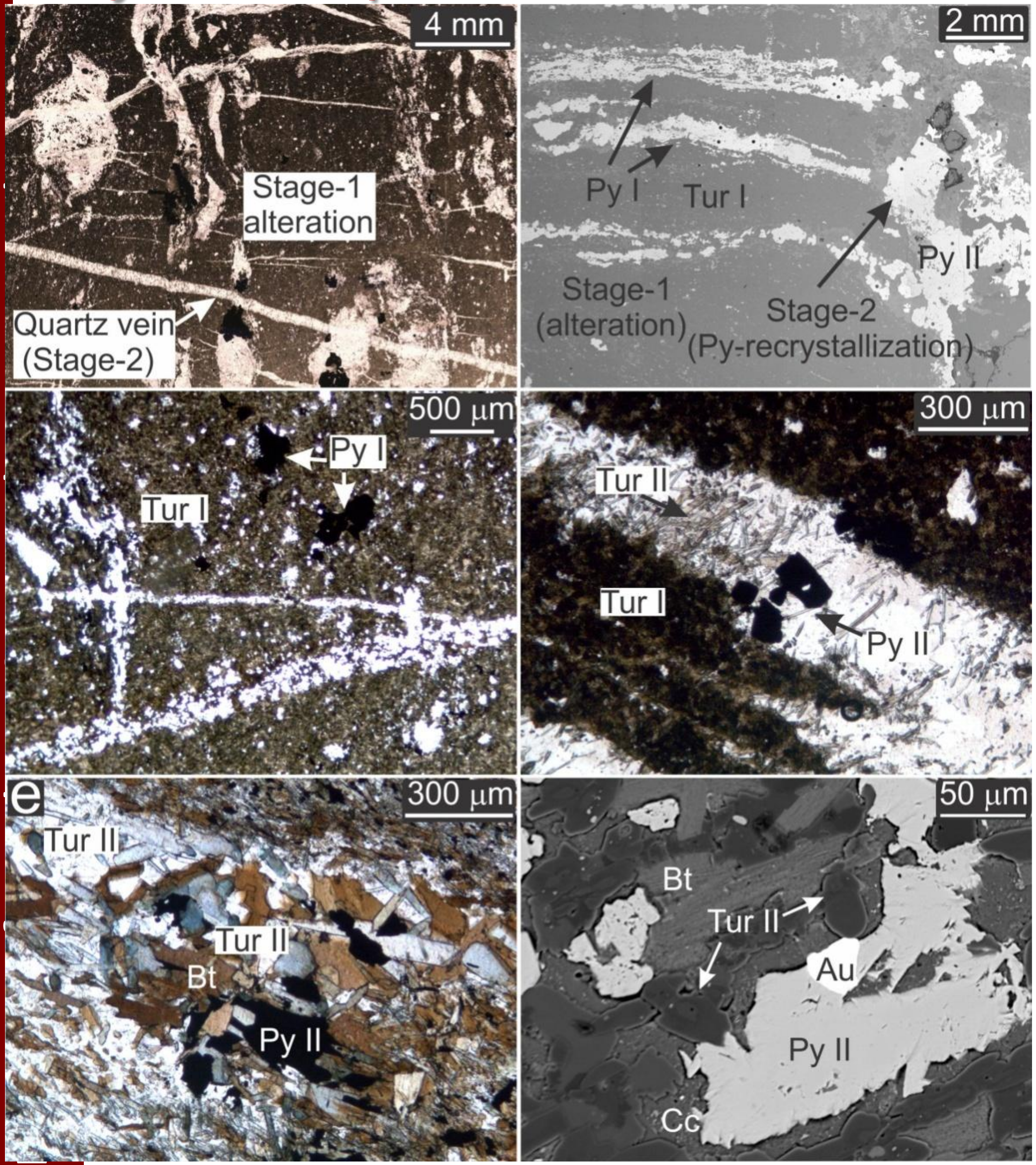
Another fluid pulse

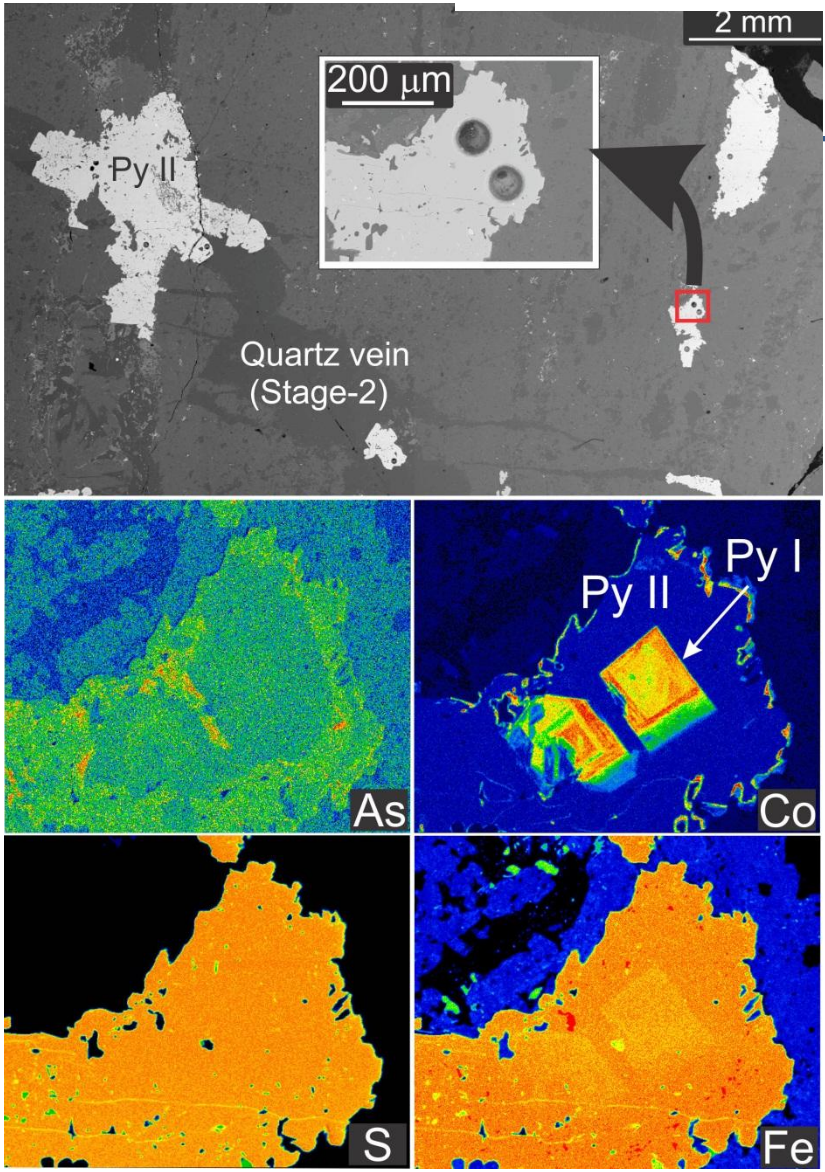
(Salinity decrease) $CoCl_4^{2-}$ unstable and Co precipitates

- Revers
- Sharp c
  Phase … luid flow regime (Deditius et al., 2009, *Geology*) as a result of fault-valve actions
- Phase separation to NaCl+H_2O and CO_2+CH_4 → fluctuation of fluid salinity→ Oscillatory cobalt zoning (Co transport salinity dependent, Liu et al., 2011, *GCA*)

Pyrite compositions

Hira-Buddini





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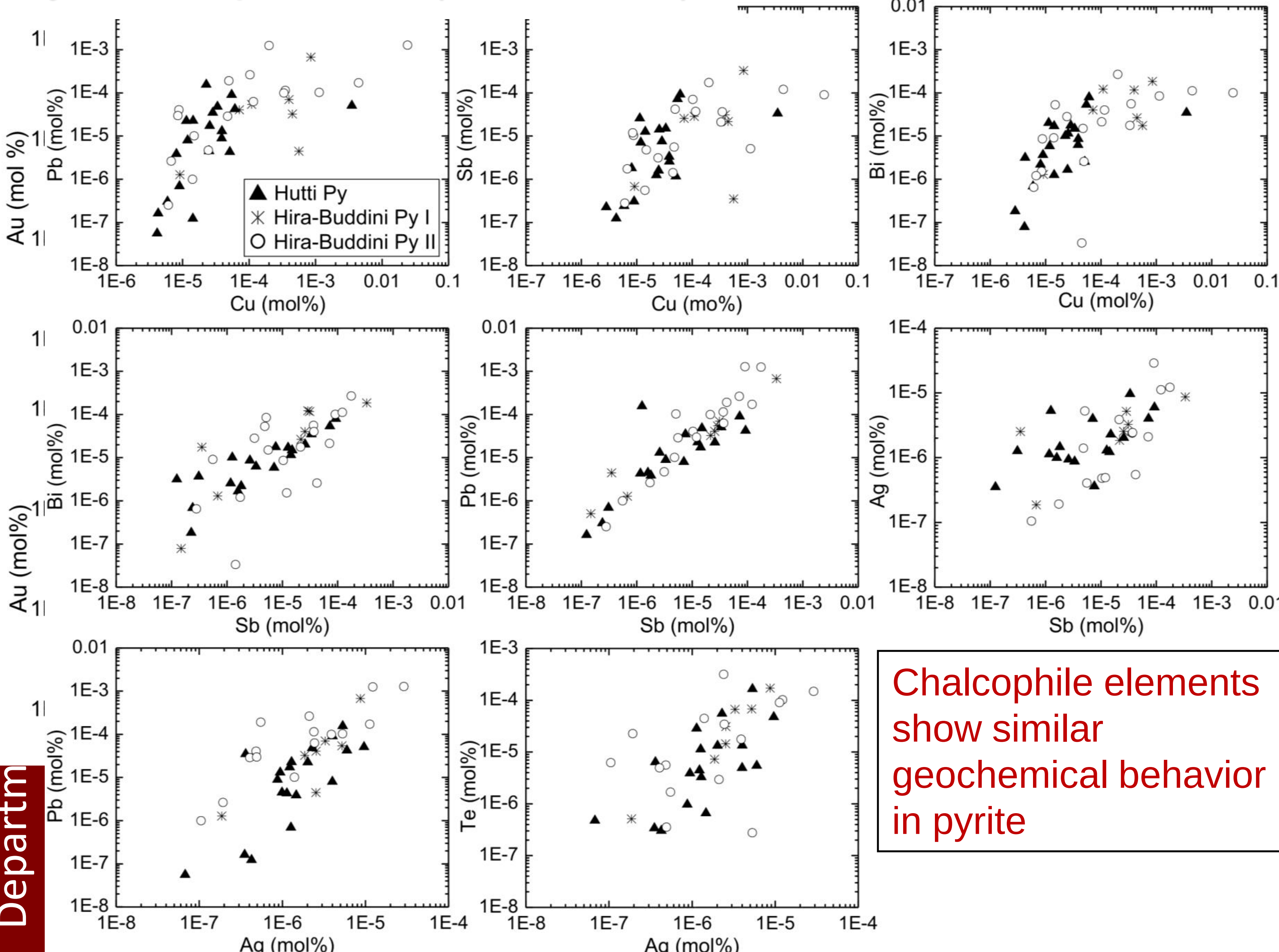
Pyrite compositions (LA-ICP-MS)

Hutti and Hira-Buddini



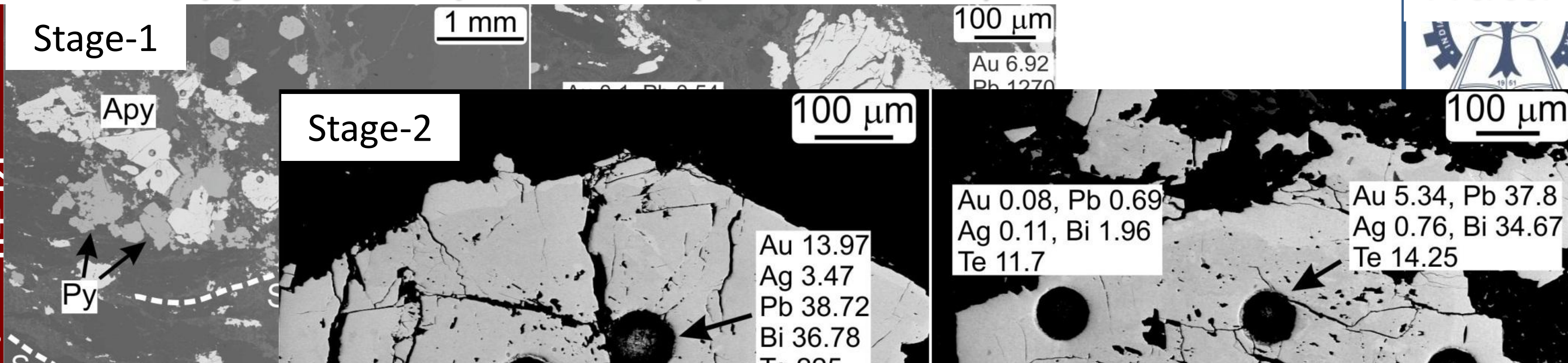
Chalcophile elements show similar geochemical behavior in pyrite

Departm

2015

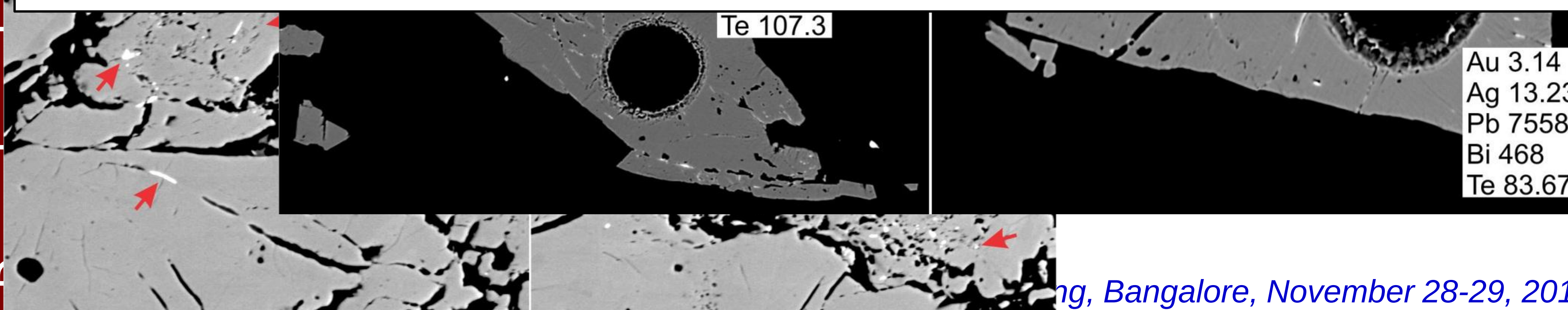
Arsenopyrite compositions (LA-ICP-MS)

Hutti



- ➢ High Au, Ag, Pb, Bi and Te contents along fractures
- ➢ No alteration in Apy adjacent to fractures

1. Precipitation of Au-Ag-Pb-Bi-Te micro-particles from ore the fluid
2. Gold coupled with chalcophile elements in orogenic gold deposits
3. No role of As for Au incorporation into sulfides!



Synthesis

Magmatic fluid source model

- Granites are 50 Ma older than ore (Wallaby, Cleo-Sunrise, Kalgoorlie) and ~60 Ma younger than the ore (Ballarat and Bendigo) in Yilgarn Craton (WA)?
- Explanation of low salinity H_2O-NaCl-CO_2±CH_4-$Au(HS)_2^-$ fluid?
- No granite in Au-productive Otago terrain (New Zealand)
- Source of Au and S?

Ages of metamorphism of 2564 ± 12 Ma in HMGB and syn-tectonic TTG plutonism of 2543 ± 9 Ma (Kavital granodiorite; Rogers et al., 2007) are indistinguishable within errors making a geochronology-based resolution of the existing debate on metamorphic vs. magmatic fluid source impossible.

Metamorphic fluid source model

(Goldfarb & Groves, 2015, *Lithos*)

- Mostly in greenschist facies terrain (Yilgarn & Abitibi)
- Unlike amphibolite facies in Kolar, Hutti, Jonnagiri?

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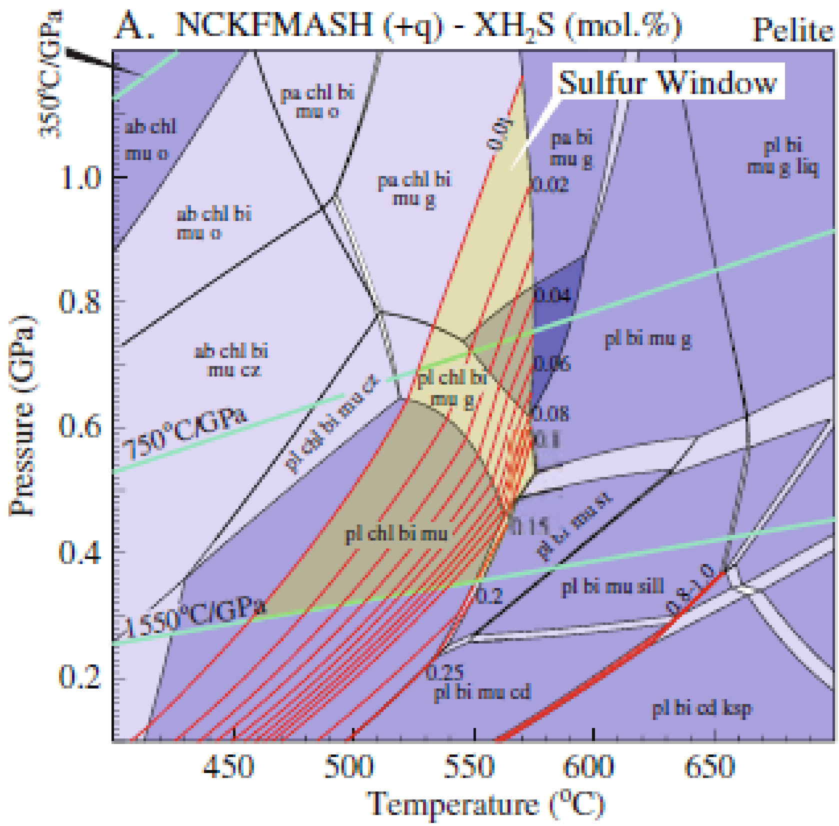
S-windows during metamorphism

Chl-breakdown reactions in mafic rocks

Pelitic

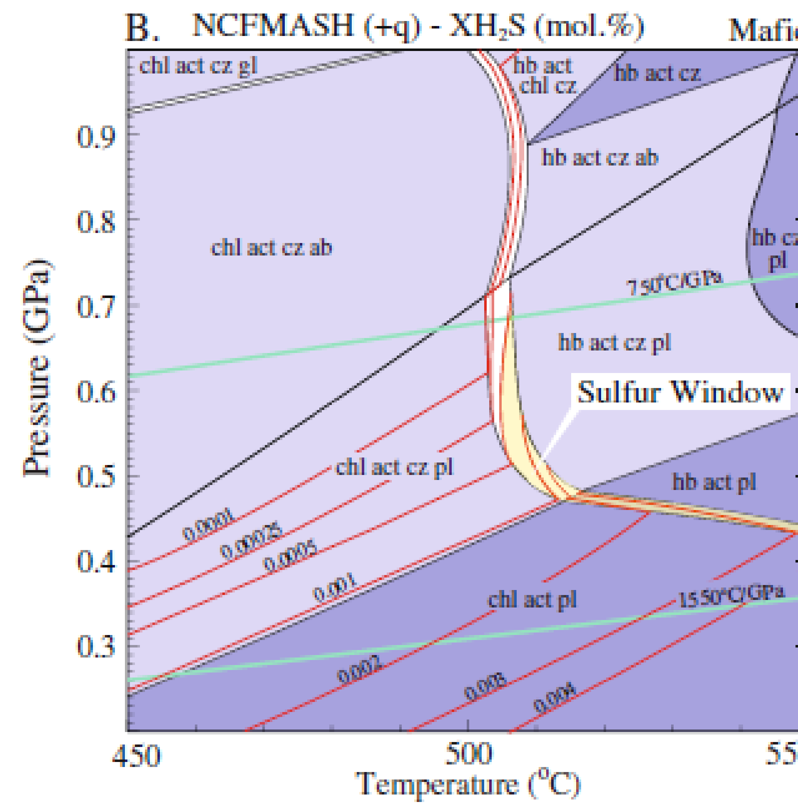


3 … $+12Ca_2Al_3Si_3O_{12}(OH)$ (Al-Ep) +

2 … $)_2$ (Tschermakitic Hbl) +

4

Mafic



C

(

2

F

F

$2FeS_2 + 2H_2O + C = CO_2 + 2H_2S +$ …

$4FeS_2 + CH_4 + 2H_2O = 4FeS + 4H_2S$ …

$4FeS_2 + 3CO_2 + CH_4 + 6H_2O = 4FeC$ …

Tomkins (2010, *GCA*)

Accepted model with exploration implications

- Metamorphic devolatization of greenstone pile

- Maximum H_2O released at greenschist-amphibolite facies boundary by terminal breakdown of chlorite at 550–600 °C/ 5 kbar)

- Explains observed low salinity H_2O-NaCl-CO_2±CH_4-$Au(HS)_2^-$ fluid

- Cupled with pyrite desulfidation generating S-rich fluid ← $Au(HS)_2^-$ complexing

- Pyrite acts as source of S and Au

- Gold-only deposits are expected to occur in the greenschist facies greentones

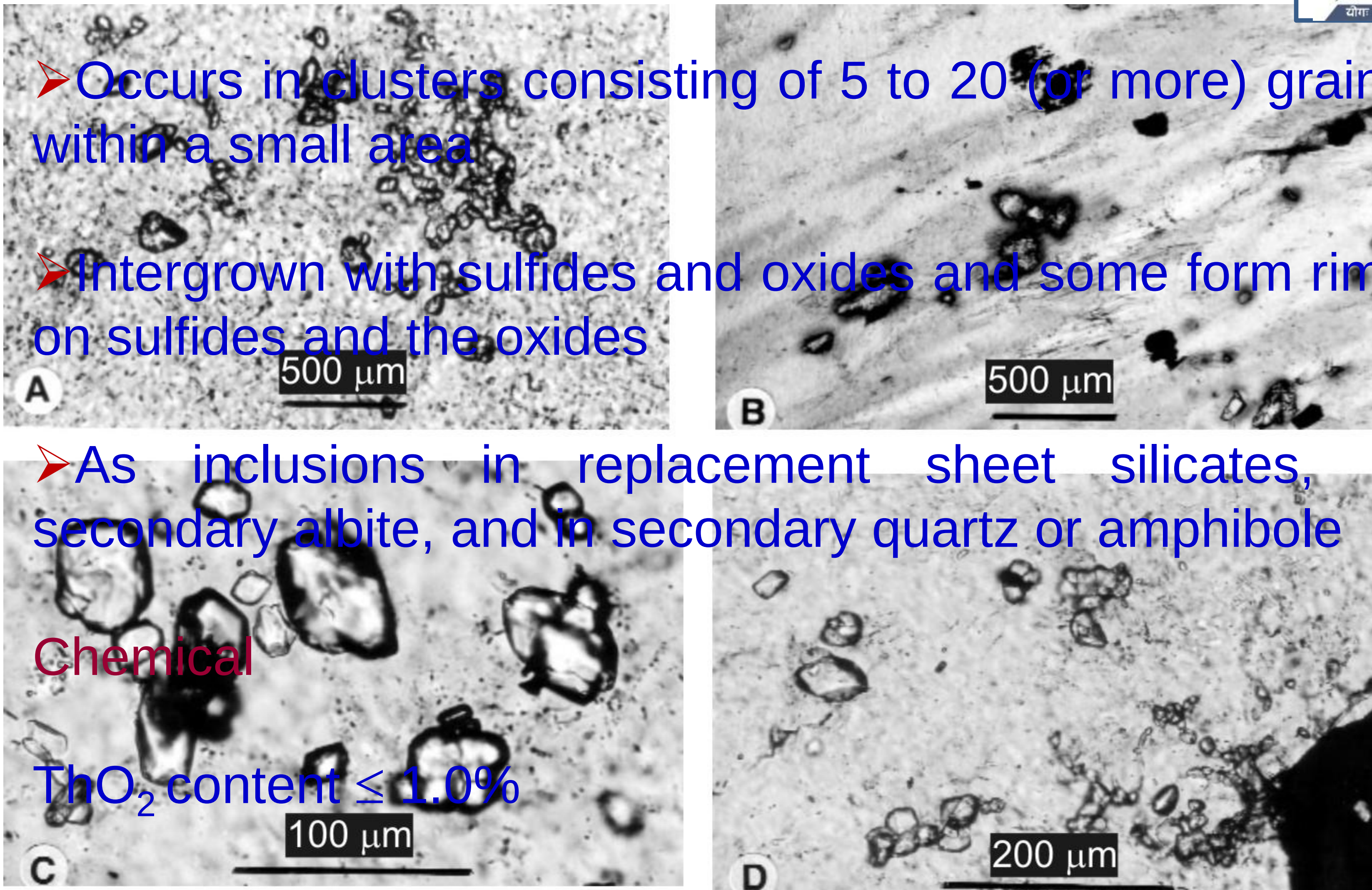
Scopes for future research

Timing of mineralization/hydrothermal alteration

- Rb-Sr in biotite and whole rock from hydrothermal zones (TIMS)
- Sm-Nd in scheelite (TIMS/ HR-MC-ICP-MS)
- Re-Os in sulfides (complicated chemistry)
- Fluid source characterization by $^{87}Sr/^{86}Sr$ and $\delta^{11}B$ in tourmaline (HR-MC-ICP-MS)
- Thermodynamic evaluation of fluid CO_2 by construction of isobaric T-X_{CO2} psedosections of the hydrothermally altered host rock (Elmer et al, 2007, *Econ Geol)*

Hydrothermal monazites: textural and chemical criteria

Textural:



- Occurs in clusters consisting of 5 to 20 (or more) grains within a small area

- Intergrown with sulfides and oxides and some form rims on sulfides and the oxides

- As inclusions in replacement sheet silicates, in secondary albite, and in secondary quartz or amphibole

Chemical

ThO_2 content ≤ 1.0%

(Schandl & Gorton, 2004, *Econ Geol*)

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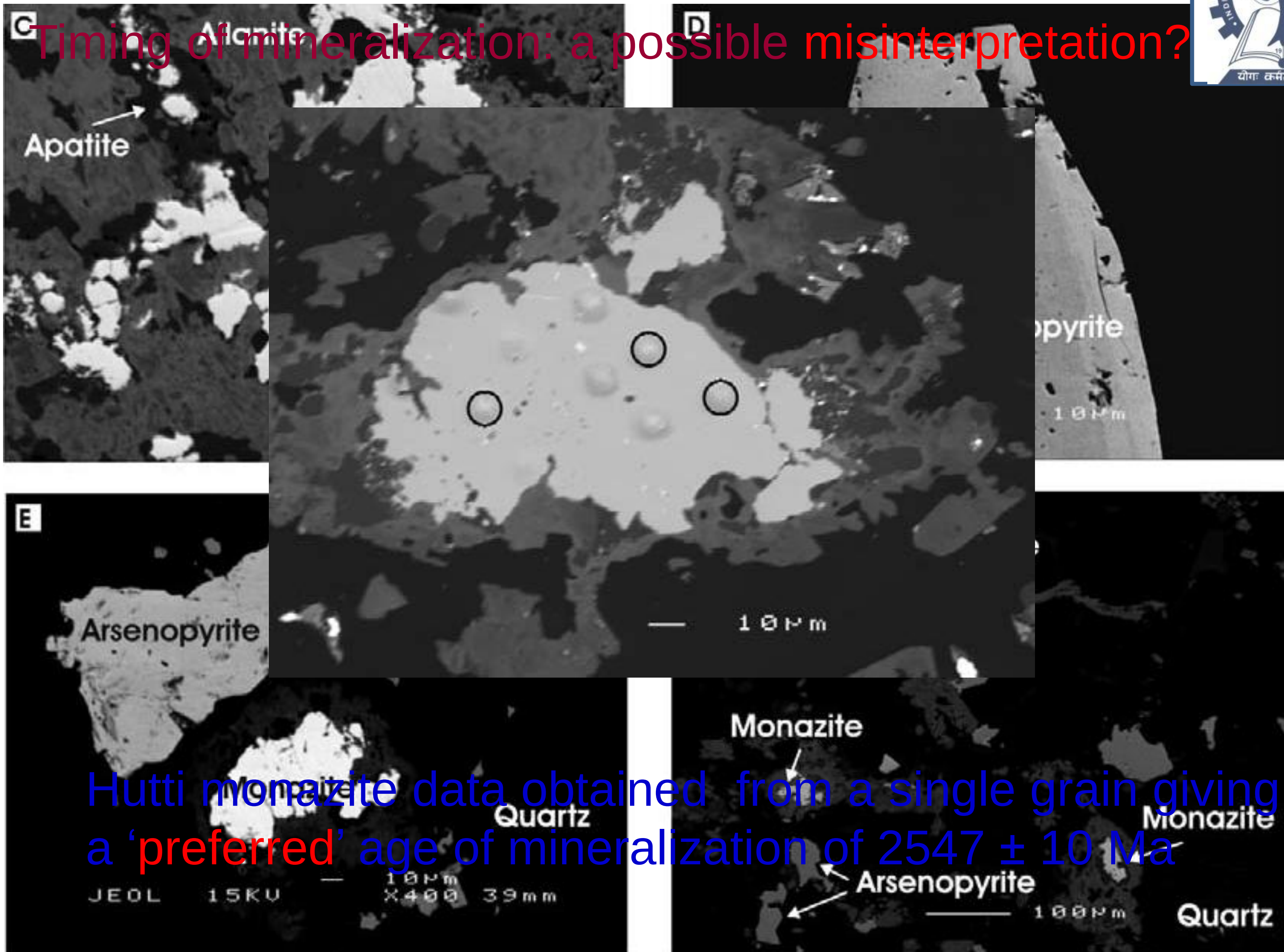
But there are monazite clusters as well!

Timing of mineralization: a possible misinterpretation?



Hutti monazite data obtained from a single grain giving a ‘preferred’ age of mineralization of 2547 ± 10 Ma

Acknowledgements

- DST (3 … HPA project (2008) to … SX-100 and JEOL JSM…
- IIT Kgp f…
- Rupam a… nt sections
- Saptarsh…
- D. Upad… n for many discussion…
- My former students, Nabarun (Pal), Ranjan (Roy), Amit (Basu Sarbadhikari), Sakthi (Saravanan Chinnasamy), and presently Pranjit (Hazarika) who taught me to think more about the gold ores

Its only words and words all that I have