The Source and timing of Gold in Orogenic Gold Deposits;

A Case Study from the Giant Sukhoi Log Sediment-Hosted Deposit in Siberia

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We are in for a Revolution in Gold Ore Genesis Theory

At Last we have a Technique to Place Gold into the Paragenesis of Orogenic Gold Deposits

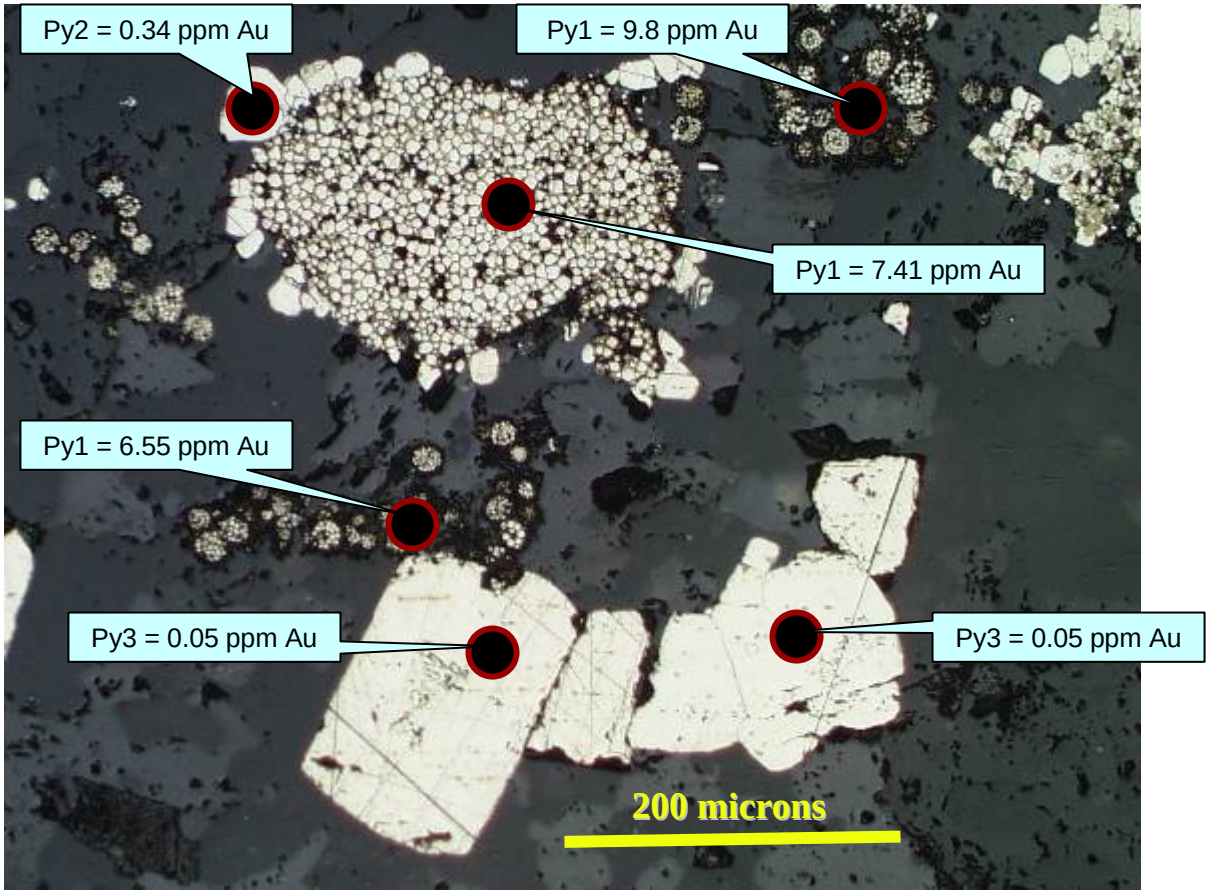
The Technique?

Laser Ablation-Q-ICPMS

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

The Technique?

Laser Ablation-Q-ICPMS



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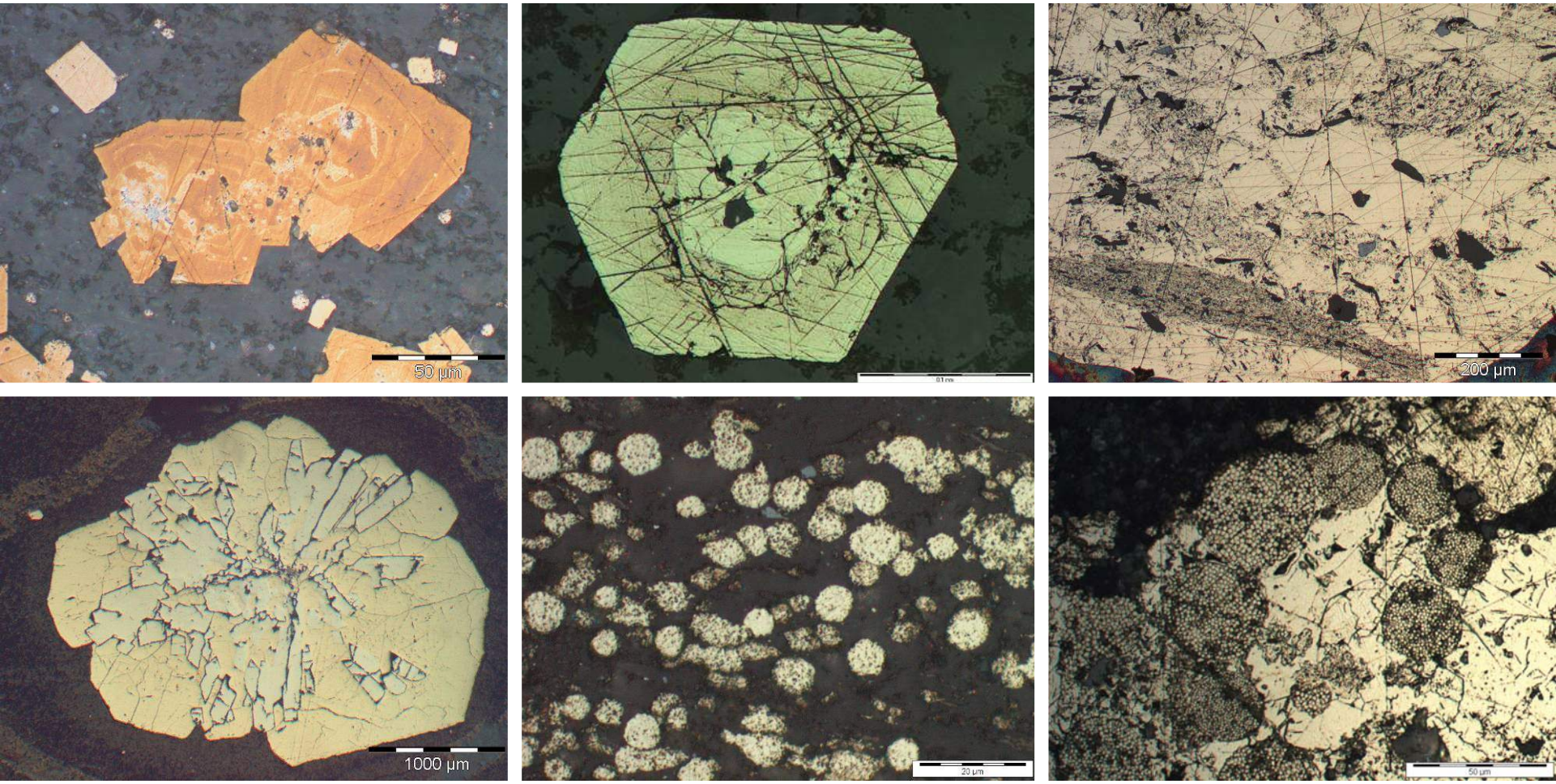
INTRODUCTION



Robert Scott, Ross Large, Stuart Bull
(CODES, University of Tasmania)

- Project Sponsors
  - Barrick , Newcrest, Newmont, Perseverance, St Barbara

Photo: Dark arsenian pyrite (<933 ppm Au) rims earlier formed diageneticor hydrothermal pyrite nodule, Roberts Mtn Fmn, Gold Quarry, Northern Carlin Trend, Nevada

AMIRA P923: STUDY AREAS

Three world-class sediment-hosted gold districts hosting deposits of contrasting style

- Carlin District, NE Nevada (50 %)
  - Periphery and host-rocks to Post-Betze-Screamer deposit (>38.6 Moz), Gold Quarry (~24 Moz)
- Central Victoria – NE Tasmania (25 %)
  - Fosterville (>1 Moz), Bendigo (>34 Moz), *Tarnagulla (0.56 Moz),* Lefroy (~0.23 Moz, historical)
- Lena Goldfield, Siberia (25 %)
  - Sukhoi Log (>46 Moz)

Challenge to Current Beliefs
Related to Orogenic Gold Deposits

Belief 1: “Gold is coming from some deep source or from crustal granites”

NO……..

Gold is Already Present in the Sedimentary Basin

Belief 2: “Graphitic Sediments are Good Trap Rocks for Gold”

Yes, But……..

Graphitic sediments are
Ideal Source Rocks for Au & As

plus Se, Te, V, Zn, Mo, Ni, PGE…….

Belief 3: “Gold is introduced Late; i.e. Syn-tectonic or Post-tectonic”

NO……..

Gold is Introduced Early;
i.e. Pre-tectonic and Moved Around Late During Tectonism

Multi-stage Origin of Pyrite and Gold in the Giant Sukhoi Log Deposit, Lena Goldfield, Russia

Ross Large, Valeriy Maslennikov, Sarah Gilbert,
Rob Scott, Leonid Danyushevsky and Zhaoshan Chang


NORWAY
SWEDEN
SEA
FINLAND
GERMANY
POLAND
BALTIC
ARCTIC OCEAN
BARENT SEA
KARA SEA
LAPTEV SEA
EAST SIBERIAN SEA
CHUKCHI SEA
ALA
Minsk
BYELORUSSIA
UKRAINE
Kiev
Moscow
Trans
Sverdlovsk
Yenisey River
RUSSIA
Yakutsk
Lena River
SEA OF OKH
BLACK SEA
GEORGIA
ARMENIA
AZERBAIJAN
CASPIAN SEA
Siberia
Novosibirsk
Krasnoyarsk
Kirensk
BODAIBO
PROJECT AREA
Bam Railway
Tayshet
Bratsk
Ust-Kut
Irkutsk
Chita
Railway
Khabarovsk
KAZAKHSTAN
Karaganda
TURKMENISTAN
UZBEKISTAN
Taskent
Alma Ata
TAJISTAN
KIRGHIZIA
IRAN
AFGHANIS
CHINA
MONGOLIA
Vladivostok
NORTH KOREA
(A)

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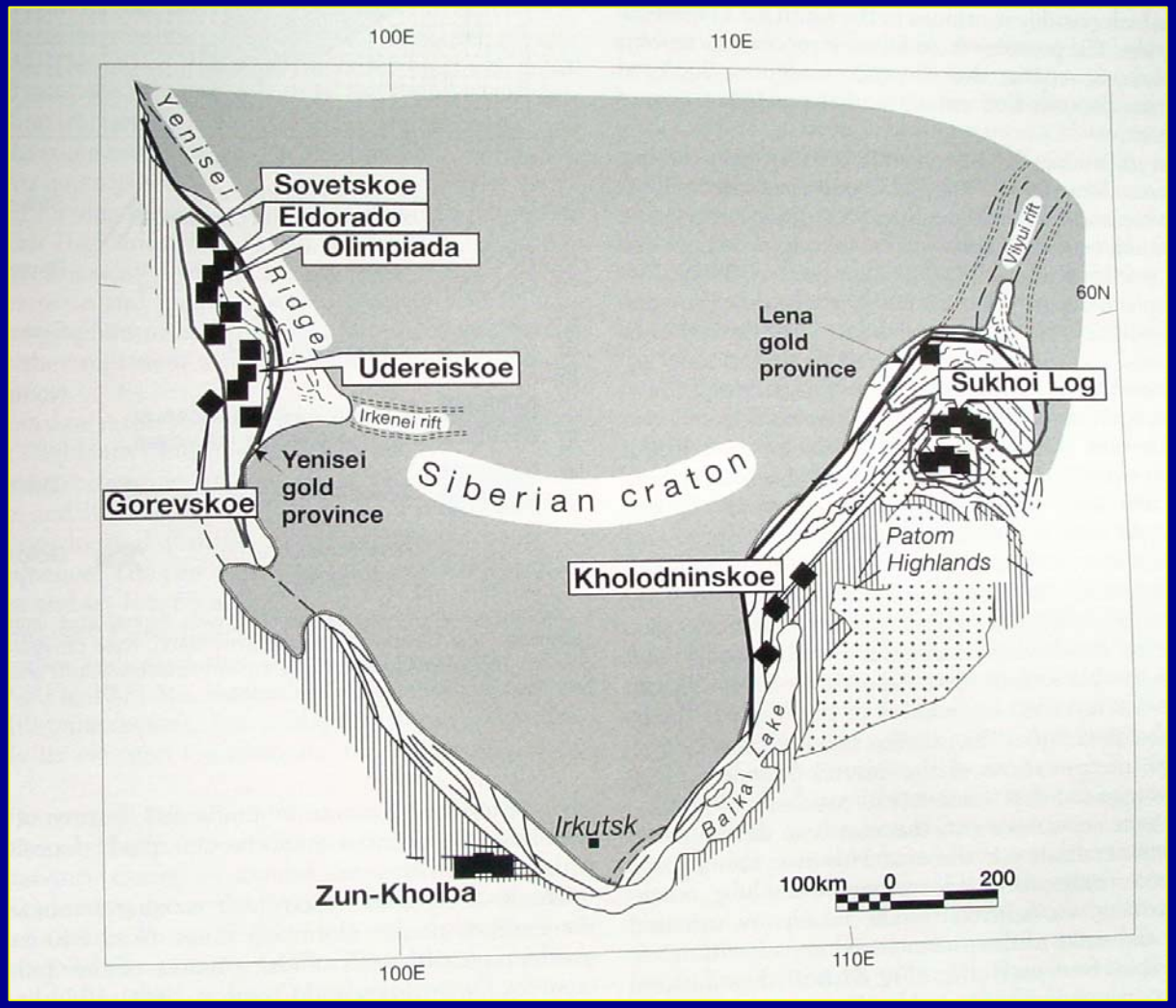
Major Gold Deposits around Siberian Craton



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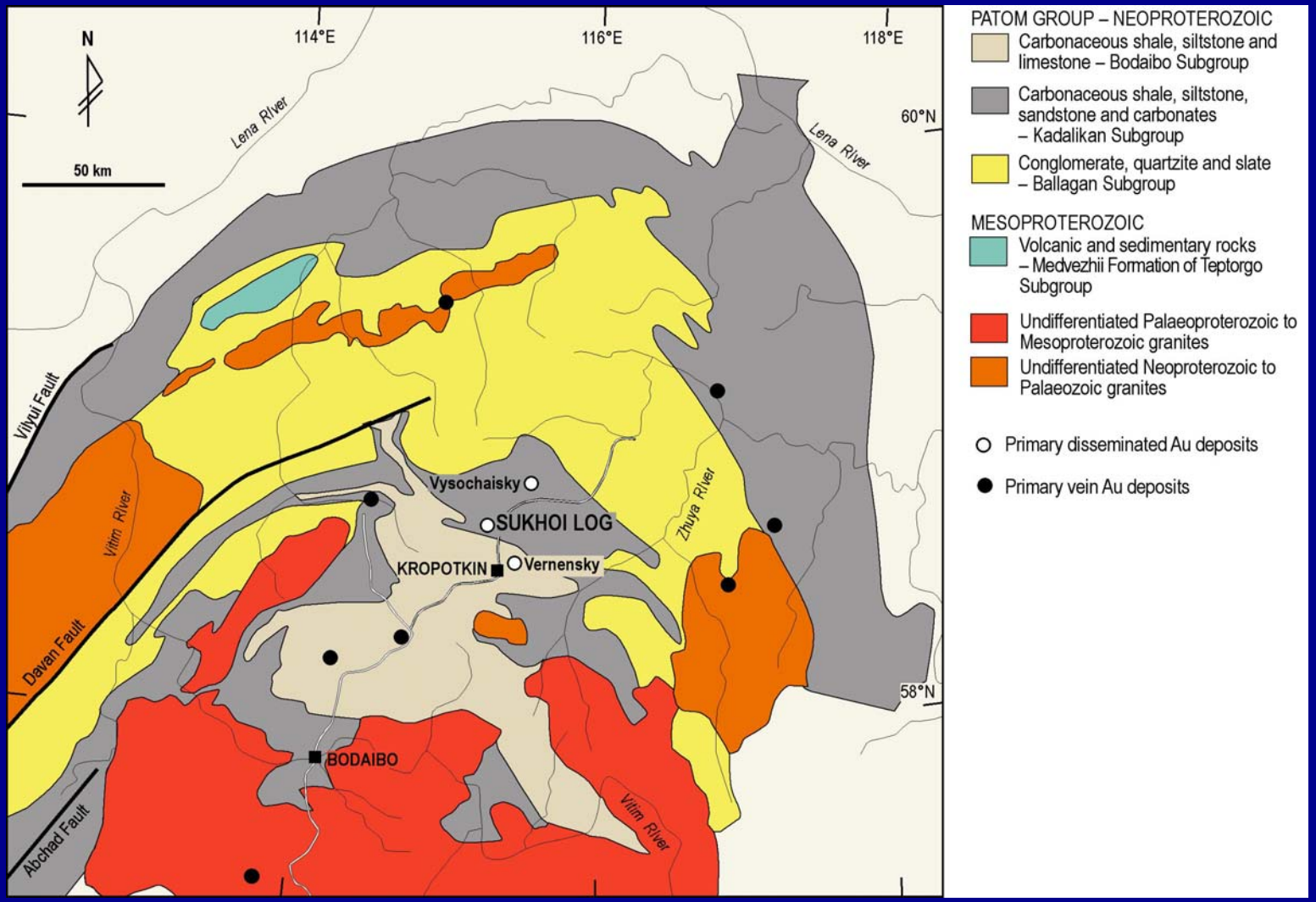
Regional Geology



Sukhoi Log: Resource

- Sukhoi Log is a giant low grade sediment-hosted gold deposit
- Open Pit resource: 384 Mt @ 2.6 g/t Au

Geological plan and Cross Section

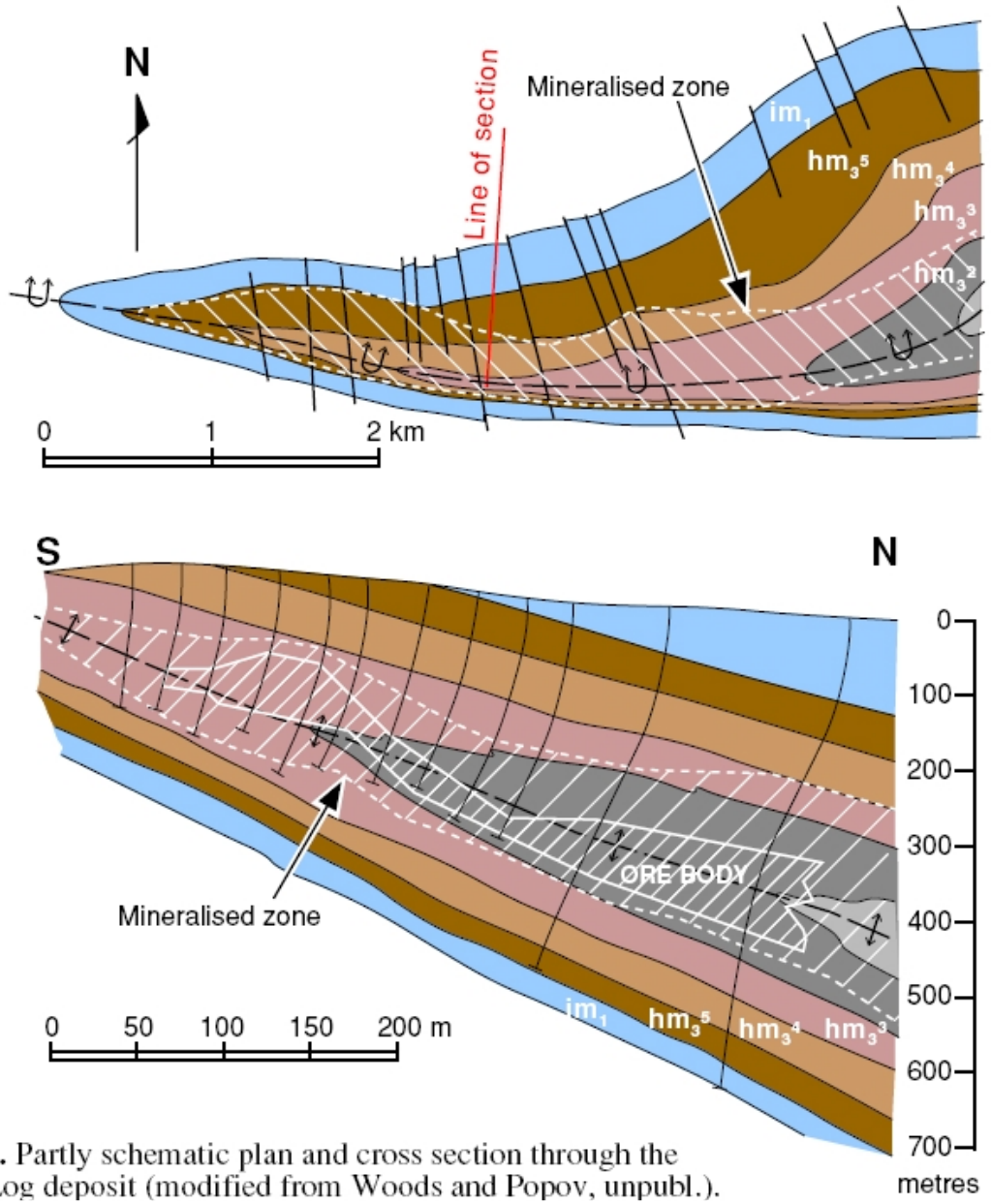
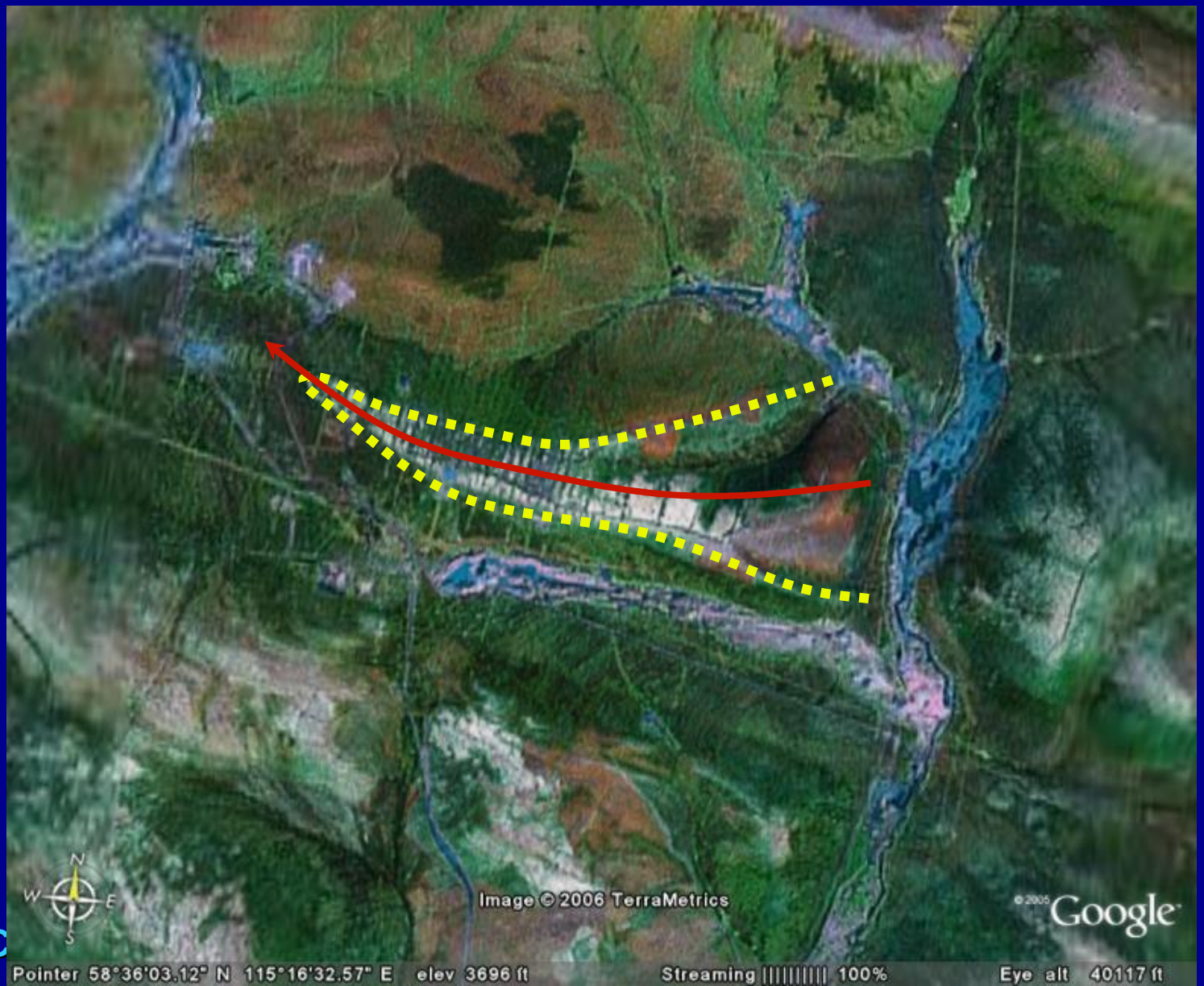


Figure 3. Partly schematic plan and cross section through the Sukhoi Log deposit (modified from Woods and Popov, unpubl.).

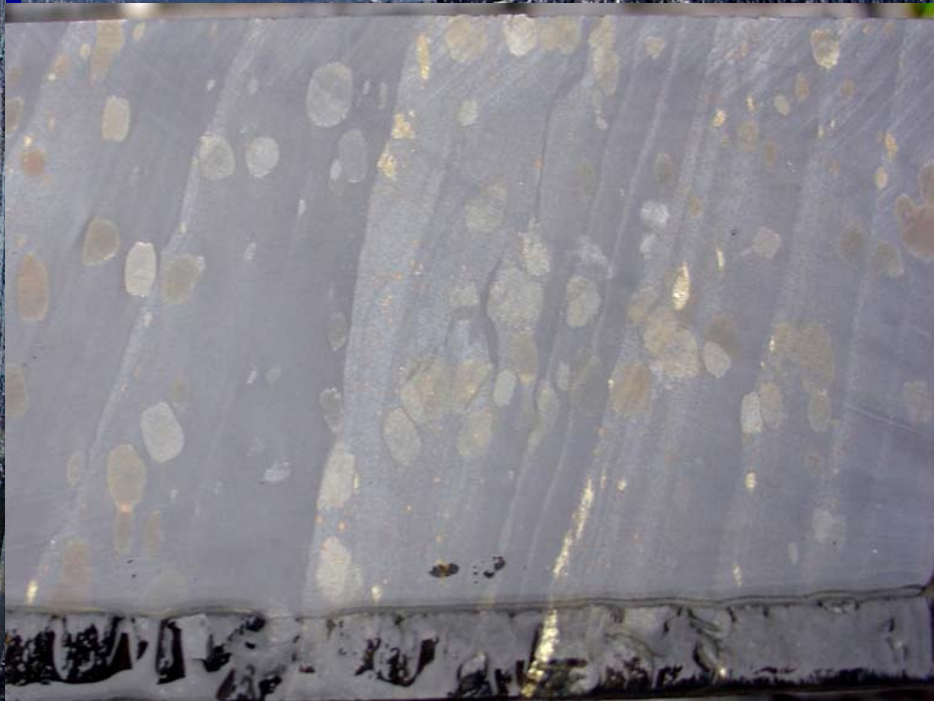
Exploration Grid- Sukhoi Log



Sukhoi Log Ridge

Sukhoi Log Core Shed

Core Layout



Quartz-pyrite veins

Bedding Parallel & Folded

Previous Models

- Orogenic deposit: gold introduced and concentrated during metamorphism (Goldfarb, et al., 2005)
- Intrusion related gold deposit (Distler et al., 2004)
- Syngenetic gold deposit with remobalisation into anticlinal core during metamorphism (Buryak, 1982; Kribek, 1991)
- Three suggested sources of gold: metamorphic fluids, magmatic fluids, exhalation into seawater
- Recent detrital zircon dating in our lab by Sebastian Mefre shows the host sediments have a maximum age of ~600 Ma
- The main metamorphic event has been dated at 520 Ma (Laverov et al., 2000), and emplacement age of local granitoids is around 360 Ma (Rundquist el al., 1992)

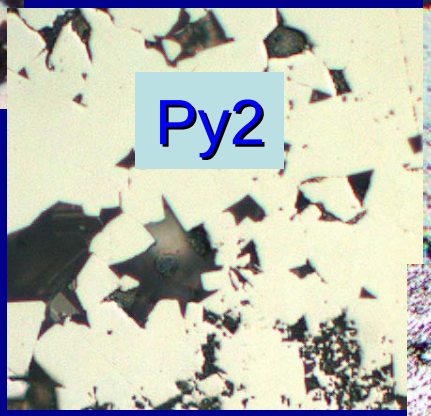
Aims of this phase of the Research

- To determine the sulfide paragenesis at Sukhoi Log
- To determine the gold and trace element contents and associations for the various stages of pyrite
- Was gold introduced during sedimentation & diagenesis, or later during metamorphism and/or granite intrusion, or at several times?

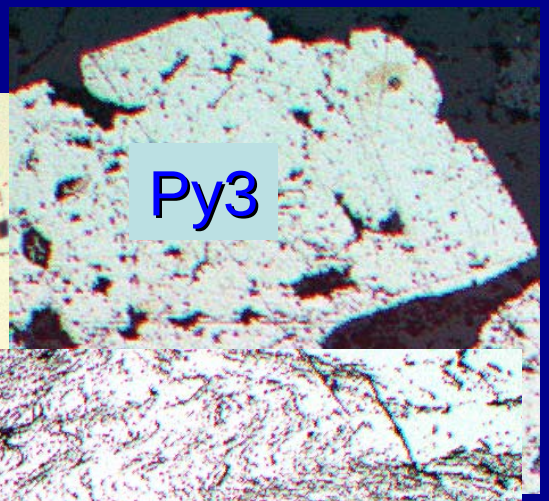
Pyrite History

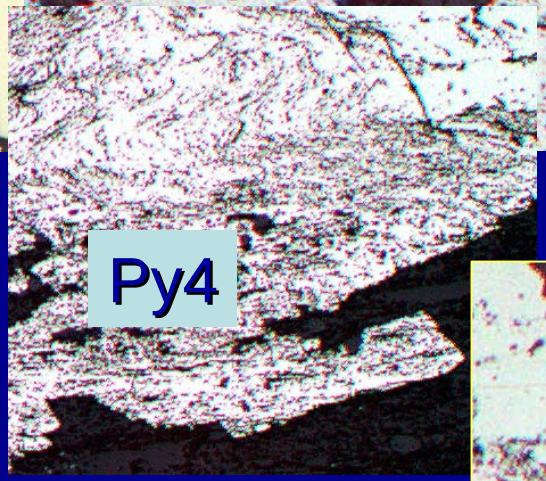
Sedimentary-diagenetic

diagenetic



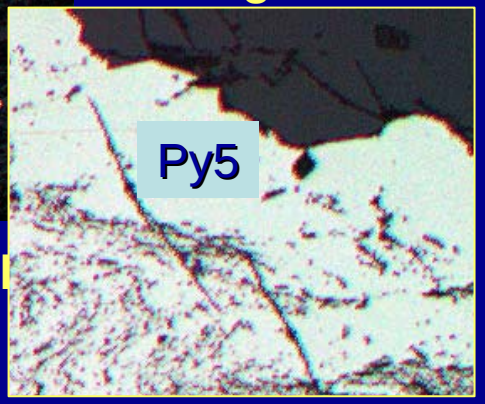
Metamorphic in sst





Metamorphic in shal

Hydrothermal overgrowth



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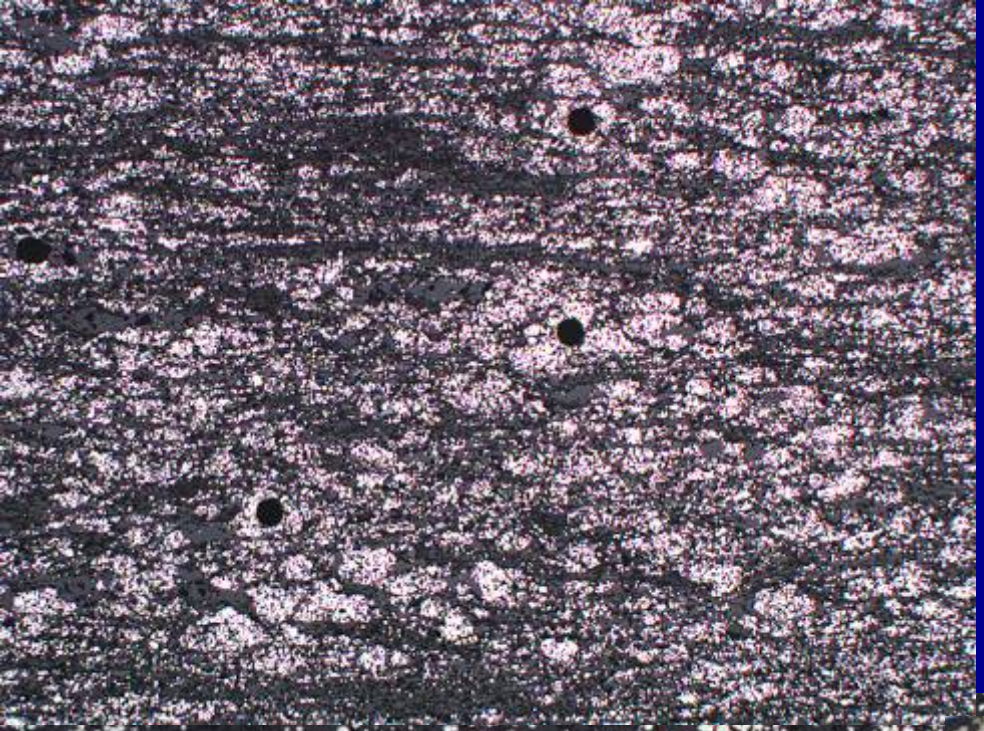
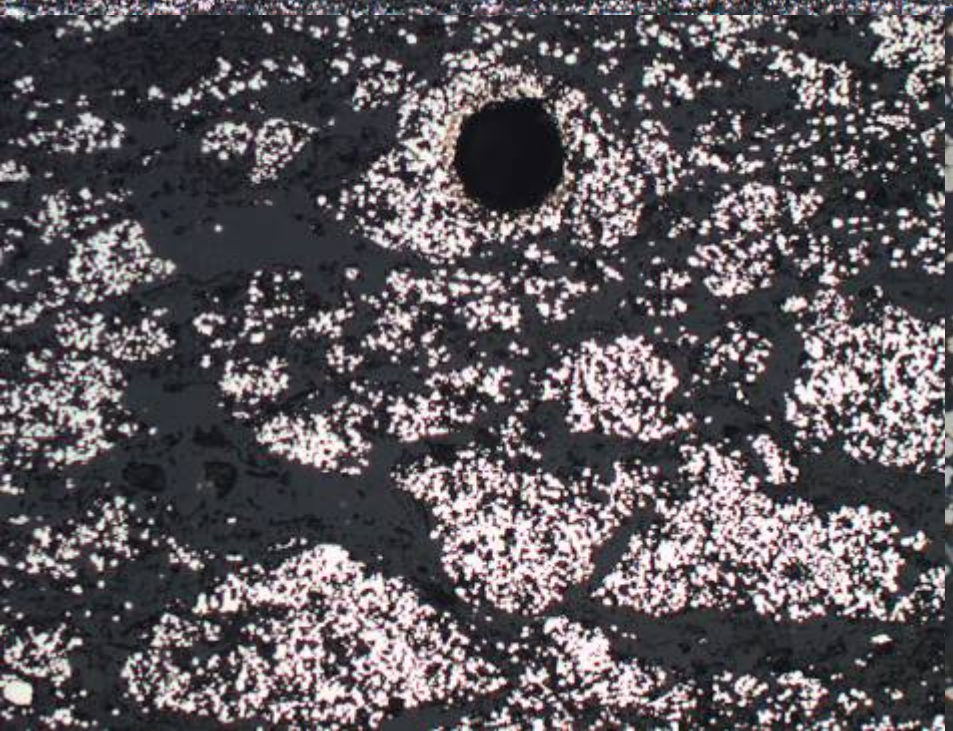
Pyrite 1

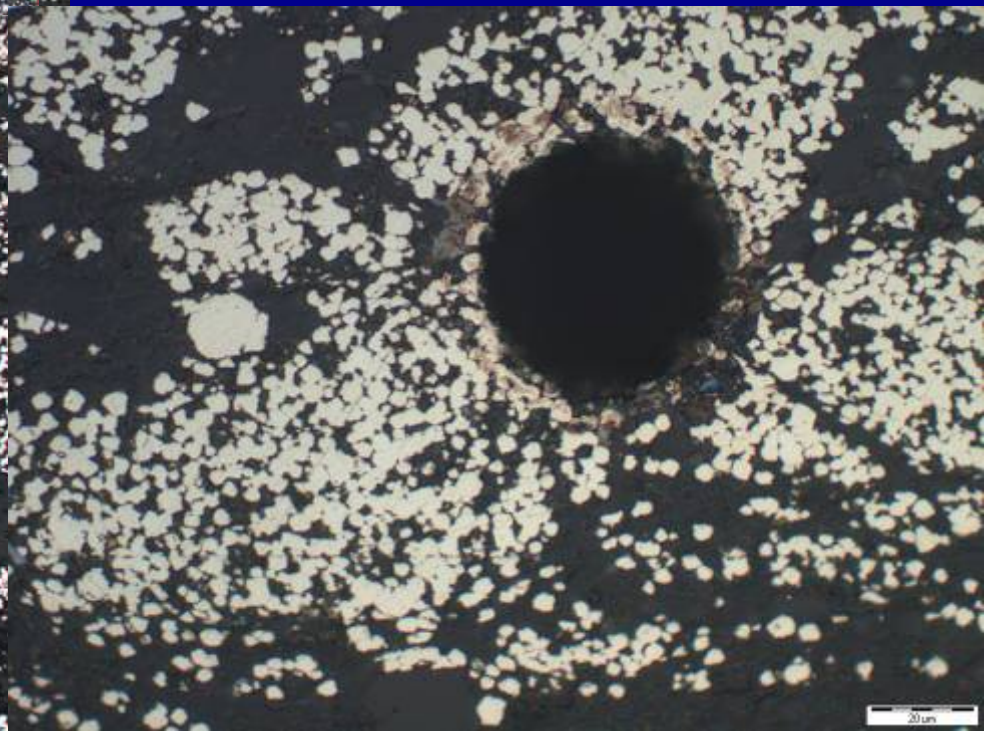
- Fine grained stratiform py
- Three types -
  - micron sized pyrite clusters
  - Framboidal pyrite
  - “sooty” pyrite
- Interpretation: syn-sed. to early diagenetic



. Microtexture of the stratiform Py1;

Clusters of fine 1-2 micron py



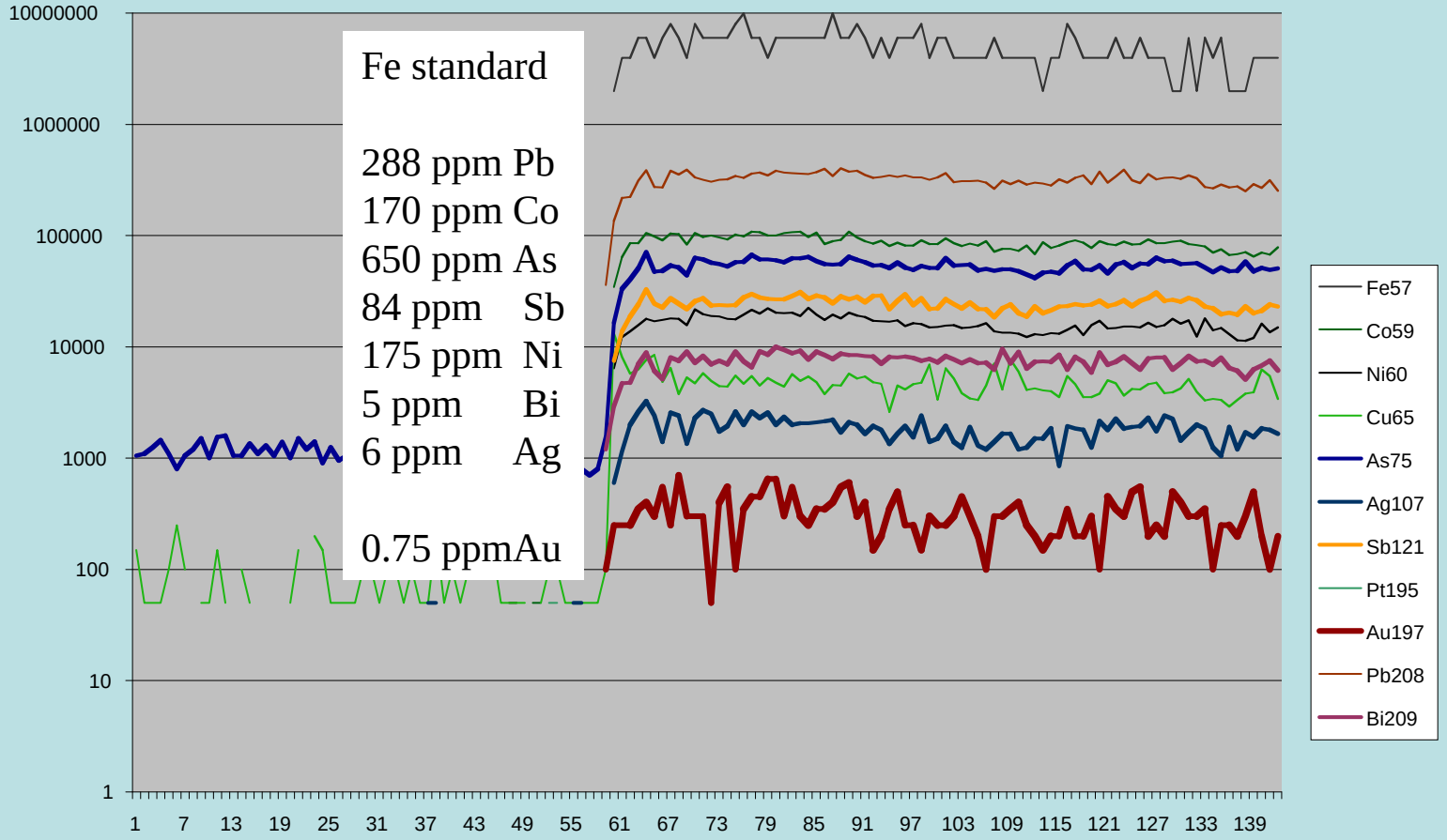


Py1 Chemistry

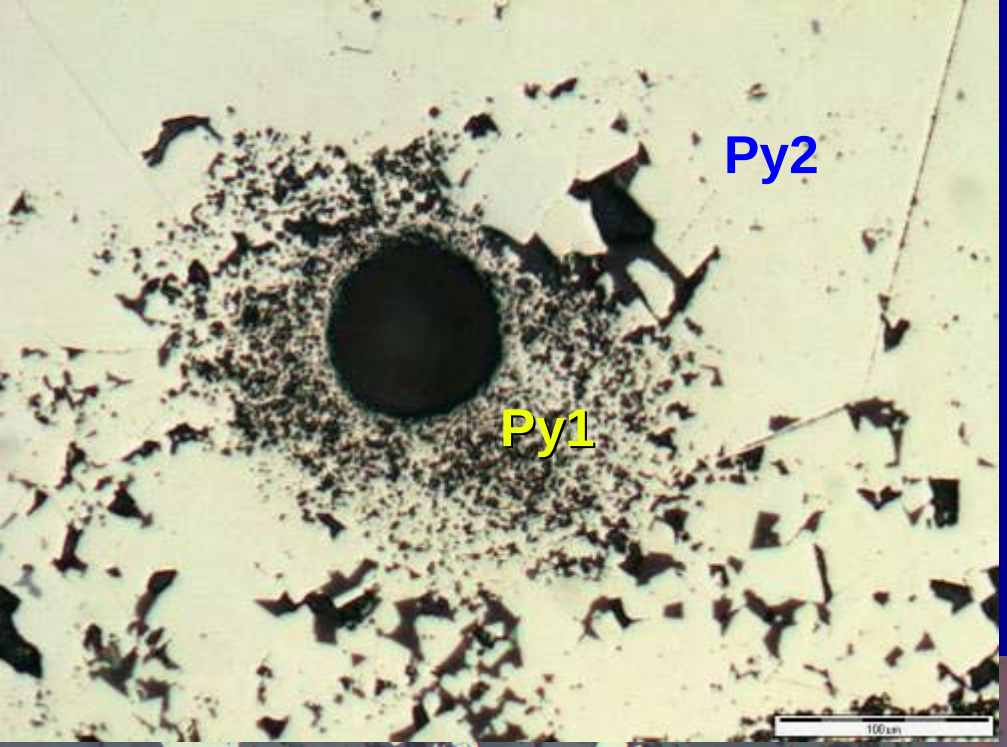
- **Py1 is rich in a wide range of trace elements**
- **Gold content varies from 0.44 to 12.10 ppm; mean = 3.32 ppm Au**
- **Arsenic varies 180 to 14,000 ppm ; mean = 1900 ppm As**
- **Elements which show a positive correlation with Au in Py1; Cu, Ag, Pb, As, Sb, Te**

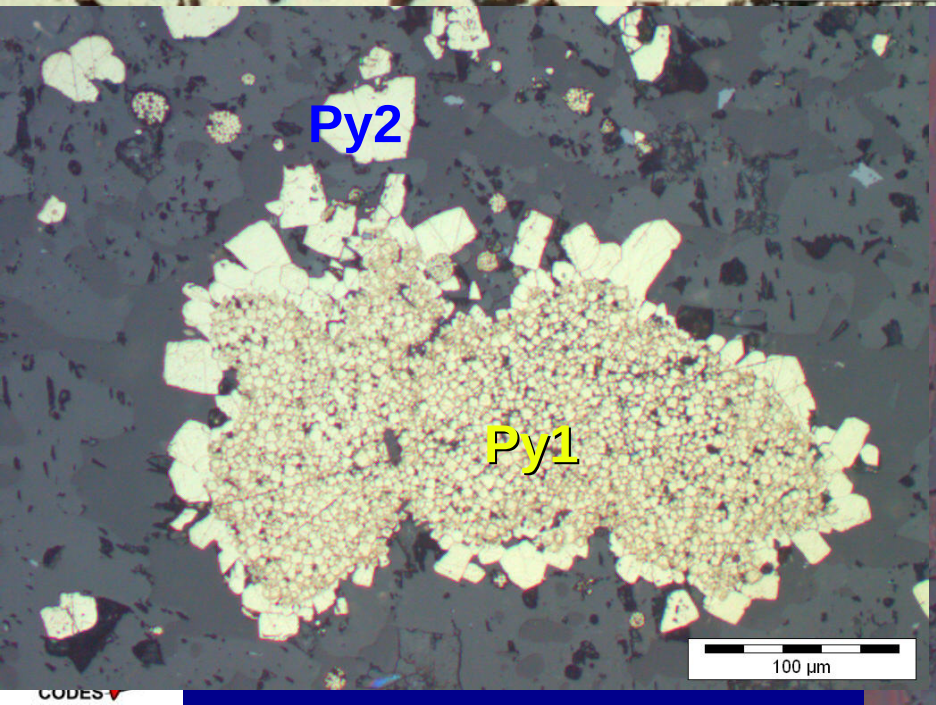
Py1 Chemistry

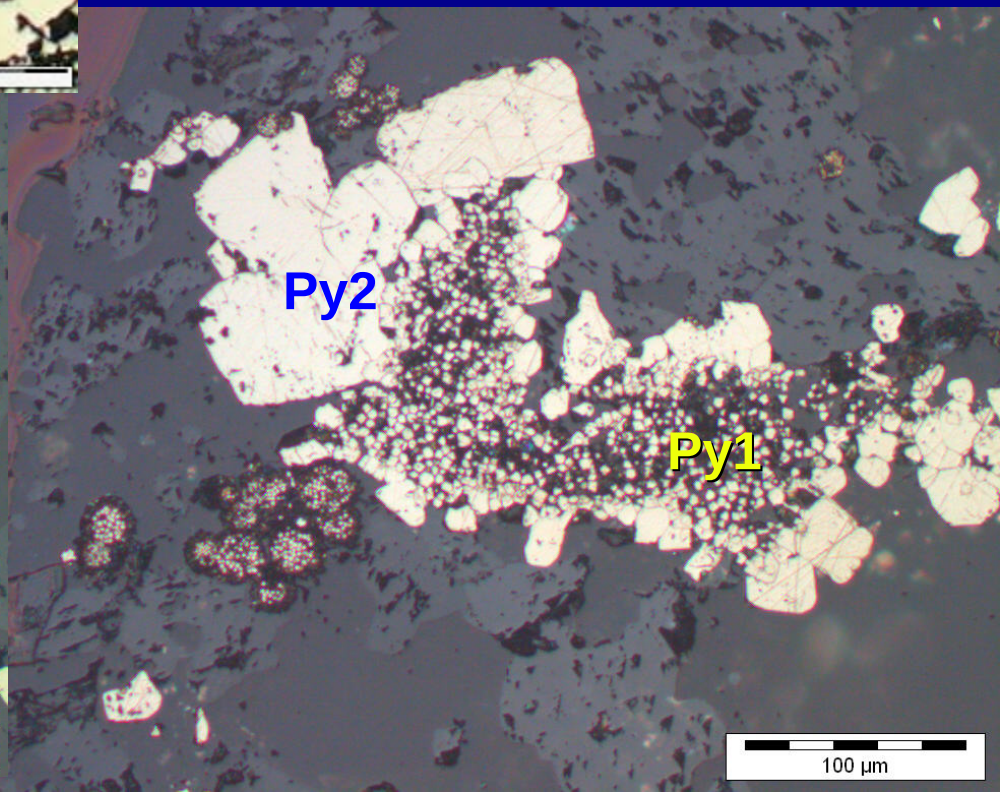
Laser analysis: Fe09A17



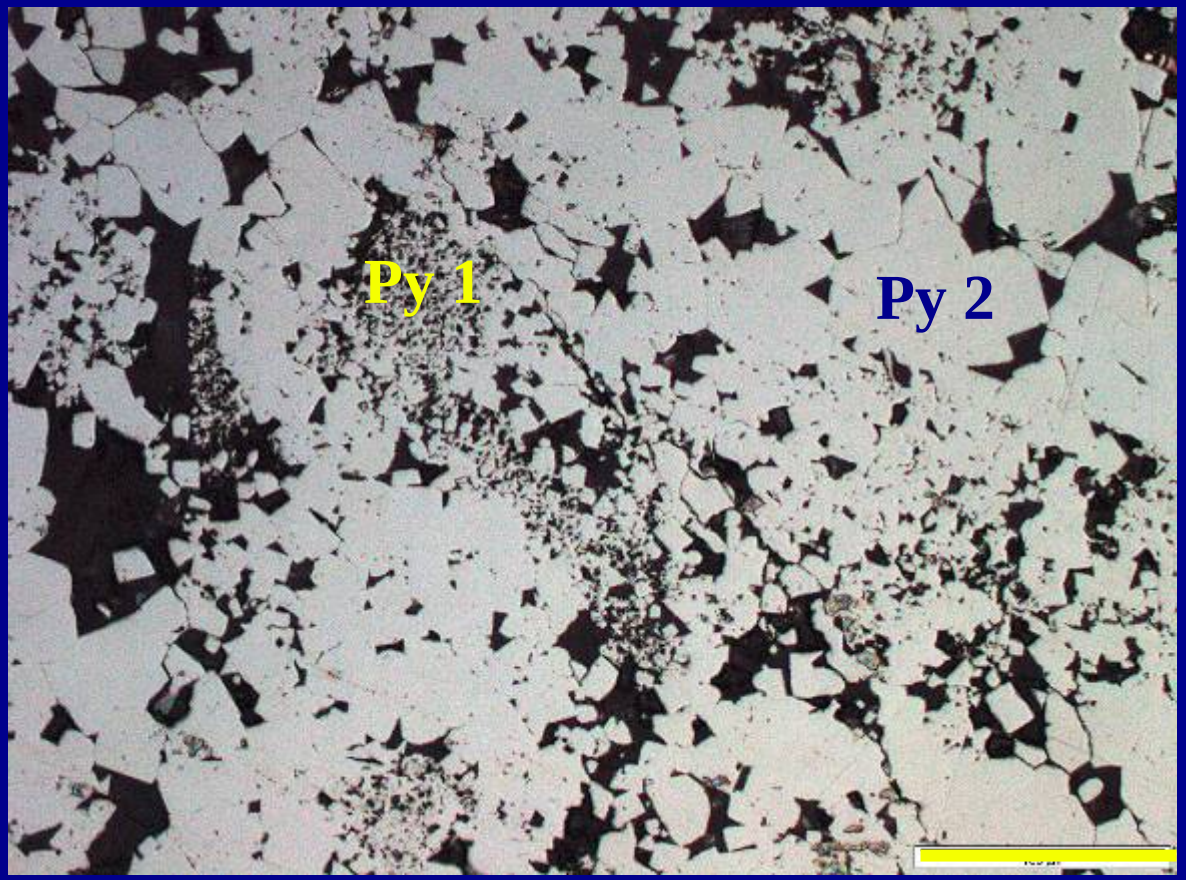
Py2 euhedra overgrow and replace Py1





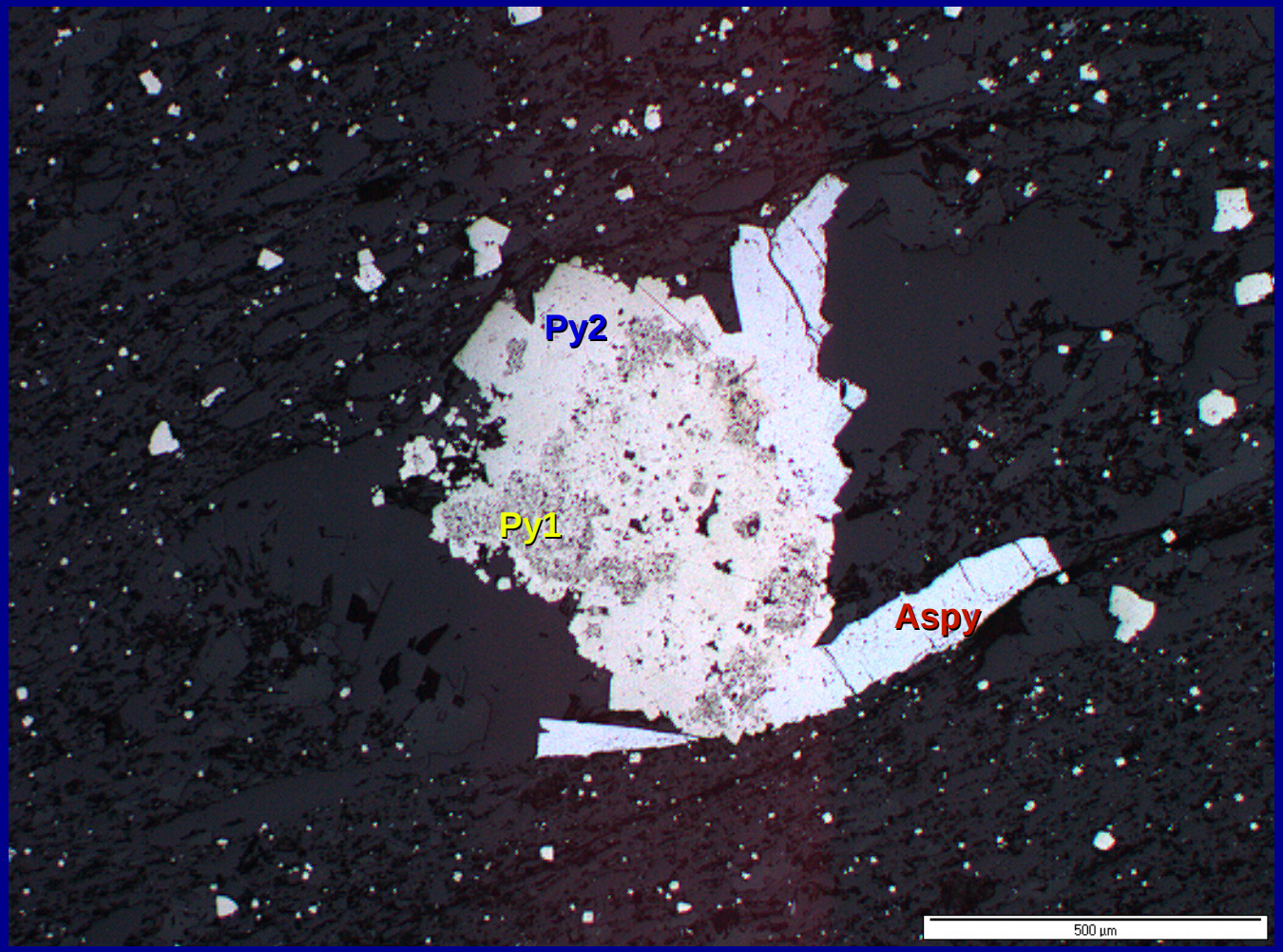


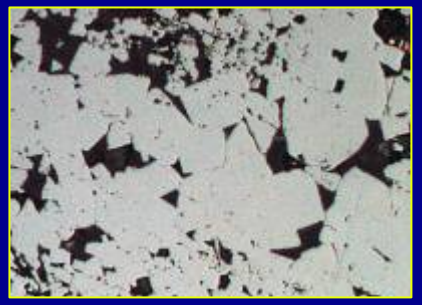
Pyrite 2



- Clear py euhedra
- Overgrows and surrounds py 1
- Interpretation: early diagenetic; may involve recrystallization of pyrite 1

Py1 overgrown by Py2 overgrown by arsenopyrite

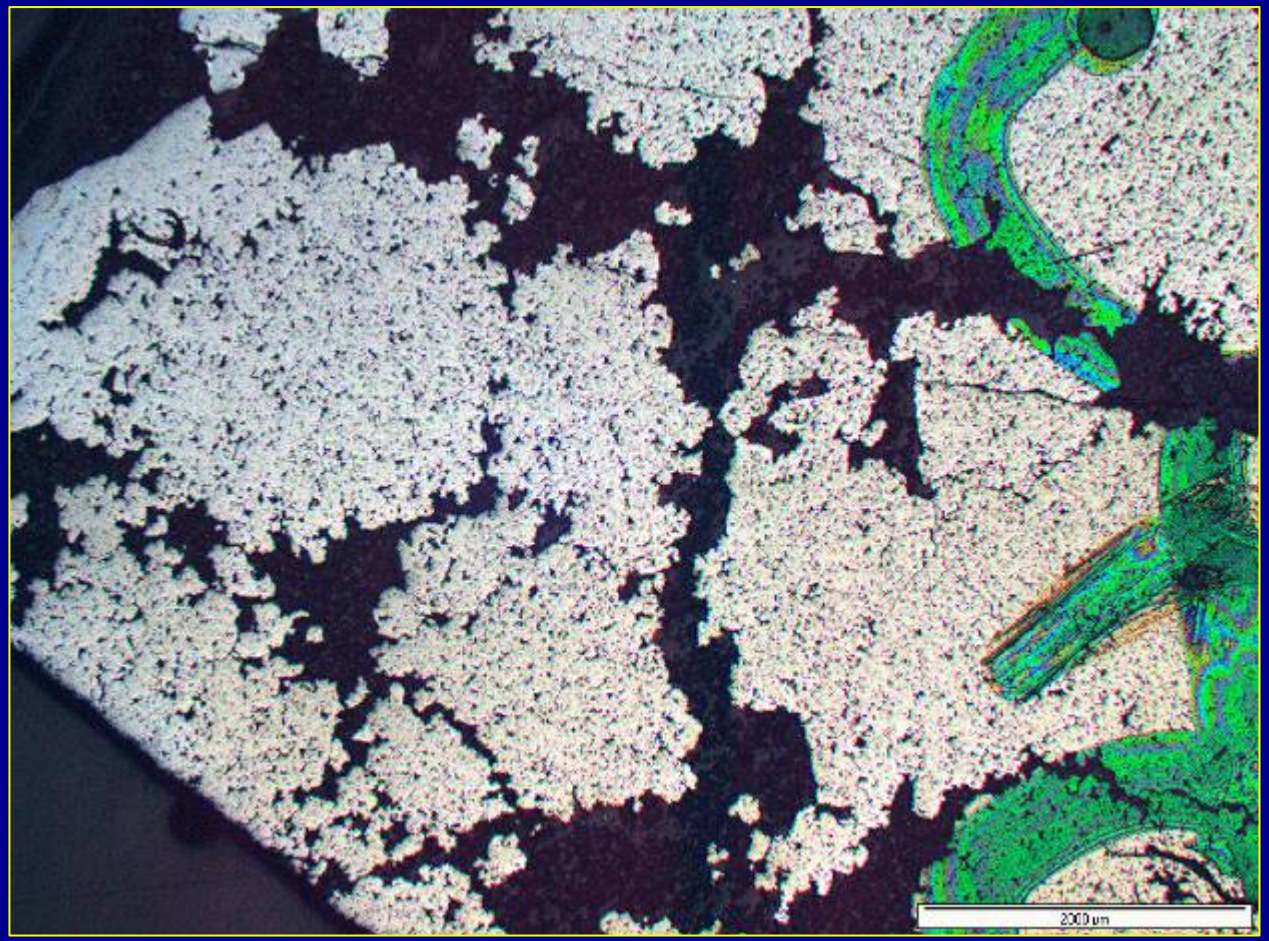




Py2 Chemistry

- **Py2 is depleted in most trace elements compared to Py1; Au, Ag, Cu, Pb, Te, Zn, Sb**
- **As, Ni and Se remain at similar levels to Py1**
- **Gold content varies from 0.02 to 13.00 ppm; mean = 1.02 ppm Au**
- **Arsenic varies 2 to 18,550 ppm ; mean = 4260 ppm As**

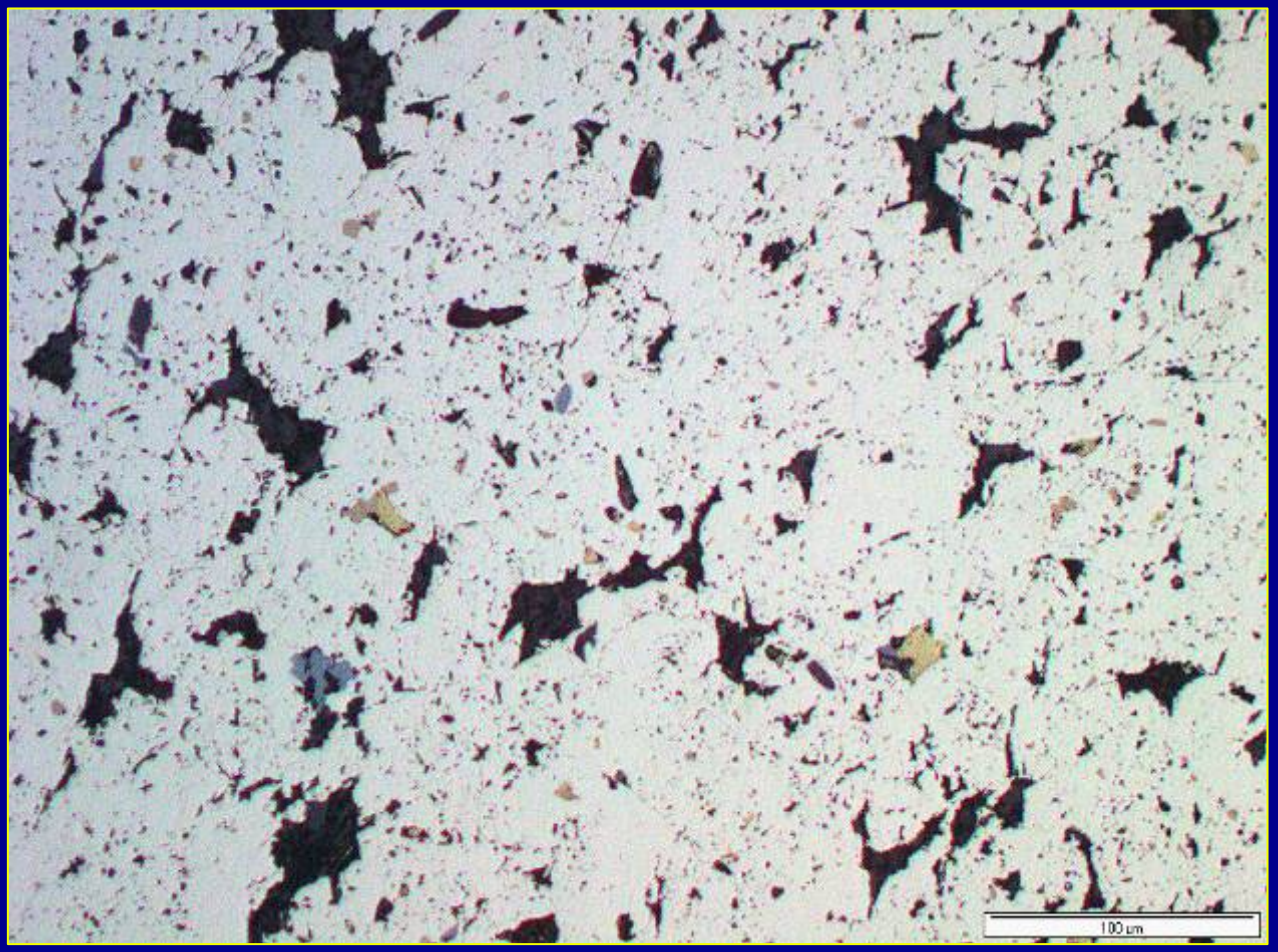
Pyrite 3



- Inclusion rich
- Irregular outlines
- Fluffy or porous texture
- No obvious structural fabric
- Aligned along bedding
- Confined to sandstone layers
- Interpretation: diagenetic or metamorphic??

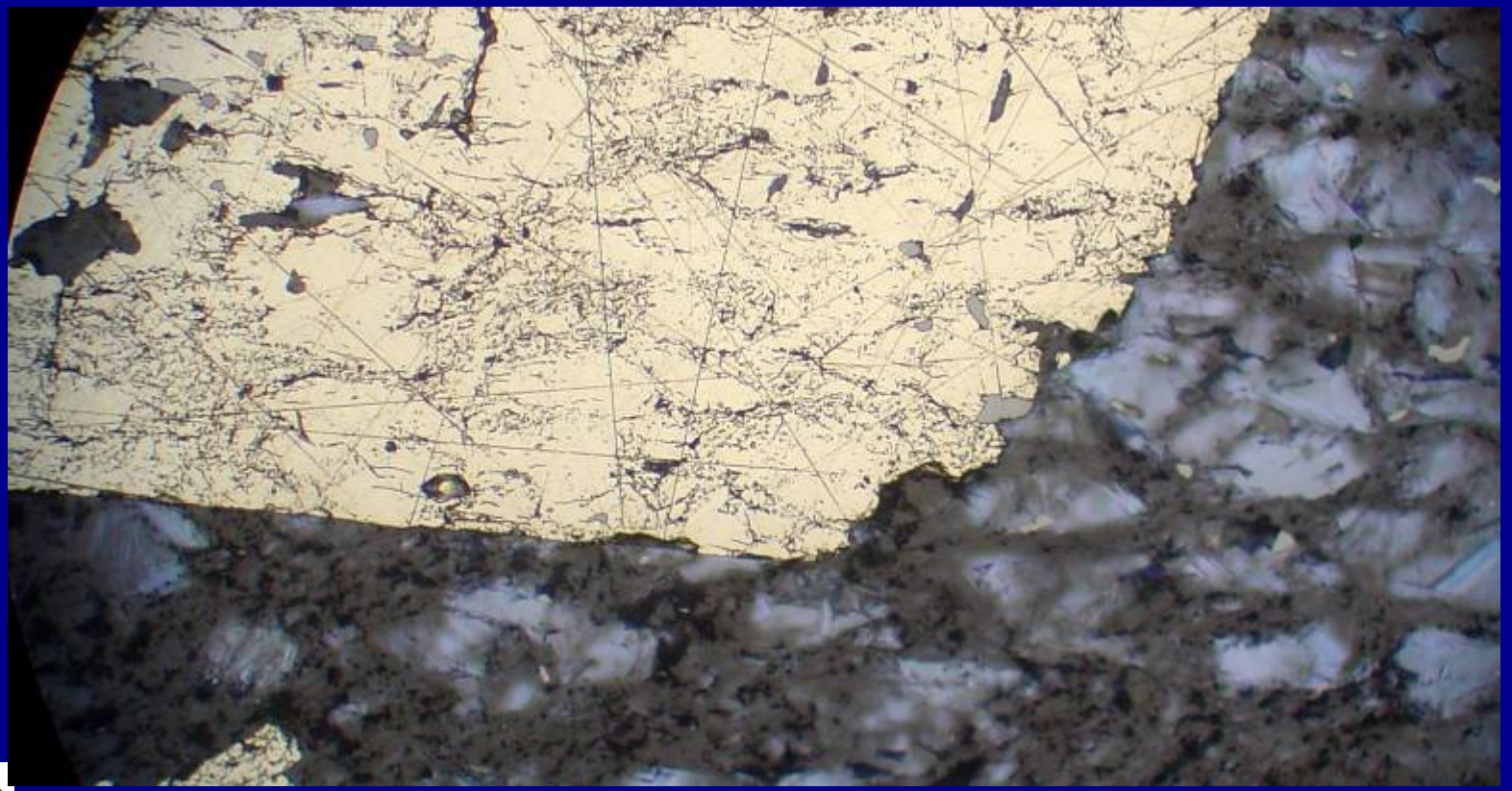
Pyrite 3

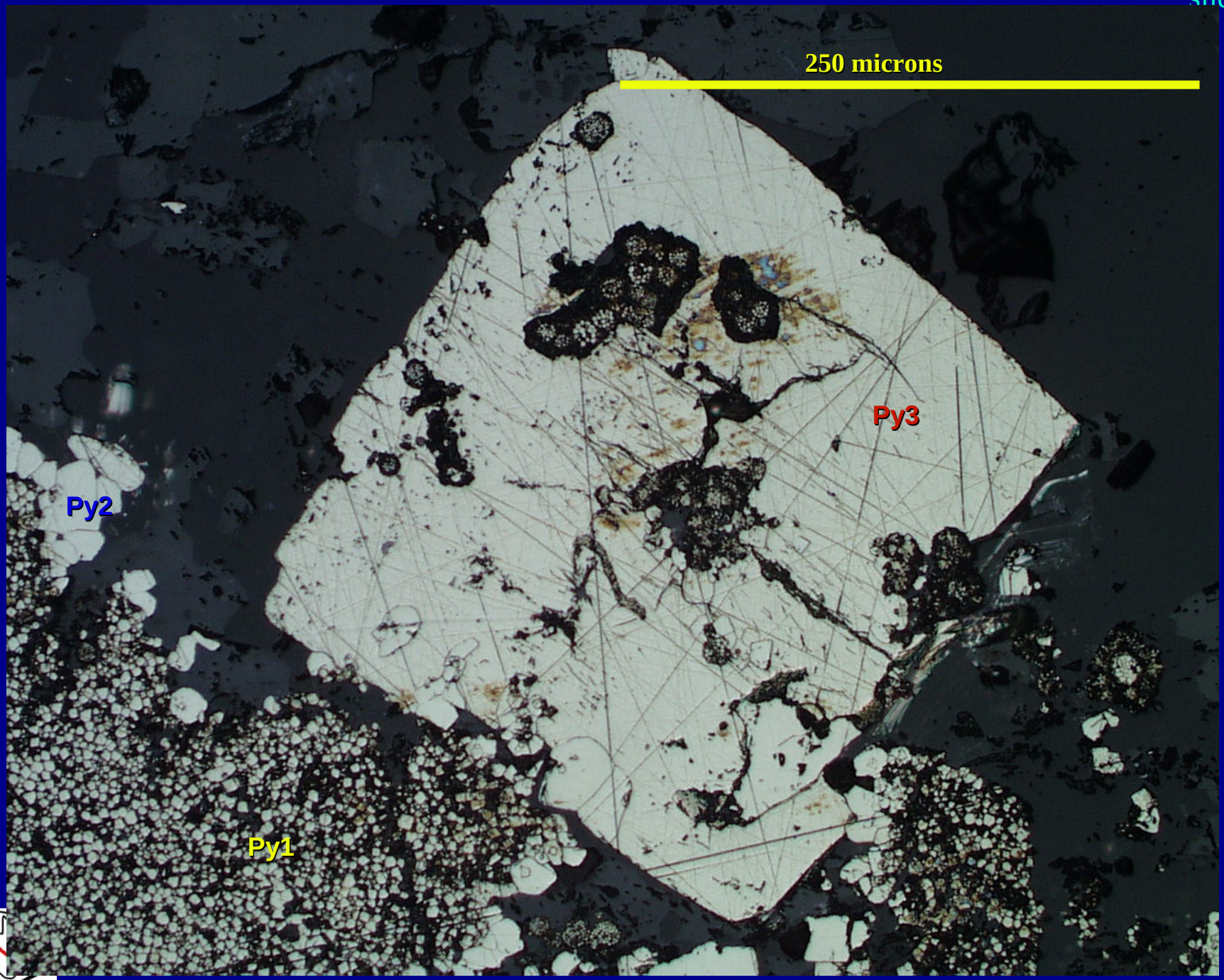
Pyrite 3

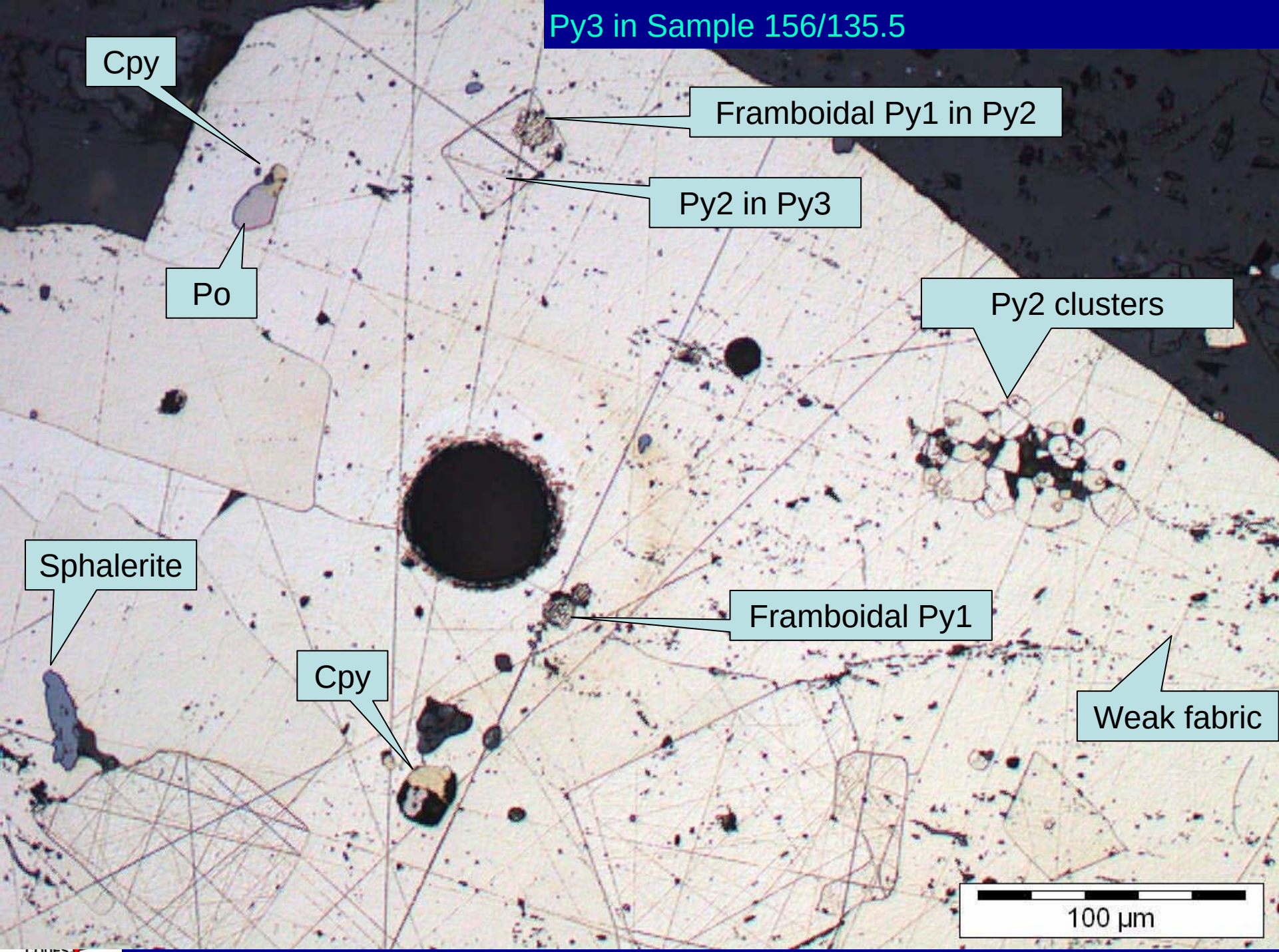


- **inclusions of po, cpy, sp and silicates**
- **no aligned internal fabric**

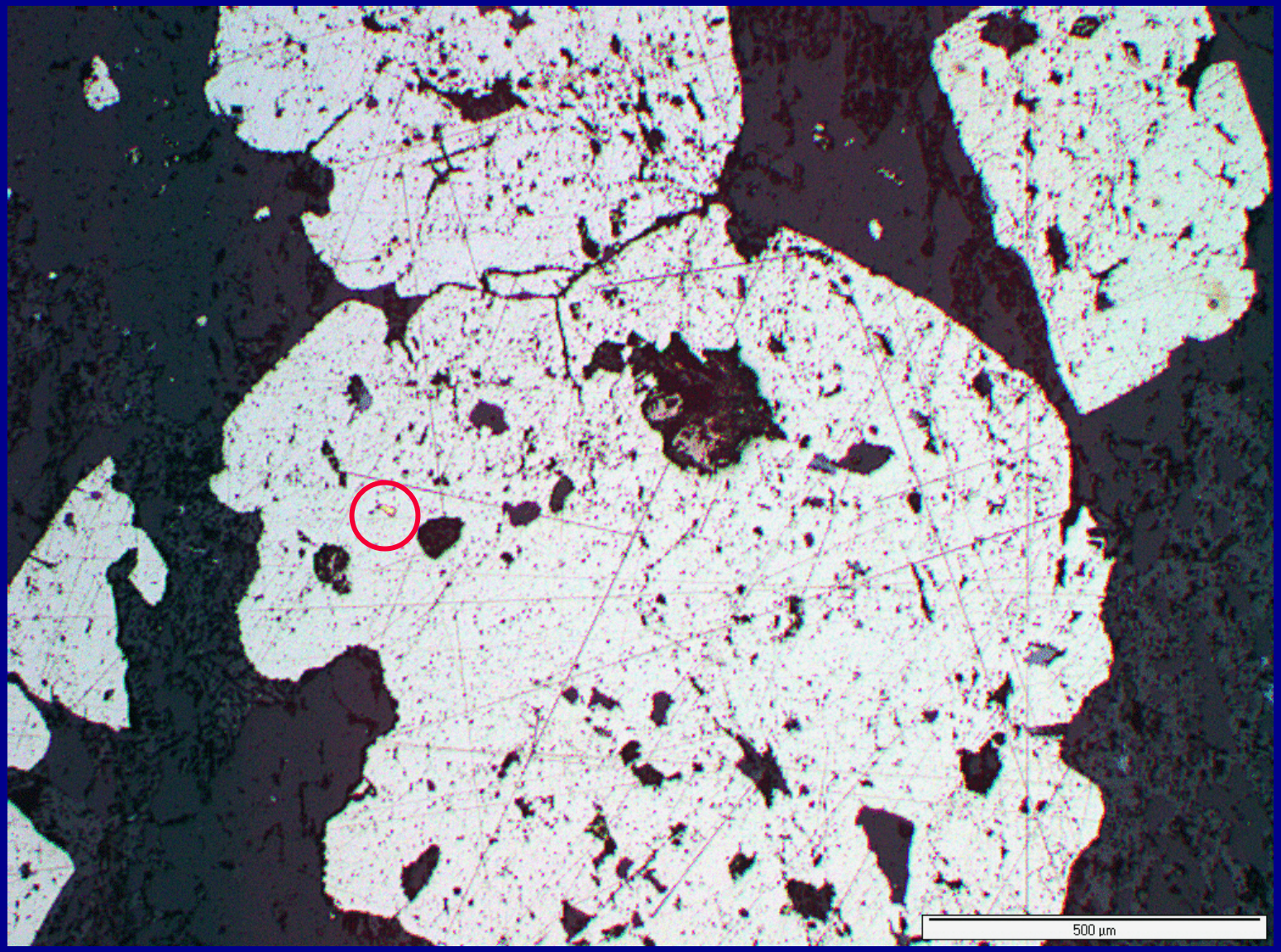
Pyrite 3: internal fabric revealed after etching indicates Py3 most likely has a late diagenetic to early metamorphic timing overprinting a weak D1 sandstone fabric

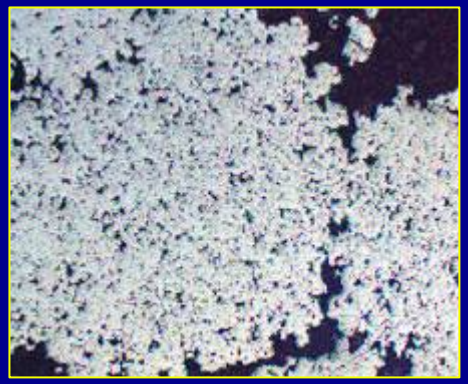



250 microns
Py3
Py2
Py1


Py3 in Sample 156/135.5
Cpy
Framboidal Py1 in Py2
Py2 in Py3
Po
Py2 clusters
Sphalerite
Framboidal Py1
Cpy
Weak fabric
100 µm

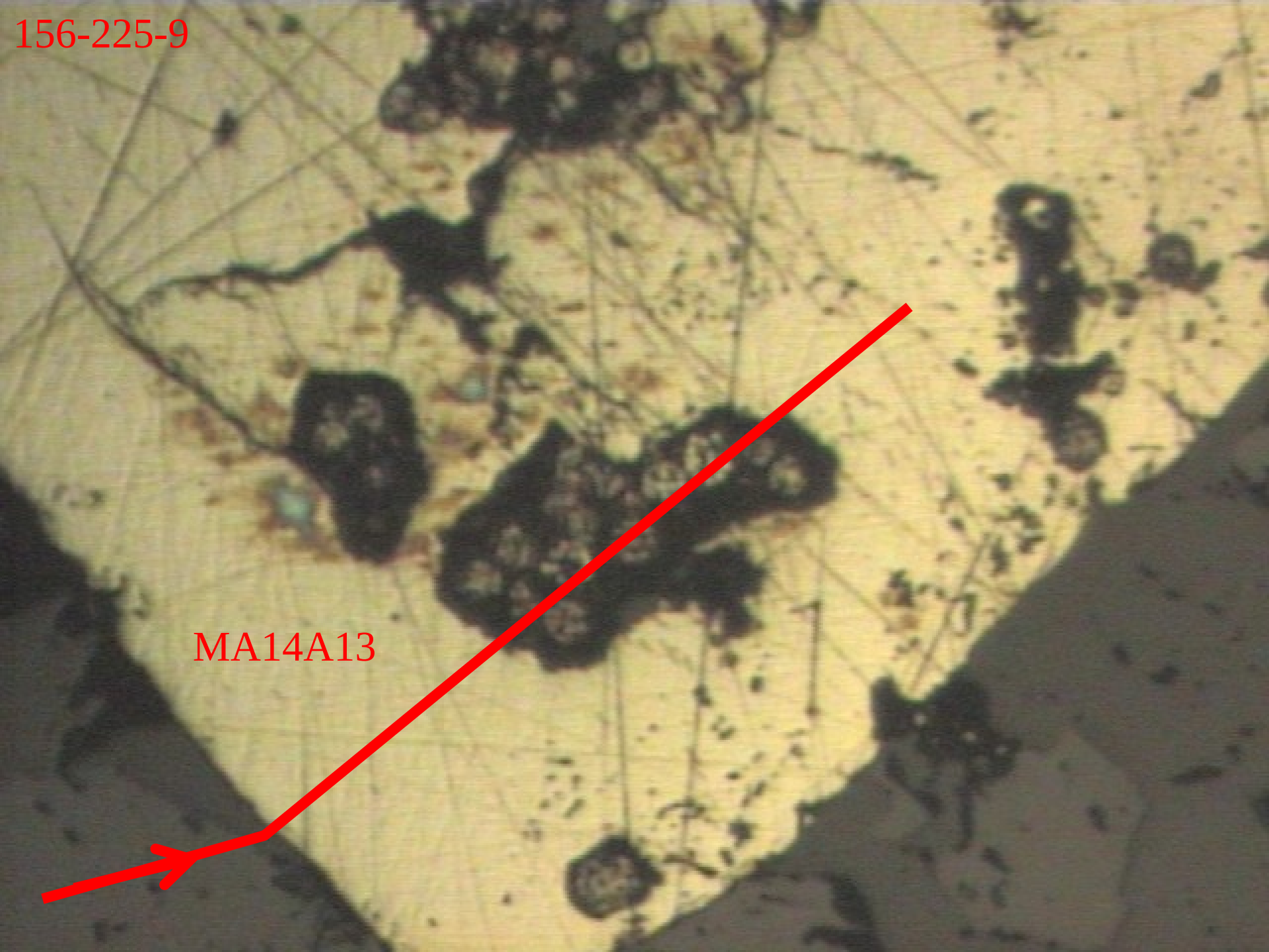
Pyrite 3, also has Au inclusions





Py3 Chemistry

- Although Py3&4 may contain microscopic gold grains, the pyrite itself is depleted in gold compared to Py1&2
- Gold exhibits two populations: a low gold and high gold population.
- Over 80% of Py3 is the low gold population which varies from 0.05 to 2.2 ppm; mean = 0.16 ppm Au
- The minor high gold population varies from 4 to 82 ppm gold, with a mean of 30 ppm Au
- Arsenic varies 7 to 31,000 ppm; mean = 2900 ppm As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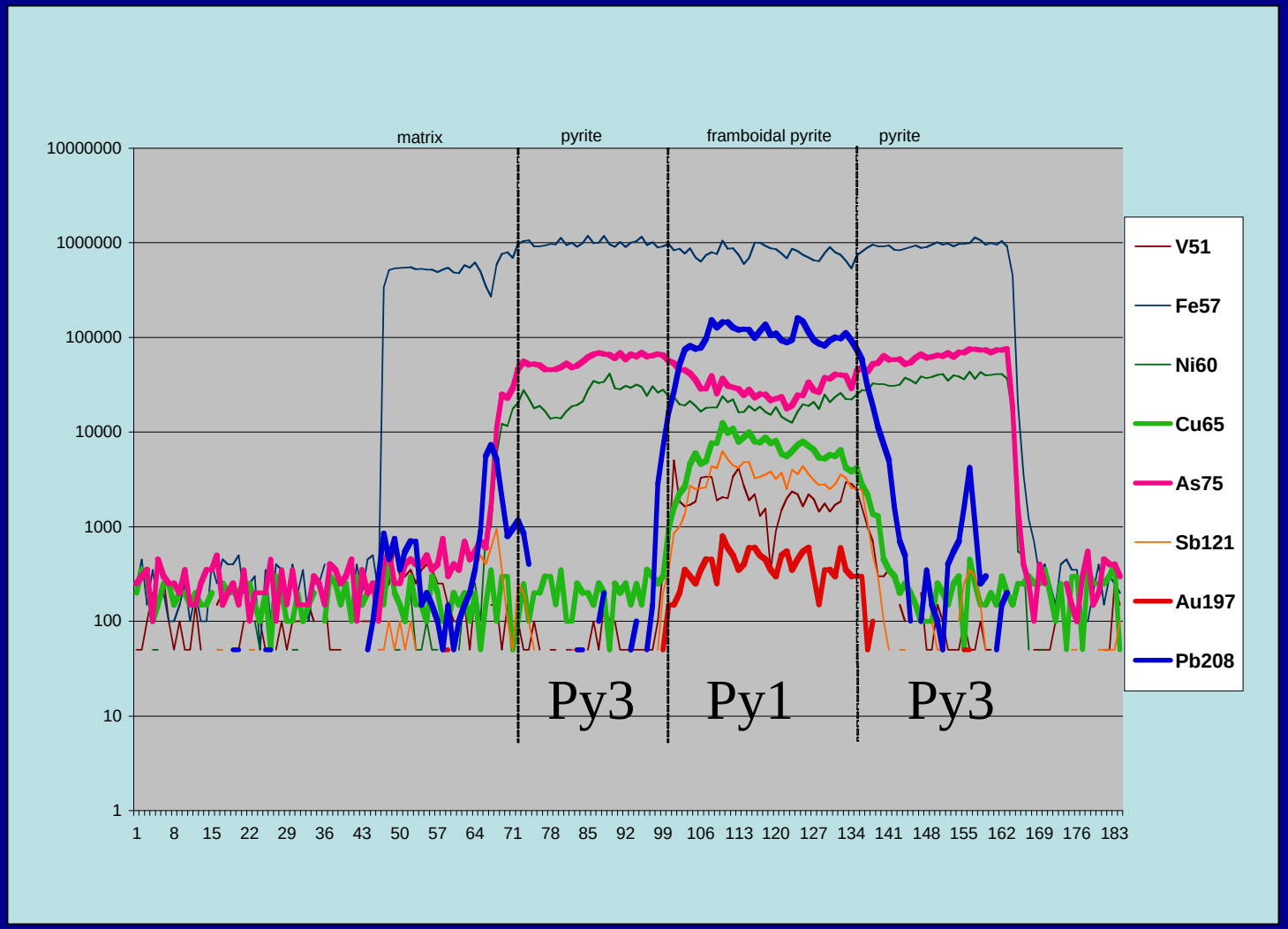
MA14A13

Py1 is enriched in Au, Pb, Cu, V, Sb, but depleted in As & Ni cf Py3



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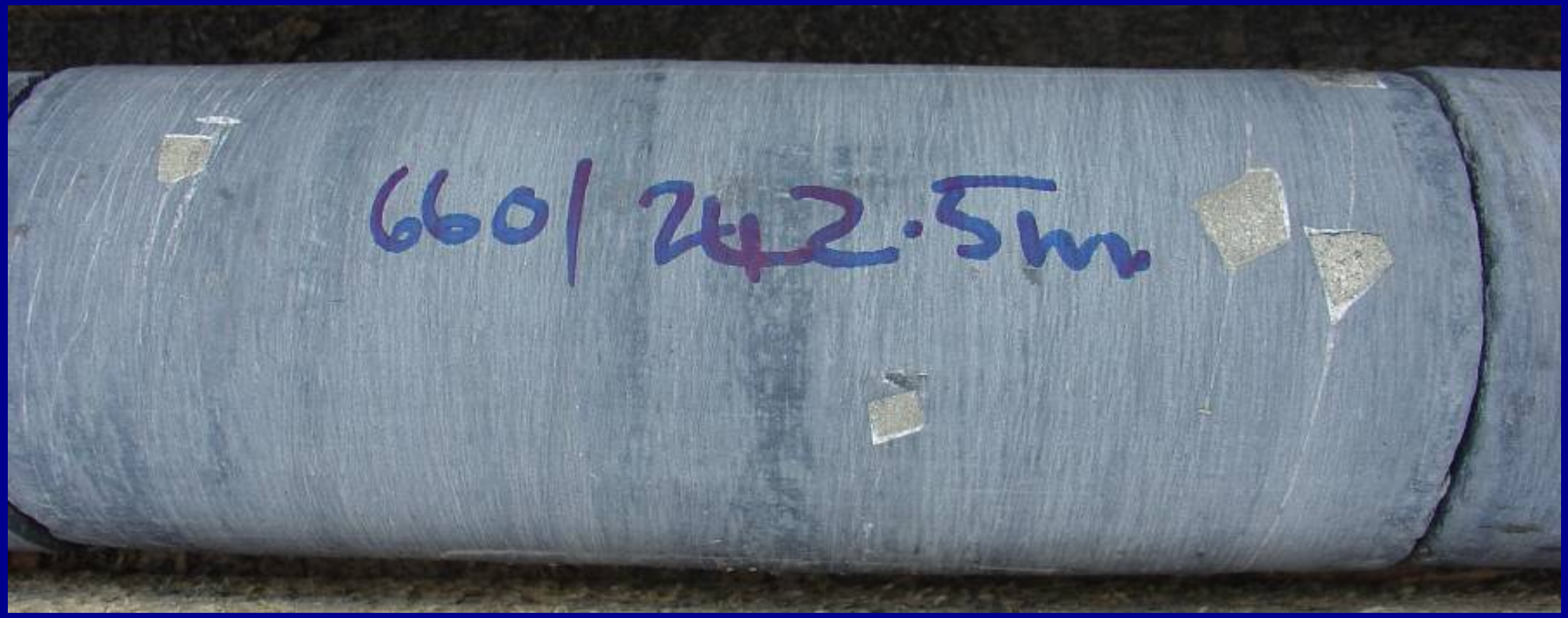
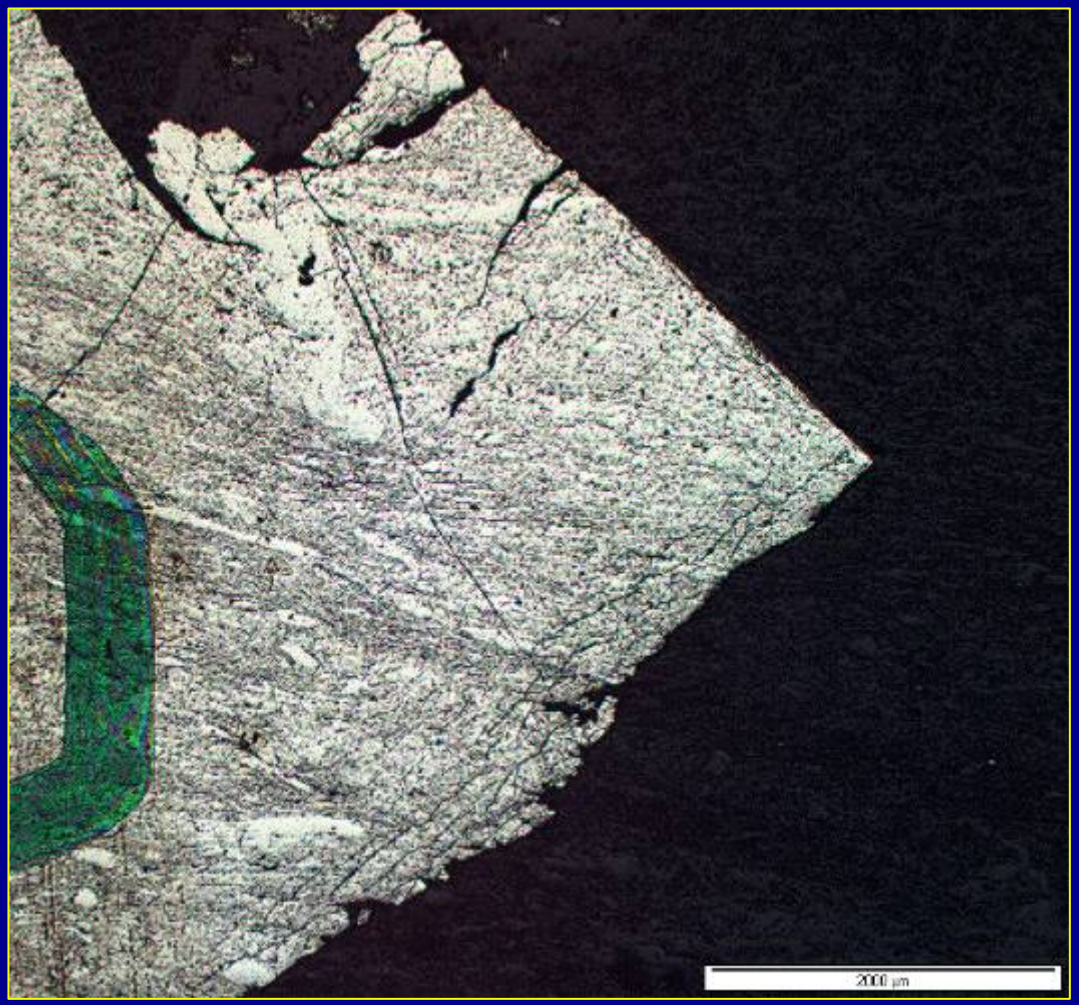
Pyrite 4
Isolated large euhedra

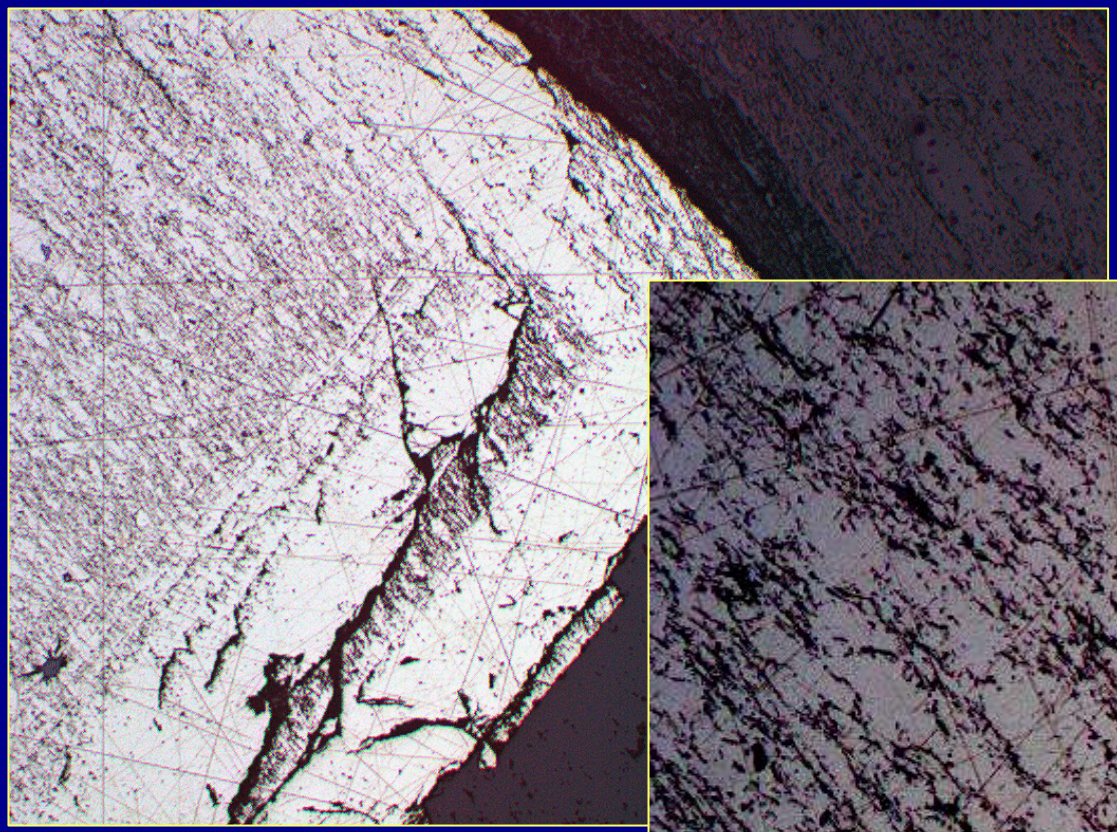


Pyrite 4

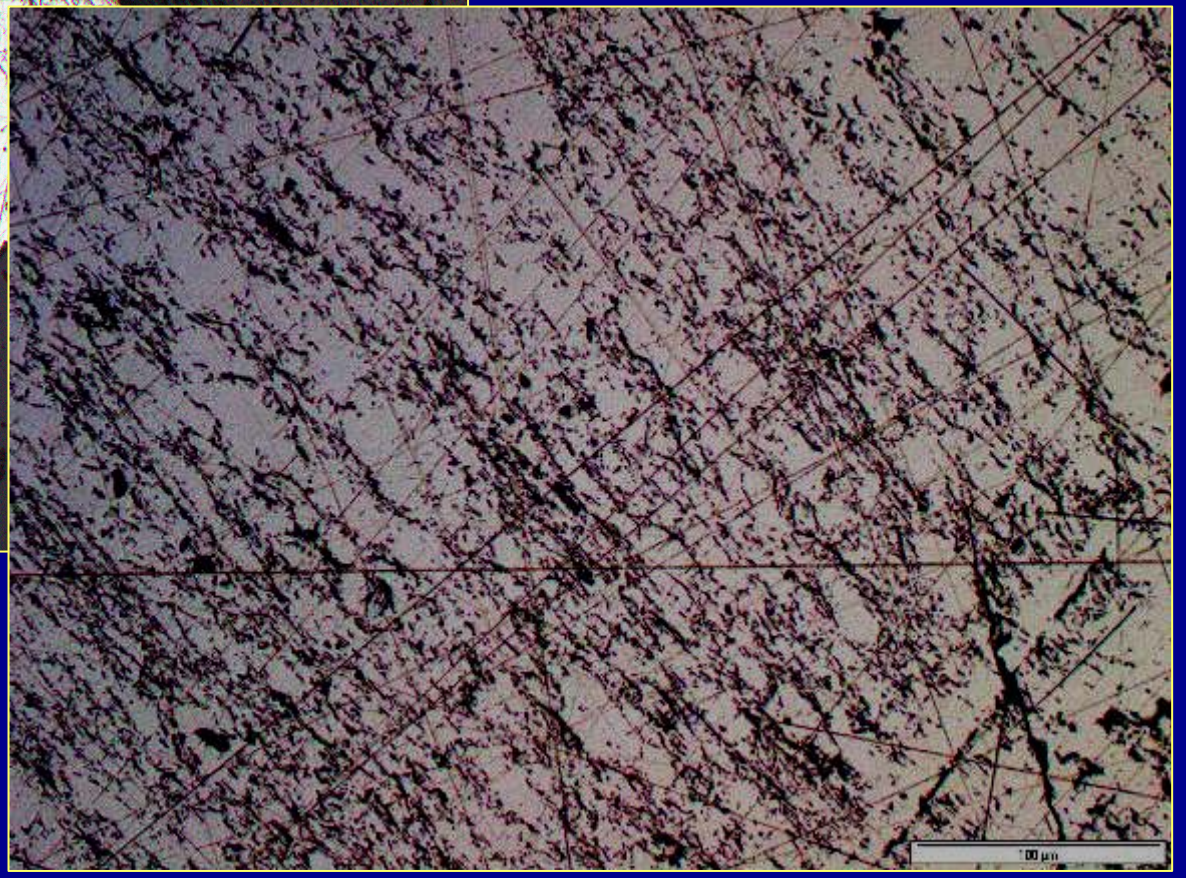


- Large isolated euhedral pyrite in shale
- quartz pressure shadows are common
- Internal fabric in Py4 shows the main cleavage(s)
- Abundant aligned micro-inclusions
- Interpretation: pyrite replaces all sediment components and inherits the structural fabric of sediments: Late metamorphic

Pyrite 4



Internal deformation
Fabric revealed by acid etch



Growth zoning

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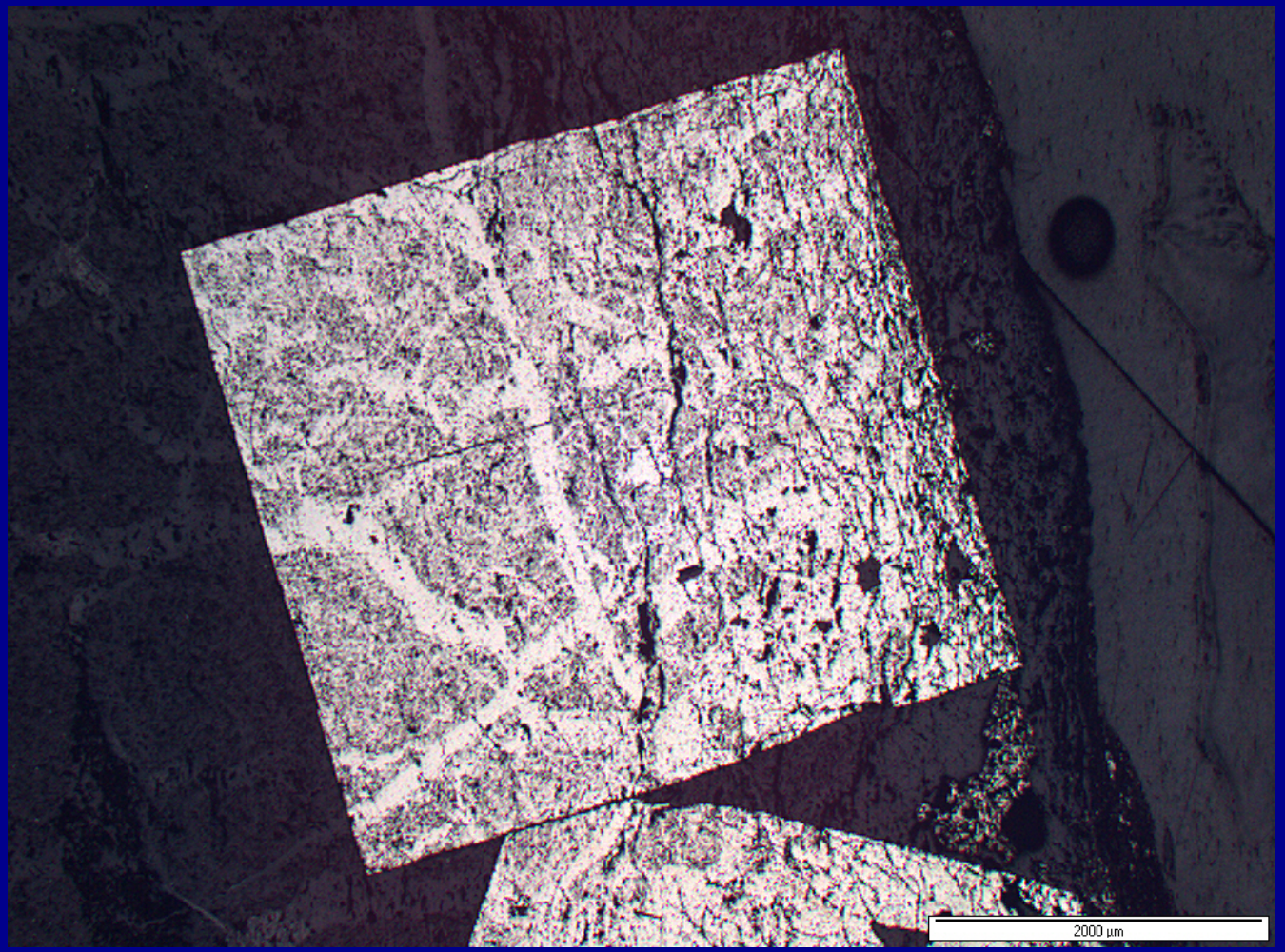
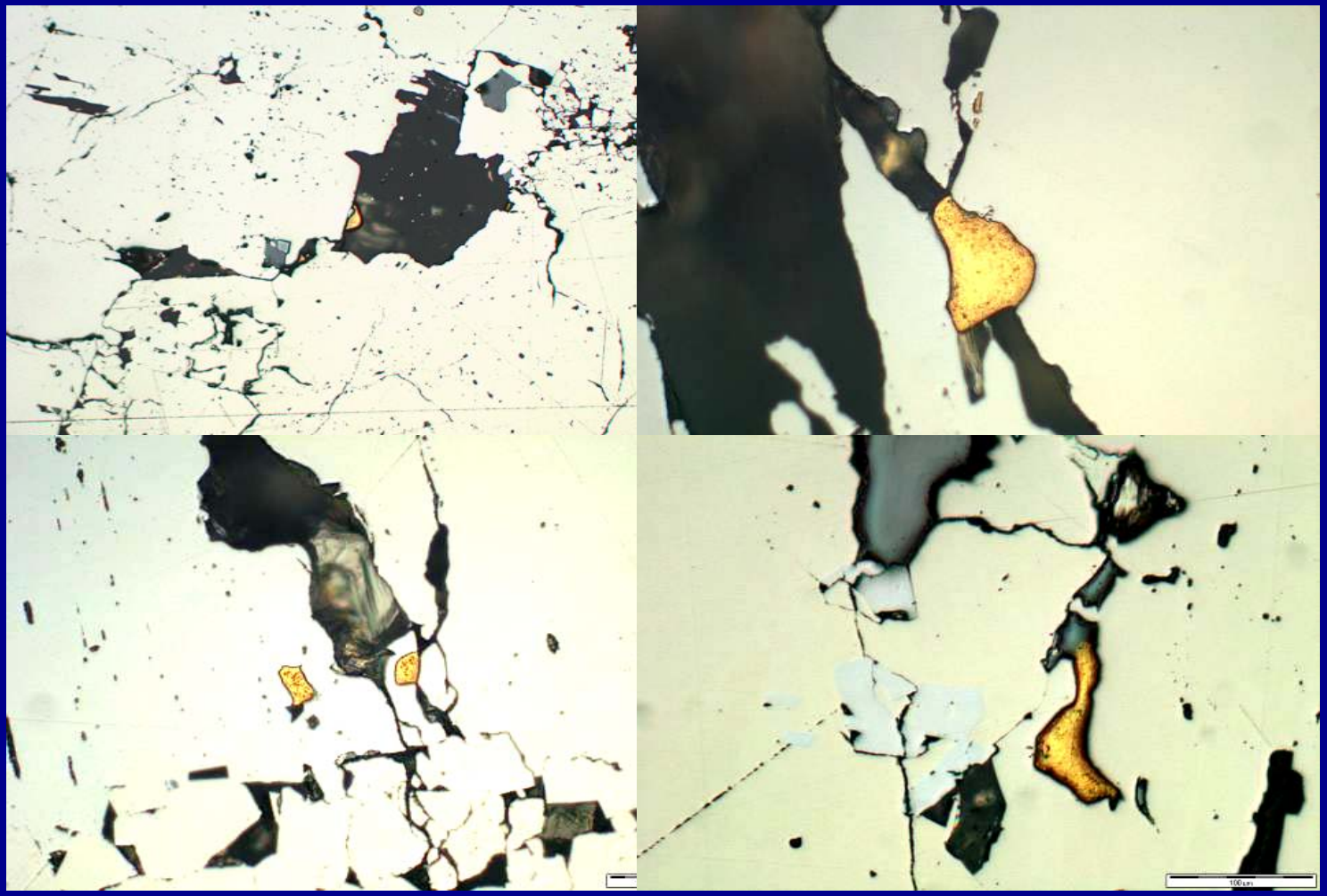
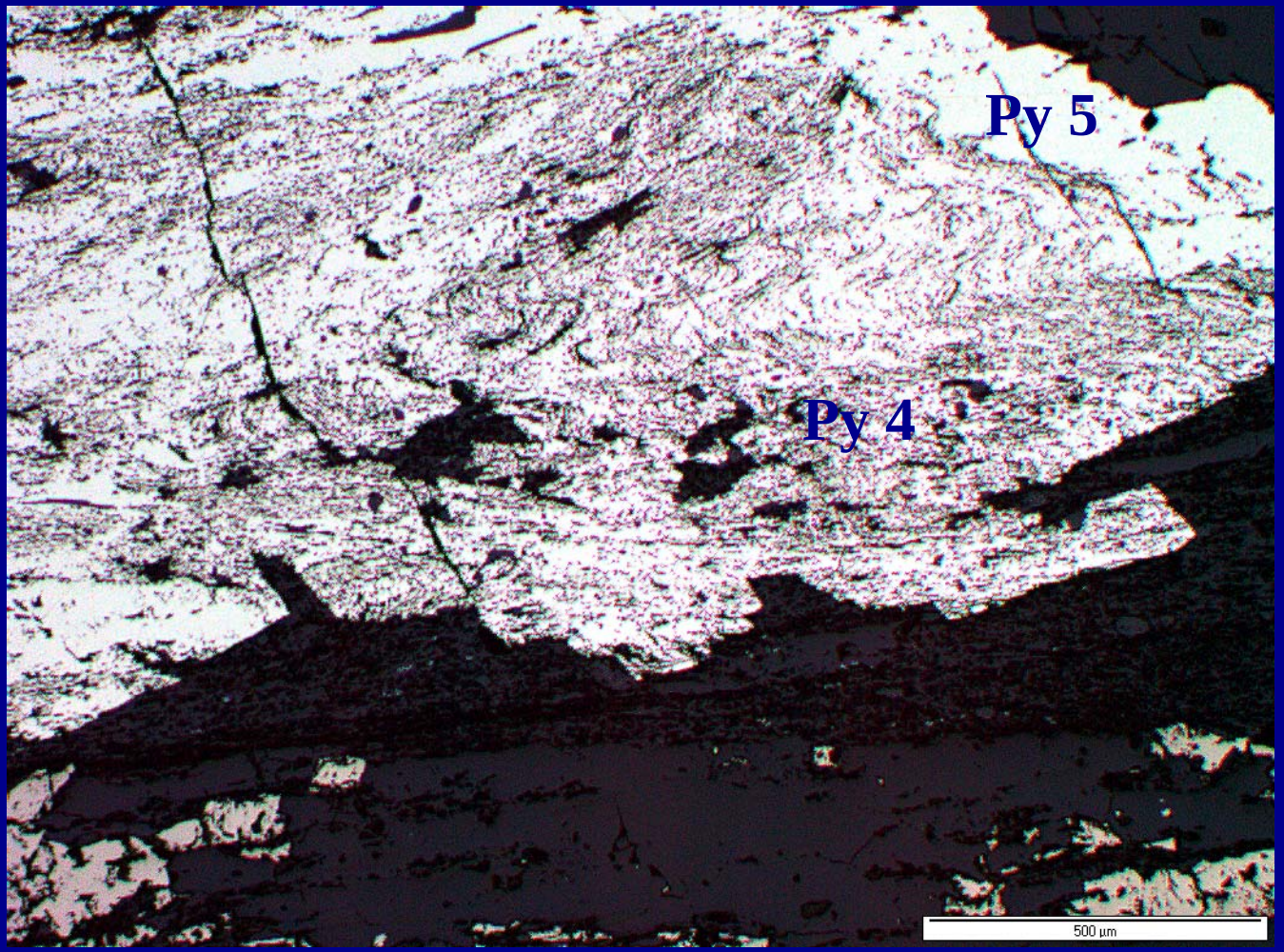
Py4 overprinting rock fabrics

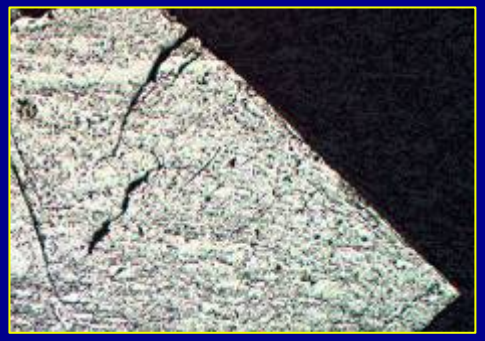


Free Gold in Py3/4



Pyrite 4/ Pyrite 5



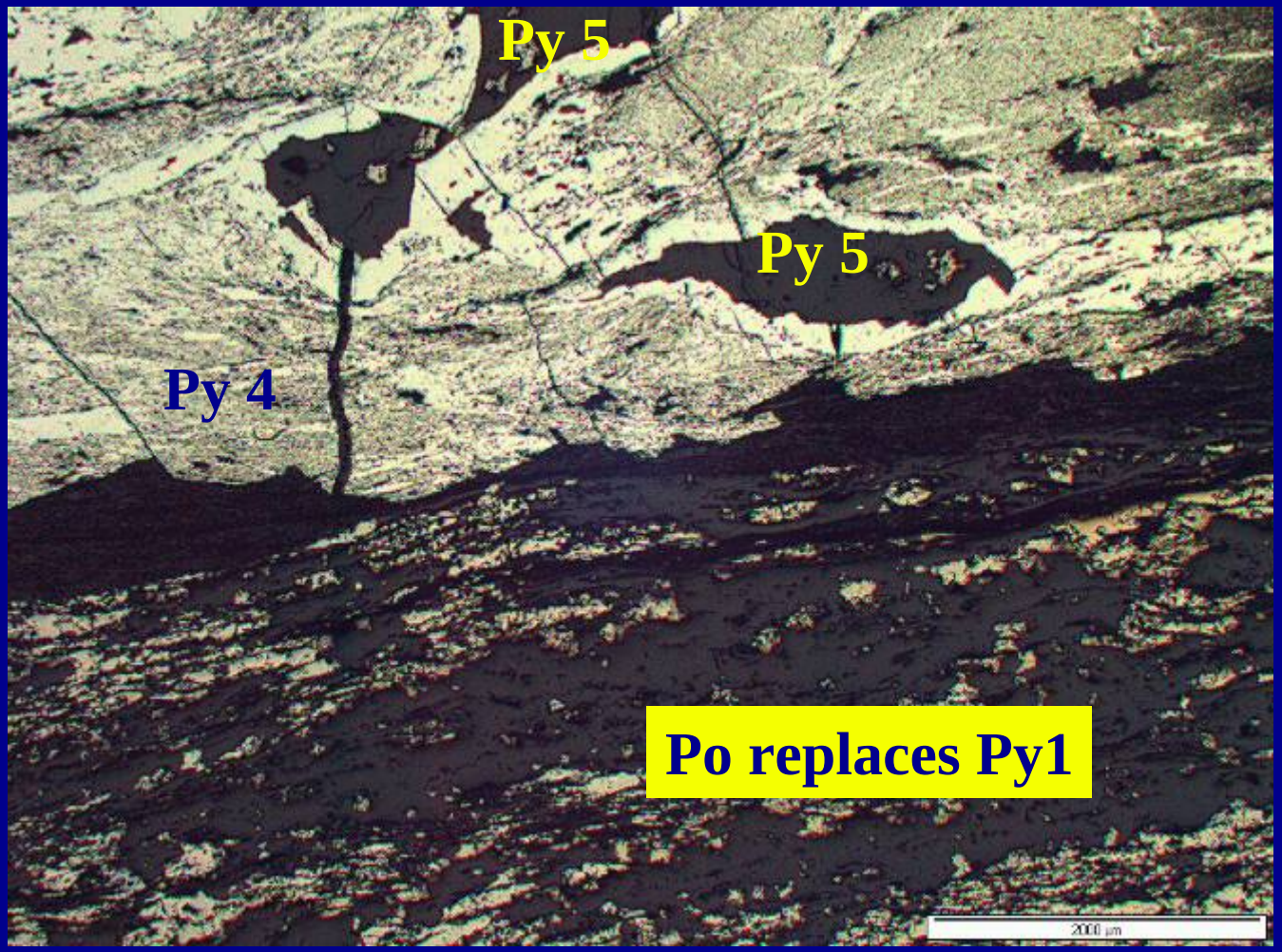


Py4 Chemistry

- Although Py3&4 may contain microscopic gold grains, the pyrite itself is depleted in gold compared to Py1&2
- Gold content of Py4 varies from 0.02 to 1.30 ppm; mean = 0.25 ppm Au
- Arsenic varies 400 to 5560 ppm ; mean = 2270 ppm As
- Py4 is characterised by high Ti, up to 15,000 ppm (mean 1500 ppm). This relates to the abundant inclusions.

Pyrite 5

overgrows and may cut pyrite 4 (open space growth)



Pyrrhotite is common in Py 4 assemblages

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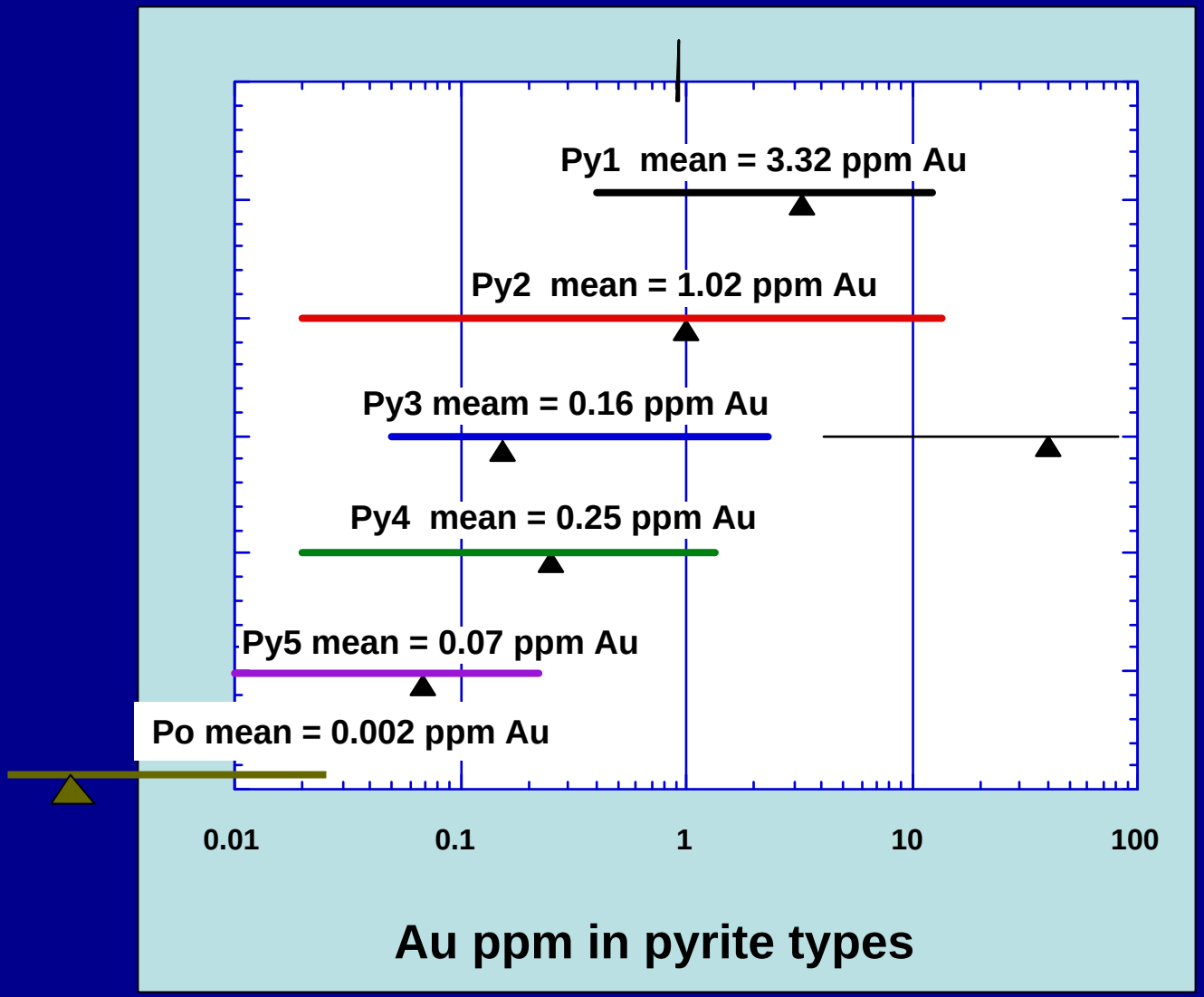
Pyrite is progressively depleted in gold from Py1 to Py5



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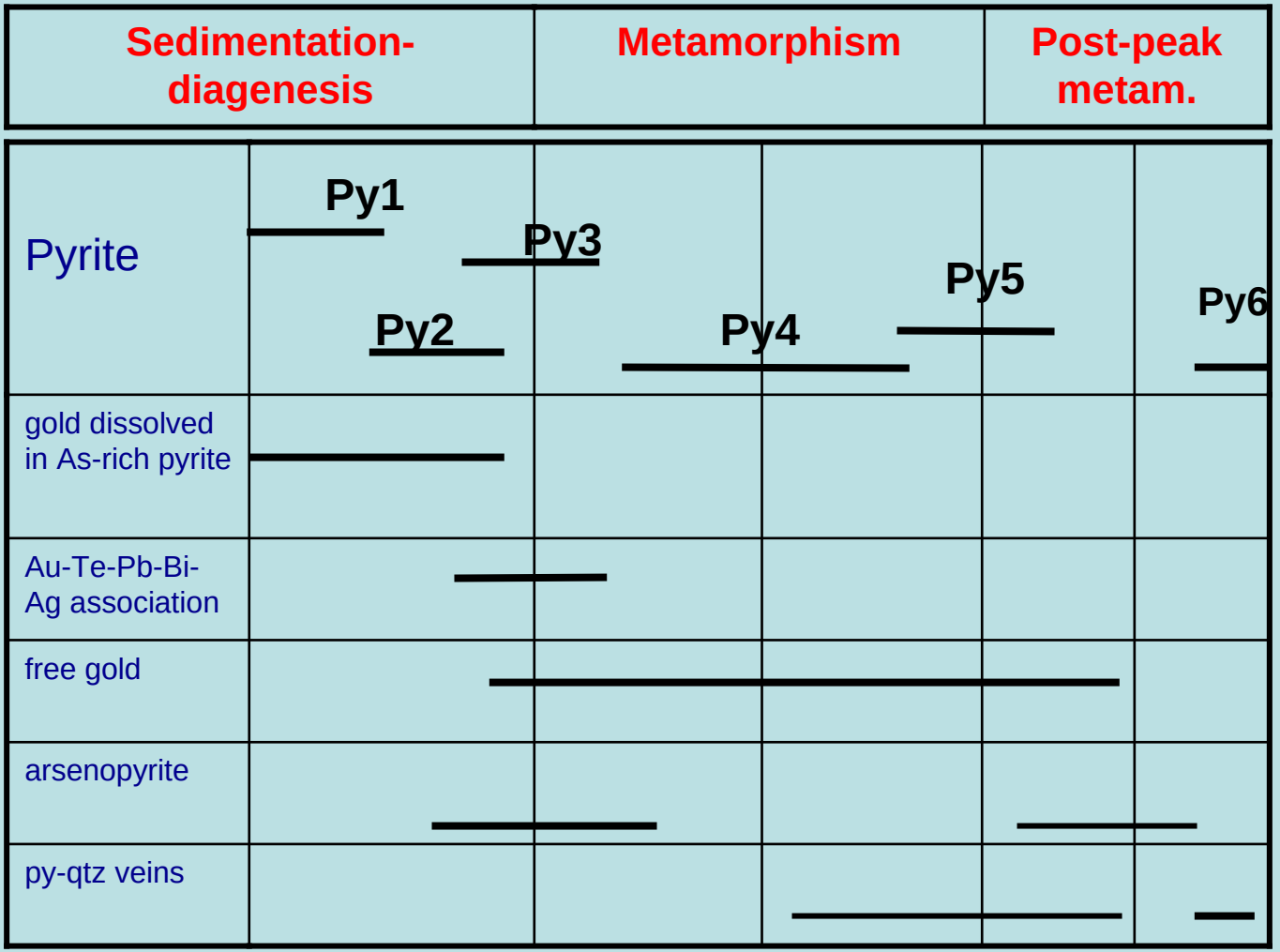
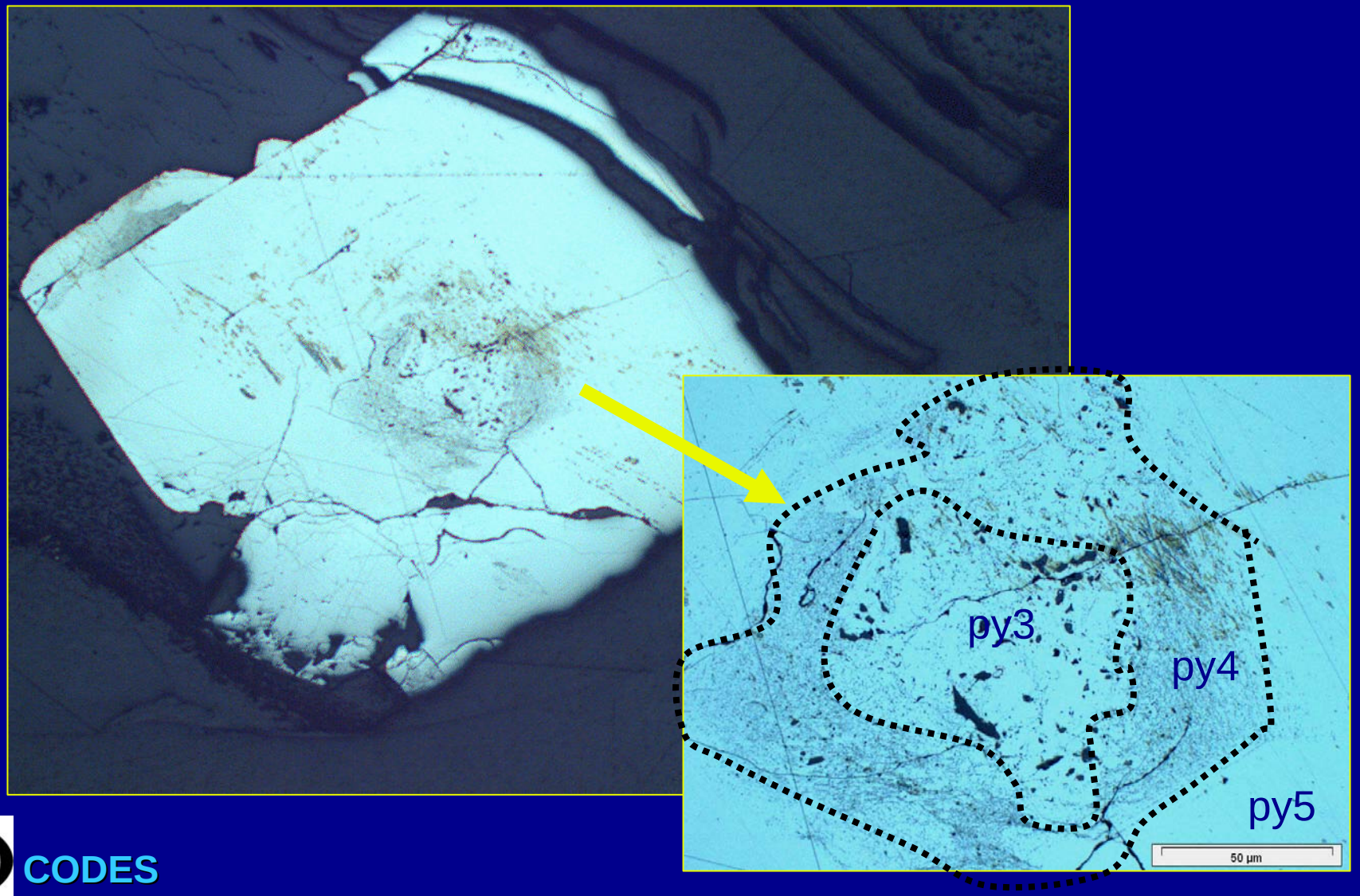
Pyrite and Gold Paragenesis

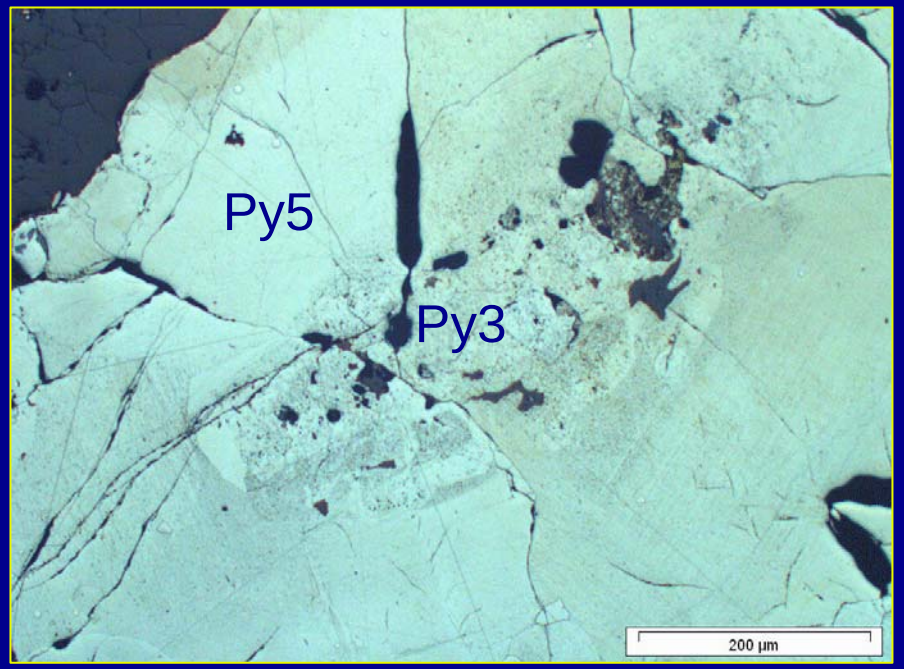


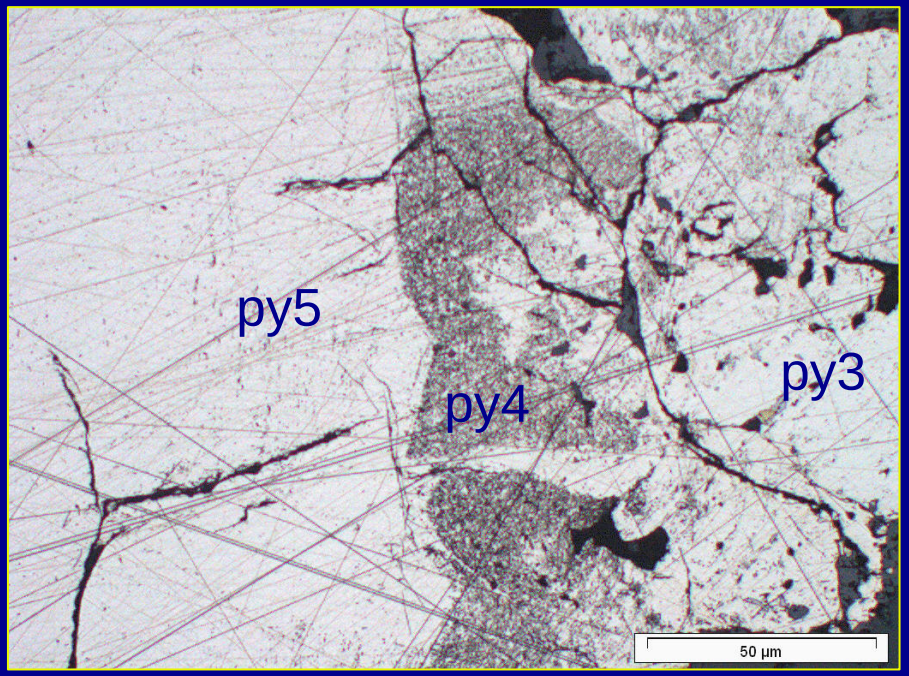
Pyrite in Py-Qtz Veins

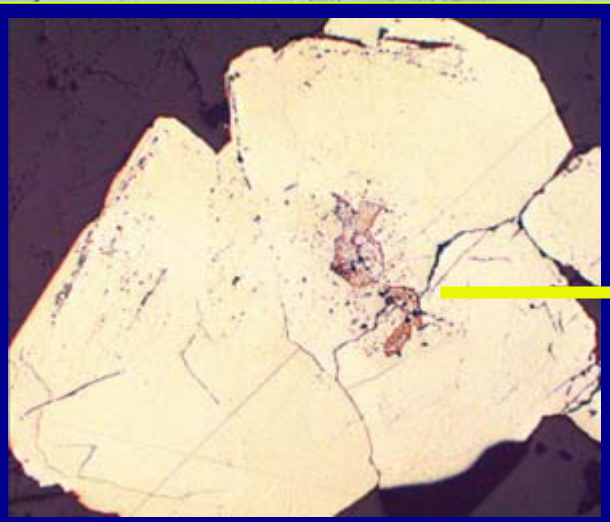
Pyrite in py-qtz veins is zoned

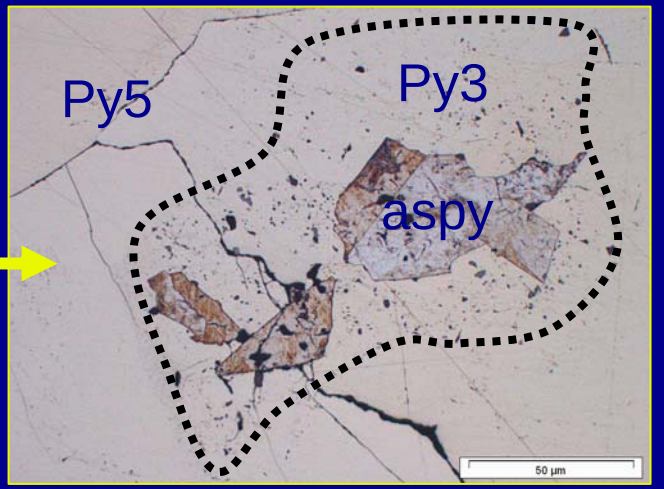


Pyrite in py-qtz veins



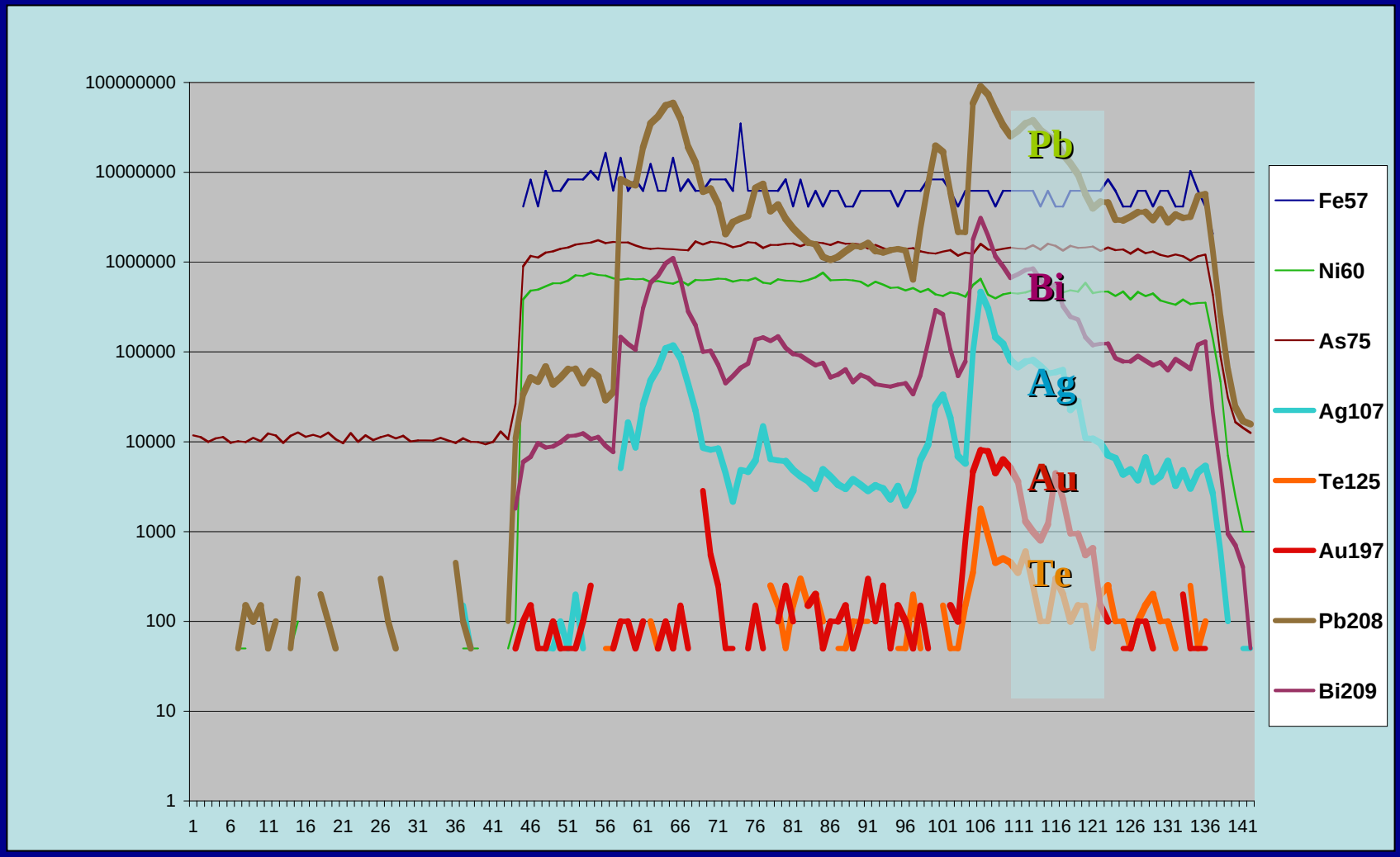






CODES

Analysis of py3 core

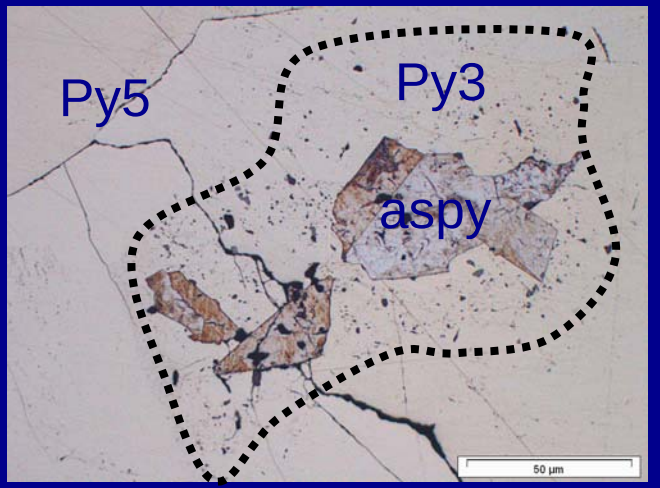


Inclusions of galena with dissolved Bi-Ag-Au-Te

CODES

Galena Inclusions in Py3 Cores

- Bi, Ag, Au, Te are dissolved in the structure of the galena
- 1.9 wt% Bi
- 1.1 wt% Ag
- 257 ppm Au
- 423 ppm Te

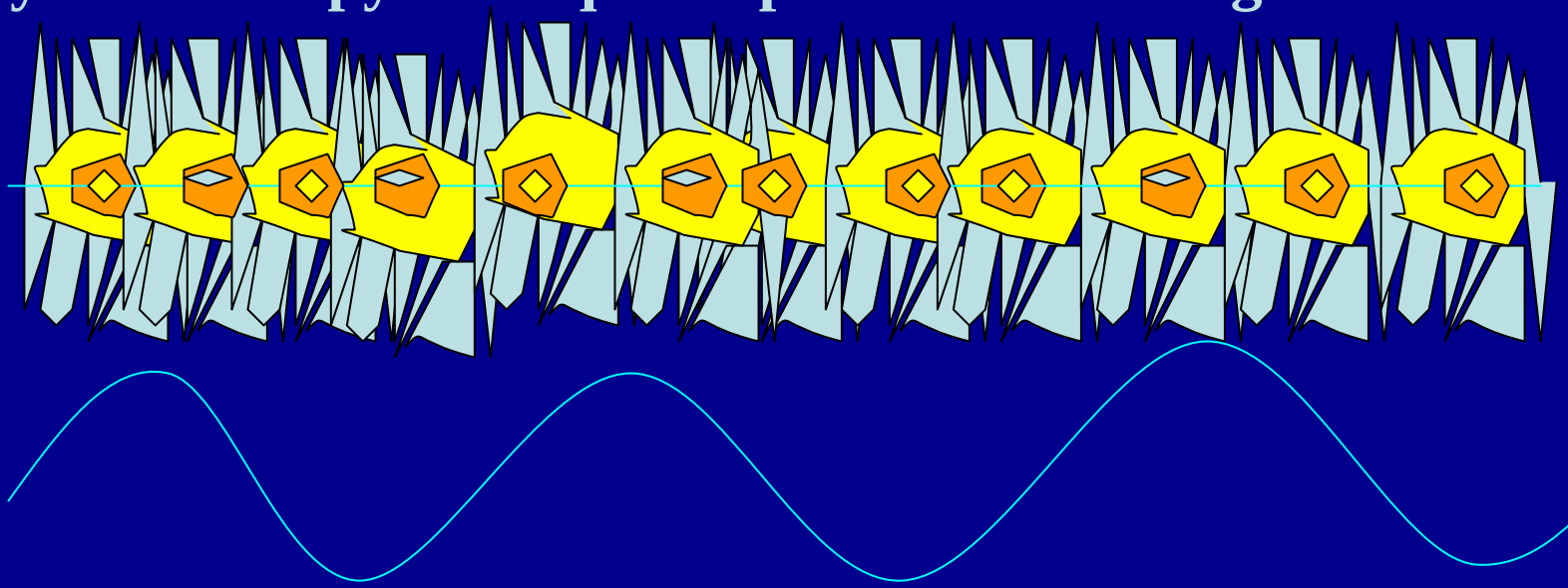


Growth of py-Au-qtz veins

1) Early diagenetic pyrite and arsenopyrite growth along bedding

2) Late diagenetic py3 and early metamorphic py4 overgrowths

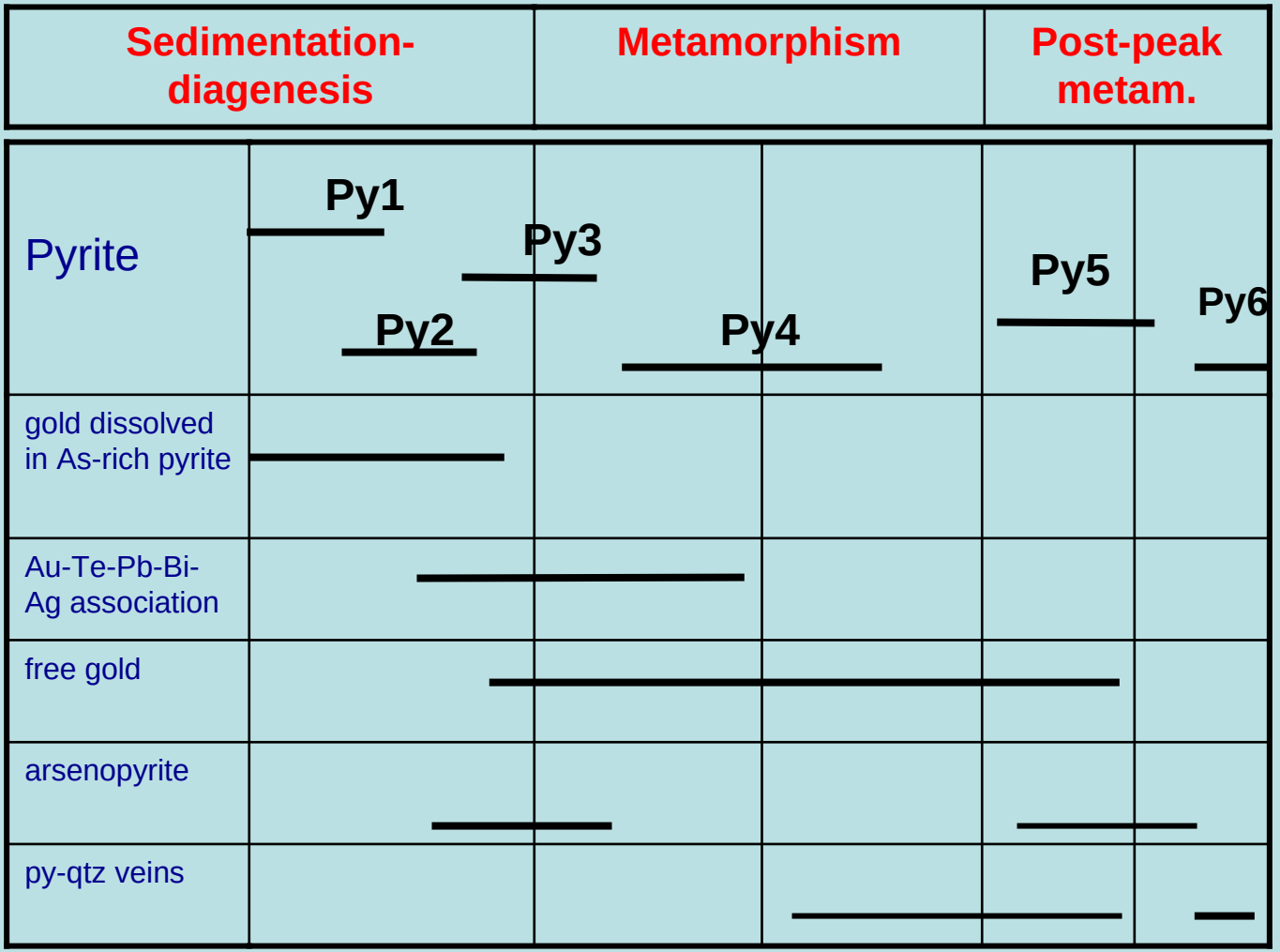
3) syn-tectonic py5 and quartz pressure shadow growth



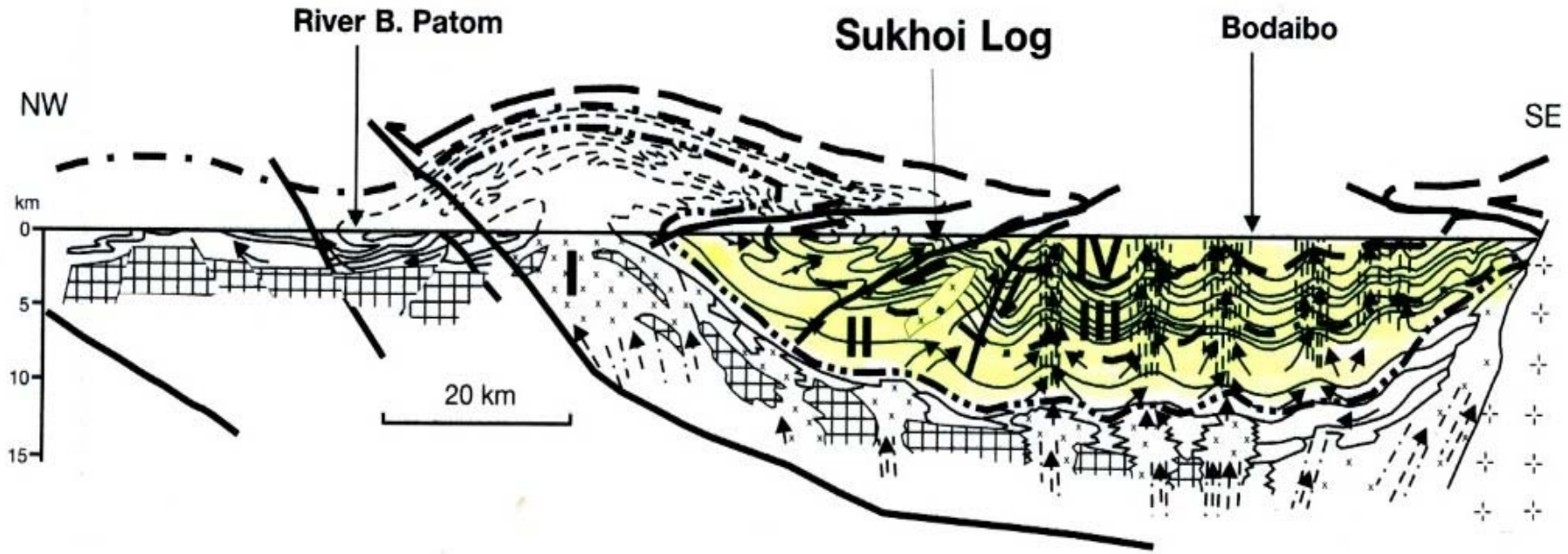
Gold Events at Sukhoi Log

- The stratiform py1 represents the first (SEDEX) gold event (Au-As) from shallow basinal fluids
- The dageneitic cores to the bedding parallel veins represent the second gold event (Au-Ag-Pb-Te-Bi) from deeper basinal fluids
- On-going metamorphism led to remobalisation of free gold into later, more radiogenic, pyrite generations

Pyrite and Gold Paragenesis



Bodaibo Basin: Reduced and Gold-rich



From Buryak (1982) and Yakubchek et al. (2005)

Key message: *Free gold in late pyrite does not mean the timing of gold is late, ie. syn- or post-tectonic*

Much gold is introduced early into sedimentary and volcanic basins, where it resides in arsenian pyrite

Thank You