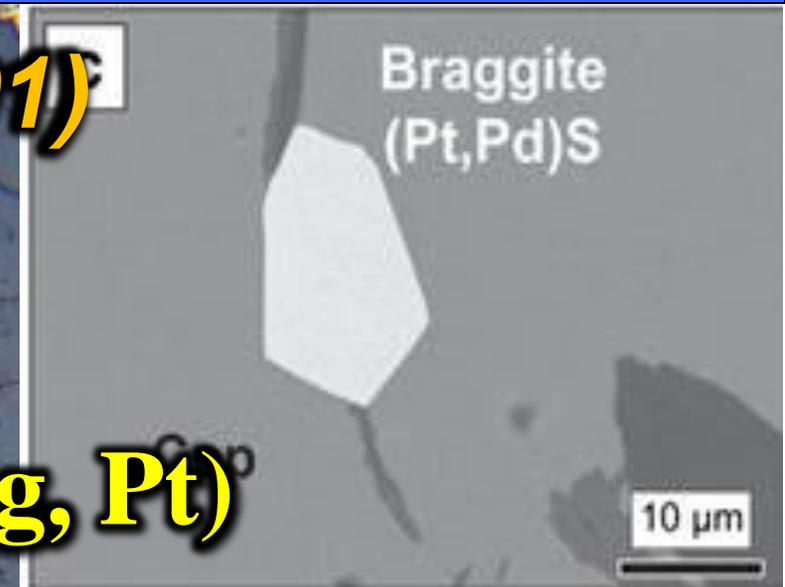
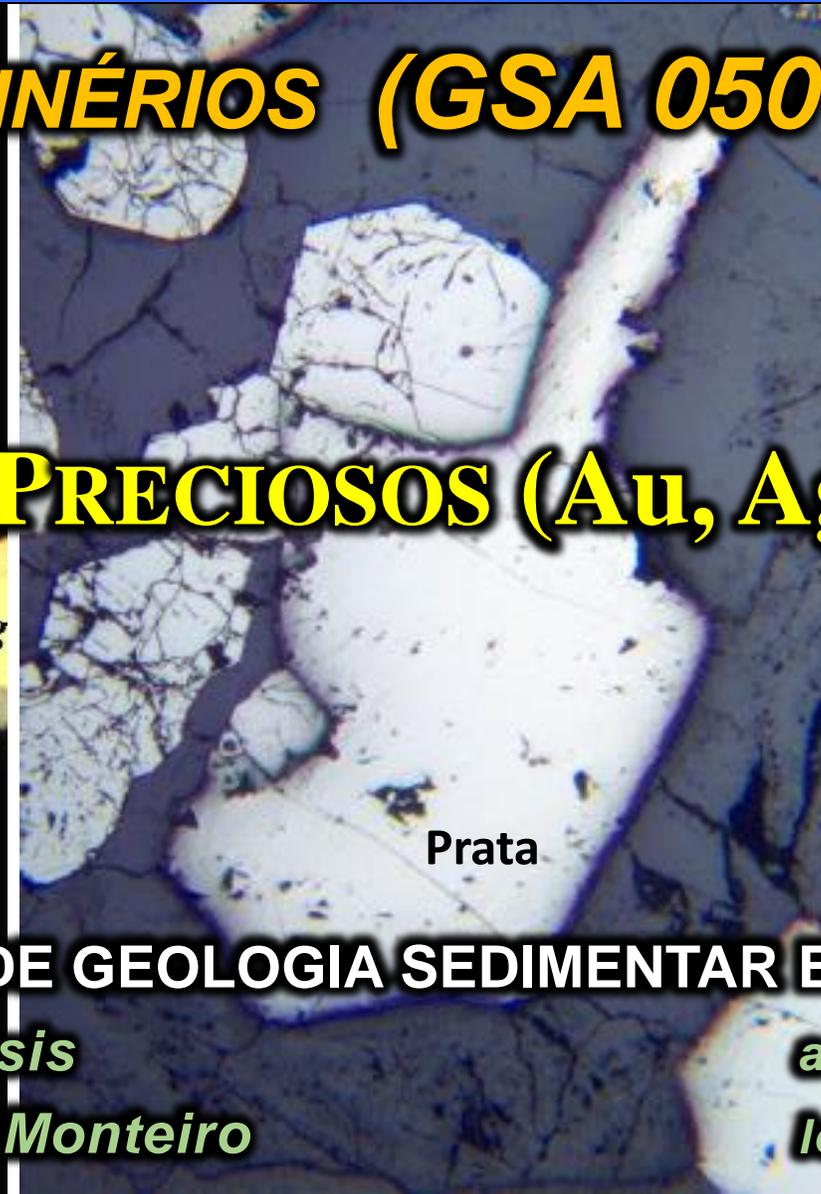
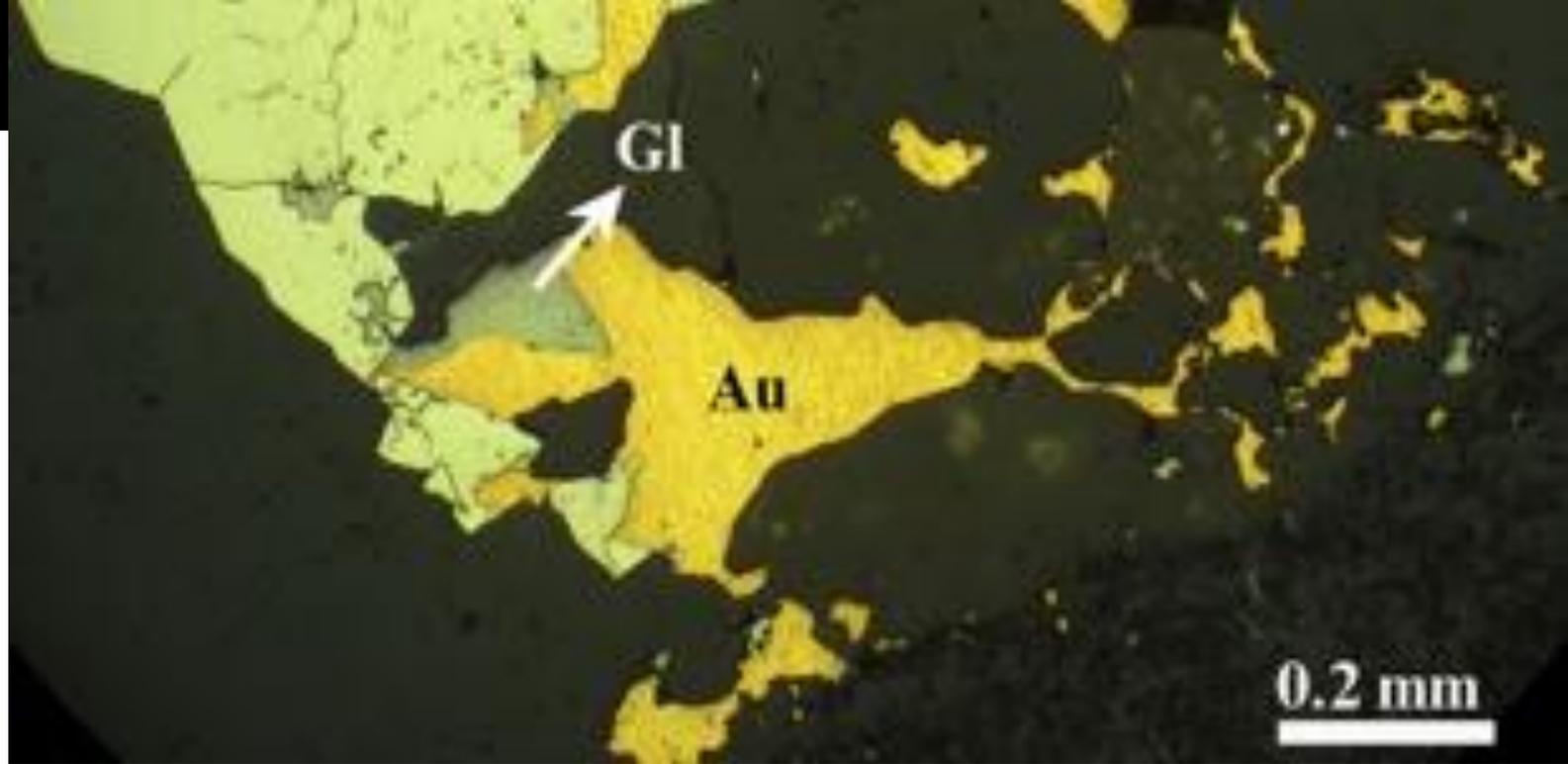


PETROGRAFIA DE MINÉRIOS (GSA 0501)**METAIS PRECIOSOS (Au, Ag, Pt)****DEPARTAMENTO DE GEOLOGIA SEDIMENTAR E AMBIENTAL***Prof. Dr. Rafael Rodrigues de Assis**Profa. Dra. Lena Virginia Soares Monteiro**assis.rafael@usp.br**lena.monteiro@usp.br*

OURO NATIVO – Au



Heinrich Frank

OURO NATIVO → LUZ REFLETIDA
(POLARIZADORES DESCRUZADOS E CRUZADOS)

https://www.youtube.com/watch?v=4VJ7e9dZXKA&list=PL5k_2NCH5I4Ct1G_H8gehEM_zWMhdOD5X

COR

Amarela dourada, afetada pelos conteúdos de Ag (“mais esbranquiçado”) e Cu (“avermelhado”).

REFLECTÂNCIA

Muito Alta (~71-72%).

PLEOCROÍSMO E BIRREFLECTÂNCIA

Ausentes

ANISOTROPIA

Sistema cúbico (isótropo, porém, raramente).

Sulcos de polimento produzem interferência, com anisotropia anômala verde (diagnóstica)

OUTRAS CARACTERÍSTICAS

Sem reflexões internas.

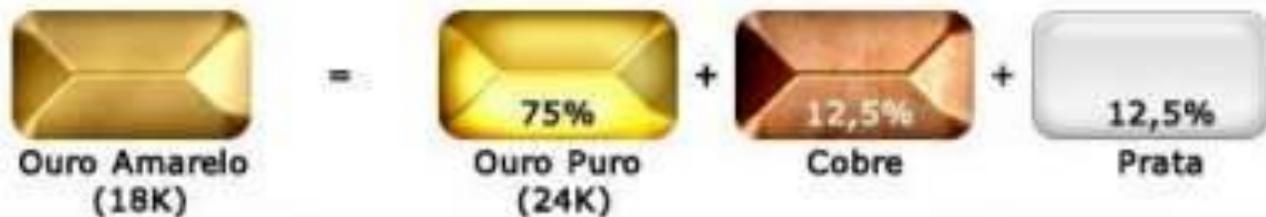
Anisotropia verde anômala.

PUREZA DO OURO E SUA RELAÇÃO COM A INDÚSTRIA DA JOALHERIA

Na joalheria, **não é prático e eficiente o uso do ouro puro**, por conta de **sua baixa dureza** e, portanto, **elevada maleabilidade**.

→ *Au deve ter uma maior dureza;*

→ ... Para **maior durabilidade e resistência** (ao risco e deformação), o **Au é fundido com outros metais (ligas)**.



PRATA, COBRE, ZINCO, PALÁDIO, ETC..
Metais comumente adicionados ao Au para formação de ligas.

É justamente a **quantidade dos outros metais adicionados** ao ouro que vai **determinar o teor do ouro**.

PUREZA DO OURO E SUA RELAÇÃO COM A INDÚSTRIA DA JOALHERIA

QUILATE

01 quilate equivale a **0,20 gramas** (para pedras preciosas e metais nobres).

KILATE (K)

→ Para o **ouro**, entretanto, o **kilate representa uma medida de pureza do metal (logo, não de sua massa)**.

$$\text{Kilate} = \frac{\text{massa de ouro}}{\text{massa total da amostra}} * 24$$

→ Cada quilate equivale a **4,1666% de ouro na amostra.**

PUREZA DO OURO



ouro amarelo14k
58,3% ouro



ouro amarelo18k
75% ouro



ouro amarelo24k
100% ouro

→ **QUANTOS KILATES TERIA O OURO PURO??**

→ *toda a massa da amostra corresponderia à massa de ouro, logo:*

$$\text{Kilate} = \frac{100 \text{ g de Au}}{100 \text{ g de massa total da amostra}} * 24$$

Ouro 24 kilates (puro)

PUREZA DO OURO E SUA RELAÇÃO COM A INDÚSTRIA DA JOALHERIA

KILATES DO OURO:

Ouro 24 kilates = ouro puro - como é praticamente impossível o ouro ter uma pureza completa, o teor máximo é de 99,99% e assim chamado de ouro 9999. Impróprio para fabricação de joias por ser muito maleável.

Ouro 22 kilates = $22/24 = 91,6\%$ de ouro, também chamado de ouro 916.

Ouro 20 kilates = $20/24 = 83,3\%$ de ouro, também chamado de ouro 833.

Ouro 19,2 kilates = $19,2/24 = 80,0\%$ de ouro, também chamado de ouro 800 ou Ouro Português.

Ouro 18 kilates = $18/24 = 75\%$ de ouro, também chamado de ouro 750.

Ouro 16 kilates = $16/24 = 66,6\%$ de ouro, também chamado de ouro 666.

Ouro 14 kilates = $14/24 = 58,3\%$ de ouro, também chamado de ouro 583.

Ouro 12 kilates = $12/24 = 50\%$ de ouro, também chamado de ouro 500.

Ouro 10 kilates = $10/24 = 41,6\%$ de ouro, também chamado de ouro 416.

Ouro 1 kilate = $1/24 = 4,1666\%$ de ouro, também chamado de ouro 41

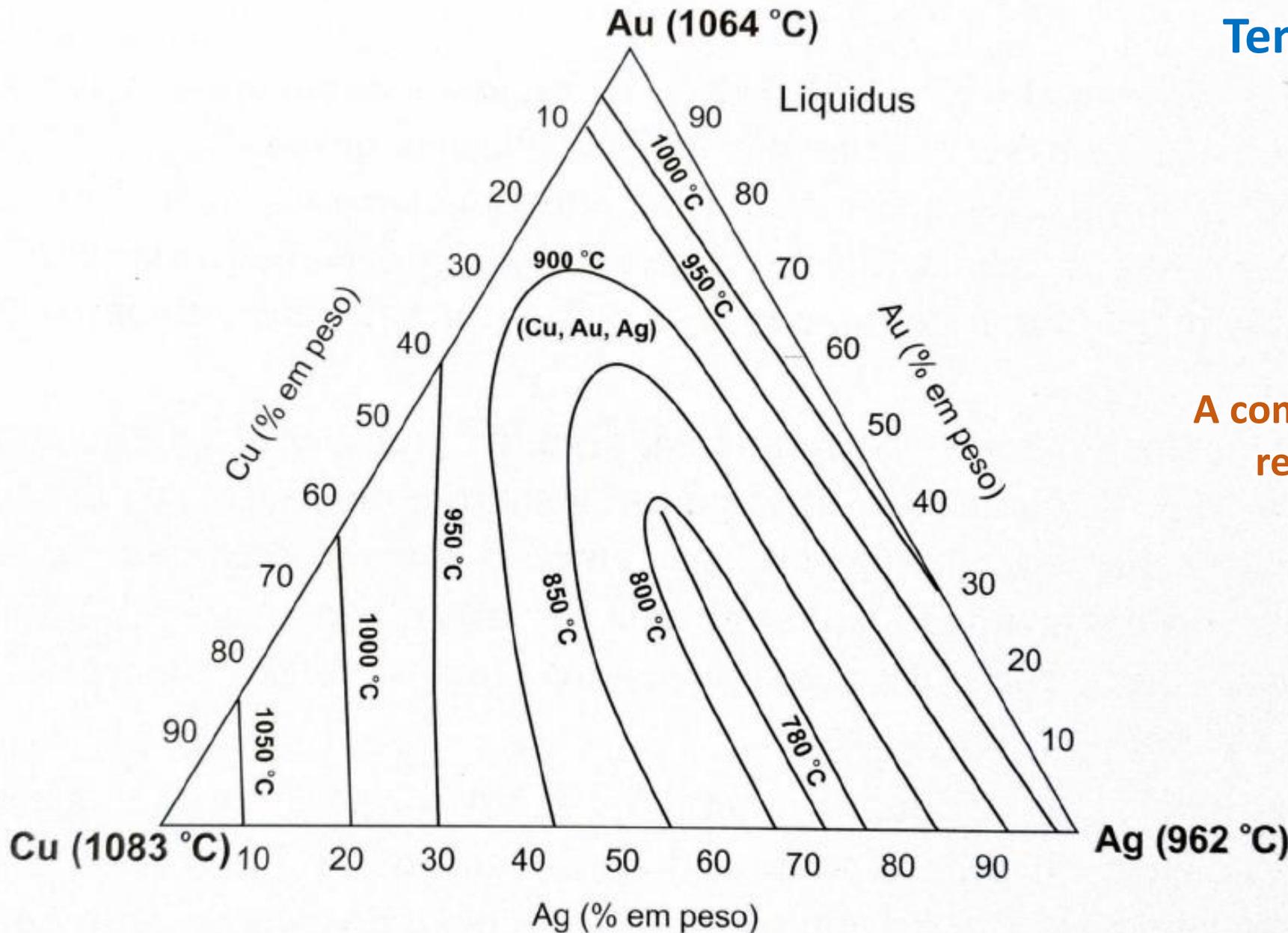


EXEMPLO

Um objeto (aliança?) de **ouro 18k ou 750**, representa fabricação com material composto por 75% de ouro puro, e 25% de outros metais (liga)

→ *12 partes de ouro e 6 partes de outros metais (12 + 6 = 18 partes/peso da amostra).*

SISTEMA Au – Ag – Cu



Temperaturas e fusão:

Cu → 1.083 °C

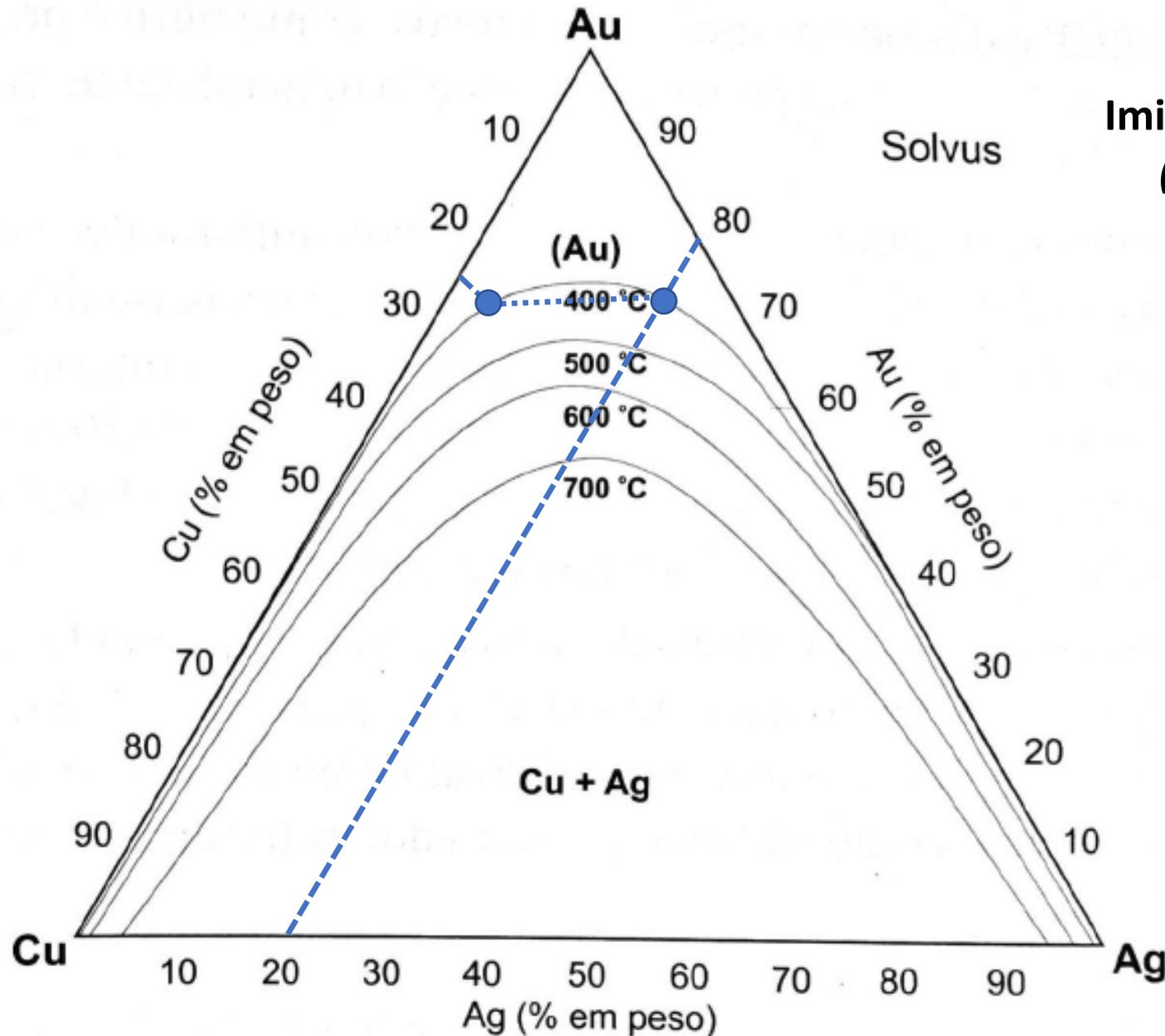
Au → 1.064 °C

Ag → 962 °C

A composição das ligas de Au-Ag-Cu reflete em suas temperaturas de fusão.

A região de líquidos do sistema ternário para ligas de Au-Ag-Cu, com indicação de suas respectivas temperaturas de fusão (Figueiredo, 2000).

SISTEMA Au – Ag – Cu



700 °C

Imiscibilidade completa entre Cu-Au e Au-Ag
(entre Cu-Ag é parcial → presença de solvus)

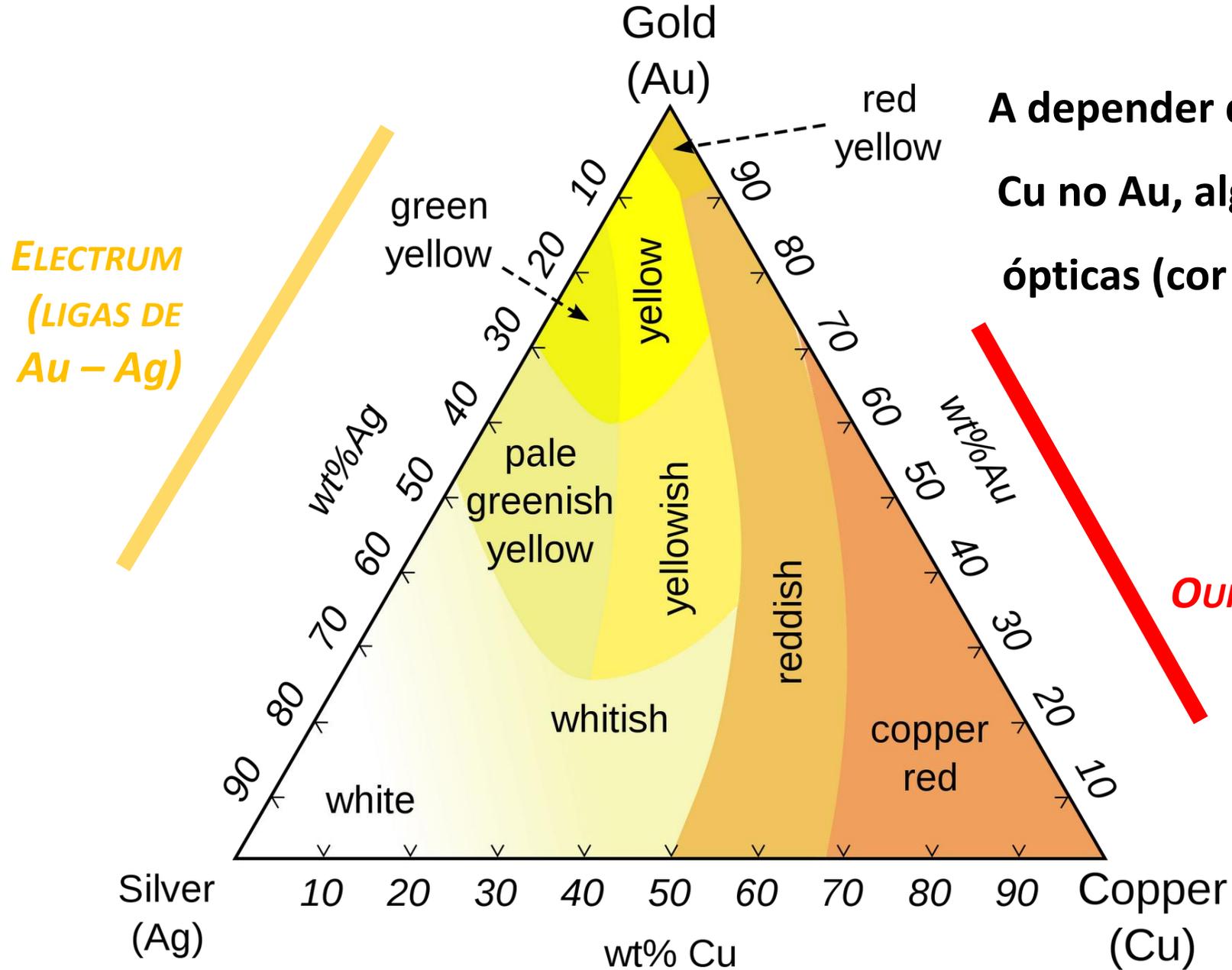
T < 400 °C

Liga de Au com 20% de Ag poderá
conter no máximo 26% de Cu.

Liga de Au com 20% de Cu poderá conter,
no máximo, 7% de Ag.

A região de soluções sólidas do sistema
ternário Au-Ag-Cu (Figueiredo, 2000).

SISTEMA Au – Ag – Cu



A depender das concentrações de Ag e/ou Cu no Au, algumas de suas características ópticas (cor e reflectância) podem variar.

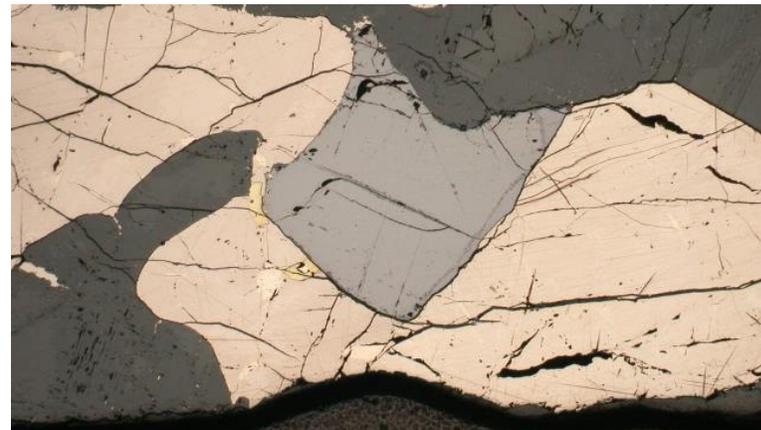
OURO VERMELHO / AVERMELHADO

PRINCIPAIS DEPÓSITOS AURÍFEROS

DIVERSOS SISTEMAS MINERAIS

MAGMÁTICOS

Sulfeto Magmático



HIDROTERMAIS

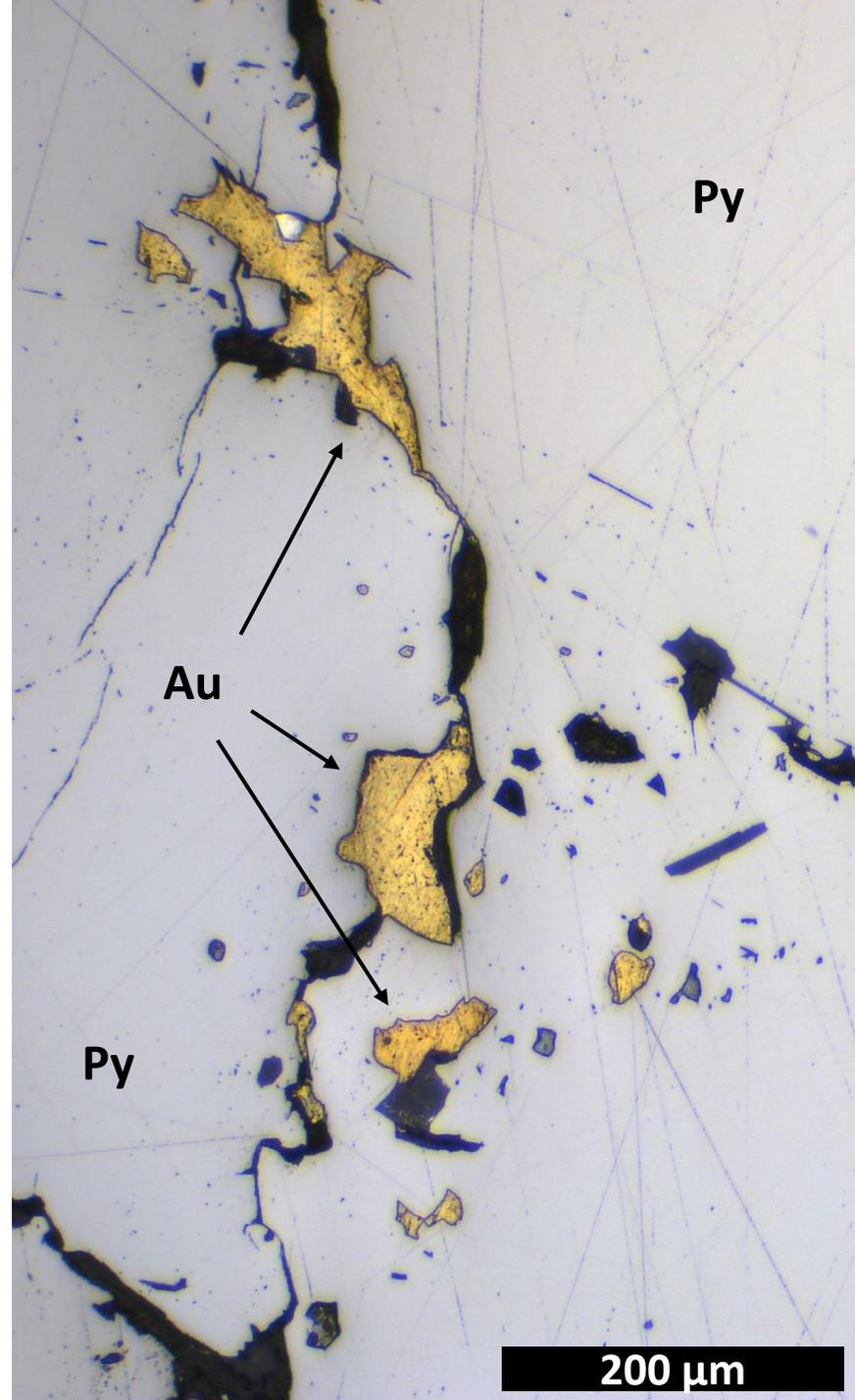
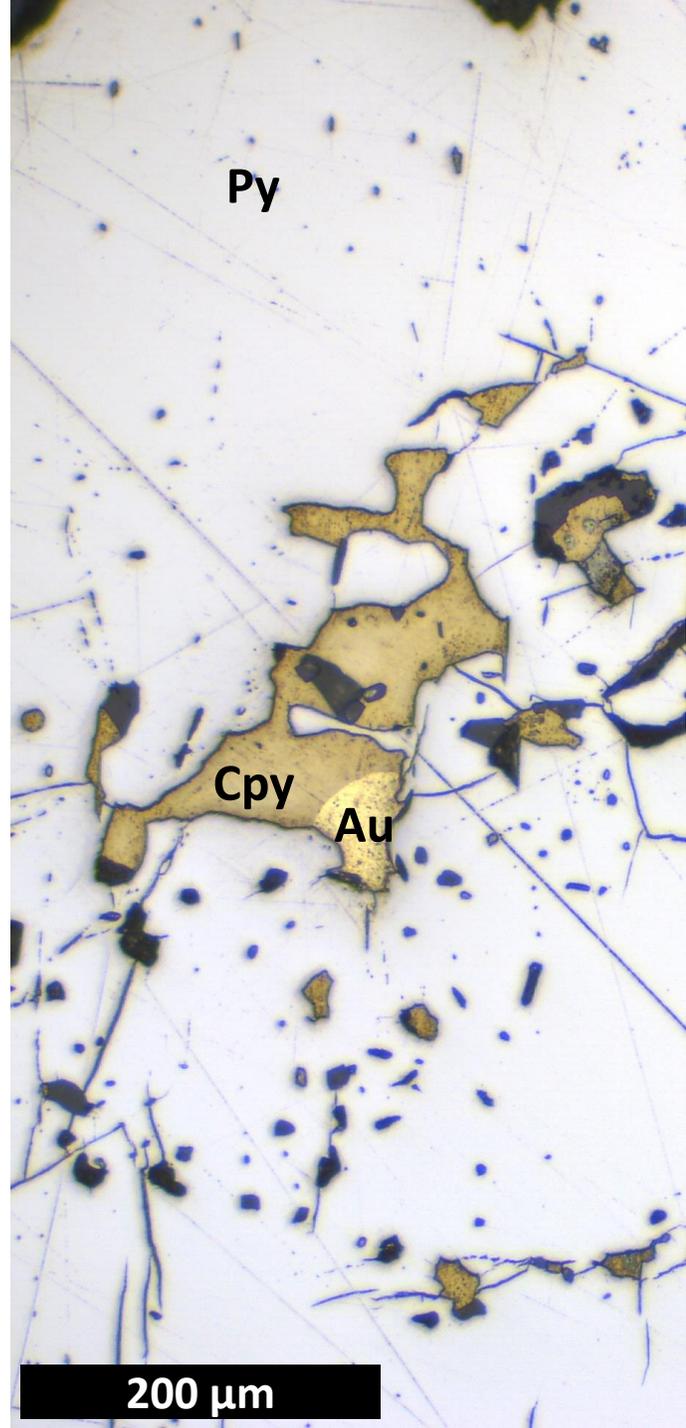
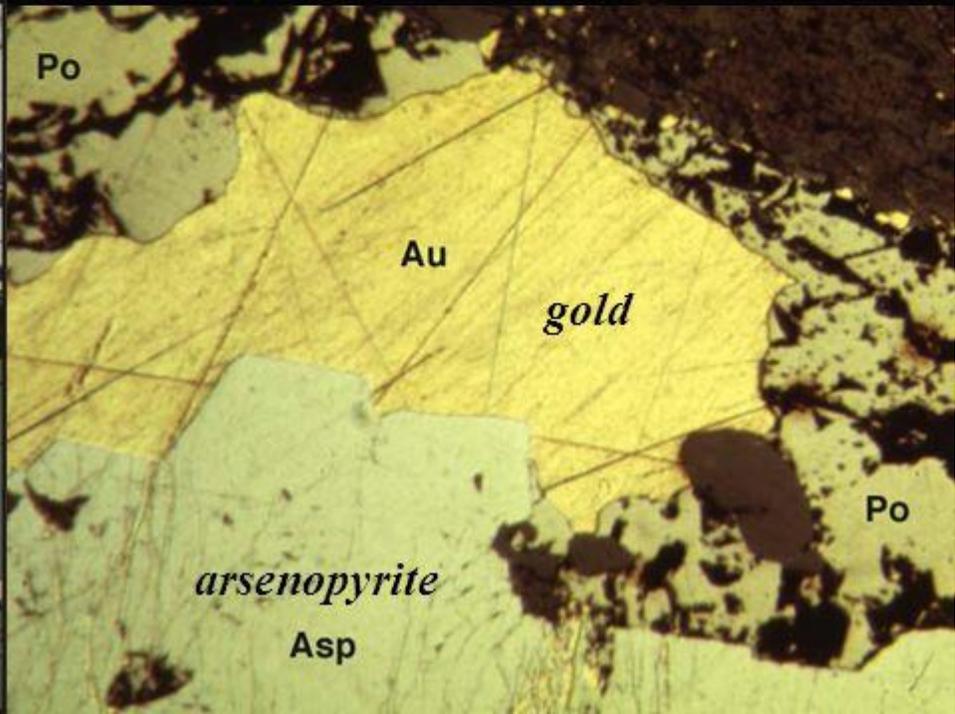
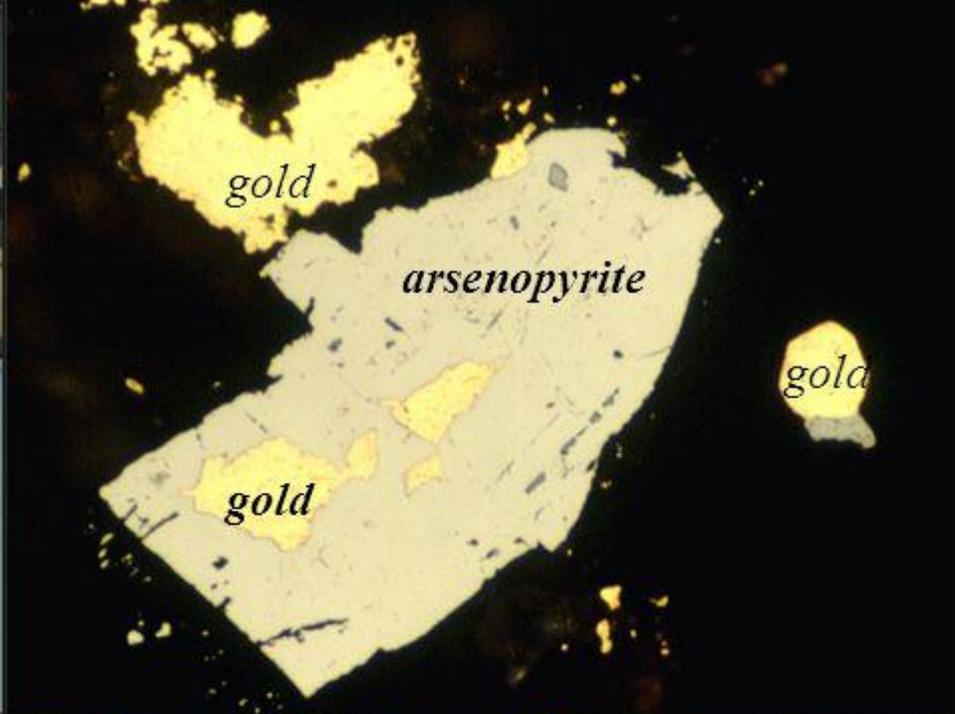
*Pórfiros Au-(Cu)
Epitermais
IOCG
Au orogenético
Intrusion-related (IRGS)
Skarn*

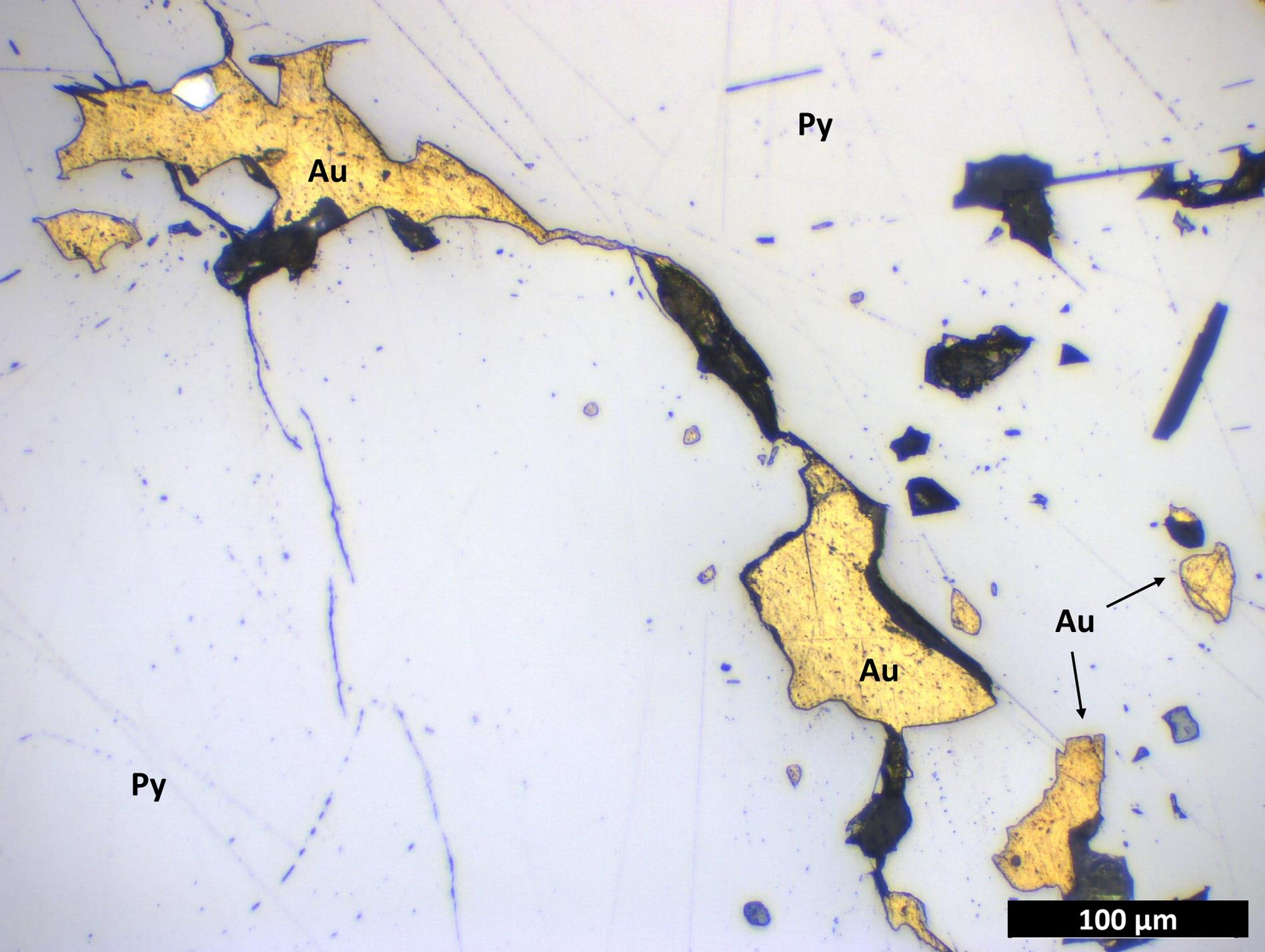


SEDIMENTARES E LATERÍTICO

*Placers e Paleoplacers
Au Laterítico*







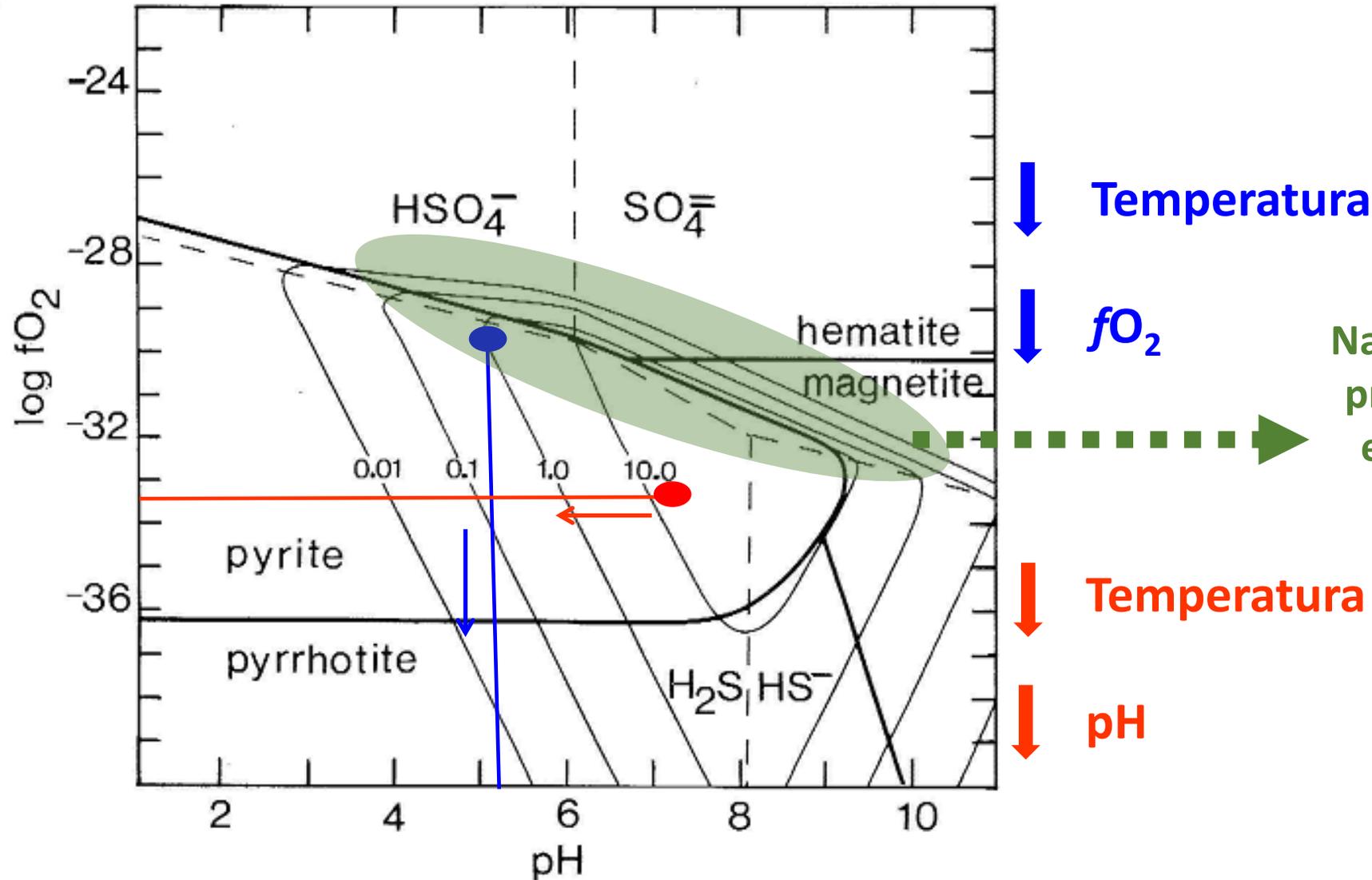
**Minério aurífero da
Província de Alta
Floresta (MT)**

**Depósito Pé Quente
Pirita – Au**

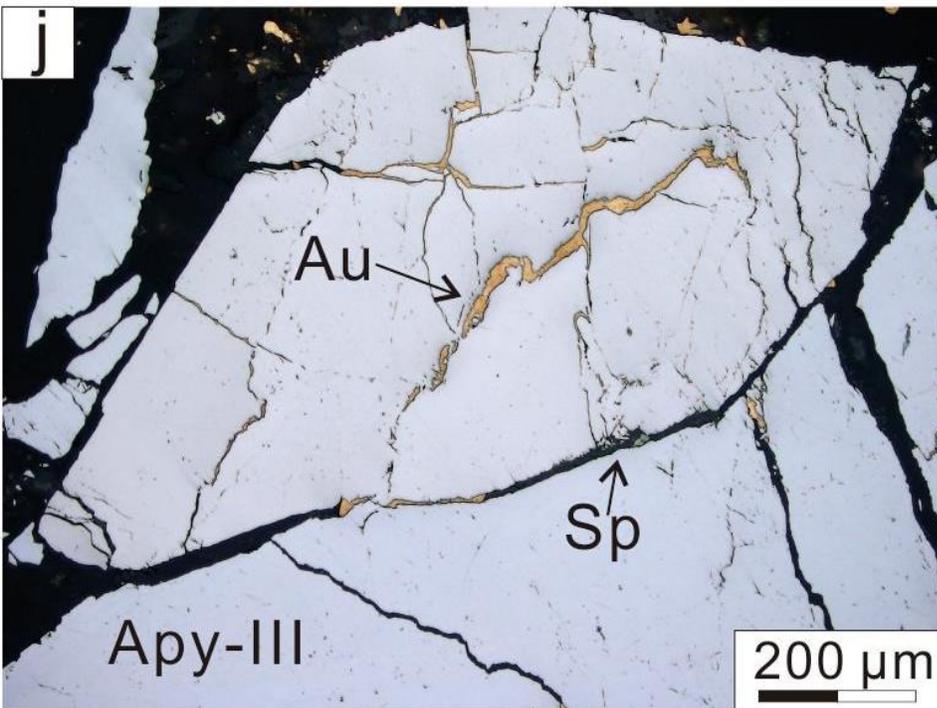
Fonte:
Meyer (in prep.)

100 μm

PRECIPITAÇÃO DO OURO A PARTIR DE FLUIDOS METAMÓRFICO-HIDROTERMAIS

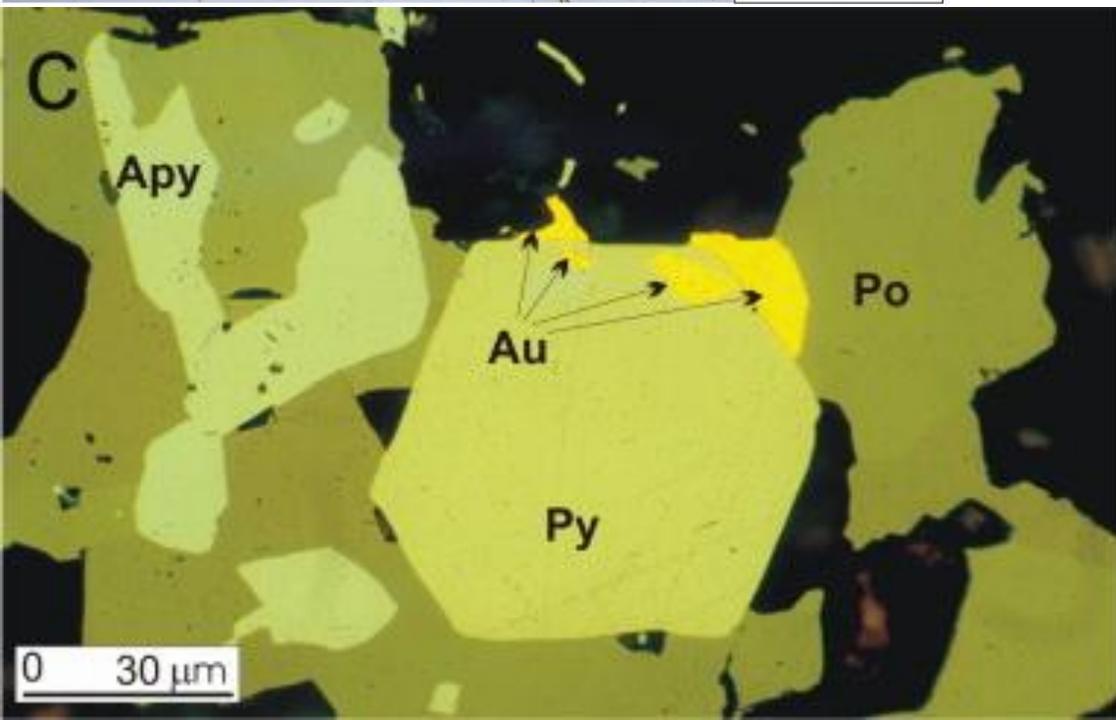
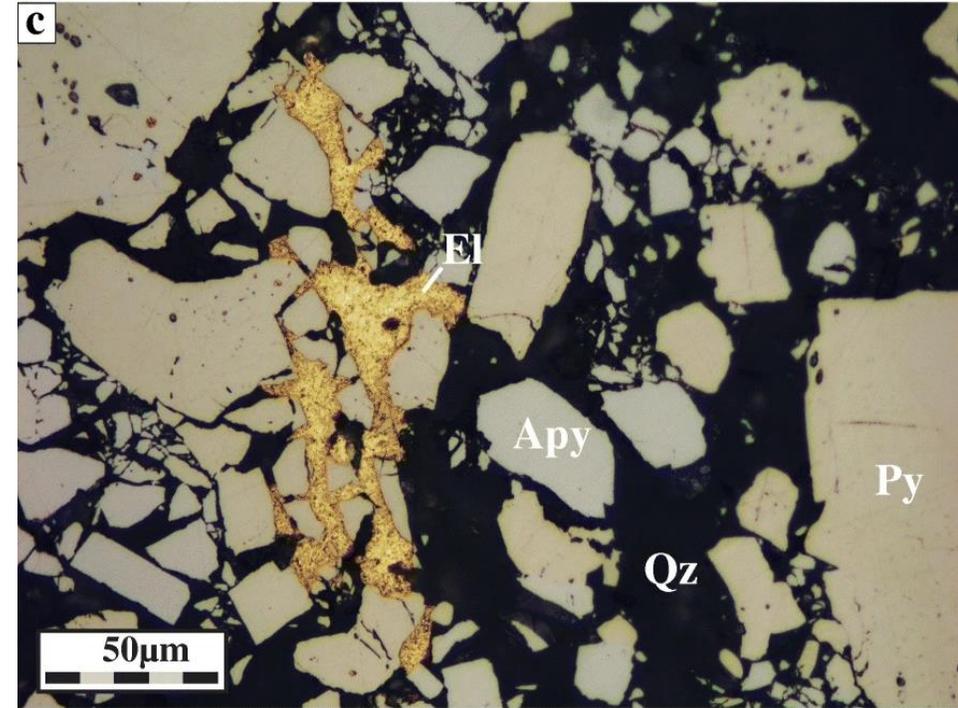


Na prática, o melhor mecanismo de precipitação corresponderá àquele em que ocorre maior precipitação com menores oscilações das condições físico-química.



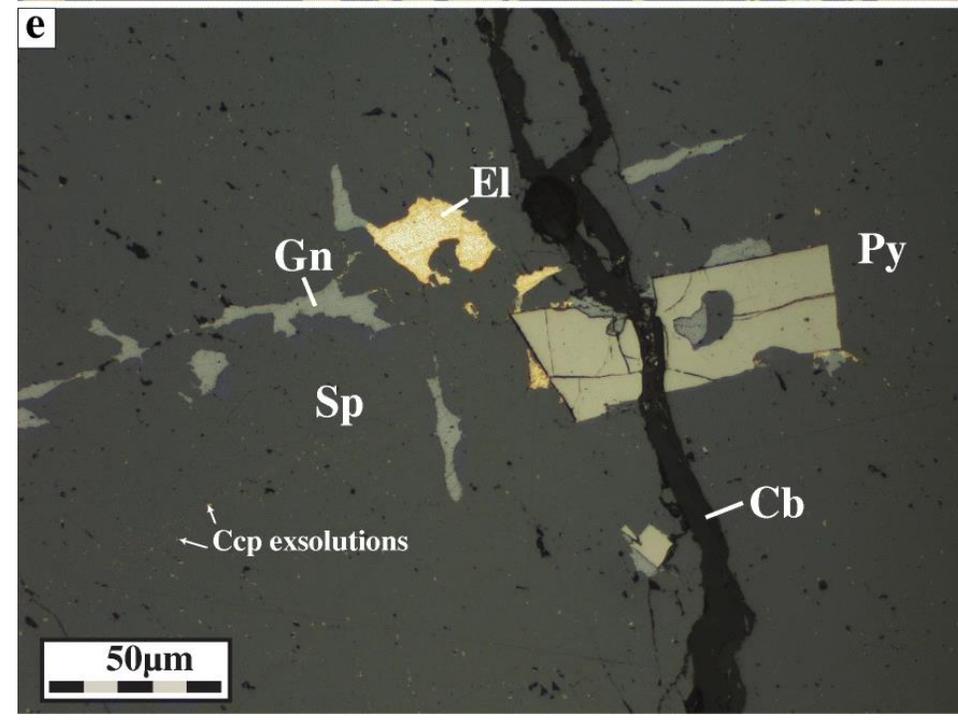
◀ (J) Irregular to regular arsenopyrites (Apy-III) aggregates with two colors as light-white (upward) and off-white (downward), and native gold preferentially occurred in various fractures of irregular one (Sun et al., 2020).

(C) Pyrite partially replaced by arsenopyrite with quartz in fractures and electrum occupying interstitial position (Voute et al., 2019) ▶



(E) Sphalerite showing classic chalcopyrite exsolution with later precipitation of galena together with electrum (Voute et al., 2019) ▶

◀ (C) Reflected polarized light image of the sulphide-gold ore mineralogy (Kolb et al., 2015).



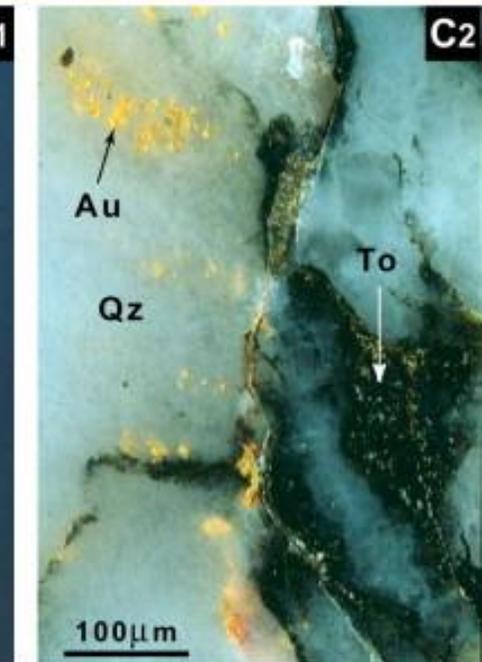
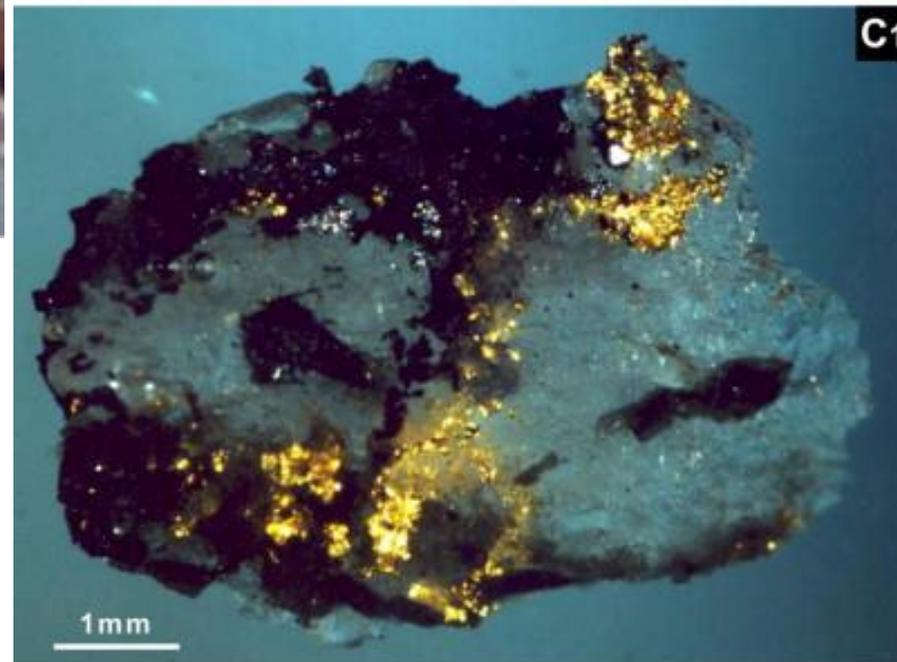
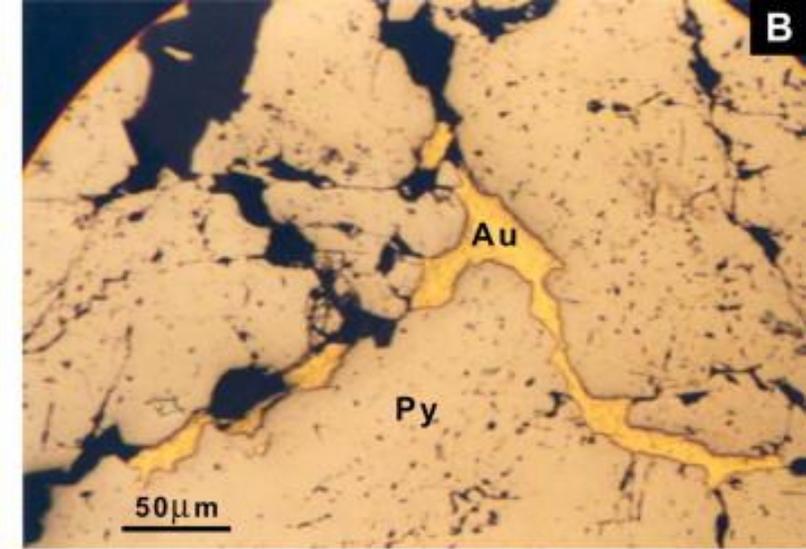
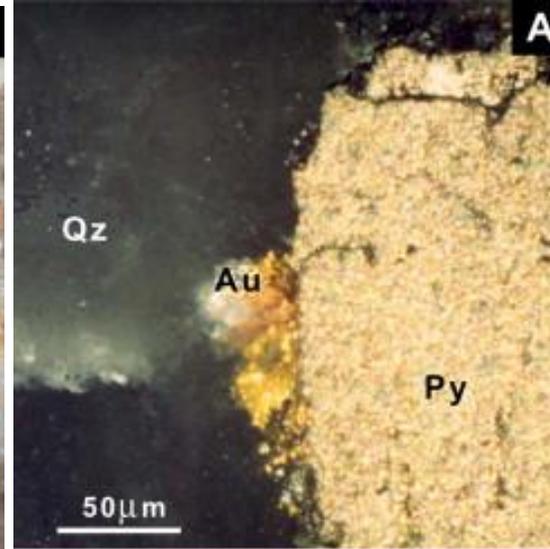


Fig. 6. Petrographic observations of ore minerals in hand sample and polished section (reflected light): (A) Sample Tap7; gold along pyrite faces and between quartz-fibres (Taparko). (B) Sample GanFB1; gold in fractures cross-cutting pyrite crystals (Gangaol). (C) Sample GuiBKP; C1 (hand specimen), C2 (polished section); gold at the tips of tourmaline crystals (Guibaré). (D) Sample GanFB7; supergene gold in pyrite boxworks within quartz fibres (Gangaol).

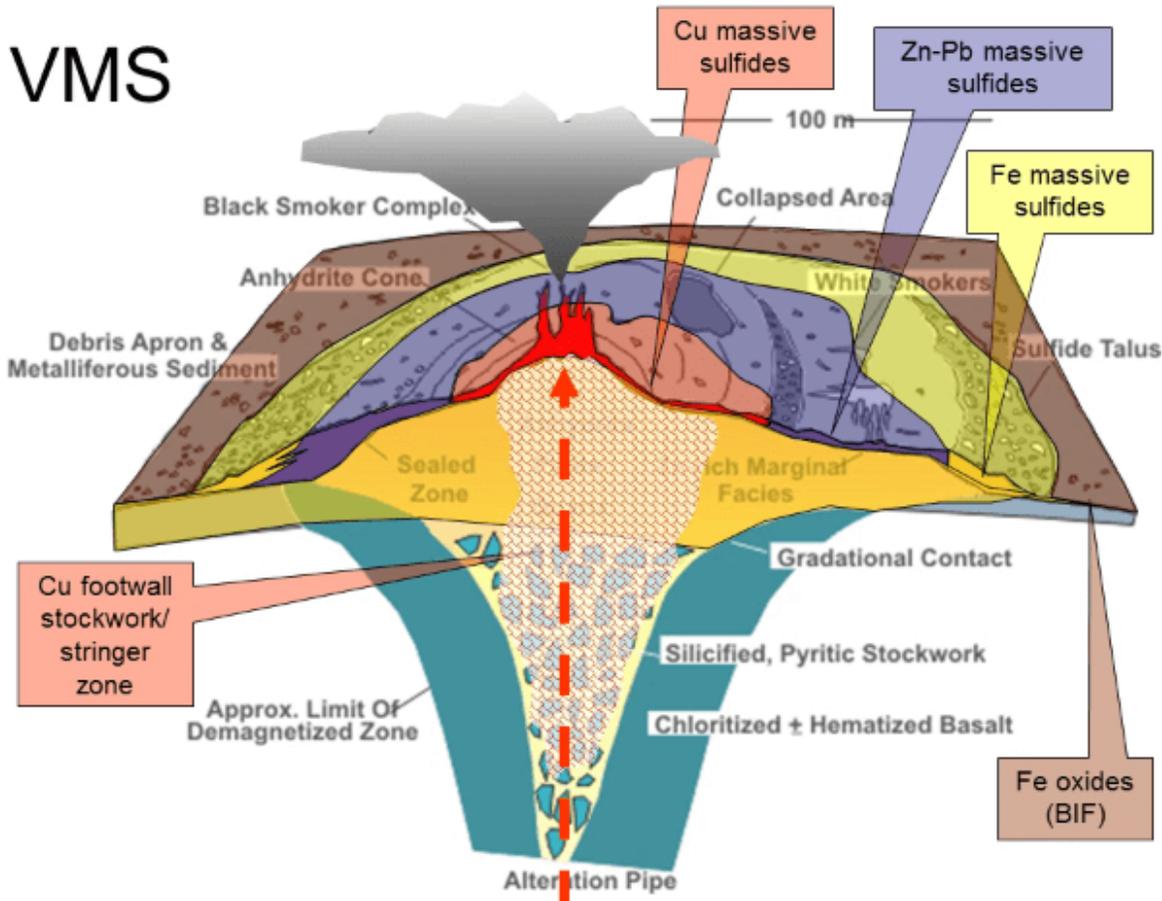
FONTE:

Béziat et al. (2008)

<https://www.sciencedirect.com/science/article/pii/S1464343X07001744#fig9>

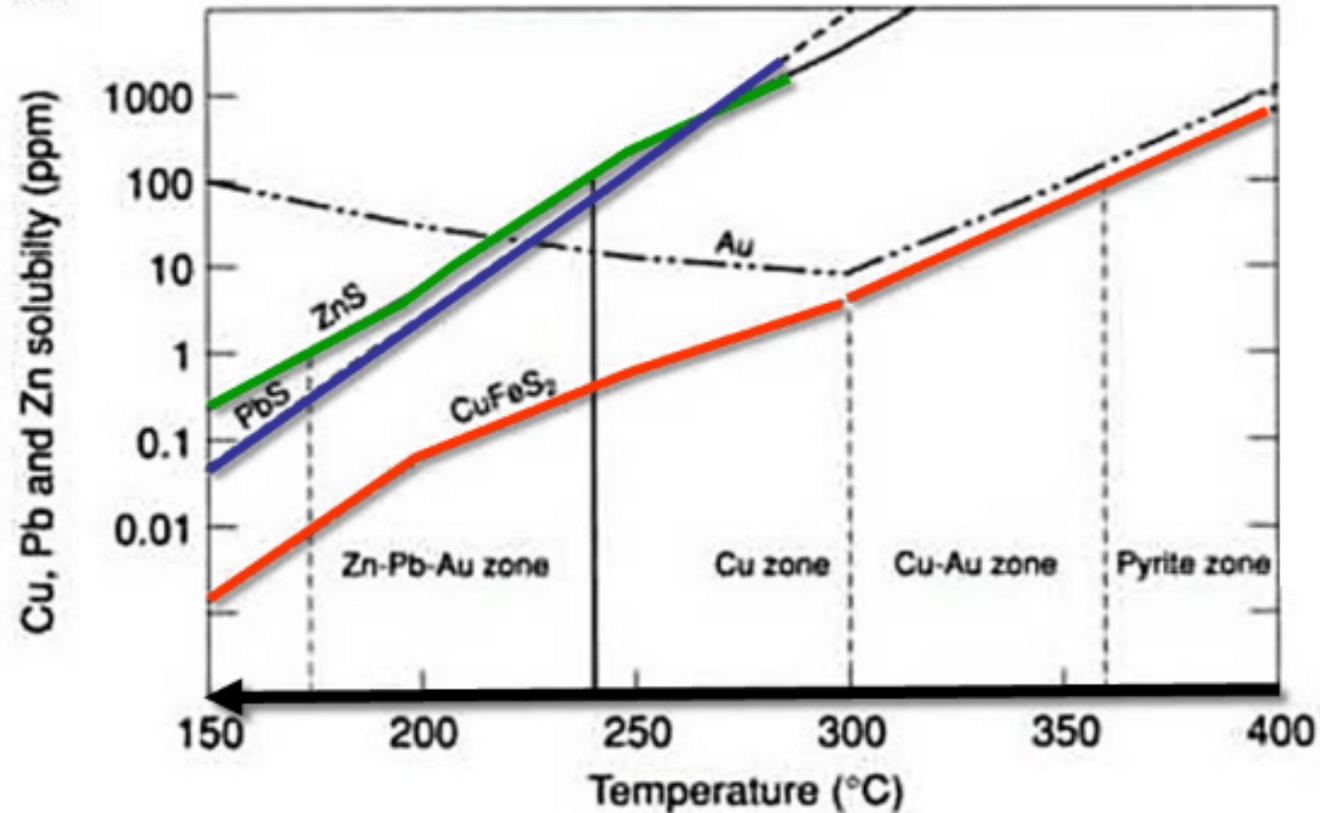
PRECIPITAÇÃO DO OURO A PARTIR DE FLUIDOS MARINHO-HIDROTERMAIS (SISTEMA VHMS)

VMS



Solubilidade dos metais em sistemas VHMS

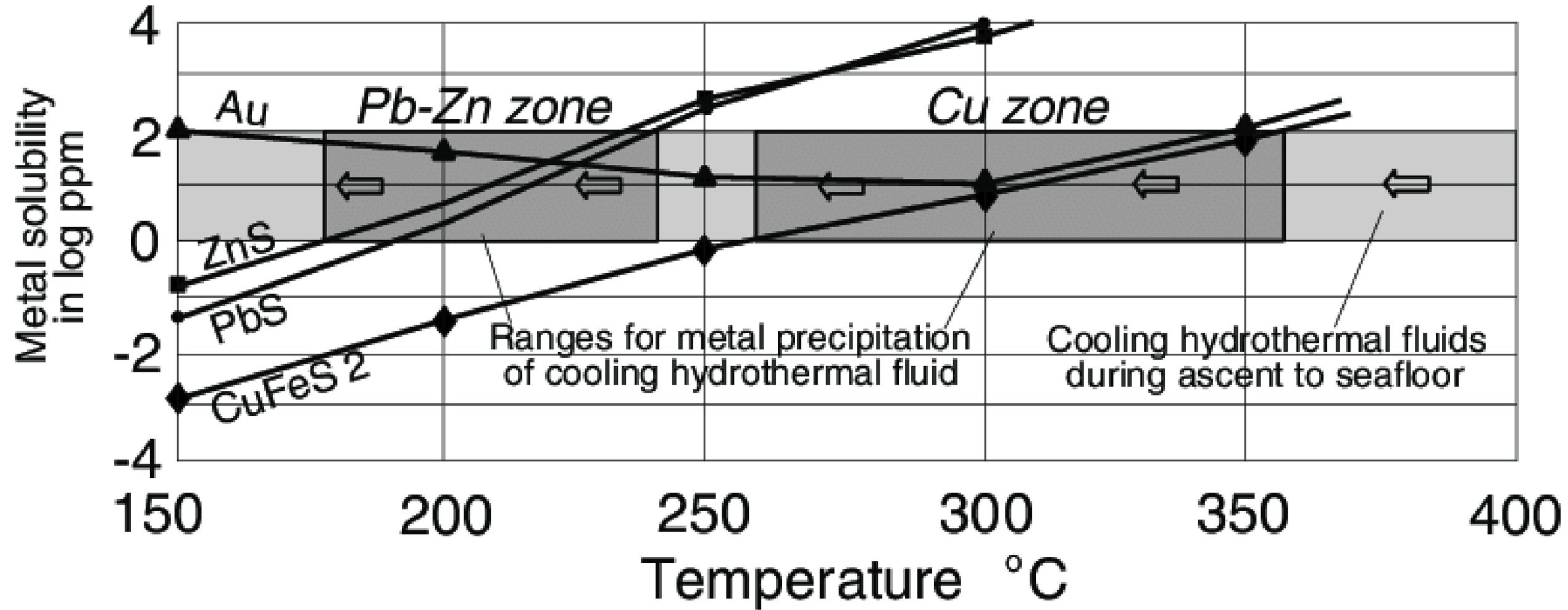
(b)



FONTE:

<https://www.911metallurgist.com/blog/vms-volcanogenic-massive-sulphide-deposits-ore-mineralization>

PRECIPITAÇÃO DO OURO A PARTIR DE FLUIDOS MARINHO-HIDROTERMAIS (SISTEMA VHMS)

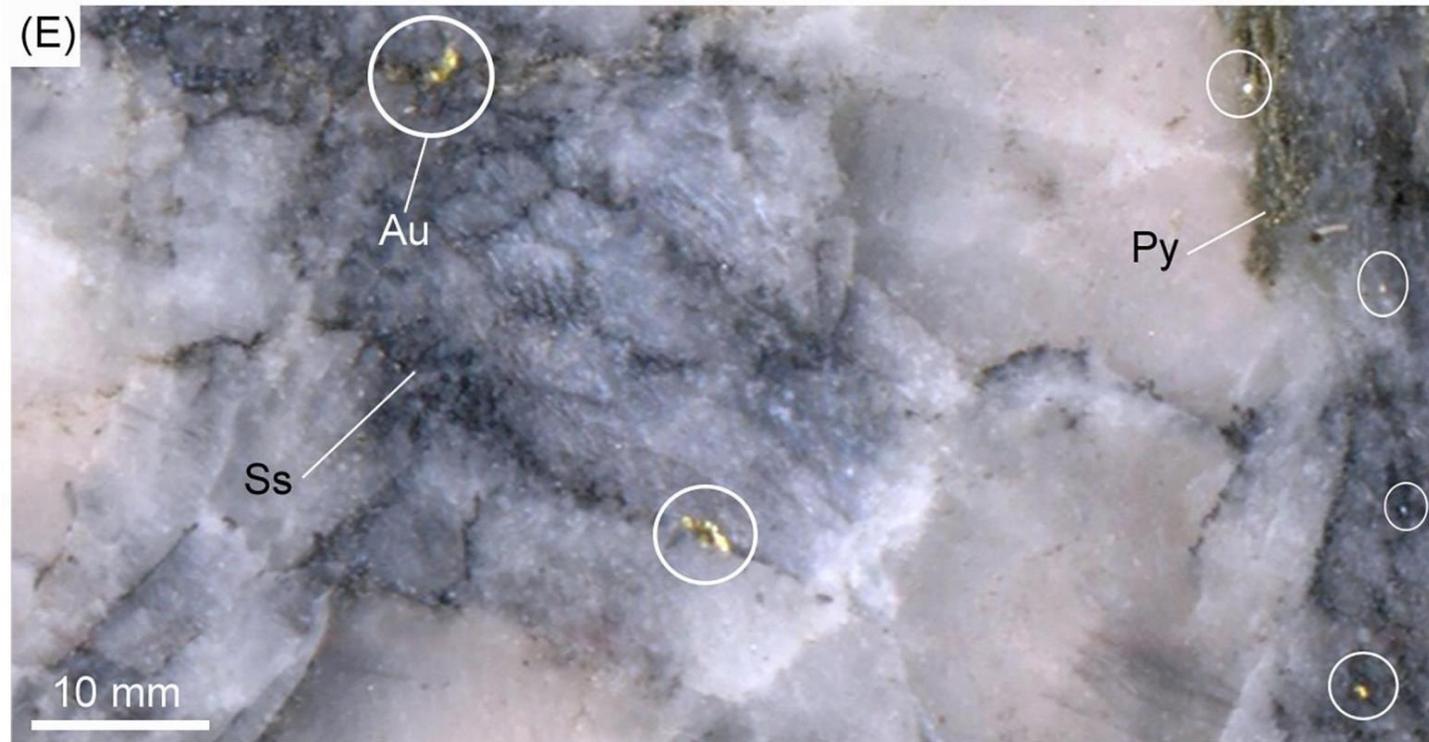


FONTE:

Barrie et al (1999)

<https://www.researchgate.net/publication/266734256> Heat and Fluid Flow in Volcanic-Associated Massive Sulfide-Forming Hydrothermal Systems

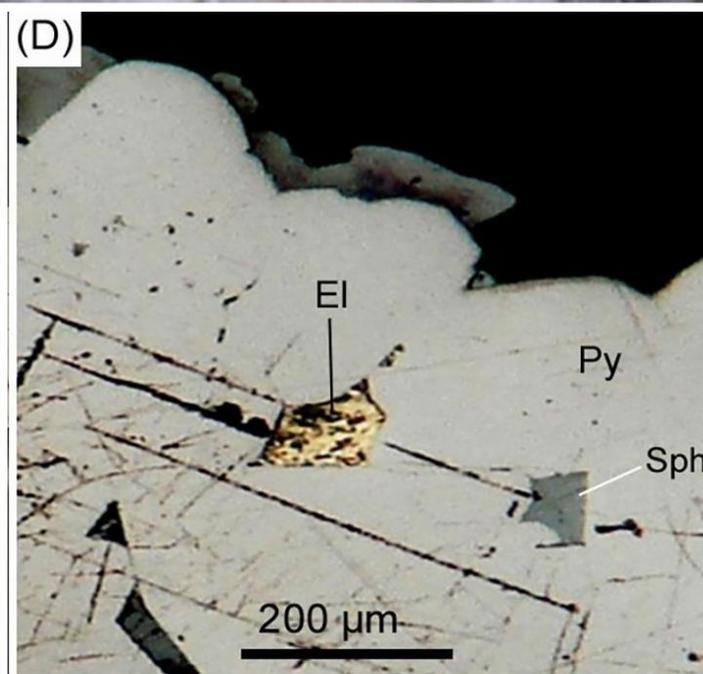
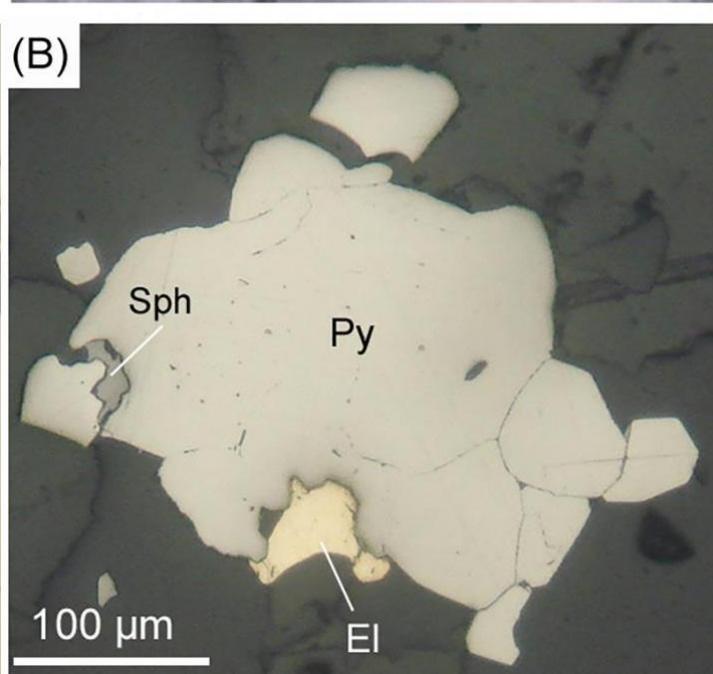
The Barika gold-bearing Kuroko-type volcanogenic massive sulfide (VMS)



(B) euhedral to subhedral pyrite grains showing triple junctions in massive and semi-massive mineralizations with electrum in its ridges;

(D) Brittly deformed siliceous exhalite bands.

(E) Electrum filling interstices between recrystallized pyrite grains is formed during regional metamorphism.



Mineral abbreviations:

(Py) pyrite; (Sph) sphalerite; (El) electrum; (Ss) sulfosalt.

Fonte:

Tajeddin et al. (2019)

https://www.sciencedirect.com/science/article/pii/S0169136819301684?casa_token=q8Hku1YVVNoAAAAA:7x5haV0Bjq1ZNyZLYZQLMRQBDLO7TMYaiKBv7XBe7XF1tMISaeJW0XUaZTt-1USIMM7kgLtruYo#f0060

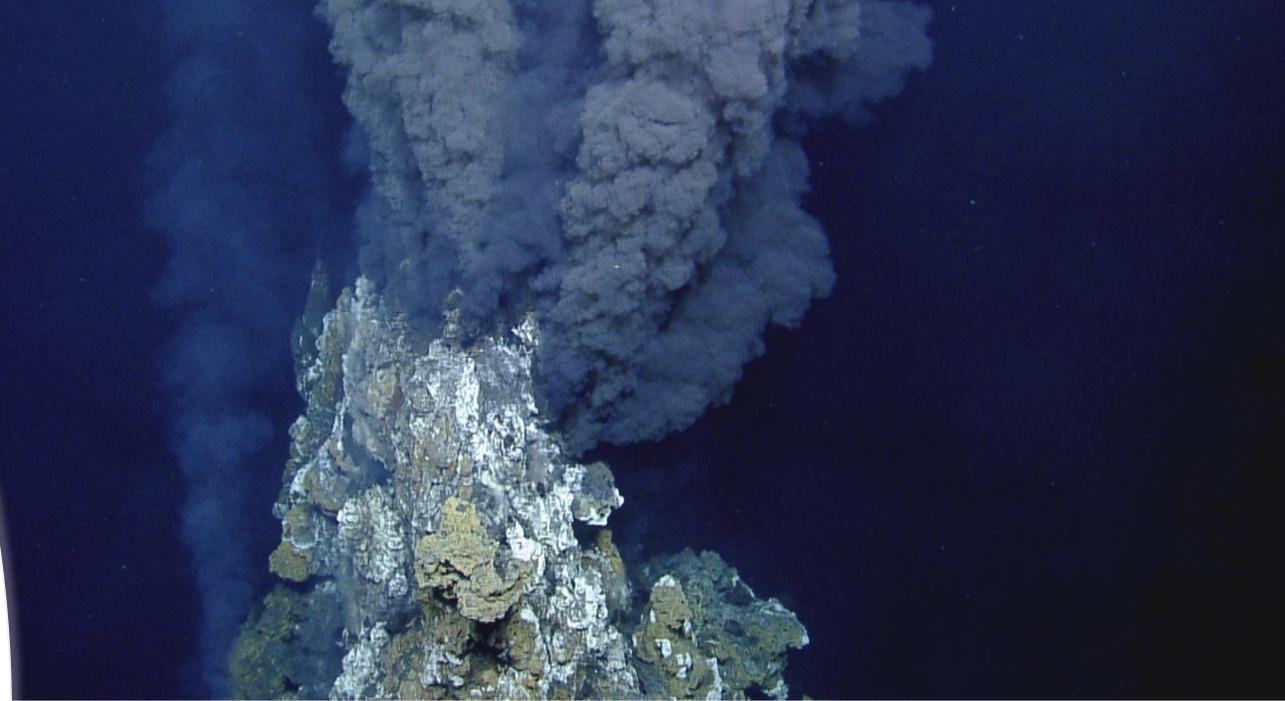
PRINCIPAIS DEPÓSITOS DE PRATA

→ Sistemas VHMS (*volcanic-hosted massive systems*)

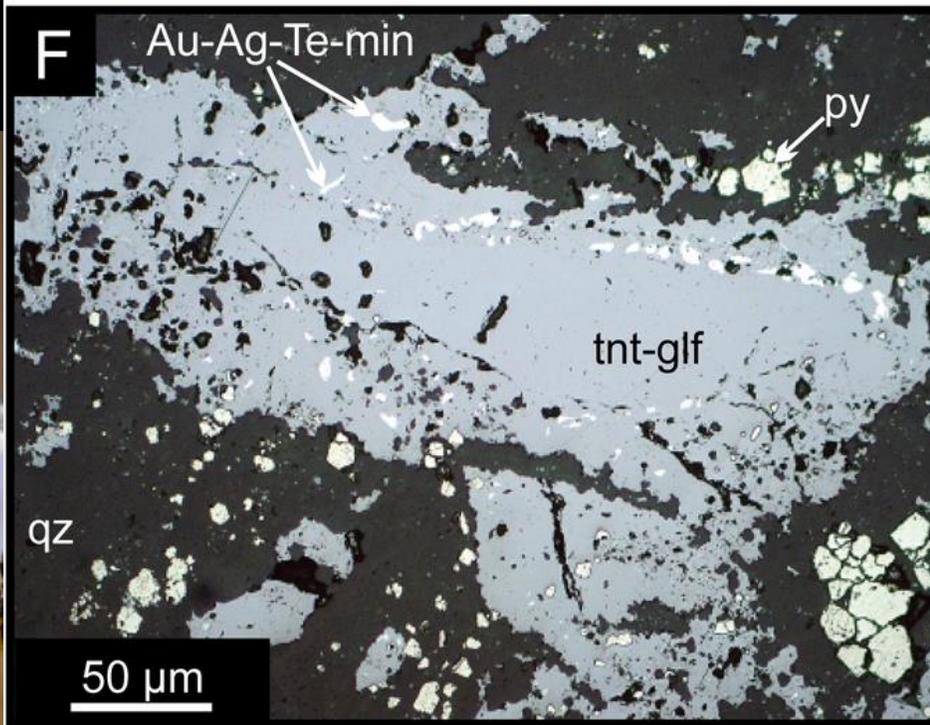
Sistemas marinho-hidrotermais vinculados à percolação de fluidos em assoalho oceânico, devido a vulcanismo submarino (fumarolas)

→ Sistemas Epitermais (*high e low sulfidation*)

Principais fontes de prata. Sistemas magmático-hidrotermais relacionados à atividade vulcânica cálcio-alcálica.



PRATA NATIVA – Ag



◀ **FONTE:**
Takács et al., 2017;

COR

Branca a cinza muito claro, mais clara do que a galena.

REFLECTÂNCIA

Extremamente alta (~82-83%).

PLEOCROÍSMO

E

BIRREFLECTÂNCIA

Ausentes

ANISOTROPIA

Deveria ser isotrópica, porém, com anisotropia anômala por conta dos sulcos de polimento.

OUTRAS CARACTERÍSTICAS

Baixo relevo, reflectância muito alta (diagnósticas)

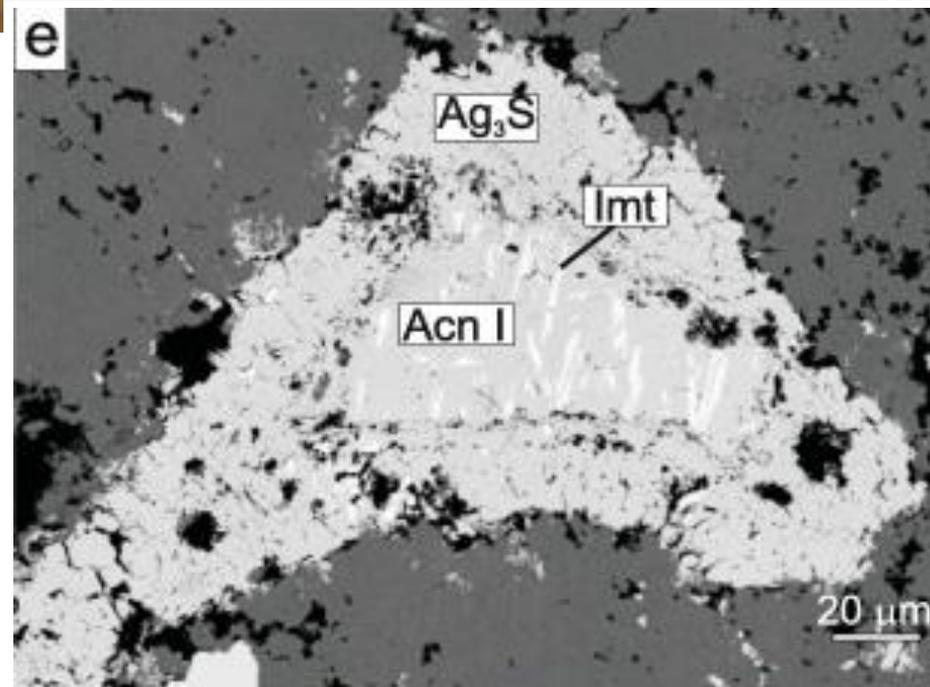
FONTE: ▶
Baksheev et al., 2018



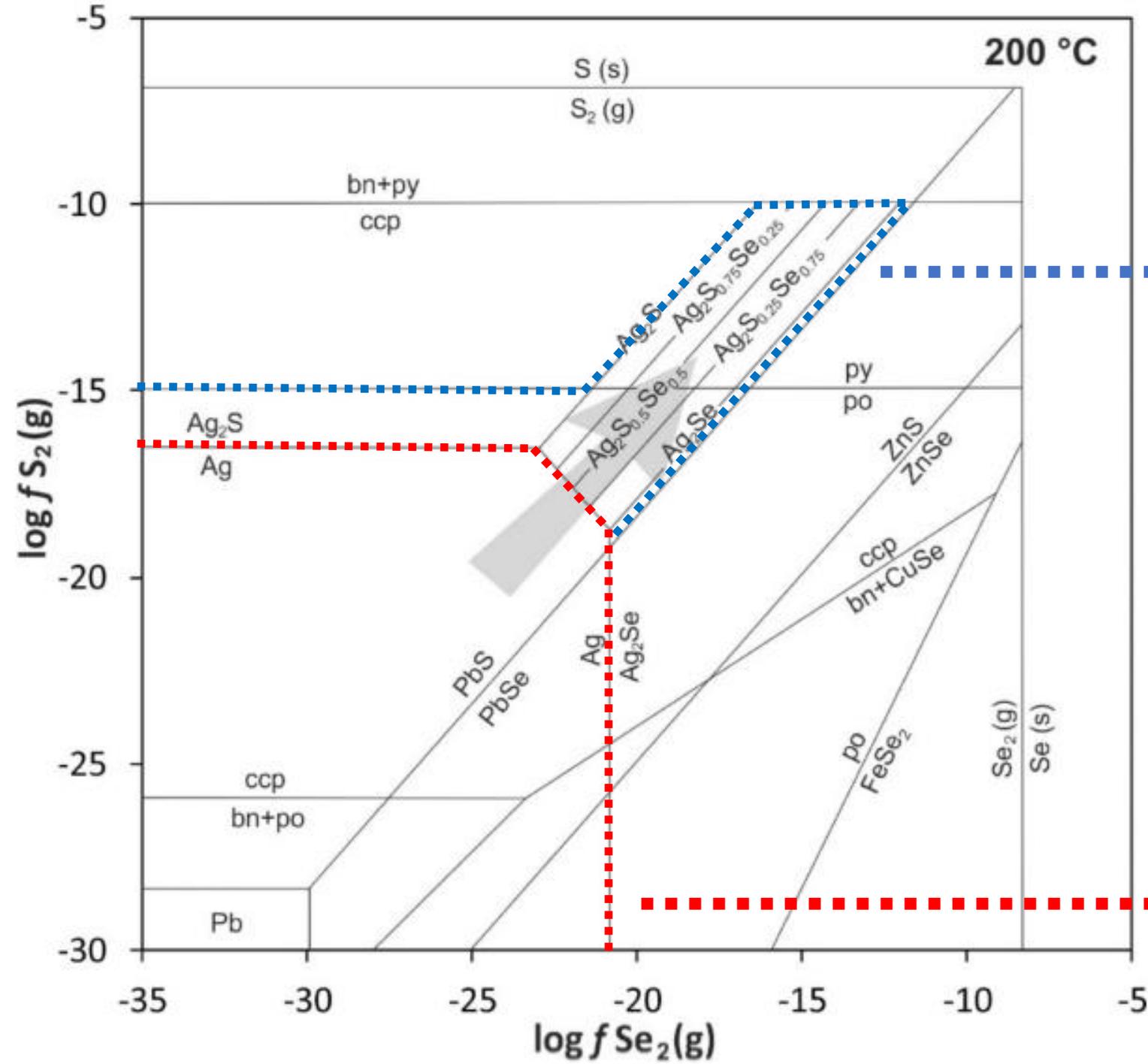
Heinrich Frank

PRATA NATIVO → LUZ REFLETIDA
(POLARIZADORES DESCRUZADOS E CRUZADOS)

https://www.youtube.com/watch?v=Y_ct2_1gBYw&list=PL5k_2NCH5I4Dg34kl1Niy4xnxsPsO2akl



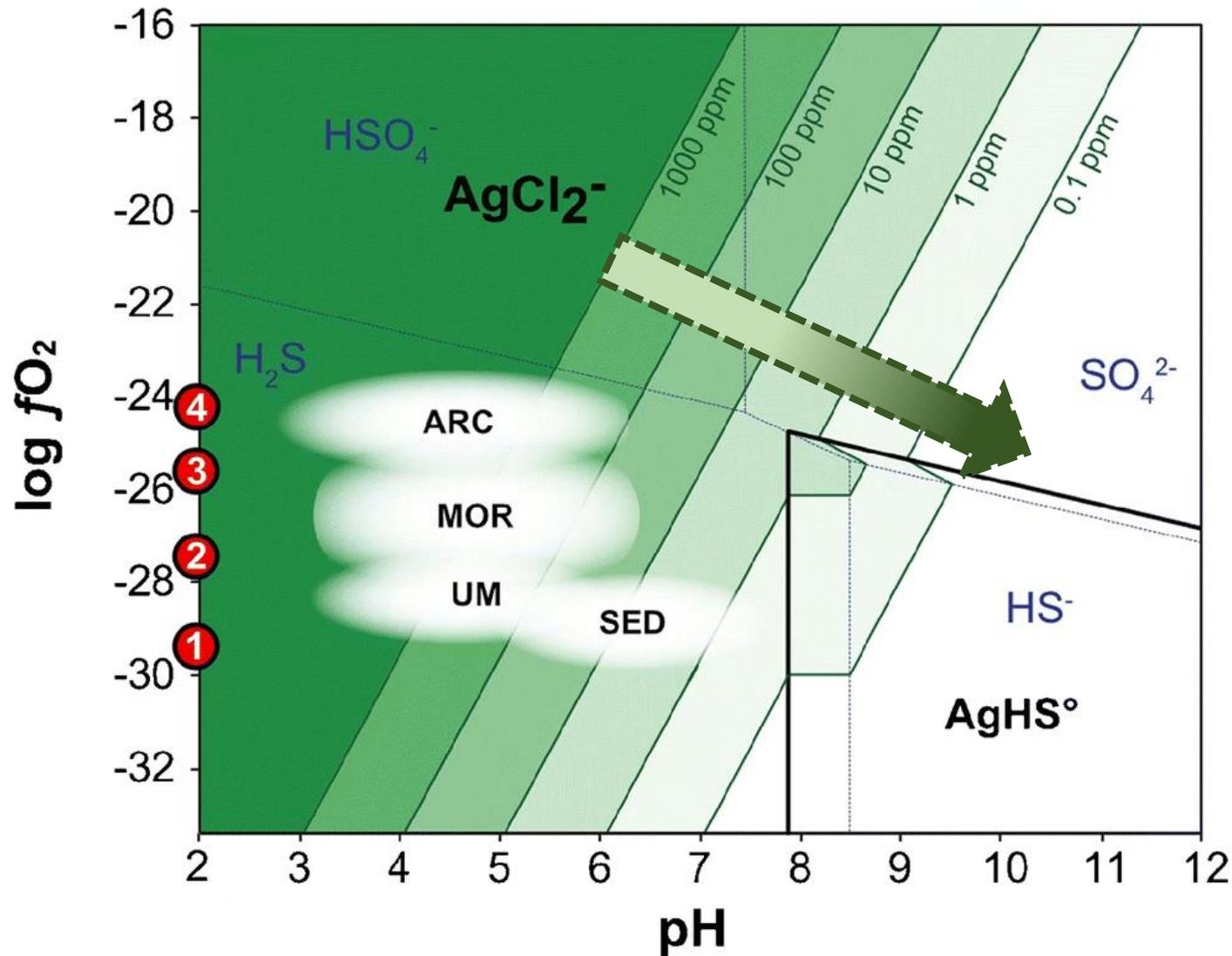
PRINCIPAIS DEPÓSITOS DE PRATA → EPITERMAIS



Sulfetos e selenetos de Ag
Baixas condições de f_{S_2} e f_{Se_2}

Prata nativa (Ag)
Condições muito baixas
de f_{S_2} e f_{Se_2}

PRINCIPAIS DEPÓSITOS DE PRATA → VHMS



Phase diagrams of hydrothermal fluids under “reaction zone” conditions at 400 °C, 500 bar, 0.5 m Cl⁻ (seawater) and quartz saturation:

Show the solubility contours for native silver from 0.1 to 1000 ppm. The labeled red circles refer to redox buffers in a expressed as $\log f_{O_2}$. The white-shaded ellipses indicate the approximate ranges of pH and $\log f_{O_2}$ for the corresponding fluids in mid-ocean ridge settings (MOR), ultramafic rock-hosted (UM), sediment-hosted s (SED), and arc-related systems (ARC).

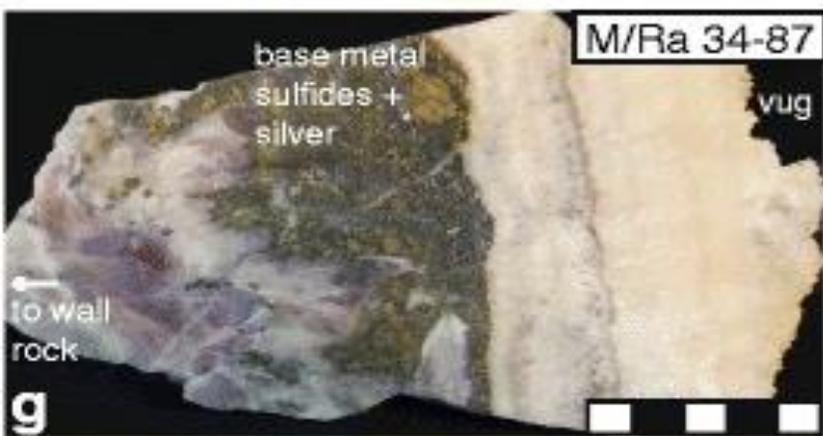
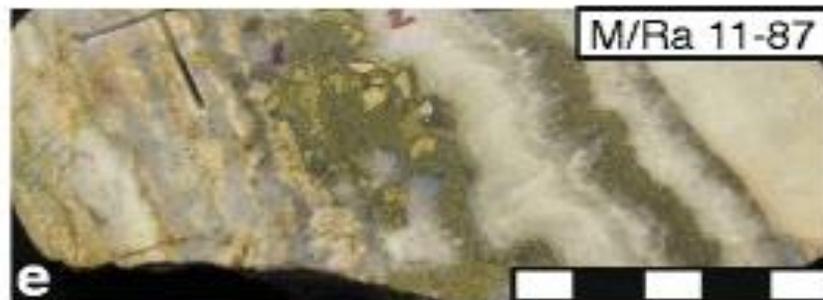
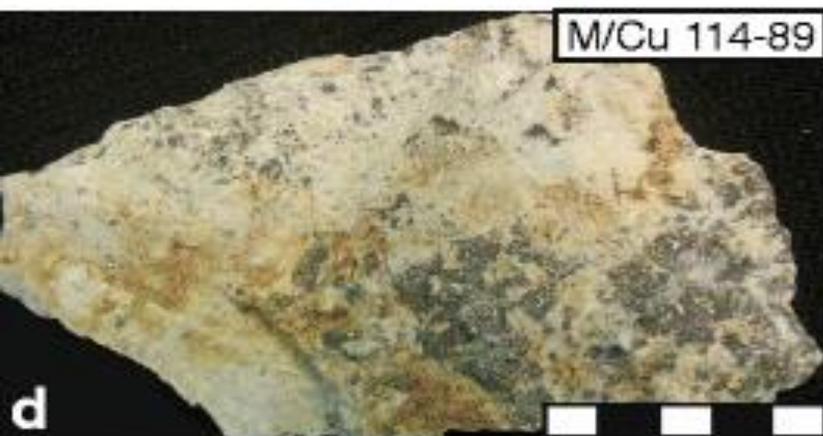
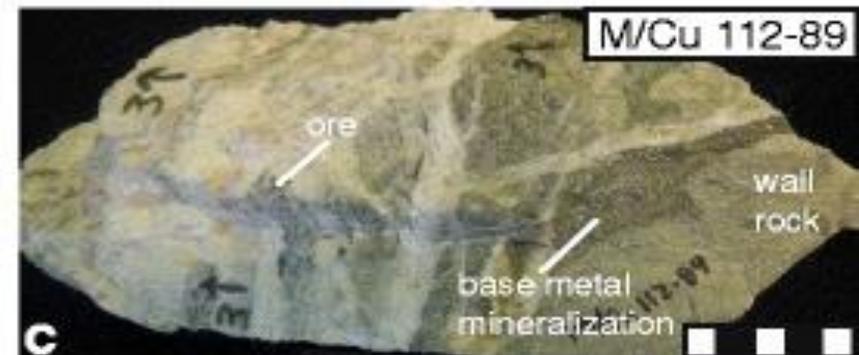
FONTE:

Fuchs et al. (2019)

<https://link.springer.com/article/10.1007/s00126-019-00895-3>

Em sistemas vulcanogênicos de fundo oceânico, a Ag tende a precipitar com o aumento do pH e redução da f_{O_2} .

SISTEMAS EPITERMAIS → ENRIQUECIDOS EM Ag e Au (MINÉRIO TIPO BONANZA)

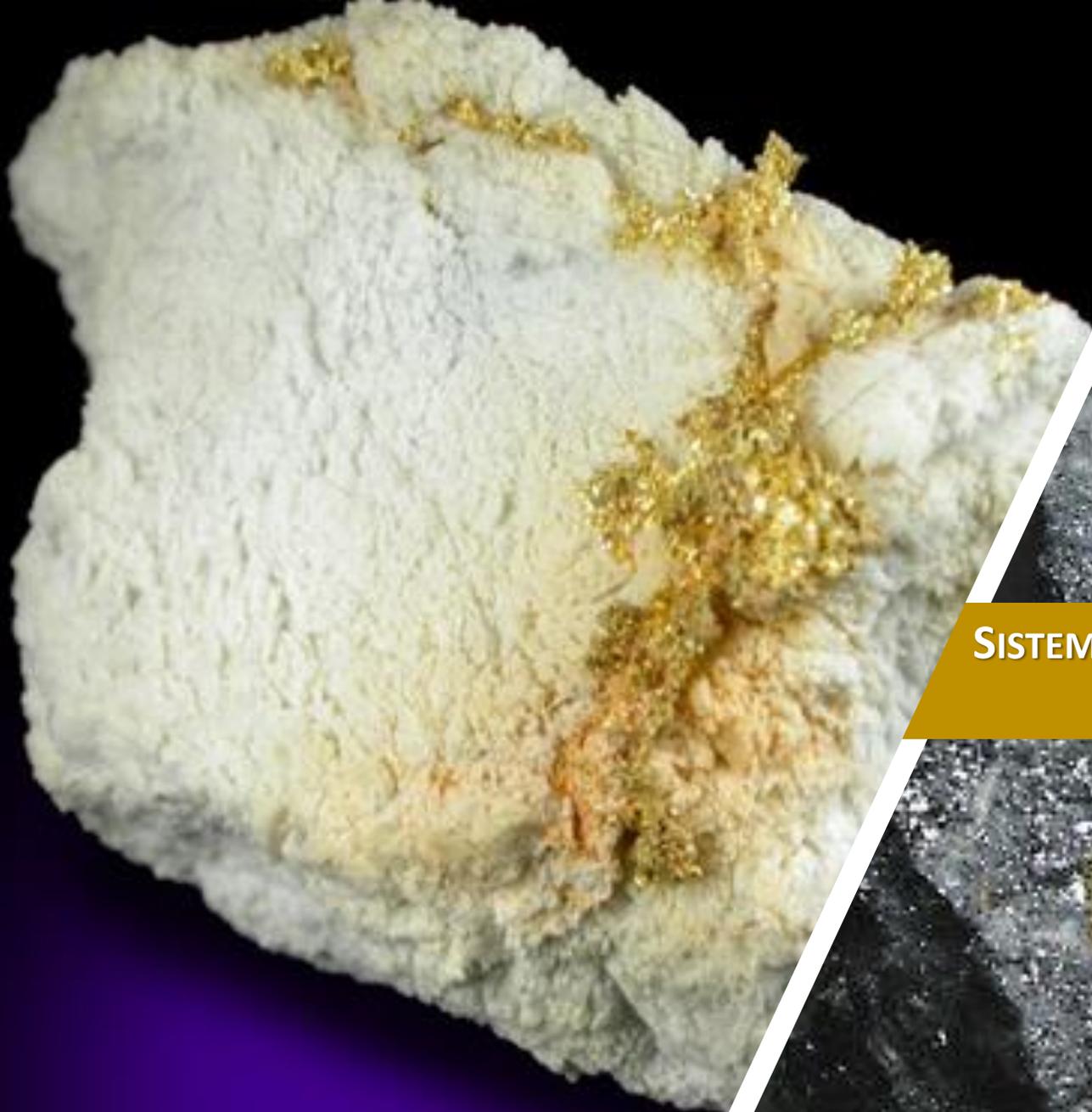


Photographs of hand samples of representative styles of mineralization. In every photograph, the scale bar is 5 cm. (Note that these photographs were taken indoors, which has affected the colors somewhat.) a M/Ce 77–89 (Cebada mine): mineralization consists of fine-grained dots and layers of silver sulfides and sulfosalts, with minor base metal sulfides, in the brecciated material on the left side of the sample; banded white quartz, fine-grained colorless quartz, chalcedony, coarse amethyst, and calcite+sericite are barren. b M/Ce 90–89 (Cebada mine): symmetrically banded vein with colloform crustiform banding; mineralization (silver sulfides and sulfosalts and minor base metal sulfides) in dark bands near wall rock; center filled with barren colorless clear quartz, white quartz, and amethyst. c M/Cu 112–89 (Cubo mine): wall rock and vein breccia; base metal sulfides along vein in wall rock fragment, and precious metal mineralization (electrum and silver sulfides and sulfosalts) as dark dots. d M/Cu 114–89 (Cubo mine): high-grade mineralization (100–200 g/ton Au, 2,000 g/ton Ag) as dots and small masses in fine-grained white quartz. e M/Ra 11–87 (Rayas mine): multiple-banded colloform crustiform vein with coarse base metal sulfides (largest crystals are chalcopyrite and pyrite); silver mineralization and electrum are in base metal sulfide layers. f M/G 39–88 (Guanajuatito mine): cockade banding of white quartz and coarse amethyst around host rock (altered Esperanza Fm.) with rare bladed calcite. g M/Ra 34–87 (Rayas mine): typical “Clavo de Rayas” ore (1 g/ton Au, 600 g/ton Ag) with coarse-grained galena, sphalerite, chalcopyrite and pyrite, with coarse amethyst and multiple-banded crustiform white and colorless quartz and calcite; wall rock to left, open space in center of vein to right. h M/Ra 41–89 (Rayas mine): ore breccia consisting of highly altered host rock and vein fragments rimmed with base metal sulfides, silver sulfides and sulfosalts, and electrum; ore mineralization also scattered in quartz breccia cement and as very thin layers in banded quartz and chalcedony. i M/T 8–89 (Torres mine): typical vein calcite and host rock (silicified Bufa Fm.); silver-bearing minerals as small dots in the center of coarse calcite vein.

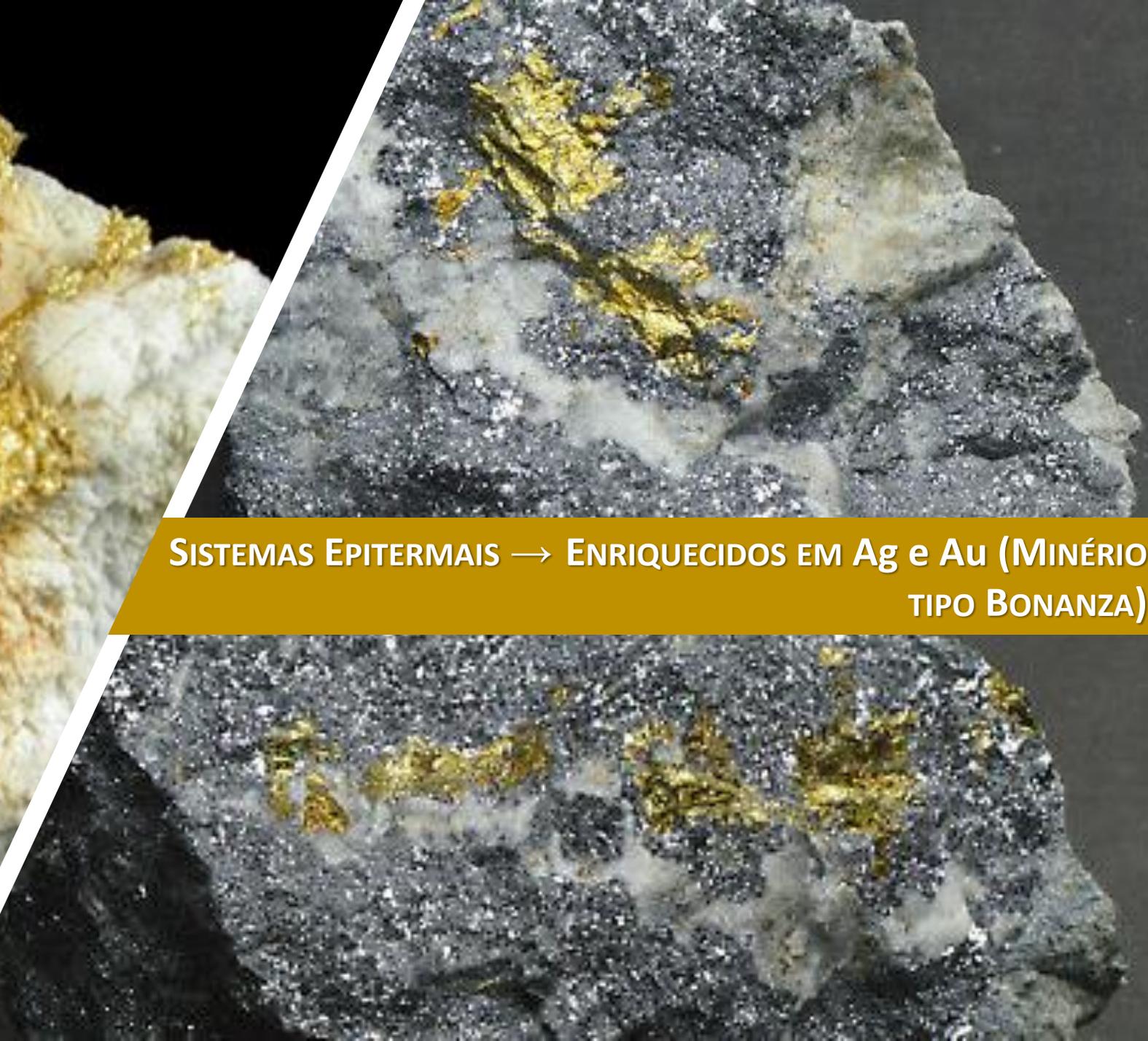
FONTE:

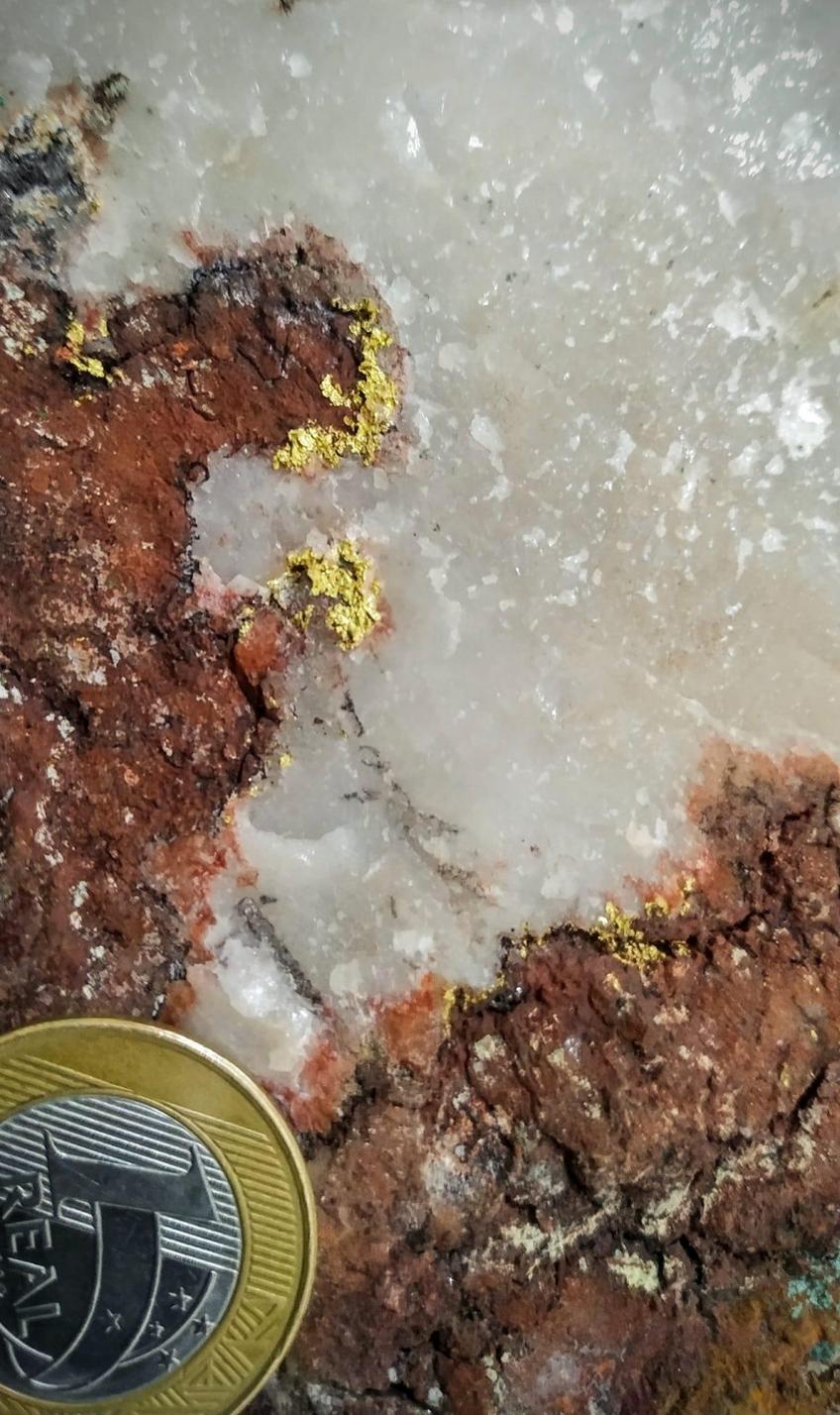
Mango et al. (2013)

<https://link.springer.com/article/10.1007/s00126-013-0478-z>



SISTEMAS EPITERMAIS → ENRIQUECIDOS EM Ag e Au (MINÉRIO TIPO BONANZA)





◀ **Minério aurífero do tipo bonanza**

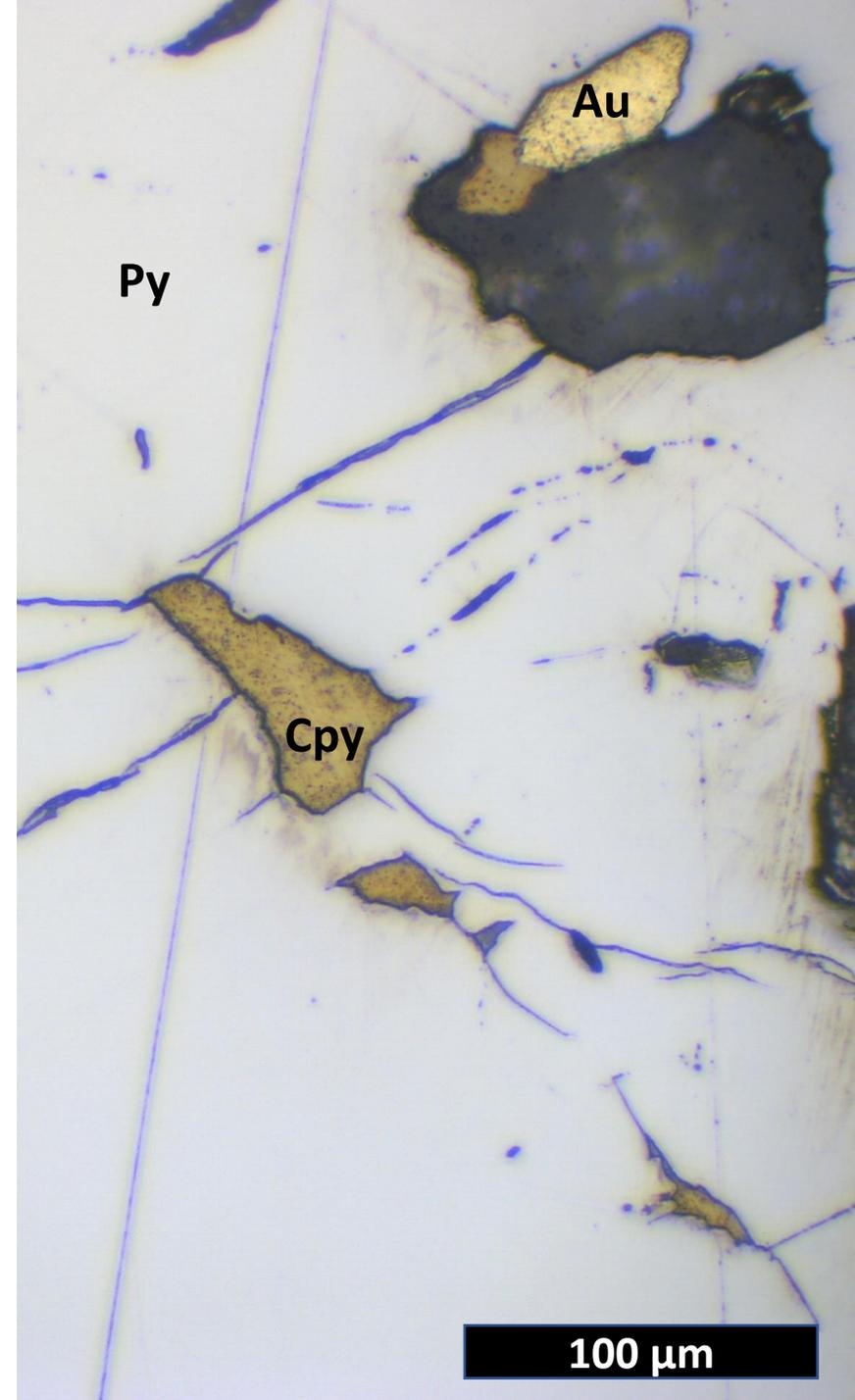
Província de Alta Floresta (MT).

Veio de quartzo + Au em granitoide hidrotermalizado.

Minério aurífero sulfetado ▶

Província de Alta Floresta (MT).

Inclusão de Au e Calcopirita em pirita (Depósito Pé Quente).



PRINCIPAIS DEPÓSITOS DE PLATINA

→ Depósitos de Sulfeto Magmático
(*Filiação magmática*)

Ligas de EGP associadas a sulfetos magmáticos em depósitos geneticamente atrelados à cristalização de magmas ultramáficos (*fundido silicático e sulfetado imiscíveis*).



→ *Placers e Paleoplacers* de platinóides
(*Sistemas sedimentares detríticos*)

Concentrações detríticas de platinóides (mineral de alta densidade; $d = 12-21,5 \text{ g/cm}^3$) concentrados em níveis cascalhentos de sistemas fluviais e glaciais.



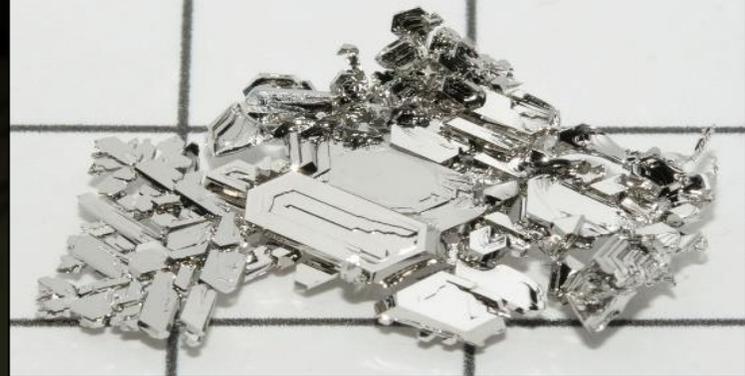
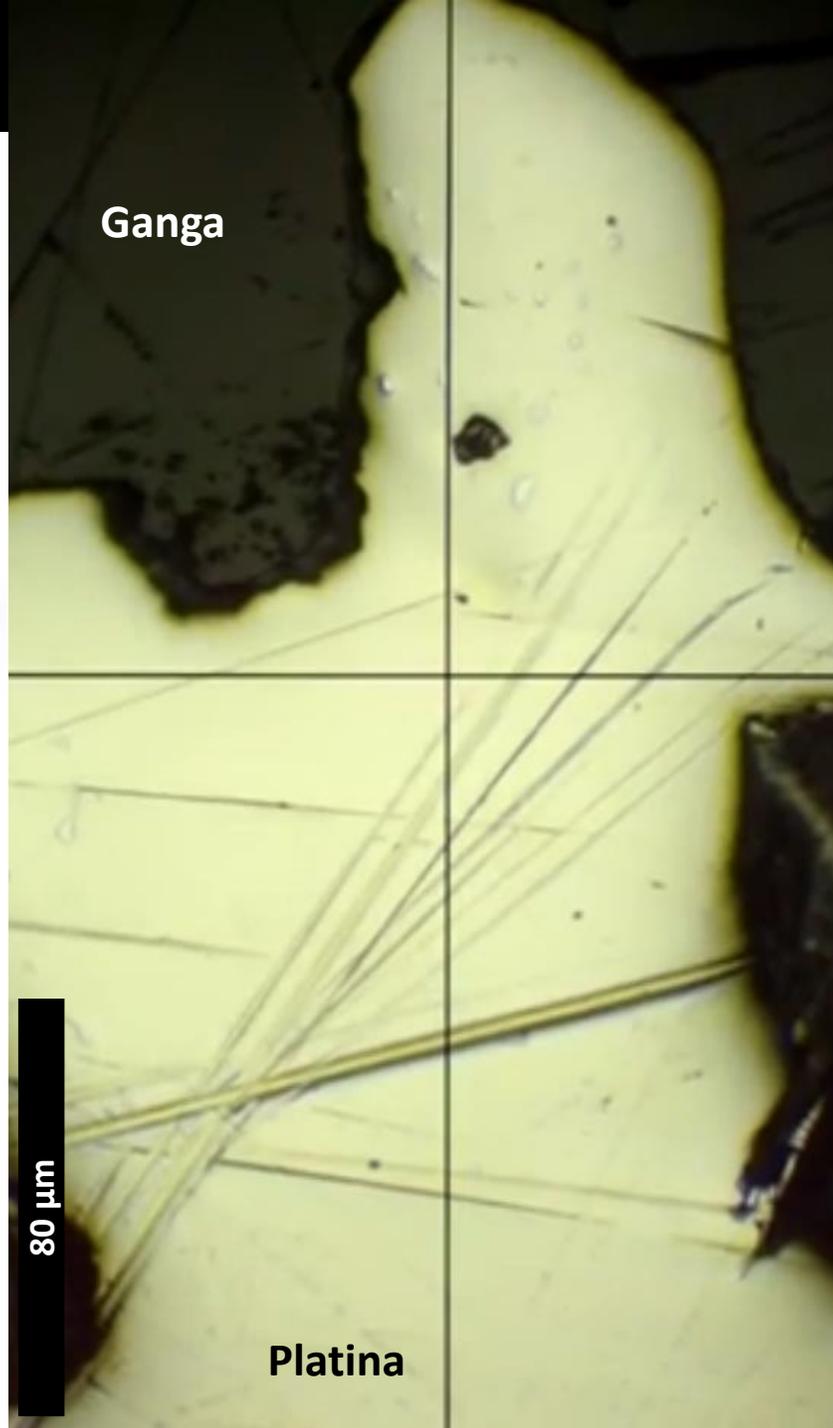
PLATINA – Pt



Heinrich Frank

PLATINA NATIVA → LUZ REFLETIDA
(POLARIZADORES DESCRUZADOS E CRUZADOS)

<https://www.youtube.com/watch?v=TRbwEW-zOeg>



COR

Cor branca, com sutil cor creme.

REFLECTÂNCIA

Muito alta (~65%).

PLEOCROÍSMO E BIRREFLECTÂNCIA

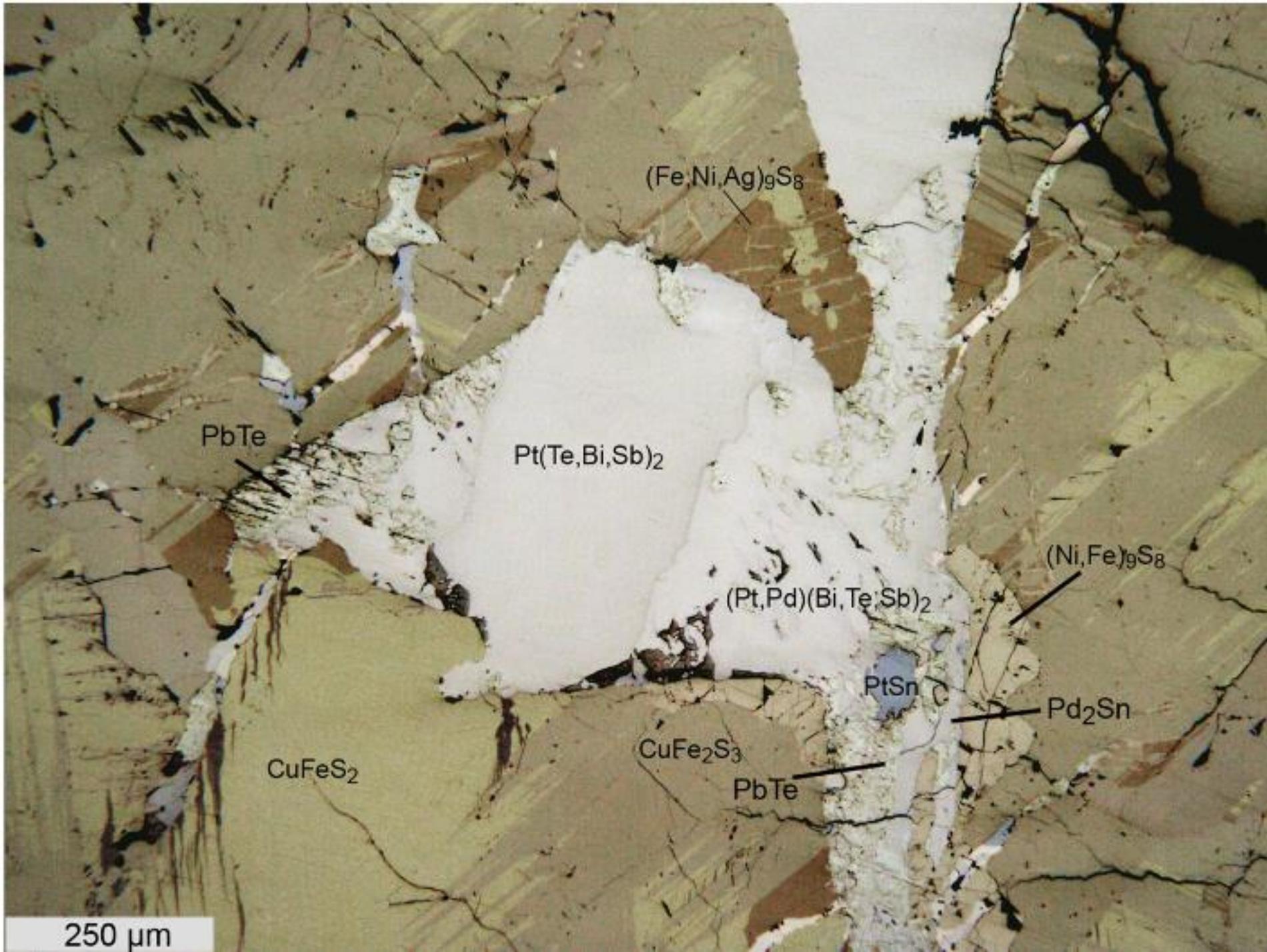
Ausentes

ANISOTROPIA

Isotrópica (sistema cúbico), com sulcos de polimento anômalos.

OUTRAS CARACTERÍSTICAS

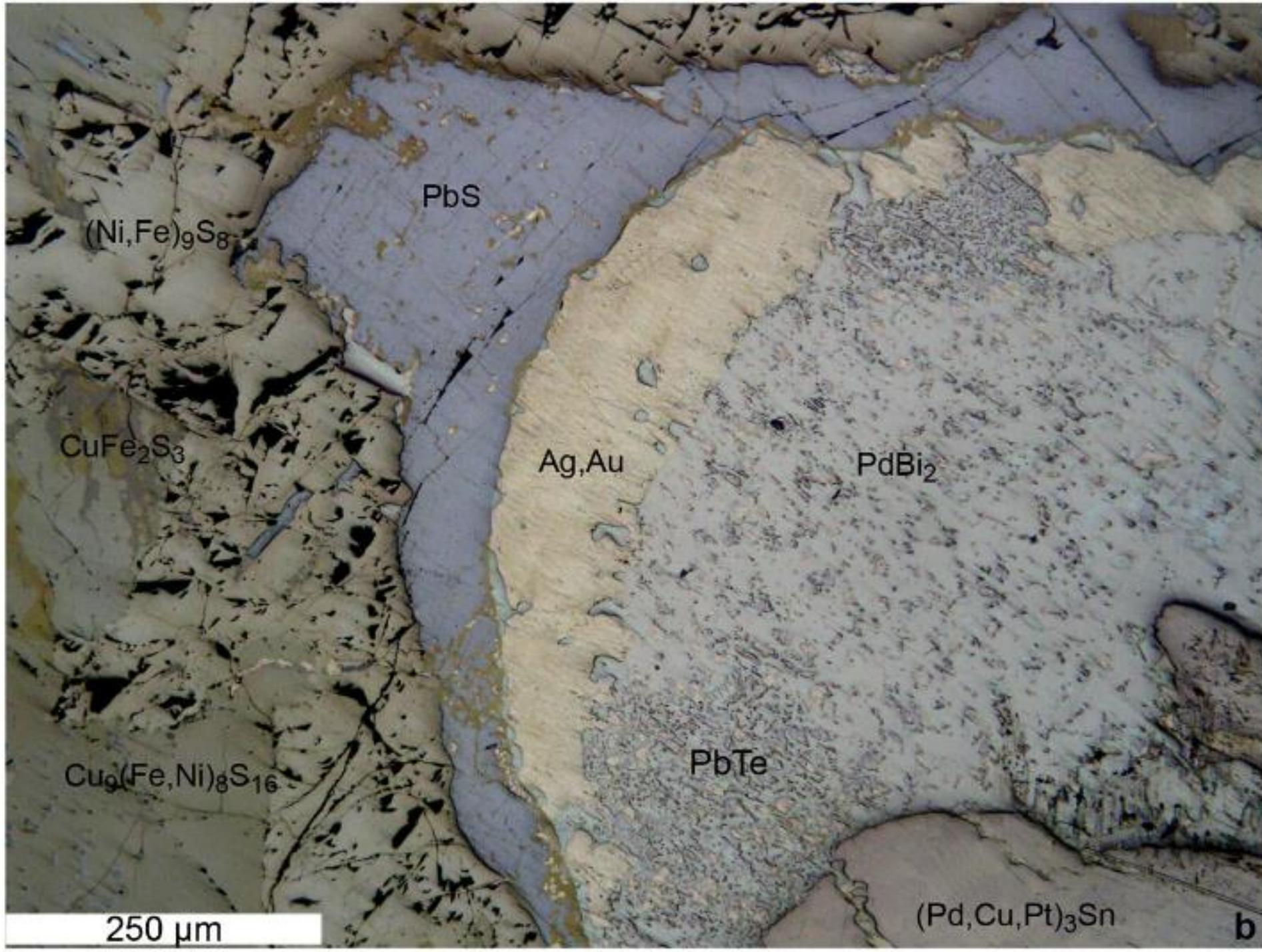
Muitos sulcos de polimento; completamente isotrópica.

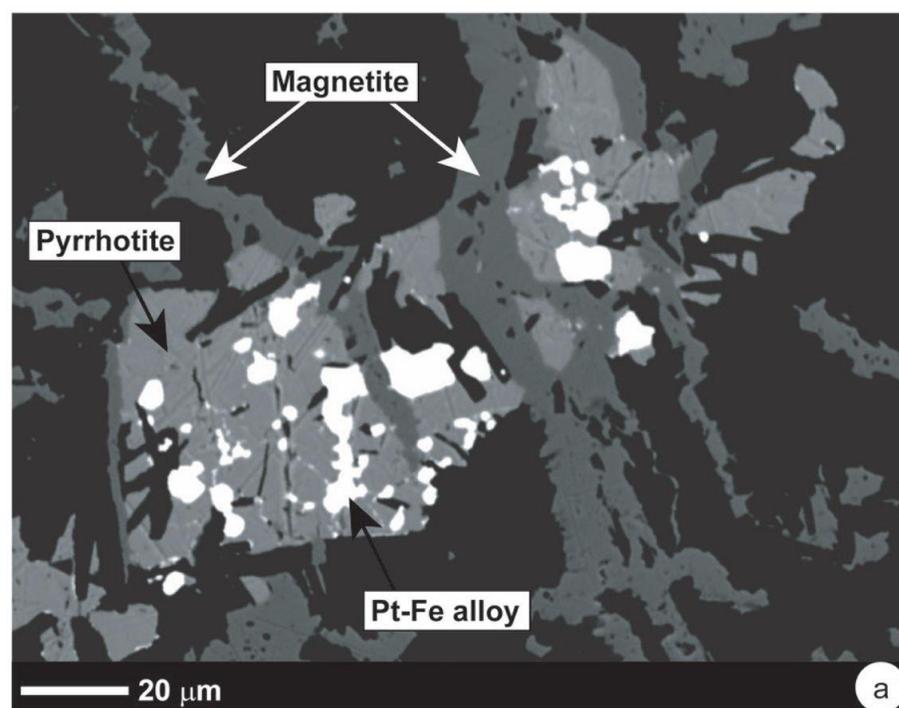


Morphology of argento pentlandite from massive sulphide ore. Argento pentlandite $(\text{Fe,Ni,Ag})_9\text{S}_8$ occurs in an intergrowth of Sb-Bi-bearing moncheite $\text{Pt}(\text{Te,Bi,Sb})_2$, Pd-bearing Sb-Te-rich insizwaite $(\text{Pt,Pd})(\text{Bi,Te,Sb})_2$, niggliite PtSn , froodite PdBi_2 , altaite PbTe and paolovite Pd_2Sn within chalcopyrite and cubanite. Pentlandite-pyrrhotite-cubanite-chalcopyrite ore, Oktyabrsk deposit, Oktyabrsk Mine. Reflected light image of a polished section

FONTE:
Sluzhenikin & Mokhov (2013)

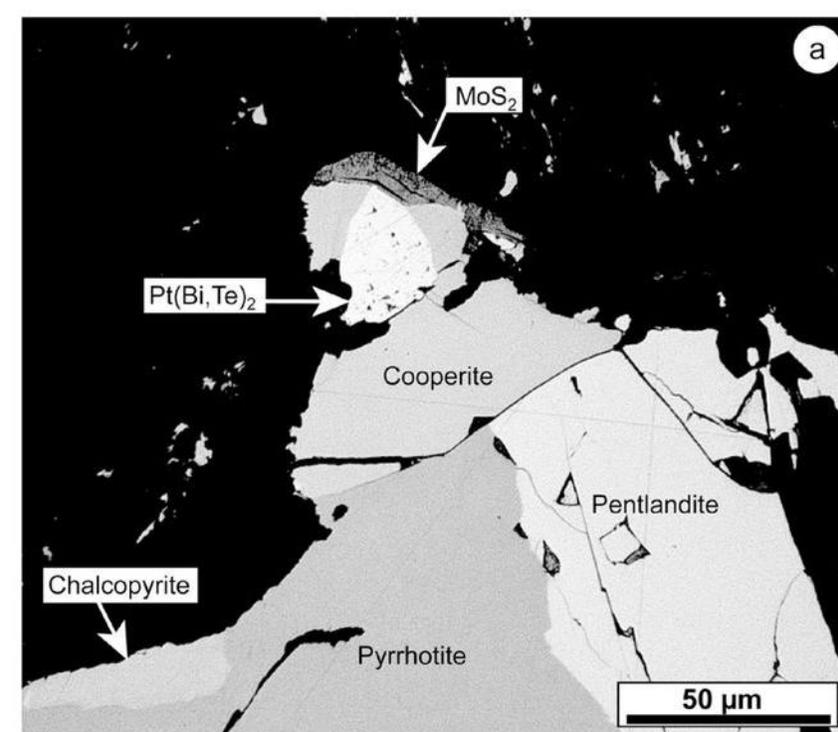
Morphology of Au–Ag alloys in intergrowths with PGM:
Rim of Au-rich native Ag and galena PbS around an intergrowth of taimyrite $(\text{Pd,Cu,Pt})_3\text{Sn}$, froodite PdBi_2 and altaite PbTe . Massive pentlandite $(\text{Ni,Fe})_9\text{S}_8$ – cubanite CuFe_2S_3 – talnakhite $\text{Cu}_9(\text{Fe,Ni})_8\text{S}_{16}$ ore, Oktyabrsk deposit, Oktyabrsk Mine (Reflected light images of polished section).



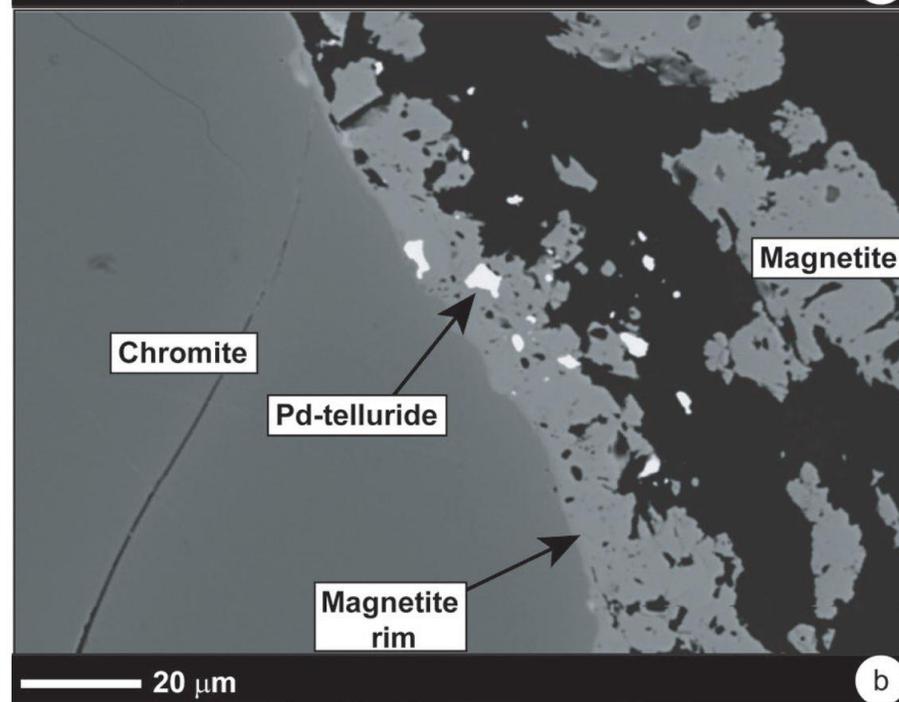


◀ Textural relationships of PGM illustrated in backscatter electron micrographs of the Stillwater J-M Reef as follows: **(a)** Irregularly shaped bright Pt–Fe alloy grains (example arrowed) are included in pyrrhotite and crosscut by ~10 μm thick secondary magnetite veinlets (arrowed).

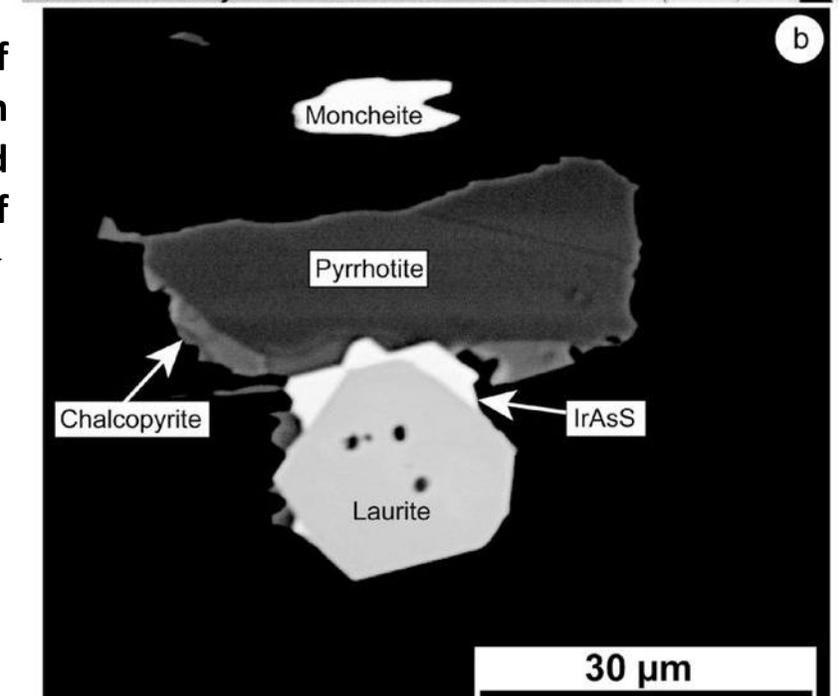
(a) Reflected light image (oil immersion) of braggite and moncheite grains (labelled in image) in the MSZ ore of the Great Dyke. ▶



(b) Backscatter electron micrograph of euhedral laurite grain intergrown with base-metal sulfides (chalcopyrite and pyrrhotite) from the MSZ. A grain of moncheite (labelled) also occurs. ▶

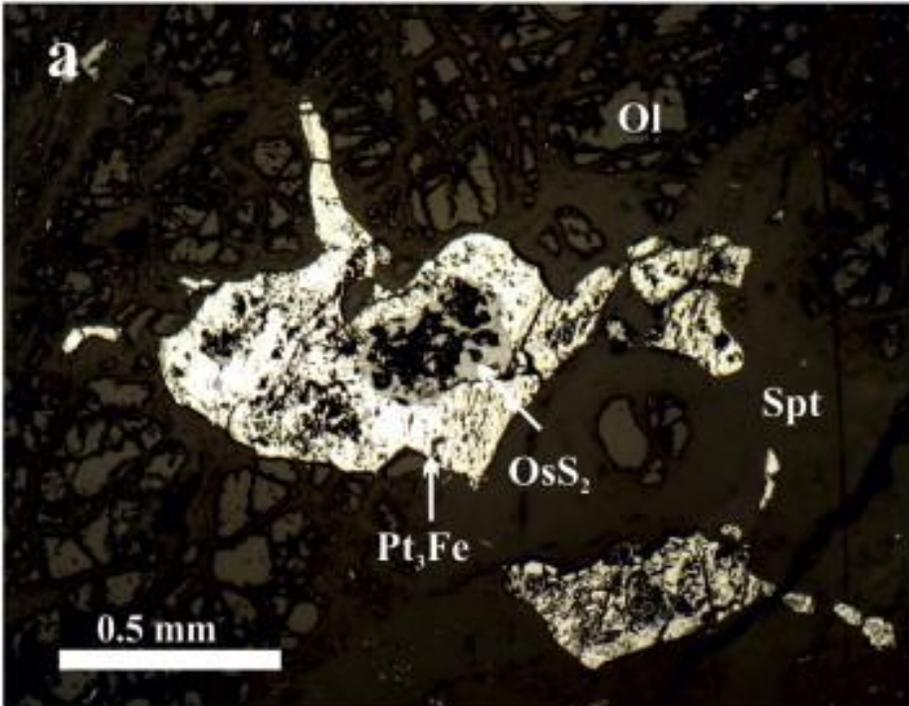


◀ **(b)** Sieve-textured magnetite rim (on Cr-spinel crystal) containing Pd-telluride inclusion.



FONTE: O’Driscoll & Jiménez (2016)

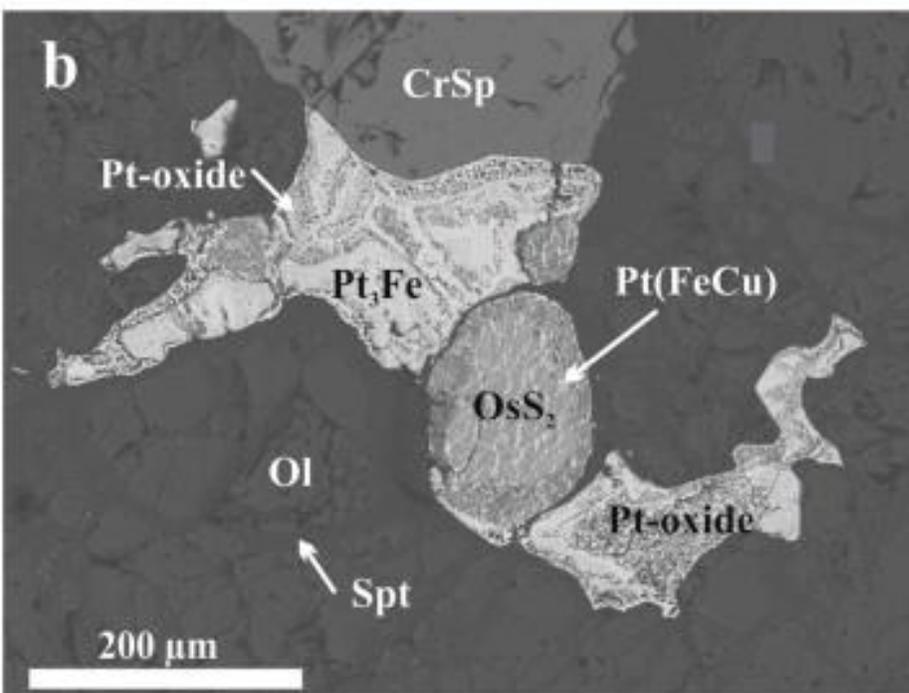
<https://pubs.geoscienceworld.org/msa/rimg/article/81/1/489/141100/Petrogenesis-of-the-Platinum-Group-Minerals>



◀ Backscattered-electron images of Pt–Fe alloys from the Svetly Bor intrusion in serpentinized dunite.

(A) Anhedral grain of partially oxidized isoferroplatinum (Pt_3Fe) with inclusion of erlichmanite (OsS_2) within olivine (Ol)-serpentine (Spt) matrix;

(B) anhedral and partially oxidized grain of isoferroplatinum in aggregate with chromite (CrSp) and erlichmanite in dunite.

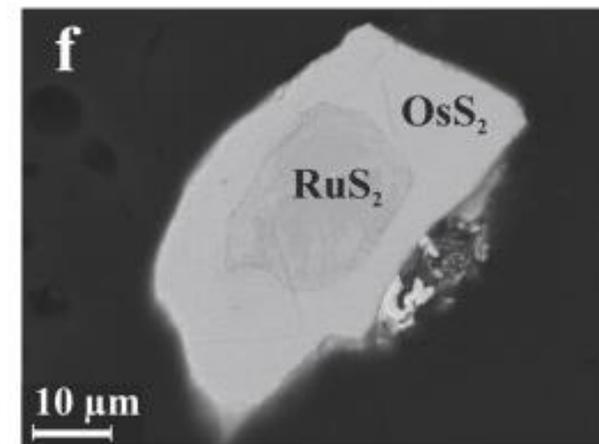
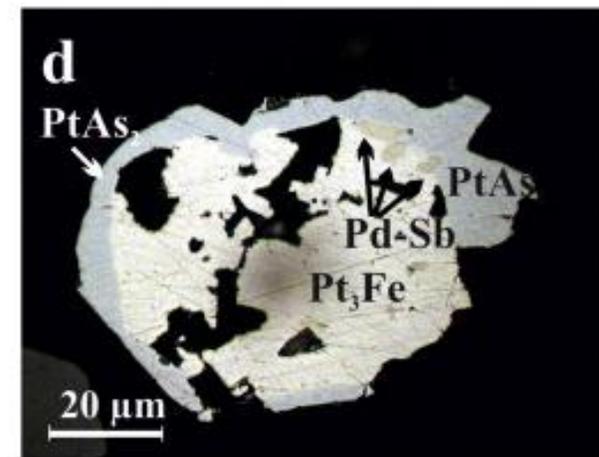
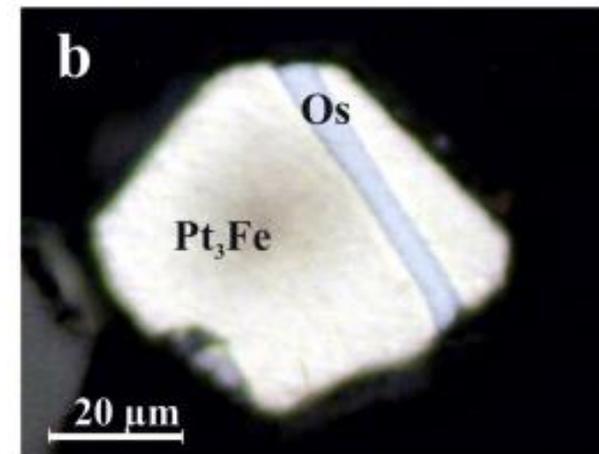


Backscattered-electron images of Pt–Fe alloys and others PGM micro-parageneses from the Svetly Bor intrusion. ▶

(B) Cubic crystals of isoferroplatinum with inclusion of osmium (Os);

(D) isoferroplatinum grain, with inclusions of Pd–Sb phase, partially replaced by sperrylite ($PtAs_2$);

(F) zoned grain of erlichmanite (OsS_2) with laurite (RuS_2) in the core.;



FONTE:
Tolstykh et al. (2015)

