

PETROGRAFIA DE MINÉRIOS (GSA 0501)

MINÉRIO DE NÍQUEL E SULFETO DE ARSÊNIO

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

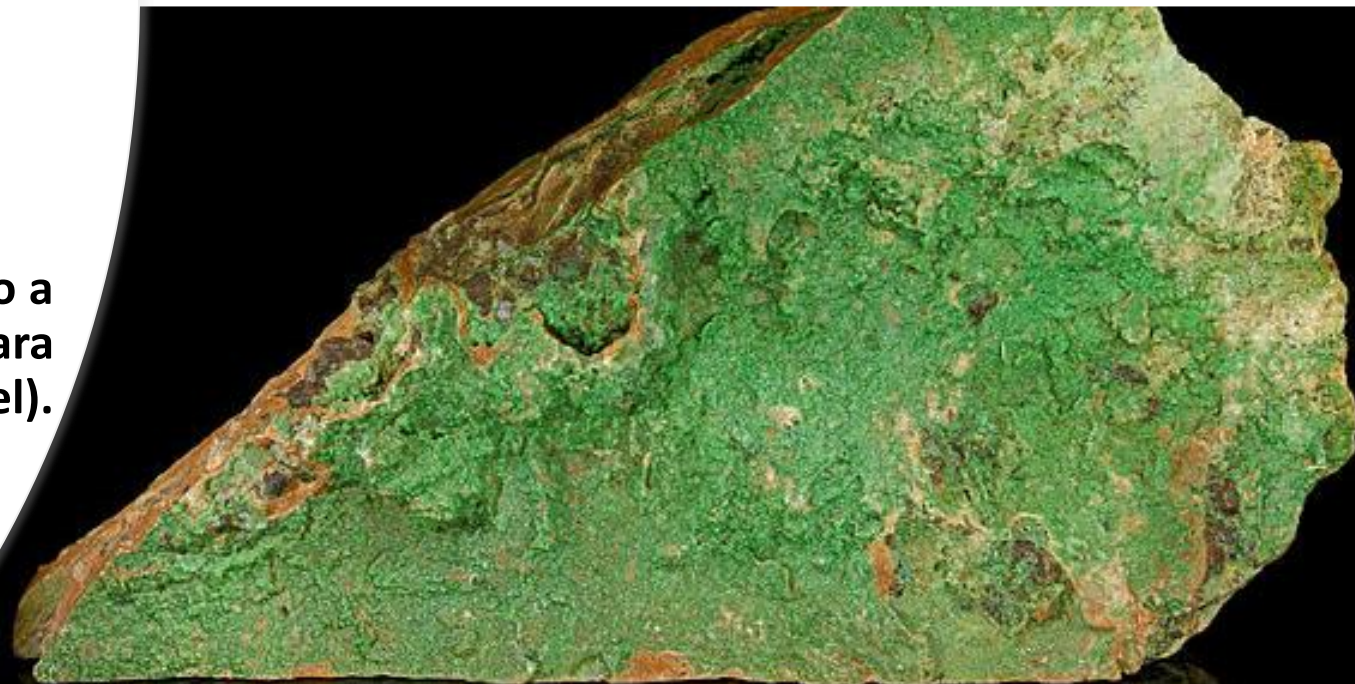
CONTEXTO GEOLÓGICO DOS PRINCIPAIS MINERAIS DE MINÉRIO DE NÍQUEL

Sulfetos de Níquel estão geneticamente atrelados à cristalização de sulfetos a partir de magmas ultramaficos que foram submetidos a processos de segregação magmática (fundido silicático e sulfetado imiscíveis).

→ depósitos de filiação magmática.

Minério niquelífero também está relacionado a relogioned conversão intempérica da Ni-olivina para garnierite (silicato hidratado de níquel).

→ depósitos de lateríticos de níquel.



DEPÓSITOS DE SULFETO MAGMÁTICO

MINERALOGIA DO MINÉRIO

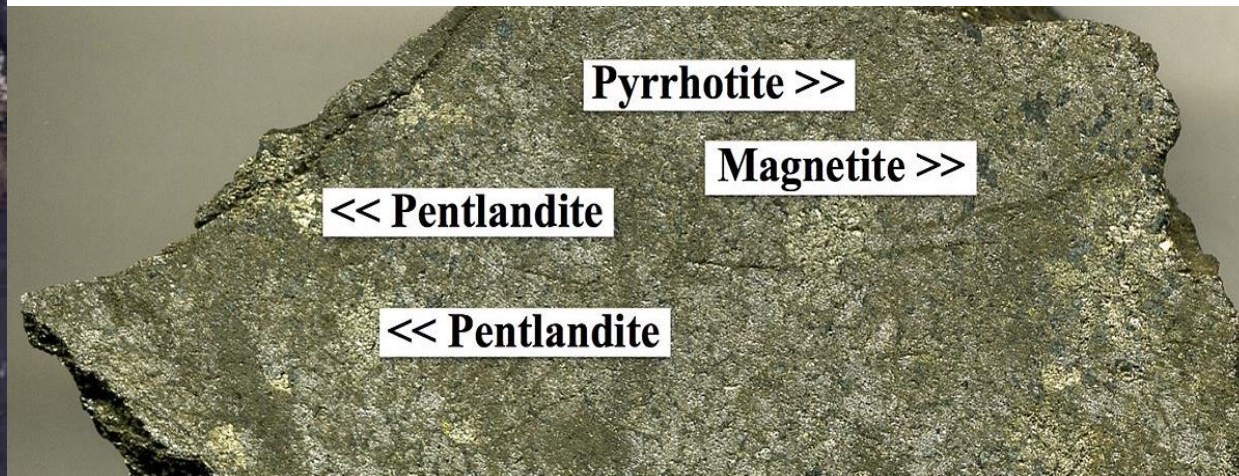
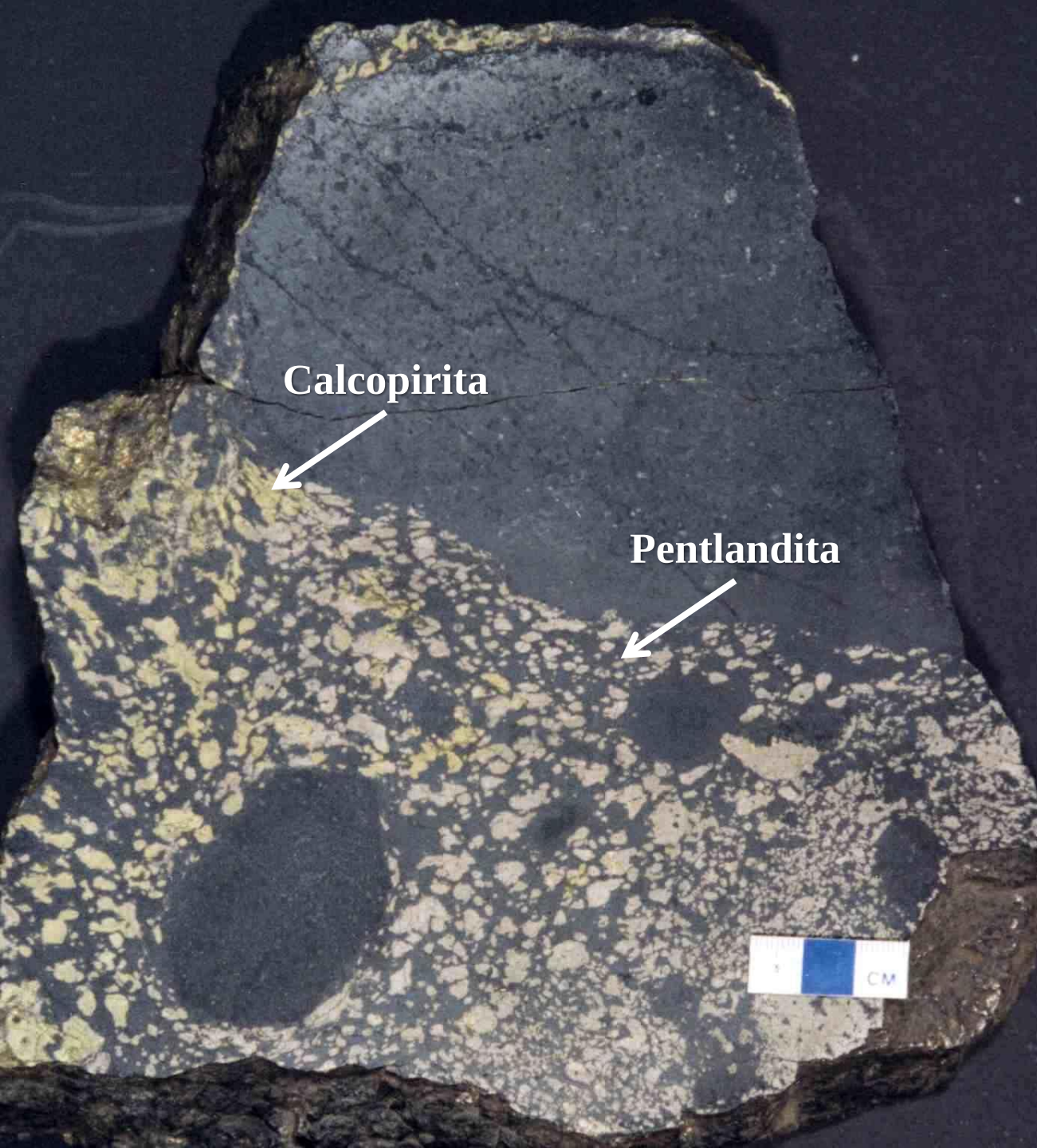
Pirita (FeS_2)

Pirrotita (Fe_{1-x}S)

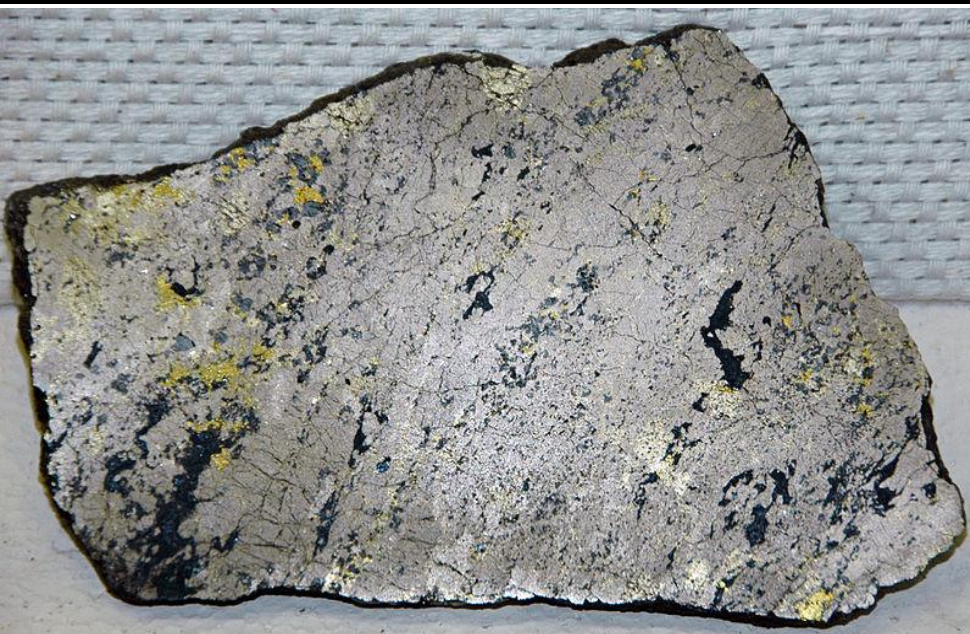
Calcopirita (CuFeS_2)

Pentlandita $[(\text{Ni},\text{Fe})_9\text{S}_8]$

*Associação mineral
muito comum para
a pentlandita.*



PENTLANDITA $(\text{Fe,Ni})_9\text{S}_8$



Heinrich Frank

**PENTLANDITA - LUZ REFLETIDA
(POLARIZADORES DESCRUZADOS E CRUZADOS)**

<https://www.youtube.com/watch?v=B-iiiSVqPo>

<https://www.youtube.com/watch?v=XnV8YyCbNMk>

Fonte: Barnes et al. (2020) ►

COR

Cor creme a creme amarelada,
superior à pirita, mas inferior à
da calcopirita.

REFLECTÂNCIA

Alta (~51%).

PLEOCROÍSMO E BIRREFLECTÂNCIA

Ausentes

ANISOTROPIA

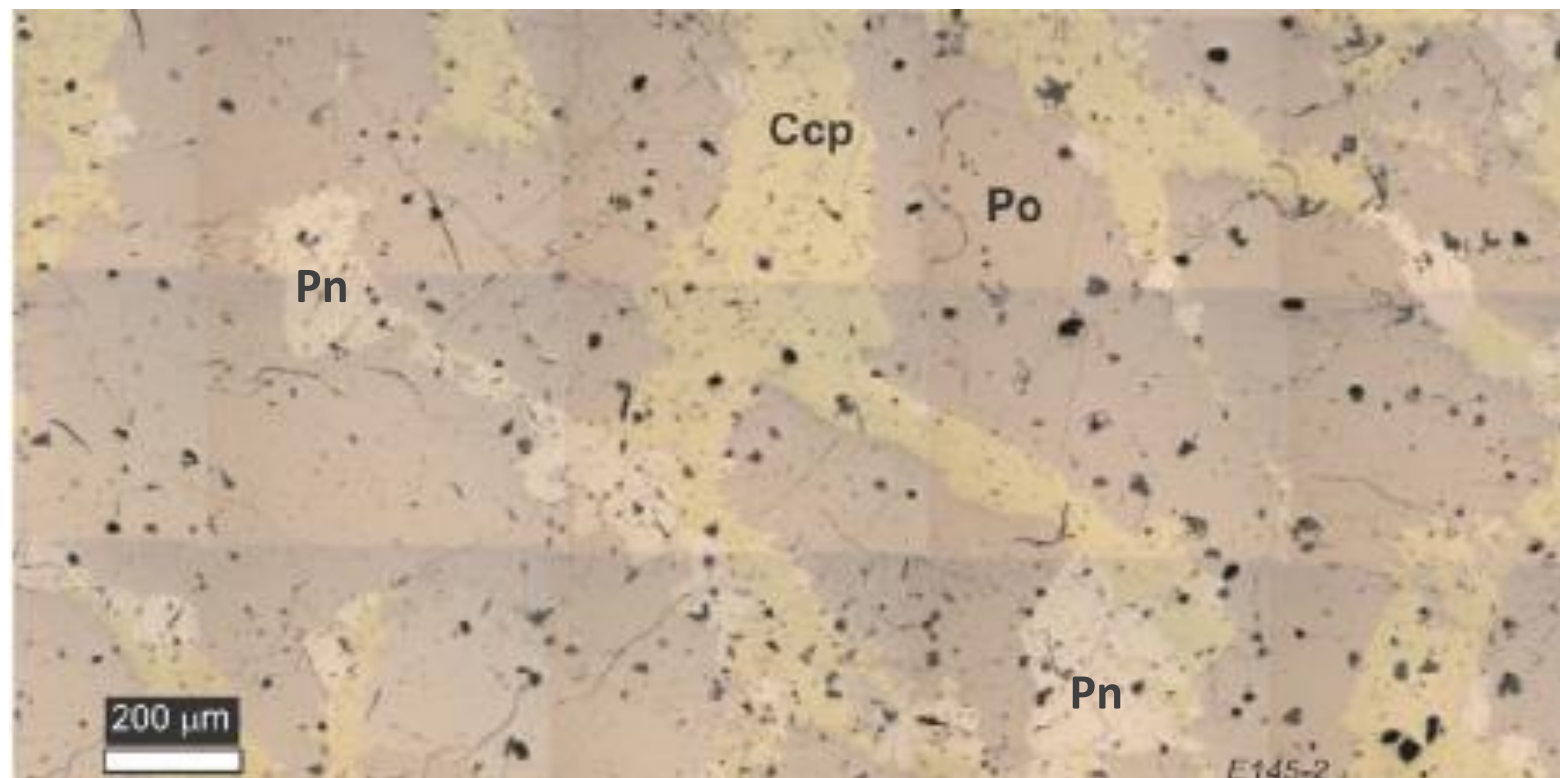
Isotrópica (*sistema cúbico*).

REFLEXÕES INTERNAS

Ausentes.

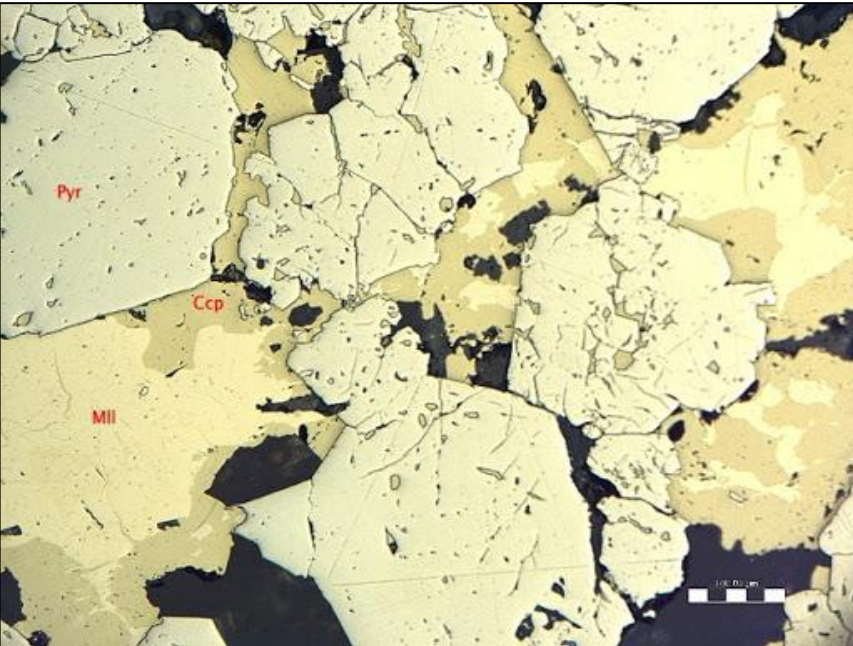
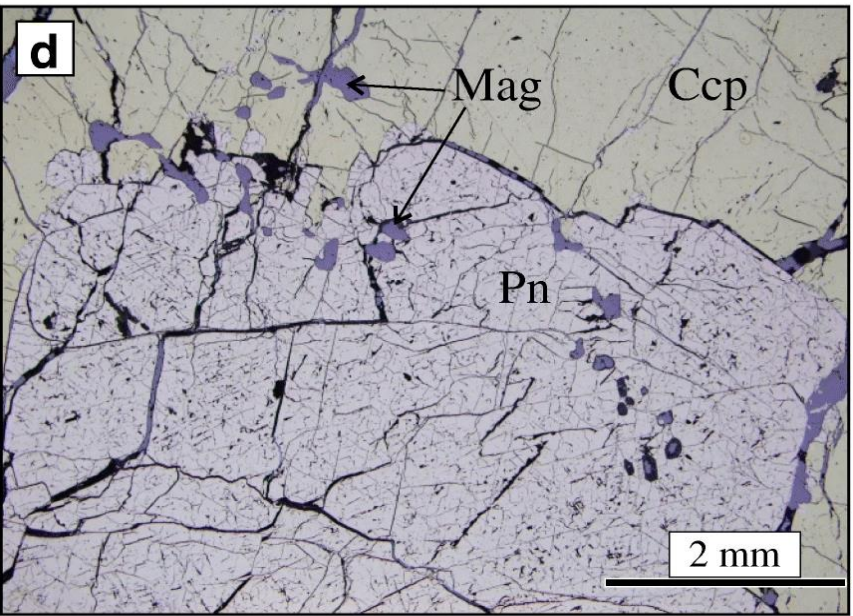
OUTRAS CARACTERÍSTICAS

Sulcos de polimento (*com falsa
anisotropia e reflexões internas*).
Geralmente como massas ou
lamelas.



PRINCIPAIS FASES NIQUELÍFERAS DO SISTEMA Ni-S E Fe-Ni-S

Mineral	Fórmula	Estrutura	T máx (°C)	T min (°C)
Haezlewoodita s.s	Ni _{3+x} S ₂	Cúbica	806	524
Haezlewoodita	Ni ₃ S ₂	hexagonal	556	
Godlevskita s.s	Ni _{7+x} S ₆		573	400
Godlevskita	Ni ₇ S ₆	Ortorrômbica	400	
Millerita	Ni _{1-x} S	Hexagonal	999	282
Millerita	NiS	Hexagonal	379	
Polidimita	Ni ₃ S ₄	Cúbica		
Pentlandita	(Fe,Ni) ₉ S ₈	Cúbica	610	
Vaesita	NiS ₂	Cúbica	1007	
Solução sólida monosulfetada - mss	(Fe,Ni) _{1-x} S	Hexagonal	1192-992	200
Violarita	(Fe,Ni) ₃ S ₄	Cúbica	461	
Bravoita	(Fe,Ni)S ₂	Cúbica	137	



DEPÓSITOS DE SULFETO MAGMÁTICO

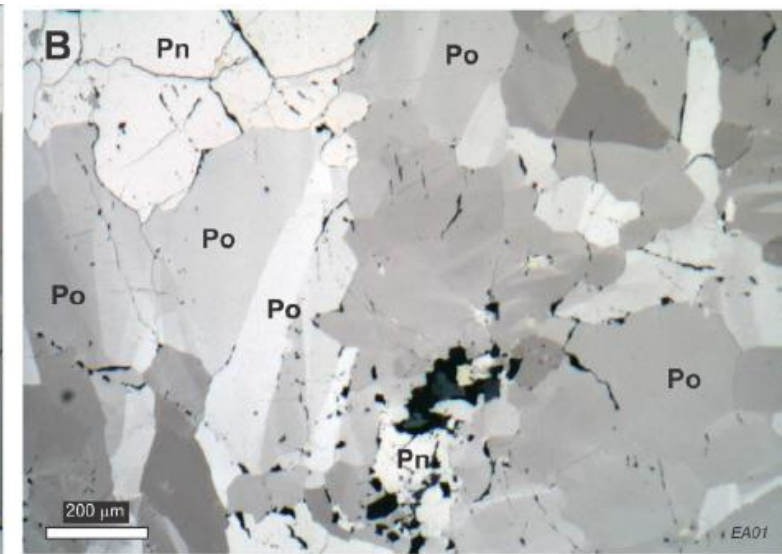
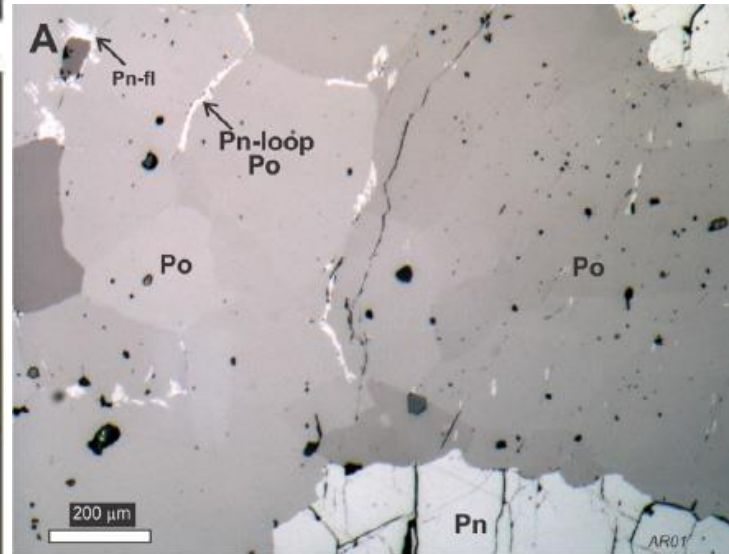
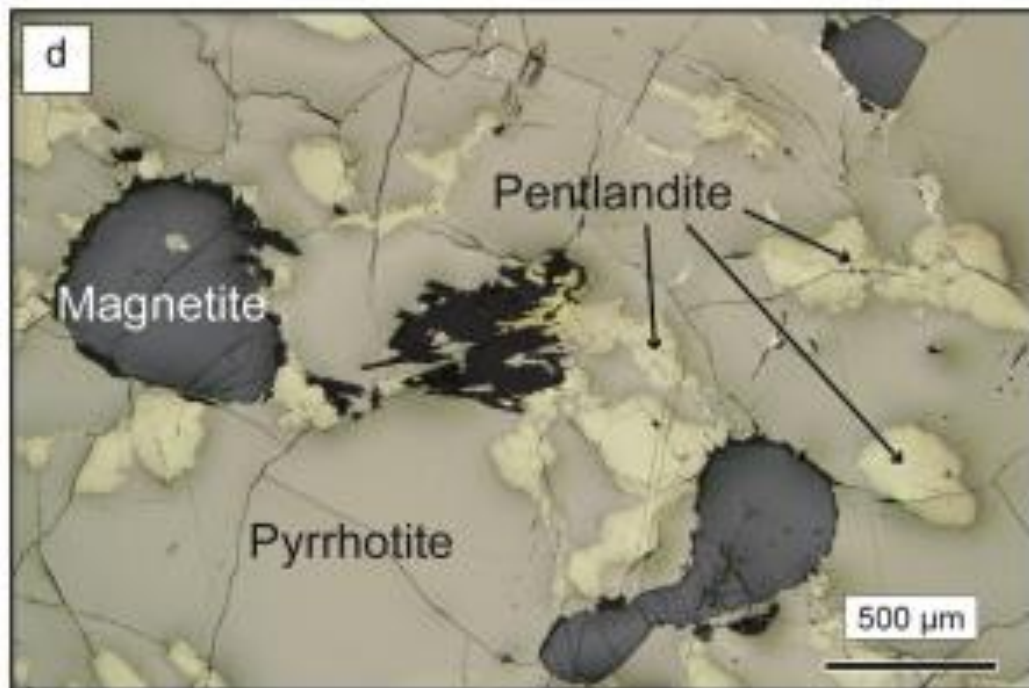
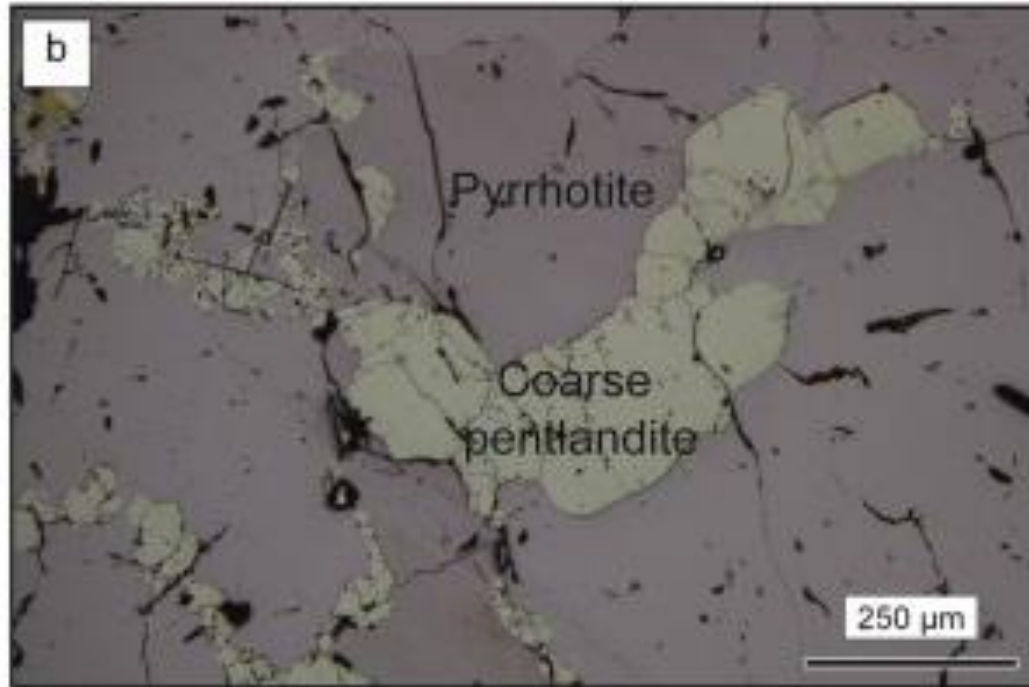
◀ *Photomicrographs in reflected light of the primary sulfide-rich pods:*

(B) *Pyrrhotite with coarse pentlandite;*

(D) *Pyrrhotite–pentlandite assemblage with small rounded anhedral magnetite.*

Fonte: Duran et al. (2016)

<https://www.sciencedirect.com/science/article/pii/S0375674216300930#f0010>

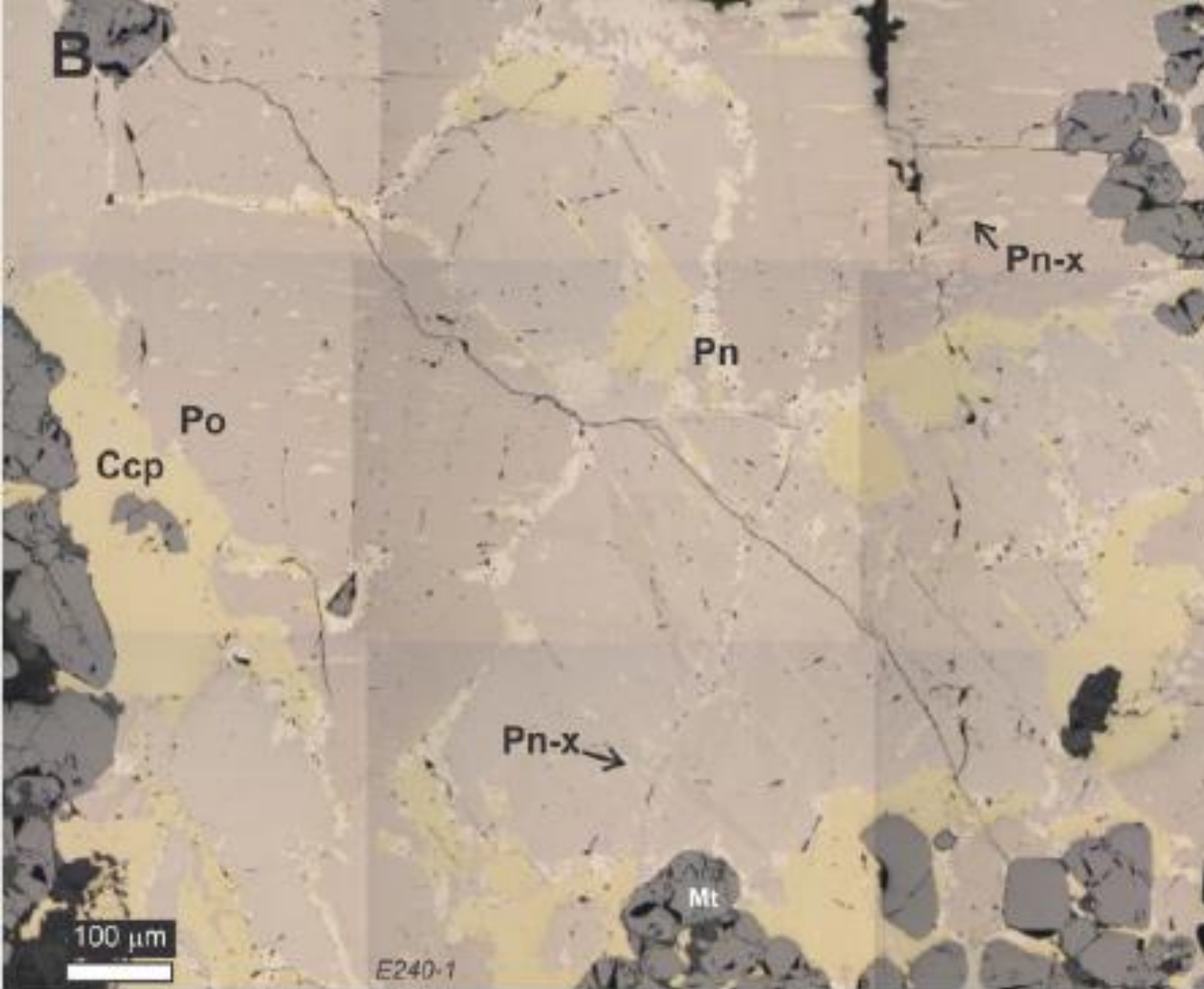


Fonte: Barnes et al. (2020)

[https://pubs.geoscienceworld.org/segweb/economicgeology/article/115/8/1777/590567?casa_token=WPGRYt1H_gQAAAAA:IO-](https://pubs.geoscienceworld.org/segweb/economicgeology/article/115/8/1777/590567?casa_token=WPGRYt1H_gQAAAAA:IO-FDYJQMxvLhnV8ZIOhr_riC5FdqFBahfNZK7EXtKsAHphk1phGtdrw2XWMTlgvpwaUH_GF)

[n=WPGRYt1H_gQAAAAA:IO-](https://pubs.geoscienceworld.org/segweb/economicgeology/article/115/8/1777/590567?casa_token=WPGRYt1H_gQAAAAA:IO-FDYJQMxvLhnV8ZIOhr_riC5FdqFBahfNZK7EXtKsAHphk1phGtdrw2XWMTlgvpwaUH_GF)

[FDYJQMxvLhnV8ZIOhr_riC5FdqFBahfNZK7EXtKsAHphk1phGtdrw2XWMTlgvpwaUH_GF](https://pubs.geoscienceworld.org/segweb/economicgeology/article/115/8/1777/590567?casa_token=WPGRYt1H_gQAAAAA:IO-FDYJQMxvLhnV8ZIOhr_riC5FdqFBahfNZK7EXtKsAHphk1phGtdrw2XWMTlgvpwaUH_GF)



Associação paragenética entre pentlandita (Pn) – pirrotita (Po) – calcopirita (Ccp)

→ sulfeto magmático (*Eagle deposit*)

Optical photomicrographs of loop-textured massive ores:

◀ (B) Eagle deposit, primary loop textures comprising pentlandite (Pn) and chalcopyrite (Ccp) enveloping equant pyrrhotite (Po) grains, besides coarse oriented pentlandite lamellae in cores of pyrrhotite

Fonte:

Barnes et al. (2020)

<https://pubs.geoscienceworld.org/segweb/economicgeology/article-abstract/115/8/1777/590567/The-Occurrence-and-Origin-of-Pentlandite?redirectedFrom=PDF>

DEPÓSITOS DE SULFETO MAGMÁTICO

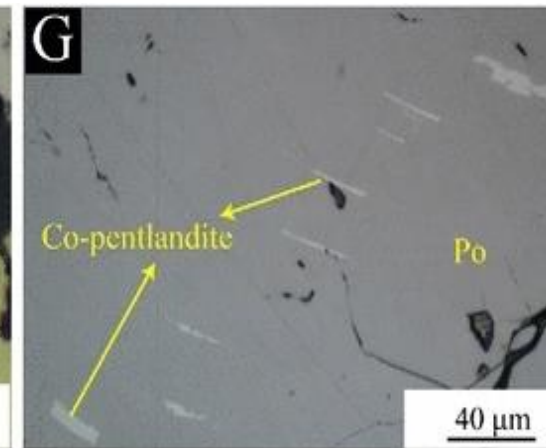
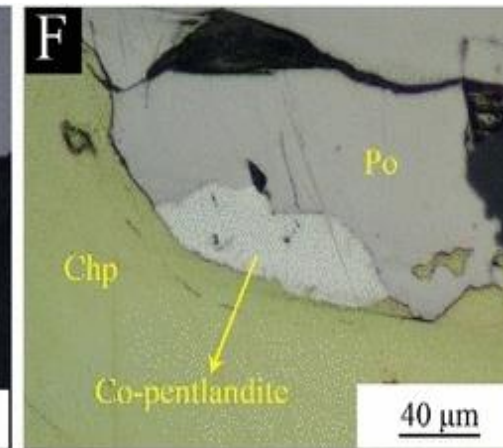
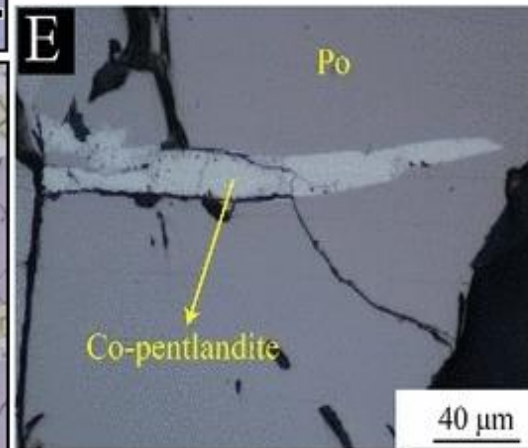
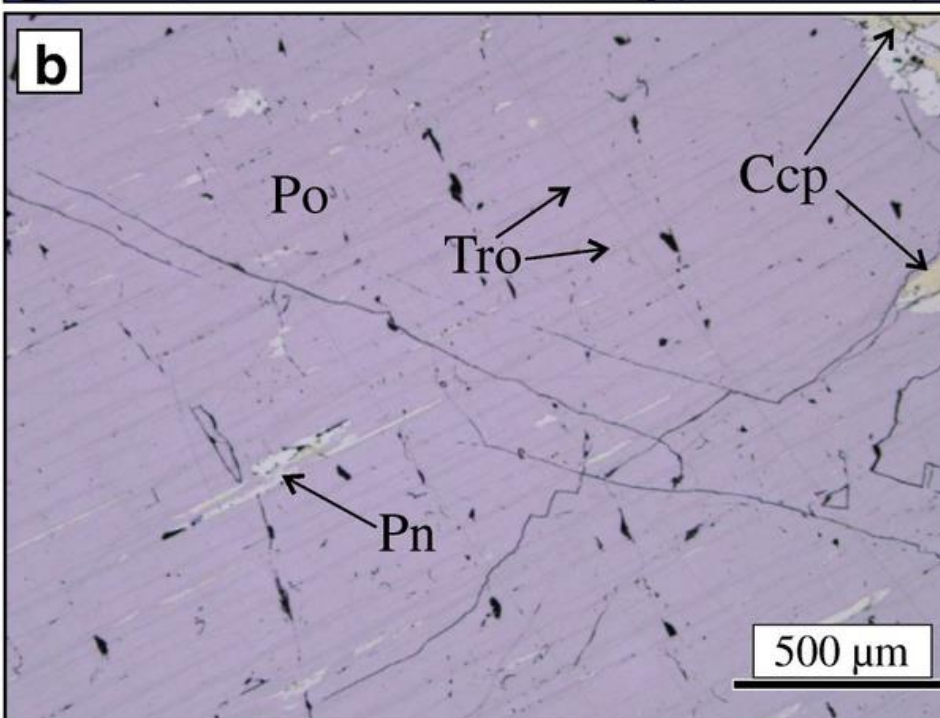
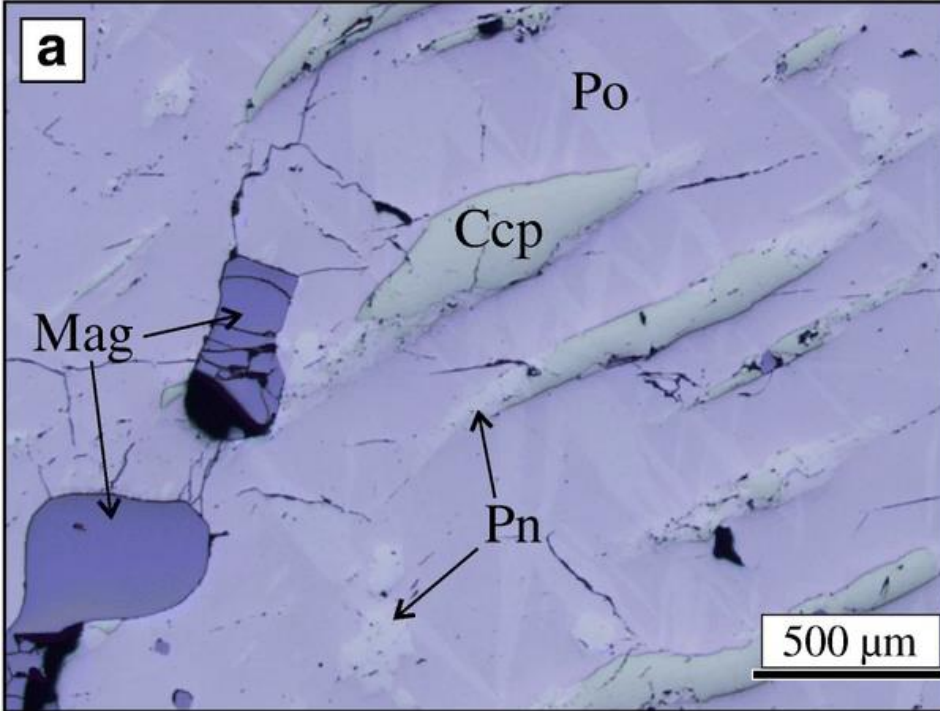
◀ *Reflected light photomicrographs of representative textures of main massive sulfides from Noril'sk-Talnakh mining district, and backscattered electron images of platinum-group minerals in Cu-poor and Cu-rich ores:*

(A) *Exsolutions of pentlandite and chalcopyrite in pyrrhotite;*

(D) *Thin exsolution lamellae (< 20 μm) of troilite in pyrrhotite..*

Fonte: Mansur et al. (2019)

<https://link.springer.com/article/10.1007/s00126-019-00926-z>

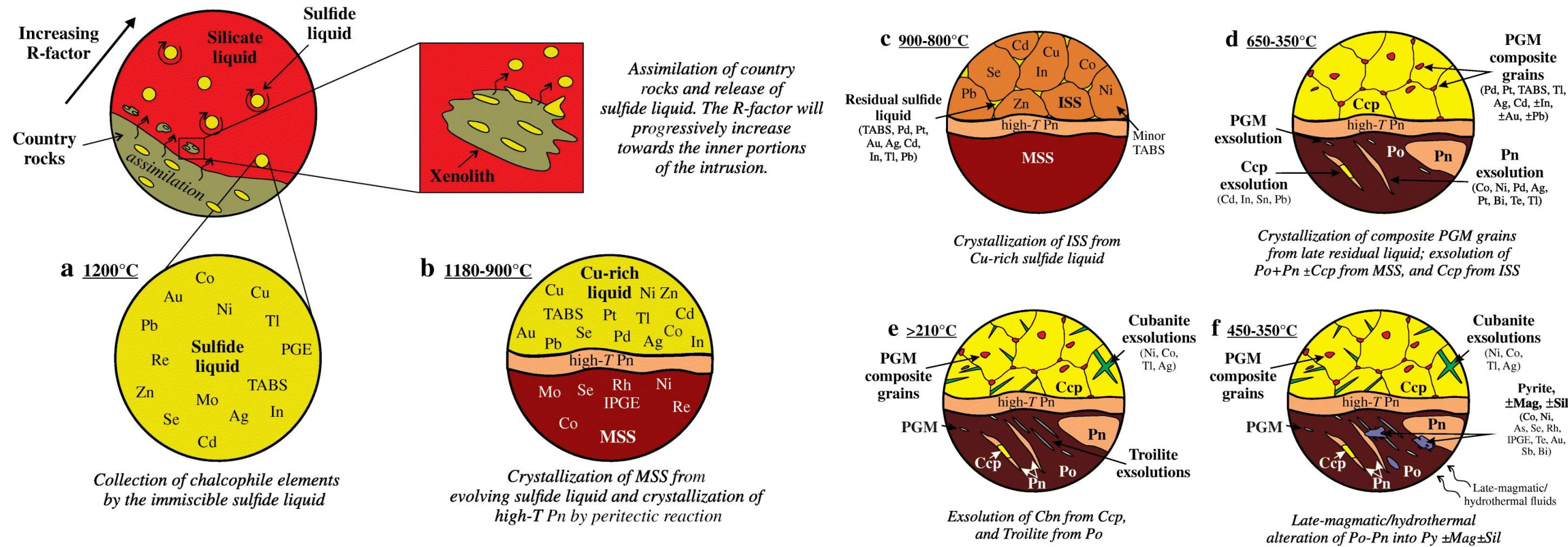


(E) *Cobalt-pentlandite is present as inclusions of different shape in pyrrhotite;*
(F) *along the contact zone of pyrrhotite and other minerals; and*
(G) *as exsolved tabular/elongated oriented lamella in pyrrhotite.*

Fonte: Baidya et al. (2018)

<https://link.springer.com/article/10.1007/s12040-018-0954-z>

LAMELAS DE PENTLANDITA EM DEPÓSITOS DE SULFETO MAGMÁTICO)



Schematic models illustrating the segregation of an immiscible sulfide liquid (a), crystallization and exsolution (b to e), and late magmatic/hydrothermal alteration (f) of base-metal sulfides in a magmatic sulfide deposit. See text for further explanation. MSS, monosulfide solid solution; ISS, intermediate solid solution; PGM, platinum-group minerals; Po, pyrrhotite; Pn, pentlandite; Ccp, chalcopyrite; Py, pyrite; Mag, magnetite; Sil, silicates. The R-factor is the ratio of silicate liquid to sulfide liquid.

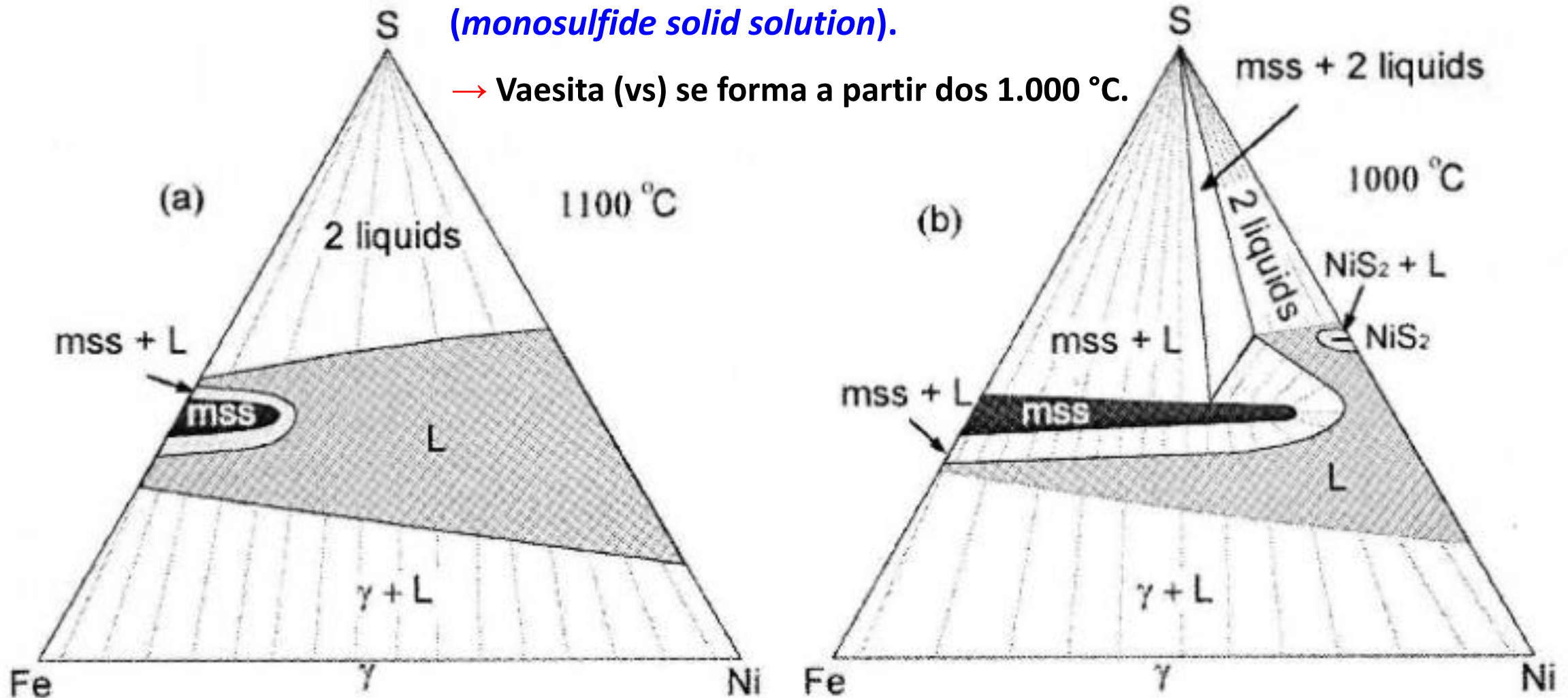
Fonte: Mansur et al. (2019)

<https://link.springer.com/article/10.1007/s00126-019-00926-z>

O TERNÁRIO Fe-Ni-S

...acima dos 1.000 °C: ampla área de MSS
(monosulfide solid solution).

→ Vaesita (vs) se forma a partir dos 1.000 °C.



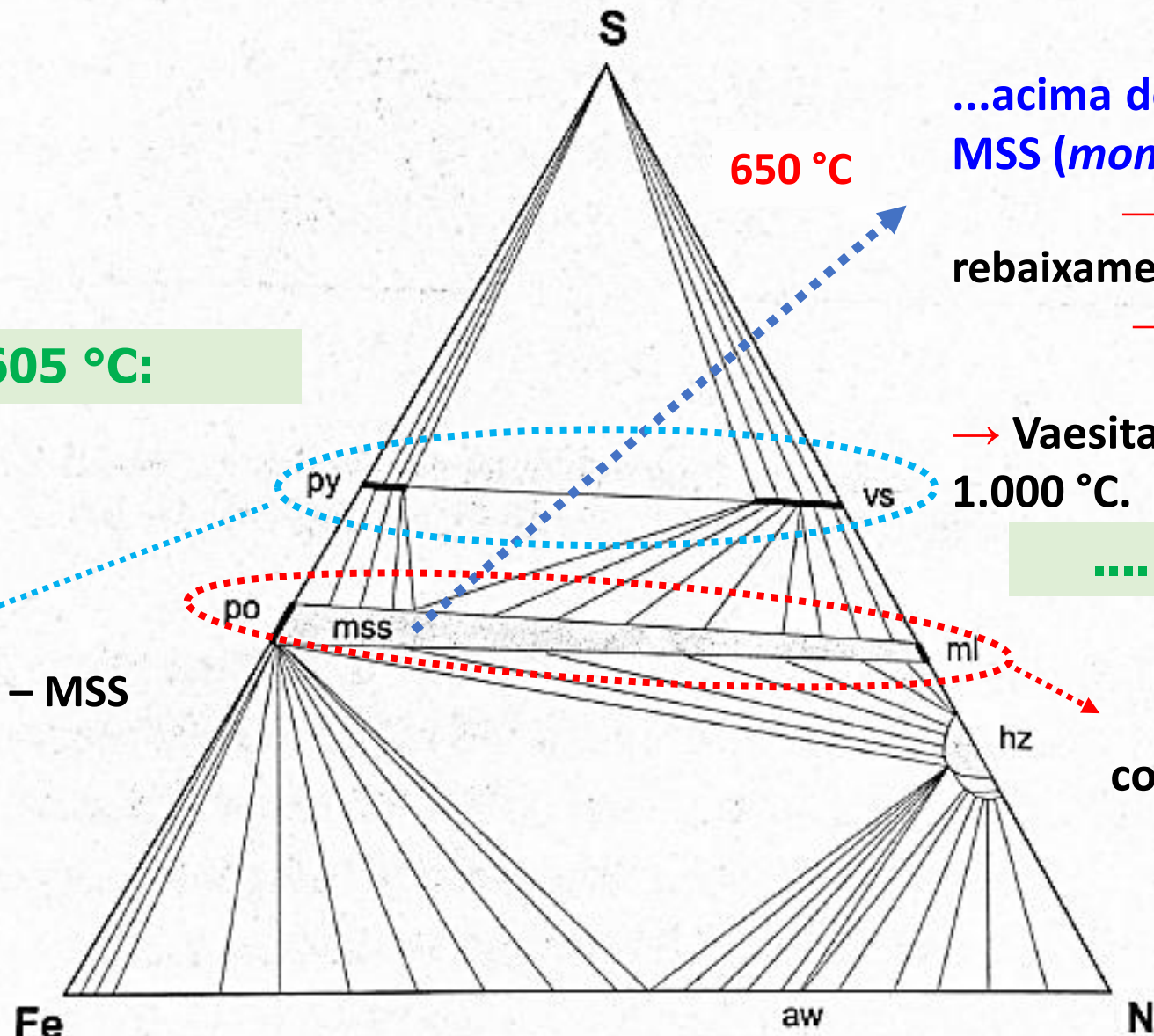
Phase relations in the Fe-Ni-S system at (a) 1.100 °C and (b) 1.000 °C (Firdu & Taskinen, 2010).

O TERNÁRIO Fe-Ni-S

.... A PARTIR DOS 605 °C:

Pirita (py) – vaesita (vs) – MSS

MSS ricas em S não coexistem com $S_{\text{líquido}}$:
→ *tie-line* entre Ni-pirita e Fe-vaesita



...acima dos 1.000 °C: ampla área de MSS (*monosulfide solid solution*).

→ Redução da MSS com o rebaixamento da T.

→ $1.192\text{ °C} < \text{MSS} < 200\text{ °C}$

→ Vaesita (vs) se forma a partir dos 1.000 °C.

.... A PARTIR DOS 605 °C:

MSS entre os extremos composicionais pirrotita (po) e millerita (ml)

Figura 6.2 — Seção isotérmica do sistema Fe-Ni-S a 650 °C. As fases presentes são pirita s.s. (py), vaesita s.s. (vs), solução monossulfetada (mss), heazlewoodita s.s. (hz) e a liga awaruita (aw) (fonte: Kullerud, Yund e Moh, 1969).

O TERNÁRIO Fe-Ni-S

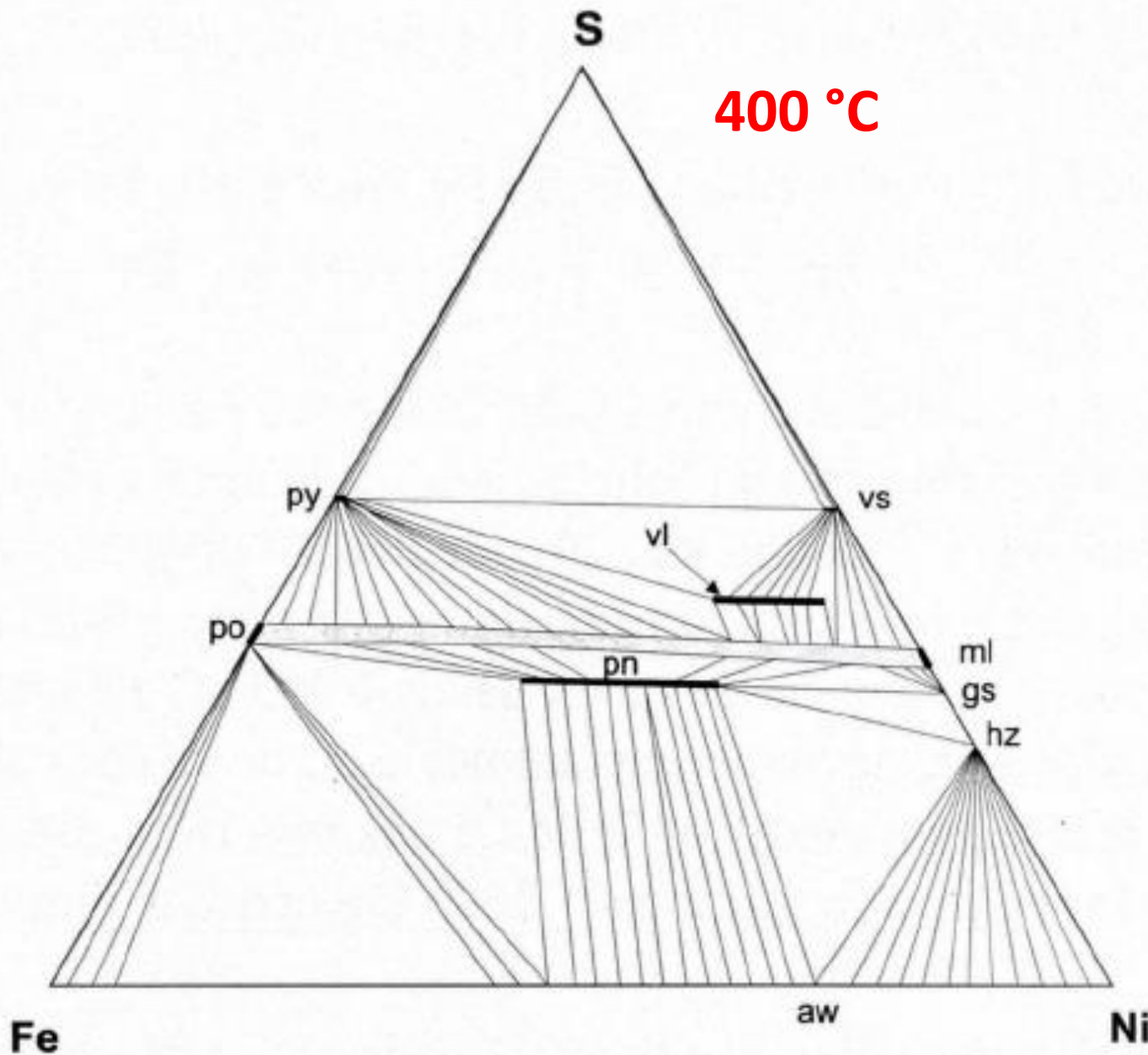
...com o rebaixamento: redução do campo da MSS.

PENTLANDITA

- ✓ estável a $T < 610\text{ °C}$
- ✓ Coexiste com MSS rica em metal, ligas metálicas e heazlewoodita (hz)

MSS RICAS EM:

- níquel: em equilíbrio com godlevskita (gs)
- enxofre: coexistem com Ni-pirita e violarita.

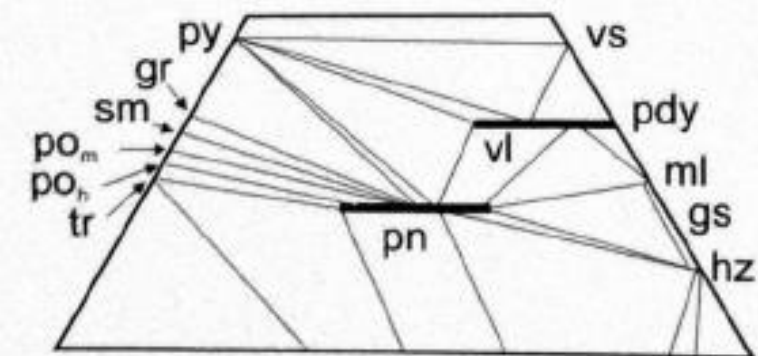
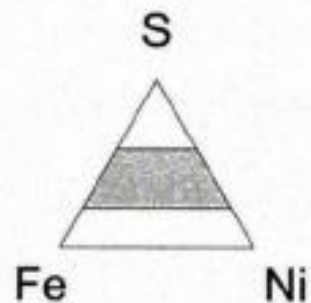


Seção isotérmica do sistema Fe-Ni-S a 400 °C . As fases violarita (vl), pentlandita (pn) e godlevskita (gs) já estão presentes no sistema (fonte: Craig, Naldrett e Kullerud, 1968).

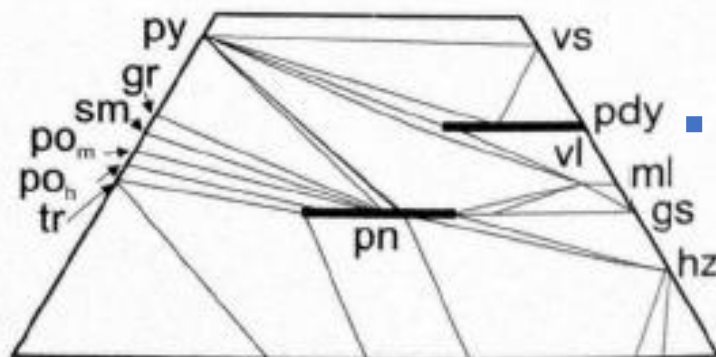
O TERNÁRIO Fe-Ni-S

Desaparecimento da MSS
(temperaturas inferiores à
200°C).

$T < 200\text{ °C}$



a



b

Figura 6.4 — Seções isotérmicas hipotéticas do sistema Fe-Ni-S a baixas temperaturas (fonte: Craig e Scott, 1974).

Tie-lines entre pentlandita e millerita
(mais provável).

Tie-lines entre pentlandita e violarita

... Ou...

DEPÓSITOS DE NÍQUEL LATERÍTICO



◀ MINÉRIO OXIDADO

horizontes com goethita
(60 Mt com 1,45 % Ni)



ASBOLANA

Óxido hidratado de magnésio com cobalto e níquel
 $(\text{Ni,Co})_2\text{-xMn}^{4+}(\text{O,OH})_4 \cdot n\text{H}_2\text{O}$

DEPÓSITOS DE NÍQUEL LATERÍTICO



GARNIERITA (*FALCONDOITA*)

Silicato hidratado de níquel
 $(\text{Ni}, \text{Mg})_4\text{Si}_6\text{O}_{15}(\text{OH})_2 \bullet 6(\text{H}_2\text{O})$

ESMECTITAS

$(\text{Na}, \text{Ca})\text{Al}_4(\text{Si}, \text{Al})_8\text{O}_{20}(\text{OH})_4 \bullet 2(\text{H}_2\text{O})$

◀ **MINÉRIO GARNIERÍTICO (SILICATADO)**

horizontes com esmectita e garnierita

Garnierita (Southern Province, New Caledonia, France)



▲ FONTE: <https://www.mindat.org/min-10936.html>

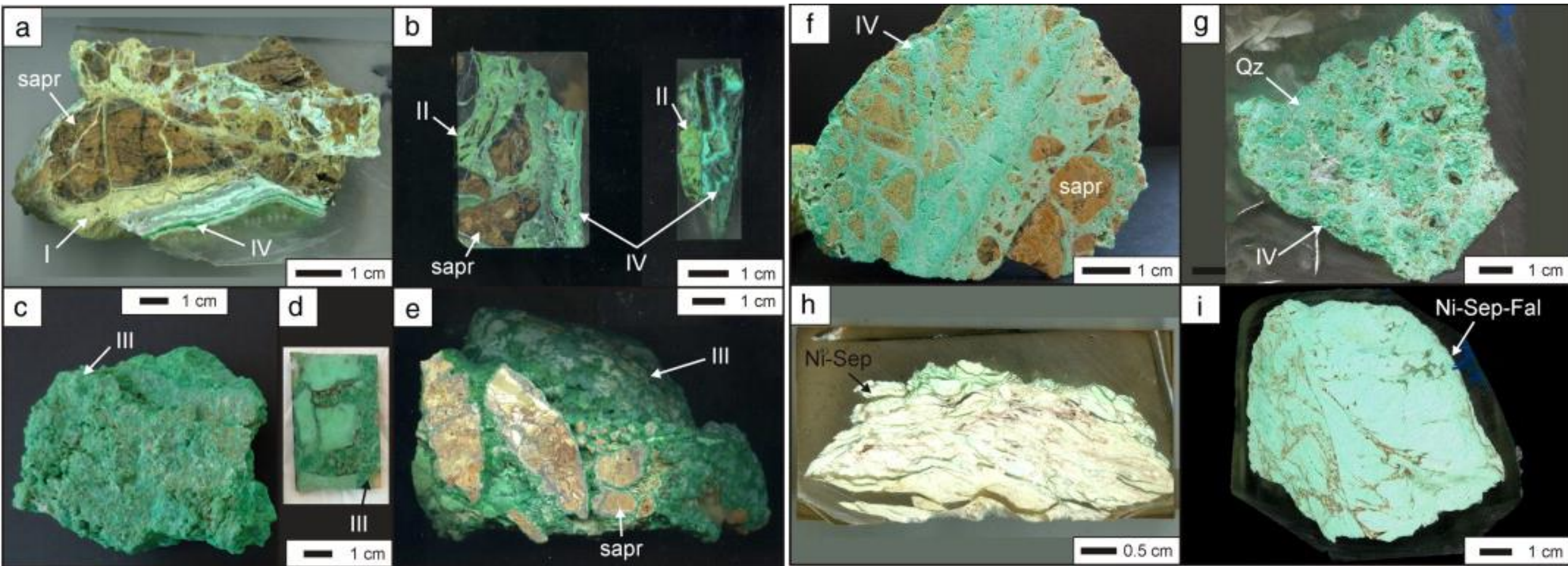
▼ FONTE: <https://www.mindat.org/gm/384>

Asbolana (Cazaquistão e New Caledonia, France)



Amostras de Ni-serpentinhas e minério de garnierita

(Falcondo Ni-laterite deposit; República Dominicana)



Hand specimens of the samples selected for this paper: a) LC-100Aa. b) LC-100B, c) GAR-1, d) GAR-2, e) GAR-6, f) GAR-5, g) F-0, h) F-3.

Legend: I–IV = types I–IV, *sapr* = saprolite fragment, *Qz* = quartz, *Ni-Sep* = Ni-sepiolite, *Fal* = falcondoite. See text for explanation.

Fotomicrografia de cristais de garnierita.

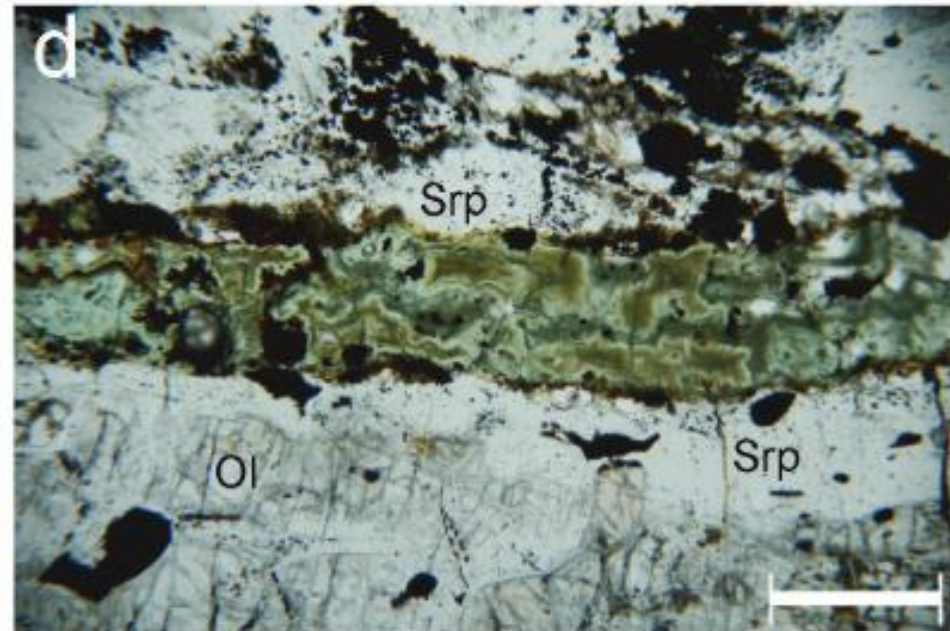
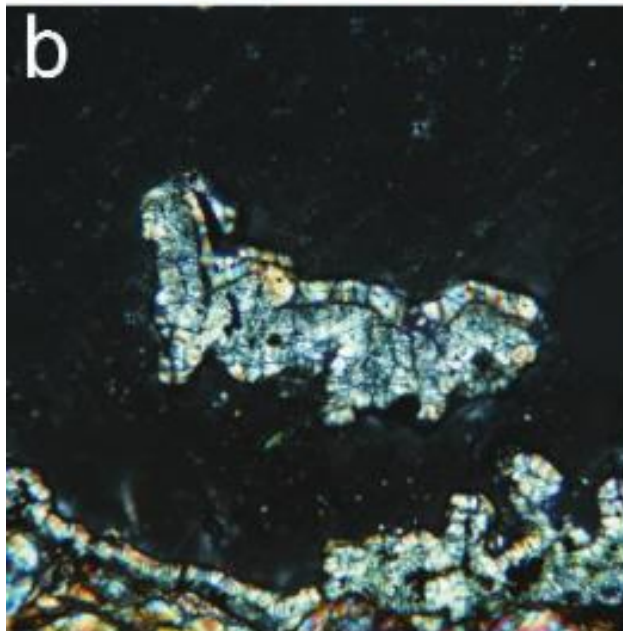
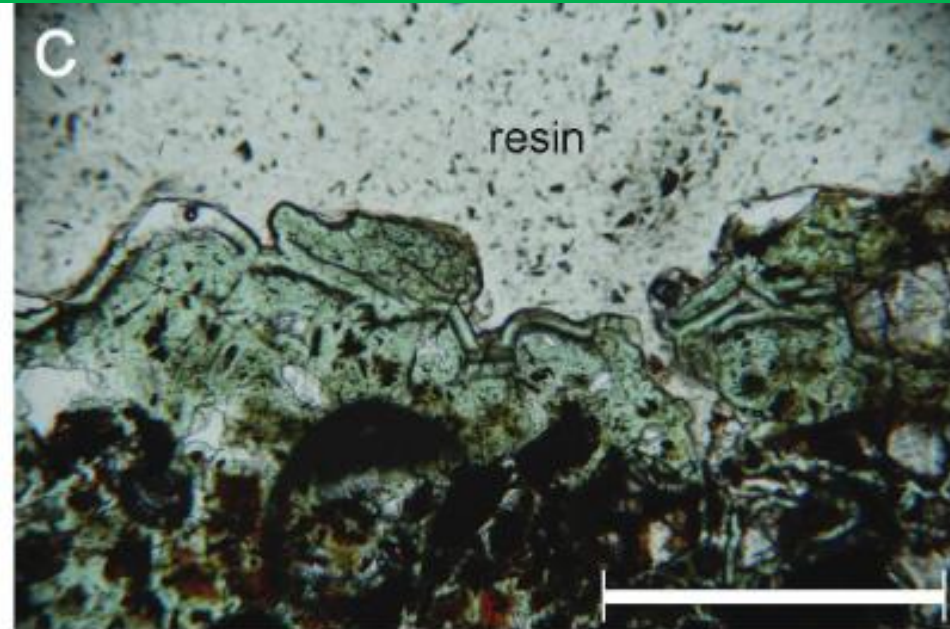
Campello Monti (Strona Valley, Italy)

Optical micrographs of garnierite (scale bar is 0.5 mm):

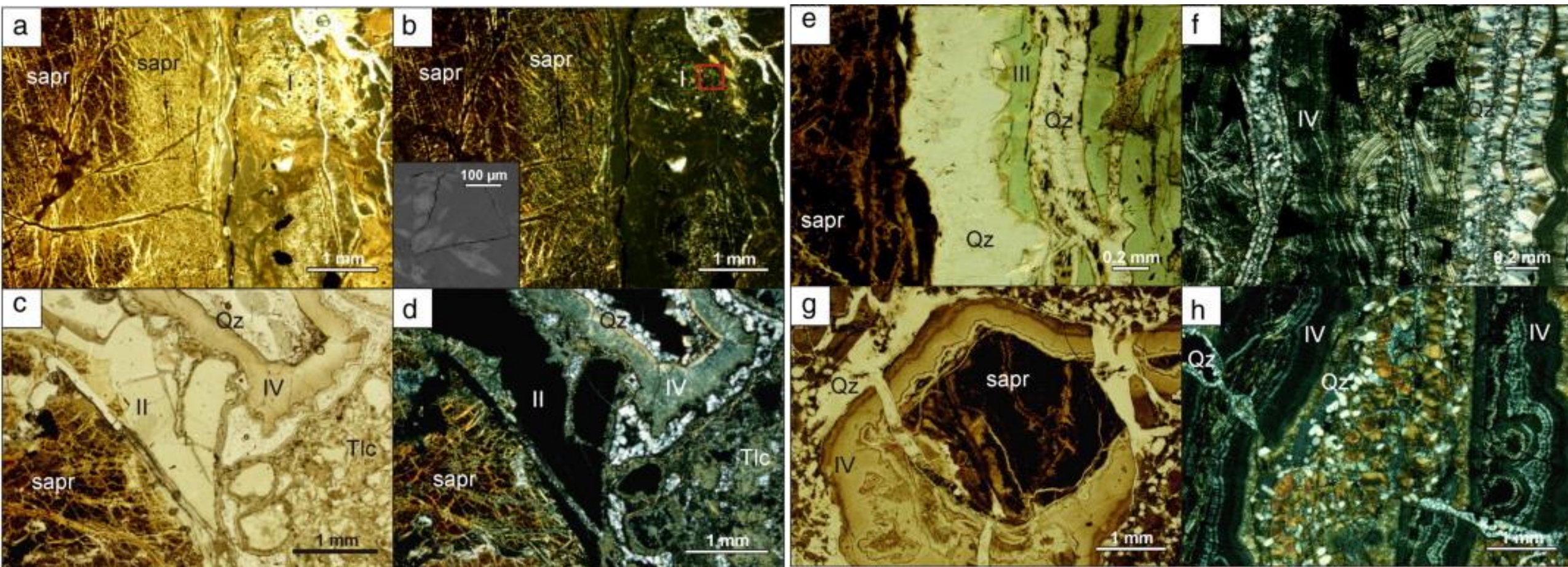
- (A) parallel light image and;
- (B) crossed polars image of the green coating;
- (C) parallel light image of a cross section through the garnierite coating (green) and the host rock (lower part). The opaque minerals are mostly iron oxides (black) and hydroxides (reddish);
- (D) single polar image of a garnierite vein intruding the host rock. Note the colorless Mg-serpentine (Srp) bordering the vein and altering the surrounding olivine (Ol). (Color online.)

Fonte: Capitani & Ventruti (2018)

<https://www.degruyter.com/view/journals/ammin/103/4/article-p629.xml>



Ni-serpentininas e minério de garnierita ao microscópio (*Luz transmitida – silicatos hidratados de Ni-Mg*) (*Falcondo Ni-laterite deposit; República Dominicana*)



Optical photomicrographs showing characteristic textures of the described garnierite typologies (*legenda na próxima página*).

Fonte: Benavent et al. (2014).

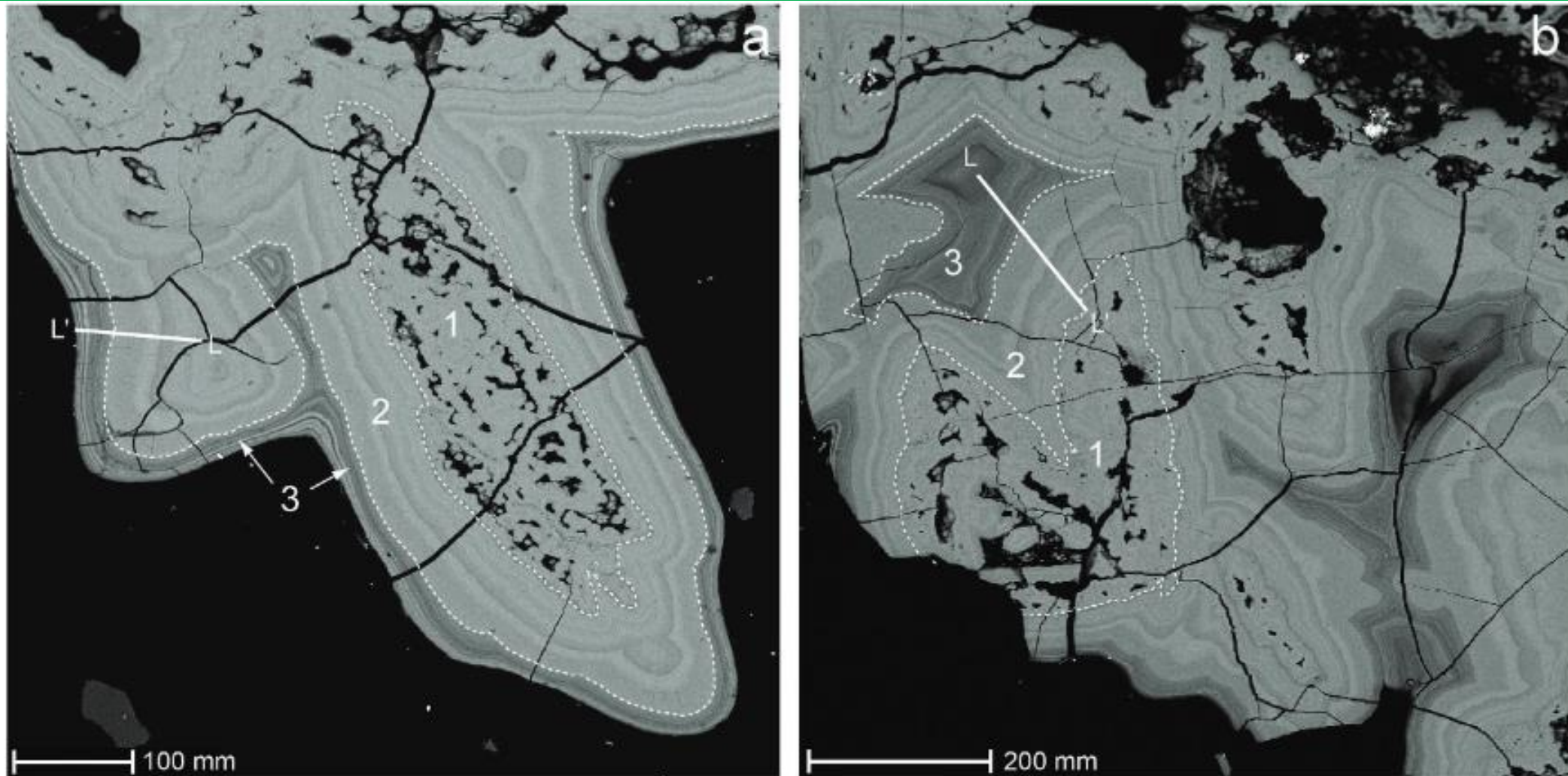
<https://www.sciencedirect.com/science/article/pii/S0169136813002333#f0025>

Optical photomicrographs showing characteristic textures of the described garnierite typologies. a–b) Plane polarised light (a) and crossed polars image (b) of saprolite and type I garnierite. b) includes a backscattered electron image of the selected area in the red box). c–d) Plane polarised light (c) and crossed polars image (d) of type II garnierite with brownish grey talc-like matrix (Tlc), saprolite and type IV garnierite. e) Plane polarised light image of type III garnierite enveloping euhedral quartz crystals, over a saprolite fragment. f) Crossed polars image of type IV botryoidal aggregates interstratified with quartz layers. g) Plane polarised light image of saprolite fragment wrapped by type IV in a matrix of rounded quartz and garnierite. h) Crossed polars image of type IV botryoidal aggregates in a matrix of rounded quartz and garnierite, crosscut by microcrystalline quartz veinlets. Legend: I–IV = types I–IV, sapr = saprolite fragment, Qz = quartz.

Fonte: Benavent et al. (2014).

<https://www.sciencedirect.com/science/article/pii/S0169136813002333#f0025>

Imagens elétrons retroespalhados (BSE), ao microscópio eletrônico de varredura (MEV) de cristais de garnierita.
Campello Monti (Strona Valley, Italy)



BSE images of two selected areas from sample GC1 (a) and GC3 (b) analyzed using the WDS microprobe. Dotted lines limit three different zones, indicated by numbers 1, 2, and 3, characterized by different microstructure/composition (for explanation see text). L–L' lines represent the traces of the major element intensity profiles (See [Capitani & Ventruti, 2018](#)).

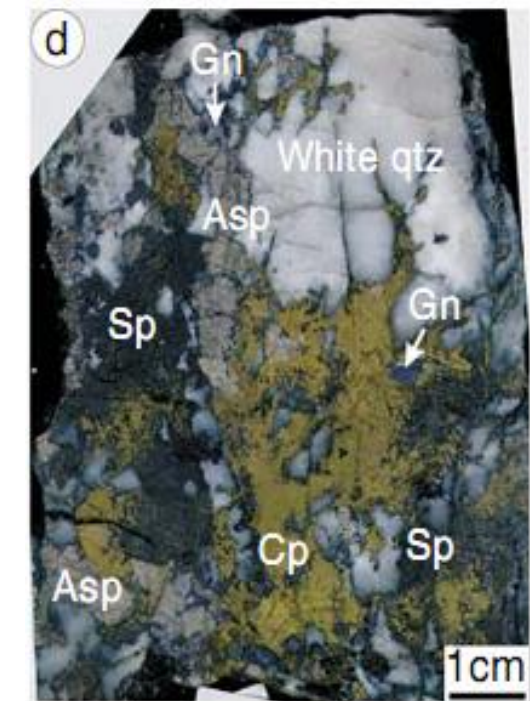
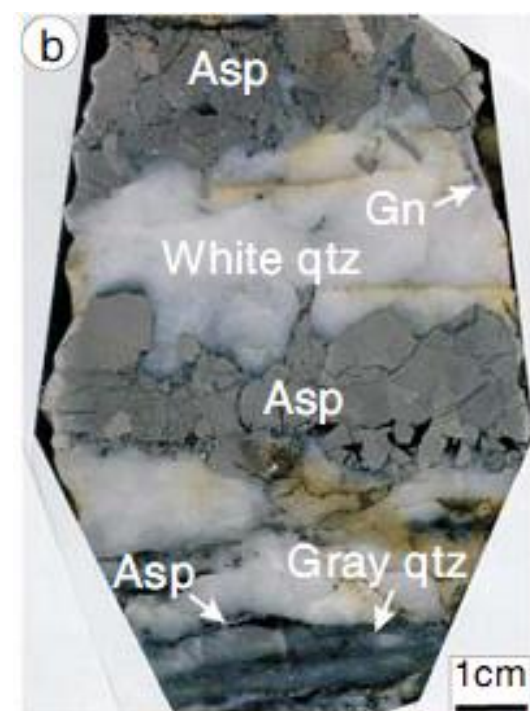
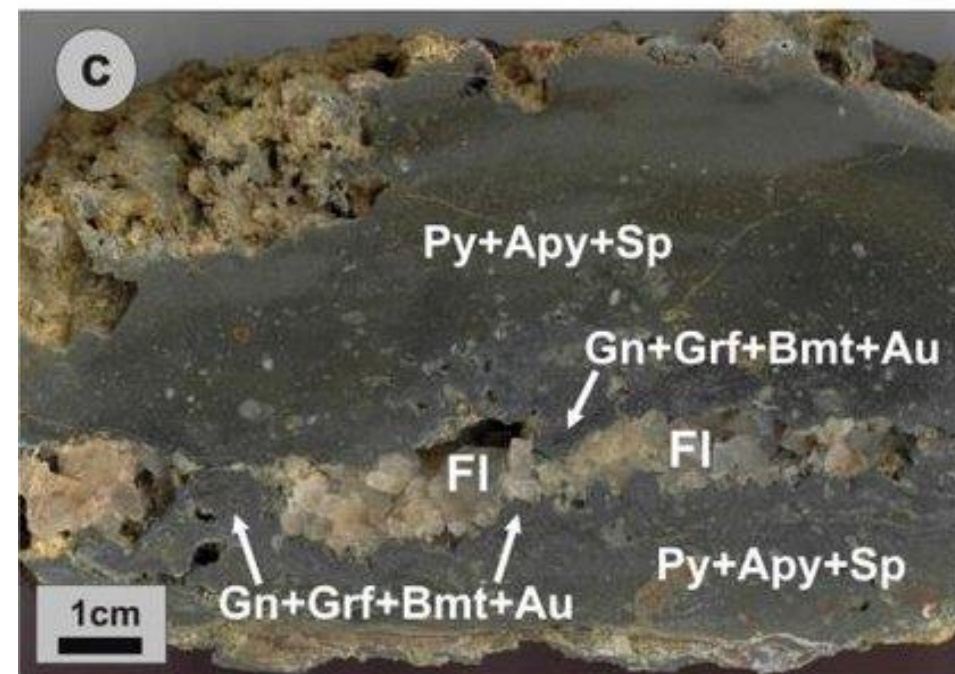
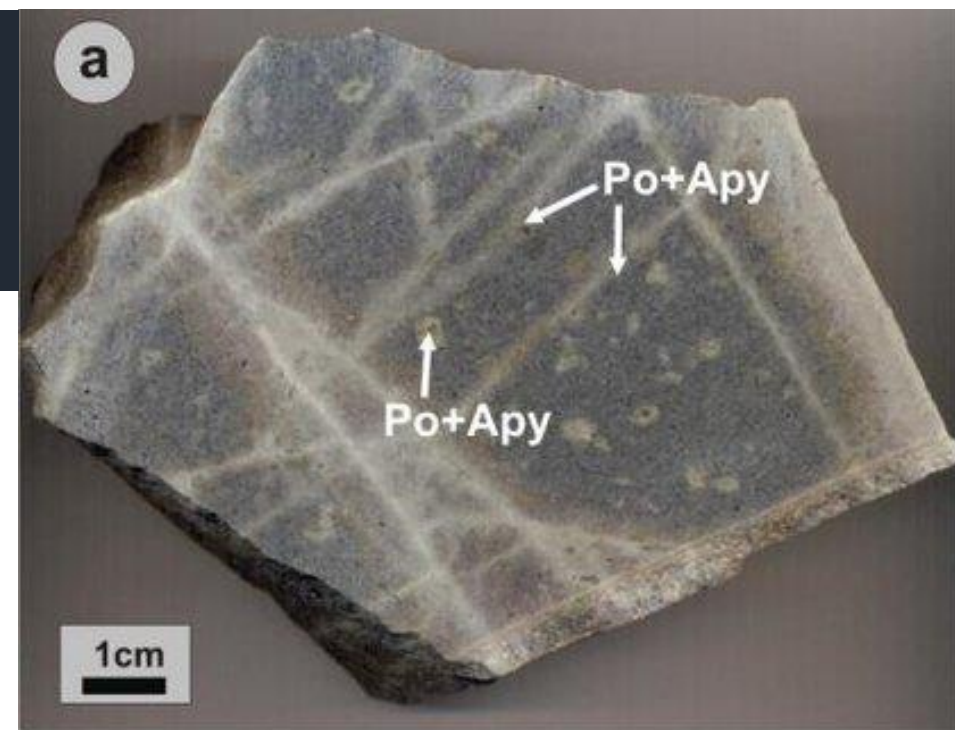
<https://www.degruyter.com/view/journals/ammin/103/4/article-p629.xml>

CONTEXTO GEOLÓGICO DOS PRINCIPAIS MINERAIS DE MINÉRIO DE ARSÊNIO

Arsenopirita (FeAsS) corresponde ao principal sulfeto de arsênio. Ocorre, sobretudo, em **contextos hidrotermais**.

► Uma das principais fases que hospedeira do minério aurífero em **sistemas de Au orogénético**.

... Embota também possa estar presente, como fases menores, em sistemas epitermais *low sulfidation*, e em alguns sistemas skarníferos ►



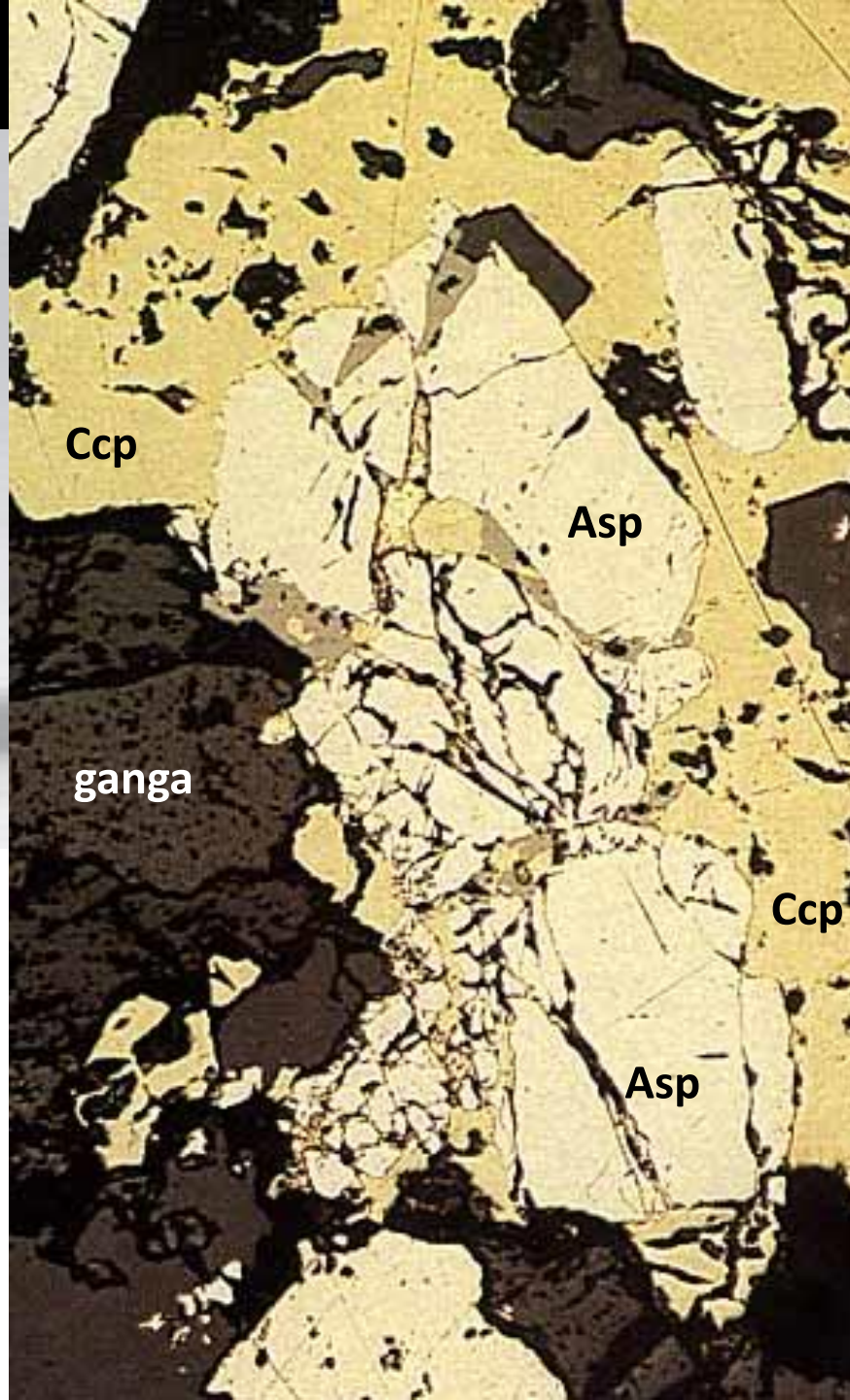
ARSENOPIRITA – FeAsS



Heinrich Frank

ARSENOPIRITA - LUZ REFLETIDA
(POLARIZADORES DESCRUZADOS E CRUZADOS)

https://www.youtube.com/watch?v=tB7Urb4pCWo&list=PL5k_2NCH5I4Bb3dirmZgesOGjS2jGjKXs



COR

Cor branca, com sutil cor creme.

REFLECTÂNCIA

Alta (~50-51%).

PLEOCROÍSMO E BIRREFLECTÂNCIA

Ausentes

ANISOTROPIA

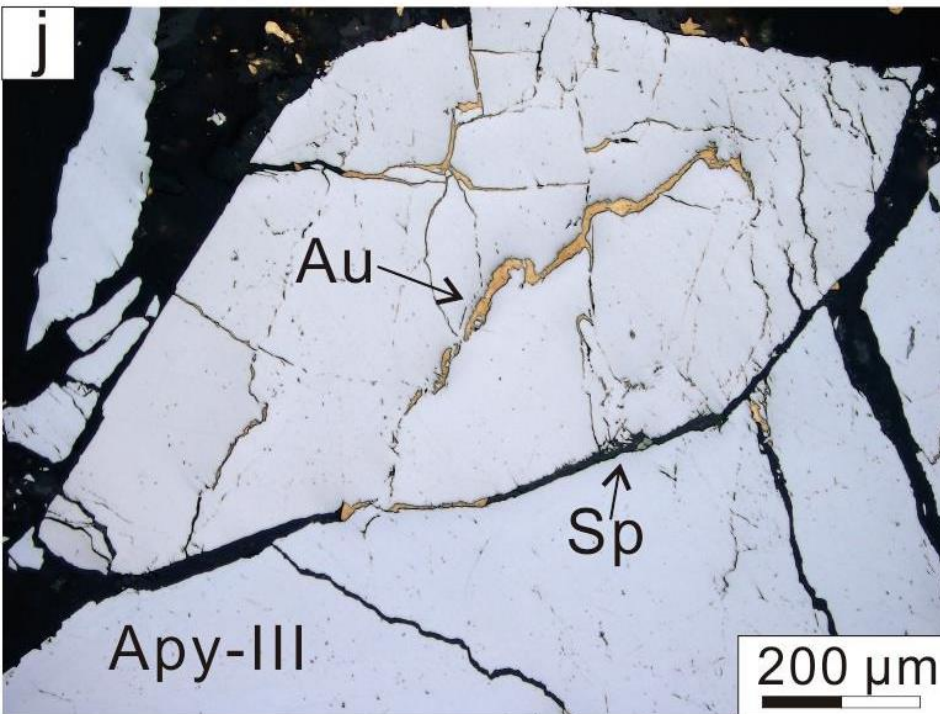
Muito forte (*diagnóstica*), de azul escuro (azul da Prússia) a vermelho-marron claros.

OUTRAS CARACTERÍSTICAS

Ausência de sulcos de polimento. Formas poligonais que tendem a ser idiométricas (hexágonos). Maclas são frequentes.

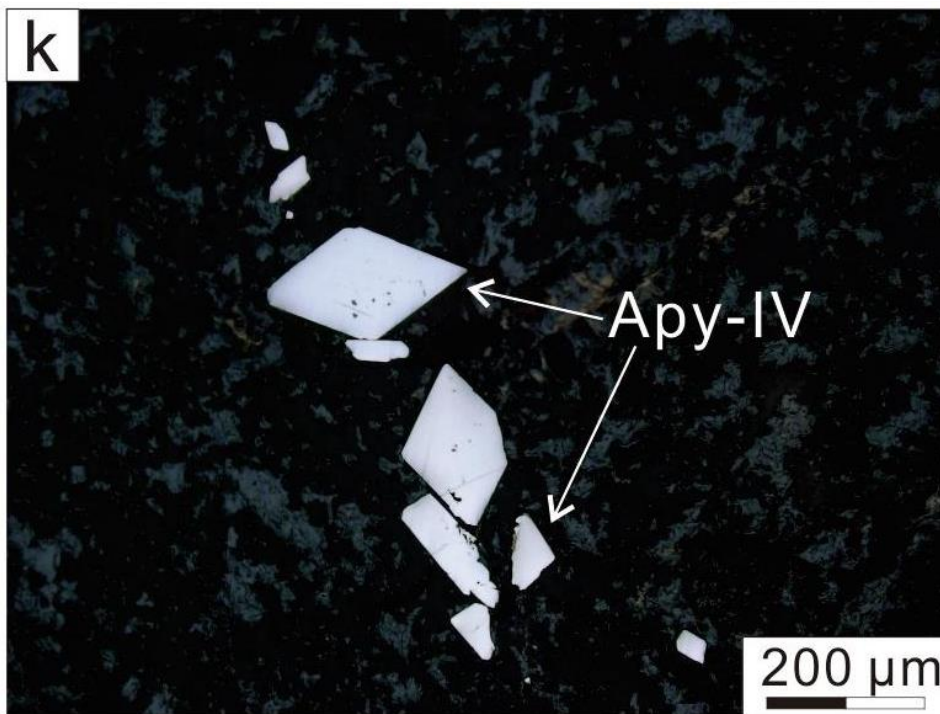
◀ Fonte:

<http://www.atlas-of-ore-minerals.com/plate34d.htm>



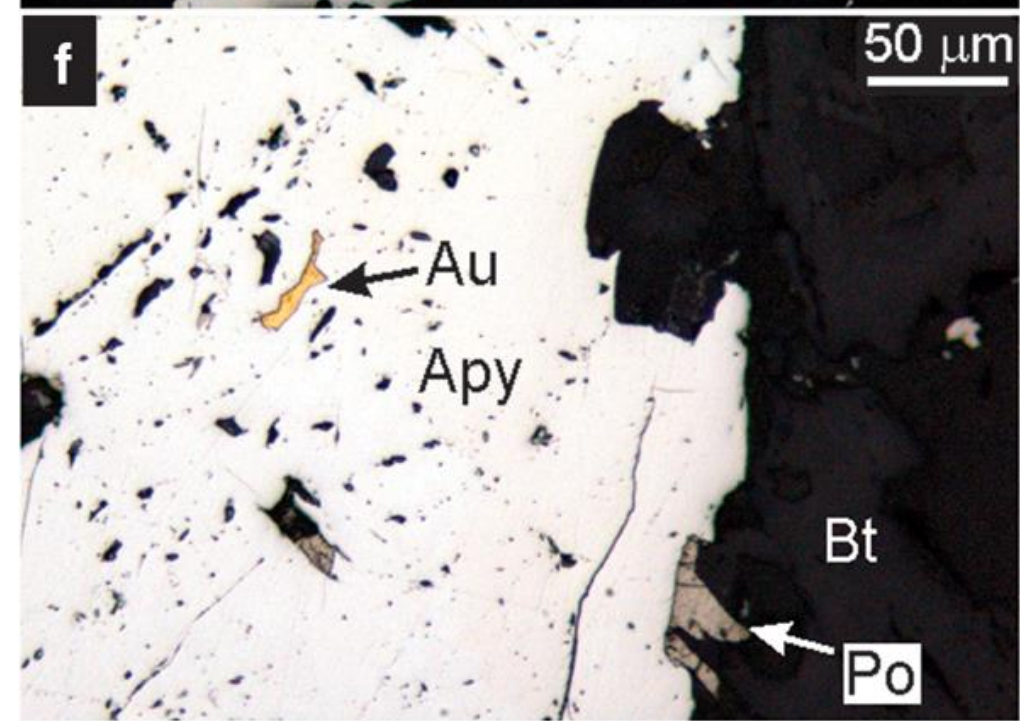
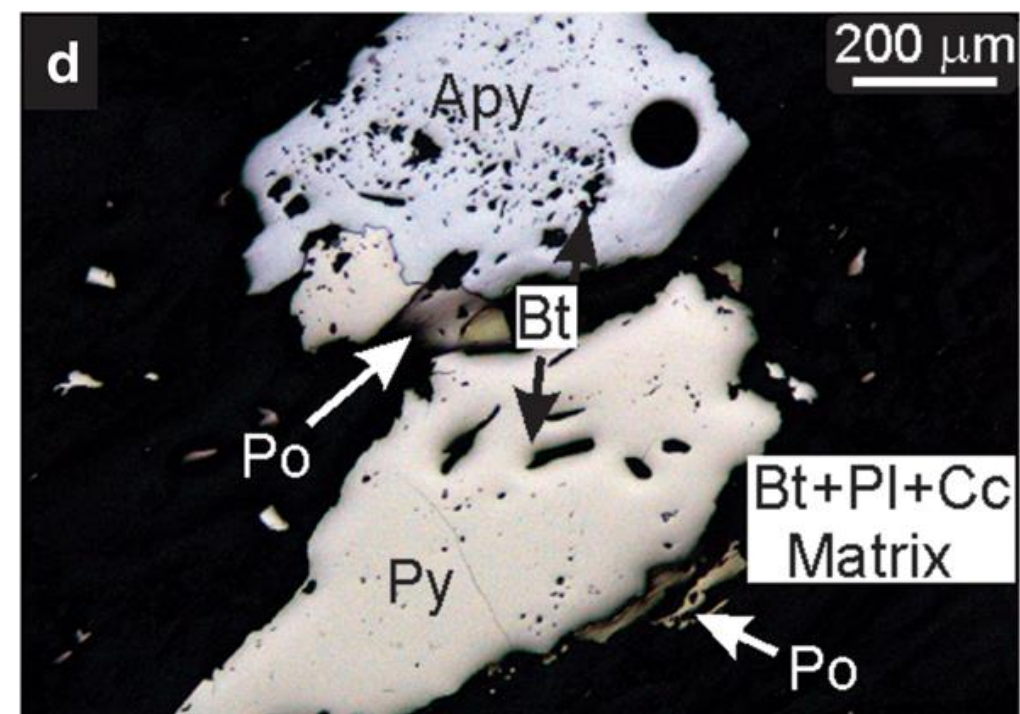
(D) reflected light photomicrograph of stage-1 alteration assemblage showing buffered assemblage Py + Apy + Po (Hazarika et al., 2017). ►

◄ **(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).



◄ **(K)** Minor, euhedral to subhedral arsenopyrite (Apy-IV) occur without any porous and fractures in NW-trending quartz vein (Sun et al., 2020).

(F) occurrence of gold as inclusions and at the margins of pyrite and arsenopyrite (Hazarika et al., 2017). ►



O SISTEMA Fe-As-S

Importância nos estudos paragenéticos
com o Au

→ *Au mesotermal*

ARSENOPIRITA

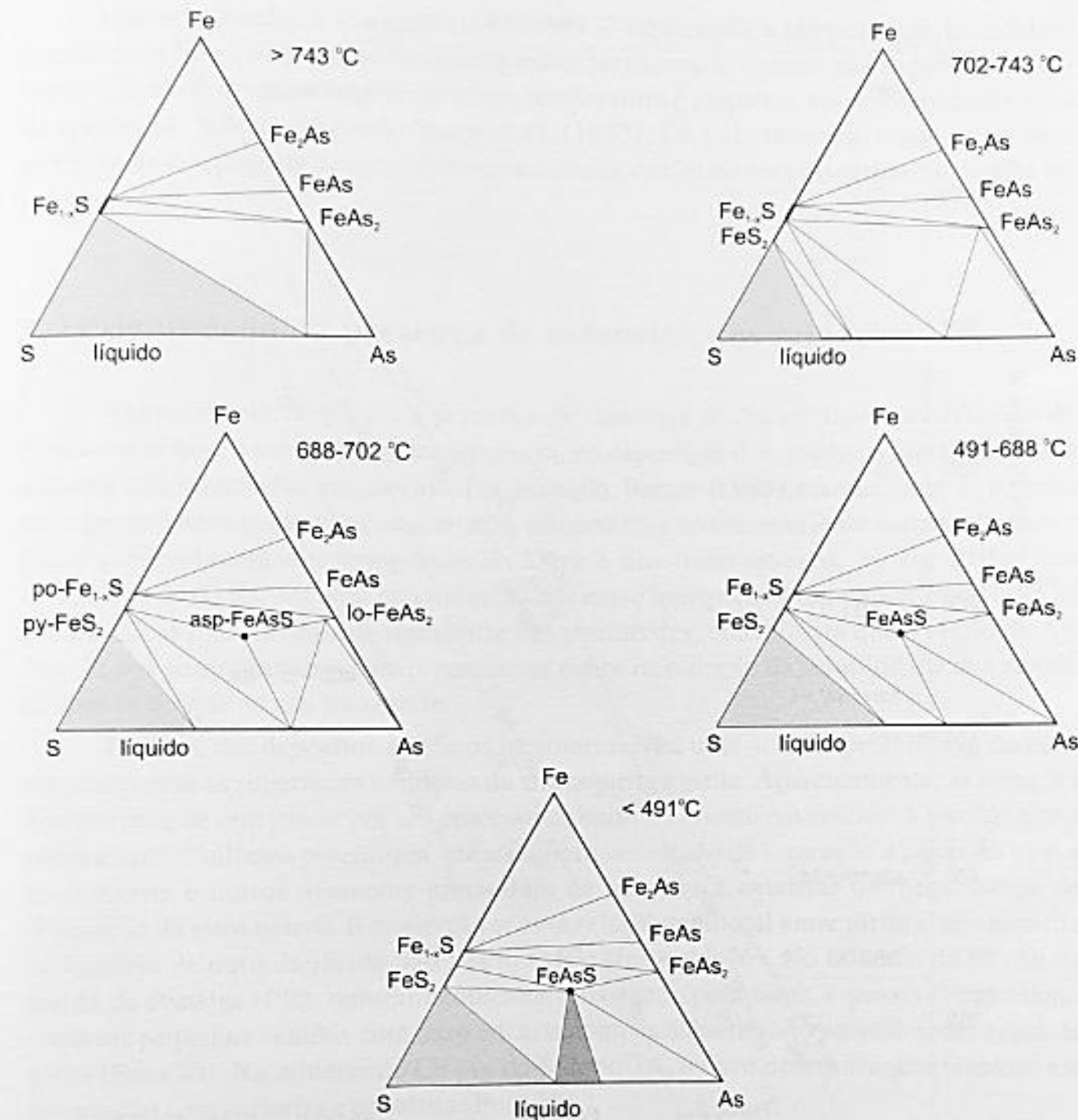
Única fase ternária do sistema Fe-As-S
Estável abaixo dos 702 °C

Arsenopirita – pirita – pirrotita
(*Asp mais rica em S*)

Arsenopirita – loellingita – As metálico
(*Asp mais rica em As*)

FONTE:

Figueiredo (2000); Minérios e ambiente.



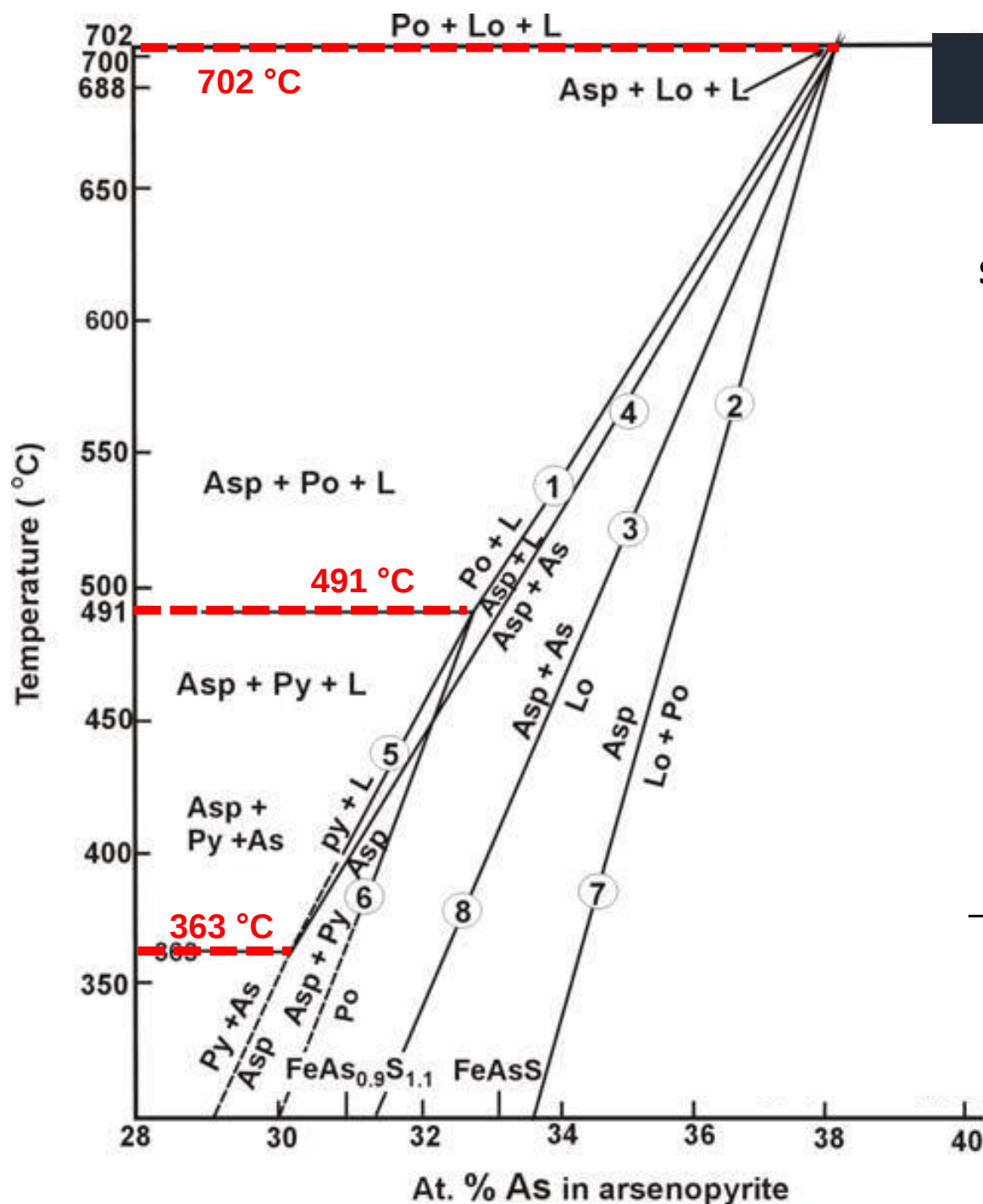
O SISTEMA Fe-As-S

A concentração de As na arsenopirita é dependente de sua temperatura de estabilidade, o que permite que ela possa ser utilizada como geotermômetro.

Em função da f_{S_2} , o tamponamento das paragêneses ocorre da seguinte forma:

Asp + Lo + Po,
Asp + Py + Po,
Asp + Py + As

→ para as quais, a concentração de As (% atômico As) na arsenopirita é fixa tanto para T quanto f_{S_2} .



FONTE:

Figueiredo (2000); Minérios e ambiente.

