Cubanite & associated sulfides in CI chondrites & comet 81P/Wild 2: Implications for aqueous processing

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Characteristics of Stardust Sulfides
Fe, Ni, Cu, Zn, Mn-bearing
Mineralogy, Structure, Associations

Modified by capture into aerogel

Unmodified by capture into aerogel

Nebular Formation via gas-solid processes

Parent Body Precipitation

Aqueous Modification

on Wild 2

on other body

Implications for the genesis of Wild 2 sulfides, source material(s), and mixing in the early Solar System as indicated by compositions, structures, and uniformity/heterogeneity of phases.

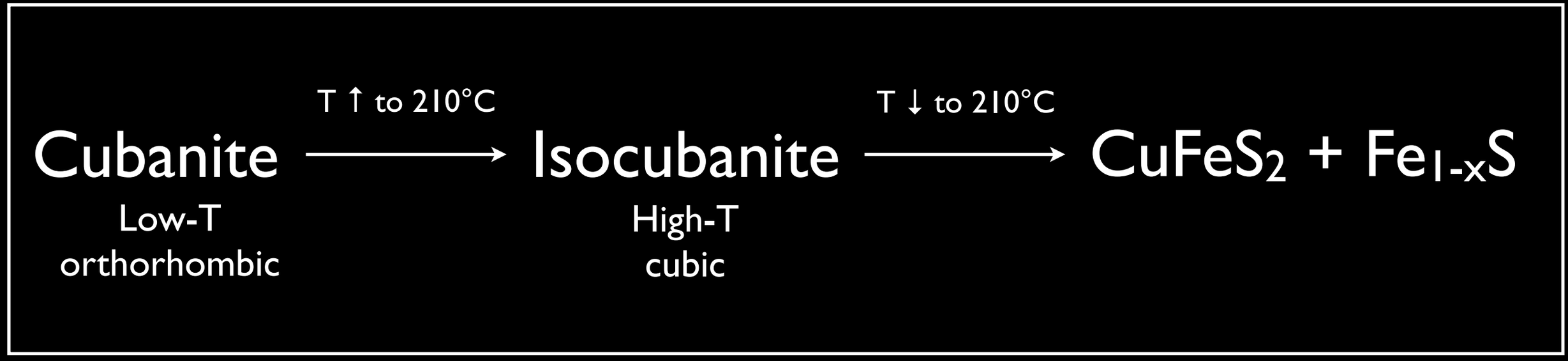
Sulfide Populations

		Comet Wild 2	CI Chondrites
Minerals	Cubanite $CuFe_2S_3$	✓*	✓*
	Pyrrhotite $(Fe, Ni)_{1-x}S$	✓*	✓*
	Pentlandite $(Fe,Ni)_9S_8$	✓*	✓
	Sphalerite $(Fe,Zn)S$	✓*	?
Assemblages	Cubanite & Pyrrhotite	?	✓*
	Pyrrhotite & Pentlandite	✓*	✓
	Pyrrhotite & Sphalerite	✓*	?

* Berger et al. (2011); Pentlandite: e.g., Bullock et al. (2005)

$CuFe_2S_3$

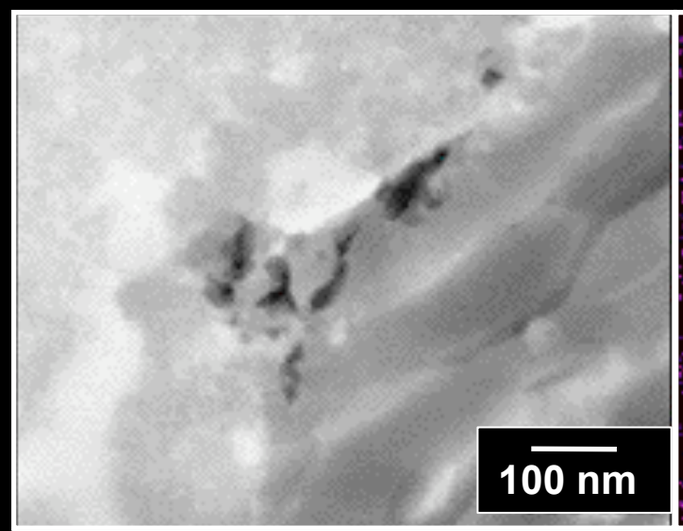
Cubanite undergoes an irreversible phase transition at 210°C

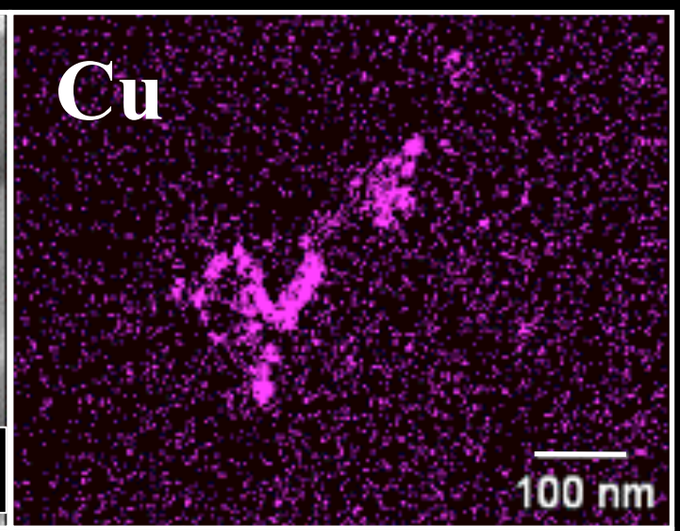


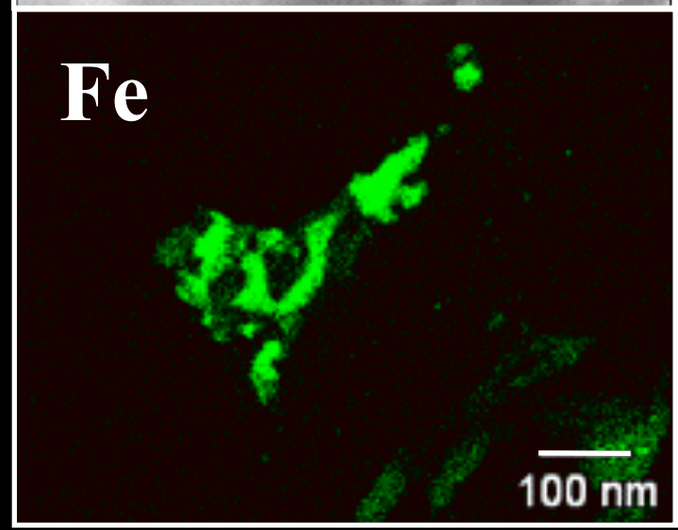
Caye *et al.* (2000), Miyamoto *et al.* (1980), Pruseth *et al.* (1999), Putnis *et al.* (1977)

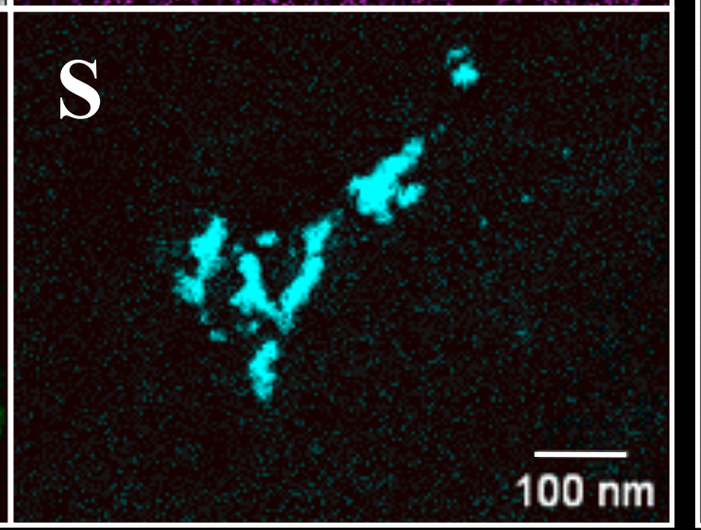
Stardust Cubanite

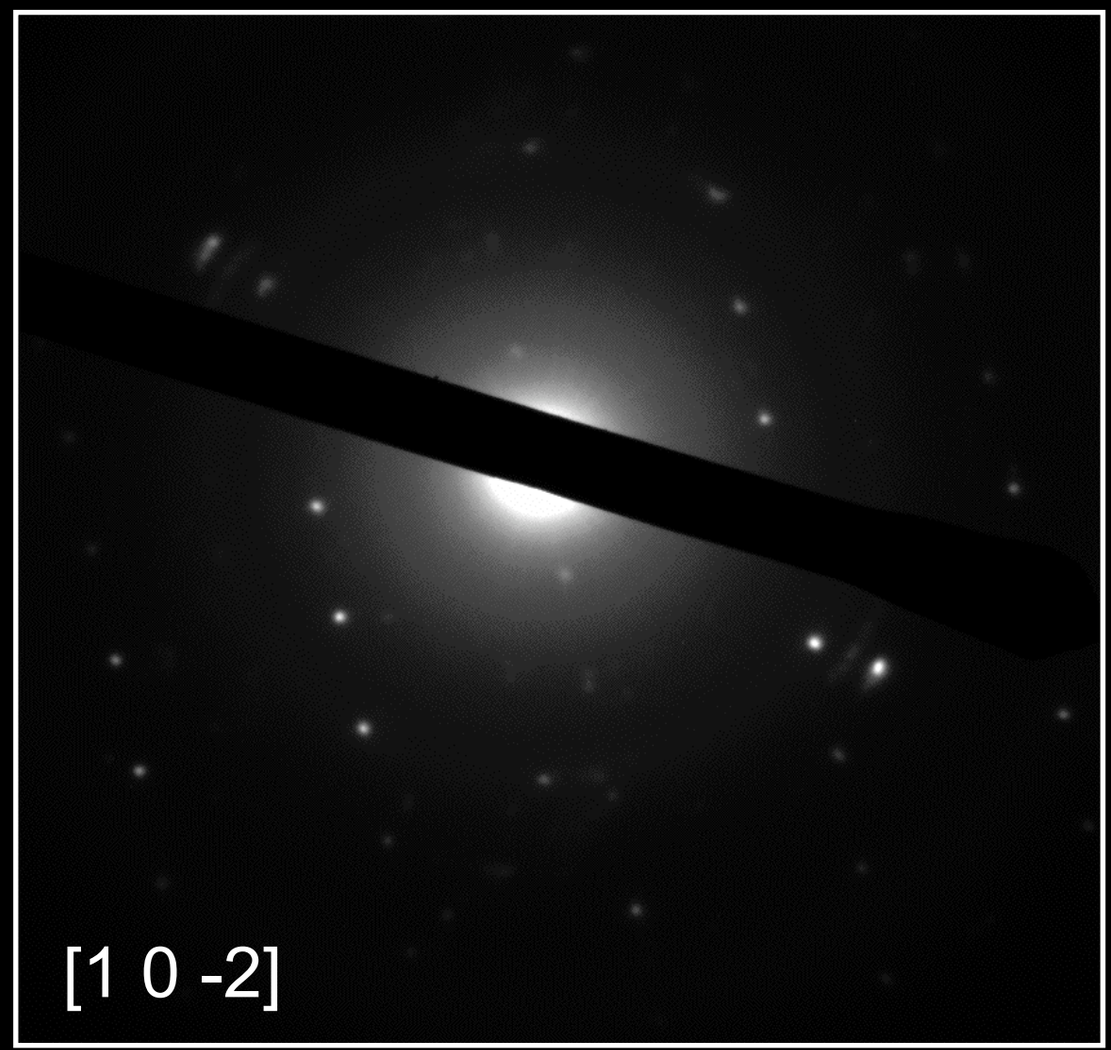
C2054-5-26-1-16







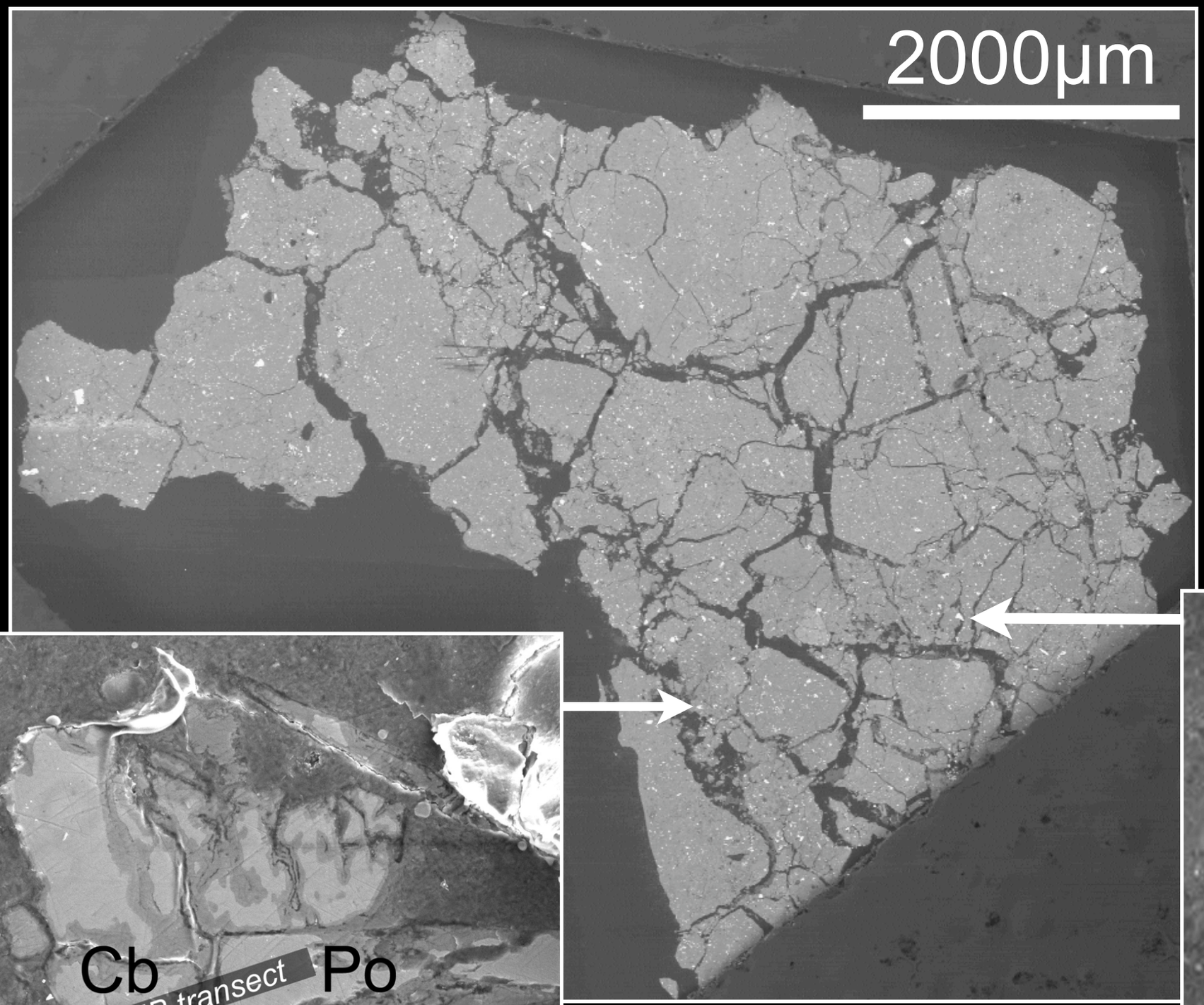




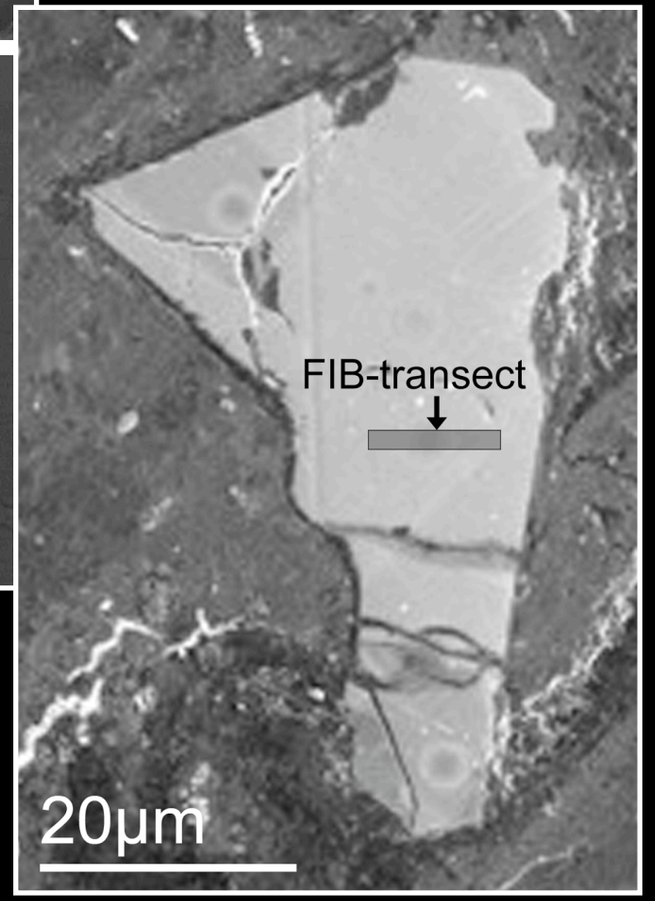
15.3 at.% Cu
35.0 at.% Fe
49.7 at.% S

Low-temperature orthorhombic cubanite never experienced T > 210°C

CI-chondrite Sulfides

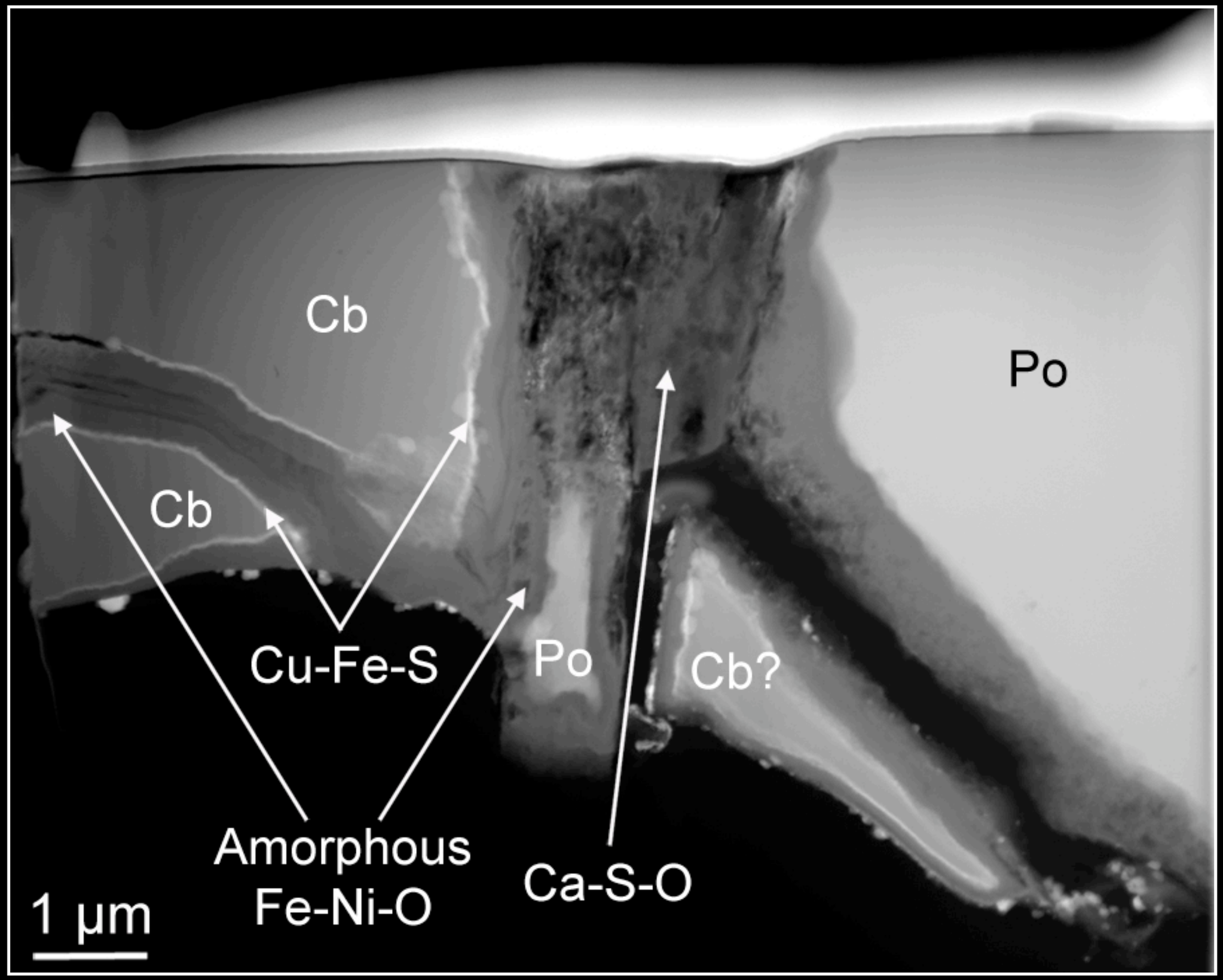


Cubanite

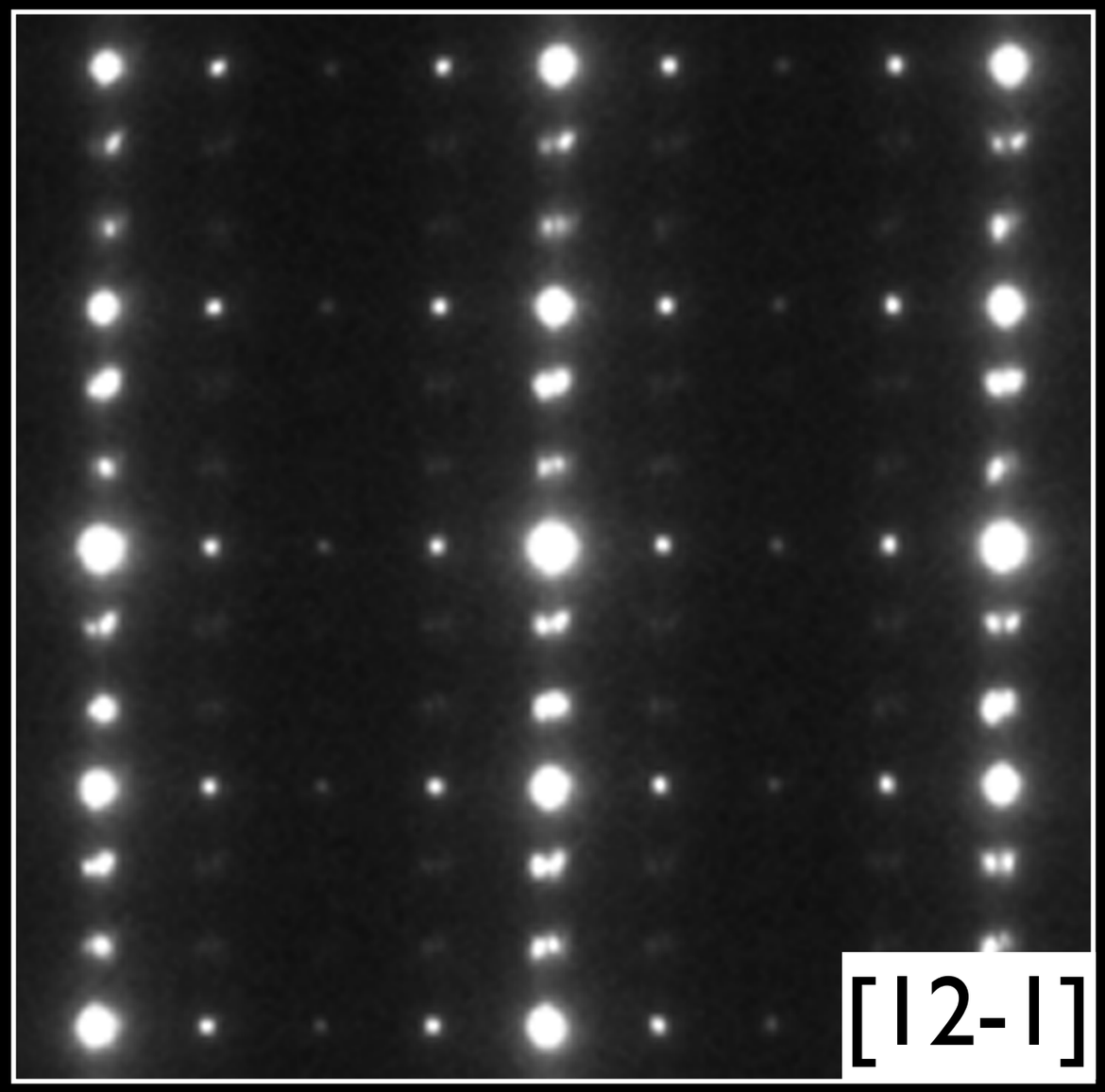


Cubanite
& Pyrrhotite

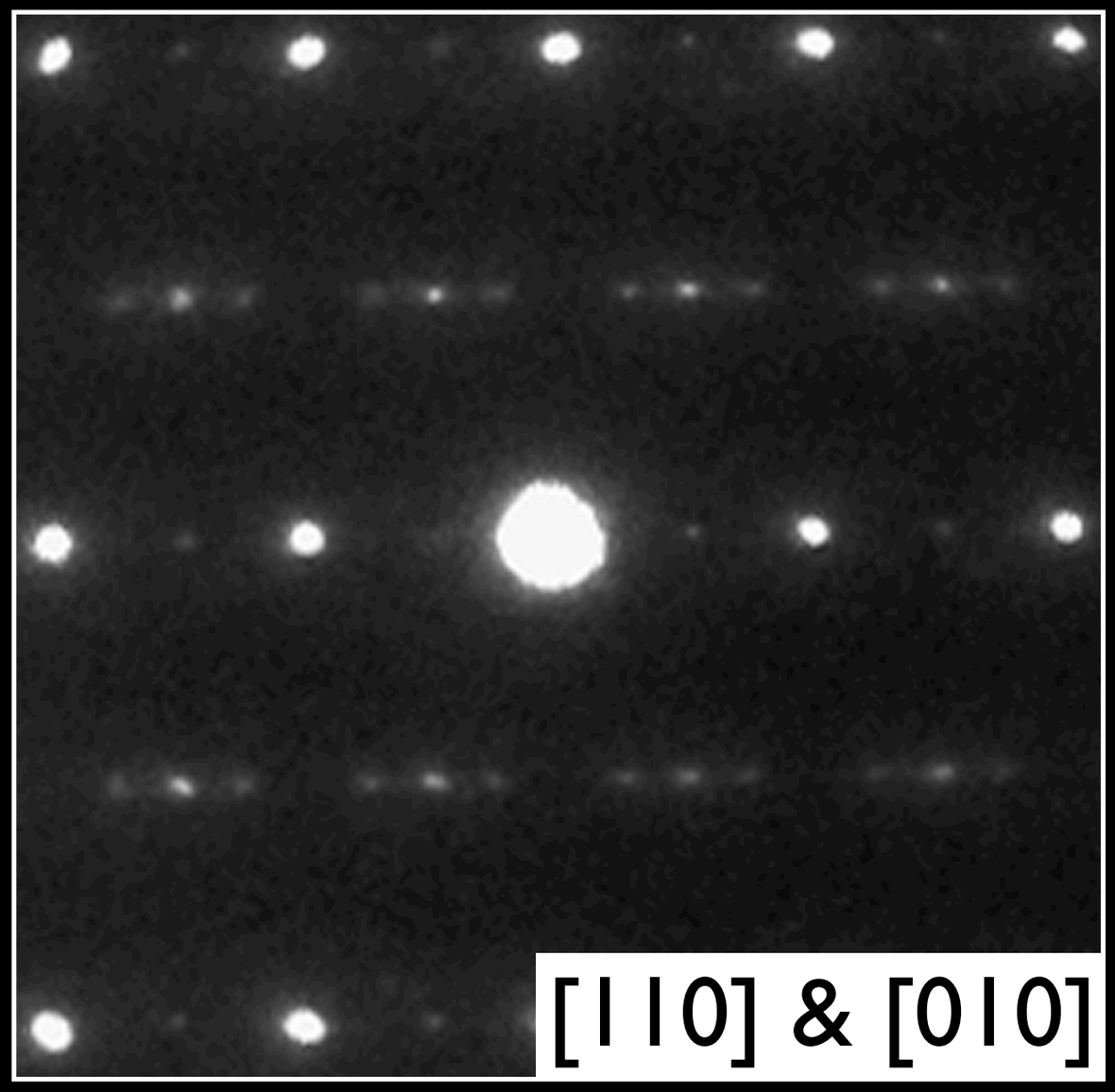
CI-chondrite Cubanite & Pyrrhotite



CI-chondrite Cubanite & Pyrrhotite



cubanite
$CuFe_2S_3$

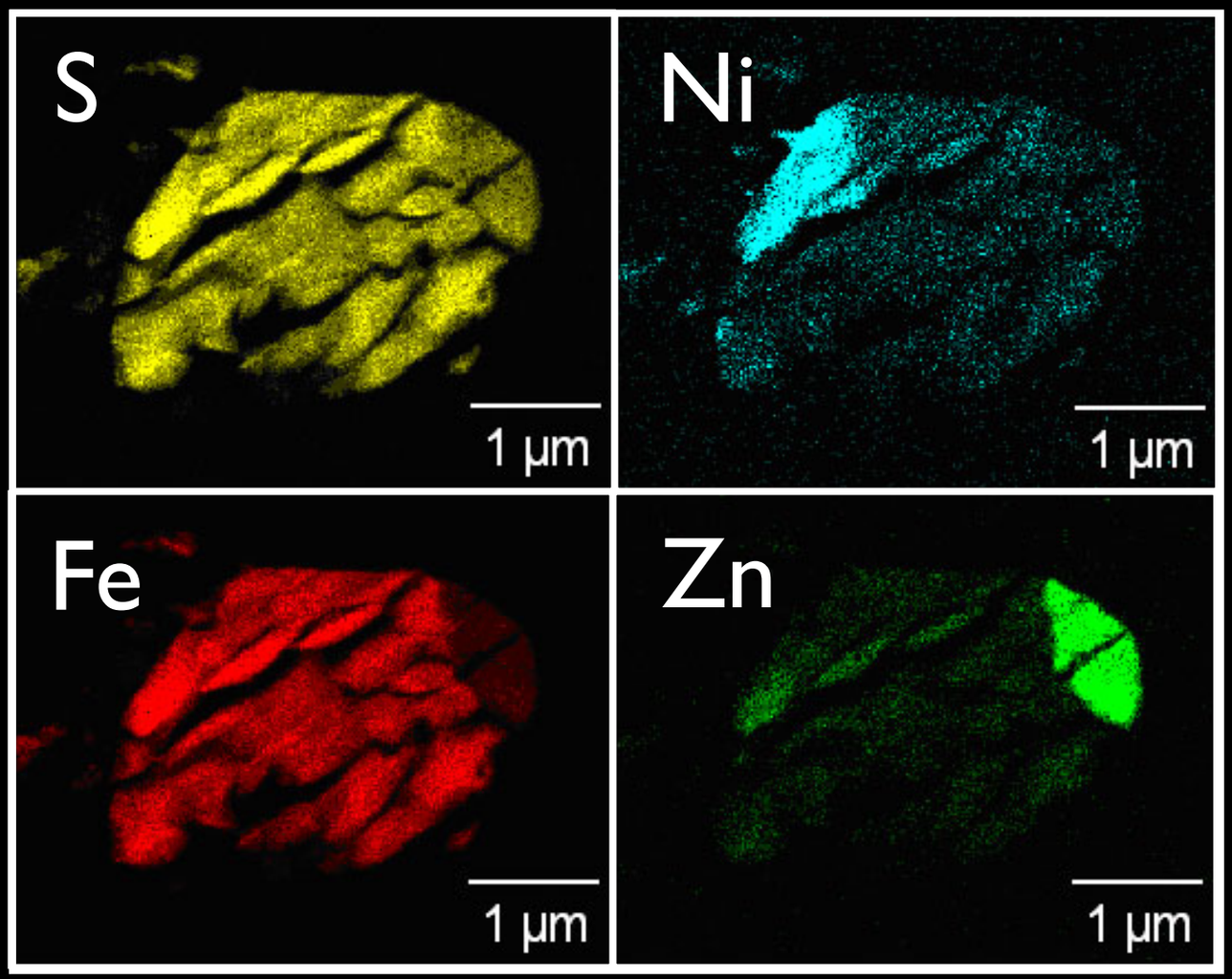


4C monoclinic pyrrhotite
$(Fe,Ni)_7S_8$

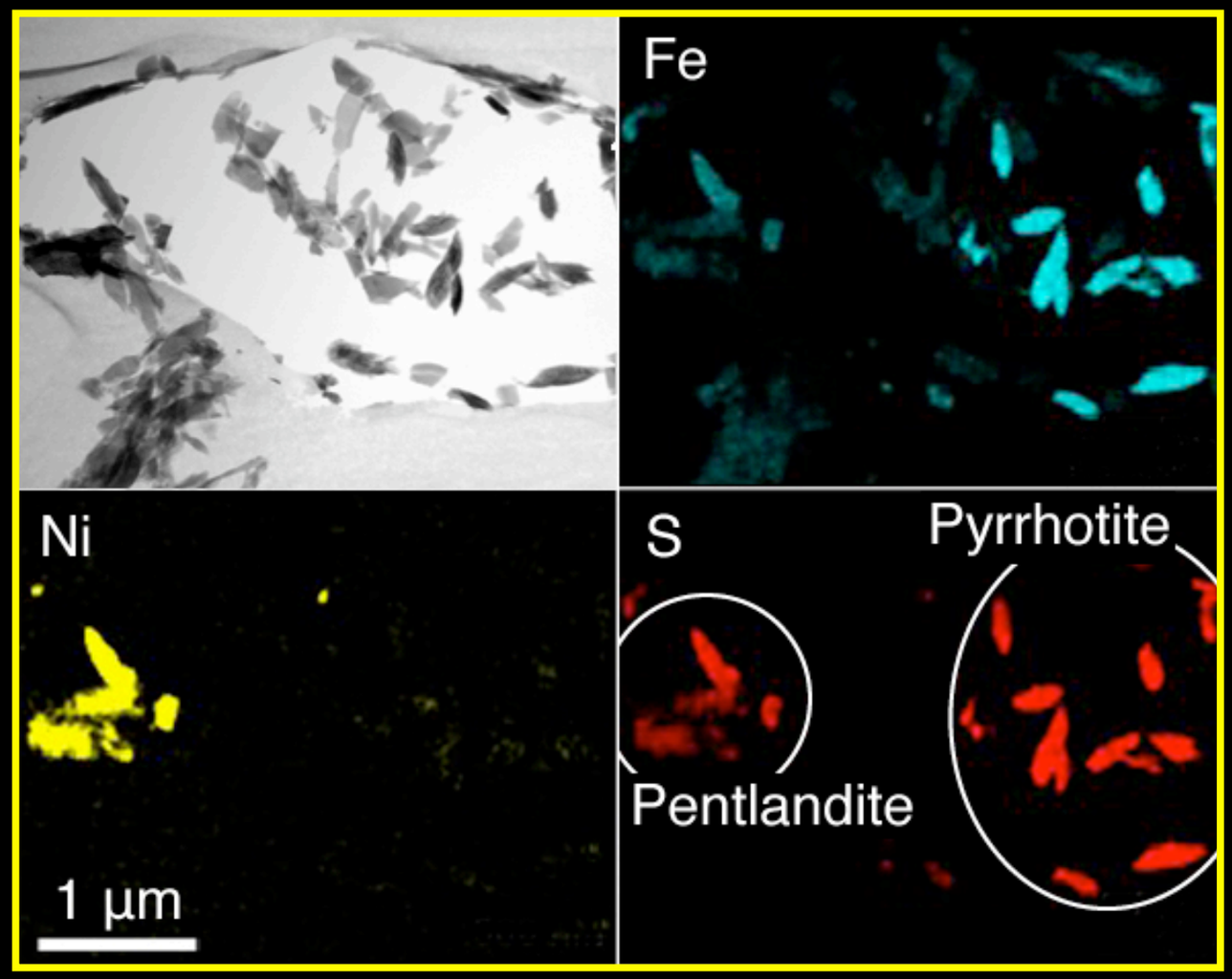
Combination of pyrrhotite & cubanite indicates T<200°C

Stardust Fe-Ni-Sulfides

Pyrrhotite
FC6-0-10-0-85



Pyrrhotite & Pentlandite
C2054-5-27-1-11



4C monoclinic pyrrhotite indicates T<250°C

4C monoclinic pyrrhotite & pentlandite are a stable assemblage on the 100-135°C Fe-Ni-S ternary diagram

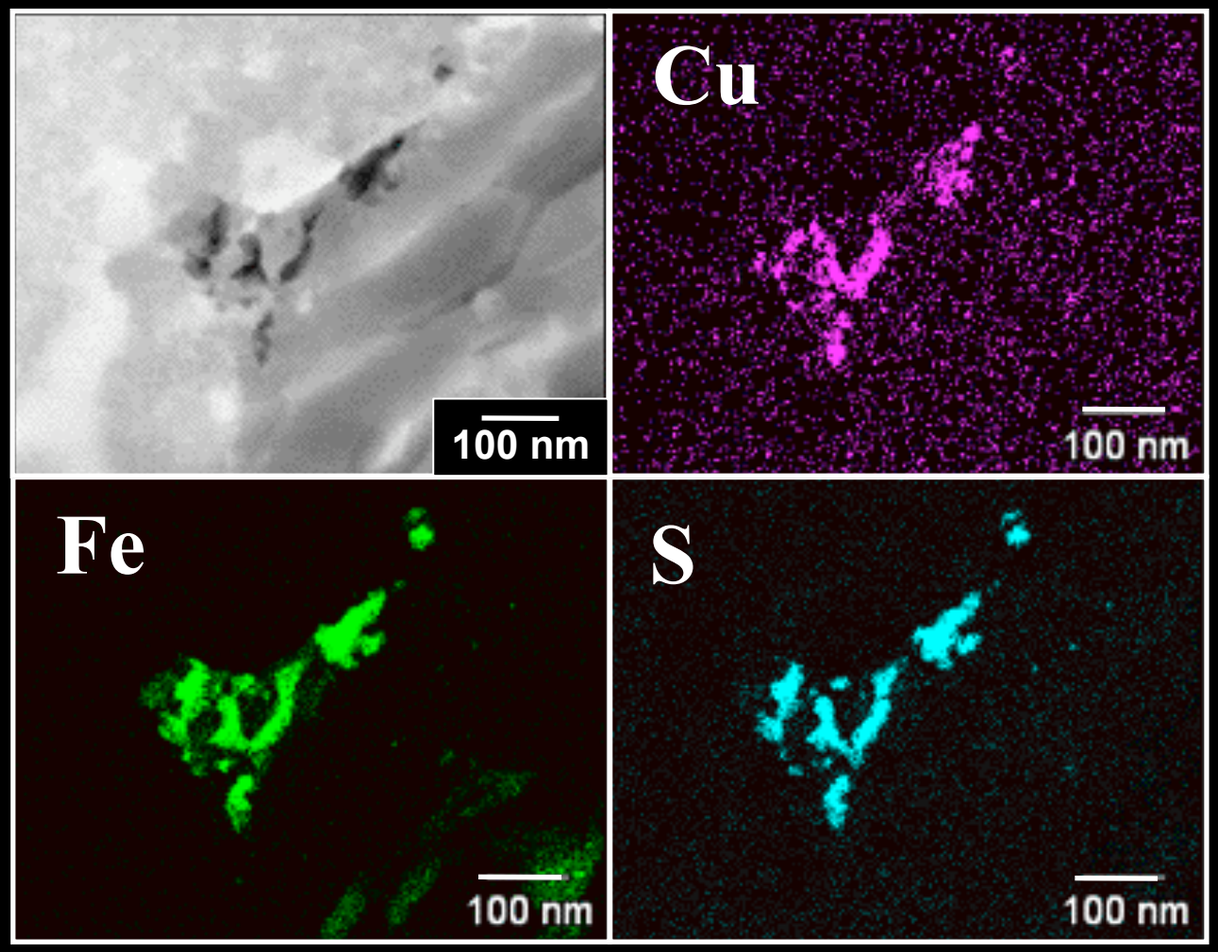
Mineral Constraints

		Wild 2	CI Chondrites	
Minerals	Cubanite $CuFe_2S_3$	✓	✓	$T_{max} = 210°C$ *1*
	4C Pyrrhotite Fe_7S_8	✓	✓	$T < 250°C$ *2*
	Pentlandite $(Fe,Ni)_9S_8$	✓	✓	$T < 610°C$ *3*
	Sphalerite (Fe,Zn)S	✓	?	$T < 1200°C$ *4*
Assemblages	Cubanite & Pyrrhotite	?	✓	$T<200°C$ Fe-Cu-S *5*
	4C Pyrrhotite & Pentlandite	✓	✓	$T<250°C$ Fe-Ni-S *6*
	4C Pyrrhotite & Sphalerite	✓	?	$250°C$ Fe-Zn-S *7*

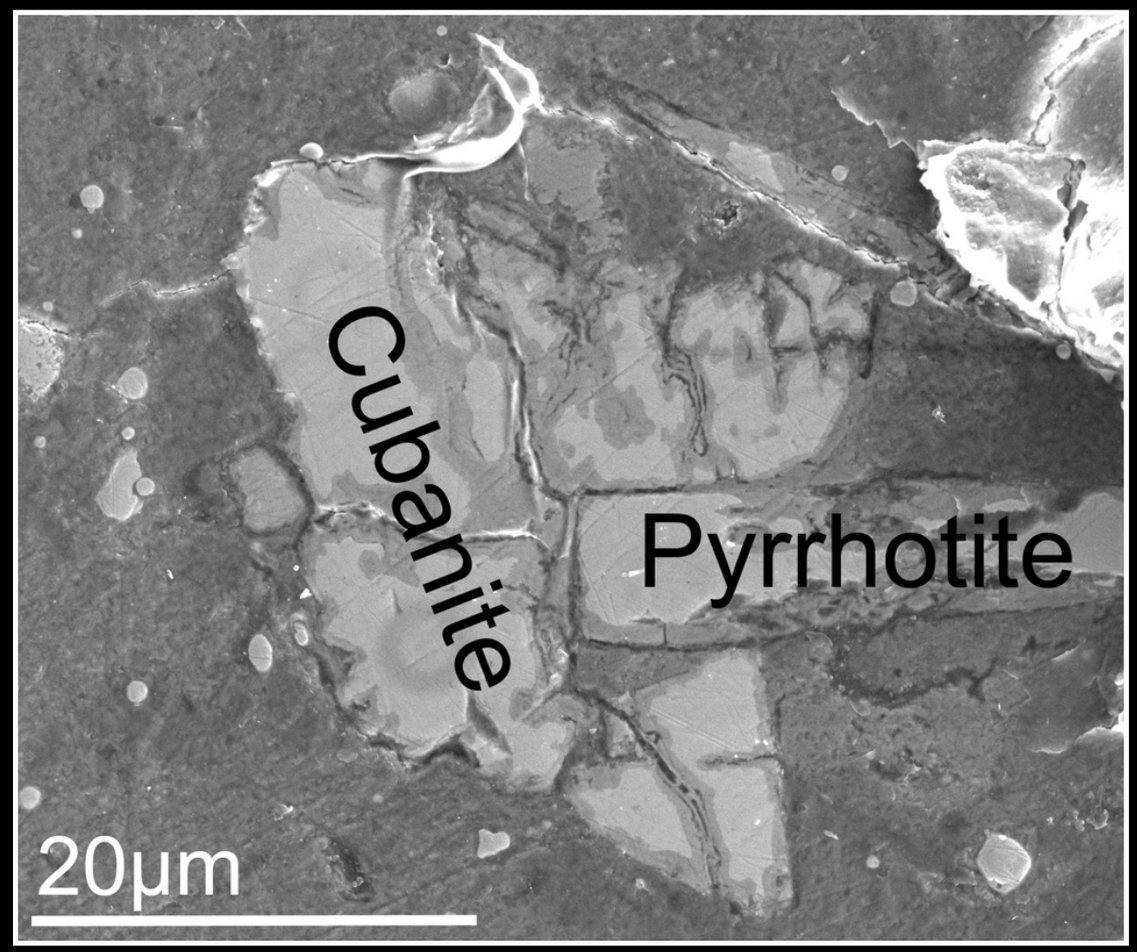
1: Caye *et al.* (2000), Miyamoto *et al.* (1980), Pruseth *et al.* (1999), Putnis *et al.* (1977); *2*: Wang *et al.* (2006); *3*: Fleet (2006); *4*: Ihto (1999); *5*: Vaughan & Craig (1997), Yund & Kullerud (1966); *6*: Naldrett (1989); *7*: Kojima & Sugaki (1984), Scott & Kissin (1973), Vaughan & Craig (1997).

In situ hydrothermal recrystallization

Stardust Cubanite



Orgueil Sulfides



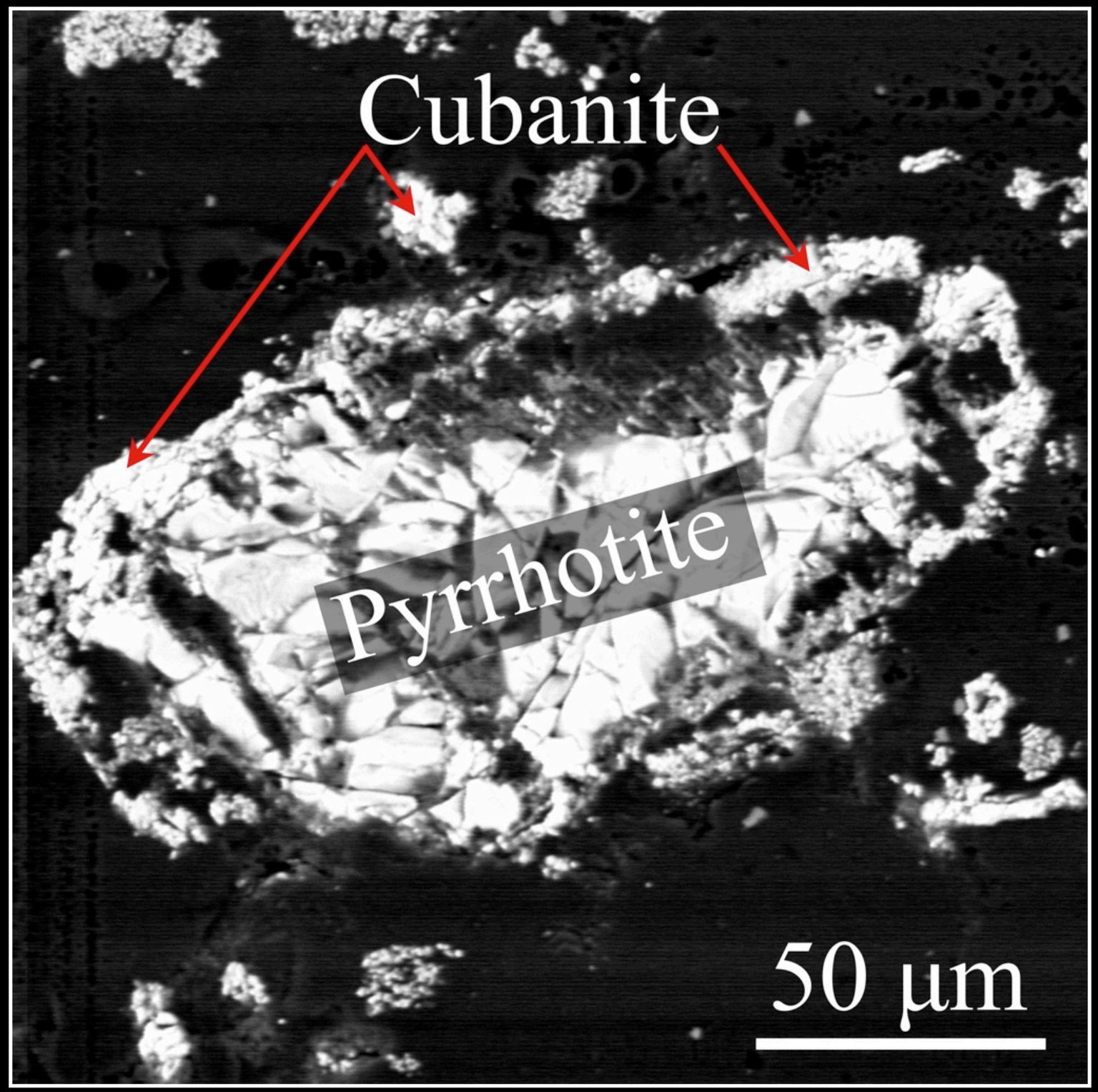
150-200°C

starting pH = 9, 9.5, & 10

starting fO_2 at IM buffer (solids and powders)

Cu, Fe, S, FeS, CuS

Experimentally produced Cubanite/pyrrhotite assemblage



Fluid conditions consistent with those predicted for the CI-chondrite parent body:

- ★ *200°C*
- ★ *FeS + CuS*
- ★ *Starting pH = 9.01*
- ★ *Started in the presence of Fe and Fe_3O_4 powders*

Cubanite overgrowths on pyrrhotite are directly comparable to Orgueil sulfide assemblages

Genesis of Wild-2 Cubanite

Scenario 1

Nebular formation of cubanite

Delivery to the comet-forming region

Scenario 2

Nebular formation of troilite

Parent-body aqueous alteration

Delivery to comet-forming region

Scenario 3

Nebular formation of troilite

Delivery to comet-forming region

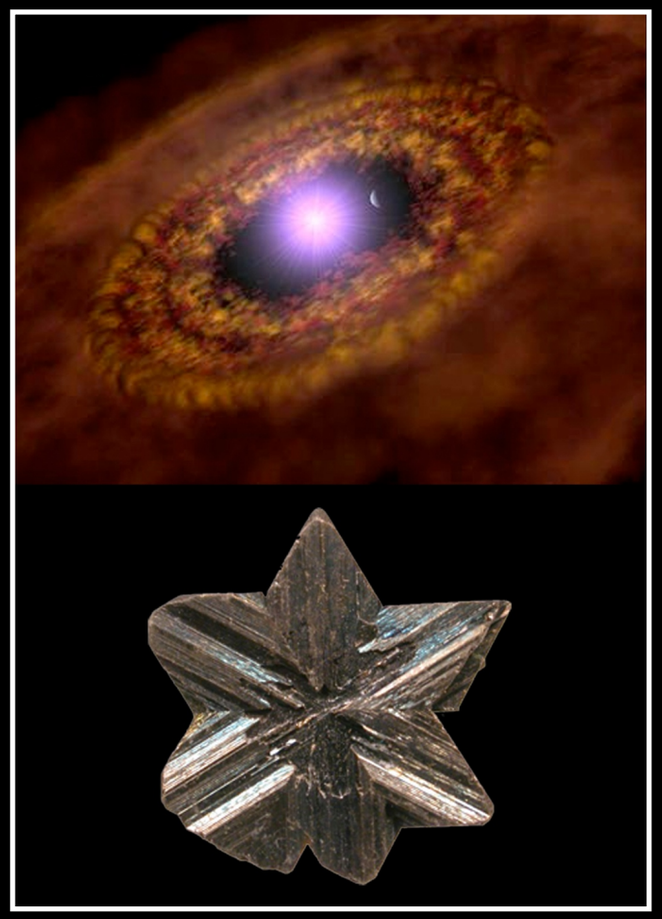
Cometary-body aqueous alteration

Genesis of Wild-2 Cubanite

Option I

★ Nebular formation of cubanite

★ Delivery of cubanite to comet-forming region



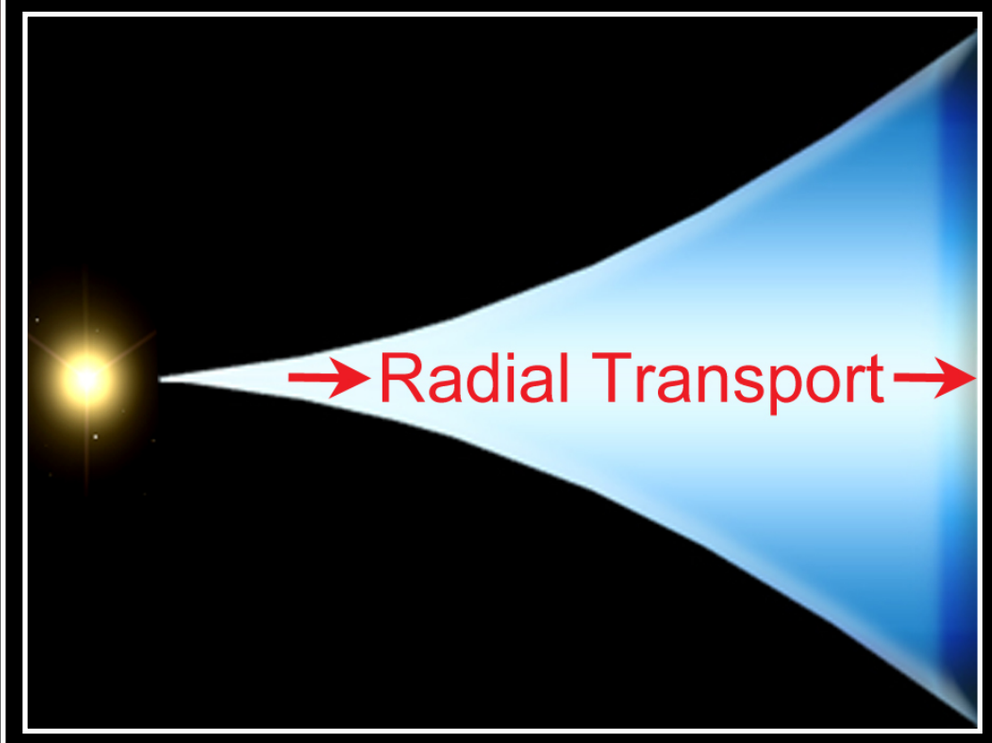
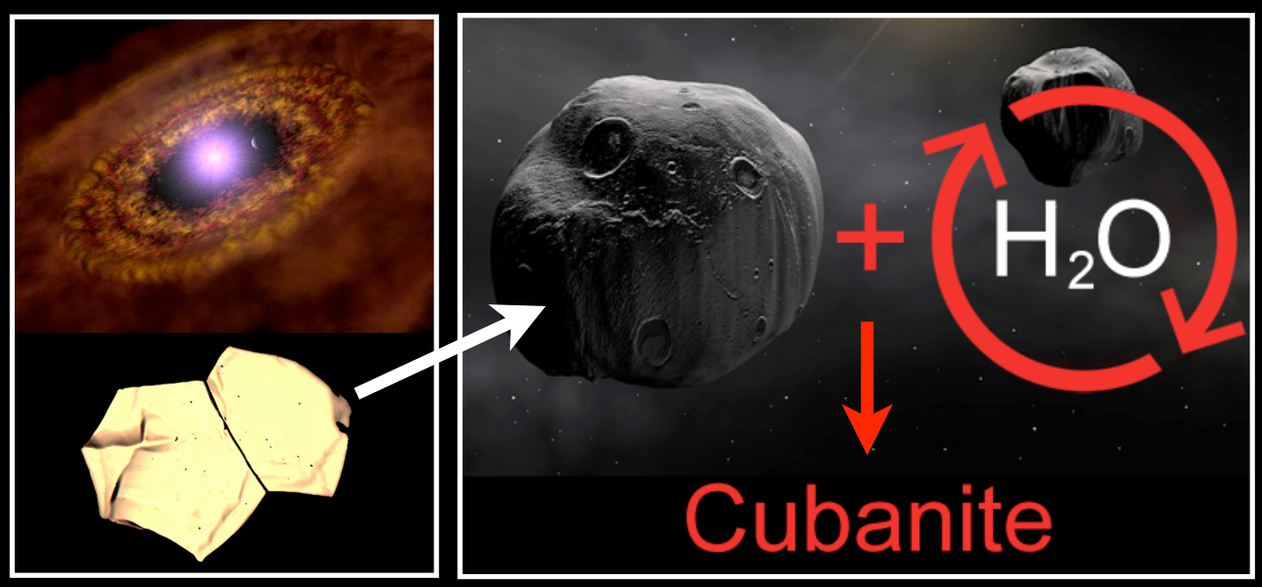


Image credits: protoplanetary disk: J. Setiawan, Max Planck Institute; cubanite grain: D. K. Joyce

Genesis of Wild-2 Cubanite

Option 2

- ★ Nebular formation of troilite
- ★ Parent-body aqueous alteration & break-up
- ★ Delivery of cubanite to comet-forming region
- ★ Incorporation onto Wild 2



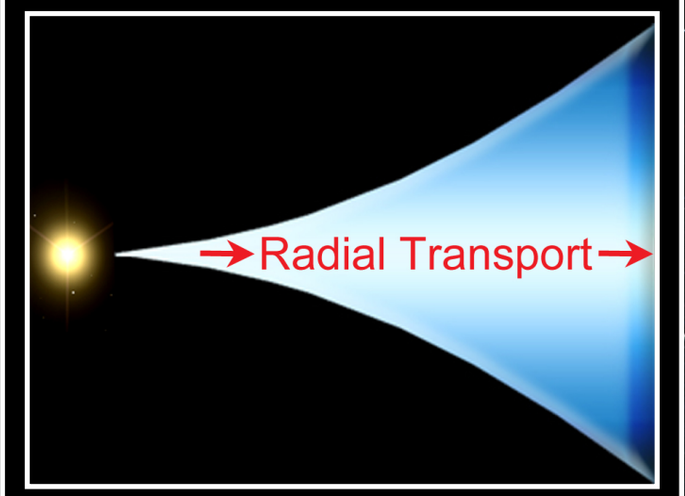
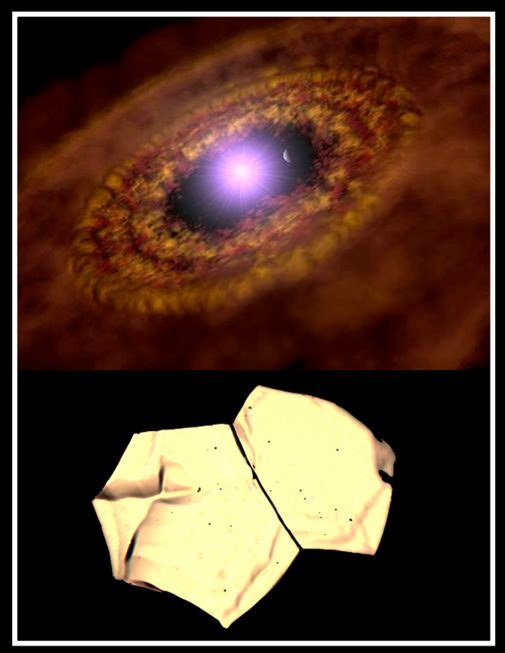


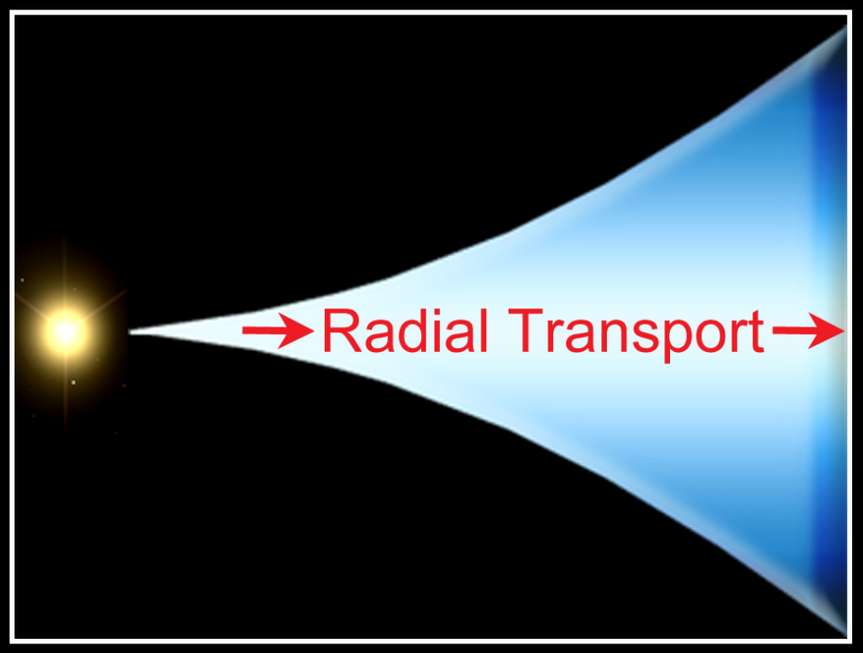
Image credits: protoplanetary disk: J. Setiawan, Max Planck Institute; asteroid: ESO; Comet: R. Scott Ireland

Genesis of Wild-2 Cubanite

Option 3

- ★ Nebular formation of troilite
- ★ Delivery of troilite to comet-forming region
- ★ Incorporation onto Wild 2
- ★ Cometary-body aqueous alteration





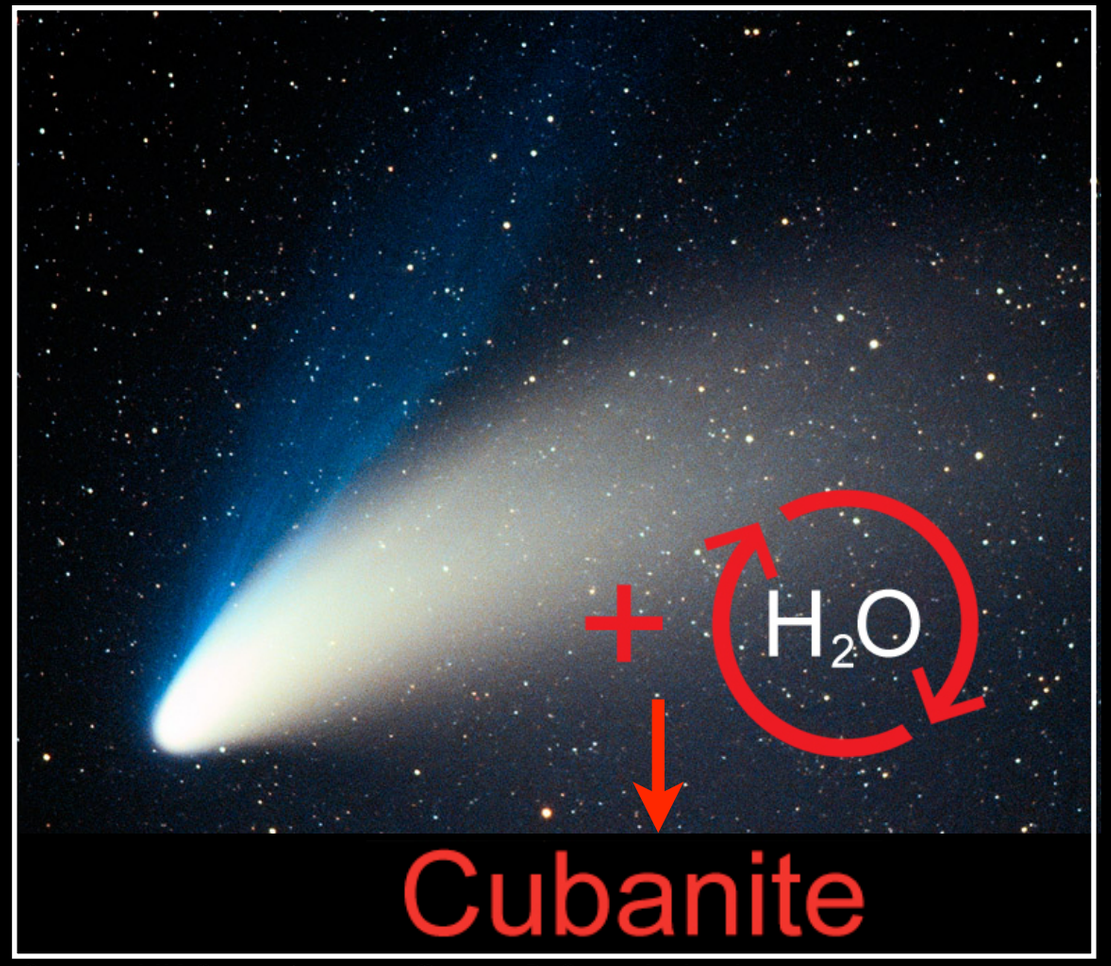


Image credits: protoplanetary disk: J. Setiawan, Max Planck Institute; Solar System: UK Space Agency; Comet: R. Scott Ireland

Characteristics of Stardust Sulfides
Fe, Ni, Cu, Zn, Mn-bearing
Mineralogy, Structure, Associations

Modified by capture into aerogel

Unmodified by capture into aerogel

Nebular Formation via gas-solid processes

Parent Body Precipitation

Aqueous Modification

on Wild 2

on other body

Implications for the genesis of Wild 2 sulfides, source material(s), and mixing in the early Solar System as indicated by compositions, structures, and uniformity/heterogeneity of phases.

Characteristics of Stardust Sulfides
Fe, Ni, Cu, Zn, Mn-bearing
Mineralogy, Structure, Associations

Modified by capture into aerogel

Unmodified by capture into aerogel

Nebular Formation of FeS via gas-solid processes

Parent Body Precipitation

Aqueous Modification

on Wild 2

on other body

Implications for large-scale solar system processes, including heat sources and aqueous alteration on a cometary body, as well as mechanisms and extent of radial mixing of material.

Cubanite...

- ⋆ *is the low-T form of $CuFe_2S_3$*
- ⋆ *is rare in the extraterrestrial collection*
- ⋆ *forms via low-T aqueous processes*

Stardust Cubanite...

- ⋆ *is evidence of radial mixing of sulfides from the inner Solar System to the comet-forming region*
  - ⋆ *mechanism & extent of mixing*
- ⋆ *likely formed in situ on Comet Wild 2*
  - ⋆ *heat sources for secondary processing*