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Abstract: The Southern Arburèse district, SW Sardinia, hosts several granite-related W-Sn-Mo deposits and a 10 km-long system of Ni-Co-As-Bi-Ag±Au-bearing five-element veins. To understand the spatial and metallogenic relationships between these systems, new investigations were conducted in the Pira Inferida mine area where massive wolframite-quartz (W-Bi-Te-Au) veins, linked to the Mt. Linas granite (289±1 Ma), are cross-cut by the five-element veins. In the wolframite-quartz veins, OM and SEM-EDS revealed abundant native Bi, Bi-Te phases and native Au suggesting a W-Bi-Te-Au hydrothermal system. The five-elements veins exhibit breccia and cockade textures enveloping clasts of the Ordovician host-rocks and small fragments of the earlier wolframite-quartz veins. The five-element vein paragenesis includes three main stages, from older to younger: 1) native elements (Bi±Au); 2) Ni-Co arsenides-sulfarsenides in quartz gangue; and 3) Pb-Zn-Cu±Ag sulfides in siderite gangue. The mineralogical, geochemical and isotopic features of the five-element veins are comparable to five-element deposits elsewhere in Europe (Germany, Switzerland, Italian Alps). The source of Ni-Co is still hypothetical; the high Bi contents and the Au enrichment in the five-element veins suggest selective remobilization from the granite-related W-Bi-Te-Au veins. The five-element vein system was likely formed during a post-289±1 Ma and post-Variscan metallogenic event.

Keywords: Five-element veins; granite-related deposits; Ni-Co arsenides; native Bi; late Variscan metallogenesis

SW Sardinia
South Arburése district

hosts a wide variety of orebodies including:

a. Mo-Sn-W veins and greisens

b. Skarns

→ Early Permian; Mt. Linas granite (289 Ma)

c. Giant Zn-Pb hydrothermal vein system of Montevecchio

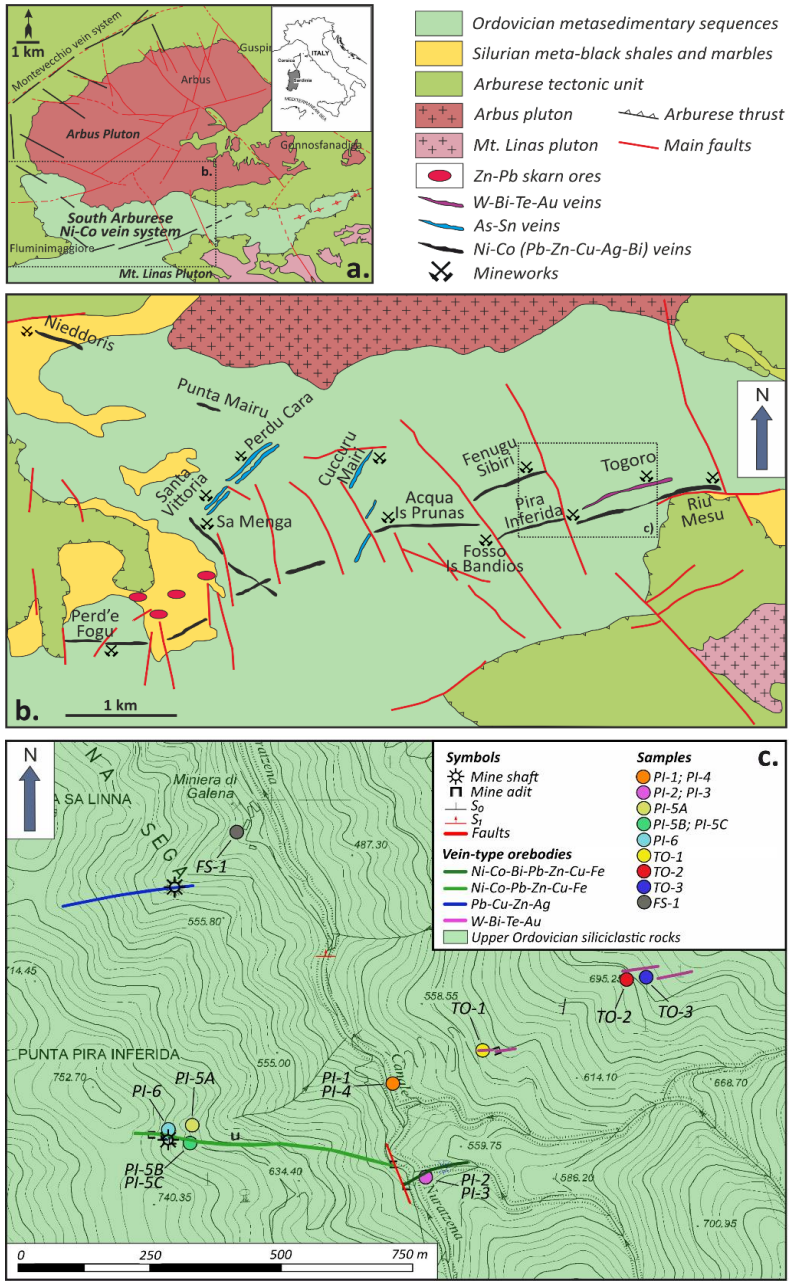
d. Five-element veins

→ Undefined age; Undefined source of metals

The **spatial and metallogenic relationships** between these systems are **poorly defined**.

Some new evidences suggested cross-cutting relationships.

A key area is the **Pira Inferida mine area** where both **five-elements veins and W-veins** occur.



Mod. after Moroni et al, 2019

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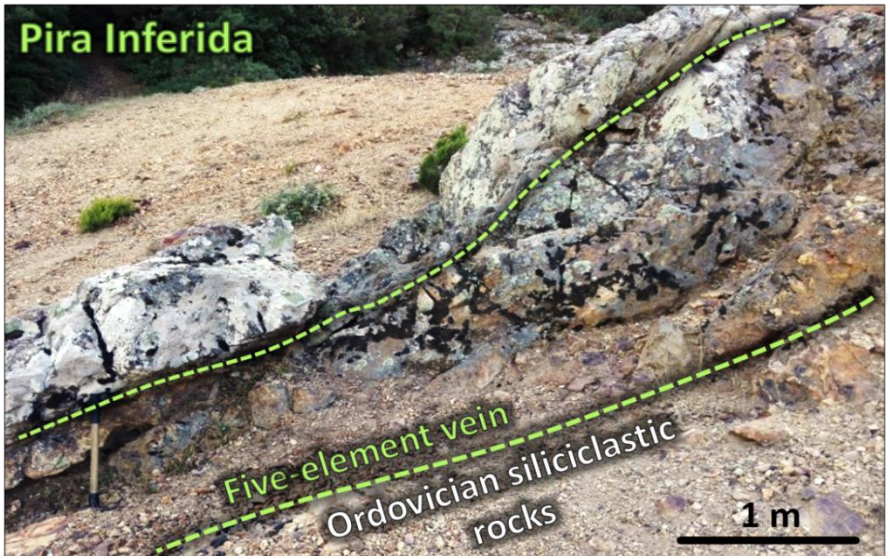
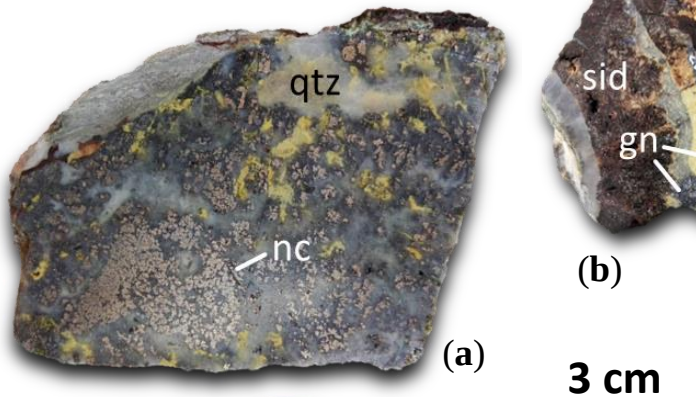
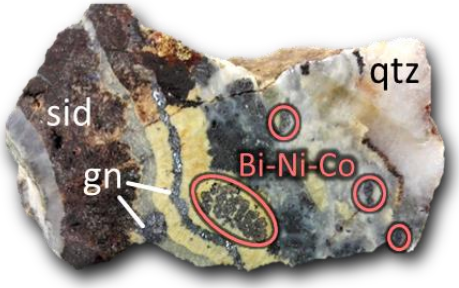
Results: field relationships



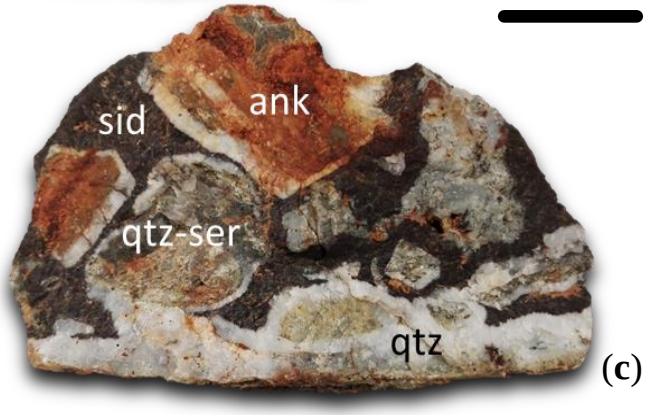
Pira Inferida Five-element veins

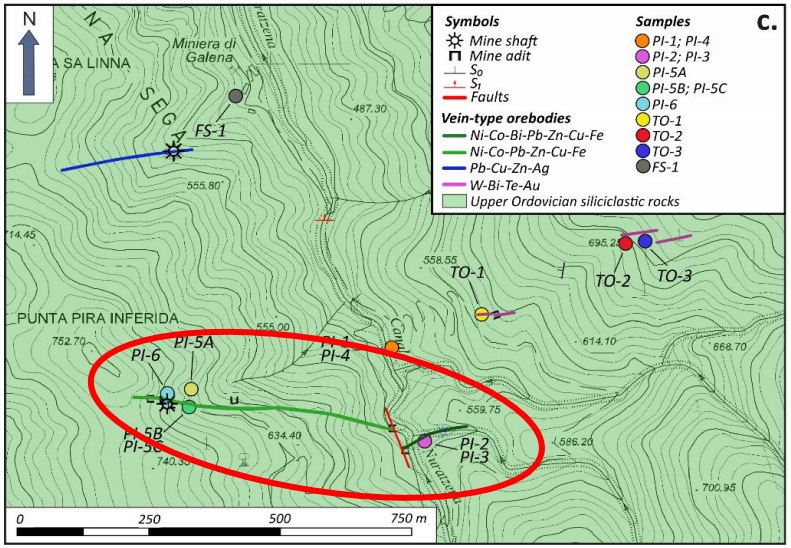
- **1-3 m thick veins**
- E-W striking and **S-dipping**
- outcropping discontinuously for over **500 m along their strike**
- **native elements, Ni-Co arsenides-sulfarsenides and base metal sulfides in siderite-quartz gangue with** brecciated and cockade textures
- evidences of contact-metamorphism on the **Ordovician siliciclastic host rocks** (spotted schists)





3 cm





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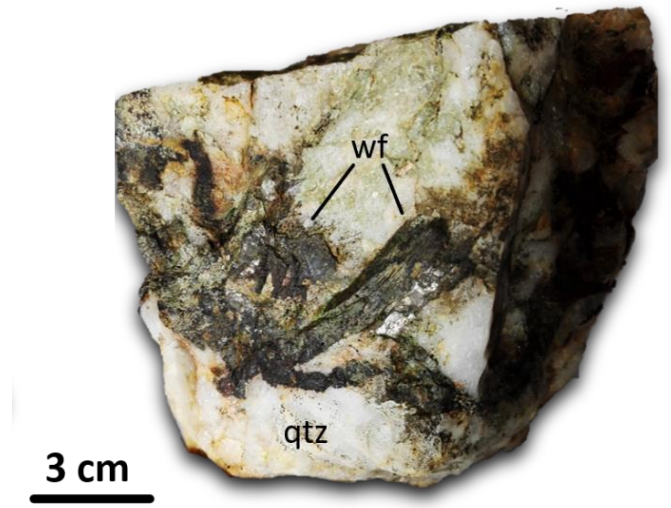
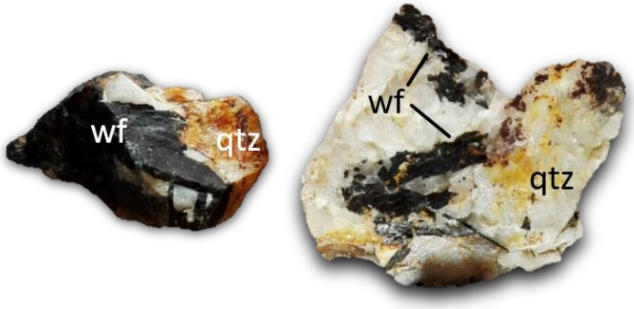
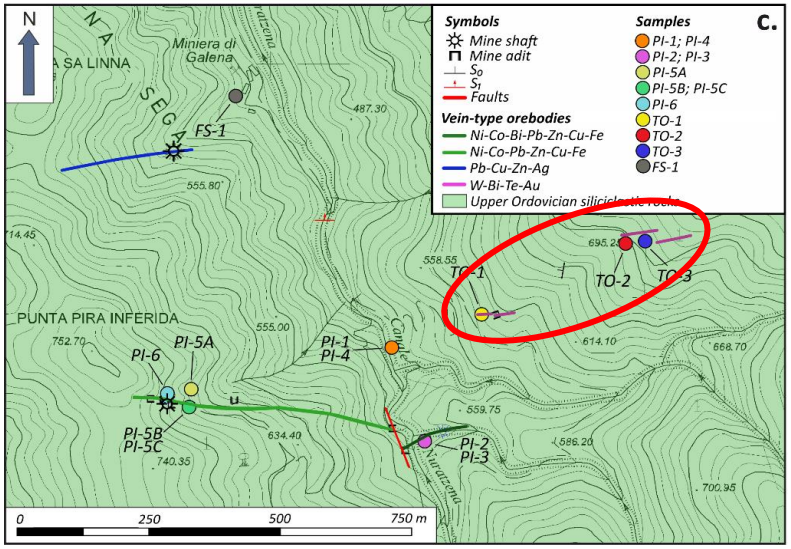
Results: field relationships

Togoro: W-Bi-Te-Au veins

- **Wolframite, native elements (Bi-Au), tellurides**
- **15 cm to 1 m thick veins**
- NNE-SSW striking and **N-dipping**
- outcropping discontinuously for **1 km along their strike**
- Idiomorphic **wolframite crystals (max. 6 cm)** in a **massive quartz gangue** with mica aggregates on the selvages
- **Rare sulfides**
- **No evidences of brecciation**







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Results: OM and SEM-EDS

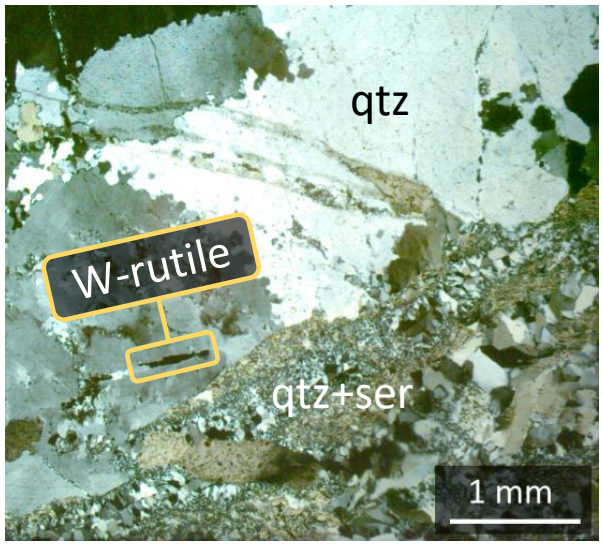
Pira Inferida: five-element veins

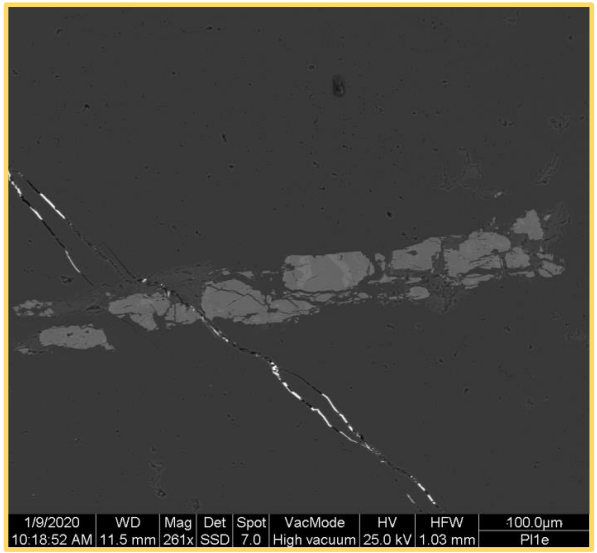
	Pira Inferida Five-element type (Bi-Ag-Ni-Co-As)			
	Native element stage	Ni-Co arsenides-sulfarsenides stage	Sulfide-siderite stage	Late quartz stage
Gold-electrum	● ● ● ● ● ● ●			
Bismuth	▬▬▬			
Niccolite		▬▬		
Gersdorffite		▬▬▬		
Ullmannite		▬▬		
Breithauptite		▬▬		
Bismuthinite			▬	
Pyrrhotite			▬	
Sphalerite			▬ ● ● ▬	
Pyrite			▬	
Chalcopyrite			▬ ● ▬	
Tetrahedrite			▬ ● ●	
Galena			▬▬	
Siderite			▬▬	
Quartz			▬ ● ●	▬▬▬
Sericite-Mica			▬ ● ●	▬▬▬

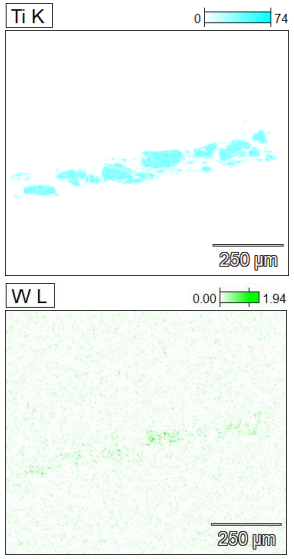
3 main ore mineral stages: **1. native elements (Bi+Au); 2. Ni-Co arsenides and sulfarsenides; 3. sulfides-siderite**. **Late quartz** deposition.

Gangue:

- **Brecciated, cockade and colloform textures**
- **Multiple brecciation events** at the beginning and during each ore stage (cemented by **quartz** and **siderite**)
- Host-rock and **quartz+W-rutile fragments**
- Quartz brecciated fragments enclosed in the vein are **massive**







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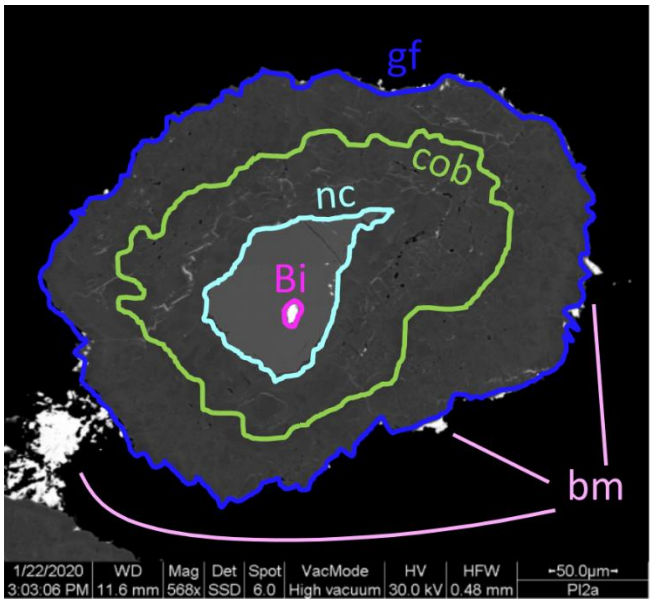
Results: OM and SEM-EDS

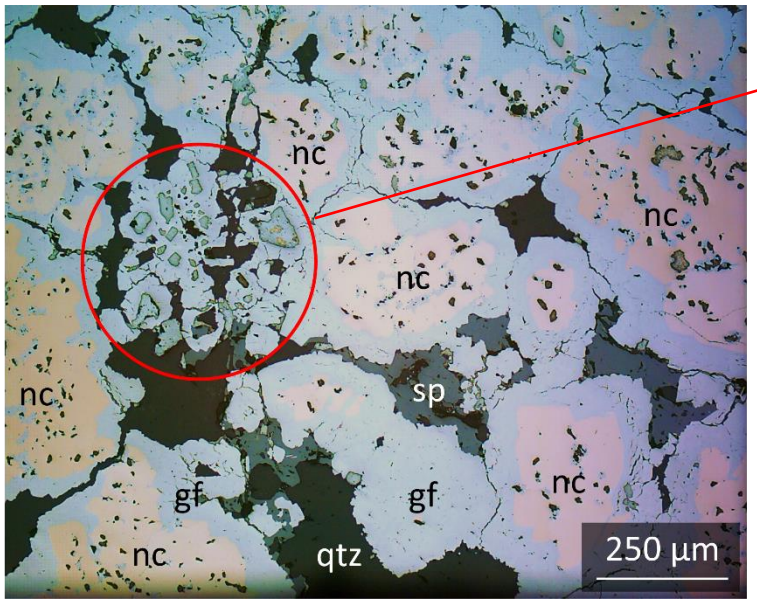
Pira Inferida: five-element veins

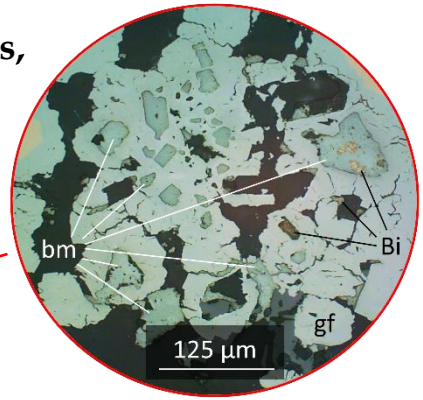
Pira Inferida
Five-element type (Bi-Ag-Ni-Co-As)

	Native element stage	Ni-Co arsenides-sulfarsenides stage	Sulfide-siderite stage	Late quartz stage
Gold-electrum	● ● ● ● ● ● ●			
Bismuth	▬			
Niccolite		▬		
Gersdorffite		▬		
Ullmannite		▬		
Breithauptite		▬		
Bismuthinite			▬	
Pyrrhotite			▬	
Sphalerite			▬ ● ● ● ▬	
Pyrite			▬	
Chalcopyrite			▬ ● ● ▬	
Tetrahedrite			▬ ● ● ●	
Galena			▬	
Siderite			▬	
Quartz			▬ ● ●	▬
Sericite-Mica			▬ ● ●	▬

- **Native elements (native Bi±Au) grains enclosed in Ni-Co arsenides-sulfarsenides**
- **higher Bi contents in the lower parts of the vein along the intersection zone**
- Colloform and cockade aggregates of inner **niccolite → gersdorffite-cobaltite → ullmannite-breithauptite**
- **Local arsenopyrite overgrowths on löllingite**
- **Enveloped by late sulfides, carbonate and quartz assemblages**







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Results: OM and SEM-EDS

Pira Inferida: five-element veins

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Gold-electrum	● ● ● ● ● ● ●			
Bismuth	▬▬▬			
Niccolite		▬▬		
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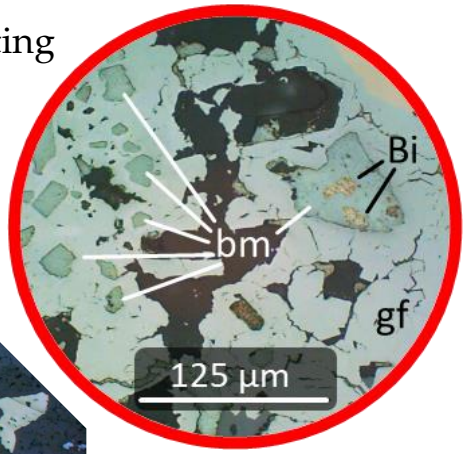
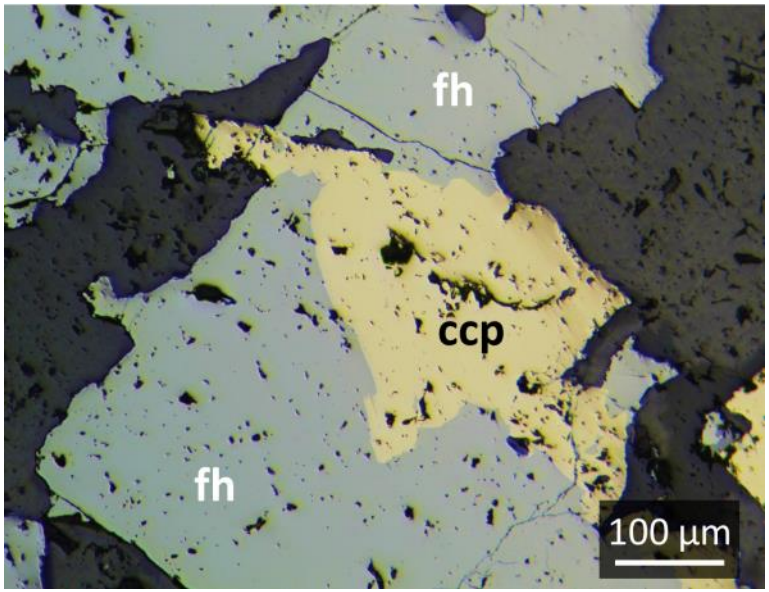
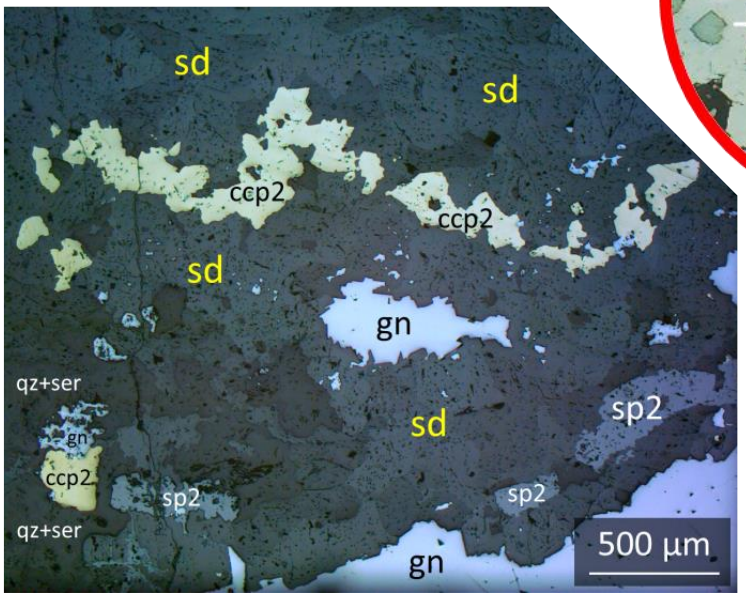
Ullmannite		▬▬		
Breithauptite		▬▬		
Bismuthinite			▬	
Pyrrhotite			▬	
Sphalerite			▬ ● ● ▬	
Pyrite			▬	
Chalcopyrite			▬ ● ▬	
Tetrahedrite			▬ ● ●	
Galena			▬▬	
Siderite			▬▬	
Quartz			▬ ● ▬	▬▬
Sericite-Mica			▬ ● ▬	▬▬

- **Fe-Zn-Cu-Pb sulfides** in a **siderite gangue**
- **Bismuthinite as native Bi grains replacements and infillings**
- **Early Fe-sulfides (pyrrhotite-pyrite)**
- **Sphalerite-chalcopyrite-tetrahedrite (Ag)**
- **Late sphalerite-chalcopyrite-galena infillings**
- **Siderite gangue** cementing the Ni-Co ore minerals and the base metal sulfides







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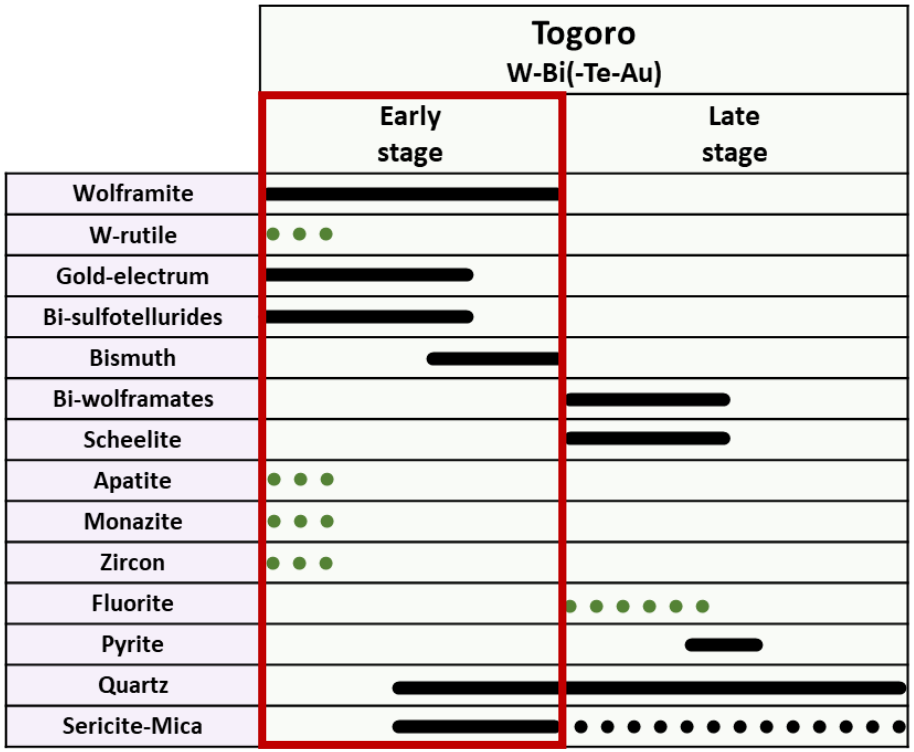
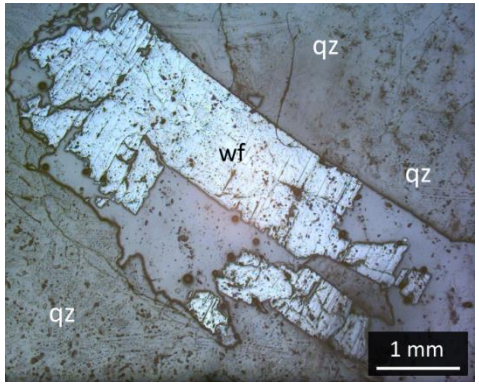
Results: OM and SEM-EDS

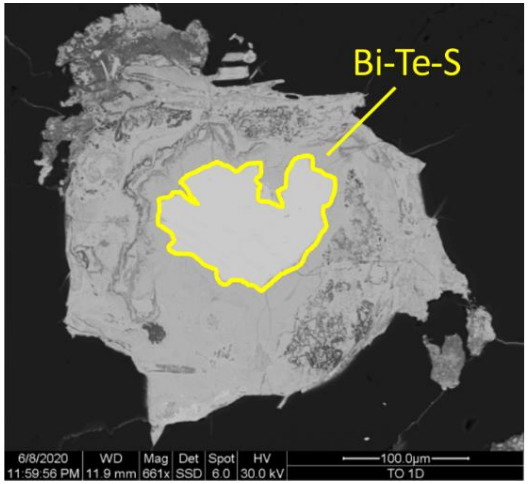
Togoro: W-Bi-Te-Au veins

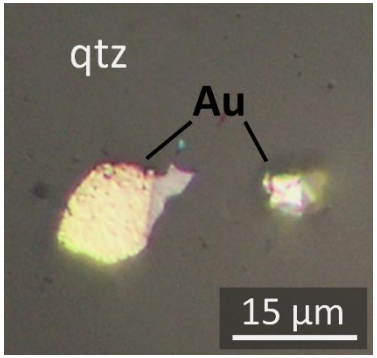


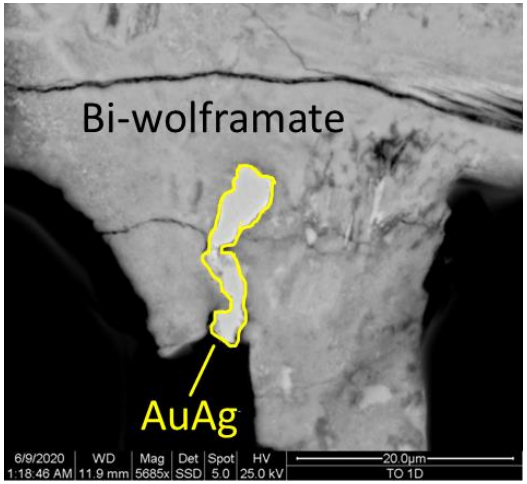
- **early stage** with **wolframite (ferberite term), electrum (AuAg), Bi-sulfotellurides and native Bi**
- **W-rutile, apatite, monazite, zircon** in the brecciated quartz fragments of the five-element veins
- **quartz-mica gangue**



- **Visible AuAg blebs associated to native Bi, Bi-Te-S and Bi-W phases**







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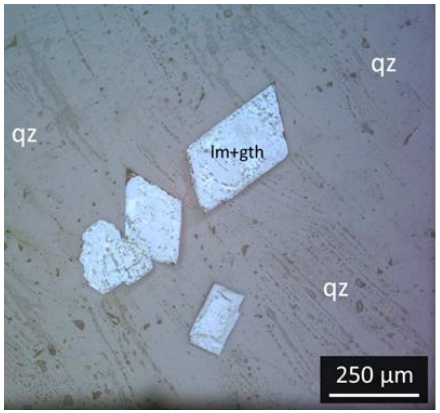
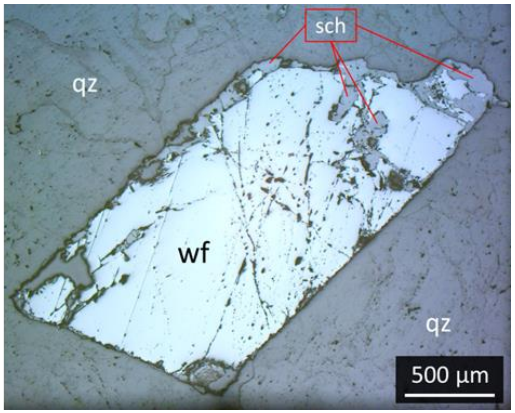
Results: OM and SEM-EDS

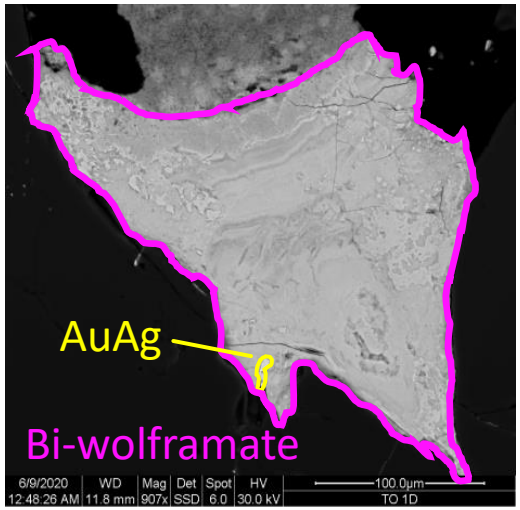
Togoro: W-Bi-Te-Au veins

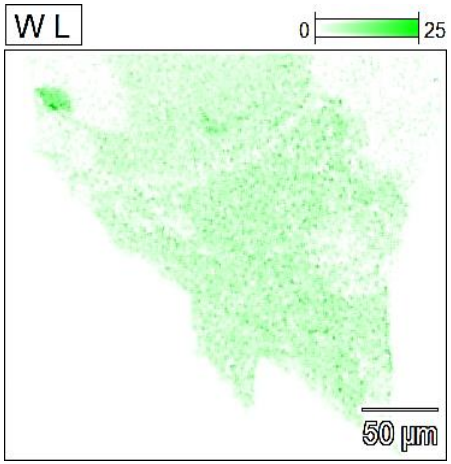
- **late stage** with **scheelite replacement on wolframite**
- **Bi-wolframates and bismite**
- Rare sulfides limited to pyrite
- **hematite-goethite** substitutions on wolframite and probable arsenopyrite

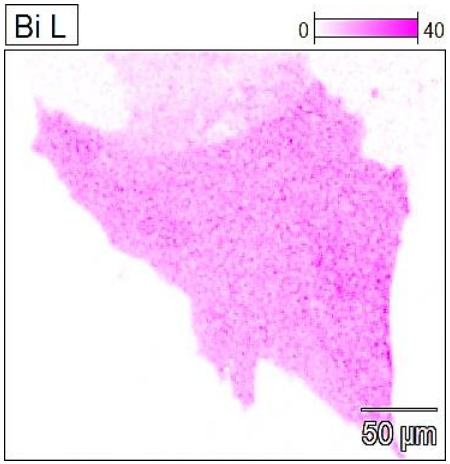
	Togoro W-Bi(-Te-Au)	
	Early stage	Late stage
Wolframite	▬▬▬	
W-rutile	• • •	
Gold-electrum	▬▬▬	
Bi-sulfotellurides	▬▬▬	
Bismuth	▬▬	
Bi-wolframates		▬▬
Scheelite		▬▬
Apatite	• • •	
Monazite	• • •	
Zircon	• • •	
Fluorite		• • • • • •
Pyrite		▬▬
Quartz	▬▬▬	▬▬▬
Sericite-Mica	▬▬▬	• • • • • • • • • • • •











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Discussion

Crosscutting relationships

1. The W-Bi-Te-Au veins are N-dipping; the five-element veins are S-dipping

2. W-rich rutile in brecciated quartz fragments enclosed in the five-element veins

3. Molybdenite-quartz fragments have been observed in other five-element veins (Acqua Is Prunas; Moroni et al, 2019)

4. Bi contents in the five-element veins are higher approaching to the W-Bi-Te-Au veins

5. The five-element veins formed under seismic activity at shallower environments (<2km on the basis of their cockade textures; Masoch et al, 2019) with respect to the W-Bi-Te-Au veins (1kbar for the Mt. Linas granite; Naitza et al, 2017). Thus, at least 0,5 kbar of exhumation can be assumed for the wolframite veins.

This set of observations support the idea that **the five-element vein system crosscut the W-Sn-Mo vein system.**
The W-Bi-Te-Au vein may had a role as **a local source of Bi and Au for the five-element veins.**

Thus, the five-elements vein system **may belong to a late or possibly post-Variscan metallogenic event** similarly to the large-scale ones recorded in various mining poles across Europe.

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Discussion

Togoro W-Bi-Te-Au veins

1. **The Togoro wolframite-quartz veins can be included among the Mo-Sn-W deposits related to the Mt. Linas granite** (ferroan, reduced and ilmenite-series, F-rich; Naitza et al, 2017).

2. **Hypothermal to mesothermal conditions (410°-320°C)** can be reasonably assumed accordingly with the other Sn(-W) and Mo(-W) veins of the area (Naitza et al, 2017)

3. The **new discovery of Au, Bi-sulfotellurides, Bi-wolframates and native Bi** in the wolframite-quartz veins allows to expand the metallogenic endownement of this types of deposits. Thus, **a W-Bi-Te-Au system could be assumed**.

4. In order to better understand the **relationships with Au deposition** (Ciobanu et al, 2009), further and more in depth investigations and analyses could be focused on the **mineralogical and chemical characterization of the Bi-Te phases**.

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Discussion

Pira Inferida five-element veins

1. Formation in **active seismic environments** can be assumed by cockade and breccia structures of ore and gangue minerals (Masoch et al, 2019);

2. The **typical sequence of native elements → Ni-Co arsenides → Ni-Co-Fe sulfarsenides → Sulfides in a quartz-carbonate gangue is verified** (Scharrer et al, 2019)**;**

3. Strong disequilibrium conditions and precipitation of the ore minerals may be ascribed to **the interaction between hydrothermal fluids and reducing agents (methane, Fe^{2+}, graphite) from the local Ordovician-Silurian host rocks**;

4. **Low-temperature** (max. 110°C for the late stage) and **high salinity** (20% NaCleq.; Moroni et al, 2019);

5. A **post Variscan age of the five-element mineralizations** has been recognized in various areas worldwide

The features of the five-element veins of the Pira Inferida and South Arburése district are **comparable with other systems worldwide and with the recently developed genetic models** (Scharrer et al, 2019; Burisch et al, 2017; Markl et al, 2016; Kissin, 1992)

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Discussion

Pira Inferida five-element veins

This study also presented **some minor differences** between the five-element veins of the South Arburése district and the genetic models which **may be due to regional and/or local conditions**:

1. The **absence of the early uraninite and sulfide stages**;
2. The **absence of Ag** in the native element stage, which is mostly characterized by **native Bi and Au**;
3. The Bi-Au enrichments may be ascribed to their selective remobilization from the Togoro W-Te-Bi-Au hydrothermal veins;
4. Despite the Ni-Co monoarsenide stage being well represented, **di- and tri-arsenides have not been recognized**;

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Supplementary Materials

Links:

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Acknowledgments

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