minerals

Review

Post-Collisional Tectonomagmatic Evolution, Crustal Reworking and Ore Genesis along a Section of the Southern Variscan Belt: The Variscan Mineral System of Sardinia (Italy)

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Abstract: Since the early Paleozoic, numerous metallogenic events produced in the Sardinian massif a singular concentration of mineral deposits of various kinds. Among them, the Variscan metallogenic peak represents a late Paleozoic phase of diffuse ore formation linked to the tectonomagmatic evolution of the Variscan chain. Two main classes of ores may primarily be attributed to this peak: (1) mesothermal orogenic-type As-Au $\pm$ W $\pm$ Sb ores, only found in E Sardinia, and (2) intrusion-related Sn-W-Mo-F and base metals-bearing ores found in the whole Sardinian Batholith, but mainly occurring in central–south Sardinia. Both deposit classes formed diachronously during the Variscan post-compressional extension. The orogenic-type ores are related to regional-scale flows of mineralizing fluids, and the intrusion-related ores occur around fertile intrusions of different granite suites. Metallogenic reconstructions suggest almost entirely crustal processes of mineralization without a significant contribution from the mantle. We summarized these processes with a holistic approach and conceptualized the Sardinian Variscan Mineral System (SVMS), a crustal-scale physical system of ore mineralization in the Sardinian basement. The SVMS required suitable metal sources in the crust and diffuse crustal reworking triggered by heat that allowed (a) the redistribution of the original metal budget of the crust in magmas by partial melting and (b) the production of metal-bearing fluids by metamorphic dehydration. Heat transfer in the Sardinian Variscan crust involved shear heating in lithospheric shear zones and the role of mantle uplift as a thermal engine in an extensional tectonic setting. Lithospheric shear zones acted as effective pathways in focusing fluid flow through a large-scale plumbing system into regional-scale structural traps for ores. Pre-Variscan metal sources of metallogenic relevance may have been (1) the magmatic arc and magmatic arc-derived materials of Ordovician age, extensively documented in E Sardinia crust, and (2) an inferred Precambrian crystalline basement lying under the Phanerozoic crustal section, whose presence has been assumed from geophysical data and from petrological and geochemical characteristics of granite suites. At shallower crustal levels, important contributions of metals may have come from pre-Variscan ore sources, such as the Pb-Zn MVT Cambrian ores of SW Sardinia or the REE-bearing Upper Ordovician paleoplacers of E Sardinia.

Keywords: metallogeny; mineral deposits; orogenic Au; granite-related ores; metal sources

Citation: Naitza, S.; Casini, L.; Cocco, F.; Deidda, M.L.; Funedda, A.; Loi, A.; Oggiano, G.; Secchi, F. Post-Collisional Tectonomagmatic Evolution, Crustal Reworking and Ore Genesis along a Section of the Southern Variscan Belt: The Variscan Mineral System of Sardinia (Italy). *Minerals* **2024**, *14*, 65. https://doi.org/10.3390/min14010065

Academic Editor: Yanjing Chen

Received: 21 November 2023
Revised: 28 December 2023
Accepted: 31 December 2023
Published: 4 January 2024

1. Introduction

The Variscan orogenic belt of W Europe (Figure 1) is a relevant world-class metallogenic province widely exploited since pre-historical times. In the last thirty years, several studies highlighted the complex relationships among the Variscan tectonic, metamorphic, and magmatic events and the genesis of ore deposits in all of the Paleozoic massifs of Europe, including the French Central Massif, Bohemia, Renohercynian

Zone, and Iberia [1–22]. The main mining districts typically constitute continental-scale clusters of different classes of ore deposits, from base-metals-dominated VHMS (Volcanic-Hosted Massive Sulfide) and SHMS (Sedimentary-Hosted Massive Sulfides) to orogenic Au-Sb and granite-related Sn-W-Mo, U, and rare metal ones.

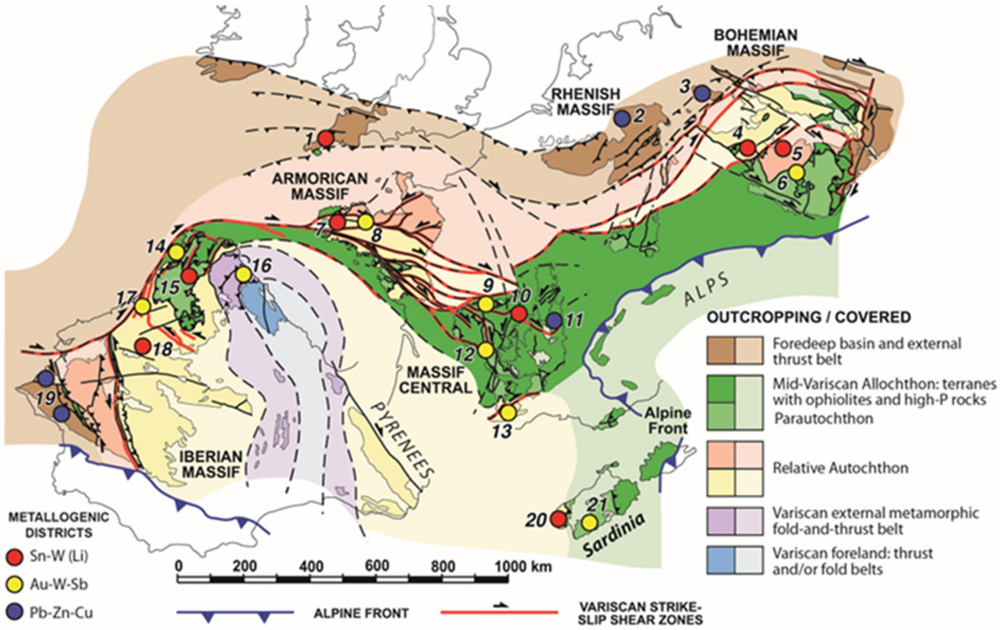

Figure 1. Metallogenic districts in the Variscan belt of Europe. 1. Cornwall, 2. Meggen, 3. Rammelsberg, 4. Erzgebirge, 5. Cinovec, 6. Mokrsko and Jilové, 7–8. Armorican Massif, 9. La Marche, 10. Beauvoir-Echassières, 11. Chessy, 12. Limousin-St. Yrieix, 13. Salsigne, 14–15. Galicia, 16. Rio Narcea, 17. Puentedeume, 18. Panasqueira, 19. Iberian Pyrite Belt, 20. Sulcis-Iglesiente, 21. East Sardinia. Based on [5,6,20–23], modified from [24], 2021.

Sardinia is the most important mining district of Italy and displays a long-lasting metallogenic evolution spanning from the early Cambrian [25,26] to the Ordovician [27,28], Carboniferous–Permian [29], Mesozoic [30], and Cenozoic [31]. The result is a metallogenic province characterized by a singular richness and variety of ore deposits in relation to its relatively small extension (Table 1).

Table 1. Metallogenic periods and peaks in Sardinia. Based on [32], modified.

District	Ores	Type	References
Pre-Sardic phase metallogenic peak (early Cambrian–early Ordovician)			
SW Sardinia (Iglesiente district)	Fe-Zn-Pb	SEDEX	[25]
SW Sardinia (Iglesiente district)	Pb-Zn	MVT/Irish-type	[25,26]
Sardic and Sarrabese phases period (early–middle Ordovician)			
SW Sardinia (Iglesiente district)	Ba-Pb	Unconformity-related	[27]
SW Sardinia (Iglesiente district)	Ba, Zn-Pb	Karst, supergene	[33,34]
SE Sardinia	base metal protores	Sedimentary, volcanic exhalative	[35]
Post-Ordovician phases period (late Ordovician–late Devonian)			
SE Sardinia (post-Sarrabese phase)	Ti, Zr, REE	Placers	[28]
NW Sardinia (Nurra district)	Fe	Oolitic iron	[36]
E Sardinia	base metal, U, V protores	Sedimentary	[37,38]
Variscan metallogenic peak (Carboniferous—early Permian)			
SE Sardinia (Gerrei district)	As-Sb-W-Au (Pb-Zn-Cu-Ag)	Orogenic-type: mesothermal to epithermal veins	[39]
Southern and central Sardinia	Sn-W-Mo-Bi-F, Cu-Fe-Pb-Zn-Ag, REE	Granite-related hydrothermal, greisen and skarn	[40]

Table 1. *Cont.*

District	Ores	Type	References
	Post-Variscan I period (early Permian–Jurassic?)		
SW Sardinia (Arburèse district)	Pb-Zn (Ag, Ga-Ge-In), Bi-Ni-Co-As-Fe	Low-temperature Montevecchio-type or five-element-type veins	[41–43]
E Sardinia	F-Ba-Pb-Ag, REE	Low-temperature fluorspar veins, Silius-type veins	[44,45]
SW Sardinia	Ba, Zn-Pb	Karst, supergene	[33,34]
	Post-Variscan II period (Cretaceous)		
NW Sardinia (Nurra district)	bauxite	Paleosoil	[46]
	Cenozoic metallogenic peak (Oligocene–Miocene)		
W Sardinia	Au-Ag-Te-Cu	High sulfidation and low sulfidation, epithermal, porphyry	[47]
W Sardinia	Mn	Volcano–sedimentary/exhalative	[48]

In this study, we present an up-to-date review of the metallogenic stages recorded in Sardinia during the late Paleozoic in relation to the tectonomagmatic evolution of the Variscan orogenic cycle.

2. The Variscan Chain of Sardinia

2.1. The Collisional Structure

Along with Corsica, the Paleozoic crystalline basement of Sardinia forms one of the more complete and well-exposed sections of the Southern Variscan chain [49]. In Sardinia, the crustal section exposes, from NE to SW, an inner domain composed of migmatites and middle- to high-grade metamorphic rocks, a greenschist stack of tectonic units (the nappe zone), and an external structural domain (the external zone) [50] (Figure 2a,b). This structural frame resulted from early Carboniferous NS shortening related to convergence between the northern margin of Gondwana and a collage of Gondwana-derived microcontinents supporting a persistent Ordovician magmatic arc. From the inner zone to the external domain, syn-collisional polyphase ductile deformation is associated with Barrovian-type metamorphism [51], showing a regional gradient characterized by a decreasing metamorphic grade from NNE to SSW. Geochronological constraints for the collision-related metamorphic peak range from about 360 to 320 Ma [52–58]. This large timespan indicates that shortening was likely diachronous at a regional scale.

In detail, the inner zone consists of a heterogeneous crystalline nappe made of migmatites, ortho- and para-gneisses, mafic granulites, and eclogites, interpreted as the Variscan orogenic roots [56,58]. In the northern sectors, both Ar/Ar ages on post-collisional metamorphic muscovite and amphibole and U/Pb dating of zircon, monazite, and xenotime indicate that the Variscan crust recorded a regional HT-LP metamorphic event in upper Carboniferous times, between about 320 and 305 Ma [55–59]. Extensive crustal reworking and post-collisional HT deformation transposed all of the previous fabric, preventing any stratigraphic correlation with the sedimentary and volcanic sequences of the low-grade tectonic units exposed in the greenschist zone [51,58].

During the main shortening phase, the nappe zone first recorded top-to-the-SSW thrusting, resulting in a stack of highly deformed tectonic units. The southern part of the nappe stack experienced a second thrusting episode, with top-to-the-W direction of tectonic transport, also recorded in the external zone [51,60,61] (Figure 2c). In the tectonic units of the external nappe zone, sedimentary and volcanic successions spanning the Middle Cambrian to the Lower Carboniferous were deformed by kilometer-scale isoclinal recumbent folds, while wide ductile shear zones and mylonitic belts developed under low-grade metamorphism [51,61,62]. Finally, in the final shortening stage, the whole stack of tectonic units was deformed by open WNW-ESE antiform and synform with a 10–30 km wavelength. It is noteworthy that the geometry of these gentle folds controlled the following extensional evolution of the basement by forcing the direction of the lateral flow during the thermal and gravitational re-equilibration of the crust [61] (Figure 2c).

The Paleozoic basement of SW Sardinia represents the external structural domain (the external zone) and is made of an almost unmetamorphosed Lower Cambrian–Upper Devonian succession [63], remarkably different (e.g., by lacking Ordovician volcanics) from those outcropping in E Sardinia [64]. During the Variscan shortening, the original asset of the pre-Variscan succession, previously affected by the EW folds related to an Early–Middle Ordovician tectonic event ("Sardic phase") [65–67], was upset by nappe emplacement. The shortening stage caused folding and repetition of the stratigraphic successions, kilometer-scale offset of the stratigraphic boundaries, and the development of brittle–ductile shear zones [68]. Thrusts and folds developed at upper crustal levels, with a hinterland-verging direction [69].

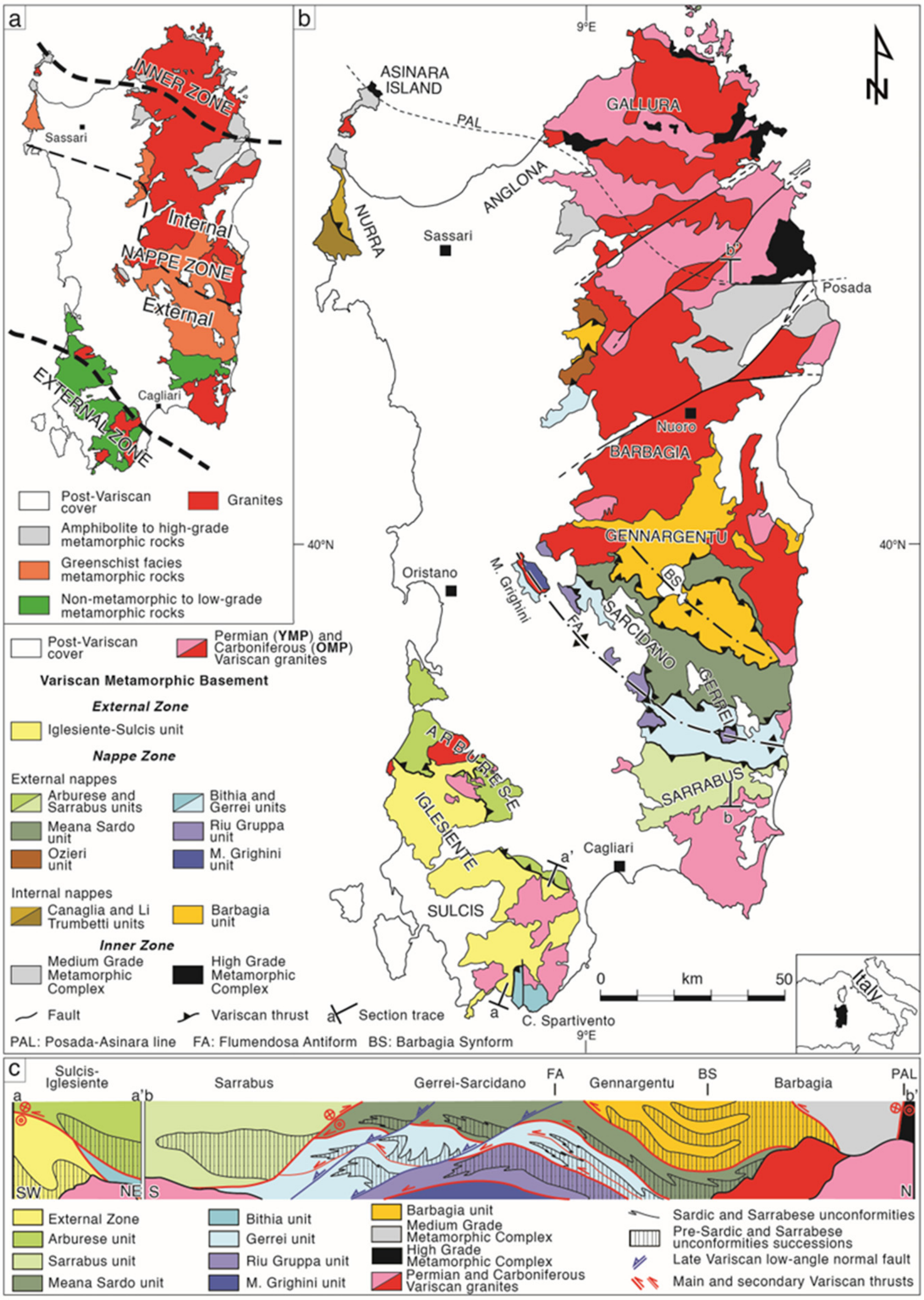

Figure 2. Schematic map of the Variscan basement of Sardinia. (**a**) Metamorphic zonation; (**b**) tectonic sketch map; (**c**) a section along the basement (a–b trace in Figure 2b). Modified after [64], 2023.

2.2. Late Variscan Shearing and Extension: The "Sardinian Puzzle"

In late Carboniferous–early Permian times, besides the collapse and thermal relaxation, the evolution of the Southern Variscan Branch went on with dextral mega-shears, which caused the westwards shift of some southern sectors of the newborn Meso-European crust. A large dextral shear zone running from the Bohemian Massif through the Alps, Maures-Esterel, and the Sardinia Corsica massif (South Variscan Shear Zone, SVSZ) [49] affected the southern branch of the chain. The shearing accommodated by the SVSZ and conjugate structures resulted in a large (>90°) clockwise rotation during the southwestward displacement (900–1500 km) of the Sardinia–Corsica–Maures crustal ensemble from a sector facing the Vosges and the Bohemian Massif [70,71]. The final result of this Variscan dynamic was a new crustal puzzle whose components (passive margins, volcanic arcs, continental terranes) were sometimes obliterated by a deep structural, metamorphic, and magmatic reworking. Nevertheless, recent studies [64–67] highlighted remarkable differences between the stratigraphic records of the different structural zones of the Sardinian crust, suggesting that crustal pieces of different provenances may have been dragged, incorporated, and stitched by the intrusions during the mega-shear activity from the late Carboniferous to the early Permian.

2.3. The Sardinia Batholith

The Sardinian portion of the Sardinia Corsica Batholith (SCB) is constrained within the post-collisional stages of the Variscan orogen. It is essentially made of several coalescing calc-alkaline granitoid plutons incrementally emplaced at shallow crustal levels (1–3 kbars) [72]. In Sardinia, the growth of the batholith was coupled with calc-alkaline felsic volcanism, limited in space and time [73], similar to Corsica [74]. In a wide schematization of the SCB, the Sardinian Batholith was framed into a composite pluton association (U2), including part of the Corsican granitoids [75]. However, this schematization only partially supports the complexity of the Sardinian portion of the Batholith. Indeed, from studies of the last two decades, it is increasingly evident that granitoid magmas intruded in different tectonic-metamorphic zones (i.e., the inner, nappe, and external zones), showing distinctive characteristics and evolution, leading to different magmatic suites. In this way, the intrusive events have been grouped [76] around two main magmatic peaks (Figure 2b):

(1) The older magmatic peak (OMP), prevalently represented in N Sardinia and referable to a period of time spanning from 322 ± 8 Ma in N Sardinia [77,78] to 299 ± 3 Ma in Central Sardinia [79];
(2) The younger magmatic peak (YMP), represented by several plutons emplaced during a shorter span of time, from 291 to 286 Ma [80–82].

In N Sardinia, the OMP produced peraluminous monzogranitic and subordinate granodioritic magmatic pulses; the volume of granodiorites increased in the internal nappe zone of northern–central Sardinia. In the external nappe zone and toward the contact with the external zone in S Sardinia, the OMP is represented by a few zoned plutons ranging from granodiorites to peraluminous cordierite-bearing granites with small, olivine-bearing gabbronoritic bodies [83–85]. OMP plutons (e.g., the Arbus pluton of SouthW Sardinia or the Mandrolisai pluton in central Sardinia) may pertain to ilmenite to magnetite rock series and were considered as related to different kinds of base metal mineral deposits [79,86], but at a regional scale, their real metallogenic fertility has not yet been properly evaluated.

The short-lived YMP was characterized by the widespread production of felsic intrusions, which were emplaced at shallower levels than the OMP-related plutons (0.5–2 kbar) [40,76,87] over the entire Sardinia area. The calc-alkaline felsic/intermediate volcanism, related to an extensional/transtensional tectonic regime [88], fell in the same span of time (299–288 Ma) [73] and may be considered as part of the YMP. A few mafic intrusions also cluster within this magmatic peak. The YMP intrusions are peraluminous (N Sardinia) to subaluminous (SW Sardinia). Remarkably, in the external zone of the chain, metaluminous to subaluminous granites are by far dominant over peraluminous ones. In Southern Sardinia, the YMP plutons have been grouped into three main rock series named GS1, GS2, and GS3 [76]. The GS1 granites mainly belong to ilmenite rock series and show an F-bearing ferroan character, as well as a specific metallogenic signature marked by Sn-W-Mo and F ores [40]. They may be thus considered tin-tungsten granites [89,90] that approach some characteristic of the rare-metal granites [91].

The dominant felsic character of magmatism appears as a primary crustal signature for the post-collisional magmatism forming the entire SCB. Magma production has been largely interpreted as related to partial melting of crustal materials and interactions of felsic melts with mafic magmas at different levels in the crust [82,83,92–100]. Interactions of crustal magmas with mantle-derived melts are testified by mixing/mingling evidence resulting in hybrid varieties, and by the widespread occurrence of hornblende–pyroxene bearing mafic to tonalitic enclaves in granodiorites [82,99,100]. Trace element distributions and Sr-Nd-Pb isotopic compositions support the partial melting of igneous and sedimentary crustal sources combined with limited mixing with mantle-derived melts [74,76,92,95,99–102]. A substantial Ordovician crustal source has been suggested to explain the voluminous felsic activity of N Sardinia [95,102]. Otherwise, F-bearing granites from S Sardinia are interpreted as substantially primary magmas originating from lower degrees of melting of an inferred Paleoproterozoic crustal source [76,100,103].

Recent studies discussed the problem of the heat source required to raise the geotherm and enhance melting in the crust, highlighting the role of heat flow from the mantle [75]. Accordingly, the final voluminous felsic activity corresponding to YMP was related to a post-collisional phase of crustal heating triggered by lithospheric delamination and the intrusion of mafic magmas into the lower crust [76]. The contribution of shear and radiogenic heating is also claimed as an important heat source, particularly for OMP-related magmas [58,78,104–106]. Remarkably, the emplacement time span documented by YMP overlaps the HT-LP granulitic event in the deep Variscan crust exhumed along the thinned "European" margin of the Alpine Tethys in Corsica and Calabria, which in fact is in the range of 285 Ma (U/Pb age on zircon) [75].

The post-intrusive history of SCB bears evidence of a sustained influx of mantle-derived magmas in the crust [82,100]. As a result, several generations of mafic and felsic dikes widely cut across the batholith and the metamorphic basement. Mafic magmas are calc-alkaline to tholeiitic up to transitional and alkaline; calc-alkaline mafic dikes provided U/Pb ages on zircons spanning from 302 Ma in SE Sardinia [107] to 279 Ma in Corsica [80]; transitional dolerites have been dated 290–248 Ma by $^{40}Ar/^{39}Ar$ in Northern Sardinia [108]; while the alkaline mafic dikes provided an $^{40}Ar/^{39}Ar$ age of 230 ± 10 Ma in N Sardinia [109]. The transition from the calc-alkaline activity to a straight alkaline one possibly reflects the evolution from the still collapsed and cratonized Variscan chain to a new reorganization of the Pangea through rifting and drifting processes that ended in the opening of the Alpine Thetis.

3. The Variscan Metallogenic Stages

As described in the previous sections, the late orogenic evolution of the Sardinian Variscides was characterized by a long-lasting positive regional thermal anomaly associated with widespread magmatism and lithospheric-scale shearing. In this context, the basement was pervasively infiltrated by large-scale flows of fluids, only in part directly related to ascending magmas, focused on and entrapped at shallow crustal levels. This is particularly evident in central–southern Sardinia, where different ore deposits and mineralization styles occur within epimetamorphic successions. According to their relationships with the late Variscan intrusive magmatism, two main groups of ores may be proposed [29,32] (Figure 3):

(1) Orogenic-type ores, including mesothermal to epithermal vein systems marked by the As-Au ± Sb ± W metallogenic association, structurally controlled by regional-scale shear zones and fold structures; they may be considered as "amagmatic" [110] as they do not display any direct field relationships with granitoids;
(2) Intrusion-related ores, which exhibit quite a large variability, consisting of pegmatite, greisen, and skarn, as well as different types of hypothermal to epithermal veins; these ores are marked by very different associations (Sn-W-Mo-Bi-F, Cu-Fe-Pb-Zn-Ag, REE, etc.).

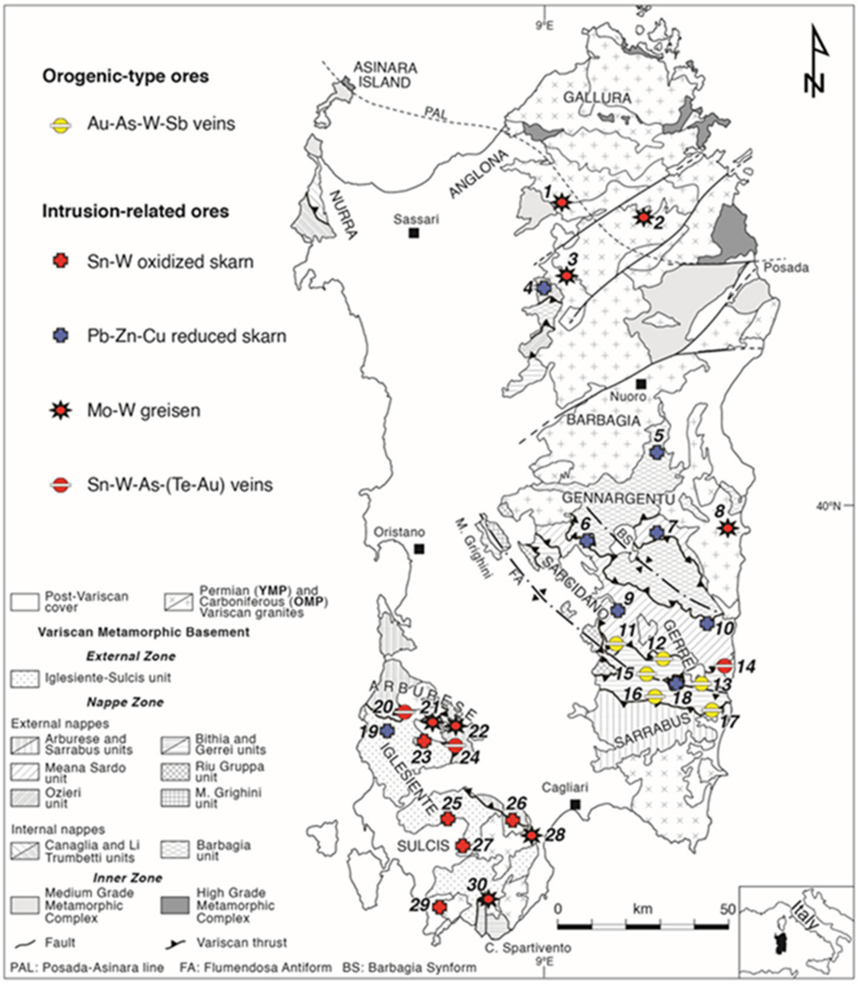

Figure 3. Regional distribution of selected orogenic-type and intrusion-related Variscan ores of Sardinia. Deposits and occurrences are reported in Tables 2 and 3. 1. Su Laccheddu, 2. S'Abbagana, 3. Monte Unne, 4. Bena de Padru, 5. Correboi-Funtana Bona, 6. Funtana Raminosa-Giacurru, 7. Lago Alto Flumendosa, 8. Goene, 9. Monte Nieddu, 10. Talentinu, 11. Genna Ureu, 12. Monte Ollasteddu, 13. Baccu Locci, 14. Perda Majori-Quirra, 15. Corti Rosas, 16. Su Suergiu, 17. Brecca, 18. Sa Lilla, 19. Perda S'Oliu-Medau Ganoppi, 20. Santa Vittoria-Perdu Cara-Togoro, 21. Perd'e Pibera, 22. Perda Lada, 23. Perda Niedda-Oridda, 24. Canale Serci, 25. Rosas-Sa Marchesa, 26. San Leone, 27. Monte Tamara, 28. Su Seinargiu-Flumini Binu, 29. Teulada, 30. Malfatano. Base map modified after [64], 2023.

3.1. The Orogenic-Type Ores

Orogenic-type mesothermal to epithermal As-Au ± Sb ± W ores are typical of the Gerrei district in the Variscan external nappes of SE Sardinia [39,111–115] (Figure 4). They are hosted in a variety of lower greenschist facies country rocks in relation to different tectonic structures (Table 2). The district has been of economic relevance in the past, as the Villasalto and Ballao antimony mines were the most important Sb producers in Italy until the '70s [116]; arsenopyrite and Pb-Ag-bearing minerals were also mined in several zones within the district, as in the Baccu Locci mine area [113]. Some of these mineralized deposits were supposed for decades to be classical examples of stratabound ores [117–119], but they have all been progressively re-interpreted as structurally controlled hydrothermal ores [111,115,116]. Indeed, the regional distribution of the mineralized occurrences is chiefly related to the main Variscan collisional structures, namely the mylonitic belts and cataclastic zones between nappe units, and the large-scale folds related to late-collisional stages that affected the Variscan nappe stack (e.g., the Flumendosa Antiform: Figure 4). On a more local scale, the geometry and distribution of the mineralized systems were strictly controlled by the reactivation of collisional structures during the Late Variscan extension [115]. Ore systems can be either concordant to the main collisional foliation (i.e., where the mylonitic shear zones were reactivated in the brittle regime, forming sheeted As-Au-bearing quartz vein systems), but also discordant, injecting faults generated during the post-collisional collapse of the Flumendosa Antiform, such as the Sb-W-bearing veins along the faults bordering the Early Permian intracontinental basins. The main ore shoots mostly occur in second- or third-order faults and dilatational domains [111]. Moreover, the variable geometry and mineralogical composition of the mineralized occurrences were apparently controlled by their structural position inside the Flumendosa Antiform nappe stack, as deeper deposits are rich in base metals (Pb, Zn, Cu) and Ag sulfides, whereas shallower deposits have low base metal contents and become progressively enriched in As and Sb-W minerals with the locally abundant native Au [115].

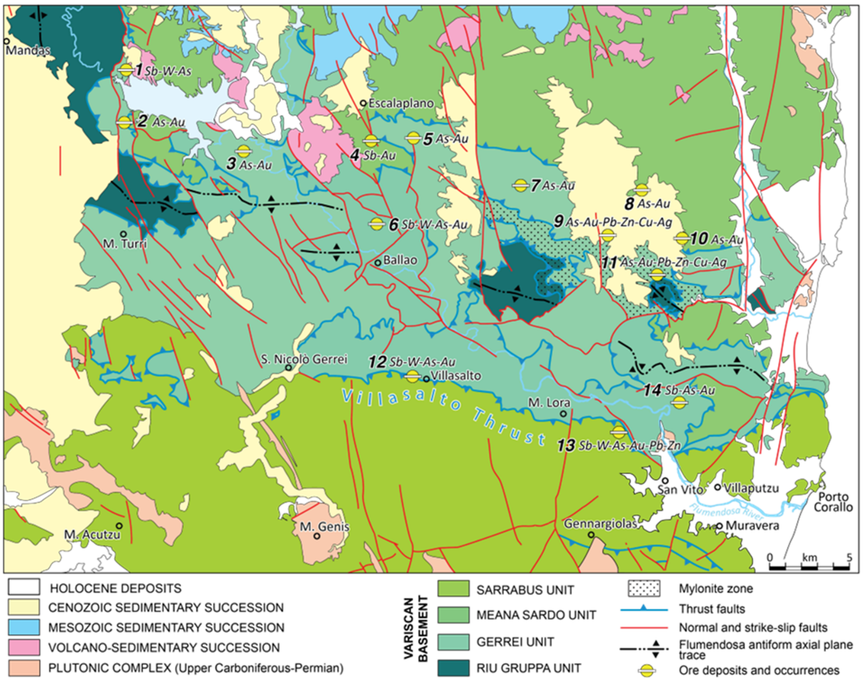

Figure 4. Distribution of the orogenic-type ore deposits and occurrences in the Gerrei district of SE Sardinia. 1. Genna Ureu, 2. Siurgus Donigala, 3. Goni, 4. Masoni Pitzudu, 5. Mulone Is Arrantas, 6. Corti Rosas, 7. Monte Ollasteddu, 8. Buddidorgiu, 9. Baccherutta, 10. Baccu Foxi, 11. Baccu Locci, 12. Su Suergiu, 13. Su Leonaxi, 14. Brecca. Modified after [115], 2018.

Table 2. Selected localities of the orogenic-type ores in the Gerrei district. Mineral abbreviations according to [120]. Ank: ankerite; Apy: arsenopyrite; Au: native gold; Ausb: aurostibnite; Bou: boulangerite; Btr: berthierite; Cal: calcite; Ccp: chalcopyrite; Gn: galena; Py: pyrite; Qz: quartz; Sbn: stibnite; Sch: scheelite; Sp: sphalerite; Ttr: tetrahedrite; Zkn: Zinkenite.

Locality	Geological Features	Ore	Notes	References
BACCU LOCCI 39°32′40″ N 09°32′05″ E	*Tectonic units:* **Gerrei Unit** (Arcu de Su Bentu sub-unit); **Riu Gruppa Unit** *Host rocks*: mylonite, Middle–Upper Ordovician metarhyolite ("porphyroid") *Type of orebodies*: saddle reefs, veins *Related structures*: mylonitic shear zone, late (post-collisional) folds; dilational jogs in dextral, high-angle reverse faults. Emplacement of mafic dikes between (2) and (3) ore mineralizing stages	(1) Qz-Sp-Ccp-Gn (2) Qz-Apy-Py (3) Qz-Gn-Ccp-Sp-Apy-Ttr-Fb-Au *Textures*: massive to banded and/or brecciated *Alteration*: sericitic, silicification, bleaching	*Economic resources*: As, Pb, Zn, Ag, Cu, Au (up to 12 g/t). NW-SE vein system extended for >2 km in length, >1 km in width.	[111,113–115,121]

Table 2. *Cont.*

Locality	Geological Features	Ore	Notes	References
MONTE OLLASTEDDU 39°34′59″ N 09°27′27″ E	*Tectonic units*: **Gerrei Unit** (Arcu de Su Bentu sub-unit) *Host rocks*: Middle–Upper Ordovician metarhyolite ("porphyroid"), Lower Ordovician metasandstones *Type of orebodies*: sheeted veins, stockwork *Related structures*: mylonite zone, hinge zone of km-sized isoclinal recumbent fold; mylonitic foliation	(1) Qz-Ank-Apy-Py (2) Qz-Au-Ccp-Gn *Textures*: brecciated *Alteration*: sericitic, silicification, bleaching	*Economic resources*: Au (>30 g/ton in stringer zones) NE-SW vein system > 3.5 in length, >1 km in width *Fluid inclusions* (*Qz*): (1) 300–310 °C CO_2-bearing low-saline fluids, traces of CH_4, N_2, and H_2S (2) <270 °C, low-CO_2, low-saline fluids	[111,112]
GENNA UREU 39°39′47″ N 09°12′46″ E	*Tectonic units*: **Meana Sardo Unit, Gerrei Unit** (Arcu de Su Bentu sub-unit), **Riu Gruppa Unit** *Host rocks*: Middle Ordovician metarhyolite, Upper Ordovician shales, Silurian black shales and limestones, Devonian phyllites and marbles *Type of orebodies*: veins, sheeted veins, stockwork *Related structures*: high-angle normal faults conjugate of two major thrust faults	(1) Qz-Ank-Apy- Py-Sch (2) Qz-Cal- Sbn-Au *Textures*: brecciated *Alteration*: sericitic, bleaching	Economic resources: Sb, W NW-SE mineralized zone >2 km in width with various Au-bearing structures. Au up to 16 g/ton Small gold nuggets in stream sediments.	[111]
CORTI ROSAS 39°34′02″ N 09°22′04″ E	*Tectonic units*: **Gerrei Unit** (Monte Lora sub-unit) *Host rocks*: Silurian black shales and limestones, *Type of orebodies*: veins, sheeted veins, stockwork *Related structures*: low-angle normal fault	(1) Cal-Qz-Py (2) Cal-Ank-Qz-Apy-Sch-Sp-Zkn (3) Cal-Qz-Sbn-Au *Textures*: brecciated *Alteration*: sericitic, carbonation	*Economic resources*: Sb; Au (up to 10 g/ton) NW-SE vein system >1 km in width *Geothermometry* (*Apy*): 350 °C for mineralizing stage (2) by Apy geothermometer	[111,122]
SU SUERGIU 39°29′46″ N 09°22′39″ E	*Tectonic units*: **Gerrei Unit** (Monte Lora sub-unit) *Host rocks*: cataclasite made of Silurian–Devonian black shales and limestones, *Type of orebodies*: veins, stockwork *Related structures*: cataclastic shear zone on a major thrust, conjugate faults	(1) Cal-Qz-Py (2) Cal-Ank-Qz-Apy-Sch-Sp-Ccp-Gn- (3) Cal-Qz-Sbn-Btr-Au *Textures*: brecciated *Alteration*: sericitic, carbonatic	*Economic resources*: Sb, W; Au (>2 g/ton) E-W vein system >2 km in length, 1 km in width	[111,118]
BRECCA 39°28′45″ N 09°33′09″ E	*Tectonic units*: **Gerrei Unit** *Host rocks*: Middle-Upper Ordovician metarhyolites ("porphyroid") *Type of orebodies*: veins, stockwork *Related structures*: hinge zone of a km-sized isoclinal recumbent fold; reverse faults	(1) Qz-Apy-Py-Au (2) Qz-Sbn-Btr- Bou-Ausb *Textures*: massive to brecciated *Alteration*: silicification, sericitic, bleaching	*Economic resources*: Sb; Au (>30 g/ton in high-grade stringer zones) E-W mineralized zone >2 km in length, 1 km in width	[111,121]

Previous ore mineralogy and fluid inclusion studies recognized the polyphasic character of mineralization [39,111,112,115]. In the key area of Baccu Locci (E Gerrei), the mineralization was hosted in a deep section of the Flumendosa Antiform and resulted from three mineralizing events. The first event caused Zn-Cu-Pb sulfide–quartz mineralization along pervasive mylonite foliation in late (extensional) fold hinges, forming saddle reefs of orebodies [115]. The second event formed large quartz–arsenopyrite sub-vertical veins crosscutting the mylonitic foliation. The third event produced extensive brecciation of the quartz–arsenopyrite veins and diffuse precipitation of Pb-Zn-Cu-Ag sulfides and gold/electrum [115]. The mineralized veins were locally crossed by mafic dikes between the second and the third event. These different mineralizing pulses were associated with different tectonic phases in the general frame of the late- to post-collisional exhumation and collapse of the Flumendosa Antiform [115]. The highly prospective Monte Ollasteddu secto is located at higher structural levels, close to the top of the Baccu Locci Mylonite Zone. The ore system consists of arsenopyrite–gold–quartz sheeted veins and stockworks [39]. As in many orogenic-type orebodies throughout the district, the quartz gangue is volumetrically dominant over the metallic minerals. Fluid inclusion data [112] defined a twofold succession of hydrothermal events, including:

(1) Early As-(W)-quartz veins resulting from hot (300–310 °C) CO_2-bearing (and, possibly, CH_4, N_2, and H_2S-bearing), low-saline fluids at trapping pressures of 30–35 Mpa;
(2) Late Au ± Sb ± Pb-Zn-Cu quartz veins related to cooler (<270 °C), low-CO_2, low-saline fluids.

At even shallower structural levels, in the reactivated, hundred-meters-thick cataclastic zone of a regional thrust (Villasalto thrust: Figure 4) located in the southern limb of the Flumendosa Antiform, preliminary fluid inclusion studies performed in the stibnite ± scheelite ± gold deposits of the Villasalto mine confirm a sequence of mineralizing events involving comparable fluids. Similar evidence has been also collected in Sb-As ± W ± Au veins along the main faults bounding the late- to post-Variscan intracontinental basins, which represent the shallowest tectonic structures controlling orogenic-type ores. Field and microscopic features of the orogenic-type ores from SE Sardinia are shown in Figure 5a–l.

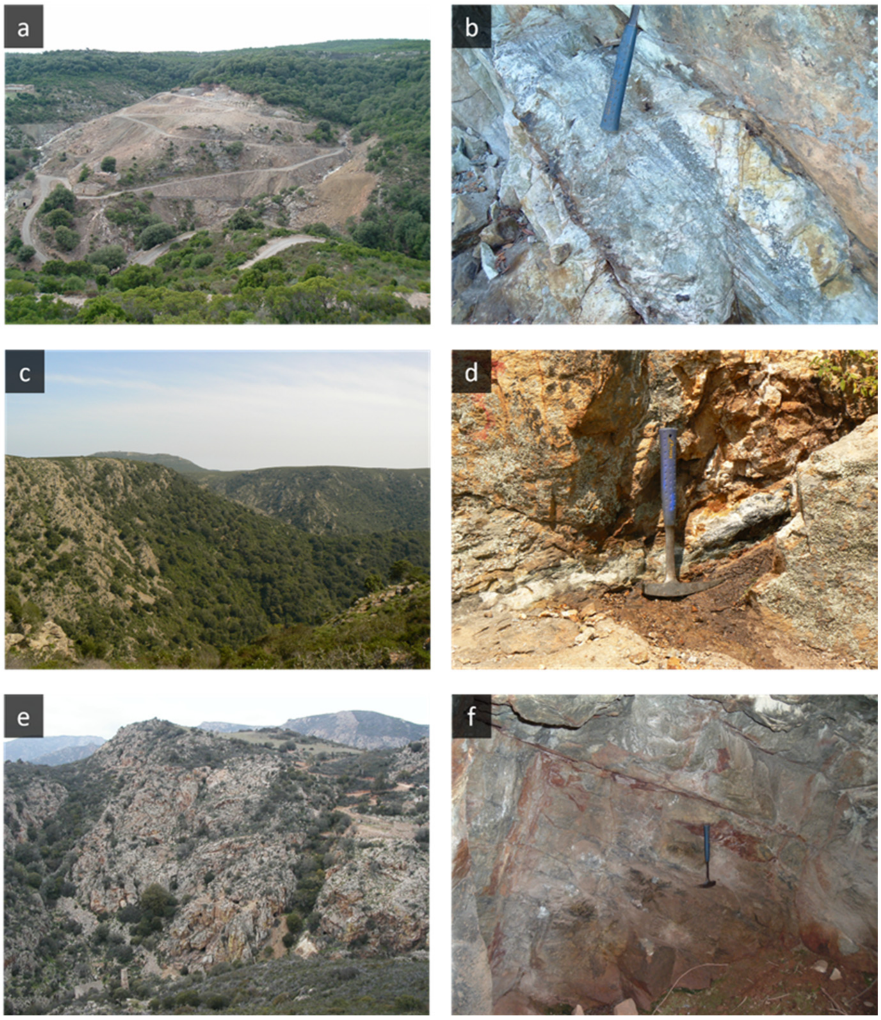

Figure 5. *Cont*.

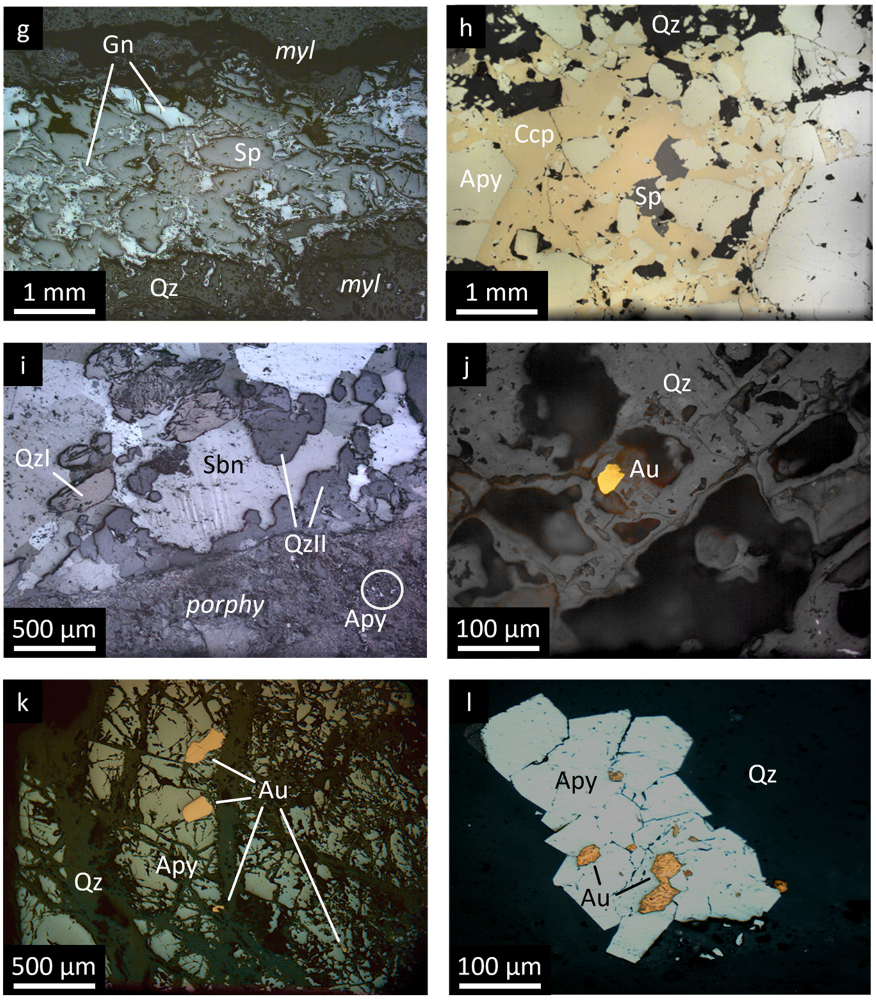

Figure 5. Selected localities and textural and mineralogical features of orogenic-type ores of the Gerrei district, SE Sardinia. (**a**) Old mineworks in the Baccu Locci mine; (**b**) As-Pb (Zn, Cu, Ag, Sb, Au) quartz–sulfide vein (Au up to 12 g/t) hosted in dark mylonite—San Riccardo lode, Baccu Locci mine; (**c**) Overview of the main mineralized zone (Sa Fraigada ridge) in the Monte Ollasteddu area; (**d**) detail of an As-Au (quartz–arsenopyrite–gold: Au up to 200 g/t) vein hosted in Middle–Upper Ordovician porphyroids in the Monte Ollasteddu deposit; (**e**) Overview of the Brecca past mine area—all of the featured porphyoid outcrops are intersected by multiple arrays of As-Au (Au up 110 g/t) and Sb-As veins; (**f**) Stockwork of quartz–stibnite–arsenopyrite–gold veinlets, San Samuele underground mineworks, Brecca mine; (**g**) Mylonite (myl)-hosted, first-stage Zn-Cu-Pb sulfide ore of Baccu Locci: a first infill of sphalerite–quartz in S2 mylonitic foliation is cataclased and, in turn, infilled by galena; (**h**) Second-stage As-Pb-(Zn, Cu, Sb, Ag, Au) vein ore of Baccu Locci: cataclased arsenopyrite is infilled by chalcopyrite and sphalerite; (**i**) Quartz–stibnite vein ore of Brecca, hosted in sericitized porphyroids (porphy): fragments of wallrock and of early quartz are enveloped by stibnite and quartz. The deformation lamellae in the stibnite indicate tectonic activity during and after the precipitation of the ore; (**j**) A gold grain in "vuggy" quartz: altered quartz–arsenopyrite vein, Brecca; (**k**) Cataclased quartz–arsenopyrite vein with visible gold grains, hosted in porphyroids, Monte Ollasteddu: gold grains fill the spaces in fractured arsenopyrite; (**l**) Detail of the arsenopyrite–gold association in Monte Ollasteddu: gold is present as pure gold (Au > 95%) or electrum (>25% Ag). All of the photomicrographs were taken of polished samples under reflected polarized light conditions (only image (**i**) is under crossed nicols). Apy: arsenopyrite; Au: native gold/electrum; Ccp: chalcopyrite; Gn: galena; Qz: quartz; Sbn: stibnite, Sp: sphalerite. Mineral abbreviations according to [120].

The duration of the late Variscan hydrothermal activity related to extensional tectonics in the Gerrei district has been constrained by ^{40}Ar–^{39}Ar dating [112]. White mica from Ordovician metarhyolitic host rocks and K-feldspars from mineralized veins in Monte Ollasteddu provided a wide time interval, spanning from 307 to 260 Ma. For orogenic-type ores, further constraints come from some geological evidence:

(1) In the whole district, the orogenic-type ores apparently predate the granites of the Younger Magmatic Peak;
(2) In the W part of the district (the Genna Ureu mine: Figure 4) orogenic-type Sb-As $\pm$ W $\pm$ Au veins are unconformably covered by sedimentary deposits that have been attributed to the late Carboniferous–early Permian [123];
(3) In the Baccu Locci mine area, mafic dikes dated to about 302 Ma [107] were emplaced between two stages of mineralization.

Overall, this evidence points to an age of mineralizing events close to 300 Ma, in good agreement with the "gold 300" metallogenic event defined on the scale of the European Variscides [6].

3.2. Intrusion-Related Ores

Intrusion-related ores are a relevant part of the metallogenic budget of the Variscan basement of Sardinia. Some of their macroscopic and microscopic features are summarized in Table 3 and in Figure 6a–l.

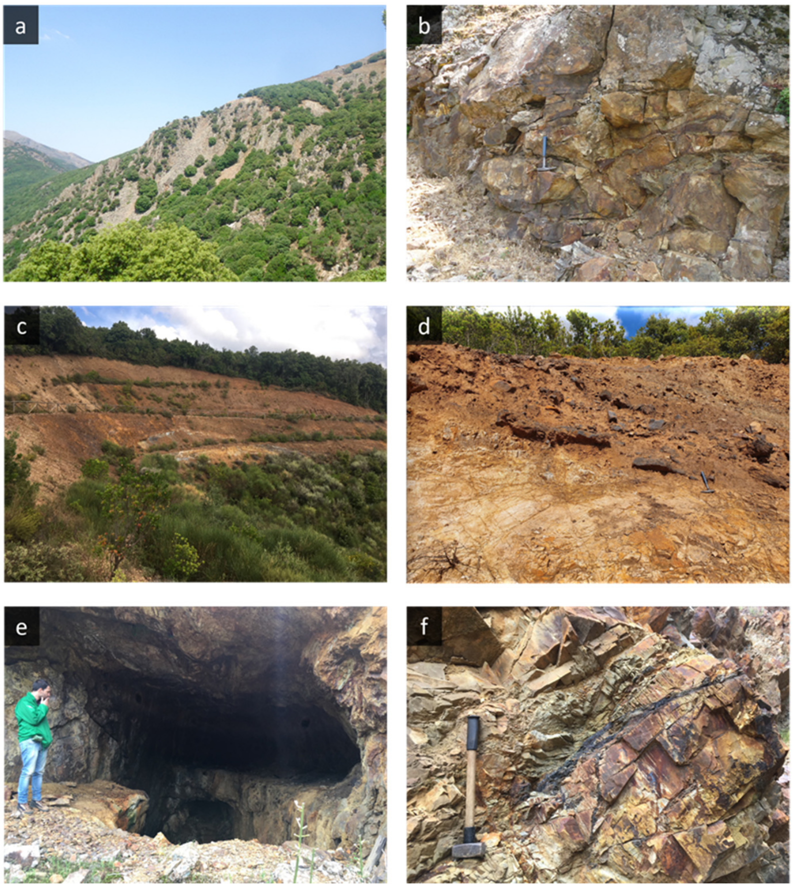

Figure 6. *Cont.*

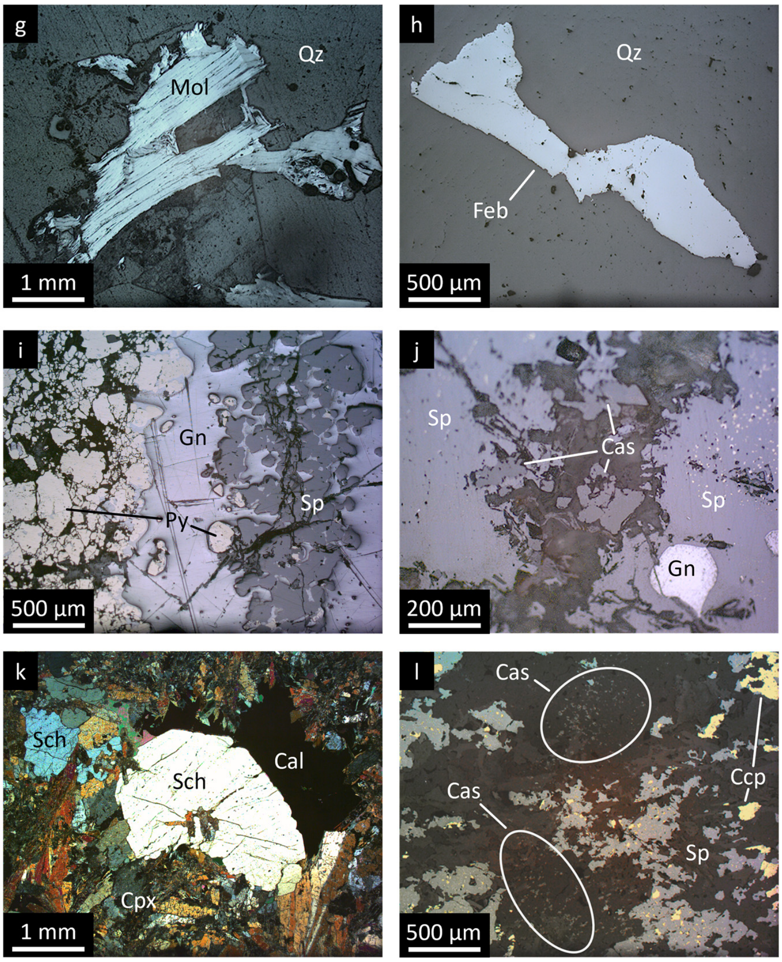

Figure 6. Selected examples and textural and mineralogical features of intrusion-related ores in the Monte Linas district of SW Sardinia: (**a**) overview of the Perda Lada Mo-Cu prospect; (**b**) Mo-Cu exogreisen outcrop in Perda Lada; (**c**) old mine excavations of the Perda Niedda Fe (F-Zn-Cu-Sn) mine, Oridda area; (**d**) contact between magnetite skarn and greisenized granite, Perda Niedda mine; (**e**) old mine adit along the main vein, Canale Serci Zn- Sn mine; (**f**) stockwork of sphalerite–cassiterite veinlets in the selvage zone of the main vein, Canale Serci; (**g**) molybdenite aggregate in quartz gangue, Perd'e'Pibera mine, Mo greisen ore; (**h**) ferberite in quartz gangue, Nuraghe Togoro W-Bi-Te-Au vein; (**i**) brecciated sphalerite–pyrite infilled by galena, Canale Serci mine main vein; (**j**) cassiterite–sphalerite–galena association, Canale Serci mine main vein; (**k**) scheelite crystal in clinopyroxene–calcite gangue, Monte Tamara skarn ore; (**l**) fine-grained cassiterite associated with sphalerite, Perda Niedda sulfide skarn ore. Photomicrographs (**g**–**j**,**l**) were taken on polished samples under reflected polarized light conditions; photomicrograph (**k**) was taken under transmitted polarized light. Cas: cassiterite; Cal: calcite; Ccp: chalcopyrite; Cpx: clinopyroxene; Feb: ferberite; Gn: galena; Mol: molybdenite; Py: pyrite; Qz: quartz; Sp: sphalerite; Sch: scheelite. Mineral abbreviations according to [120].

Mineral systems related to Sardinian granitoids follow the petrological evolution and the timing of the batholith growth. General overviews on the metallogenic productivity of the batholith, with a focus on Mo-bearing ores, have been drawn in early 1980s studies [124–126]. They distinguished a first intrusive event of low metallogenic potential, mainly related to the emplacement of granodioritic magmas for which a mantle-derived component is recalled, followed by a later, way more productive, crustal-derived granitic event (the so-called "leucogranite association") [126]. These concepts were further elaborated by recent studies in S Sardinia that highlighted the higher fertility of F-bearing ferroan granite rock series belonging to the YMP [76]. Remarkably, within this granite rock series, the GS1 granites, belonging to the ilmenite rock series, are associated with a Sn-W-Mo metallogenic province [40].

The asymmetrical regional distribution of magmatic deposits, in large part concentrated in central–southern Sardinia (Figure 3), is positively correlated with the timing of batholith growth, with the maximum concentration of ores in zones where the youngest intrusions of the early Permian YMP suites prevail [76,82,112,127]. The main types of mineralization related to Sardinian granitoids may be summarized as follows (Table 3):

(1) Skarn systems, including compositionally heterogeneous Fe-Pb-Zn-Cu ± F ± Sn ± W ± Bi ± As oxidized skarns [128] associated with GS1 suite granites, like the Sulcis and Monte Linas plutons [40,129–133], and Fe-Cu ± Pb-Zn, ±Ag-Au, ±W, ±LREE reduced skarns, are more diffused in central–eastern Sardinia [79,134,135]; mineralized ores of both types of skarn systems are typically hosted in retrocessed exoskarns, forming massive to lentiform or vein-type bodies [129,133,135]; high contents of rare metals are also reported in primary skarns and related hornfelses [79,133].

(2) Mo-(W-Sn-Bi ± Cu ± Au) endo- and exo- greisens; in 1980s studies [124,125], these ores have been interpreted as porphyry–Mo deposits; in S Sardinia, Mo-bearing deposits and occurrences are exclusive of the GS1 suite of granites, but they are also present in E Sardinia (e.g., Goene: Table 3) and in the Oschiri-Alà dei Sardi district of N Sardinia [125], always associated with YMP granites;

(3) Greisen-related Sn-W-Mo-Bi (±As, ±F) vein systems, constantly related to GS1 suite granites [40,136].

Pegmatite-related ores are poorly documented on a regional scale, although the occurrence of rare element types [137] of pegmatite bodies could be inferred from past studies [138]. Albitized pegmatites are associated with various intrusions [139] and included in albitized belts resulting from the circulation of late Variscan fluids along regional scale shear zones [140]. They are relevant as sources of industrial minerals for ceramics and as potential sources of REE [141].

Table 3. Selected Variscan intrusion-related deposits from Sardinia. Mineral abbreviations [120]: Aca: acanthite; Amp: amphibole; Apy: arsenopyrite; Au: native gold; Bin: bismuthinite; Bsn-Ce: bastnaesite–Ce; Bt: biotite; Cal: calcite; Ccp: chalcopyrite; Cas: cassiterite; Ep: epidote; Feb: ferberite; Flr: fluorite; Gn: galena; Grt: garnet; Ilv: ilvaite; Mag: magnetite; Mol: molybdenite; Py: pyrite; Pyh: pyrrothite; Px: pyroxene; Qz: quartz; Sch. Scheelite; Sp: sphalerite; Tpz: topaz; Ttr: tetrahedrite; Wo: wollastonite.

Locality	Geological Features	Ore	Notes	References
		Skarn deposits		
PERDA NIEDDA (SW SARDINIA) 39°23′30″ N 08°35′51″E	*Related intrusion*: Oridda pluton-granite, I-type, ilmenite-series, F-bearing—YMP (289 Ma) *Host rocks*: Grt-Px-Wo skarn in Lower Cambrian limestones *Type of orebodies*: massive lenses	(1) Grt-Amp-Bt-Mag-Cas (2) Cas-Flr (3) Chl-Qz-Cal-Sp-Ccp-Gn	*Economic resources*: Fe, F, Sn Oxidized, proximal iron–tin–skarn, partially greisenized. *Fluid inclusions* (*Flr*): Th: 340°–390 °C	[40,131,142]
ROSAS DISTRICT (SW SARDINIA) Rosas mine 39°12′10″ N 08°35′51″ E Sa Marchesa Mine 39°10′48″ N 08°45′05″E	*Related intrusion*: Sulcis pluton—granite, I-type, ilmenite-series, F-bearing—YMP (289 Ma) *Host rocks*: Grt-Px-Wo skarn in tectonic slices of Lower Cambrian limestones and in mafic calc-alkaline dikes *Type of orebodies*: massive lenses	(1) Amp-Ep-Mag-Cas-Sch (2) Chl-Qz-Cal-Sp-Pyh-Apy-Ccp-Bin-Gn-Ttr-Aca-Au	*Economic resources*: Pb, Zn, Ag, Cu Oxidized, distal base-metals skarn.	[130,143]
MONTE TAMARA (SW SARDINIA) 39°08′54″ N 08°45′04″ E	*Related intrusion*: Sulcis pluton—granite, I-type, ilmenite-series, F-bearing—YMP (289 Ma) *Host rocks*: Grt-Px-Wo skarn in Lower Cambrian limestones along tectonized stratigraphic contacts *Type of orebodies*: massive lenses	(1) Cpx-Amp-Ep-Sch-Flr-Mag-Cas-Bin (2) Chl-Qz-Cal-Sp-Pyh-Apy-Mol-Ccp-Stn-Gn-Bi sulf-Py	*Economic resources*: Pb, Zn, Cu, Oxidized, distal tungsten–tin–skarn. *Geothermometry* (*Apy and Stn*): 425°–460 °C (Apy); 284°–315 °C (Stn I) and 255°–270 °C (Stn II)	[133]

Table 3. *Cont.*

Locality	Geological Features	Ore	Notes	References
SINIBIDRAXIU (SW SARDINIA) 39°09′38″ N 08°44′44″ E	*Related intrusion*: Sulcis pluton—granite, I-type, ilmenite-series, F-bearing—YMP (289 Ma) *Host rocks*: Wo skarn in Lower Cambrian limestones *Type of orebodies*: columnar subvertical body (manto-type)	(1) Qz-Cal-Apy-Sch (2) Qz-Cal-Sp-CCp-Gn	*Economic resources*: W, As Oxidized, distal tungsten–skarn *Geothermometry* (*Apy*) 375°–400 °C	[133]
SAN LEONE (SW SARDINIA) 39°10′16″ N 08°55′53″ E	*Related intrusion*: Sulcis pluton—granite, I-type, ilmenite-series, F-bearing—YMP (289 Ma) *Host rocks*: Grt-Px-Wo skarn (Ordovician ? limestones) *Type of orebodies*: massive lenses	(1) Ep-Ilv-Qz-Cal-Mag-Sch-Flr	*Economic resources*: Fe Oxidized, proximal iron–skarn *Fluid inclusions* (*Flr*): Th: 315 °C	[129,142]
FUNTANA RAMINOSA DISTRICT (E SARDINIA) Funtana Raminosa mine 39°52′40″ N 09°10′18″ E Giacurru mine 39°54′23″ N 09°08′57″ E	*Related intrusion*: Mandrolisai pluton (?)-granodiorite, I-type, OMP (299 Ma) *Host rocks*: Px-Grt and Px skarns in Silurian limestones and black shales *Type of orebodies*: massive lenses	(1) Ep-Mag-Sch (2) Qz.-Cal-Ccp-Sp-Gn-Pyh	*Economic resources*: Pb, Zn, Ag, Cu, Fe Reduced/oxidized distal base metals–skarn *Fluid inclusions* (*Qz, Sp*) Th: 360°–410 °C salinity: 3.4–14.7 wt% $NaCl_{eq}$. (Qz) Th: 235°–335 °C salinity: 5.4–12.4 wt% $NaCl_{eq}$ (Sp)	[79,135]
CORREBOI (E SARDINIA) 40°04′20″ N 09°21′39″ E	*Related intrusion*: Fonni pluton-granodiorite/monzogranite, I-type, magnetite-series, -OMP ? *Host rocks*: Px-Grt skarn in Silurian limestones *Type of orebodies*: massive lenses	(1) Ep-Mag (2) Qz-Cal-Pyh-Ccp-Sp-Gn	*Economic resources*: Pb, Zn, Cu, Reduced base metals–distal skarn	[134]
		Greisen deposits		
PERD'E'PIBERA (SW SARDINIA) 39°27′19″ N 08°39′07″ E	*Related intrusion*: Monte Linas pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: granite *Type of orebodies*: veins and disseminations	(1) Qz-Ms-Mol-Feb (2) Qz-Py-Ccp-Flr	*Economic resources*: Mo Endogreisen *Fluid inclusions* (*stage* 2 *Qz*) Th: 250 °C salinity: 0–4wt% $NaCl_{eq}$	[40]
PERDA LADA (SW SARDINIA) 39°26′42″ N 08°40′36″ E	*Related intrusion*: Monte Linas pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: granite, Lower Ordovician shales *Type of orebodies*: disseminations and stockwork	(1) Qz-Ms-Mol-Feb (2) Qz-Mol-Py-Ccp-Flr-Au	*Economic resources*: Mo, Cu Au up to 1 g/ton (1) Endogreisen (2) Exogreisen	[40,125]
SU SEINARGIU (SW SARDINIA) 39°04′35″N 08°58′29″ E	*Related intrusion*: Sulcis pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: granite, Lower Ordovician shales *Type of orebodies*: disseminations and stockwork	(1) Qz-Ms-Mol-Cas	*Economic resources*: Mo Endogreisen, veins	[125]
GOENE (E SARDINIA) 39°52′49″ N 09°35′06″ E	*Related intrusion*: Mt. Tarè intrusion—(leuco-) granite, I-type, magnetite-series (?)–YMP (?) *Host rocks*: granodiorite, *Type of orebodies*: disseminations and *dry veins*	(1) Qz-Ms-Mol-Ccp-Mag	*Economic resources*: Mo Exogreisen, veins	[125]
SU LACCHEDDU (N SARDINIA) 40°46′52″ N 09°02′37″ E	*Related intrusion*: Monte Lerno Pluton leucogranite, I-type, YMP (?) *Host rocks*: granite, paragneiss *Type of orebodies*: disseminations and *dry veins*	(1) Qz-Ms-Mol-Feb-Ccp	*Economic resources*: Mo, W Exo- and endo-greisen	[125]

Table 3. *Cont.*

Locality	Geological Features	Ore	Notes	References
S'ABBAGANA (N SARDINIA) 40°43′19″ N 09°21′46″ E	*Related intrusion*: Monte Lerno Pluton leuco granite, I-type, YMP (?) *Host rocks*: fine-grained leucogranite *Type of orebodies*: disseminations and *dry veins*	(1) Qz-Ms-Mol-Flr	*Economic resources*: Mo Endogreisen	[125]
MONTE UNNE (N SARDINIA) 40°36′59″ N 09°06′14″ E	*Related intrusion*: Monte Lerno Pluton leuco granite, I-type, YMP (?) *Host rocks*: fine-grained leucogranite *Type of orebodies*: disseminations and stockwork of veins and *dry veins*	(1) Qz-Ms-Bt-Mol-Flr	*Economic resources*: Mo Endogreisen	[125]
	Hydrothermal veins			
NURAGHE TOGORO 39°27′28″ N 08°35′21″ E	*Related intrusion*: Monte Linas pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: Upper Ordovician shales *Type of orebodies*: sheeted veins	(1) Qz-Ms-Feb-Tpz (2) Bi-Bin-Bi telluride-Mld-Au *Textures*: massive *Alteration*: sericitic	*Economic resources*: W Au up to 1 g/ton	[40,136]
PERDU CARA-SANTA VITTORIA 39°27′ 38″ N 08°32′26″ E	*Related intrusion*: Monte Linas pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: Upper Ordovician shales *Type of orebodies*: veins	(1) Qz-Chl-Cas (2) Qz-Apy-Bin (3) Qz-Sp-Ccp-Gn *Textures*: massive to brecciated *Alteration*: sericitic, argillic	*Economic resources*: Sn, As Au < 1 g/ton *Fluid inclusion* (*Cst and Qz*) Th: 380°–410 °C salinity: 24–25 wt% $NaCl_{eq}$ (Cst) Th: 260–280 °C salinity: 0–12 wt% $NaCl_{eq}$ (Qz)	[40]
CANALE SERCI 39°27′19″ N 08°39′07″ E	*Related intrusion*: Monte Linas pluton—granite, I-type, ilmenite-series, -YMP (289 Ma) *Host rocks*: Upper Ordovician shales *Type of orebodies*: veins	(1) Qz-Chl-Cas (2) Qz-Sp-Py-Ccp-Gn-Stn *Textures*: massive to brecciated *Alteration*: sericitic, argillic	*Economic resources*: Zn, Pb, Sn *Fluid inclusion* (*Qz*) Th: 100 °C Salinity: 21–23 wt% $NaCl_{eq}$	[40]
FLUMINI DE BINU (SW SARDINIA) 39°06′19″ N 08°59′17″ E	*Related intrusion*: *Sulcis pluton—granite, I-type, ilmenite-series, -YMP (289 Ma)* *Host rocks*: *granite* *Type of orebodies*: *sheeted veins, stockwork, dry veins*	(1) Qz-Ms-Mol-Cas-Py *Textures*: massive *Alteration*: sericitic, argillic	*Economic resources*: Mo Veins and exogreisen system	[125]
SANTA LUCIA (SE SARDINIA) 39°24′36″ N 09°34′53″ E	*Related intrusion*: San Vito pluton (?)—granite, I-type, ilmenite-series, -YMP (285 Ma) *Host rocks*: Lower Ordovician shales, Middle-Upper Ordovician rhyodacite *Type of orebodies*: veins	(1) Qz-Feb-Sch-Py (2) Qz-Apy-Ccp-Sp-Gn *Textures*: massive to brecciated *Alteration*: sericitic (?)	*Economic resources*: Pb, Zn, Cu	[144]
ARCU IS PANGAS (SE SARDINIA) 39°28′05″ N 09°35′01″ E	*Related intrusion*: San Vito pluton—granite, I-type, ilmenite-series, -YMP (285 Ma) *Host rocks*: Upper Ordovician *Type of orebodies*: veins and dry veins	(1) Qz-Ms-Mol-Ccp-Py *Alteration*: sericitic	*Economic resources*: Mo Veins and exogreisen system	[125]
PERDA MAJORI (SE SARDINIA) 39°34′17″ N 09°36′02″ E	*Related intrusion*: Quirra pluton—granite, I-type, ilmenite-series, -YMP (285 Ma) *Host rocks*: Lower Ordovician shales *Type of orebodies*: veins	(1) Qz-Mol-Feb-Sch-Cas-Tpz-Bin (2) Qz-Flr-Sp-Py-Ccp-Gn *Textures*: massive to brecciated *Alteration*: sericitic	*Economic resources*: Mo, W *Fluid inclusion* (*Qz, Feb, Flr*) Th: 320°–420 °C salinity: 1–4.5 wt% $NaCl_{eq}$ (Qz) Th: 310°–330 °C (Feb) salinity: 6–7 wt% $NaCl_{eq}$ Th: 120°–180 °C salinity: 0.5–3 wt% $NaCl_{eq}$ (Flr)	[145,146]

4. Discussion

4.1. Variscan Extension, Crustal Fertilization, and Ore Systems: The Sardinian Variscan Mineral System

At the European continental scale, the sequence of tectonic-metamorphic and magmatic events related to the Variscan orogen determined the onset of metallogenic inputs over a period of time ranging from late Devonian to late Permian, with a peak from 305 to 280 Ma [14]. The resulting ores are clustered in districts that represent sectors of the chain where the metallogenic fertility of defined crustal sections was enhanced by their interactions with multiple factors. These factors included [21,22]: (1) the presence of a geochemically anomalous source of metals, (2) the accumulation of that source was caused by sedimentary and/or tectonic processes, and (3) the concurrence of a heat source that triggered melting processes and fluid flows at the crustal scale. All of these factors were present in Sardinian Variscides.

As described in the previous sections, the complex series of tectonic and magmatic events related to the post-collisional evolution of the Southern Variscan belt determined the repeated regional-scale metallogenic pulses in Sardinia. These phases of metallogenic fertilization essentially consisted of heat-induced, fluid/melt-assisted redistributions of elements from crustal sources, which modified the geochemical budget of the corresponding crustal sections during protracted metamorphism and crustal anatexis. The migration of fluids and the ascent of melts through suitable pathways to upper crustal levels produced both orogenic-like and intrusion-related ores, in chronological succession. Geochronological data and fluid inclusion studies pointed out the metamorphic pre-granite signature of mineralizing fluids in the Au-As veins of the Gerrei district [112], thus supporting their attribution [39] to the orogenic-type class of deposits [147]. In agreement with what has been reported and discussed in studies on orogenic gold deposits in other Variscan districts [6,12,14,22], in the Gerrei district there is a large time interval between the peak of Barrovian metamorphism (360–340 Ma) [52,56–58] and the inferred first emplacement of orogenic-type ores (307 Ma) [29,112]. For this reason, the formation of orogenic-type ores after the occurrence of metamorphic fluids related to prograde dehydration is unlikely, because a very long storage of these fluids in some crustal reservoir should be assumed. Therefore, the metallogenic event must be related to post-collisional stages. The compositional data available for the fluids in the Gerrei deposits fall within the range defined for orogenic gold deposits on a global scale, for which a derivation from a single source rather than a multi-source origin has been suggested [148]. This is in good agreement with the lead isotope data, which suggest that the orogenic-type ores of the Gerrei district are derived from a homogenous source consistent with the Ordovician metarhyolites and the early Permian granites [112]. In this view, fluids are part of a unitary, crustal-scale hydrothermal–magmatic mineral system defined here as the Sardinian Variscan Mineral System (SVMS), for which the whole available geological, petrological, and geochemical data for the E Sardinia basement support a derivation from low-crustal processes related to post-collisional extension. A heat source, i.e., a suitable thermal engine for these processes, must be primarily sought in a partially melted Sub-Continental Lithospheric Mantle (SCLM). Indeed, several models have been proposed to explain the thermal budget required for extensive anatexis, HT/LP metamorphism, and magmatism in the Variscan belt:

(1) Radiogenic heating due to selective enrichment in U-Th-K and other radiogenic elements during crustal thickening [149];
(2) Advection of mafic magmas;
(3) Increased mantle heat flow due to thermal erosion or lithospheric delamination [150];
(4) Shear heating [104,151].

Based on petrological arguments, advection combined with lithospheric delamination and asthenosphere upwelling has been proposed as a suitable heat source for triggering decompression melting of the SCLM [74]. In N Sardinia, the anatectic precursor of OMP has been explained in terms of localized shear heating [58]. Yet, a mantle-driven heat engine can better explain the long-term regional mechanism for the OMP and YMP, testified by:

(1) the huge volume of granitoids, particularly in N Sardinia; (2) the progressive increase of mantle-derived melts from the Carboniferous to the Permian, and (3) the persistency of magmatism and the apparent increase of melt-production rates over time.

In this setting, syn-metamorphic dehydration and devolatilization of the lower and middle crust may have fed a regional scale reservoir of "orogenic" fluids, forced to migrate upwards in the shallow crust by decompression of the orogen, similar to what is assumed to have occurred to create the diffuse granulitization of the lower crust during the post-thickening collapse and exhumation in the French Central Massif [12,152].

The timing of these events in Sardinia, especially in relation to the mineralizing events, is still poorly constrained. The prograde thermal peak in northern Sardinia corresponds to the 320–305 Ma HT-LP metamorphic event. In southern Sardinia, the white mica lepidoblasts marking the S2 foliation in Ordovician metarhyolite, the host rock of an orogenic-type As-Au ore, were dated at 307 Ma [112]. This age likely represents an upper bound for the post-collisional thermal peak in this part of the chain [29]. In the SVMS crustal-scale system, fluid transfer may have occurred concurrently with the ascent of magmas derived from partial melting of the same source materials. The different mobility of magmas and the low viscosity of the fluids, rich in volatiles, could explain the apparent diachronicity of the orogenic-type and magmatic-related mineralizing events. The orogenic-type deposits were strongly controlled by the structure of the crust, molded by inherited collisional and post-collisional structures. Such structures were critical in focusing the path of mineralizing fluids and eventually leading to the formation of larger deposits in favorable sites where multiple structures intersect. On the other hand, the regional distribution of intrusion-related ores is closely associated with the geometry and volume of the magmatic complexes, which generally decrease from north to south in Sardinia. This decrease may be explained as a lower degree of partial melting of magma sources [76] that, in fact, corresponds to an increase in the metallogenic specialization and higher fertility of melts, driving a much higher ore potential of the resulting intrusions (e.g., the GS1 suite granites of YMP).

The proposed model of SVMS may conceptually approach the classical crustal continuum model of orogenic gold systems in compressive settings [147,153], but it is more coherent with the schemes of hydrothermal and magmatic/hydrothermal mineralizing systems suggested by several studies for the main Variscan massifs of Europe [12,17,20–22], being also consistent with the magmatic–metamorphic systems defined for the Euro-Asiatic Variscan belt [14,15].

4.2. Crustal-Scale Plumbing Systems

A key concept for the SVMS model is the architecture of the crust, which is essential for establishing crustal-scale plumbing systems necessary to transfer fluids and magmas from deep reservoirs to shallower, colder, emplacement levels (Figure 7). The Variscan collisional structures, such as mylonitic shear zones and the main thrusts, are of primary relevance to control the fluid pathways as they form dynamically permeable layers that control the pathways of fluids and magmas [58,72,115,143]. Besides, most late collisional regional structures such as the kilometer-scale open antiforms recorded in the nappe zone represent nearly ideal traps for the accumulation of the mineralizing fluids, particularly at places where post-collisional extension during the exhumation of the chain generated wide open spaces. Suitable first-order fluid pathways are lithospheric transpressional shear zones developed during the late orogenic rotation and displacement of the Sardinia Corsica microplate along the South Variscan Shear Zone, resulting in the "Sardinian puzzle" [66,70,71]. The role of these shear zones in the emplacement of various plutons during the final growth stage of the batholith from about 315 to 286 Ma was highlighted by several studies [58,72,81,82,86]. We suggest that these structures might also represent major feeders of fluids contributing to the formation of orogenic-type ores in regional-scale structural traps (e.g., the Flumendosa Antiform), as already documented in other Variscan massifs of Europe [6,12,14,22]. Finally, differential uplift of the basement and the development of tectonically-controlled intracontinental basins might also have played a subsidiary role in the selective preservation of newly formed ores.

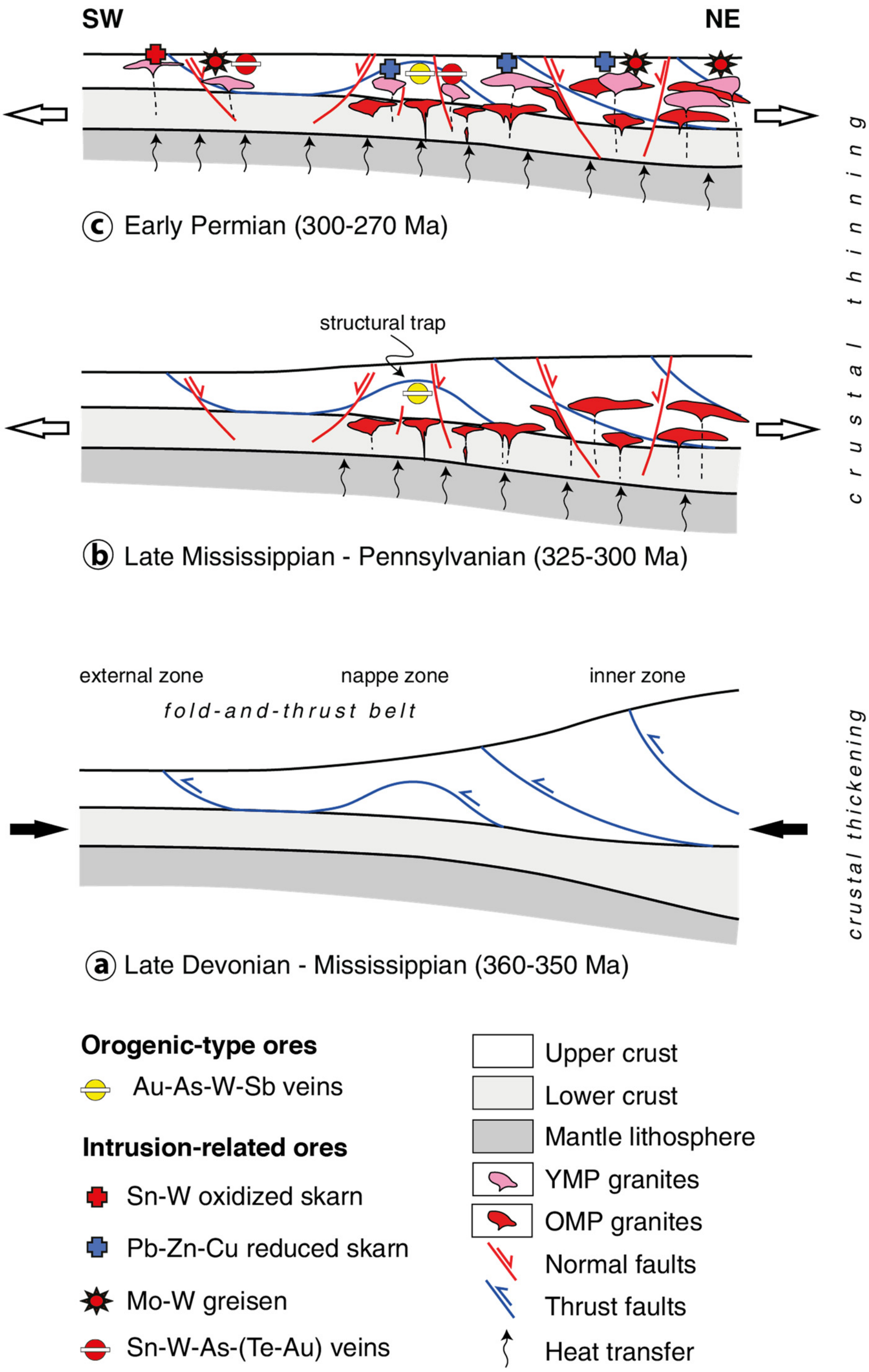

Figure 7. Metallogenic events in the Variscan basement of Sardinia: (**a**) main collision, crustal thickening, and the development of a fold-and-thrust belt in the upper crust (Late Devonian—Mississipian, 360–350 Ma); (**b**) early post-collisional extension, crustal thinning, initial production of anatectic melts (OMP granites), dehydration, fluid production, and migration toward structural traps to generate As-Au-W-Sb orogenic-type ores (Late Mississipian—Pennsylvanian, 325–300 Ma); (**c**) late post-collisional extension, shallow emplacement of F-bearing YMP ferroan granites with Sn-W-Mo and Pb-Zn-Cu intrusion-related ores (Early Permian, 360–350 Ma).

4.3. The pre-Variscan Metallogenic Sources

In the proposed regional-scale mineral system, metallogenic fertilization processes were mainly proceeded by reorganization of the available crustal geochemical budget and by the concentration of metals in structurally controlled zones, whereas an only subordinate contribution from mantle sources may be inferred [49,95,100]. Investigations on the nature and composition of such sources are at present constrained by the (limited) knowledge of the structure of the Variscan crust framework, as well as by petrological considerations arguing for granite magmas [76,100]. Geophysical data indicate that the crust of E Sardinia evidently retained a nearly unmodified Variscan structure. Seismic refraction profiles [154] show a crustal section made of an about 15 km thick upper crust (P-waves velocity of 6.3 km/s), and a 10–12 km thick middle/lower crust (6.8–7.0 km/s). The Moho (7.9 km/s) is between about 27 and 30 km. This structure is not recognized in SW Sardinia, where relatively low-velocity P-waves (6.3–6.4 km/s) are recorded until reaching the Moho at a 25–30 km depth.

Middle–lower crustal sections of the basement with anatectic evidence are exposed in numerous sectors of N Sardinia. They consist of subordinate amphibolite with granulitic relicts and migmatites derived from meta-sedimentary protholiths or orthogneisses [58,155]. The protoliths of orthogneisses are calc-alkaline granitoids, representing the remnants of the Middle–Late Ordovician magmatic arc [156]. From the trace elements distribution and the ages of inherited zircons found within the late Variscan granitoids, Ordovician orthogneisses are considered the major sources for late Variscan magmatism in northern Sardinia [95,102]. Consequently, (1) the pre-anatectic composition of the northern Sardinia crust was likely dominated by orthogneisses rather that metasediments, and (2) the late Variscan magmatism involved extensive reworking of both small volumes of mature crustal materials and a much larger amount of less evolved (i.e., Ordovician arc-derived) components enriched in incompatible elements. On the contrary, in S Sardinia, geological constraints and Pb, Nd, and Sr isotope tracers suggest that late Variscan magmas are derived from mixed sources involving a critical contribution from an underlying crystalline basement of inferred Proterozoic or even Neoarchean age [40,76,100]. Indeed, the presence of fragments of an ancient Archean lithosphere in the W Mediterranean, including Sardinia, has been suggested, based on several findings of SCLM-derived peridotite xenoliths of Archean age in Tertiary volcanics from SE Iberia and Sicily [157]. Besides, the existence of a different crustal source in the southern part of the island is also supported by the external position of SW Sardinia in relation to the Variscan orogen, which excludes the occurrence of an Ordovician arc in this area [64–66].

The nature of deep metallogenic sources in the Sardinian basement is still quite speculative; yet, the regional distribution of several key elements is available to propose a unified model that accounts for the role of different crustal layers in relation to the pre-Variscan geodynamic evolution and metallogenic stages. As previously evidenced, more certainties may arise from the study of intrusion-related deposits. As highlighted by recent studies [20,21], the major Sn and W Variscan provinces are related to metallogenic sources involving anatexis of ancient, craton-derived, deeply weathered sediments, and, at the same time, to heat sources capable of attaining the temperatures required for biotite—or other mineralogical carriers of Sn and W in pre-anatectic crust—breakdown. The slightly peraluminous, F-bearing GS1 suite of southern Sardinia, ascribed to HT granites—860 °C calculated for the liquidus temperature—and related to the Sulcis-Iglesiente Sn-W province [40], may fit into these requirements. Conversely, the metallogenesis of other intrusion-related districts (e.g., the central Sardinia reduced skarn districts), dominated by the Pb-Zn-Cu association, may be more related to the less evolved sources derived from the Ordovician magmatic arc; the absence of significant granite-related Sn and W mineralization in these districts may involve partial melting of these sources at temperatures below that of biotite breakdown.

Additional and relevant metallogenic sources for Variscan ores are definitely represented by the mineralized deposits derived from the pre-Variscan metallogenic stages summarized in Table 1.

The most relevant pre-Variscan event recorded in SW Sardinia is represented by the huge (>120 Mt of mined ore) SEDEX-to-MVT Pb-Zn stratabound deposits hosted in the early Cambrian carbonate sequences of the Iglesiente and Sulcis districts [25,26]. These deposits were deformed by the Middle Ordovician "Sardic phase", experiencing a first remobilization phase [27,158]; in a second phase, during the Variscan collision and deformation, they were remobilized again. Finally, these deposits were also reactivated during the Variscan magmatic metallogenic stage, sourcing at least partially some Pb and Zn magmatic-related ores, as evidenced by lead isotopic ratios always displaying the original Cambrian signature [27,130,132]. In E Sardinia, deformation developed earlier than in SW Sardinia [65], followed by a conspicuous subduction-related calc-alkaline arc volcanism [156]. The metallogenic relevance and ore productivity of this Ordovician volcanic cycle has been conjectured and discussed since the early 1980s [35,158,159], but at present, no volcanic-related or even SEDEX-type mineralization may be undeniably attributed to it [29]. However, as previously suggested for deep sources, the potential of the magmatic arc-related materials as a geochemical reservoir of metals and incompatible elements is reasonably expressed during the metallogenic events of the SVMS. Arc-related volcanic/subvolcanic and volcaniclastic materials, in fact, were likely leached by "orogenic" hydrothermal fluids and successively intruded by late Variscan granitic magmas, leading to partial remobilization of incompatible elements [29]. Similar considerations may be made for the Upper Ordovician post-arc sequences, where Ti-Zr- and LREE-rich paleoplacers have been identified in sedimentary rocks of E Sardinia [160]. Highly mineralized layers (enriched in anatase, monazite, zircon, etc.) of these volcanic arc-derived siliciclastic rocks occur with good lateral continuity in the Sàrrabus Unit of SE Sardinia [28], but they have been also found in central Sardinia, where relevant remobilization and enhancement of metallic ores has been documented [79]. Because of their regional extension and degree of mineralization, the Upper Ordovician post-arc sequences must be regarded as first-order metallogenic sources of rare metals in the E Sardinia basement. In SW Sardinia, Upper Ordovician successions lack these volcanic-derived sediments, instead hosting Ti-rich and rare Zr-rich paleoplacers and multicentimetric sedimentary strata of Mn oxide and Mn carbonate [64,161]. The metallogenic role of Silurian black shales has been also discussed in the past, as these carbonaceous metasediments have been alternatively regarded as ore sources [38,117,118,158,162] or preferential host rocks to target metallic ores [116,134]. The geochemistry of Sardinian Silurian black shales is relatively poorly constrained: high V contents (thousands of ppm) have been reported in E Sardinia black shales [37], whereas their role as Ni, Co, As, and Sb sources has been pointed out [38]. Regardless of their potential as a source of metals, Silurian carbonaceous rocks may have provided large amounts of reducing agents (methane, carbonaceous matter, pyrite), and thus they represent effective chemical conditioners for fluids and magmas in deep sources and along crustal pathways, and for lithological/chemical traps for ores at shallow levels in the crust.

4.4. Crustal Metallogenic Fertility and Distribution of Variscan Ores in Sardinia

A striking feature of the Variscan basement of Sardinia is the uneven distribution of mineral deposits and the occurrences of different ore types framed in the SVMS. The structure of the Variscan crust and the nature of metallogenic sources provide numerous indications to explain this distribution. The Variscan structural setting shows remarkable differences between the eastern and southwestern parts of Sardinia, whence different crustal metallogenic fertility rates may be inferred. In terms of Variscan metallogeny, a remarkable difference concerns the distribution of orogenic-type mineral deposits, which are characteristic of SE Sardinia but totally absent in SW Sardinia. The persistence in E Sardinia of a thick Ordovician arc composed of various volcanic and sedimentary units, for which fertility in terms of Au, As, Sb, W, and base metals may be inferred—also from zircon typologies compared to those of major arc volcanics [163,164]—provides an argument to explain the uneven distribution of ores in relation to such inherited pre-Variscan paleogeography. As observed in many other orogenic gold districts worldwide, the occurrence of a previous subduction zone—such as that associated with the Ordovician arc of Sardinia—is apparently a critical controlling factor for the gold fertility of a region [165,166]. As explained in previous sections, in E Sardinia, these structurally controlled hydrothermal deposits are concentrated in the Gerrei district, where large-scale fluid flow exploited a pattern of brittle to viscous brittle shear zones folded by the Flumendosa Antiform. This structural control was a critical factor in the formation of the ore district.

The regional distribution of granite-related ores is instead more associated with variations in the deep structure and composition of the crust contributing to SVMS. The existence of an ancient, pre-Phanerozoic crystalline basement under some areas of Sardinia is still hypothetical but is supported by geological, petrological, and geochemical indications. The petrology and metallogeny of F-Sn-W-Mo, Mn and rare metal-rich granites, particularly those of SW Sardinia (i.e., the GS1 suite) [76], is a strong argument supporting this hypothesis. The geochemical characteristics of this granitic suite more likely reflect a source signature rather than intra-crustal differentiation [40]. The unusually high Mo fertility of the GS1 suite is a regional singularity [40] considering its strongly reduced (ilmenite series) petrological character, generally referred to as Sn and Sn-W mineralization [167]. In fact, granite suites associated with Mo mineralization usually display oxidizing petrological signatures (magnetite-series granites) [91,128,167]. Such a peculiarity may be subject to various interpretations. In a first hypothesis, we may infer simultaneous inputs of metals from (1) oxidized sources enriched in Sn and W, and (2) from anoxic sources rich in Mo. As the isotope geochemistry and petrological features of GS1 granites indicate a provenance from deep crustal sources, we may also infer for them a possible Paleoproterozoic age [76]. Accordingly, anomalous concentrations of Mo, Mn, and other redox-sensitive elements have been related to weathering processes occurring during rapidly changing redox conditions (i.e., the Great Oxigenation Event) [168], with strong consequences for magma sources [169], mineral diversification [170], and on the type and amount of ore deposits [171,172]. The geochemical characteristics of the ores related to different suites of granitoids in other parts of Sardinia (e.g., the Funtana Raminosa district, central Sardinia: Pb-Zn-Cu-Fe deposits and strong LREE and Au anomalies) [79], suggest a dominant contribution from Ordovician arc-related metallogenic sources.

5. Conclusions

The Variscan metallogenic stages recorded in the Sardinian Paleozoic basement occurred during the late evolution of the orogen, well after the main collision and the regional Barrovian metamorphic peak. The main events that led to the metallogenic peak may be summarized as follows:

(a) Starting from about 320 Ma, post-collisional shearing coupled with general extension and decompression of the crust marked the tectonic evolution of the Sardinia–Corsica massif. The late Variscan extension characterizing the Carboniferous–Permian transition is documented up to about 280 Ma. Generalized decompression triggered partial melting of the Sub-Continental Lithospheric Mantle (SCLM) and asthenosphere upwelling, producing lithospheric delamination, high heat flow, and mantle–crust interactions. In this setting, the resulting thermal engine produced devolatilization by HT/LP metamorphism and large amounts of felsic melts, partly contaminated by mantle-derived components. This tectonic and magmatic evolution paved the way to what we call the Sardinian Variscan Mineral System.

(b) In the initial stages of the SVMS, fluids and magma from disparate reservoirs both migrated from lower–middle crustal source zones to upper crustal levels, interacting along the way with upper crustal materials whose composition was determined by pre-Variscan events, and particularly (i.e., E Sardinia), by the Middle–Late Ordovician subduction zone products and related magmatic arc. Fluid flow was focused along pre-existing crustal anisotropies, and fluids were entrapped at different crustal levels above the ductile–brittle transition, producing the orogenic-type mineralization characterized by a distinctive Au-As-Sb-W metallogenic association, principally clustered in SE Sardinia. The age of these events in SE Sardinia may be roughly constrained in the range of 305–295 Ma.

(c) The ascent of magmas generated the huge Sardinia Corsica Batholith through repeated emplacement at shallow crustal levels of coalescing granitoid pulses; the distribution and chronology of intrusions result from the evolution and migration of the heath flow, affecting compositionally different portions of the middle and lower crust. A thermal peak was constrained at about 315–310 Ma in N Sardinia, where partial melting produced large volumes of magma and fed granitoid intrusions. In central—southern Sardinia, partial melting was more limited and temporally localized in the Early Permian (290–280 Ma), resulting in the emplacement of smaller granitoid intrusions, though more specialized and fertile for mineralization. A great variety of ore deposits is associated with various granite suites of central–southern Sardinia, including the F-bearing ilmenite series GS1 granite suite, related to Sn-W-Mo-Bi mineralization, particularly relevant in SW Sardinia, and the more oxidized granites of central Sardinia, related to Pb-Zn-Cu-Fe ± LREE ± Au ores.

(d) In the above-described Mineral System, the strong compositional differences between the crust of E and SW Sardinia are reflected by the different Variscan granite-related metallogenic associations and ore distribution. This relation with the Variscan structure of the crust is further confirmed by the exclusive presence of the orogenic Au-As-Sb-W association in E Sardinia only. As the Variscan crusts inherit the compositional characteristics derived from their pre-Variscan history, the Variscan ore generation peak of Sardinia also inherits the geochemical signature of the pre-Variscan metallogeny.

Author Contributions: Conceptualization, S.N., L.C., A.F., A.L., G.O. and F.S.; writing—original draft preparation, S.N.; writing—review and editing, S.N., L.C., F.C., M.L.D., A.F., A.L., G.O. and F.S.; visualization, S.N., F.C. and M.L.D.; supervision, S.N.; funding acquisition, S.N., A.F., F.C. and L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the RAS/FdS research program "Sustainable land management: the tools of geology for the environment"—CUP F75F21001270007 (S.N and A.F.), by the RAS/FdS research program F73C22001210007 (F.C.), and by the FdS program FDS2223MULASG (L.C. and F.S.).

Data Availability Statement: Publicly available datasets were analyzed in this study.

Acknowledgments: The authors are grateful to V. Festa and F. Tursi, Editors of the Special Issue, and to two anonymous reviewers for their comments and suggestions that helped to improve the quality of the manuscript in several critical points.

Conflicts of Interest: The authors declare no conflicts of interest.

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