The metallogenic potential of an old European mining region: the case of Sardinia (Italy)

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Abstract. The current needs of supplying critical raw materials (CRM's) for the European Union lead to reconsidering the residual potential of many old districts in Western Europe. Sardinia was the most important Italian mining region, with some district (Iglesiente, Montevecchio) relevant at continental scale. Despite the intensive exploitation of last centuries, Sardinian districts still retains a metallogenic potential, involving: (1) large amounts of mine wastes; (2) marginal or poorly explored deposits; (3) new deposits, principally of precious metals and CRM's, emerging from new geological and metallogenic studies.
Keywords: Sardinia, old mining districts, metallogenesis, CRM's.

1 Introduction

Critical raw materials (CRMs) have been defined by EU Commission as a list of materials of high importance for EU economy and industry, for which there are concerns about supply risks, both for geological and geopolitical factors. The list is regularly updated and now comprises 27 CRMs, including large groups as HREEs, LREEs and PGMs (EU Commission, 2014, 2017). Moreover, from the first document of 2010, the Commission proposed a series of recommendations regarding EU policies on raw materials, indicating among the different lines of intervention the systematic re-evaluation of domestic mineral resources. Accordingly, in several ancient mining areas of Europe where old deposits have been mined for several centuries and are now considered as exhausted, new activities have begun to evaluate their residual potential in terms of CRMs resources.

The island of Sardinia represents one of these areas, as it has been the most important mining region in Italy. Sardinian districts hosted in the past several Pb-Zn-Ag deposits of continental relevance, as those of the Iglesiente and Montevecchio districts, which have been mined up to late 1990s. Even if the old resources can be considered technically exhausted by decades, the potential of the districts for new resources, also those falling within the CRMs list, remains to be assessed. Some resources are linked to marginal deposits of little economic interest at the time of the extensive exploitation of larger deposits; other resources are materials deriving from old mining activities (mine wastes, tailings), which constitute a major environmental problem in the region; moreover, further resources are mineral deposits up to now under-explored and never exploited for technical, economic as well as political/administrative reasons.

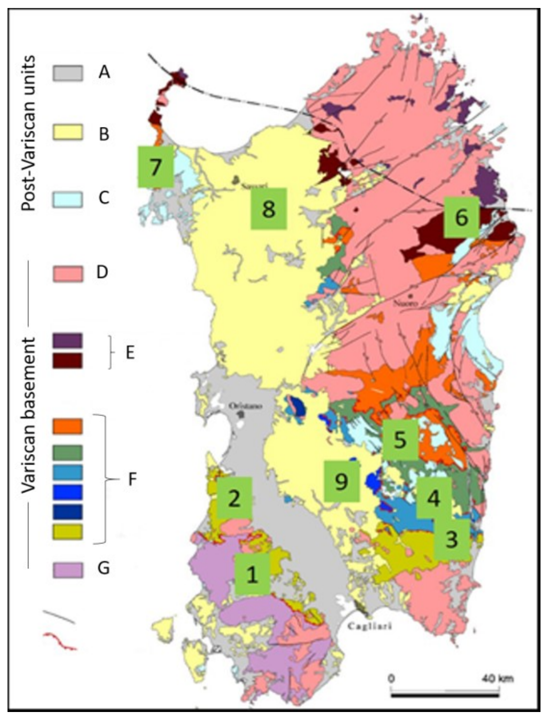

Figure 1. Schematic geological map of Sardinia (simplified and modified from Carmignani et al., 2001). A: Quaternary; B: Tertiary C: Mesozoic; D: Variscan intrusive complexes; E: Variscan Axial Zone; F: Variscan Nappe Zone; G: Variscan Foreland. Numbers refer to the main mining districts cited in the text. 1: Iglesiente; 2: Montevecchio; 3: Sarrabus; 4: Gerrei; 5: Funtana Raminosa; 6: Lula; 7: Nurra-Argentiera; 8: Osilo and Logudoro; 9: Furtei.

2 The metallogenic framework of Sardinia

The Sardinian mineral deposits embrace a wide variety of types, resulting from the complex geological evolution of the island. Sardinian metallogenesis is multi-stage, encompassing several epochs from early Paleozoic to Quaternary. Schematically, seven different metallogenic periods may be recognized (Table 1): phases of relative metallogenic stasis alternated with metallogenic peaks marked by extensive mobilization, migration, concentration and re-concentration of elements to form different kinds of mineral deposits.

Table 1. Summary of the metallogenic periods in Sardinia (numbers refer to district reported in Figure 1)

DISTRICT	ORES	TYPE
Pre-Sardic phase peak (early Cambrian-early Ordovician)		
1	Ba, Pb	Evaporite
1	Fe-Zn-Pb	SEDEX
1	Pb-Zn	MVT
Sardic phase period (middle-late Ordovician)		
1	Ba, Zn-Pb	Karst, Supergene
3, 4, 5	base metals protores	Sedimentary, volcanic exhalative
Eo-Variscan period (late Ordovician-late Devonian)		
3, 4, 5	Ti, Zr, LREE	Placers
7	Fe	Oolitic Fe
1, 3, 4, 5	base metals, U, V protores	Sedimentary
Variscan peak (Carboniferous – early Permian)		
3, 4, 5	As-Sb-W-Au (Pb-Zn-Cu-Ag)	Orogenic Mesothermal
2, 6, 7	Pb-Zn (Ag, Ga-Ge-In), Ni-Co	Hydrothermal granite (OMP)-related "five elements-type" veins
5	Pb-Zn-Cu (Ag, Au)	Skarn, granite (OMP)-related
1, 2, 3,4	Mo-W-Sn-F, F-Ba-Pb-Ag	Hydrothermal, greisen and skarn granite (YMP)-related
Post-Variscan I period (Permian-Triassic)		
1, 2, 3	F-Ba-Pb-Ag	Low-temperature veins
1	Ba, Zn-Pb	Karst, supergene
Post-Variscan II period (Cretaceous)		
7	bauxite	Paleosoil
Cenozoic peak (Oligocene-Miocene)		
8, 9	Au-Ag-Te-Cu	HS and LS epithermal, porphyry
1, 8	Mn	Volcano-Sedimentary/exhalative
8	Cu, Pb	Sedimentary

The **Pre-"Sardic phase" metallogenic peak** (early Cambrian- early Ordovician), resulted in the Pb-Zn ores of the Iglesiente district (SW Sardinia). Accumulation of metals occurred in a sedimentary basin evolving from siliciclastic to carbonatic. Initial small evaporite deposits with barite were followed by SEDEX deposits with Fe-Zn sulfides and by very large MVT Pb-Zn sulfide deposits (Boni et al. 1996, and references therein). Ore deposition took place during transition from extensional tectonics and passive margin conditions (Cambrian), to compressive tectonics with folding in an active margin setting (Ordovician "Sardic phase"). SW Sardinia became an area of wide circulation of basinal brines that produced the MVT deposits. The "**Sardic phase" period** (middle-late Ordovician), followed crustal subduction and development of a magmatic arc whose evidences are widely exposed in E Sardinia. This phase resulted in a thick volcano-sedimentary succession with calc-alkaline magmatic products and arguably was a relevant phase of geochemical accumulation and formation of pre-concentrations of metallic elements into the geological pile of the upper crust (Garbarino et al., 1989). In SW Sardinia, mineralized deposits of karst and clastic type with barite and Pb-Zn sulfides originated in a continental environment. The **Eo-Variscan period** occurred in the Ordovician-late Devonian passive margin. In E Sardinia erosion of the volcanic arc produced marine placers of heavy minerals (zircon, rutile and LREE-bearing monazite: Loi et al. 1992). In NW Sardinia oolitic Fe deposited in proximal siliciclastic sedimentary sequences. Silurian anoxic conditions led to widespread deposition of carbonaceous black shales, starting a new "pre-ore" phase of geochemical accumulation of a large set of elements (base metals, U, V). The onset of the Variscan collision (early Carboniferous) initiated a series of metamorphic, tectonic and magmatic events in which the **Variscan metallogenic peak** took place. The Variscan basement in Sardinia includes three tectonometamorphic zones (Fig.1): Axial Zone (North Sardinia), Nappe Zone (E Sardinia) and Foreland (SW Sardinia). During the post-collisional extension (late Carboniferous-early Permian), the basement was affected by extensional tectonics and intruded by various granitoid suites. Lithospheric delamination (Conte et al.,2017) triggered partial melting in the crust, with granitoid magma production and large-scale fluid circulation. Granitoids emplaced at high crustal levels during two main magmatic peaks (Old Magmatic Peak - OMP and Young Magmatic Peak – YMP, at 310-305 and 290-285 Ma, respectively: Conte et al., 2017). OMP granitoids are high-K, calc-alkaline, I-type (subordinately S-type) and B-bearing; YMP granitoids are in prevalence I-type ferroan, ilmenite-series and F-bearing. Naitza et al. (2015) schematized two main kinds of Variscan late-orogenic hydrothermal deposits: a) "orogenic" mesothermal As-Sb-W-Au deposits, not directly related to the granitoids, typical of SE Sardinia (Gerrei district), and b) granite-hosted/related deposits. The "orogenic" deposits of Gerrei are strictly structurally-controlled and related to regional folds and shear zones; they include some potentially economic target for gold (Garbarino et al., 2003). OMP-related deposits may include the large Pb-Zn hydrothermal veins of the Montevecchio (Cuccuru et al., 2016) and Lula districts and the Pb-Zn-Cu skarns of the Funtana Raminosa district (Central Sardinia). YMP-related and -hosted ores are more various and include numerous small Sn-W-Mo-Fe-As and Pb-Zn-Cu-Ag-F-Ba skarn, greisen, and hydrothermal vein deposits, mostly occurring in S Sardinia (Naitza et al., 2017). The **Post-Variscan I period** took place in a post-orogenic setting. The late Permian-early Triassic erosion and weathering of the basement led to extensive remobilization of the pre-existing ores. Boni et al. (1992) pointed out that several Pb-Zn-Cu-Ag-F-Ba vein deposits are associated to large-scale low-temperature fluid flows in the basement. In SW Sardinia, weathering of the Cambrian Pb-Zn MVT deposits produced large supergene Pb and Zn non-sulfide ores (Boni et al., 2003). In the same area numerous Ba deposits are related to karst processes (Garbarino et al., 1989).

During Mesozoic, a long period of metallogenic stasis ended in middle Cretaceous (**Post-Variscan II period**) with the formation of bauxite deposits along a paleosurface within the carbonate sequences of NW Sardinia (Mameli et al., 2007). The Cenozoic drift and eastward migration of Sardinian-Corsican microplate from the European continent are crucial for the **Cenozoic metallogenic peak**. Migration was related with westward subduction and opening of the Liguro-Provencal back-arc basin. In Oligocene-Miocene large amounts of calc-alkaline volcanics were produced in W Sardinia. These tectonic and magmatic events are associated with: 1) Cu-Au-Mo porphyry type deposits, related to andesitic intrusions; 2) high sulfidation Au-Cu-As-Te and low sulfidation Au-Ag-Sb-base metals epithermal deposits; (Fiori et al., 1994; Lattanzi, 1999) 3) stratiform to discordant volcano-exhalative and volcano-sedimentary Mn deposits in the Miocene volcano-sedimentary sequences; 4) Cu and Pb oxide deposits in clastic sediments at the top of the Miocene volcanics (Fadda et al., 1998).

3 The remaining metallogenic potential of Sardinian districts

Despite over one century of industrial mining, the Sardinian districts still preserve a significant metallogenic interest, and may be regarded as potential sources of raw materials, including several CRM's. Three kinds of sources must be considered: (1) mine wastes and tailing dam deposits from old mines; (2) known, but under-explored or under-exploited resources; (3) totally new themes and targets for mineral exploration.

3.1 Mine wastes as sources of raw materials.

The large Pb-Zn deposits of SW Sardinia districts (Iglesiente and Montevecchio) are now virtually exhausted. After the closure of the last mines (1999), a legacy of large volumes of mine wastes and tailings remains in the area. Only in SW Sardinia, the Regional Administration estimated about 66 millions of cubic meters (Mm^3) of different mine wastes and tailings (Regione Autonoma Sardegna, 2003). The total tonnage of the ore deposits mined in the Iglesiente MVT district amounted to 120-150 Mt of Pb and Zn sulfides; accordingly, 13 Mm^3 of wastes are now accumulated in the Iglesias valley, which hosts three of the largest mine sites. Among these wastes, the metallurgical red muds resulting from the electrolytic plant that in the Monteponi mine treated non-sulfide Zn ores have been identified as the most relevant potentially economic resource: about 3 Mm^3 of fine-grained deposits at an average of 8 wt% Zn, 1 wt% Pb and 400 ppm Cd (Buosi et al., 1999). In the Montevecchio district, wastes and tailings amount to 10.5 Mm^3. The ore parageneses of hydrothermal veins exploited in the past display a wide list of metals, including Zn, Pb, Ag, Cu, Cd, Ge, Ga, In, Co, Sb (Moroni et al., 2019). Studies are currently underway by public agencies to assess the economic potential of these large wastes in terms of base metals and CRM's. In SE Sardinia, about 1 Mm^3 of mine and metallurgical wastes resulting from exploitation of Variscan "orogenic" or granite-related ores from Sarrabus and Gerrei district include potential sources of Sb, W and Au (e.g., Su Suergiu and Corti Rosas mines), Ag, F and Ba (e.g., Monte Narba mine). In Central Sardinia (Funtana Raminosa district), mining of Pb-Zn-Cu skarn ores left small wastes (0.35 Mm^3) of potential interest for base metals, Ag, Au, and several CRM's, including Ge, Ga, In and REE. The potential of mine wastes in the small districts of N Sardinia (i.e Lula, Argentiera) is limited, although they likely include a set of CRM's as large as that of the Montevecchio district. Small volumes of mining wastes are also present in Furtei (S Sardinia), the only mine that, between 1990's and 2000's exploited a high sulfidation epithermal deposit for gold: the wastes have been evaluated as interesting sources for Au and Te.

3.2 Under-explored or under-exploited resources

As documented in many European mining districts, also Sardinia include several minor deposits that in the past were considered sub-economic and are under-explored or under-exploited. Moreover, in major (and now exhausted) mineral deposits, there were marginal and under-exploited ores that may have some economic potential, in many cases for raw materials different from those mined in the past. A far from exhaustive list include, among others: 1) Mo ores (greisens, skarns, hydrothermal veins) related to YMP granites, occurring in different areas of the Sardinia batholith (Fadda et al., 2015; Naitza et al., 2017); 2) Ni-Co ores in "five elements"-type hydrothermal veins, associated to Montevecchio-type mineralization (Southern Arburèse district: Cuccuru et al., 2016); 3) F-Ba ores, still unexploited, related to YMP granites (e.g. SE Sardinia districts: Monte Genis, Bruncu Molentinu); LREE ores associated to fluorite deposits (e.g., Silius mine, SE Sardinia: Mondillo et al.,2017); "orogenic" Variscan Au deposits of Gerrei district in SE Sardinia (e.g.: Monte Ollasteddu, Dini et al., 2005); epithermal Au, Ag and Te ores associated to tertiary volcanics in Northern (Osilo district), Central (Montiferru area) and southern Sardinia (Cixerri area).

3.3 New themes and targets for mineral exploration

In last two decades, new geological studies have greatly improved the metallogenic framework of Sardinia, suggesting new themes, new targets for mineral exploration, as well as new metallotects. In many cases, this is associated with systematic re-evaluation of the old districts: for instance, a more precise knowledge of structural traps and the tectonic phases and correlated styles controlling the formation of "orogenic" gold ores in Gerrei district (Funedda et al., 2018) brings out new perspectives for an extension of Au explorations to the whole Paleozoic basement of

Eastern Sardinia. In the same district, W (scheelite) occurrences frequently associated with “orogenic” Au ores are underexplored and probably deserve new consideration. In the old districts of SW Sardinia, Sn skarn deposits are related to YMP granites; highly mineralized cassiterite occurrences in proximal exoskarn environment suggest a possible new Sn metallogenic province (Naitza et al., 2017). In other cases, the integration between new geological data and sequential stratigraphy led to identify very rich zircon and monazite paleoplacers in late Ordovician rock sequences (Loi et al., 1992) as possible sources or metallotects of LREE. In the Funtana Raminosa district, recent studies suggest the possibility of further re-concentration of LREE in previously not exploited skarn deposits (Meloni et al., 2017).

4 Conclusions

Among the old mining regions of western Europe, Sardinia stands out for the variety of its mineralized deposits. In the light of the new studies on the geology and the metallogenesis of this region, many possible targets emerge for future explorations of different mineral resources, including several CRM's. These targets include primarily the mining dumps of the old districts and numerous marginal or under-explored deposits. New data from geological and metallogenic studies indicate possible new exploration themes and suggest that Sardinian districts still retain a metallogenic potential for the years to come.

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