Part 2

MID-SESSION FIELD TRIPS IN SOUTHERN AND CENTRAL SARDINIA

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The Iglesiente former mining district (SW Sardinia):
an itinerary in the Iglesias valley
and along the Western Coast

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Abstract. In the following pages are briefly described the main characteristics of the hydrothermal ore deposits hosted in the Lower Palaeozoic lithologies of the Iglesiente district (SW Sardinia), where extensive exploitation for base metals has been active until recent past. Particular attention has been given to pre- and post-Variscan stratabound sulfides, to «Geodic Dolomites» and, especially, to the «Calamine» ores. We have followed the itinerary of the mid-session field trip organized during the «Tenth International Symposium on Water-Rock Interaction». For each one of the visited, still accessible localities of both geological and economic interest, a brief description has been given.

Riassunto. Vengono qui brevemente riassunte le caratteristiche principali delle mineralizzazioni, con associati fenomeni di alterazione idrotermale, ospitate nei litotipi del Paleozoico inferiore dell'Iglesiente (Sardegna SW), che sono state in passato oggetto di coltivazione per metalli di base. L’accento è stato posto sui solfuri stratabound pre- e post-Varistici, sulle «Dolomie Geodiche» e, soprattutto, sulle mineralizzazioni a «Calaminari». Cogliendo l’occasione dell’escursione effettuata nell’ambito del «Tenth International Symposium on Water-Rock Interaction», è stato tracciato un itinerario comprendente alcune località d’interesse geo-giacimentologico ancora accessibili nell’area in esame, di ognuna delle quali viene fornita una breve descrizione.

1. INTRODUCTION

The Iglesiente-Sulcis area in SW Sardinia is one of the oldest mining districts in the world, with production dating to pre-Roman times. Exploitation in the district was initially for silver-lead-copper and later for zinc and barium deposits. In the first decades of the twentieth century, the number of active mines was more than 50, and until the eighties both exploration and exploitation was carried out by the Italian state (ENI) and regional (Ente Minerario Sardo) mining companies. Due to increasing technical and
economic difficulties, however, the last producing mine was closed in 1998.

Most of the ores occur within Lower Paleozoic carbonates: they can be subdivided into pre-Variscan ores (stratiform/stratabound Zn > Pb > Ba [1] amounting to >150 Mt Zn + Pb), and post-Variscan (Pb-Zn-Ba-Ag-Cu-F skarn, vein, paleokarst [2] [3], whose economic importance was significantly smaller) deposits. Primary mineralisation consists of sulfides locally associated to barite: hydrothermal alteration is limited to local dolomitization and silicification.

Sardinia is also one of the few places in the world where the association between «primary» Zn-Pb sulfides and «secondary» non-sulfide mineralisation can be typefied. Historically, prior to the development of sulfide flotation in the early decades of this century, «zinc-oxide» mineralisation (the so-called «Calamine» ores, consisting of a
mixture of Zn-(hydroxy-)carbonates, silicates and hydroxides) was the principal source of zinc from this mining district. In 1969 (when exploitation was already completely shifted to sulfides), the annual Zn-oxides production reached 84,000 metric tons of «Calamine» concentrate [4], comprising low- and high-grade ores (20-35% Zn). The oxidation processes, often reaching to several hundred of meters below the surface in the whole area, are often independent from the oscillations of the current water table, and should be related to Quaternary and even Tertiary geomorphologic settings.

2. GEOLOGICAL SETTING

The geology of SW Sardinia is largely dominated by Paleozoic lithotypes, of sedimentary as well of igneous origin (fig. 1). Second in abundance are Tertiary and Quaternary volcanics, together with sedimentary rocks of similar ages [5]. Among the sedimentary successions, Cambro-Ordovician lithologies predominate. These are metamorphic rocks of epizonal facies, and belong to the so-called «External Zones» of the Variscan orogen [6].

The Lower Cambrian succession (fig. 2) is subdivided into the basal Nebida Group, which consists of 400-500 m of silicic clastic, shallow-water sediments, with carbonate intercalations toward the top, and the overlying Gonnesa Group, containing 300 to 600 m of shallow water platform carbonates [7]. The abrupt carbonate sedimentation of the Gonnesa Group was related to the inset of a tensional tectonic regime, recording an aborted rifting, well recorded in the carbonate lithologies [8].

Middle and Upper Cambrian? - Lower Ordovician strata are represented by nodular limestones (Campo Pisano Fm, Iglesias Group, 50-80m) and slates (Cabitza Fm, Iglesias Group, 400 m) respectively, both recording the deepening of the sedimentary basin.

The Cambrian to Lower Ordovician sediments underwent extensive deformation during the intra-Ordovician «Sardic» tectonic phase. Erosion and deposition of Upper Ordovician sediments in angular unconformity followed this phase on both the Gonnesa and Iglesias Groups deposits. They consist of thick successions of continental conglomerates and sandstones («Puddinga» AUCT.), followed by marine slates, lasting until Upper Ordovician-Silurian time.

At least two compressional and one extensional phase of deformation characterize the Variscan orogeny [6]. The Variscan deformation also produced low-grade metamorphism and several types of magmatic intrusions, which affected the deformed Palaeozoic successions.

During the Permain and Mesozoic, several pulses of extensional tectonics caused repeated opening of fractures, as well as the circulation of hydrothermal fluids in the whole Sardinia [2] [3] [9]. In the Iglesiente-Sulcis region, a widespread erosion penneplain developed after the late-Variscan uplifts, causing also deep karstification phenomena in the Cambrian carbonates. This karstic network was almost completely filled by internal sediments, collapse breccias and hydrothermal cements. It was eventually fossilized by Tertiary continental deposits.
Mesozoic marine sediments are restricted to the western margins of the peneplained massif, whereas the sedimentary and volcanic lithotypes of Tertiary age are fairly widespread throughout the whole region. Among the former, we should mention the carbonatic-marly sediments of the Sulcis basin (Eocene), containing brown coal deposits.

Figure 2. Schematic stratigraphic column of the Lower Palaeozoic in SW Sardinia (from Perejón et al., 2000, modified).
and the arenaceous sediments of the Cixerri Formation (Oligocene). Among the Tertiary volcanics, Oligo-Miocenic andesitic to rhyolitic and rhyodacitic types prevail along the southwestern coast, as well as in association with the lineaments controlling the Cixerri and Giba tectonic graben.

Quaternary sediments are limited. Conglomerates of fluviatile origin and Holocene sand dunes characterize the coastal belt north-west of Gonnesa, while small travertine deposits occur along the flanks of the Cambrian carbonates.

The Cambrian carbonate sequence was subjected during Tertiary and Quaternary to further karstic dissolution, clearly enhanced by the high sulfide content of the carbonates. In the mining areas often have been encountered spectacular caves with abundant speleothems, carbonate concretions and euhedral calcite and barite crystals, as the Santa Barbara cave at the San Giovanni mine, and the Phaff caves at Masua-Acuquaresi [10].

3. SULFIDE ORE DEPOSITS

In the Iglesiente district, namely in the hills around the town of Iglesias, the biggest mines of the whole island occur. The ores exploited there could be distinguished in pre- and post-Variscan: the first ones being deformed together with their host rocks by Variscan compressive tectonics, the second ones clearly cutting in turn the Variscan deformed lithotypes.

3.1. Pre-Variscan Ores

The pre-Variscan orebodies are stratiform and/or stratabound in shape, hosted in the Lower Cambrian carbonates (Gonnesa Group). They can be regarded as the result of a combination of favorable sedimentary environments, with Paleozoic tensional tectonics. Two groups of genetically distinct ore types are known.

To the first group belong syngenetic and early diagenetic massive sulfides (pyrite>>sphalerite>>galena) and barite layers, interpreted as Sedimentary Exhalative. The ore grade in the massive sulfides was generally high, locally exceeding (as in the San Benedetto and Campo Pisano mines) 12% combined Zn + Pb. The deposition of these ores, occurring at the base of the tidal dolomites of the Santa Barbara Formation, has been related to the onset of strong tensional tectonics during the Cambrian [8]. In fact, most ores are enriched along important tectonic lines, which controlled the distribution of the sedimentary facies during the Lower Paleozoic.

A second group of ores, with a greater Pb/Zn ratio and much less pyrite, occur as void-filling, breccia cements and late-diagenetic replacement bodies in the shallow water limestones of the San Giovanni Formation. Sphalerite contains variable amounts of Fe, Cd and Ge; low grades of Ag accompany galena. They have been interpreted as MVT deposits [1] [8] [11], possibly related to a widespread fluid-flow event associated to the Caledonian «Sardic» tectonic phase. Their metal content is in the range of low-grade MVT ores, averaging 5-7% combined Zn + Pb.
At the intra-Ordovician angular unconformity, occur small barite-galena ores of minor economic importance. They are associated with a very strong hydrothermal silica alteration [1].

The metals for both Cambrian and Ordovician-hosted stratabound ores originated from a crustal source [12]. The lead belongs to the same isotopic province as that occurring in the mineral deposits of southern Alps, Austro-alpine nappes, southern France and Spain [13].

3.2. Hydrothermal Dolomitisation («Dolomia Geodica») and Post-Variscan Ores

Between the end of Variscan orogeny and the beginning of Alpine cycle, southwest Sardinia was the site of several hydrothermal phases, comparable with those occurring in other parts of central and western Europe. They produced a widespread hydrothermal dolomitization («Dolomia Geodica») of the Lower Palaeozoic carbonates [14], and a range of base metal-Ba-F vein- and paleokarst mineralizations showing well distinct characteristics [2] [3].

3.2.1. «Dolomia Geodica»

Epigenetic replacive and saddle dolomite, frequently forming zebra structures, affect Cambrian limestones and early diagenetic dolomites across large areas of the Iglesiente-Sulcis district. This dolomite crops out in an area of more than 500 km² and reaches a thickness of up to 600 m (or even more). Prior to dolomitization, the Cambrian carbonates underwent ductile deformation and anchimetamorphic conditions.

The epigenetic dolomitization is mainly controlled by the Variscan foliation and late-
Fluid inclusion analyses combined with O- and Sr-isotope data indicate that the dolomitizing fluid can be categorized as a «basinal brine» [14]. The spread in homogenization temperatures shows a gradient with values decreasing from east to west. The higher temperatures (mean of around 100°C) have been measured in eastern parts of the Iglesiente area, whereas the lowermost temperatures (mean of about 85°C) have been found along the western coast of Iglesiente. This fluid certainly can neither have come directly from the low-grade metamorphic lithotypes undergoing dolomitization nor from the low-temperature metamorphic rocks within the overlying nappes.

No absolute dating was possible: the relative age of the «Dolomia Geodica» can only be inferred by the crosscutting relationships of younger Pb-Ag-Ba low temperature veins on the epigenetic dolomites. Though the low temperature-high salinity nature of the dolomitizing fluids (similar to that of the younger veins), in consideration of the pervasive nature of this phenomenon and of its lithologic control, we are inclined to assign also a Permian(?) age to the hydrothermal dolomitization, as in other European late Variscan domains [15] [16].

It is assumed [14] that a late-Variscan hydrothermal event, which coincided with extensional tectonics, set brine circulation into motion. Dolomitization may have occurred within circulation cells, which were driven by high heat flow. Fluids originated in the underlying rocks and circulated upward to affect the overlying Cambrian carbonates. An alternative model is that the dolomitization was caused by hydrothermal brines that originated within basinal areas of the Variscan orogenic pile and circulated deep within the crust, then ascending in the Iglesiente-Sulcis External Zone. Whatever the origin,
these reducing very saline fluids, which carried radiogenic Sr, dolomitized a large volume of Early Paleozoic rocks. The many subhorizontal open cavities within the Geodic dolomite, only partly filled with cement, might indicate fluid overpressure at the time of dolomitization.

### 3.2.2. Post-Variscan Ores

Post-Variscan, low-temperature (< 200°C) base metal-barite veins occur throughout the Iglesiente-Sulcis region [2] and are especially common in the carbonate ridges (Gonnesa Group of Lower Cambrian age) along the Nebida coast and on the San Giovanni-San Giorgio and Barega hills [8]. They represent the filling of vein- and paleokarst structures (fig. 4), with a simple ore mineral association of Ag-rich galena and barite. They are called the «Ricchi Argento» deposits. Owing to the paucity of geological constraints, the age of these mineralizing events was set between Permian and Mesozoic. Deposit tonnages are quite low, but, due to their high Ag content, they were first exploited by the Phoenicians and Romans and then by the Pisans in the Middle Ages. In several Iglesiente and Sulcis areas, zebra-texture barite occur in paleokarstic sediments (Fig. 5).

We propose to relate the low temperature-high salinity Pb-Ag-Ba vein- and paleokarst deposits, controlled by a younger set of fractures, to the inset of a Mesozoic (eo-Alpine) rift phase. Unfortunately, every attempt of direct dating ore and gangue minerals related to this hydrothermal phase has failed so far.

Figure 5. Internal sediment with zebra texture barite-dolomite. Barega Mine, Mount Barega.
This kind of low temperature-high salinity ores are ubiquitous in Europe, even if their ages appear to range from Triassic to Jurassic, depending on their original position with regard to the European intra-plate geometry [2 and references therein], [17 and references therein], [18], [19], [20]. Because the first Alpidic rifting stages in Sardinia (evidenced by alkaline dykes and marine deposits) have an age set of 230 Ma (Middle Triassic), we think that this could be also the age for this hydrothermal event.

The post-Variscan, base metal-barite paleokarst fillings are probably the precursors of the later developed Zn-Pb oxides, the so-called «Calamine» also karst-related deposits. After Moore [4], there is a temporal, as well as geometrical continuity between these two types of mineralization phenomena.

4. NON-SULFIDE ORE DEPOSITS: THE «CALAMINE»

Most of the known and formerly exploited non-sulfide zinc deposits in the Iglesiente area belong to the carbonate-hosted «Calamine» category, in which smithsonite and hydrozincite together with haemimorphite are the principal zinc-bearing minerals [21] [22]. Cerussite and anglesite also occur, generally associated to nodules and lenses of residual galena (so called «semi-ossidati» ores). A complex association of iron oxihydroxides with a characteristic red staining (goethite, lepidocrocite, hematite) and residual clay minerals is generally hosting the «Calamine» minerals, in the past locally hindering their economic exploitation, as well as the beneficiation of the ore.

The mineralogy of the oxidized ores is very complex, comprising not only the most common Zn- and Pb-carbonates and silicates, but also very exotic species [23] [24], extensively sought by mineral collectors. Ore grade of the «Calamine» is recorded to have been very variable throughout the mining district, ranging from a few percent in Zn-Pb oxides combined, to more than 13% in the areas where the alteration profile allowed a complete replacement of the sulfide phases by secondary carbonates (Buggerru-Planu Sartu, Campo Pisano, Monteponi, Nebida).

All these mineralisations are considered to be the result of the in situ oxidation of primary sulfide ores, and subsequent remobilisation and redeposition as internal sediments into dissolution vugs and karst cavities, in relation to distinct oscillations of the Tertiary and/or Quaternary water table. Throughout the whole district are often recognised several styles of non-sulfide mineralisation, including both the partial replacement of the host carbonates and stratabound primary sulfides, as well as transported concentrations of ferruginous, «earthy» smithsonite and haemimorphite-rich clay, filling a maze of interconnecting karst cavities and open conduits in the upper levels of the mines.

There is a marked difference between the form and the general metal contents of the main non-sulfide ores, in regard if they were derived primarily from the stratigraphically lower massive sulfides (pyrite-sphalerite) in the Cambrian succession, as in the San Benedetto, Seddas Moddizzis and Campo Pisano mines, or from the MVT ores (sphalerite-galena) hosted in the «Ceroide» limestone, as in Monteponi, San Giovanni and Nebida.
The equilibria between different mechanisms as weathering, uplift and erosion in the formation and preservation of non-sulfide zinc mineralisation in south-west Sardinia, as well as the actual timing of these processes are so far unclear. Neither is established yet the systematic role played by a series of predisposing factors, as lithology/permeability contacts, recent faults-fractures, the proximity of older paleokarstic structures and/or the pervasive late-Variscan hydrothermal dolomitization replacing the limestones in great part of the mining district [14].

Some of these inter-relationships have been analysed in detail by Moore [4]. From the old mining records, and from the still available geological outcrops, it can be deduced that the «Calamine» deposits in the whole Iglesiente area extend downwards between 200 and 500 m below the post-Variscan morphological peneplane [4] [22]. Partial oxidation can affect a further 100 m in depth before completely unaltered sulfide ores are encountered. The base of the oxidation profile is only seldom coincident (Buggerru area) with the present natural water table, but is elevated above (Marganai-Oridda), or submerged beneath it (Iglesias Valley) in different blocks delimited by post-Variscan faults.

Along the south-western coast (Nebida-Masua), but especially in the mines occurring in the downfaulted carbonate blocks bordering the Iglesias Valley (e.g. Monteponi, San Giovanni and Campo Pisano), partial alteration (where newly formed «Calamine» coexist with residual sulfides) extends 100 to 150 m below the level of the present water
table. According to Zuffardi [22] the presence of a horizontally zoned alternance of zinc-enriched and zinc-impoverished bands in these ores should reflect several oscillations of the Tertiary and Quaternary water table levels, cyclically interfering with the naturally deepening oxidation profiles.

A stable carbon and oxygen isotope study on secondary zinc and lead carbonates from the Iglesiente area was conducted in order to constrain the origin of oxidising waters (meteoric versus marine) and the temperatures of oxidation. Preliminary results from this study [25] reveal a relatively narrow range of $\delta^{18}O_{\text{VSMOW}}$ values of smithsonites between 25.6 and 28.1‰. The delta values of hydrozincites are slightly lower, ranging from 24.1 to 26.9 ‰. Using the oxygen-isotope composition of present-day local meteoric waters ($\delta^{18}O_{\text{VSMOW}} = -6.5‰$ [10]) and the fractionation equation of Zheng [26], smithsonite-formation temperatures are calculated at 25 to 32°C. The $\delta^{13}C_{\text{VPDB}}$ values of both secondary Zn carbonates vary from −10.5 to −1.8‰, indicating the participation of variable amounts of reduced organic and marine carbonate carbon in the oxidising fluid. The absence of a correlation between oxygen and carbon isotope values, however, suggests that dissolution of marine limestones hosting the primary Pb-Zn ores by acid sulfide-oxidation waters of meteoric origin rather than participation of Mediterranean sea water is responsible for the $^{13}$C-enriched component in smithsonites and hydrozincites.

**ITINERARY STOPS**

1. The «Ricchi Argento» at Miniera San Giovanni (Gonnesa)

From Cagliari the Strada Statale 126 takes to the mining town of Iglesias, as well as to the whole Iglesiente district. The first destination of the itinerary is near the Gonnesa village, south west of Iglesias. At Gonnesa village, it should be started the ascent (about 1 hour on an old mine road) to the San Giovanni mountain, to reach the abandoned ore deposits of the paleokarst-hosted «Ricchi Argento».

Along the path it will be first encountered the horizon of the Gonnesa «Quarzite», a hydrothermally strongly silicified zone, marking the contact between Cambrian carbonates and Ordovician conglomerates and slates. Locally the «Quarzite» contains some barite mineralization and patches of iron sulfides.

Almost at the top of the San Giovanni mountain, some small adits at the levels +267 and +290 are the entrance to the old «Ricchi Argento» orebodies. Silver is contained in several sulphosalts (mostly freibergite) in the galena. Near the entrance of the galleries the Gonnesa limestone (locally called «Ceroide») is patchily dolomitized («Geodica» to «Yellow» dolomite) and shows evidence of polyphasic karstic dissolution. Underground, the ore deposits show concretionary textures and collapse breccias, cemented by several generation of calcite, quartz, barite and Ag-rich galena. Also repeated generations of internal karst sediments occur, possibly related to different dissolution and filling episodes (from silicified and dolomitized deposits, to speleothemes with aragonite and bone beds with «terra rossa»).
2. The «Dolomia Geodica» along the «Strada Camionabile» (Nebida)

From Gonnese the road to the coast goes first to the Funtanamare beach, then aims to Nebida along a winding scenic road. Along the road red continental lithologies (conglomerate and slates) of the Middle Ordovician «Puddinga» occur. In view of the Nebida village it can be observed the spectacular unconformity between the «Puddinga» and the Upper Cambrian Cabitza Slates (Iglesias Group).

Shortly before the village of Nebida a small private road turns right, to follow the N-S trending contacts between Gonnese carbonates, Cabitza slates and Ordovician conglomerates. In a small valley cut in the Gonnese carbonates, local evidence of hydrothermal dolomitization («Geodica Dolomite») on the «Ceroide» limestone is shown clearly. Due to its high Fe-content, the hydrothermal dolomite turns brown-reddish when subjected to weathering. The contacts with non-dolomitized host rock are very sharp, sometimes marked by a slight silicification. The dolomite bands seem to be mostly controlled by the vertical schistosity planes, seldom by fractures.

The crystals are typically saddle-shaped, lining concretionary voids and small horizontal cavities. A last generation of cavity filling cements, consisting of calcite and/or barite crystals occur locally.

In one of the mentioned valleys, the dolomite generation can be seen following a post-Variscan brecciation episode. Younger karst dissolution and internal sedimentation also occur in the same area (bone beds and terra rossa).

3. The Nebida mining area. Old exploitation at Canale San Giuseppe and the Santa Margherita «Calamines»

Shortly after the village of Nebida, aiming to Masua, a small path takes to the old mining area of the Canale San Giuseppe. This was a very rich area for «Calamine» ores, testified by several small open pits and winding adits set along the ravinous landscape of the valley. Near one of the adits, there are still some unweathered sulfide ores (sphalerite>galena), which follow the NS tectonic trend of the Gonnese carbonates. Patches of «Dolomia Geodica» are also present, as well as thin veins and laths of post-Variscan barite.

The next stop focuses on the Zn-oxides of the Nebida mine. The itinerary follows the Santa Margherita incline till reaching the entrance of the +92 level. In this level, situated well above the old water table, there are almost no sulfides left, and the exploitation (sub-level stoping) was running on the oxidation ores. In the lower levels, a continous transition to Zn-Pb sulfides takes place. The direction of the ore bodies is NS, following the general tectonic trend of the whole area.

There are still some areas of the level prepared for immediate exploitation but, due to sudden problems in the oxides market at the end of the seventies, the last «calamine» ores were left still in place. The carbonate host rock is heavily dolomitized («Dolomia Geodica»), but also karstified and altered as a mixture of de-carbonated material, Zn-
carbonates and hydrocarbonates, Zn-silicates, Pb-carbonates and Fe oxides/hydroxides. The «Dolomia Geodica» is also strongly oxidated and locally de-dolomitized.

Smithsonite exhibits in Nebida several habits, including earthy, stalactitic, crustiform and perfectly crystalline varieties (fig. 6), together with pseudomorphs after scalenohedric calcite. The stalactitic, cadmium-rich, yellow concretions were characteristically abundant in the higher levels of the Nebida mine, where they were often altered to hydrozincite. Haemimorphite (the real «Calamina») occurs together with smithsonite: it is generally concretionary in shape, and might locally contain copper.

REFERENCES


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