The abandoned mining area of Montevecchio-Ingurtosu

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Abstract. The Montevecchio-Ingurtosu area (Sardinia SW) was one of the most important mining districts for Pb and Zn in Sardinia. For its very important cultural and industrial heritage this area, located in a natural context of scenic beauty, is included in the Geo-mining Park of Sardinia, sponsored by the Unesco. The field trip included the visit of fascinating examples of industrial archeology (Piccalinna plants and the village of Montevecchio) and areas where the natural environment is degraded by mine wastes weathering (Casargiu stope and Rio Naracauli). The field trip ran in a natural context of spectacular beauty in front of the Mediterranean Sea (giant sand dunes and the woody habitat of Sardinian deer, a rare endemic species).

Riassunto. L’area di Montevecchio-Ingurtosu (Sardegna sud-occidentale) ha rappresentato uno dei maggiori distretti minerari della Sardegna per la coltivazione del Pb e dello Zn. Quest’area, per la presenza di un importantissimo patrimonio culturale ed industriale e per la sua localizzazione in un contesto naturale di spettacolare bellezza, è stata inclusa nel Parco Geominerario della Sardegna, sponsorizzato dall’UNESCO. Il fied trip ha incluso la visita di affascinanti esempi di archeologia industriale (l’impianto di Piccalinna ed il villaggio di Montevecchio) ed aree dove l’ambiente naturale risente del degrado dovuto ai processi di mobilizzazione dei contaminanti dagli sterili di coltivazione e trattamento (Galleria Casargiu e Rio Naracauli). Il percorso del field trip è stato sviluppato in un contesto naturale di eccezionale bellezza di fronte al Mare Mediterraneo (le gigantesche dune di sabbia ed il boscoso habitat del cervo sardo, una rara specie endemica).

INTRODUCTION

The mining history of Sardinia has a remote origin. The numerous deposits, characterised by the predominance of Pb-Zn-(Ag) and subordinately Ba-F mineralizations, have been exploited since at least two-three millennia (the first finds date to Roman times, [1]), affecting the history, economy and culture of this island in a very important way.

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The Sardinian deposits attracted different Mediterranean people: from the Phoenicians and Punics (from V to II Century B.C.) to the Roman Empire domination until the V Century A.D. Despite the alternate fortunes, the mining exploitation continued during the Middle Age, but only in the second half of the XIX Century started to be ruled by industrial criteria. Along with the industrial development of the big mines in the Sulcis-Iglesiente and Arburese district (Monteponi and Montevecchio), exploration began in other areas of Sardinia not only for Pb, Zn and Ag, but also for Cu, Fe and Sb, and then new mines were opened. Moreover, in the first half of the XX Century, the coal extraction in the Sulcis basin, one of the largest in the Mediterranean area, had a great economic relevance.

Since the late Sixties, the exploitation of the Pb and Zn Sardinian ores became uneconomic. This was due to the exhaustion of resources, and the extreme competition of other mining districts in the world. Nowadays, following the example of other European countries where the remains of the mining activities are now remarkable sources of culture and income, several activities for a revaluation and reconversion of the historical, industrial, naturalistic and human heritage are in progress in different areas of Sardinia. The Montevecchio-Ingurtosu area, together with other significant abandoned mining areas in Sardinia, is included in the Environmental and Mining Historical Geopark of Sardinia, sponsored by the UNESCO. One of the aims of the Geopark is to ensure the reclamation of the lands where the ceasing of mining activities caused an environmental degradation and the abandonment of large areas. Actually, scenarios of potential environmental risk, in particular due to the heavy metal pollution, are present in these areas.

Although the traditional exploitation of Pb and Zn has been at present completely abandoned, the mining activity is still a remarkable sector of the Sardinian economy. The economic interest on exploration and exploitation has moved to industrial minerals (feldspars, clays, silica sands), ornamental stones (granites, basalts, dacites) and recently discovered Au-epithermal deposits.

**GEOLOGICAL SETTING**

The Paleozoic basement of Sardinia is constituted of «autochtonous» and «allochthonous» geological units.

In the Arburese district, the autochthonous unit is constituted of rocks from Charadoc-Ashgill to Lower Silurian, and crops out only in the southern area. The allochthonous is the so called «Arburese Unit» [2]. The Arburese Unit is made up of sedimentary and volcanic low grade metamorphic rocks dated to Cambrian-Ordovician. It is a nappe thrust during the Hercynian orogeny from NNE to SSW over the autochthonous successions (fig. 1, [3]). At the end of the Hercynian orogeny, the Arburese igneous complex was emplaced. It is characterised by a roughly concentric structure, with dominant granodiorite in the border zone, and leucogranite in the core [4]. The emplacement
of the plutonic complex caused the formation of a metamorphic aureole, extended for almost 1 km in the metasediments. The igneous complex is characterised by radial fractures filled by acid and basic magmatic dykes, and by quartz and metalliferous (Pb, Zn, Ag) hydrothermal veins emplaced during the late stages of the Hercynian orogeny. These veins constitute the Montevecchio-Ingurtosu ore deposit.
Cenozoic outcrops are formed of sedimentary and volcanic complexes. The first one is made up of conglomeratic, marly and carbonatic facies of a fluvial-palustrine environment dated to the Upper Oligocene-Lower Miocene. The volcanic complex, known as «the Monte Arcuentu volcanic complex», is constituted of basaltic flows overlapped by breccias and pillow lavas. The volcanic activity started with tuffs and tuffites, and ended with autoclastic lavas, breccias and ashes. The whole complex is injected by several dykes, in general with a basaltic composition. The Quaternary covers are made up of eolian dunes along the coast (the Piscinas dunal complex) and of fluvial deposits and talus in the internal area.

ORE DEPOSIT

The vein system, prevailingly oriented NE-SW, extends for 10 km, and was exploited down to 800 metres in depth; the vein thickness ranges from 1.50 to 7-8 metres, and the total belt width is never less than 6 metres.

The main metalliferous minerals were galena and sphalerite, together with argentite, chalcopyrite, pyrite, anglesite, cerussite, pyromorphite, arsenopyrite, pyrrhotite, tetrahedrite, greenockite, monheimite, covellite and others at a minor extent. The gangue was essentially quartz, with barite, siderite, ankerite, calcite and fluorite. Mineralization was remarkably continuous, with variable proportions of the two main sulphides. The superficial parts of the mineralized veins were characterised by an alteration zone of iron, lead and copper oxides (with a width between 10 and 80 meters). Galena was essentially associated with a quartz-barite gangue, while blenda with a carbonatic gangue (ankerite and siderite).

The main veins of the Montevecchio deposit are, from the East to the West: Sant’Antonio, Piccalinna, Sanna, Casargiu and Telle.

The S. Antonio vein was the most important in the Montevecchio deposit; it was developed in length for 1500 meters, in depth for around 600 meters, and its width reached 15 meters on average. As all the others, this vein showed a vertical zonation with the prevalence of galena (Ag) in the upper parts, Ag-rich galena and Cd-rich sphalerite in the intermediary parts, and pyrite with chalcopyrite and sterile quartz in the deepest zones.

The Piccalinna vein was characterised by the same extension and vertical zonation than the S. Antonio vein, but with a smaller width.

The Sanna and Casargiu veins, limited in width and depth, had a primary mineralization at sphalerite in ankeritic gangue. Finally, the Telle vein had a mineralization at galena without gangue, or with a calcitic gangue.

According to Salvadori & Zuffardi, the Montevecchio ore production over the period 1848-1973 added up to 1,600,000 tons of Pb and 1,100,000 tons of Zn, with Ag (600-700 grams for Pb ton) and others byproducts such as Bi, Sb, Cu, Cd and Ge. The exploitation reached 190 metres under the sea level, with more than 100 km of haulageway.
HISTORY

The first mining activities in the Montevecchio area date to Roman times, when Sardinian ores were an important supply of lead and silver. Some documents attest to an ongoing exploitation during the Middle Age and subsequent centuries, but the exploitation was occasional and the production rather limited. The first intensive and industrial exploitation of the Montevecchio mine dates to 1848, when a society, owned by the Sardinian lawyer Giovanni Antonio Sanna, obtained a mining concession extended for more than 1200 hectares. Under the Sanna’s management, the mine exploitation was systematically organized following industrial criteria. The development was facilitated by the building of new roads, modern treatment plants, and a private railroad for the transport of the material to the San Gavino smelter (about 15 km to the east). From 1848 to 1913, the number of workers employed in the Montevecchio mine increased from 150 to 1476, and the galena exploited from 200 to 14523 tons per year.

A temporary stop was given by first World War, that brought the mine to a big crisis. At the end of the conflict, different societies owned the Montevecchio property, developing the modernisation strategy, expanding the concessions, opening new pits and improving the treatment plants, constructing a 5 km long cableway and upgrading the San Gavino smelter. Because of the Autarchy policy imposed by Mussolini the exploitation activity was particularly flourishing, and in 1939-40 the exploited material added up to 67667 tons of PbS and 89302 tons of ZnS. For the first time hydraulic drills were utilised. During the second World War and until late Forties, the mining company organised also the production of a large variety of articles (shoe polish, beauty products, pieces of cutlery, ploughs), and, despite the reduced number of workers, the industry did not close [9]. After the war the exploitation started again, the modernisation work continued, and during the decade 1950-60, the mine reached the maximum development. Because of the big improvement of work conditions, the total production in this decade reached one of the highest values for PbS (205509 tons), and the maximum value for ZnS (384490 tons). In spite of these innovations, a big crisis started at the beginning of the Sixties. Because of the strong competition by other mining districts in the world, the exploitation of Sardinian mines became uneconomic. At the Montevecchio mine, the management started to reorganise the personnel and to close concession areas. In 1991, the mine definitely shut down, but there was the immediate perception that such an important heritage should not be lost [10]. Soon the first projects for reconversion and revaluation of the area were presented: they were the seed for the currently planned Geo-mining park.

TREATMENT PLANTS

The treatment plants of Montevecchio (both West and East concessions) were schematically composed of three parts: a primary crushing, a pre-concentration plant and a flotation section (fig. 2, [11]; [12]).
The tout-venant from Sartori shaft was first carried to the primary crushing plant and its size was reduced to < 16 mm.

The pre-concentration section, originally a jig washer, was later substituted by a sink-float plant. The process implied the treatment of the mineral in a finely milled galena-water suspension and allowed a good efficiency of the whole process.

The flotation plant was made up of three sections. The material was further milled to 80 mesh in a Krupp ball mill, and organised in a closed circuit with a classifier. Sphalerite deactivation was effected by the action of NaCN during the milling process. In the classifier, galena was collected using potassium xanthogenate and pine oil as frother medium.

The cyanide pulp from the classifier mill was then channelled into the lead circuit, where the galena float trapped in the foam was removed. Due to the pyrite abundance, it was necessary to submit the galena float to a further flotation treatment. Floats from the lead circuit were firstly added with calcium oxide, and pyrite was deactivated by NaCN. The cyanide pulp arrived in the Callow Mac Intosh cells, and the galena foam was removed.

After the lead circuit, the pulp arrived in a conditioning cell, where, by using CuSO₄, the cyanide effect was neutralised, and the sphalerite activation was obtained. By the action of potassium xanthogenate and a material called Aerofloat, a sphalerite foam was obtained and removed.

Figure 2. Schematic section of the Piccalinna treatment plant [11, modified]. Pictures from [12].
Both end products were channelled toward Dorrs thickeners, and finally filtered. The final products consisted of a Pb-rich and a Zn-rich concentrate (50-55 % Pb and 60-65 % Zn, respectively). The waste material from the sink-float plant contained 0.1 % Pb and 0.6 % Zn, whereas tailings from the flotation plant contained about 0.5 % Pb and 0.8 % Zn.

The wastes from sink-float were reutilised as flux for the lead smelter of San Gavino, for refilling excavation voids, building materials, and covering the impoundment formed by the accumulation of flotation tailings to prevent wind erosion and hence the transport of polluted materials.

Another very important feature of the plant was the possibility to use acid mine waters mixed with re-used waters from the plant. In particular, because those naturally acidified waters were rich in ZnSO₄, which acts as a deactivator of sphalerite and pyrite, the alkaline neutralisation in the galena flotation cycle was not necessary. In the sphalerite cycle thiophosphate was utilized as flotation agent for pyrite depression in a non alkaline pulps. Moreover, there was an important reuse of water from treatment plants. After the treatments, waters were channelled in a dehydration plant composed of three rake classifiers, a Dorr thickener and a disk filter. The plant was completed by three static basins (2400 square meters), and by a semicircular collection basin, from where vacuum pumps collected the treated water and recycled it to treatment plants [11, 12].

ENVIRONMENTAL CHARACTERISATION

Since the ceasing of all mining activities in 1991, the mining works and waste piles have posed serious threats to the environment. Poor management has led to intense heavy metal contamination over a large area (fig. 3).

The main sources of contaminants are the flotation tailings impoundments, the seepages along the base of the spoil, the water flowing out of the mine adits, and the tailings that are transported and re-deposited along the river banks [13].

Mineralogy and chemistry of tailings from the three main impoundments, both in the West (Sanna and Naracauli) and East (Piccalinna) areas of Montevecchio, have been investigated by the Mineralogical-Geochemical Group of the Department of Earth Sciences (University of Cagliari). In the East area, soils downstream of the Piccalinna impoundment have been studied also by the PROGEMISA for the EU founded project ROLCOSMOS (No. BRPR-CT96-0297).

Fine-grained (< 63 mm) flotation tailings are the predominant material in all impoundments. The mineralogical and chemical composition of tailings and soils, that are often made up of re-deposited waste materials, are fairly homogeneous. The main primary minerals are quartz, siderite, ankerite, muscovite and/or illite, sphalerite and galena; minor to trace phases include barite, dolomite, pyrite, chalcopyrite, cerussite, arsenopyrite and pyrrhotite.

Weathering, with consequent development of secondary minerals, is more pronounced at Naracauli, where anglesite, cerussite, gypsum and Mg-Fe-Zn-sulphates such as
epsomite were found [14]. Table 1 (from [13]; [15]; [16]) shows the contents of main heavy metals in some samples of tailings and soils.

Figure 3. Schematic distribution of the main impoundments and of the tailings dispersion.
Sequential extraction procedures (modified after [17]; [18]; [19]) applied on tailings showed that lead, zinc and cadmium were very easily extracted in the soluble + exchangeable fraction, and may be therefore considered potentially bioavailable elements. Several studies on the heavy metal effect on the biosphere evidenced that metals are transferred to some vegetal species that grow on the dumps or in nearby areas [20]. It was also recognised a degradation effect on detritivores communities of the main rivers of the area [21]. High metal contents are recorded even in the beach sediments of Piscinas and in the _Posidonia oceanica_ population within a radius of 1 km from the contaminated river mouths [22].

**Water chemistry**

The Montevecchio village delimits roughly two catchments: in the West section, Rio Irvi, Rio Piscinas and Rio Naracauli flow to WSW, debouching in the Piscinas beach; in the East section, the system Rio Montevecchio-Rio Sitzerri flows toward East, then North and finally West, reaching the Marceddì lagoon.

Upstream of mining works, stream waters are unpolluted with a dominant sodium chloride character. All rivers downstream of the mining works interact with tailings and/or the mineralization and show a sulphate character, with high contents of potentially toxic metals (e.g. Zn up to 133, Cd 0.8, Ni 0.3 ppm). The pH and dissolved metal concentrations for Montevecchio waters are illustrated in figure 4 (data from [13]; [23]).

West of Montevecchio (Rio Irvi-Piscinas and Rio Naracauli), pollution is essentially the result of interaction between waters and tailings piles. Nevertheless from 1997 a large amount of water (25 l/s) rich in heavy metals started to flow out of the Casargiu shaft, as soon as the natural recharge flooded a large extent of the underground workings [24]. The pH values are close to the neutrality (6-8), due to the buffering effect of carbonate gangue minerals. Both rivers are polluted along their entire length, but Rio Naracauli is less polluted than Rio Piscinas, probably due to a minor interaction between Rio Naracauli water and tailings and/or to an earlier ceasing of the mining activity in this sector, with a consequent washing away of heavy metals. In spite of this attenuation, the heavy metal content is high: CABOI et al. [25] estimated that the Zn discharge at the Rio Naracauli mouth was 34 kg/day, together with several kg of other heavy metals.

**Table 1. Main heavy metals content of tailings and soils at West and East Montevecchio mine site (minimum, maximum, mean (X) and standard deviation (s)).**

<table>
<thead>
<tr>
<th>Element</th>
<th>West</th>
<th></th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Naracauli(^1)</td>
<td>Sanna(^1)</td>
<td>Piscarinna(^2)</td>
</tr>
<tr>
<td>N(^0)</td>
<td>20</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Pb(%)</td>
<td>0.03</td>
<td>7.1</td>
<td>1.5±2.1</td>
</tr>
<tr>
<td>Zn(%)</td>
<td>0.2</td>
<td>2.9</td>
<td>1.3±0.8</td>
</tr>
<tr>
<td>Cu(ppm)</td>
<td>38</td>
<td>230</td>
<td>108±55</td>
</tr>
<tr>
<td>Cd(ppm)</td>
<td>20</td>
<td>190</td>
<td>84±47</td>
</tr>
</tbody>
</table>

\(^1\)[13]; \(^2\)[15]; \(^3\)[16].
metals. Local metal content attenuation is due to the inflow of unpolluted tributaries, and/or to precipitation/sorption in/on secondary minerals. Biological processes are also quite effective in the precipitation of some secondary minerals: hydrozincite of biological origin with high concentrations of Pb, Cd, Ni and Cu was observed in the stream sediments of the Naracauli river [26].

East of Montevecchio, pollution is mainly due to the acid mine drainage from adits (especially Piccalinna adit, pH~4) and seepages (pH 2.5÷5) that come out at the bottom of the Piccalinna impoundment. Concentration of pollutants is decreased by influx of unpolluted tributaries, but increases again where streams interact with redeposited tailing material, that was either transported during high flow periods, or discharged during plant operations. Actually pollution effects are felt for several km downstream of the Piccalinna spoil bank. Metal loads measured in superficial waters of the agricultural plain of San Nicolò Arcidano are about 70 ppm Zn and 400 ppb Cd [23]. The heavy metal content is also considered one of the main causes of desertification in this area [27].

DESCRIPTION OF STOPS

In figure 5 is shown the localization of the stops.
Stop 1: Piccalinna Dump

A quite remarkable area is the dump in the Eastern section of Montevecchio, called Piccalinna, where the amount of tailings material is estimated in the order of 5 million of cubic metres. This area is an excellent natural laboratory for studying the weathering processes affecting the tailings and their effects on the environment. In addition, it offers fascinating examples of industrial archaeology, such as the remnants of treatment plants and hauling shafts.

The Piccalinna stope, the oldest in the mine, is especially remarkable. The buildings date to 1876. The main ones are the San Giovanni shaft and the nearby «Cameroni a bocca di pozzo» (= Shaft mouth Rooms – workers housing).

The Sartori shaft was built in 1937, and started to operate in 1941. It was built in a central point between Sant’ Antonio and Piccalinna mining stopes. The tower is 32 metres high. The shaft is 510 metres deep, and is subdivided in 19 levels. All material extracted from Sant’Antonio and Piccalinna stopes was conveyed in this shaft as the pit was equipped with special, fully automated skip cabins, that allowed haulage of as much as 100 tons/hour. Four silos were connected to the shaft.

The washing plant «Principe Tommaso» was built in 1877, and for that time it was technologically advanced. Here women and children handpicked the ore, to separate gangue material from the ore, that was then carried to the washing and grinding plants.

Finally, there is the Sant’ Antonio shaft, called «Castelletto» (little castle), one of the finest building in Montevecchio. Digging works here started in 1872. The shaft is 400

![Figure 5. Montevecchio-Ingurtosu field trip stops.](image-url)
metres deep, and subdivided in 16 levels. Before the introduction of the mechanised transport system, the ore was brought up to the surface by mule-led ore cars.

In front of the Piccalinna dump, it is possible to observe the abandoned mining works at the S. Antonio orebody, one of the richest in the area. It extends for 1500 metres in length and 600 metres in depth, and its width reaches 15 metres. The vein is essentially composed of quartz-galena and sphalerite-ankerite, with some chalcopyrite. It is vertically zoned: argentiferous galena is mainly found in the uppermost parts, mixed argentiferous galena and Cd-bearing sphalerite in the middle, quartz and sphalerite with pyrite and chalcopyrite in the deepest zones.

Stop 2: Mine headquarters and Mineralogical Museum

The small village of Montevecchio has been organised as a little town, with its offices, school, hospital, and the heart of the dismantled mine: the headquarters, a beautiful example of industrial building.

The palace, in Liberty style, was built in 1877. The mine offices were located in the ground floor, while the apartment of the mine director was in the upper floors. In the South side of the palace the church, dedicated to S. Barbara, the patron saint of mine workers, was built.

Few years ago, the palace was largely restored and reorganised. Particularly valuable are the meeting room and the hall, both decorated with frescos. The ground floor hosts the Mine Museum, displaying mine plans, models of treatment plants, and an exhibition of work equipment. This museum gives an idea of the mine extension and importance, together with an image of the mine workers’ life style.

The mineralogical museum stands close to the direction building. It was first established as a branch of the Geological office of the mine. This museum comprises mainly local specimen, but includes specimens from other deposits of Sardinia, peninsular Italy, and from abroad. It exposes remarkable specimen of minerals and styles of mineralisation, from different sectors of the Montevecchio mine. The current arrangement is somewhat random. A project for a new organisation of the Museum was recently presented. It is based on a limited number of selected samples, integrated with posters illustrating the local geology, mineralogy and mining history [28].

Stop 3: Casargiu yard

The West Montevecchio property ended with the Casargiu stope, beyond which began the Ingurtosu mine. The extraction shaft was called Fais, and it was 85 metres deep. Together with the ceasing of the exploitation in 1990, dewatering stopped. This caused the uprising of water table, that invaded the mine voids and the fracture system in the mineralised vein complex. Groundwater rose slowly, and reached the surface in winter 1997, spilling almost 20 l/s in the Irvi river. An ochreous mat rich in Fe oxy-hydroxides is deposited from these waters during all the year, and is going to invade the Piscinas beach. These waters have a sulphate composition, and are characterised by high TDS (~
7 g/l), and significant contents of several heavy metals (e.g. Zn up to 1000 ppm, Fe 280 ppm, Cd 850 ppb, and Pb 680 ppb). It is important to stress the presence of other elements such as Co (5 ppm), Ni (8 ppm) and As (200 ppb) [29].

Stop 4: The Naracauli river

The most relevant phenomenon to be observed along the Naracauli river is the occurrence of a white mat in the stream sediments. In the upper part of the stream, this precipitate, observed especially in spring, is mainly composed of hydrozincite (Zn₅(CO₃)₂(OH)₆), with a total organic matter residue of 10 % dry weight, and high concentrations of Pb, Cd, Ni, Cu, and other elements. Precipitation of hydrozincite is effected through the action of a photosynthetic community, composed of a photosynthetic filamentous bacterium, classified as Scytonema sp. strain ING-1, associated with a microalgae Chlorella sp. strain SA1. Dormant photosynthetic organisms have been retrieved from 1-year old dry hydrozincite. Hence, this community is responsible for the natural polishing of heavy metals in the water stream by coprecipitation of hydrozincite, and, although it is a temporary attenuation process, it is of potential great interest for application in bioremediation projects [26].

Downstream the Brassey impoundment, the flocculation of an hydrated Zn-rich colloid occurs. This process, taking up dissolved metals from the water, is observed when pH increases. Chemical data of flocculated phase show up to 520 g/kg Zn, 106 g/kg Si, 6 g/kg Pb, 1 g/kg Cd and respectively 215 and 80 mg/kg Cu and Ni [30].

Stop 5 - Giant Sand Dunes

The Piscinas dunal complex is made up of Quaternary eolian dunes. This complex covers an area of almost 20 square km, reaching occasionally the height of 200 metres. The beach is 50 to 100 metres wide, and over 5 km long. The shore stream, the main modelling agent, is directed NNE-SSW, and the dominant wind is the mistral.

Sands are stabilised by an abundant amanthophilous vegetation, that can resist to strong insolation and drought.

This is an important portion of the habitat of the Sardinian deer, an endangered species now particularly protected.

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