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Geology of the Arera-Vedra Valley mining area (Gorno district, Orobic Alps, Italy)

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ABSTRACT

The 1:10,000 geological map of the Arera-Vedra Valley area covers an area of about 12 km^2 in the Orobic Alps (Lombardy, N Italy), and is accompanied by five underground maps corresponding to different levels of historic mining works. The area is characterized by a Triassic stratigraphic succession that hosts one of the most important Zn-Pb mining districts in Italy (Gorno district). Original surface and underground geological mappings have been integrated with the analysis of drillhole stratigraphies and historic underground geological maps. Detailed geological cross sections correlating surface map data with those of the underground mining tunnels have been done. This work proposes a new map representation that is consistent with new interpretation of the geometry of the orebodies at depth, to serve as a tool for mining purposes (targets definition, mine design) and for a better understanding of the genesis of the Gorno 'Alpine-type' deposits.

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Gorno mining district; Alpine-type deposit; Southern Alps; Lombardian Basin; orebodies mapping

1. Introduction

We present here a 1:10,000 geological map (Map A) accompanied by five underground maps (Maps B, C, D, E, F) of the Mt. Arera – Vedra Valley area in the Orobic Alps (Lombardy, Northern Italy), which represents a sector of the Gorno mining district hosting tens of Mt of ore over an area of about 100 km^2. The Gorno mining district belongs to the Alpine type Pb-Zn-deposits class, considered a subclass of Mississippi Valley Type (MVT) deposits (Leach et al., 2003). Alpine-type deposits are stratabound Pb-Zn sulfide bodies hosted in the Middle-Upper Triassic carbonate successions occurring in the Eastern and Southern Alps (Salafossa, Raibl, Bleiberg, Mežica; Leach et al., 2003; Schroll et al., 2006). The Gorno mining district has been the site of mining activities since the Roman period. Modern-day exploitation started in 1888 and ceased in 1985 due to government policies that led Italy to dismantle most of its mineral projects. In 2015, Energia Minerals S.r.l., which was later taken over by Vedra Metals S.r.l., obtained the exploration licenses in the district and restarted exploration activities in the Vedra Valley area, considered the most promising sector of the district.

The study area was previously mapped in the 33-Bergamo sheet of the Geological Map of Italy at 1:100,000 scale (Servizio Geologico d'Italia, 1954, see also relative explanatory notes by Desio & Venzo, 1954) and in the 77-Clusone sheet of the Geological Map of Italy at the 1:50,000 scale (Servizio Geologico d'Italia, 2012, see also relative explanatory notes by Jadoul et al., 2012). A detailed structural geological study focused on the several major N-S striking transcurrent faults in the area and their role as a transfer zone during the Alpine orogeny (Grem-Vedra Transverse Zone) was carried out by Zanchi et al. (2012). In addition, studies linking the geological structural setting with the distribution of the mineralization have been performed in the past by different authors (Omenetto & Vailati, 1977; Rodeghiero & Vailati, 1978; Vailati, 1966).

More recently the same authors of the present paper provided new stratigraphic, petrographic, paleothermometry, and radiometric (U/Pb) age data and proposed a revised metallogenic model for the stratabound Zn-Pb-Ag ± fluorite ± barite mineralization hosted in the Carnian stratigraphic succession (Giorno et al., 2022; Summino et al., 2023). According to this model, ore formation was related to a Late Triassic hydrothermal system developed shortly after the deposition of the host rocks in a shallow burial setting. It resulted in the formation of multiple ore bodies with an overall stratabound geometry, i.e. they are confined within the Breno and Calcare Metallifero Bergamasco formations, and the basal part of the Gorno formation. Subsequent

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Alpine tectonics intensely affected the whole succession, with resulting significant displacements and deformation of the orebodies themselves. An accurate reconstruction of 3D geometries is therefore essential, first of all to support current exploration activities. In order to pursue such a goal, a research agreement between Vedra Metals S.r.l. and the Earth Sciences Department of the University of Turin has been recently stipulated, and is presently in progress, and the geological maps provided in this work represent its first product. The maps are the result of surface and subsurface original geological mappings, integrated with analysis of drillhole data and historical archives. Along with the accompanying cross-sections, these maps allowed to achieve a 3D model of the Vedra Valley area, providing a fundamental tool to drive future exploration campaigns.

2. Methods

The main map was originally surveyed at the 1:5,000 scale although it has been here synthetically represented at 1:10,000 scale. It covers an area of approximately 12 km^2. Along with the main map, five underground geological maps at a more detailed scale (1:5,000) have been produced. These maps represent the geology of distinct horizontal planes, since they are derived from the interpretation of the geological mapping along historic mining tunnels (recently recovered and secured by Vedra Metals), which were arranged on underground horizontal levels connected by declines.

These maps represent the product of the combination of original geological mapping data (integrated with some data obtained from the consultation of historical underground geological maps for tunnels no longer accessible), and historic (from S.A.M.I.M., Società Azionaria Minero Metallurgica) and recent drillhole data. The latter are especially useful to better constrain both tectonic and stratigraphic surfaces shown in the geological sections attached to the main map (Map A – Geological sections A-A′-A″; C-C′-C″; Map B; Map C). All the collected data have been integrated into a specific software for 3D mining visualization (Micromine©), allowing us to better visualize and constrain the geometry and position of both stratigraphic and tectonic boundaries. The data collected during geological mapping on the field have been stored in a geographic information system (QuantumGIS, version 3.22.5-Białowieża) (Coordinate System WGS 1984 UTM, Zone 32) and represented on a vector topographic map derived from the CTRN (Carta Tecnica Regionale Numerica, Vector Regional Technical Map) of Lombardy Region (1:5,000 scale).

3. Regional setting

The investigated area is located in the central part of the Southern Alps (Figure 1(A)), which consists of a South-verging, thick-skinned retrobelt, developed South of the E-W striking Periadriatic Line and deformed during the Alpine orogeny basically under non-metamorphic conditions (Carminati et al., 1997; Curzi et al., 2023; Zanchetta et al., 2015; Zanchi et al., 2012). The study area lies between Lake Como to the West and the Giudicarie fault system to the East. Here, thrust sheets involve both the Variscan basement and the overlying sedimentary successions spanning from the Permian up to the Miocene of the Gonfolite Group, defining structural E-W trending sub-domains (Figure 1(B)). The northernmost thrust sheet is represented by the Orobic thrust, which deeply involves the Variscan basement exposed in the northern sector, thrusting it onto the Permian-Mesozoic sedimentary cover units (Figure 1(C)). South of the Orobic thrust, the Central Southern Alps are organized in three large-scale anticlines (Orobic anticlines; Schönborn, 1992) involving the Permian volcanic, volcaniclastic and siliciclastic rocks, and Lower Triassic formations (Servino and Carniola di Bovegno). Moving to the South, the Lower Triassic to Carnian succession is organized in thrust sheets which are backthrusted along the Valtorta-Valcanale fault onto the southern limb of the Orobic anticlines (Laubscher, 1985; Schönborn, 1992). The southern limit of the above described tectonic belt is represented by the Clusone fault, which bounds it from another E-W trending belt mainly consisting of Upper Triassic carbonate units (Figure 2) (Zanchi et al., 1990). The latter is overthrusted southward, along the Albino thrust, onto the external part of the belt, which mainly consists of Jurassic to Cretaceous sedimentary successions covered by Oligo-Miocene foredeep deposits of the Gonfolite Group. The external belt continues to the South, as it is buried below the Pliocene to Quaternary sediments of the Po Plain (Bersezio et al., 2001).

The area experienced a polyphase tectonic evolution characterized by non-metamorphic conditions. Two main compressional events have been recognized, predating the Adamello batholith intrusion at 43–31 Ma (Schönborn, 1992). The first event is Late Cretaceous (80–68 Ma, Zanchetta et al., 2011) and results in the emplacement of the Orobic thrust sheet (Schönborn, 1992). The second compressional phase, occurred from latest Palaeocene to Middle Eocene (D'Adda et al., 2011; Zanchetta et al., 2011) and led to the southward propagation of the Orobic Anticlines (Zanchi et al., 2012). The North-verging back-thrusting of the Upper Triassic units along the Clusone fault and the tilting of the previously stacked Middle-Triassic succession is attributed to this phase (Zanchi et al., 2012).

4. Lithostratigraphic units

The following section provides a description of the lithostratigraphic units, which have been labeled

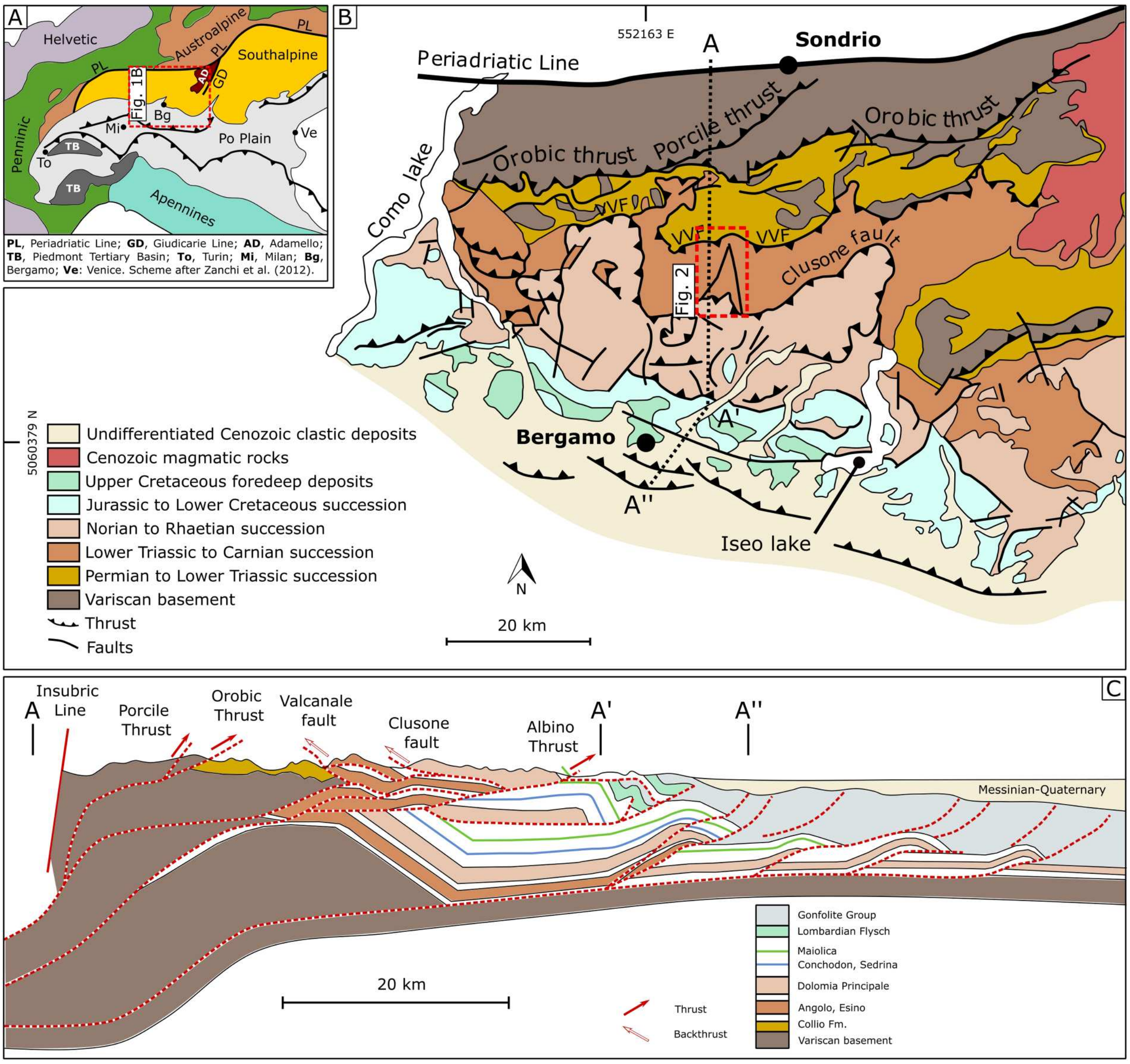

Figure 1. Geological setting of the Central Southern Alps. Modified after Schmid et al. (2004). A: General structure of Central Alps with location of Figure 1(B). B: Tectonic map of Central Southern Alps with the location of Figure 2. VVF: Valtorta-Valcanale Fault. Redrawn and modified after Zanchetta et al. (2015). C: Schematic cross section through the Central Southern Alps. Redrawn and modified after Schönborn (1992).

following the official Italian 1:50,000 geological map covering the study area (Clusone sheet, Servizio Geologico d'Italia, 2012, and relative explanatory notes by Jadoul et al., 2012).

The oldest stratigraphic units occurring in the study area are represented by Anisian to Ladinian peritidal and platform carbonates (Angolo limestone, Camorelli Limestone), followed by basinal marly limestones (Prezzo limestone). Platform carbonate sedimentation took place in the late Anisian and throughout the Ladinian with the deposition of a carbonate platform succession (Esino limestone). Late Ladinian subaerial exposures led to the development of subaerial karsts and paleosols during the deposition of shallow-water carbonate (Calcare Rosso; Assereto & Kendall, 1977; Berra & Carminati, 2010; Jadoul et al., 2012). Platform carbonate sedimentation resumed in the early Carnian, with deposition of peritidal limestones (Breno Formation) overlying the Calcare Rosso, in turn followed by peritidal-lagoonal limestones (Calcare Metallifero Bergamasco Fm.) and lagoonal marls and limestones (Gorno formation) interfingering with volcaniclastic deltaic sandstones and siltstones (Val Sabbia sandstone). The occurrence of this volcaniclastic unit and the presence of several tuff layers in the succession documents Triassic volcanic activity (De Min et al., 2020; Jadoul & Rossi, 1982). The top of the Mesozoic stratigraphic succession in the study area is represented by carbonate sabkha deposits (San Giovanni Bianco fm.).

4.1. Angolo limestone (ANG, lower – middle Anisian)

Dark gray fine-grained bioturbated limestones in dm-thick planar beds with thin silty-marly interlayers. Fossils are common (bivalves, dasycladacean algae,

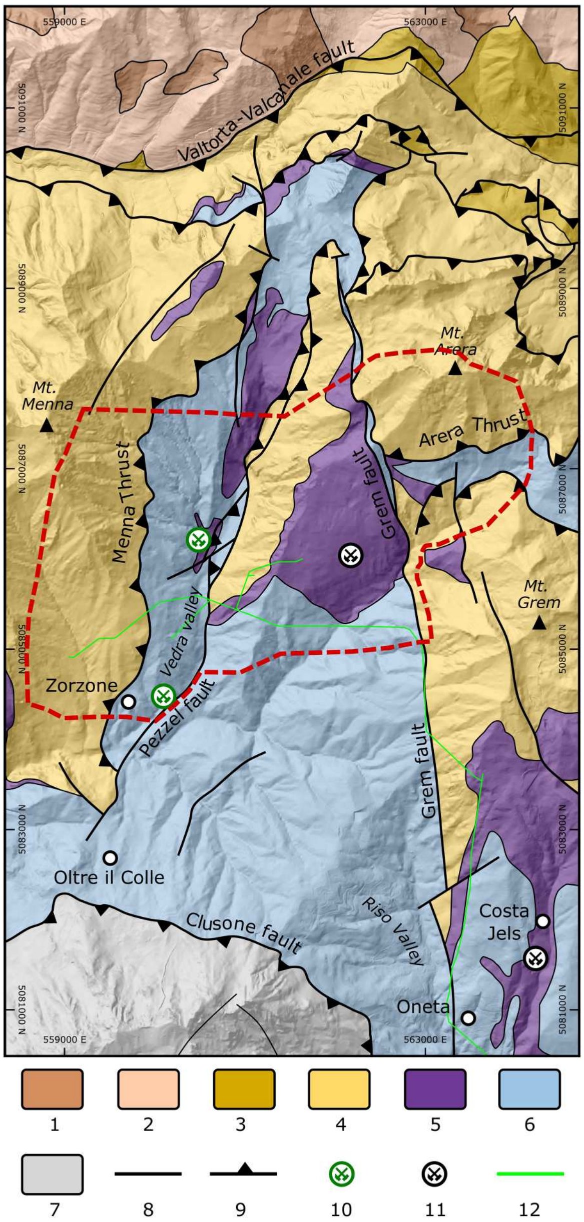

Figure 2. Geological map of the northern-western part of the Gorno district, showing the major tectonic lineaments. The area represented in Map A is indicated by the red dashed line. 1: Collio domain (Monte Cabianca Fm.; Pizzo del Diavolo Fm.; Ponteranica Conglomerates); 2: Verrucano Lombardo Fm.; 3: Carniola di Bovegno, Servino fm.; 4: Anisian to Ladinian carbonates; 5: Calcare Rosso; Breno Fm.; Calcare Metallifero Bergamasco; 6: Gorno fm.; Val Sabbia sandstone; San Giovanni Bianco fm.; 7: Upper Carnian-Norian carbonates; 8: Faults; 9: Thrusts; 10: Vedra Valley orebodies; 11: Arera and Costa Jels deposits; 12: Riso Parina tunnel trace. Redrawn and modified after Jadoul et al. (2012).

crinoids, ammonoids). These limestones represent the product of a sub-tidal depositional environment. Maximum thickness: about 100 m.

4.2. Camorelli Limestone (CMR, middle – upper Anisian)

Bioclastic rudstone and grainstone, locally oolitic or crinoid-rich, organized in dm-thick beds passing upward to peritidal limestones with bivalves and dasycladacean algae. These limestones represent the deposition in a tidal flat-inner carbonate platform. Maximum thickness: about 40 m.

4.3. Prezzo limestone (PRZ, upper Anisian)

Black marly limestones in dm-thick beds alternating to dark marls. Fossil content is represented by bivalves and ammonoids. The depositional environment is interpreted as an open marine basin with a mixed sedimentation. Maximum thickness: about 30 m.

4.4. Esino limestone (ESI, upper Anisian – lower Ladinian?)

Massive light-gray limestones in dm- to m-thick beds passing upward to peritidal limestones with prevailing subtidal intervals with dasycladacean algae, gastropods and bivalves. Oncolitic and stromatolitic layers are common in supratidal beds; a whitish-colored dolomitization is locally present in these intervals. The top of the formation is marked by an erosional surface, overlain by paleosols and breccias of the Calcare Rosso. The depositional environment is an inner carbonate platform passing up to tidal flats. Maximum thickness: about 700 m.

4.5. Calcare Rosso (KLR, upper Ladinian? – lower Carnian?)

Gray to pink limestones associated with polyphase breccias, both concordant and discordant with respect to the bedding (Figure 3(A)), with carbonate cements and calcareous and reddish to greenish clayey matrix. Meter-thick beds with tepee structures locally occur. In the mapped area this formation has been observed mainly underground. The Calcare Rosso formation was deposited in a tidal flat environment affected by prolonged and repeated subaerial exposure. Maximum thickness: about 30 m.

4.6. Breno Formation (BRE, lower Carnian)

Light gray, well-bedded limestones with dm- to m-thick beds organized in peritidal cycles (Figure 3(B)). Subtidal intervals consist of wackestones and floatstones with gastropods, bivalves, dasycladacean algae, and oncolites; the base of the beds is often marked by flat-pebble breccias, with early-dolomitized clasts in a calcareous micritic sediment. Inter- and supratidal intervals are characterized by tepee structures, stromatolitic laminae, fenestrae, and pisolites. Supratidal intervals are usually affected by a fine-grained whithish dolomitization. In this formation several cm- to dm-thick greenish tuff layers are intercalated. Some of these are easily recognizable underground and have historically been used as

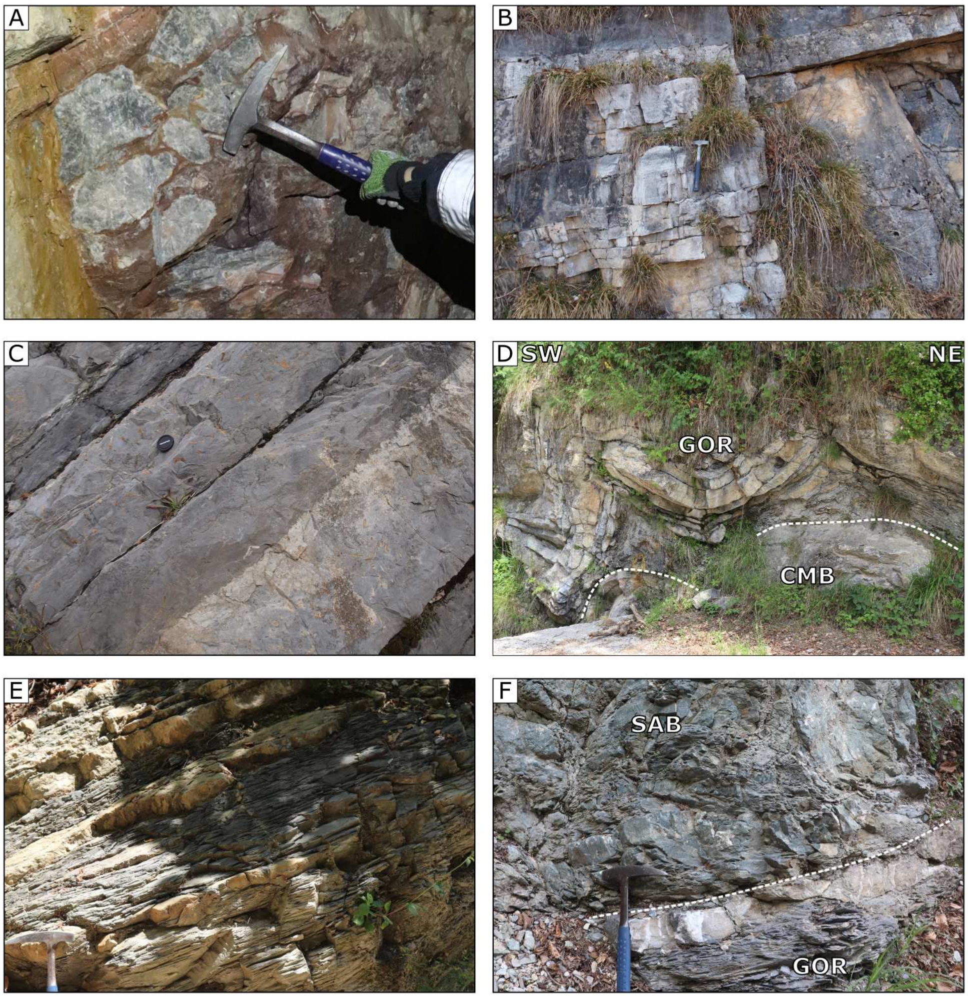

Figure 3. A: Breccia of the Calcare Rosso fm. consisting of limestone clasts in a reddish clayey matrix (Pian Bracca North sublevel). B: Thin- to medium bedded, light gray limestones of the Breno Fm. C: Gray limestone beds of the Calcare Metallifero Bergamasco Fm. The bed to the right shows a complete peritidal cycle, with a lower gray subtidal interval and an upper whitish, dolomitized, supratidal interval. D: Folded contact between the Calcare Metallifero Bergamasco and the Gorno fms., highlighted by the white dashed line. E: Interbedded light yellow limestones and gray marly shales of the Gorno fm. F: Contact between the marls of the Gorno fm. and the green volcaniclastic sandstones of the Val Sabbia sandstone fm., highlighted by the white dashed line.

stratigraphic markers for mineral exploration. They have been mapped in the underground maps, and labeled as (from base to top) tuff 1a, tuff 1b, and tuff 1c. The most important is tuff 1a, which marks the lowermost limit of the mineralized stratigraphic succession exploited in historic mining operations in the Vedra Valley. The Breno Fm. hosts Zn-Pb sulfides mineralizations and is locally affected by hydrothermal dolomitization. These limestones represent the product of sedimentation in a tidal flat environment. Maximum thickness: about 100 m.

4.7. Calcare Metallifero Bergamasco (CMB, lower Carnian)

Micritic, bioturbated dark limestones in 10–40 cm-thick beds characterized by stromatolitic laminae associated with calcarenites (Figure 3(C)). Fossil content is represented by gastropods and bivalves. In the upper part of the formation cm-thick shaly-silty beds are interlayered in the succession. In the uppermost part, a few dm below the boundary with the Gorno fm., a cm-thick, discontinuous, greenish tuff layer has been recognized and mapped in the underground maps (tuff 2). Locally, dark chert nodules are present in the upper part of the formation. The depositional setting is represented by a tidal flat environment. This formation hosts major Zn-Pb sulfides mineralization. Maximum thickness: about 30 m.

4.8. Gorno formation (GOR, lower Carnian)

Alternations of micritic, bioturbated black limestones, marls and marly-limestones, and dark marly shales in beds up to 20 cm thick, frequently fossiliferous (bivalves) (Figure 3(D,E)). The Gorno formation shows heteropic relationships with the Val Sabbia sandstone. This unit is interpreted as the result of sedimentation in a lagoonal to coastal setting. In the study area the lower part of the Gorno fm. is commonly affected by tectonic deformation and is locally intensely mineralized with Zn-Pb sulfides ('black shales' mineralization Auct., SHB in geological maps). Maximum thickness: about 200 m.

4.9. Val Sabbia sandstone (SAB, lower Carnian)

Green to purple volcaniclastic sandstones and siltstones organized in dm – to m-thick beds, sometimes characterized by lenticular geometries, and locally showing cross-bedding (Figure 3(F)). Diffuse pyrite and carbonate concretions are common. Fossils are absent in this unit. The study part of the Val Sabbia sandstone is interpreted as the eastern edge of a thick clastic delta deposited in a alluvial plain to inner delta environment, bordered by the lagoon of the Gorno fm. Maximum thickness: about 400 m.

4.10. San Giovanni Bianco formation (SGB, upper Carnian)

Greenish sandstones and siltstones in planar to lenticular beds, interlayered with dm beds of dolostones and cargneules, prevailing in the upper part of the formation. Petrographic analysis performed by Garzanti (1985) revealed the volcaniclastic origin of the sandstones. This formation has a regional importance since it represents a detachment horizon on which the main thrust surfaces developed. The depositional setting is interpreted as a shallow coastal, mixed sedimentation environment (sabkha). Maximum thickness: about 200 m.

4.11. Neogene-Quaternary continental deposits

Neogene-Quaternary deposits comprehend: mine dumps (md), slope and talus debris (td), undifferentiated alluvial and fluvioglacial deposits (al), and Zorzone conglomerate (ZOZ).

5. Structural setting

The study area is bounded by two regional N-verging back-thrust surfaces, the Valtorta-Valcanale fault to the North and the Clusone fault to the south. It is mainly composed of platform carbonates arranged in South-verging ramp-and-flat thrust sheets forming an antiformal stack (Figures 1(B,C) and 2). The emplacement of the thrusts was strongly controlled by low-competence levels that induce the development of two main detachment zones along the Carniola di Bovegno (Olenekian) and the San Giovanni Bianco (Carnian) formations. Other minor detachment zones are located along the stratigraphic boundary between the Calcare Metallifero Bergamasco and the Gorno fm. This caused the deformation of the orebodies hosted in such levels (see below, Section 6) (Figure 3(A,D)). Two main N-S fault systems also occur: the Pezzel and Grem faults. These faults have been described by Zanchi et al. (2012) as the Grem-Vedra Transverse Zone – GVTZ. The development of both the South-verging thrusts and the main N-S trending faults has been attributed to the first Late Cretaceous Alpine compressional phase (Zanchetta et al., 2015; Zanchi et al., 2012).

The overall structural setting described above is arranged, in more detail, into several tectonic units described in the followings, mainly referring to the nomenclature proposed by Zanchi et al. (2012) (see Map A, Structural scheme). Tectonic units are numbered according to their geometric position, from bottom to top. The lowest one (Branchino Unit, 3), crops out in a large part of the Vedra Valley and continues below the Menna massif and the southwestern part of the Arera slope (Figure 5; Map A, Structural scheme). It is bounded by the Menna and Pian Bracca thrusts at its top, while it is displaced by the high-angle Pezzel fault (Map A, geological sections A-A′-A″, B-B′, C-C′-C″). The Branchino Unit encompasses the whole Anisian-upper Carnian succession, which is gently dipping to the South.

The Vedra Valley Unit (4a) and the Pian Bracca Unit (4b) (Figure 5; Map A, Structural scheme) are two lens-shaped minor tectonic slices bounded by the Menna (MTH) and Pian Bracca (PBT) thrusts. These are two individual splay faults of the same thrust system with anastomosing geometry that merge in a NNE-SSW to NE-SW striking zone consisting of a dm- to m-thick calc-mylonite, gently dipping southwards. These units encompass parts of the Breno, Calcare Metallifero Bergamasco and Gorno formations, only locally preserved in their primary tectonic setting (Map A, drillhole n° 57; Map B, drillholes n° 79, 81). The maximum inferred thickness of the tectonic units does not exceed 50–80 m. They are displaced by the Pezzel fault and they continue to the East of it, as inferred by some steep drillholes (Map A, drillhole n° 57; Map B, drillholes n° 64, 79, 81) and underground direct observations along the Pian Bracca South decline, that intersects the boundary thrust.

The Menna-Nossana Unit (5) lies above units 3, 4a, and 4b, from which it is separated by the Menna floor thrust (Figure 5; Map A, geological sections A-A-A″, B-B′, C-C′-C″). It consists of a thick Anisian to Carnian stratigraphic succession from the Angolo limestone to the Val Sabbia sandstone.

Arera Unit (6) crops out in the easternmost sector of the mapped area and it represents the uppermost unit on the summit of Corna Piana-Mt. Arera (Map A, Structural scheme). It is constituted by an Anisian to Ladinian succession including the Esino limestone. The thrust at the base of the unit is represented by the Arera Thrust (ATH) that crops out on the southern

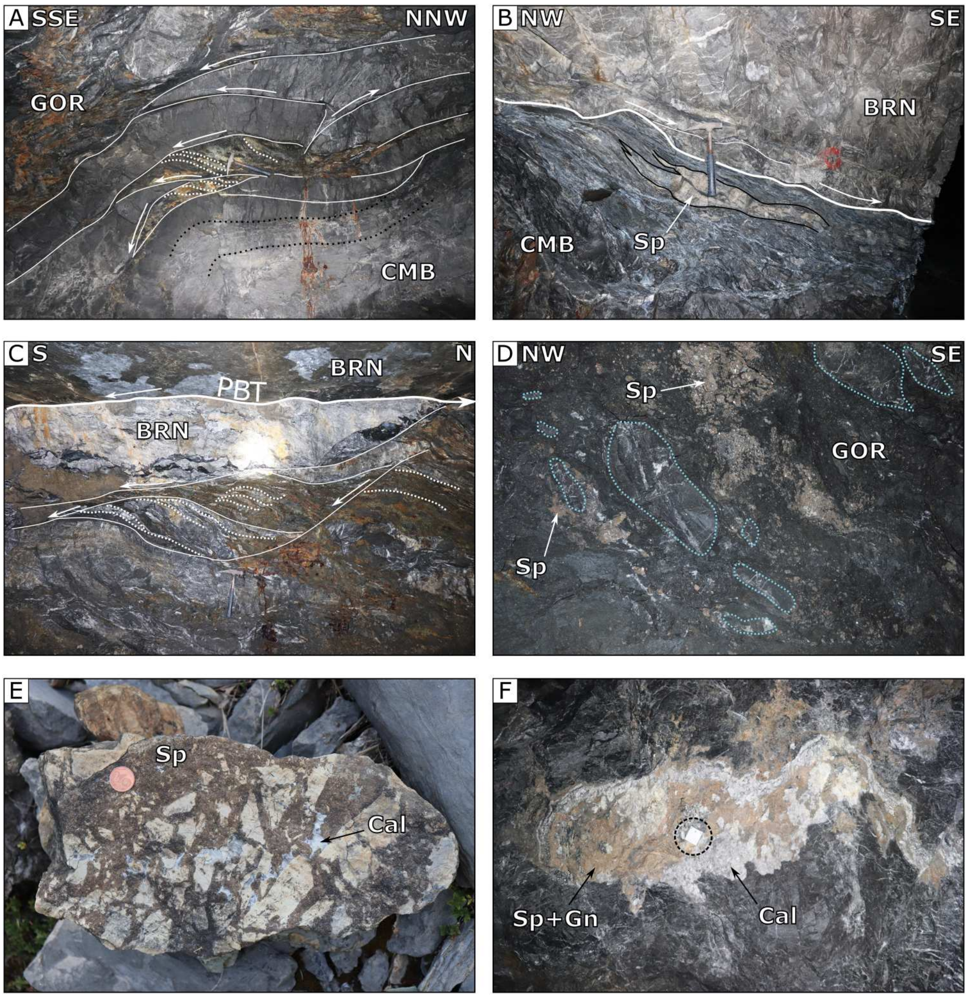

Figure 4. A: Minor detachment zone along the Calcare Metallifero Bergamasco-Gorno fms. contact (Ponente Level; Map E). B: Splay faults of the Pian Bracca thrust overthrusting massive limestones of the Breno Fm. on strongly deformed marly limestones of the Calcare Metallifero Bergamasco. Note a highly deformed sulfide lens just below the thrust surface (Sp, Parina level; Map D). C: Pian Bracca thrust surface, juxtaposing massive limestones of the Breno Fm. on a tectonic melange constituted by highly deformed marly limestones of the Calcare Metallifero Bergamasco and Gorno fm. (Pian Bracca South sublevels). D: Zorzone 'shale-associated mineralization'. Note the block-in-matrix fabric with clasts and blocks of limestones and nodules of massive sulfides (Sp, Forcella level, Map B). E: Mineralized breccia from Arera mine dumps (Arera southern slope; Map A). F: Dissolution cavity in the Calcare Metallifero Bergamasco fm. (Piazzole level, Map C). The black dashed circle indicates the compass used as scale. White lines: shear planes; white dashed lines: S planes; white arrows: movement directions; continue black lines: mineralization; light blue dashed lines: clasts; black dashed lines: bedding. Sp: sphalerite; Gn: Galena; Cal: calcite.

slope of Mt. Arera (Map A, geological section C-C′-C″). The thrust surface, locally coated by cataclastic bands, is almost flat and gently dipping to the South, forming a small angle with the bedding of the underlying Gorno fm. Below the Arera thrust, an overturned fold is recognizable, which is interpreted as a footwall syncline related to the emplacement of the thrust (Zanchi et al., 2012). The axial surface is almost flat and dips to the North, indicating a top-to-S transport direction.

All the previously described units are displaced by two main steeply-dipping transcurrent fault systems: the Pezzel (PZL) and Grem (GRM) faults (Figure 5; Map A, Structural scheme). The Pezzel fault has been observed mainly underground in old mineworks hardly accessible (Maps B and C). The Pezzel fault is steeply ESE-dipping and characterized by a vertical mylonitic foliation slightly oblique in respect to the fault strike that suggests a sinistral transtensional movement. An exploration branch of the Riso-Parina tunnel ('Riso-Parina Est'; see Map A, Tunnel plan, geological sections A-A′-A″ and C-C′-C″) documents that, across the Pezzel fault, a 900–1000 m of sinistral horizontal offset occurred. Stratigraphic relationships and drillholes suggest the splitting of the main structure in two segments (PZLa, PZLb), isolating an extensional duplex in a flower structure in the Pian Bracca area. The southern prosecution of the fault bounds the eastern side of the Vedra Valley juxtaposing Unit 5 and Unit 3 (Zanchi et al., 2012). The Grem Fault (GRM) is characterized by a NNW-SSE strike and which is followed by the Parina stream (Map A). The fault plane is steeply West-dipping and has a dextral transtensive movement.

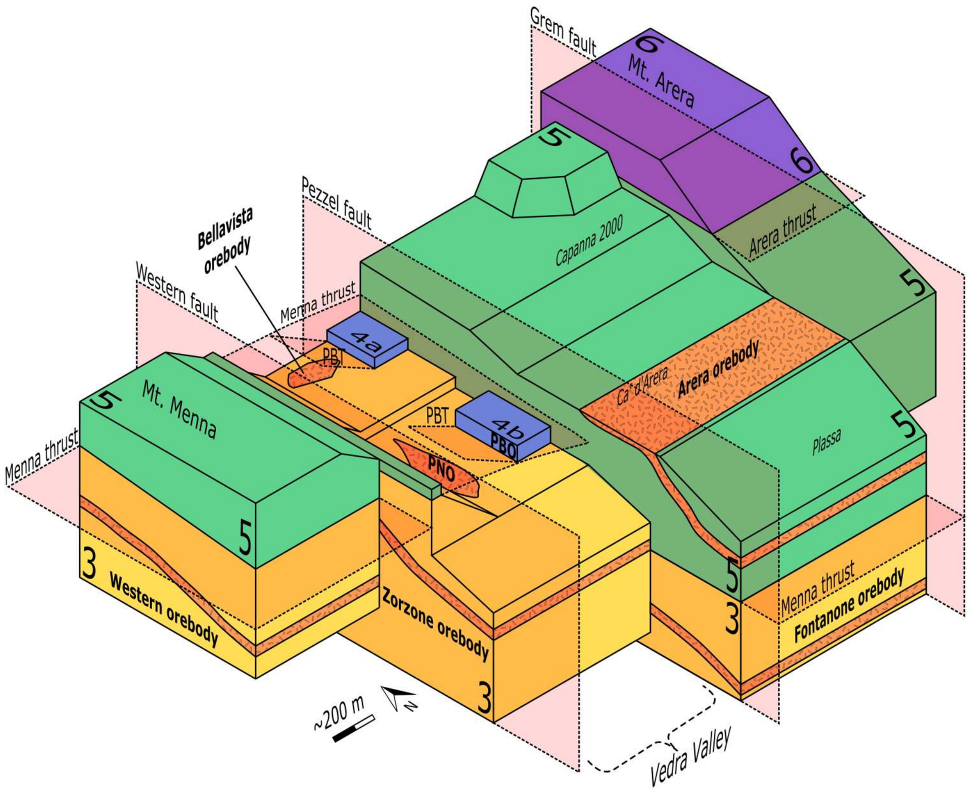

Figure 5. Simplified isometric block-diagram of the Arera-Vedra Valley mining area showing the tectonic redistribution of the orebodies in the area by the main tectonic contacts during Alpine orogenesis. 3: Branchino Unit; 4a: Vedra Valley Unit; 4b: Pian Bracca Unit; 5: Menna-Nossana Unit; 6: Arera Unit; PBO: Pian Bracca oredbody; PBT: Pian Bracca Thrust; PNO: Ponente orebody. Orebodies names in bold; locality names are in italic; faults and thrusts names in roman. Tectonic units colors are the same as in the Structural scheme of Map A. The stratigraphic interval hosting mineralization is represented by the orange volumes.

6. Ore deposits

Mineralizations in the study area are stratabound, sulfide-dominated (Zn-Pb), and confined between the uppermost portion of the Esino limestone and the lowermost, m-thick, part of the Gorno fm. ('black shales' mineralization Auct., SHB in geological maps). The mineralogy is mainly represented by sphalerite, galena, pyrite, dolomite, and calcite (Giorno et al., 2022; Summino et al., 2023). A brief description of the main mineralization types observed in this area follows:

- *Shale associated mineralization*: mainly hosted in the lowermost part of the Gorno fm. ('black shales' mineralization Auct.), which is characterized by a block-in-matrix fabric showing cm – to dm-sized limestone clasts and massive sulfide nodules in a shaly matrix (Figure 4(D)). Locally (e.g. in the Pian Bracca area), deformation is more intense, producing a strong grain-size reduction and recrystallization of the sulfides (Figure 4(B))
- *Mineralized breccias*: crackle to rubble breccias (sensu Morrow, 1982) forming dm- to m-thick irregular bodies, both concordant and discordant with the bedding and cemented mainly by sphalerite, galena, calcite, and dolomite (Figure 4(E)).
- *Dissolution cavities*: irregularly shaped cavities, cm- to m-large, with branches both roughly concordant and discordant with respect to beds, cemented mainly by sphalerite, galena, calcite and dolomite. The contact with the host rocks is commonly rounded and smooth (Figure 4(F)).
- *Supergene mineralization*: consists of nonsulfide Zn-Pb minerals (smithsonite, hydrozincite, hemimorphite, cerussite, anglesite, wulfenite, limonite, azurite, and malachite; Mondillo et al., 2020) concentrated along faults and associated fractures, deriving from sulfide alteration.

6.1. Zorzone orebody

The Zorzone orebody represents the southern continuation of the historic mineworks of the Vedra Valley (Bellavista and Ponente orebodies; Figure 5). It is currently under exploration, representing the main target of Vedra Metals. It is hosted in the tectonic Unit 3 and located in a tectonic window below Unit 5, bounded to the East by the Pezzel fault and to the West by the western boundary fault (Western Fault, WFT) (Figure 5). It is a relatively continuous stratiform shale-associated mineralization hosted mainly in the basal part of the Gorno fm. (Figure 4(D)). Mineralization can also be found in the underlying stratigraphic units (Calcare Metallifero Bergamasco, Breno Fm.), mostly consisting of mineralized breccias and dissolution cavity infills (Figure 4(E,F)).

6.2. Pian Bracca orebody

Located NE of the Zorzone orebody, close to the Pezzel fault, the Pian Bracca orebody is intensely deformed and redistributed due to the proximity to the Pian Bracca thrust (Figure 4(B); Figure 5). The mineralization is hosted both in the hanging-wall (Unit 4b) and in the footwall (Unit 3) of the Pian Bracca thrust. Traces of this orebody have been intercepted by historic drillholes in correspondence of Plassa locality (Map A, drillhole n° 57). The original mineralization, prior to the Alpine deformation, likely had characteristics similar to those of the Zorzone orebody.

6.3. Fontanone orebody

The Fontanone orebody represents the eastern prosecution of the Zorzone orebody. It is hosted in Unit 3, below the thrust stack of units 4 and 5 and is limited to the East by the Grem fault and to the West by the Pezzel fault (Figure 5). Some historic drillholes N-S-striking and North-dipping show a South-dipping mineralized succession hosted mainly in the upper part of the Calcare Metallifero Bergamasco formation.

6.4. Western orebody

This orebody, still unexplored and whose presence is only inferred, would represent the western prosecution of the Zorzone orebody, to the west of the Western Fault (Figure 5). Historic drillholes performed by S.A.M.I.M. from the Forcella level (Map B, drillholes n° 76 and 77) show that on the western side of the Western Fault the stratigraphic succession has been displaced northward of 600–650 m.

6.5. Arera orebody

The Arera orebody is hosted in Unit 5, above the Fontanone orebody, from which is separated by the Menna and Pian Bracca thrusts (Figure 5). It is hosted in the Breno and Calcare Metallifero Bergamasco formations, gently dipping to the South. Mineralization mainly occurs as mineralized breccias (Figure 4(E)). It represents the oldest minework of the area, exploited since the Roman period.

7. Conclusions

The 1:10,000 geological map of the Arera and Vedra Valley mining area proposes an updated and detailed reconstruction of the stratigraphic and structural features of the sedimentary succession hosting the mineralizations. The performed data integration led to the definition of a detailed geo-structural model that could be used both for mineral exploration, i.e. reconstructing the present distribution of the orebodies, and to support scientific research aimed at understanding the genesis of the mineralizations. In this regard, the reconstruction of the relationships between tectonic structures and orebodies allowed to highlight that the ore genesis preceded the Alpine deformations. This locally rearranged the primary Late Triassic mineralized bodies by simply deforming and displacing them. This gave further support to the genetic model presented by Giorno et al. (2022) and Summino et al. (2023) who suggested a very shallow-burial mineralization occurred shortly after deposition of the host carbonates. The map and its ancillary documents have been realized by combining surface and underground geological map data together with historic and new drillhole log data. All these data were integrated into a three dimensional model using a specific software (Micromine©), which allowed a better representation of the geometry of lithostratigraphic units, geological contacts and orebodies.

Software

The compilation of the geological maps, topographic base preparation included, has been done using QGis version 3.22.5-Białowieża. Editorial handling of the final layout of geological maps, geological sections, schemes and figures was performed using Inkscape version 1.1.2. Stereonet version 11.4.1 has been used to plot structural data. Micromine© has been used to handle historic drillholes database and to visualize the 3D geometries of the study area.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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