Geo.Alp, Vol. 7, S. 55–70, 2010

THE COPPER-WOLFRAM DEPOSIT OF BEDOVINA (TRENTO, ITALY)

Pietro Frizzo[1], Luca Peruzzo[2] and Elio Dellantonio[3]

With 29 figures

[1] Dipartimento di Geoscienze, Università di Padova
[2] CNR - Istituto di Geoscienze e Georisorse, Sede di Padova
[3] Museo Geologico delle Dolomiti, Predazzo (Trento)

Abstract

The W (Mo, Sn, Bi) and Cu (Pb, Zn, Ag, Te, Co, Ni, etc.) deposits of Bedovina mark the closure of the Middle-Triassic magmatic cycle of the Predazzo-Monzoni Eruptive Complex, composed of latiandesitic and latibasaltic lavas, monzonitic stocks with shoshonitic affinity, K-alkaline monzosyenitic bodies, and some granitic masses. The mineralization is hosted in a stockwork of veins which intersects the volcanics and, occasionally, granitoid masses, and rarely acidic and mafic veins. Two different metalliferous phases can be recognized, the first mainly wolfram-bearing, the second copper-polymetallic. The wolfram phase is represented by quartz+K-feldspar+tourmaline veins, with scheelite, minor apatite and rutile, rare cassiterite, and hematite. Sporadic synchysite-(Ce) and molybdenite occur in granite breccias.
The copper-polymetallic phase was superimposed to the wolfram one after a brittle tectonic event; it comprises quartz, chalcopyrite, minor pyrite, sphalerite, galena and traces of other sulfides and sulfosalts such as cobaltite, argentite/acantite, members of the tetraedrite-tennantite series, bismutiferous sulfosalts (arcubisite/silver-copper-cosalite), Ag (hessite) and Bi tellurides (pilsenite) with native Bi and other bismutiferous phases finely intergrown with chalcopyrite.
The mineralization of Bedovina is related to hydrothermal metal fluids derived from the crystallization of two distinct granitoid magmas: the first is of *"S type"* character, and probably would have generated the parageneses typical of the "wolfram phase" (W with minor Sn, REE, Th); the second is of *"I type"* character, is assumed to be responsible for the polymetallic associations (Cu, with Zn, Pb, Ag, Bi, etc.).

1. Introduction

The copper-wolfram Bedovina deposit outcrops of Mt. Mulàt, embedded in the Ladinian eruptive complex of Predazzo, Southern Alps (Fig. 1). It has been mined since prehistoric times for copper (Šebesta, 1992) and since 1909 also for tungsten. The mining was concentrated between 1600 and 1750 m on the north-western slope of M. Mulàt (Bedovina mine) and between 1900 and 2000 m on the south-eastern slope of that mountain (Mine of Cima del Mulàt or "Vecchia Bedovina"). *The Bedovina Mine* was active mainly in the twentieth century: the Consortium Montanistico Oss Mazzurana, which obtained the mining claim in 1895, reorganized the mine on eight levels (Fig. 2) connected by shafts and rises (Oss Mazurana, 1905-1906; Oss Mazurana and Hesser, 1909). The extracted ore was transported by cableway to the plant of Mezzavalle, just north of Predazzo, producing copper sulfate. At the beginning of World War I the Austrian government confiscated the mine and operated with military personnel extracting about 6,000 tons of ore with an average 1.6% of Cu and 0.48% of WO_3; the plants of Mezzavalle were

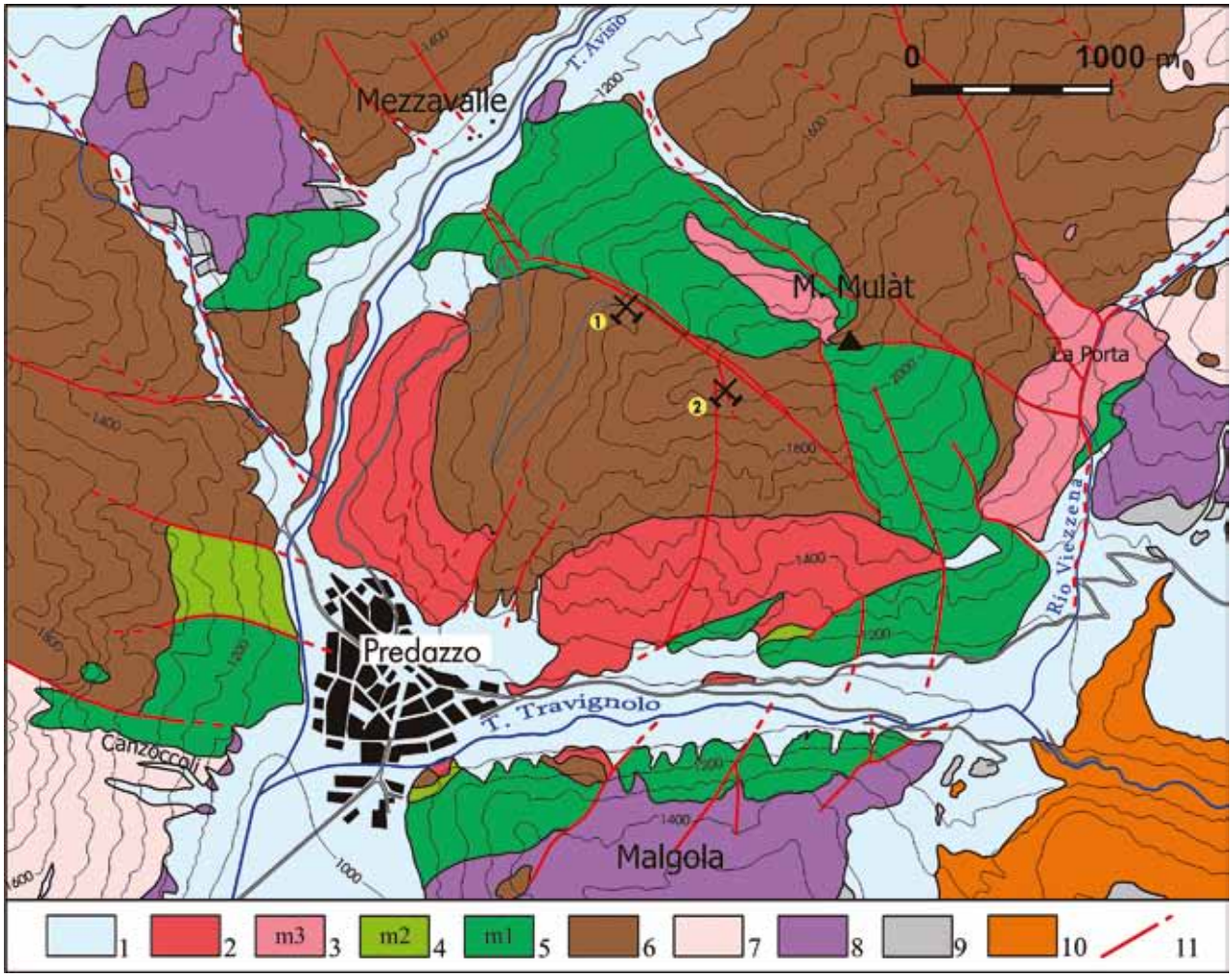

Fig. 1. Geological sketch of the Predazzo area (compiled on the basis of Vardabasso 1930, ENI-Aquater 1997, Visonà 1997 and data of the Authors). Legend: 1 - Undifferentiated Quaternary deposits. PREDAZZO ERUPTIVE COMPLEX: 2 – Biotitic amphibolic granites and muscovite-biotite tourmaliniferous leucogranites; 3 – Quartz monzo-syenites and nepheline sodalite syenites (m3); 4 - Grey-pinkish monzo-syenites and quartz-monzonites (m2); 5 – Monzonites, olivine monzo-gabbros and pyroxenite bodies (m1); 6- Latiandesitic and andesite-basaltic lava flows, volcanoclastics and subvolcanic bodies. PERMO-TRIASSIC SERIES: 7 – Undifferentiated Sciliar Fm. (Upper Anisian – Ladinian), Contrin Fm. (Upper Anisian), Morbiac Fm. (Upper Anisian), Richthofen Conglomerate (Upper Anisian); 8 – Werfen Fm. (Lower Triassic); 9 – Undifferentiated Val Gardena sandstone and Bellerophon Fm. (Upper Permian). 10 – Dacitic-rhyolitic lavas and ignimbrites of the Volcanic Permian Complex (Lower Permian); 11 – Main faults. 1. Bedovina mine; 2. Vecchia Bedovina – M. Mulàt mine.

used to produce concentrates of chalcopyrite and scheelite. After the war the mine was returned to the Consortium Oss Mazzurana but, for lack of funding, remained inactive and was progressively abandoned. In 1939 the Cogne National Society restructured the mine and the plant of Mezzavalle, resuming the mining activity that continued until 1948. After several years of stagnation in the mid "50s, the claim was taken by the M. Mulàt Company which undertook research works also on the south-eastern slope of the M. Mulàt ("Vecchia Bedovina"); during this period a few thousand tons of raw ore were retrieved, with low concentrations (0.5% Cu and 0.06% in W), taken from the ore already stored at landfills and storage rooms (Dellantonio, 2000). It is estimated that between 1910 and 1955 about 20,000 tonnes of raw ore with average concentrations of 1.2% Cu and 0.35% WO_3, have been mined. At the final closure of the mine it was estimated that 50 - 70,000 t of ore were still available, with contents comparable to those mentioned above. *The Cima del Mulàt Mine* ("Vecchia Bedovina") includes traces of opencast mining, manholes, trenches and tunnels. Mineralization, outcropping from the ridge of M. Mulàt (2030 m) to 1910 m was followed by two galleries (Fig. 3), with portals at an altitude of 1975 and 1925 m respectively. The

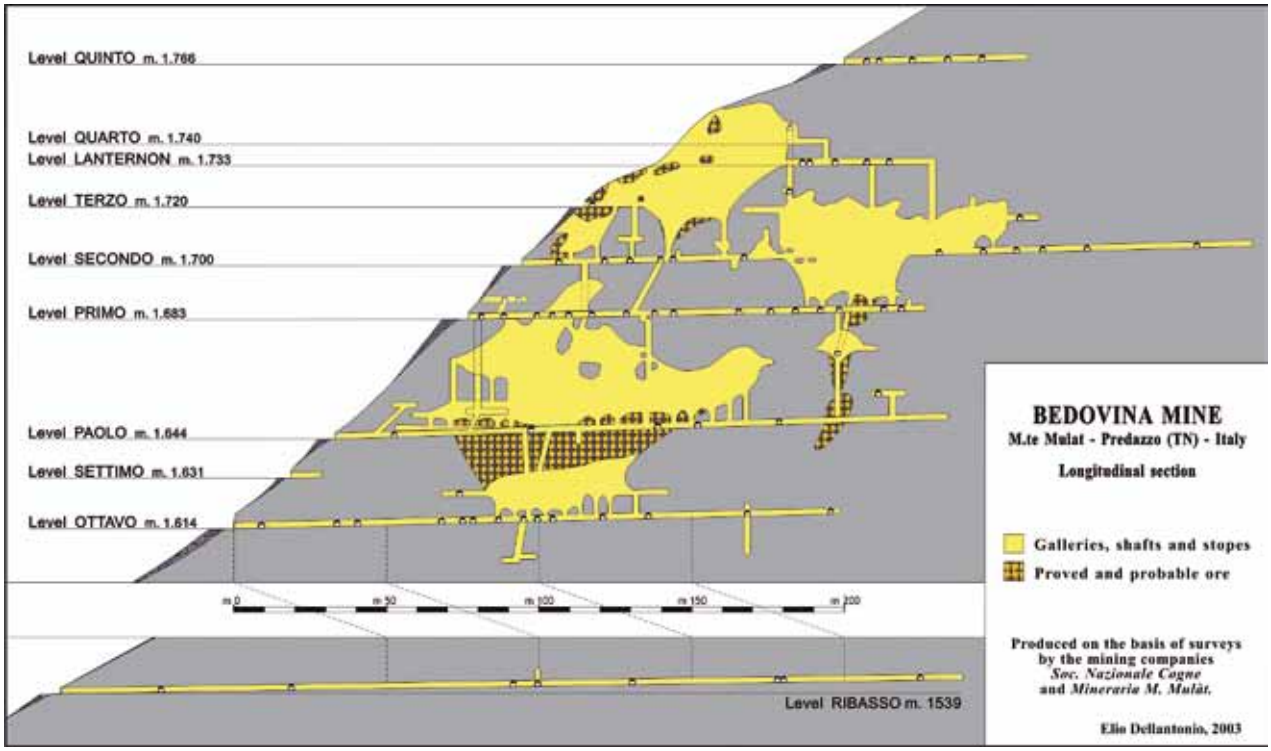

Fig. 2. Cross section of the Bedovina mine.

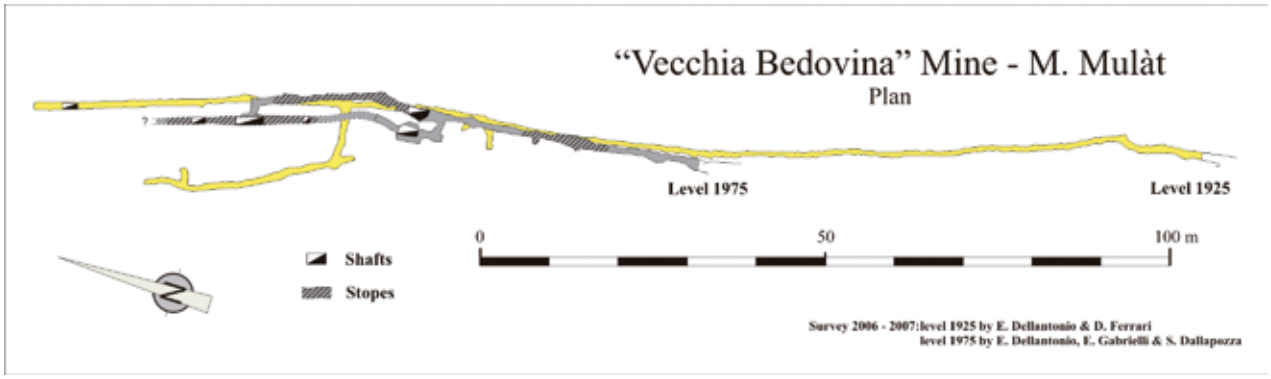

Fig. 3. Cross section of the Vecchia Bedovina-M. Mulàt mine.

lower extends for about 170 m towards the deposit, the upper one, a bit shorter, connects some digging rooms. The explorations undertaken during the "50s of the last century for estimation of ore reserves indicated 40,000 t of ore containing about 0.7% of Cu and 0.1% of W. According to some authors (e.g. Pelloux, 1919; Degiampietro, 1975, etc.) the mine was particularly flourishing in the first half of the XVI century. An examination of the traces of the underground works revealed that at least these are more recent, since they have been entirely made with the use of explosive (black powder) technique back to the XVI century (Vergani, 2002). Archival documents demonstrate that in Predazzo, around 1730, German-speaking workers mined and smelted copper on behalf of the family Hilleprandt (Stella, 1953, 1957). On the plateau just west of the portal at an elevation of 1975 m upgrading of the raw ore took place before it was transported by mule to the furnaces of Forno and Mezzavalle. The mining was active during some years in the first half of the XIX century (Pelloux, 1919), but was abandoned due to the high cost of transporting the ore to the furnaces of Chiusa (BZ). Towards the middle of the last century when, in an effort to streamline and expand the mining activity, stockworks of the south-eastern slope (M. Mulàt Mine/"Vecchia

Fig. 4. Volcanic clasts, cemented by quartz veins with K-feldspar and chalcopyrite. Bedovina mine. The maximum length of the sample is 11cm.

Fig. 5. Banded mineralization of chalcopyrite and pyrite in tourmaline (black) and quartz. Vecchia Bedovina-M. Mulàt mine. The maximum length of the sample is 8cm.

Bedovina") were also explored; reserves for the two ore deposits were estimated to be 100,000 tons containing about 1% Cu and 0.1% of W. More recent estimates (Eni-Aquater, 1997), based on the assumption of the continuity of the mineralization also in the uncharted stretch of about 400 m between the two deposits, suggest possible additional reserves of 200,000 tons.

2. Geological framework

2.1 The Predazzo Eruptive Complex

The geological context of Bedovina is basically represented by the Ladinian Eruptive Complex of Predazzo (Fig. 1) produced by a single magmatic cycle developed roughly between 237 and 228 Ma. The Eruptive Complex includes effusive, intrusive and dike products, crossing the lithostratigraphic sequence that ranges from Vulcaniti Atesine (Lower Permian) to the terrigenous and carbonate formations of the Lower and Middle Triassic. Magmatism started with the emission of subaerial pyroclastics of volcano-phreatic origin which was followed by emission of pyroclastics and lavas with latitic, lati-andesitic and lati-basaltic chemistry (Coltorti et al., 1996) to form a large volcanic complex with central pipe, many hundreds meters thick, lying on the Sciliar Fm. (Upper Anisian – Lower Ladinian). The large initial outflow of volcanic products was followed by the collapse of the volcanic caldera with major slumps in the M. Mulàt area (Castellarin et al., 1982). The fractures of the collapse favoured the rising of plutonic bodies (Laurenzi and Visonà, 1996). These bodies form an outer ring of monzonites (Fig. 1) with fewer masses of quartz monzo-syenites and nepheline-sodalite syenites, and an innermost semi-ring of granites (Vardabasso, 1930; Visonà, 1997).

Mineral chemistry and isotope data suggest that the Predazzo Plutonic Complex (Marrocchino et al., 2002) was generated by fractional crystallisation of different magmas injected during a multiple sequence of events related to subduction processes: Menegazzo et al. (1995) and Visonà (1997) recognize (Fig. 1) *three monzonitic units (m1, m2 and m3)* and *one granitic unit (g).* These products derived from two different magma sources of mantle origin: the first is of shoshonitic composition and located at a depth of 10-12 km, and formed the monzonitic units m1 (monzonites and quartz-monzonites) and m2 (monzonites, olivine monzogabbros with pyroxenite masses). The second is of alkaline-sodic character, 15-17 km deep, and produced the monzonitic unit m3 (monzosyenites with masses of quartz syenite, and nepheline and sodalite syenites) and the granite unit (g) comprising biotite granites and two micas and tourmaline leucogranites. The petrological links with the previous units are not fully clarified (Visonà, 1997). The products of the two magmatic sources intruded and differentiated in subvolcanic environment without direct connection between them. Some petrological characters denote a significant level of crustal contamination at least for granites (Coltorti et al. 1996).

The swarm of dykes that intersects the eruptive complex and underlying Permian-Triassic formations is constituted of rocks equivalent to those of the volcanic succession and of the shoshonitic intrusion, but also K-basanitic, monzo-syenitic and nepheline-syenitic dikes (tinguaites), essexites, aplitic and pegmatitic dikes, and lamprophyric dikes (camptonites) are included. Terrigenous or carbonate rocks in contact with the intrusive masses show a thermometamorphic aureole characterized by marble locally with brucite (predazzites and "pencatites" *Auct.*) composed of complex Ca-silicate parageneses with diopside, vesuviane, grossular, andradite, forsterite, wollastonite, clintonite, tremolite, epidote, serpentine, and locally skarn with magnetite, hematite, pyrite and other sulfides.

2.2 The ore deposits

The copper-wolfram mineralization of Bedovina is represented by stockworks of millimetre to decimetre size veins, controlled by a series of faults and cracks crossing Mt. Mulàt in NW-SE direction (Figs. 4, 5). Along the main fault, known as "Fessuraccia", the monzonites (north-eastern part) are in contact with the volcanics (south-western part); within these last ones the copper-wolfram mineralization is embedded. In the belt, closest to the Fessuraccia, volcanics are crossed by numerous minor fractures oriented NW, NNW and N-S; some of these, especially the most continuous, enclose tinguaitic and lamprophyric dikes partly coupled (Eni-Aquater, 1997). A system of more discontinuous and polyphase fractures, successive to those followed by dikes, hosts the mineralized stockworks: these appear one after the other from the north-western (Bedovina mine) to the south-eastern side of Mt. Mulàt (M. Mulàt – Vecchia Bedovina mine), passing through the top. The most important mineralized bodies extend over distances of 100-200 m in both direction and dip, and are 1 to 4 m thick. The Bedovina deposit is composed of two subparallel stockworks 2-4 m thick, which extend over nearly 200 m with direction N40W, at a distance of almost 10 m, even with frequent convergences and divergences. The M. Mulàt mine is on a stockwork some meters thick that extends over about 200 m within the volcanics, along a tinguaitic dike directed N15W.

3. Materials and methods

The study was conducted on several representative samples, selected from a rich collection located at the Geological Museum of the Dolomites of Predazzo. Some of them are part of historical collections and were taken during the mining activity in the level Primo, Paolo and Ottavo in the Bedovina Mine. Because of the difficult access to the ancient galleries of the Bedovina and Mulàt mines, only some of the studied samples were taken directly from the ore body and most of them come from the dumps. The samples were mainly studied under the optical microscope on polished and thin sections integrated with SEM-EDS analysis.

4. Mineralization

4.1 The copper-wolfram ore bodies

The copper-wolfram stockworks of Bedovina are composed of a network of prevailing quartz veins that cement a breccia of pyroclastic rocks and lavas with latitic, lati-andesitic and lati-basaltic chemi-

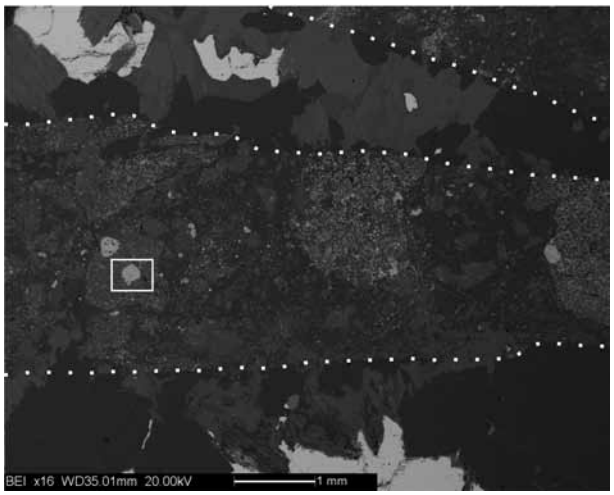

Fig. 6. Volcanic clasts, intensely altered, crossed by pneumatolytic-hydrothermal veins with quartz, tourmaline, scheelite and sulphides. The dashed lines mark the salbands. Box see Fig. 7.

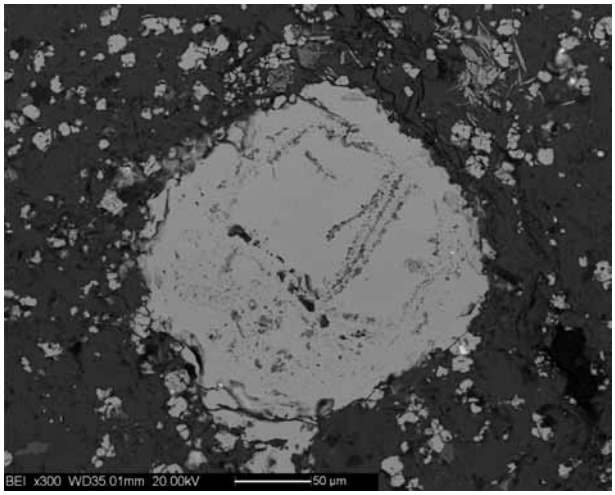

Fig. 7. Detail of Fig. 4 (box). Groundmass of the altered volcanic rock containing a phenocryst of magnetite1 with exsolutions of ilmenite, numerous tiny grains of non titaniferous magnetite2, and rare needles of rutile.

stry (in some cases with fragments of metamorphic rocks composed of quartz, plagioclase and muscovite, pulled away by magma rising through the crystalline basement); occasionally, some breccia fragments derived from acidic and basic dikes. Clasts cemented by mineralized veins show the effect of the pervasive action of pneumatolytic and hydrothermal fluids that generated the mineralization.

Clasts of lavas are characterized by a large felt-like mass with scattered phenocrysts of feldspar (K-feldspar1) locally several millimeters in size and without inclusions and, to a lesser extent, of altered femic silicates and magnetite (magnetite1). Magnetite1 phenocrysts (70-200 µm) include tiny individuals of apatite (apatite1) and plagioclase. The original groundmass hosts swarms of small grains of magnetite (magnetite2) 5-30 µm in size (skeletal the smaller, cubic the larger) and more rare rutile, partly acicular. Magnetite1 phenocrysts are titaniferous and frequently present at the nucleus oriented exsolutions of ilmenite, indicating the nature of primitive crystals from magma solidification; microgranular magnetite (magnetite2) is instead characterized by minimum content of Ti and probably represents a co-product of chloritization of femic silicates (Fig. 6 and Fig. 7). Some hematite developed around the magnetite grains of both generations.

More rarely clasts cemented by the mineralization derived from the fracturing of porphyritic dikes or masses of granitoids. In the first case it regards porphyritic breccias with feldspars and pyroxenes with scattered quartz plagues and small crystals of apatite epigenetic on chloritized pyroxene; locally thermometamorphic effects induced by porphyritic dike on hosting lava lithotypes are recognized. The action of pneumatolytic-hydrothermal fluids on clasts of granitoid rock are evidenced by sericitization and epidotization on plagioclase and/or K-feldspar (K-feldspar2). In some cases these are alkali-feldspar granite breccias with K-feldspar occurring as large crystals, both white and dark micas, quartz, chlorite and apatite, the latter represented by two generations of crystals: the first is magmatic and linked to the solidification of granite, and the second is epigenetic and formed by the early pneumatolytic-hydrothermal alteration. The K-feldspar2, frequently sericitized, is locally replaced by chlorite and/or zeolite aggregates; biotite is transformed into chlorite.

4.2 Mineralogy

The main component of the mineralized veins is quartz. Coarse quartz is normally typical of the pneumatolytic veins in which it is frequently associated with K-feldspar (K-feldspar 3), tourmaline, mainly schorl (in granular and prismatic crystals sometimes in sheaves), and minor calcite: some tourmaline crystals show a zoned core and an irregular "fibrous" periphery. Associated to the fine grained quartz are most commonly plagues of carbonate and rare chlorite, and small magnetite crystals, locally with pyrite

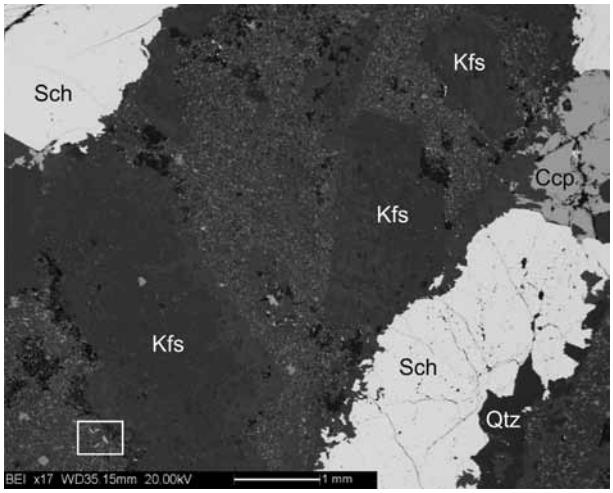

Fig. 8. Veins with scheelite (Sch), chalcopyrite (Ccp) and quartz (Qtz) cement granite clasts containing K-feldspar phenocrysts (Kfs) and tiny plates of molybdenite (in the box see Fig. 9).

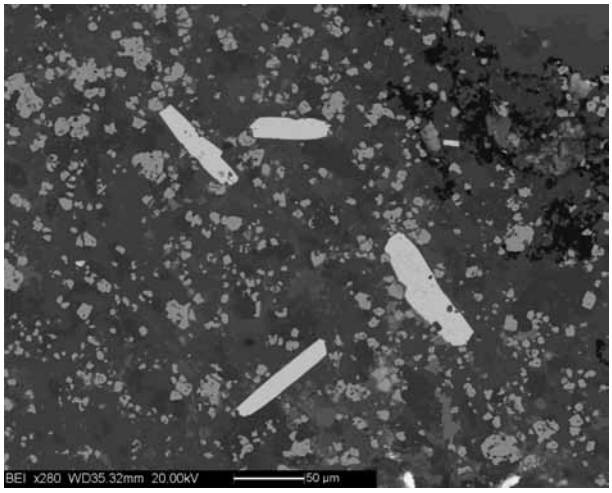

Fig. 9. Detail of Fig. 8 (box). Tiny plates of molybdenite in granite matrix.

inclusions. The metalliferous paragenesis indicates formation in two distinct phases: the first, wolfram-bearing phase, contains scheelite hosted in veins composed of quartz, K-feldspar, tourmaline, locally carbonate, chlorite, apatite and, according to Eni – Aquater (1997), allanite; the copper prevailing phase generated quartz veins with plagues and nodules of chalcopyrite accompanied by pyrite and polymetallic sulfides, less abundant, but present with a large variety of mineralogical species. The transition between lithic clasts and mineralization is usually marked by a thin band of quartz, which may occur in small "combs" of crystals oriented normally to the salband, accompanied by minor, slightly ferriferous calcite, biotite with tiny exsolutions of ilmenite, rare apatite, scattered skeletal individuals of rutile and ilmenite, magnetite grains (without titanium) and sporadic interstitial small plagues of chalcopyrite. At places chalcopyrite and quartz tend to pervade the margin of lava clasts. In the context of the Bedovina Nuova mine, sporadic occurrences of molybdenite should be reported also, independent both from the copper and the wolfram parageneses. They consist of tiny plates of molybdenite (Fig. 8 and Fig. 9), intergrown with quartz, K-feldspar and micas in a fine-grained alkaline granite. These are minor mineralizations genetically correlated to those of Aivola (Ricerca Predazzo), still attributable to the granitic magmatic event, but to a pulse of metalliferous fluids slightly preceding the wolfram-bearing phase. Traces of molybdenite are also reported from the debris of the dump of the Galleria Ventosa and other sites of the magmatic complex of Predazzo and Monzoni.

4.2.1. *The wolframiferous phase*

Wolfram occurs as scheelite grains and up to several mm large crystals disseminated in quartz-feldspar-tourmaline gangue. There is no evidence of wolframite. SEM microchemical analysis identified low, but locally significant, contents of Mo in some scheelite grains. The paragenetic sequence characteristic of wolfram veins starts with the formation of quartz (which continues throughout the whole phase) and scheelite, followed and accompanied by tourmaline (which may include scheelite), K-feldspar, chlorite, occasional crystals of apatite (apatite2, zoned for fluorine content increasing towards the edge), and finally carbonate. The quartz gangue accompanying the scheelite contains locally tiny crystals of magnetite.

The structural and textural characteristics of the mineralization of Bedovina indicate that the wolfram phase anticipates the copper phase: chalcopyrite in fact appears as late as tourmaline, which at places incorporated some relics after the selective replacement of feldspar. In other places (Fig. 10) scheelite is fractured and cemented by calcite and quartz veinlets containing chalcopyrite plagues and some small crystal of apatite. We also observed locally scheelite grains surrounded by a thin edge of sericite likely to

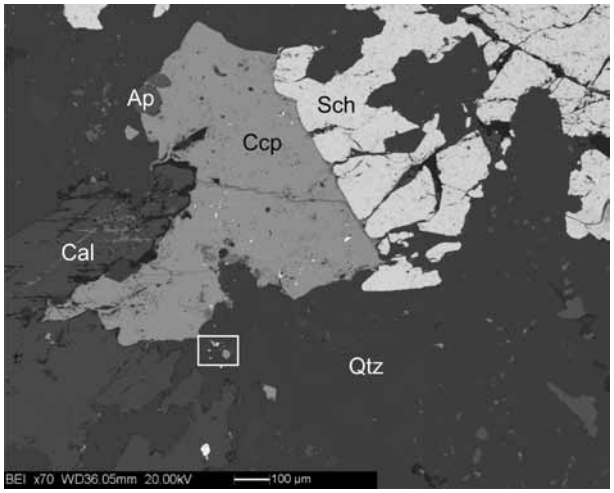

Fig. 10. Scheelite (Sch) fractured and cemented by quartz (Qtz) and calcite (Cal) gangue with chalcopyrite (Ccp) and apatite (Ap). Chalcopyrite contains small grains of galena and rare tiny tellurides. In the box, small grains of galena and sulfosalts (see Fig. 25).

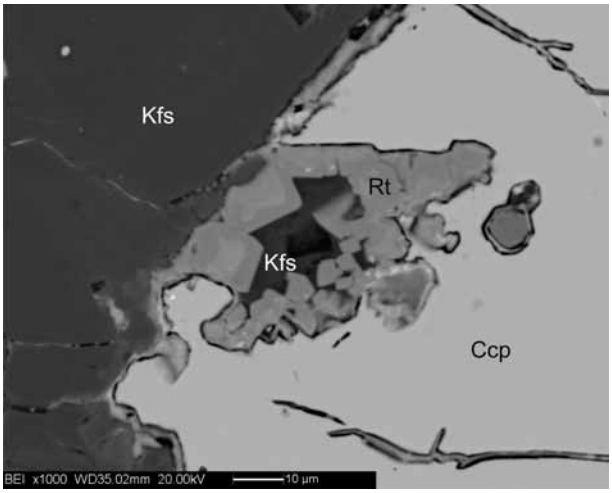

Fig. 11. Chalcopyrite (Ccp) in quartz-feldspar gangue (Kfs), containing a small "crevasse" encrusted by tiny crystals of rutile (Rt) and K-feldspar.

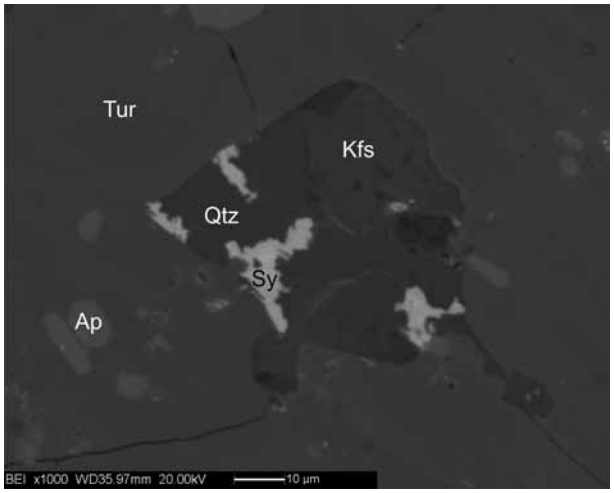

Fig. 12. Quartz (Qtz), K-feldspar (Kfs), tourmaline (Tur), apatite (Ap) and small grains of synchysite (Sy).

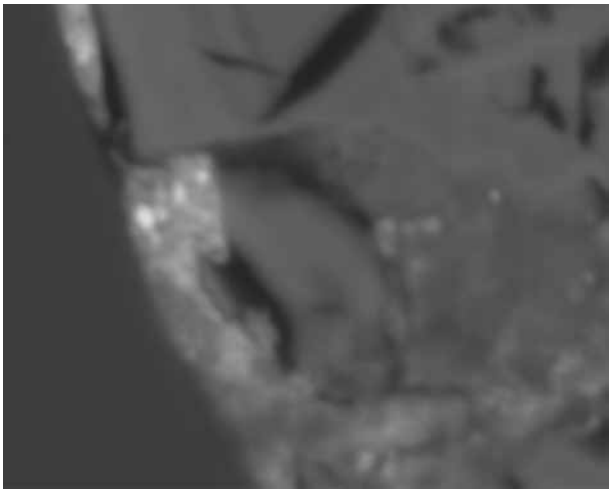

Fig. 13. Cassiterite (Cst) in quartz (Qtz) near a relic of chalcopyrite (Ccp) rimmed by an oxidation rim.

witness the action of corrosion/dissolution induced by hydrothermal polymetallic fluids.

Locally the scheelite occurs in narrow veins of quartz which cemented a granite breccia: in this context the salbands are marked by thin packages of chlorite2/biotite and rutile grains. At places the quartz veinlets also contain small crystals of pyrite, scattered or in swarms with interstitial chalcopyrite.

In the quartz, K-feldspar and tourmaline gangue, which normally characterize the wolfram phase, grains of rutile and ilmenite locally are also relatively common; in some cases the K-feldspar and quartz groundmass replaced by chalcopyrite show minuscule "crevasse" covered with tiny crystals of rutile (Fig. 11). Associated with granitic breccias, locally thorian synchysite-(Ce) (Fig. 12), a REE containing fluorcarbonate occurs, according to a SEM analysis, (Ce_2O_3 ca. 24%), La (La_2O_3 ca. 14%), Nd (Nd_2O_3 ca. 9%) Pr_2O_3 (ca. 2.5%), Sm (Sm_2O_3 ca. 1%), minor amounts of various other REE and about 2.7% of ThO_2.

Tiny grains of cassiterite (1-10µm), with minor contents of Ti (2-3%) and Fe (1-2%), are scattered across quartz gangues (Fig. 13). The closure of the wolfram phase is marked by the crystallization of hematite as marginal accretions on grains of magnetite and in flakes disseminated in quartz.

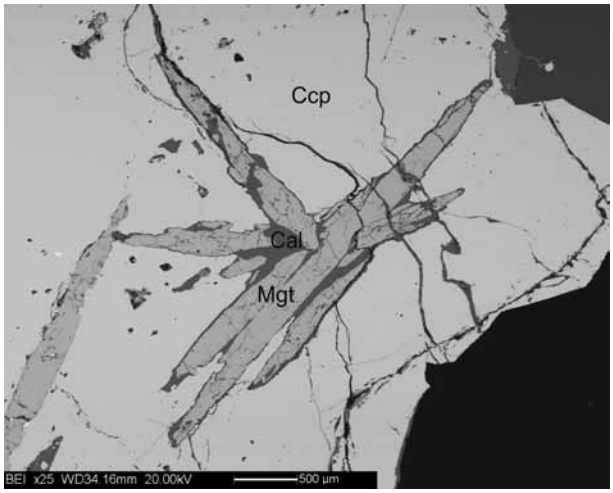

Fig. 14. Pseudomorphic magnetite (Mgt) after radiated plates of hematite (mushketowite) accompanied by some calcite gangue (Cal), inherited by penetrating chalcopyrite (Ccp). A network of thin later fractures is cemented by calcite.

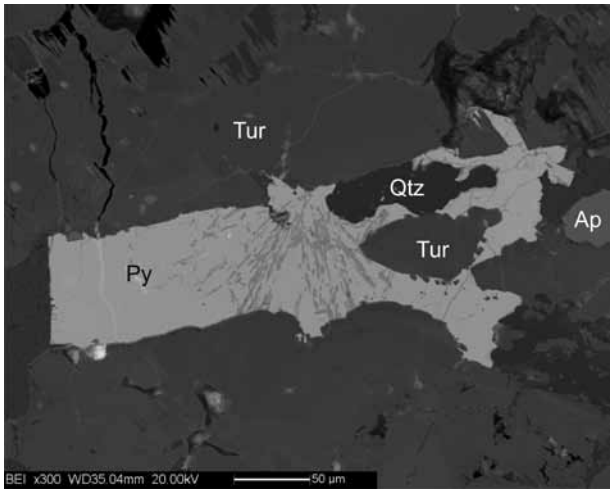

Fig. 15. Quartz (Qtz) and tourmaline (Tur), with occasional crystals of apatite (Ap) and pyrite (Py), the latter including intergrowths of ilmenite and rutile.

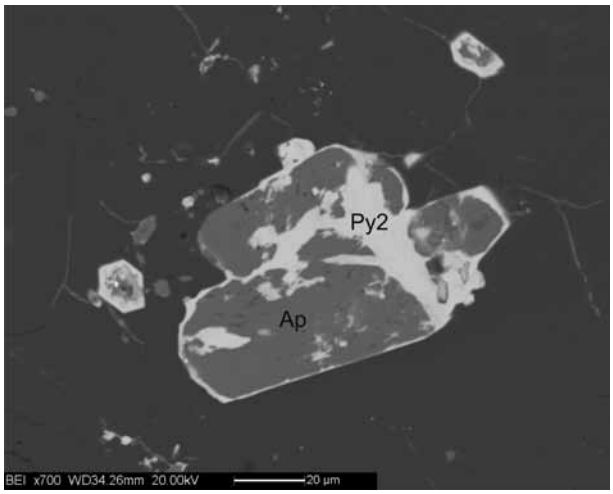

Fig. 16. Apatite (Ap) in quartz, replaced and penetrated by pyrite2 (Py2).

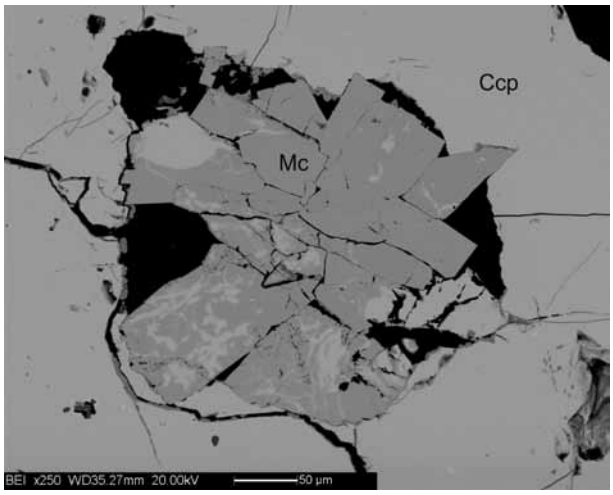

Fig. 17. Marcasite (Mc) in chalcopyrite (Ccp).

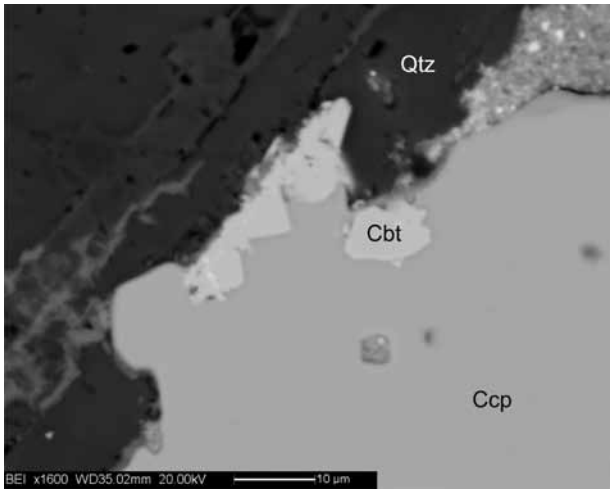

Fig. 18. Co, Fe, Ni sulfo-arsenides(Cbt) at the edge of chalcopyrite (Ccp).

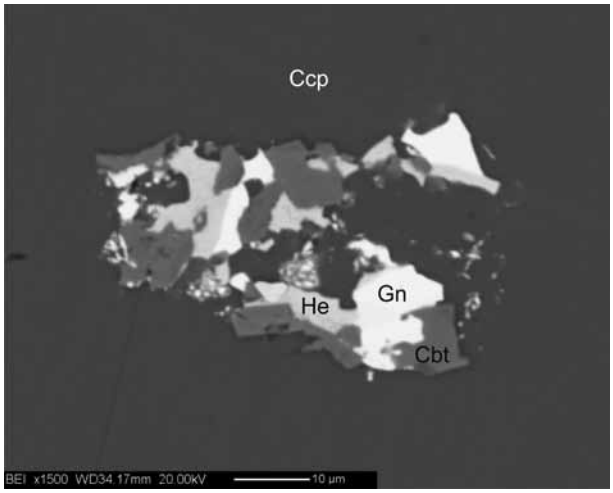

Fig. 19. Chalcopyrite (Ccp) containing a cluster of polymetallic sulfides including galena (Gn), Co, Fe, Ni sulfo-arsenides (Cbt), hessite (He) and very tiny intergrowths of sulfides, selenides and sulfosalts.

4.2.2. *The sulfidic polymetallic phase*

The sulfides phase mainly generated chalcopyrite accompanied by minor amounts of pyrite, sphalerite, galena and other sulphides and various sulfosalts. Chalcopyrite occurs as micrometer to millimetre large plagues interstitially developed with quartz, calcite and radially grown chlorite. Nodules, up to centimeters of chalcopyrite are common in the widening of some veins. Locally, granules of scheelite and small plagues of chalcopyrite coexist in the same vein, but usually occupy distinct sites in the gangue; in some cases, scheelite and chalcopyrite may be contiguous, but the structural, textural and paragenetic context indicates that the two mineralogical phases belong to different depositional steps, separated by an episode of brittle deformation.

Included in chalcopyrite, crystals of pyrite are common, up to a millimetre large, cubic, at places fractured and cemented by the same chalcopyrite. The main enrichments of chalcopyrite are subsequent to the formation of tourmaline; in fact, they cement its fractures and, in places, chalcopyrite appears to have selectively replaced feldspar, quartz and carbonate, which still remain as relic plagues, saving the tourmaline. Chalcopyrite also includes relics of magnetite and hematite (Fig. 14) accompanied by rests of the original quartz-carbonate gangue; in some instances, the paragenetic and textural character indicate original lamellar aggregates of hematite partially transformed into magnetite (muschketowite). The start of the sulfide formation seems still marked by pyrite1, which overlaps, even with phenomena of selective substitution, both on the metallic and gangue paragenesis of the wolframiferous event. This paragenesis is locally preserved as relics of mineral species relatively stable also under the new hydrothermal conditions, such as certain aggregates of ilmeno-rutile enclosed in pyrite1 (Fig. 15). Pyrite, locally with interstitial chalcopyrite, occurs generally as cubic crystals (few tens of microns up to 500-600 μm) scattered or aggregated in plagues. Some of these plagues are bordered and partially replaced by a rim of arsenopyrite which may in turn be surrounded by second-generation pyrite. Occasionally pyrite2 replaces, along boundaries and fractures, apatite crystals scattered in quartz (Fig. 16). Occasionally chalcopyrite hosts aggregates of marcasite (Fig. 17).

The metalliferous paragenesis accompanying chalcopyrite and pyrite is quantitatively incidental, but extraordinarily rich in mineral phases.

Pyrite may include tiny plagues of galena, chalcopyrite and sphalerite and, less frequently, Co, Fe, Ni sulfur-arsenide of the cobalt-glaucodoto family, at places grown on bravoite (Fig. 18 and Fig. 19). The SEM analysis of some cobaltite granules showed significant contents of Fe (about 6-8 wt%) and Ni (about 2-3 wt%).

Inclusions of sphalerite and galena are common in chalcopyrite. The small plagues of sphalerite locally show chalcopyrite exsolutions: in some cases "stars" of sphalerite are scattered in swarms in chalcopyrite. The sphalerite grown outside the plagues of chalcopyrite shows low Fe contents (1-2 wt%). Galena is generally poorly argentiferous: frequently, however, some of its plagues included in chalcopyrite contain or are accompanied by argentite/acantite occurring as both tiny grains (Fig. 20 and Fig. 21) and small plagues of discrete size (Fig. 22). Chalcopyrite also hosts few grains of hessite (Fig. 23 and Fig. 24), rare minuscule plagues of sulfosalts of the tetrahedrite-tennantite series slightly argentiferous and Zn-rich (7-8 wt% approx.) (Fig. 25). SEM analysis has also revealed the presence of tetrahedrite containing approx. 6 wt% of As and ca. 9 wt% of Bi and furthermore tiny plagues of a highly argentiferous sulfosalt of bismuth (approx. Bi 56 wt%, Cu 11-12 wt%, 17-18 wt% Ag, approx. S 14 wt%) for the identification of which more accurate microchemical and diffractometrical analyses are needed; it possibly represents an intergrowth of a phase like arcubisite/argento-cupro-cosalite/pavonite with other bismuth sulfosalts (Fig. 26).

In the quartz gangue accompanying the sulfides a variegated polymetallic microparagenesis is also disseminated: small grains of cobaltite (Fig. 27); tiny crystals of apatite and magnetite; grains of Ag-telluride, such as hessite, and Bi-telluride, probably pilsenite Bi_4Te_3 (Fig. 28); sporadic plagues consisting of fine intergrowths of chalcopyrite and various bismutiferous species (currently not defined), among which native Bi is recognizable. Eni – Aquater (1997) recorded also traces of electrum.

The closure of the hydrothermal sulphide-bearing event is preceded by a mild fracturing involving both the lithic clasts and the mineralized veins. A network of thin narrow veins of calcite with minor micro-quartz (flint-opal) cements the late fractures (Fig. 29). These veinlets contain rare tiny plagues of chalcopyrite and galena (galena2), and sporadic micrograins of rutile.

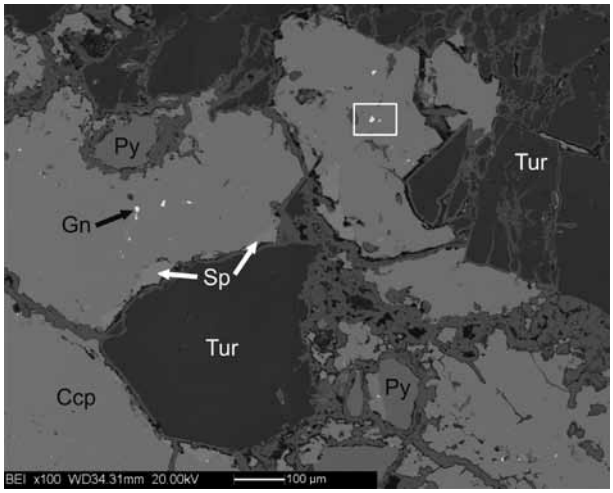

Fig. 20. Pyrite (Py) and chalcopyrite (Ccp) with small grains of sphalerite (Sp) and galena (Gn, white) associated with argentite/acantite (box, Fig. 21). Gangue of quartz and tourmaline (Tur). Alteration veinlets (mainly goethite and cuprite) cross the chalcopyrite.

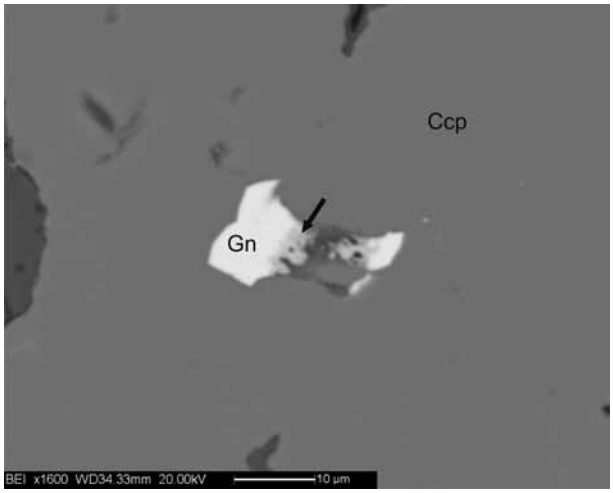

Fig. 21. Detail of Fig. 20. Chalcopyrite (Ccp) including small grains of galena (Gn) with argentite/acantite (arrow).

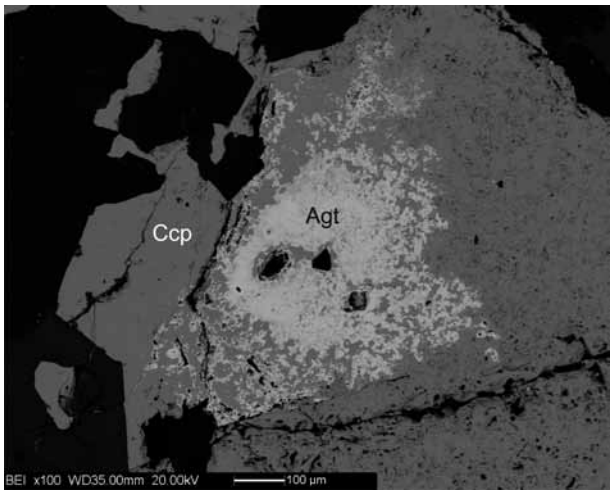

Fig. 22. Chalcopyrite (Ccp) enclosing a intergrowth with prevailing argentite (Agt), small grains of argentiferous galena and sporadic hessite.

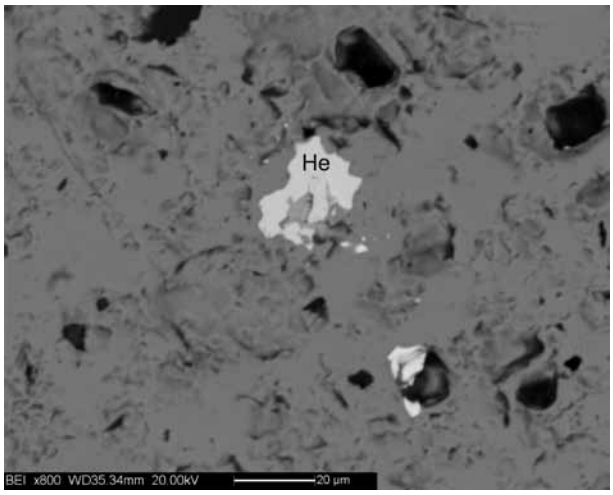

Fig. 23. Hessite (He) in argentite.

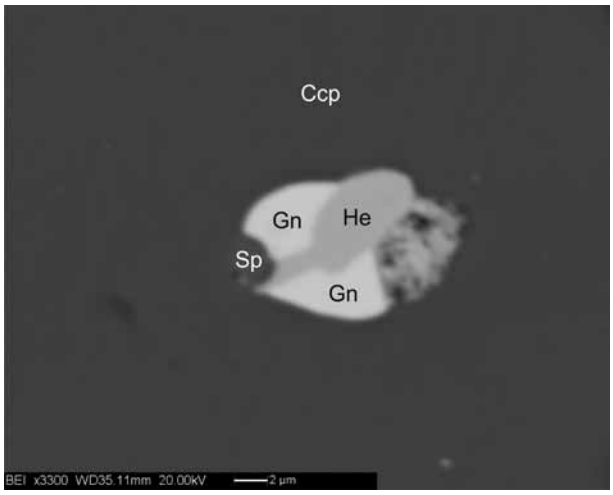

Fig. 24. Chalcopyrite (Ccp) including a polymineralic aggregate of galena (Gn), hessite (He) and sphalerite (Sp).

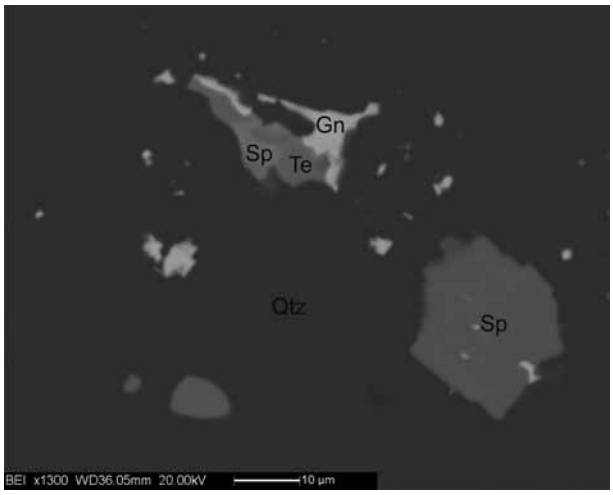

Fig. 25. Tennantite (Te), galena (Gn) and sphalerite (Sp) disseminated in gangue of quartz (Qtz). See also Fig. 10.

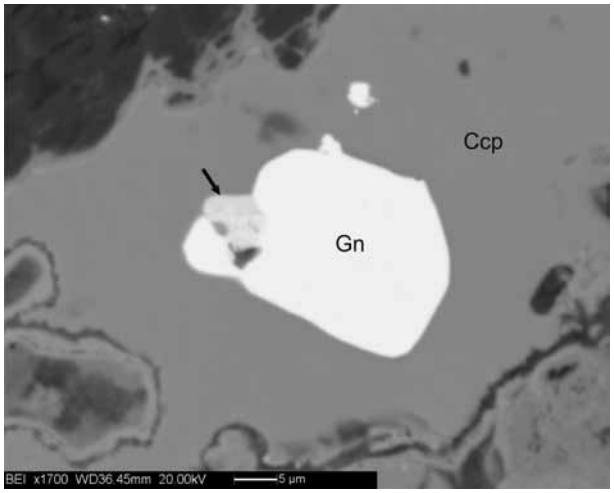

Fig. 26. Chalcopyrite (Ccp) enclosing galena (Gn) with strongly argentiferous Bi sulfosalt (arrow).

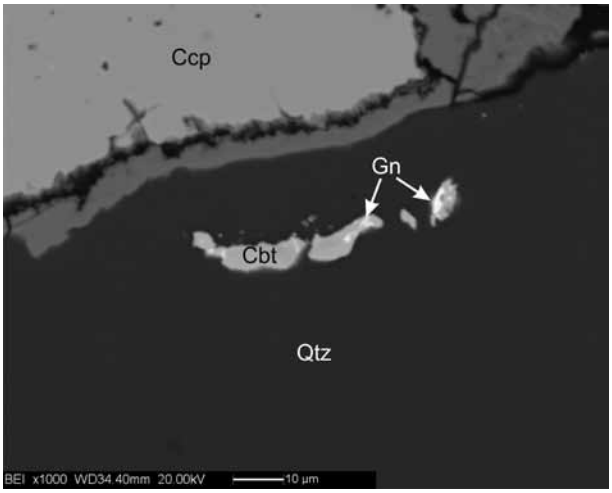

Fig. 27. Tiny grains of cobaltite (Cbt) and galena (Gn) in quartz (Qtz) close to chalcopyrite (Ccp) with an alteration vein at the quartz-chalcopyrite boundary.

Widespread supergenic alteration affects sulphides, mostly in the samples collected in the dump or outer squares of the galleries of Vecchia Bedovina. Particularly sensitive to oxidation phenomena are pyrite and chalcopyrite. Many of the minor chalcopyrite plagues isolated in the gangue are completely transformed into aggregates of covelline, malachite, azurite, cuprite, goethite etc.; nodules and the larger plagues are frequently bordered and locally crossed by characteristic composite bands of "colloform" aspect (Fig. 29) in which films of alternating goethite and cuprite are at places combined with malachite and azurite. Quite common is the alteration of pyrite to goethite which often spreads along a myriad of cryptic small uncemented fractures, presumably induced by alpine tectonics.

5 Summary and metallogenic considerations

The emplacement of the deposits of W (Mo, Sn, Bi, REE) and of Cu (with Pb, Zn, Ag, Te, Co, Ni ...) of Bedovina marks the end of the Mid-Triassic magmatic cycle of the Predazzo-Monzoni Complex. The mineralization forms a network of veins, from pneumatolytic to hydrothermal. The veins crosscut all the magmatic rocks, including the most recent terms as some minor granitic bodies and some acidic and basic dykes.

A genetic link between Bedovina mineralization and granitic intrusions has been suggested by several authors (e.g. Becke, 1895; Hoffmann, 1903; Granigg & Koritschoner, 1913; Lazarevic & Kittle, 1913; Di Colbertaldo, 1955; Bianchi & Di Colbertaldo, 1956); some of the cited authors point out the presence of small radial growths of tourmaline crystals and traces of other minerals characteristic of the mineralization of Bedovina in the "pink granite" outcropping between Predazzo and Mezzavalle, strongly altered by pneumatolytic-hydrothermal processes. Brigo (1989) instead links scheelite mineralization and polymetallic sulfides of Bedovina with fluids derived from the monzonitic-syenitic and monzodioritic masses; some minor events bearing Mo and W would be related to the granites.

Data from our study indicate that, in the area of Bedovina, the main metalliferous event is anticipated by sporadic leaves of molybdenite genetically correlated with the mineralization of Aivola, in which molybdenite was formed during the final stages of crystallization of the host granite characterized by large K-feldspar crystals. Shortly later tectonic movements originated the bands of clastesis who guided the rise of pneumatolytic-hydrothermal metalliferous fluids, late products of granite crystallization. In a regime of decreasing temperature these fluids generate stockworks of copper-wolframiferous veins forming firstly the pneumatolytic paragenesis, carriers of wolfram (and minor Sn and REE) and later the hydrothermal mainly cupriferous mineralization, but with distinct polymetallic connotations (Fe, Zn, Pb, Ag, Co, Ni, Sb, As, Bi, etc.) evidenced by sulphides, sulfosalts, telluride, etc..

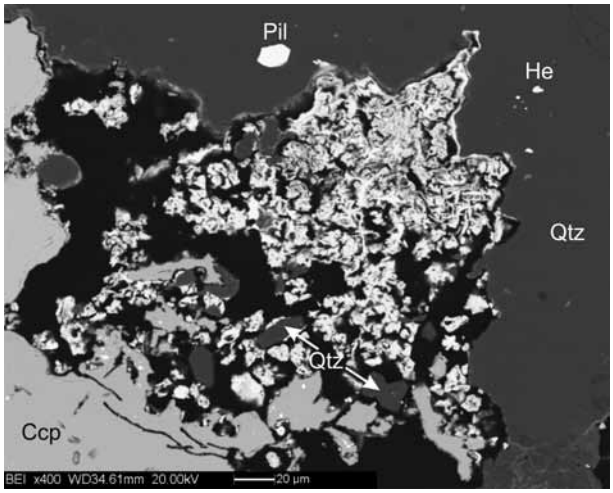

Fig. 28. Quartz (Qtz) and chalcopyrite (Ccp) surrounding a complex intergrowth of chalcopyrite, native Bi and some very tiny of not specified Bi-bearing minerals. Quartz encloses Bi-tellurides (likely pilsenite, Pil) and hessite (He)).

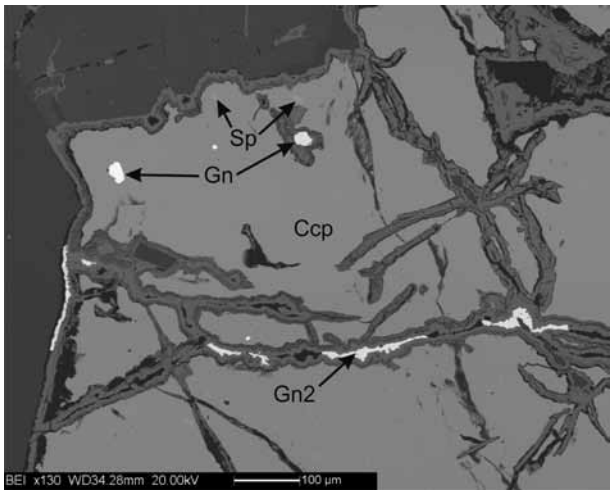

Fig. 29. Chalcopyrite (Ccp) in gangue of quartz, includes small grains of sphalerite (Sp) and galena (Gn). Alteration veinlets (mainly oxides and hydroxides of Fe and Cu) cross the chalcopyrite: some of them are arranged on late fractures cemented by carbonates and galena2 (Gn2).

The paragenesis of the wolfram phase is characterized by scheelite with quartz, tourmaline, K-feldspar, some carbonate, minor biotite and chlorite, and accessory amounts of magnetite, ilmenite, apatite (with enrichment of fluorine at the edge of crystals), rutile (locally with significant contents of Fe and Sn, especially in the core), rare cassiterite (with discrete contents of Ti and Fe), synchysite-(Ce) and finally hematite. According to Champion and Blevin (2005), Sn^{4+} is related to strongly fractionated and reduced granites in which the ratio Fe_2O_3/FeO <1 and Rb/Sr >>1, and it tends to disperse in titanium minerals; Cu and Mo probably correlate to slightly fractionated magmas, island-arc or Andean type, in which Fe_2O_3/FeO>1 and Rb/Sr >>1.

The moderate and at places high contents of Mo checked in some grains of scheelite, the persistence of apatite2 and of REE, U and Th minerals (e.g. monazite in MoS_2 occurrences, synchysite in the wolfram paragenesis) seem to emphasize a geochemical relationship between the wolfram mineralization and the molybdenite occurrences and the relationship of both with granites, which seem to have been affected by crustal contamination processes, as suggested by Coltorti et al. (1996).

The sulfide paragenesis follows, overlapping and partly replacing, the wolfram mineralization. The essentially cupriferous characters are accompanied by evident polymetallic connotations, defined by the minor but widespread presence of Zn, Pb, Ag, Te, Co, Ni, Bi, As, Sb, etc. Sulfides were deposited by hydrothermal fluids that followed the same pathways of wolfram reactivated by a new clastic event and in a substantially changed redox context. The transition between the wolfram phase and the copper-polymetallic sulfides phase is indeed marked by a "momentary" onset of oxidizing conditions evidenced by the crystallization of hematite present both as disseminated plates in the quartz gangue and as overgrowths on existing grains of magnetite; immediately after that, the local transformation of hematite into magnetite (mushketowite), as observed at Vecchia Bedovina, marks the establishing of the reducing conditions that accompanied the sulfides stage.

The sulfides paragenesis, which comprises tiny crystals of cobaltite, chalcopyrite with spread stars of sphalerite, but also sphalerite (with low contents of Fe), poorly argentiferous galena and several Ag-bearing minerals (sulfides such as argentite/acantite, tellurides like hessite, bismutides and sulfosalts), shows meso-epithermal characters.

Of a particular metallogenic significance is thorian synchysite-(Ce). It has been reported at M. Mulàt by Ravagnani (1974) and in the Vicentine Alps by Pegoraro (1998) in the context of the Val Riolo iron mineralization, genetically related to the Middle Triassic magmatism (Frizzo, 1997; 2003). According to Förster (2000) the synchysite present in the granites with "A type" affinity of Markersbach (Erzgebirge) is derived from the leaching effect of late-magmatic fluid rich in F, CO_2, Ca, on REE minerals such as monazite and xenotime present as accessories in the granite; fluids would have released REE and Th reprecipitating them nearby as fluocarbonates. Similar

processes may have acted in the context of Bedovina (and more generally on the granitoid masses of Predazzo and Monzoni Complexes), from where monazite in granites and thorian synchysite-(Ce) in the wolframiferous veins are reported.

Finally, it is important to stress that:

i) the metal paragenesis of the "wolfram phase" of Bedovina, is characterized by the association W, (Sn, Nb, Ta, REE, Th). In terms of metallogenesis (e.g. Beckinsale, 1979; Pitcher, 1983; Sawkins, 1990), it indicates a kinship with magmas of the leucogranitic series, and in particular with peraluminiferous *"S type"* granitoids, with A/CNK>1.1. These are granites poor in magnetite and with abundant ilmenite, commonly characterized by low contents of Sr with respect to Rb, with high Rb/Sr, low K/Rb ratios and $^{87}Sr/^{86}Sr>$ 0.706. Similar geochemical characters, thus favourable to W and Sn minerogenesis, are shown by *"granites"* of Predazzo (sienogranites - sensu Eni- Aquater, 1997); in the granites, SiO_2 varies from 62 wt% to 86 wt% in positive correlation with Rb, K_2O, Be, Nb and negative with Fe_2O_3, CaO, TiO_2, MgO, MnO, Co, V, Zn; the concentrations of Ba and Sr are low (about 60 ppm). The contents of B (on average present with 100 ppm), F (up to 1200 ppm) and Li (60-250 ppm) are significantly high. The high concentrations of Rb and the low values of Ba and Sr, which determine high Rb/Ba (up to 40) and Rb/Sr ratios (up to 100) and low K/Rb ratios (decreasing from 200 to 100 in the more strongly sericitized rocks), indicate granitoids and magmatic-postmagmatic residual fluids rich in incompatible elements and potentially productive for W and Sn mineralization;

ii) the metal paragenesis with Cu, Zn, Pb, Ag, Te, Co, Ni, Bi, As, Sb, (and Mo?) that characterizes the sulfide "copper phase" refers to, from the metallogenic point of view (e.g. Evans, 1993; Hutchinson, 1983 and references therein), a relationship with *"I type"* granitoids of the calcalkaline series with A/CNK<1.1, Mg-rich biotite, disseminated magnetite, absent or very scarce ilmenite and monazite, Sr/Rb ratios inverted compared to *"S type"* granitoids. Other character would be a higher fO_2.

The mineralization of Bedovina therefore seems to derive from residual metalliferous fluids produced from the crystallization of two distinct granitoid magmas: the first, marked by *"S type"* characters, would have generated the parageneses typical of the "wolfram phase" with W (Sn, REE, Th); the second, with "I type" characters, would be responsible for polymetallic associations that characterize the "copper phase". The sporadic molybdenite occurrences could be related to this last type of magma.

Alternatively, the hypothesis of a single hybrid granitic magma could justify the complexity of the copper and wolfram parageneses and the significant contents of Mo sometimes present in the scheelite.

Acknowledgments

The authors are grateful to D. Visonà for helpful suggestions and kind discussions on the evolution of magmatism which originated the Predazzo Eruptive Complex and the several mineralization related to it. The authors appreciate A. Guastoni and A. Marzoli for the critical review of the text.

The authors express gratitude to A. Braito and G. Cincelli for collaboration during field works and to D. Ferrari for graphic elaboration of the mine sections.

This work was financially supported by Comune di Predazzo.

References

Becke, F. (1895): Scheelit im Granit vom Predazzo. - Tscherm. Min. Petr. Mitt., 14: 21-22.

Beckinsale, R. D. (1979): Granite magmatism in the tin belt in the South-East Asia. - In: Atherton M. P., Tarney J. (eds.): Origin of Granite Batholiths, 34-44, Shiva, Orpington.

Bianchi, A., Di Colbertaldo, D. (1956): Osservazioni paragenetiche sul giacimento a rame e tungsteno della Bedovina presso Predazzo. - Rend. Soc. Miner. Ital., 12: 55-68.

Brigo, L. (1989): Tungsten as a geodynamic marker in the Italian continental crust. - In: Boriani A., Bonafede M., Piccardo G.B., Vai G.B. (eds.): The Lithosphere in Italy, Atti dei Convegni Lincei, 80: 407-425.

Champion, D., Blevin, P. (2005): New insights into intrusion-related gold–copper systems in the Tasmanides. - Mining 2005, Brisbane, 26 October, 30p.

Castellarin, A., Lucchini, F., Rossi, P.M., Sartori, R., Simboli, G., Sommavilla, E. (1982): Note geologiche sulle intrusioni di Predazzo e Monzoni. - In: Castellarin A., Vai G.B. (eds): Guida alla Geologia del Sudalpino centro-orientale. Guide Geol. Reg. Soc. Geol. It.: 211– 219.

Coltorti, M., Siena F., Visonà D. (1996): Aspetti petrologici del magmatismo triassico dell'area di Predazzo. - Libro dei Riassunti, 78° Riunione estiva Soc. Geol. Ital.

Di Colbertaldo, D. (1955): I minerali metallici e le ganghe del giacimento della Bedovina all'esame microscopico. - Rapporto inedito, 6 luglio 1955, 5pp.

Degiampietro, C. (1975): Cronache fiemmesi attraverso nove secoli. - 308pp, Arti Grafiche Manfrini, Calliano.

Dellantonio, E. (2000): Le miniere del territorio eruttivo di Predazzo e Monzoni. - Natura Alpina, 4: 65 – 77.

Eni - Aquater (1997): Mineralizzazioni a Cu, W, Sn e associati dell'area di Predazzo-Monzoni. - Ricerca mineraria di base (Legge 6.10.1982, n. 752, art. 4), Relazione conclusiva, Ministero dell'Industria, del Commercio e dell'Artigianato, Direzione Generale delle Miniere, 54pp.

Evans, A. M. (1993): Ore Geology and Industrial Minerals. An Introduction. - Blackwell Scientific Publications, 396pp, Chapman Hall, London.

Förster, H. J. (2000): Cerite-(Ce) and thorian synchysite-(Ce) from the Niederbobritzsch granite, Erzgebirge, Germany: implications for the differential mobility of the LREE and Th during alteration. – Can. Mineral., 38: 67-79.

Frizzo, P. (1997): Le mineralizzazioni argentifere delle Alpi Vicentine. - In Brigo L., Tizzoni M. (eds): Il Monte Calisio e l'argento nelle Alpi dall'antichità al XVIII secolo, 43-59, Temi, Trento.

Frizzo, P. (2003): I giacimenti e le miniere della Val Leogra e del Tretto. – In: Frizzo P. (ed): L'argento e le "terre bianche" del Tretto e della Val Leogra, 39-76, Menin, Schio.

Granigg, B., Koritshoner, J. H. (1913): Die turmalinführende Kupferkies-Scheelitlagerstätte am M. Mulatto bei Predazzo (Südtirol). - Z. Prak. Geol., 11: 481-497.

Hoffmann, A. (1903): Vorläufiger Mitteilungen über turmalinführende Kupferkiese von Monte Mulatto. - Sitzb. d. königl. Böhm. Akad. d. Wiss. II Classe (Separataabdruck), 16: 1-8.

Hutchinson, C. S. (1983): Economic Deposits and their Tectonic Setting. - 487 pp, Macmillan, London.

Laurenzi, A., Visonà, D. (1996): 40Ar/39Ar chronology of Predazzo magmatic complex (Southern Alps, Italy). - Libro dei Riassunti, 78° Riunione estiva S.G.I.

Lazarevic, M., Kittl, E. (1913): Einige untersuchungen der kupferkiesführenden Mineralgänge am M. Mulatto bei Predazzo. - Österreichischen Zeitschrift für Berg- und Hüttenweisen (Separatabdruck), 15 pp.

Marrocchino, E., Coltorti, M., Visonà, D., Thirwall, M.F. (2002): Petrology of Predazzo magmatic complex (Trento, Italy). – Geochim. Cosmochim. Acta, 66(15A, Suppl. 1): A486-A486.

Menegazzo Vitturi, L., Visonà, D., Zantedeschi, C. (1995): Amphibole composition of Predazzo volcano-plutonic complex (Southern Alps, Italy). - Mem. Sci. Geol. 47: 87-94.

Oss Mazurana, F., (1905, 1906): Miniere del Monte Mulatto. - Bollettino dell'Alpinista, 1(5): 94-95, 1(6): 106-108, 2(4): 164-171.

Oss Mazurana, F., Hesser, R. (1909): Die Betriebe der Kupfererzbergbau-Gewerkschaft „Oss-Mazzurana" in Predazzo. - Metallurgie, VI(18-19): 569-596.

Pelloux, A., (1919): I minerali italiani di tungsteno. - La miniera italiana, 33(3): 91-95.

Pitcher, W. S. (1983): Granite: typology, geochemical environments and melting relationships. – In: Atherton M. P., Gribble C. D. (eds): Migmatites, Melting and Metamorphism, 277-285, Shiva, Nantwich.

Pegoraro, S. (1998): Minerali rari del Vicentino: la synchysite (Ce) della Galleria Veneziana, Val Riolo, Torrebelvicino (Vicenza). – In: Dondi, M., Puggioli, G. (eds): Minerali d'Italia, 16-17, Centro Documentazione Mineralogica, Bologna.

Ravagnani, M. (1974): I giacimenti uraniferi italiani ed i loro minerali. - 188pp, Gruppo Mineralogico Lombardo, Museo Civico di Storia Naturale di Milano, Milano.

Sawkins, F.J. (1990): Metal Deposits in Relation to Plate Tectonics. - Springer Verlag, Berlin.

Šebesta G. (1992): La via del rame. – 221pp, Supplemento a "Economia Trentina" n. 3, Camera di Commercio, Industria, Artigianato, Agricoltura di Trento, Trento.

Stella, A. (1953): L'industria mineraria del Principato Vescovile di Trento nei secoli XVI e XVII. Com. Econom. Sc. Triveneto Studi, Applic. e Ric. Univ. Padova, 49-93.

Stella, A. (1957): L'industria mineraria del Trentino nel secolo XVIII. Com. Econom. Sc. Triveneto Studi, Applic. e Ric. Univ. Padova, 2:183-206.

Vardabasso, S. (1930): Carta geologica del territorio eruttivo di Predazzo e Monzoni nelle Dolomiti di Fiemme e di Fassa, Scala 1:25.000. Regia Scuola di Ingegneria, Padova.

Vergani, R. (2002): Gli usi civili della polvere da sparo (secoli XV-XVIII), in Economia e energia. Secc. XIII-XVIII. – In: Cavaciocchi S. (ed): Atti della XXXIV Settimana di studi dell'Istituto internazionale di Storia economica "F. Datini" (Prato, 15-19 aprile 2002), Le Monnier, Firenze.

Visonà, D. (1997): The Predazzo multipulse intrusive body (Western Dolomites, Italy). Field and mineralogical studies. - Mem. Sci. Geol., 49: 117-125.

Manuscript submitted 2.7.2010
Revised Manuscript accepted 20.10.2010

ZOBODAT - www.zobodat.at

Zoologisch-Botanische Datenbank/Zoological-Botanical Database

Digitale Literatur/Digital Literature

Zeitschrift/Journal: Geo.Alp

Jahr/Year: 2010

Band/Volume: 007

Autor(en)/Author(s): Frizzo Pietro, Peruzzo Luca, Dellantonio Elio

Artikel/Article: The Copper-Wolfram deposit of Bedovina (Trento, Italy) 55-70