



Journal of the Geological Survey of Brazil

Mineralization constraints on the origin of polymetallic (Pb, Ag, Zn, Cu, Au) deposits hosted in the metasedimentary Lajeado Group, Southern Ribeira Belt, Brazil

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Abstract

The sediment-hosted polymetallic (Pb, Zn, Ag, Au-Cu) mineralization of the Vale do Ribeira Mineral District has been known since the beginning of the 20th century, but exploration was interrupted just before the turn of the century. The Vale do Ribeira Mineral District is part of the Southern Ribeira Belt, developed during the Brasiliano-Pan African orogeny. Polymetallic mineralization is mainly hosted in metalimestones of the Lajeado Group, a typical platform carbonate sequence of a passive margin, which has been deformed during the Gondwana assembly. The region has a gap of research since the mines were closed, which justifies new projects on their mineral economic potential. Fieldwork, petrographic and geochemical analyses were developed in five currently inactive mines (Panelas, Barrinha, Rocha, Lajeado, and Furnas) and their surroundings, along with the description of a drill core executed in the 1980s. The main type of ore consists of polymetallic fault-fill veins of massive sulfide, which are composed essentially by argentiferous galena, sphalerite, pyrrhotite, arsenopyrite, and chalcopyrite. The highest ore grades were obtained from samples in the Panelas Mine, with contents of up to 35% lead, 5% zinc, > 1% copper and 564 ppm silver, as well as 23% iron. New ore occurrences were described in a secondary gallery of the Barrinha Mine, whose gold grades reached up to 5,630 ppb. The main controls of the mineralization are lithological - since the ore occurs exclusively in carbonate rocks, irrespective of the geological unit - and structural, related to NE high-angle strike-slip fault zones, including evidence of fault-valve behavior. Fault zones as the main control of the polymetallic veins is an innovative interpretation, increasing the perspectives for mineral exploration in the area. Although they are small deposits, the presented data indicate that the region has potential for new discoveries and that the mined deposits are probably not exhausted.

Article Information

Publication type: Research paper
Received 28 April 2020
Accepted 30 October 2020
Online pub. 15 December 2020
Editor: C. Renac

Keywords:
polymetallic mineralizations,
fault zones,
ore controls,
Southern Ribeira Belt,
carbonate rocks

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1. Introduction

The region of Southern Ribeira Belt is nationally recognized as an important Metallogenetic Province, and during the 1950s, it was the most significant metallurgical hub for production of lead and silver in Brazil, and the country's second largest producer of gold. Production of base metals in the region started in the early 1920s in the galleries of the Lajeado Group (Lajeado and Rocha targets).

Since the 1970s, several projects aiming at an evaluation of the mineral potential of the Southern Ribeira Belt have been carried out, and they have highlighted the regional geochemical investigation developed by the Geological Survey of Brazil (SGB/CPRM) (Addas and Vinha 1975; Morgental et al. 1975,

1978). These works have indicated significant anomalies of copper, lead, and zinc, and were the basis for detailed research focusing on prospecting for gold and associated sulfides. During the 1980s, owing to the region's economic relevance, the SGB/CPRM developed two major projects based on geological data compilation and consistency, and detailed mapping of the economic targets. The "Anta Gorda" project was developed in partnership with the "Japan International Cooperation Agency" (JICA) and "Metal Mining Agency of Japan" (MMAJ) (MMAJ-JICA 1981, 1982, 1983, 1984; Daitx et al. 1983; Daitx 1984), and the "Geological Integration and Detailing of Vale do Ribeira" project (Silva et al. 1981) with an agreement with the Brazilian National Mining Agency (ANM). The data of the projects were refined and compiled in



a GIS database, and part of them provided the basis for the reevaluation of the Lajeado region (Lopes et al. 2017).

The region of Lajeado and Rocha Pb mines are included in the context of the polymetallic mineralization described by Fleischer (1976) as "Panelas style". The main mines (Furnas, Rocha, Lajeado, Barrinha, and Panelas) are hosted in metalimestones of the Lajeado Group, located in the vicinity of the cities of Apiaí, Ribeira, and Adrianópolis, on the border between the states of São Paulo and Paraná (Brazil). Lead mineralization occurs mainly as sulfides, which are associated with other relevant elements, such as gold, silver, zinc, and copper. All of the mines are currently inactive.

This paper presents the results of the project of Lopes et al. (2017), which uses a multi-technique approach including the fields of geology and petrography, structural analyses, and both ore and rock geochemistry, aiming to determine the main mineral and structural controls of the polymetallic mineralizations of the Lajeado and Rocha targets. The Vale do Ribeira region has many legalized Environmental Protection Areas, Atlantic Forest, cave parks, and communities of indigenous people and Afro-Brazilian quilombolas. The correct evaluation of their geological potential is essential to optimize the economic assessment of these particular areas.

2. Geological Context

The study area is located in the context of the Southern Ribeira Belt, which comprises the Apiaí, Embu, Curitiba, Paranaguá, and Costeiro terrains (Faleiros 2008), whose current configuration is due to successive collisions that have occurred in the Brasiliano-Pan African Orogeny (Siga Junior 1995; Heilbron et al. 2004) (Figure 1).

The Apiaí Terrain, the focus of this work, comprises an association of lithostratigraphic units generated in distinct environments and ages, which are in tectonic contact through strike-slip shear zones, such as Ribeira and Lancinha shear zones (Figure 1). The ages of the geologic units range from the Calymmian (1,450-1,500 Ma: Votuverava Group, including

Perau Formation, Serra das Andorinhas Sequence, and Água Clara Formation), Stenian-Tonian (910-1,030 Ma: part of Itaiacoca and Lajeado groups) to the Ediacaran (630-580 Ma: Iporanga Formation and part of Itaiacoca Group), formed by accretion during the Brasiliano-Pan African Orogeny (Campanha, Faleiros 2005; Faleiros 2008; Faleiros et al. 2011). Deformed granitoids of the Statherian age (1,750-1,800 Ma) (Cury et al. 2002; Prazeres Filho 2005; Ribeiro 2006; Mesquita et al. 2017) occur mainly in the nucleus of restricted antiform structures. Ediacaran, high-potassium, calc-alkaline granitoids occur as intrusive bodies in metasedimentary rocks (e.g. Prazeres Filho 2000, 2005; Janasi et al. 2001).

Zooming further, the Açungui Supergroup is defined by Faleiros (2008) as formed by the Água Clara Formation, Votuverava Group, Lajeado Group, Serra das Andorinhas Sequence and Itaiacoca Group (Figure 1). However, only the three first units outcrop in the study area. From bottom to top, the Água Clara Formation consists of a Schist Unit and a Carbonate Unit with medium-grade greenschist metamorphism. The carbonate unit is the most important because it hosts the polymetallic mineralization of Rocha Mine. The Votuverava Group outcrops in the southwestern portion of the study area, at the southern part of Ribeira Fault (Figure 1). It comprises a medium-grade metavolcano-sedimentary sequence with expressive basic volcanism and does not host any of the studied mineralizations. The Lajeado Group is the main lithostratigraphic unit investigated in this work and contains most of the mineral occurrences and mines. It forms an anastomosed strip (limited by shear zones), which extends from the southwest to the northeast portions of the area, in which the two targets - Lajeado and Rocha - are located (Figure 2). The Lajeado Group is formed by low grade greenschist metasedimentary rocks that form a carbonate-siliciclastic sequence.

3. Materials and Methods

The investigation of the Lajeado and Rocha targets involves GIS database preparation, from the previously mentioned

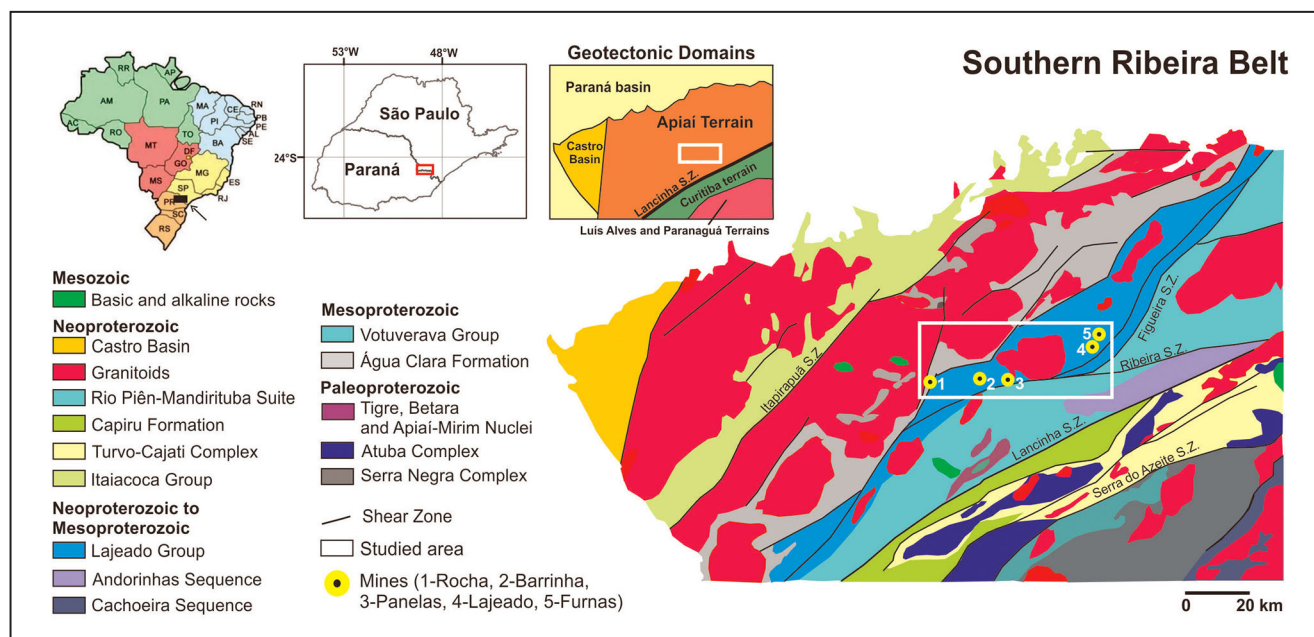


FIGURE 1. Location of the study area in the context of the Southern Ribeira Belt (modified from Rodrigues et al. 2011).

projects, including new fieldwork, petrographic analysis, and litho-geochemistry data. The fieldwork was developed in several regional geological profiles, transverse to the NE-SW mineralized trends, and in the remaining mineralizations from mine galleries. Two existing drill cores, preserved in the SGB/CPRM rock storehouse, were reconstructed, based on descriptions in previous projects (Silva et al. 1981; MMAJ-JICA 1981, 1982, 1983, 1984), and complemented by macroscopic analysis on the zones near the highest sulfide concentrations. Subsequently, samples were selected for petrographic and chemical analysis (results in the electronic supplementary data).

A remark must be made regarding the fieldwork on the mines from Rocha and Lajeado targets. After these mines were in active production for decades, they were all closed down in the late 1990s and left virtually abandoned. With the exception of the main Barrinha Mine, all others were underground works. From the 1990s to present, the access to these underground mines has degraded severely; therefore, rock exposures described in the previous works conducted where these mines were active are certainly not the same exposures as the ones described here. The entrances to several galleries have been closed off, either intentionally, to prevent access to passers-by, or naturally, owing to the collapse of the roof. Moreover, access to deeper levels of the mines was further limited owing to security implications of working in abandoned underground galleries.

Sixty-five thin and polished-thin sections were described using an Olympus BX51 microscope (SGB/CPRM, São Paulo branch). Petrographic analysis was focused on mineralization and its respective host rocks, through petrographic profiles (also on an outcrop scale), to provide further information on textural relationships and paragenesis, from the unaltered host rocks up to the mineralized zone, in an attempt to identify modifications caused by ore-forming processes.

Litho-geochemistry analyses were made in sixty-five rock and ore samples by SGS Geosol Laboratórios Ltda, especially to determining ore grades (electronic supplementary data). The composition of major elements was determined by X-ray fluorescence (XRF). For trace elements, samples were processed by total digestion using 4-acid attack (nitric, chloridric, hydrofluoric, and perchloric acids) or by fusion with lithium metaborate and then analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Optical Emission Spectrometry (ICP-OES). In the ore samples, concentrations of gold, platinum, and palladium were determined by the fire assay preparation method and analysis in ICP-OES, while silver concentration was determined by Atomic Absorption Spectrometry (AAS) analysis.

4. Main geological and structural features of the targets

The host rocks of the Rocha and Lajeado targets belong to the Lajeado Group, which are mainly formed by a low-grade greenschist metasedimentary sequence – composed of metalimestones, metarhythmites, metasilstone, and metasandstones – with preserved original sedimentary structures. The top of the sedimentary sequence (Gorotuba Formation) is intruded by a Gabbro layer (Apiaí Gabbro). It is observed intense contact metamorphism, which forms layers

with amphibole-hornfels. The rocks of Lajeado Group are intruded in the central portion (between the two targets) by a main granitic body, Itaoca Granite (Figure 2).

5. Rocha target and its mines

The Rocha target is located southwest of Itaoca Granite and comprises the inactive Panelas, Rocha, and Barrinha mines (Figure 2). The Panelas mine is located in Bairro da Serra and Betari formations of the Lajeado Group. It is the closest mine to the Itaoca Granite and Ribeira Shear Zone, in the ENE-WSW strike direction (Figure 2). The Barrinha Mine is located 5 km south of Adrianópolis town (state of Paraná). It occurs in the Bairro da Serra Formation, which is enveloped by the Água Suja Formation. Other mineralization occurrences were also described in the Água Suja Formation. The Rocha Mine is located in the southwestern part of the study area. The ore is hosted in marbles of the carbonate lithofacies of Água Clara Formation. This is the only mine outside the Lajeado Group.

In the geological profile that crosses Barrinha Mine (Figure 3A, location of profile AA' in Figure 2), the sequences of the Lajeado Group are folded, developing kilometer-scale isoclinal folds. They are cut by NE-trending reverse faults and strike-slip shear zones. The strike-slip shear zones may coincide with the isoclinal fold axes, as in the Barrinha mine. The Barrinha Mine is located in a lens of metasedimentary rocks of Água Suja Formation (Lajeado Group). The rocks comprise an intercalation of thin layers of metasilstone, metaclaystones and metasandstones.

The rocks of Betari (metasilstones, metasandstones and metaconglomerates), Água Suja (metargillites, metasilstones and metasandstones), and Serra da Boa Vista formation (metasandstones) present a well-developed primary bedding (S0). Three different foliations, denominated here as S1, S2, S3, affect the original bedding. Mica defines a pervasive schistosity S1, whose main strike is NE-SW, subparallel to the primary bedding (S0). S1 is crenulated and locally transposed to an axial surface foliation (S2) (Figure 3B). S3 has a N40-60E strike direction and is distinguished by high angle anastomosing planes and local mylonitic zones (Figure 3C). It is genetically related to the strike-slip shear zones on a regional scale. S3 is affected by brecciation and developed breccias and sub-parallel fractures filled or not by quartz and/or carbonate and/or sulfides (Figure 3D). Several veinlets cut the rocks, and are important structures for sulfide concentration, described in the following characterization of the mines.

5.1. Panelas Mine

The Panelas Mine is located in the Rocha target and very few remaining galleries are still accessible. The mineralization is hosted by predominantly banded metalimestones of Bairro da Serra Formation, alternating dark gray centimetric layers of very fine carbonate, and white layers of fine carbonate. White mica is more frequent in the darker layers.

The main ore occurs in massive sulfide veins, which are tabular veins with up to 40 cm thickness. Their preferential orientation is N55-65E, 45SE, hosted in high angle faults (Figures 4A and B). However, the veins and the sedimentary bedding could be subparallel (Figure 4C).

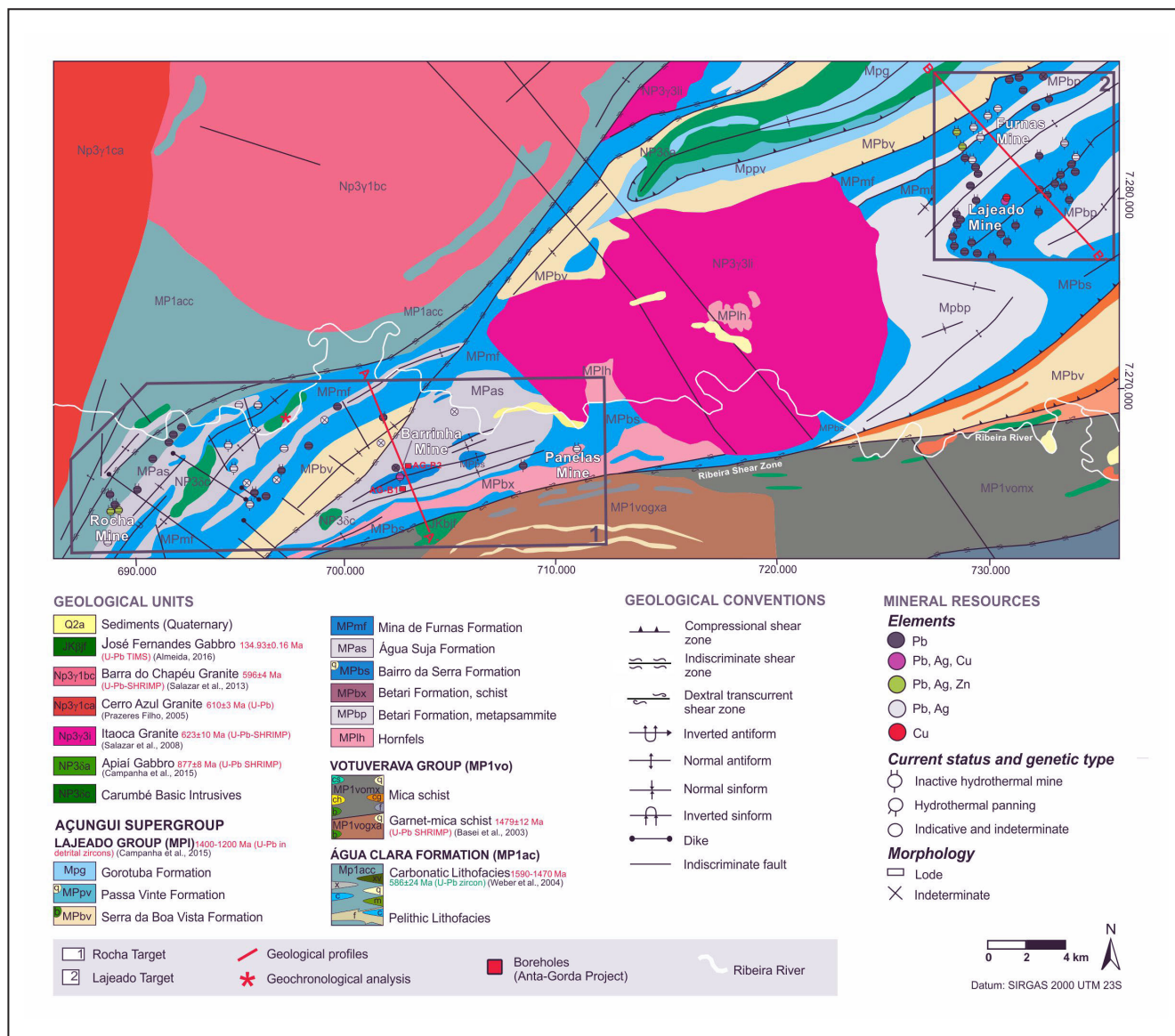


FIGURE 2. Geological map with the location of the selected areas for investigation, called Lajeado target (including Lajeado and Funas inactive mines), and Rocha target (including Rocha, Barrinha and Panelas inactive mines); the occurrence of mineral resources; the location of the studied drill cores (Silva et al. 1981; MMAJ-JICA 1981, 1982, 1983, 1984); and the location of geological profiles. The symbology for the mineral resources should be read as an integrated symbol resulting from the superposition of the three subitems “element” + “current status and genetic type” + “morphology” (Modified from Caltabelotta et al. 2017).

The host metalimestone is affected by structures, as breccias, fractures, hydraulic fractures, and several veinlets. Metric zones of breccias are found in the carbonate host rocks a few meters away from these veins (Figure 4D). They are composed of metalimestone lithoclasts in carbonate cement. Populations of fractures occur in the area, mostly close to the NE-trending strike slip faults. They are straight and continuous with centimetric thickness, while the hydraulic fractures have no preferred orientation (Figure 4D) and are filled with carbonate. Figure 4D also shows that millimetric calcite healed fractures are cross-cut and displaced by centimetric composite faults. The composite faults from wall to the inner zone are healed by calcite and oxidized sulfides. The veinlets are millimetric and range from planar to irregular shape. They are essentially constituted by varying proportions of carbonate, sulfide, and white mica. The hydraulic fractures are filled by white calcite.

Microscopically, the ore of Panelas Mine is composed of massive sulfides that cement rounded to sub-rounded quartz-carbonate vug-fills (Figures 5A and B). The outer zone of the vug-fills is composed of carbonate and traces of tremolite, while the inner zone, of quartz. Quartz is predominantly polygonized, recrystallized with straight to lobate grain boundaries. Quartz grains show undulose extinction and deformation bands (Figures 5C, D, E). The ore is composed of galena, pyrite, sphalerite, pyrrhotite (Figure 5F), and rare chalcopyrite. Large sub-idiomorphic pyrite crystals (up to 1 mm) occur in aggregates of fine xenomorphic grains of galena, pyrrhotite, and sphalerite.

Chemical analysis from veins of the Panelas Mine and the other mines are indicated in Figure 5, and the subsequent figures of the mines, and summarized in Table 1 (complete dataset in the electronic supplementary material).

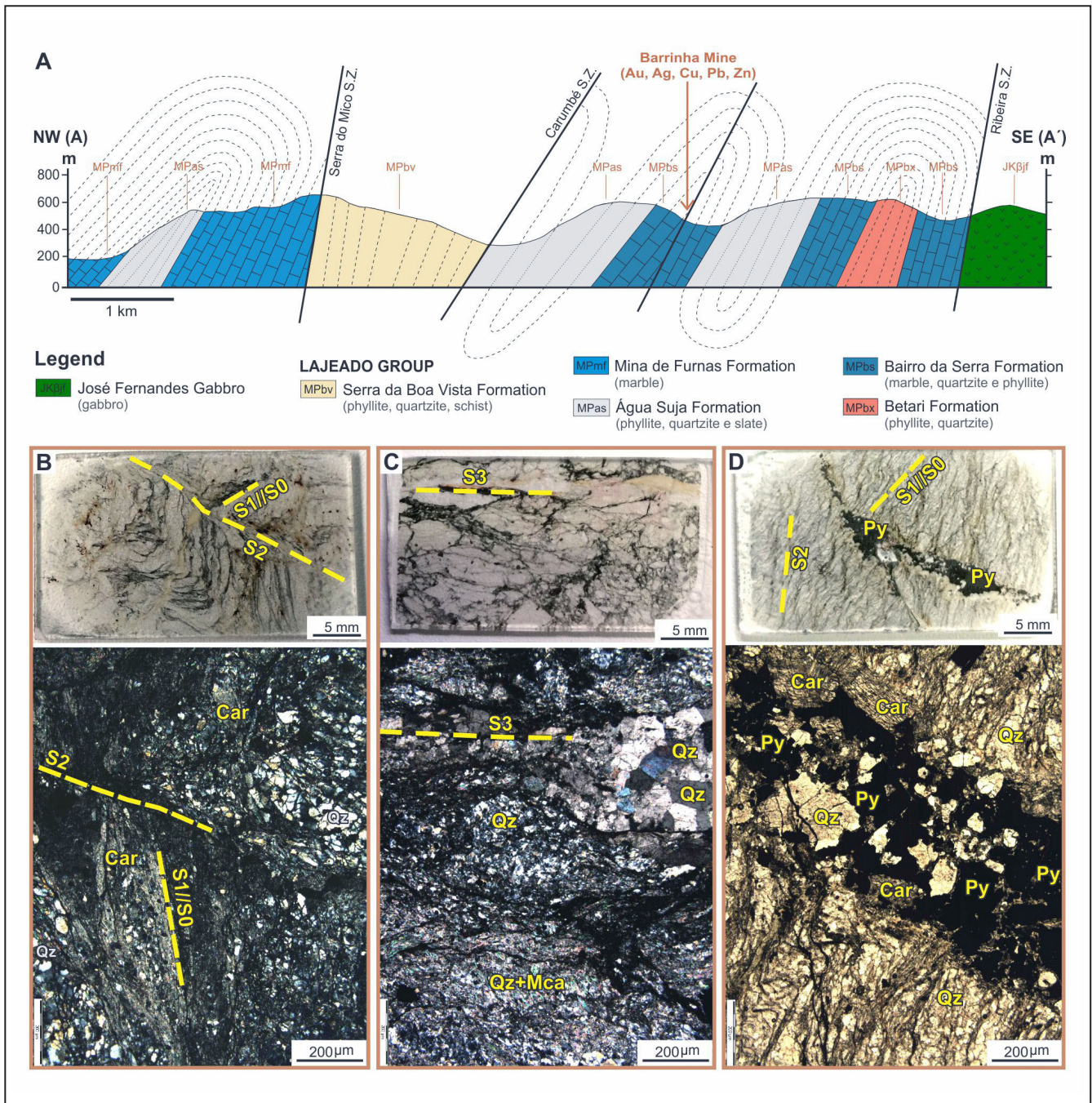


FIGURE 3. Rocha target. A) Geological profile that crosses Barrinha Mine (location in Figure 2), with the general structures of the units (geological database of Faleiros et al. 2012). B) S1 foliation, subparallel to S0, S2 as the axial plane of the crenulation (cross-polarized light). C) S3 anastomosing foliation (cross-polarized light). D) Fracture filled by quartz and pyrite (plane-polarized light). Mineral abbreviations: Qz – quartz, Car – carbonate, Py – pyrite, Mca – mica.

5.2. Barrinha Mine

The Barrinha mine is located in the Rocha target. The gallery where most of the ore was mined in the 1970s is currently collapsed and closed. Only blocks of ore were found near the main gallery area of Barrinha Mine, close to where the headquarters of the mining company was located. Consequently, most information about this mine was assessed through a drill core (AG-B1, location in Figure 2). The Barrinha Mine is located in a restricted exposure of Bairro da Serra Formation phyllite, between Água Suja Formation sequences (Figure 2).

The host rocks comprise metalimestone lenses between phyllite lenses. The thickness of these carbonate levels and lenses ranges from millimeter- to centimeter-scale. The phyllite assemblage is chlorite, sericite and quartz, and the preferred orientation of the minerals defines strong anastomosed foliation (Figure 6A).

The most promising part of the drill core (depth from 260 up to 275 meters) is characterized by an increase in quantity of carbonate and/or quartz veins and veinlets, with a localized occurrence of siliceous breccia, similar to that of the Panelas Mine. Sulfides occur as disseminated and as aggregates in the host rocks and quartz veins, as millimetric



FIGURE 4. Massive ore in the Panelas Mine. A) Part of a preserved sulfide vein and respective grades obtained. B) Massive sulfide vein in a high angle fault zone and respective grades obtained. C) Detail of massive sulfide vein hosted in metalimestone (S0 banding indicated by the white dashed line). D) Brecciated zone (BZ) with metalimestone as lithoclast close to the massive vein. Millimetric calcite healed fractures cross-cut by centimetric composed fractures (F). The composed fractures from wall to the inner zone are healed by calcite, and oxidized sulfides. The hydraulic fractures (HF) in the metalimestone host rocks are filled by white calcite.

veinlets, as well as massive sulfide (Figure 6B). The main sulfide assemblage is pyrite and pyrrhotite. Later pyrite veinlets intersect older pyrite-pyrrhotite veinlets (Figure 6C). The later monomineralic phase is also visible in fractures and interstices of the previous sulfide phase. The galena-only vein cross-cuts the previous veins.

Microscopically, the host rock foliation is well defined by oriented micas and stretched orientation of quartz aggregates. Foliation is overprinted by hydrothermal white mica and carbonate (Figure 6D). Small fractured quartz grains are commonly associated with sulfides. The main sulfides are pyrite and pyrrhotite, mostly affected by quartz and/or carbonate veinlets.

A secondary gallery of Barrinha Mine was identified at hundreds of meters from the main gallery. It is located in the Água Suja Formation (Figure 2), unlike the main Barrinha Mine, where the ore is within the metalimestone of the Bairro da Serra Formation. In the secondary gallery, the host rock

TABLE 1. Maximum values obtained in rock analysis for elements of interest in each mine. All values are in ppm, except where indicated otherwise.

	Panelas Mine	Main Barrinha Mine	Secondary Barrinha Mine	Rocha Mine	Lajeado Mine
Pb (%)	> 35	23	4,411 ppm	9,816 ppm	17.7
Zn	5.3%	196	136	1,727	454
Cu	> 10,000	1,955	1,856	169.3	760.5
Ag	564	539	40	> 10	529
Au (ppb)	765	1,052	5,634	150	680
Fe (%)	23.45	5.64	> 15	6.70	24.37
As	501	60	130	27	5,474
Bi	1.06	3.82	125	3.26	13.9
Sb	403	230	17.16	24.74	92.58
Sn	555	55.2	71.7	9.0	7.7
Mo	1.68	0.77	56.36	1.53	12.81
Te	0.30	47.42	12.61	0.52	0.47

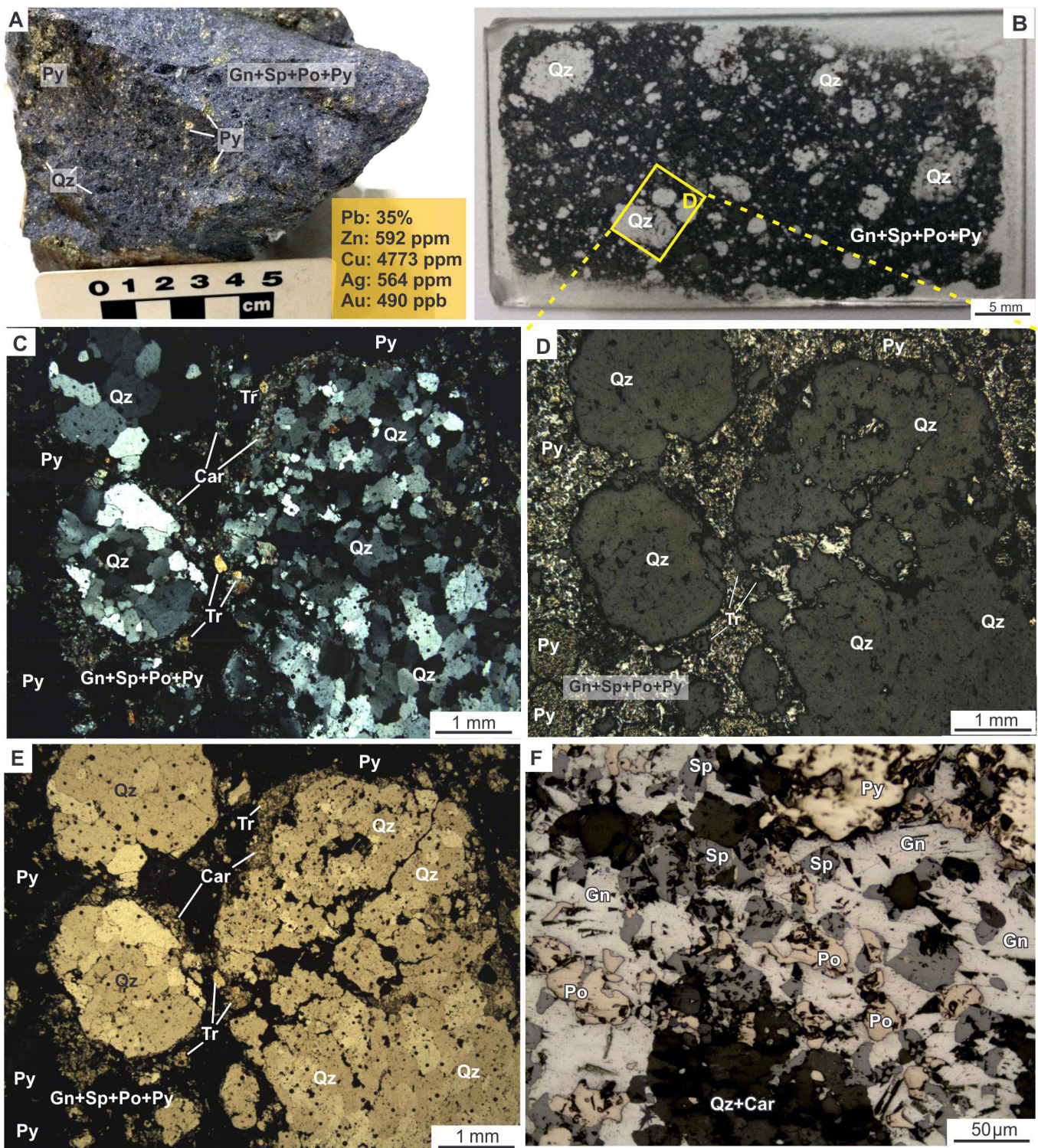


FIGURE 5. Details of the ore in the Panelas Mine. A) A representative sample of the main ore. B) Polished thin section showing the rounded quartz vug-fills embedded in the massive sulfide. C, D, E) Detailed view of (B), the same photomicrographs showing the vug-fills in the fine sulfide cement. The vug-fills are composed of a thin outer zone of carbonate and, in a smaller proportion, tremolite and an inner zone of quartz. Note the recrystallized quartz grains within undulose extinction (C: cross-polarized light, D: reflected light, E: plane-polarized light). F) Polymetallic ore constituted by pyrite, sphalerite, pyrrhotite, and galena. Note straight contact between the grains (reflected light). Mineral abbreviations: Qz – quartz, Car – carbonate, Gn – galena, Py – pyrite, Po – pyrrhotite, Sp – sphalerite, Tr – tremolite.

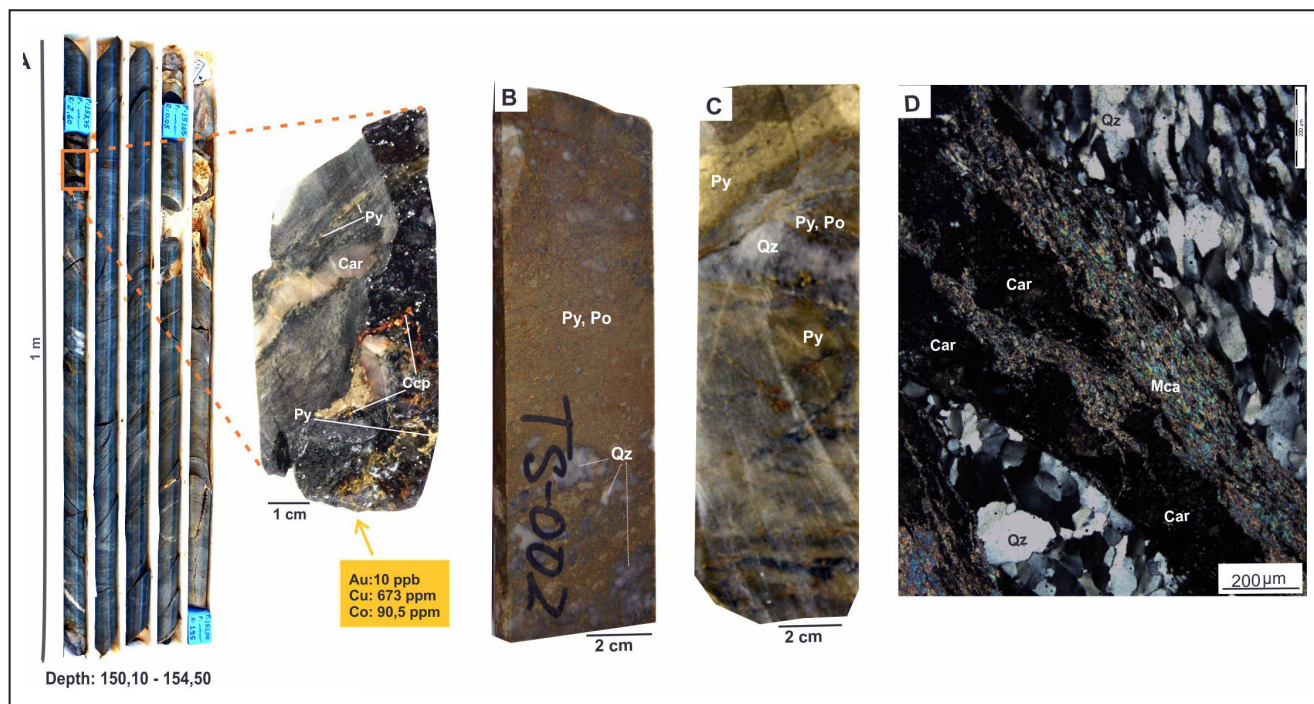


FIGURE 6. Drill core AG-B1, location in Figure 2. A) Host rock comprises metalimestone lenses between phyllite and lenticular quartz veins. B) Massive sulfide. C) Sulfides disseminated and as aggregates in the host rocks and quartz veins, as millimetric veinlets. D) Foliation in host rocks is overprinted by hydrothermal white mica and carbonate (cross-polarized light). Mineral abbreviations: Qz – quartz, Car – carbonate, Mca - mica.

is a phyllite with alternating gray and brown layers, with plane orientation in N60E direction and dip 65° to NW (Figure 7A). Close to the mine, it is observed biotite phyllonite.

Along the gallery, there is intense weathering, leaving the host rock ochre, the fragments of quartz veins dark grey, and the fractures filled by iron oxides/hydroxides. There were no visible ore minerals in the gallery, but only in samples (Figure 7B).

Microscopically, the host rocks exhibit an anastomosed foliation defined by sigmoidal-shaped quartz lithoclasts, enveloped by biotite and iron oxide/hydroxide minerals, mainly hematite. In the lithoclasts, quartz grains define lobate contacts, undulose extinction, subgrains, and new grains. Overlapping the ductile features, anastomosed brittle foliation cuts the continuous foliation. Quartz grains are fractured and the empty spaces are filled by these hydroxide/oxide materials, mainly hematite (Figures 7C, D, E). Gold was not visible.

5.3. Rocha Mine

The Rocha mine is located in the Rocha target, but the main gallery is sealed off. The present work concentrated on the description of a nearby small outcrop, prioritizing areas registered in the SGB/CPRM database as mineral (lead, silver, and zinc) occurrences and deposits. However, there is little rock exposure in the area.

The host rocks are in the contact between phyllites and marbles (Figure 8A). Disseminated small grain-size sulfides occur throughout the marble package. The marble hosts several carbonate veins and veinlets, mostly filling hydraulic fractures (Figures 8A and B). The ore is galena only, and it occurs mainly by filling microfractures inside the carbonate

veins. Galena also healed open space between carbonate grains (Figure 8C, D, E, F, G).

6. Lajeado target and its mines

The Lajeado target is located northeast of Itaoca Granite and comprises the inactive Lajeado and Furnas mines (Figure 2). The Lajeado Mine is located in the Bairro da Serra Formation, and the Furnas Mine in the Furnas Formation, both belonging to the Lajeado Group. In the geological profile (Figure 9A; the location of profile BB' is shown in Figure 2), the Lajeado Group sequence is folded as in the Rocha target; however, the regional-scale folds are more open and have smaller amplitude than in the Rocha target. The folded Lajeado sequences are affected by the strike-slip shear zones and the mines are located in these zones, as the Lajeado mine, which may or may not coincide with the axial plane of the regional-scale folds (Figure 9A).

Bairro da Serra and Furnas formations comprise metalimestones and metacalcarenites, with dark gray color with frequent plane parallel stratification, in which layers of metapelites and metasandstones are present. Both units have very similar characteristics. However, in the Bairro da Serra Formation, the layers are predominantly thinner, and intercalations of terrigenous sediments and impure carbonates are common.

In the Lajeado target, deformation is less intense than in the Rocha target; sedimentary structures are well preserved, and foliations are less frequently found. However, towards the shear zones, well-developed anastomosed and spaced foliation is defined by preferred orientation of quartz and carbonate microlithons surrounded by micas and opaque minerals (Figure 9B).

Calcite veins and veinlets are common and occur subparallel to the S0 bedding, and they are transposed to the mylonitic anastomosed foliation (Figure 9C) near the shear zones. Breccia zones and hydraulic fractures are common features filled mainly by carbonate. These structures are better described in the mines' descriptions.

6.1. Lajeado Mine

The Lajeado Mine was one of the most exploited galleries in the 1980s. The main host rocks are metalimestones of Bairro da Serra Formation. The metalimestone shows a banded color texture, with alternating white and dark gray bands that are composed of fine to very fine and very fine carbonates, respectively.

The ore veins occur within a fault zone of N45E strike with one-meter thickness (Figures 10A and B). The ore is constituted of a system of subparallel centimetric galena veins (Figure 10C). Hydrothermal goethite alteration generates ochre strips parallel to the galena veins (Figures 10B, C, D).

The fault zone and the veins are continuous and anastomosed throughout the gallery. Close to the fault zone, anastomosed foliation is defined by the preferred orientation of sigmoidal-shaped carbonate crystals.

Three kinds of ore veins are recognized: sulfide-quartz-carbonate veins, galena veins, and quartz-carbonate veins. The sulfide-quartz-carbonate veins are composed of pyrite, very fine quartz and carbonate. The veins are brecciated, and quartz druses (of up to 2 cm) were found in the breccia vugs. The galena veins intersect sulfide-quartz-carbonate veins (Figure 10C, D, E). Quartz-carbonate veins cross-cut previous veinlets.

Microscopically, the sulfide-quartz-carbonate veins are mainly composed of pyrite, and traces of arsenopyrite and chalcopyrite. The sulfides are brecciated and partially replaced with goethite and quartz (Figure 11A). Galena veins cross-cut sulfide-quartz-carbonate veins. Galena also fills breccia vugs and envelopes pyrite breccia fragments (Figure 11B). Both veinlets are intersected by quartz-carbonate veins and veinlets (Figure 11C and D). The veins are extremely irregular

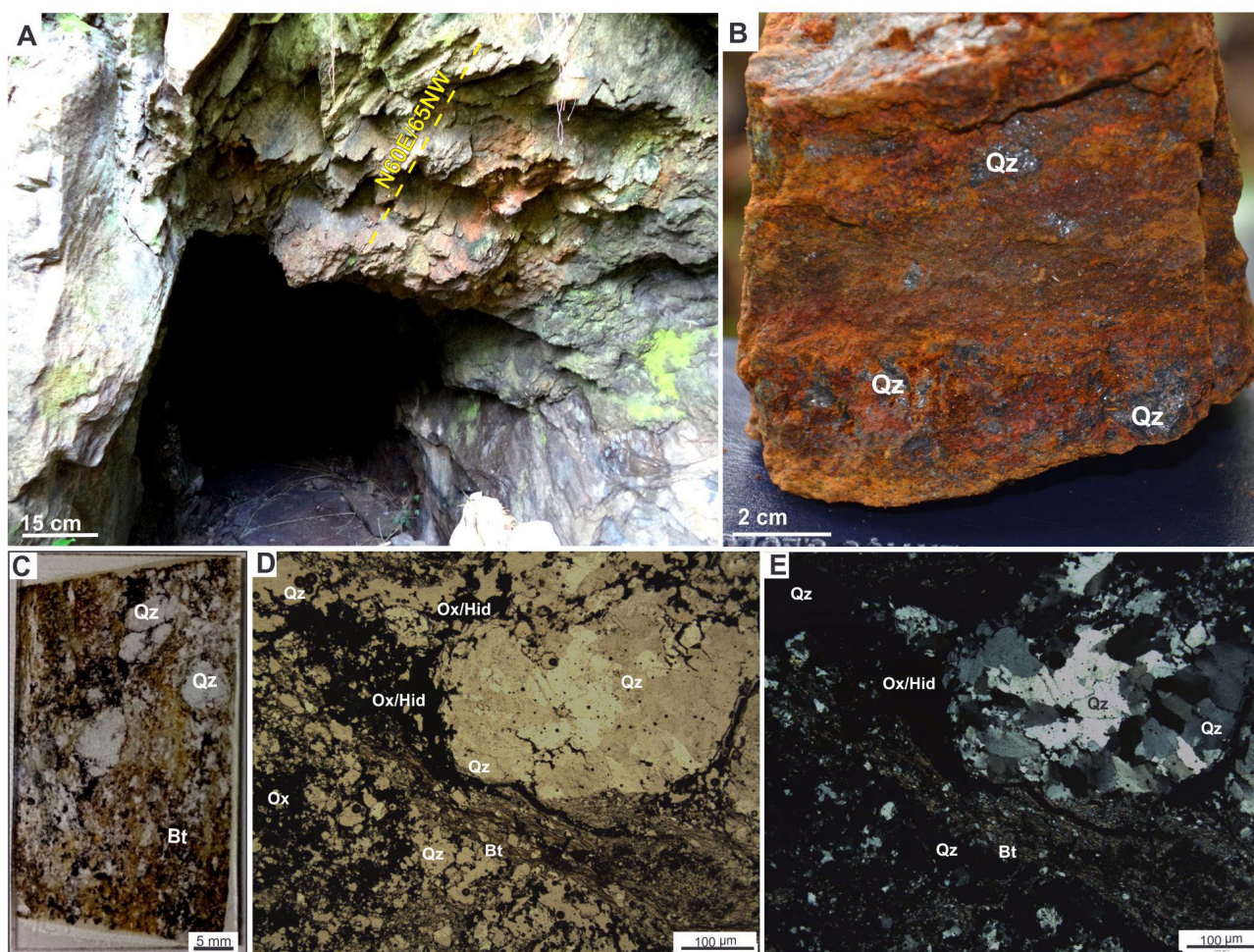


FIGURE 7. Features of the secondary gallery of Barrinha Mine. A) Rocks at the entrance of the gallery. In the hanging wall, phyllite has pronounced foliation with N60E direction and dip 65° to NW. B) Ore sample with high gold and copper content (Au: 1230 ppb; Cu: 1646 ppm). B) Whole thin section shows anastomosed foliation defined by sigmoidal-shaped quartz lithoclast enveloped by biotite. D and E) Photomicrography, anastomosed foliation defined by sigmoidal-shaped quartz elongation, surrounded by levels of biotite and fractured quartz. Note the iron oxide/hydroxides delineating the foliation planes and pressure shadows (arrows) (D – plane-polarized light, E – cross-polarized light). Mineral abbreviations: Qz – quartz, Bt – biotite, Ox – iron oxide/hydroxide minerals.

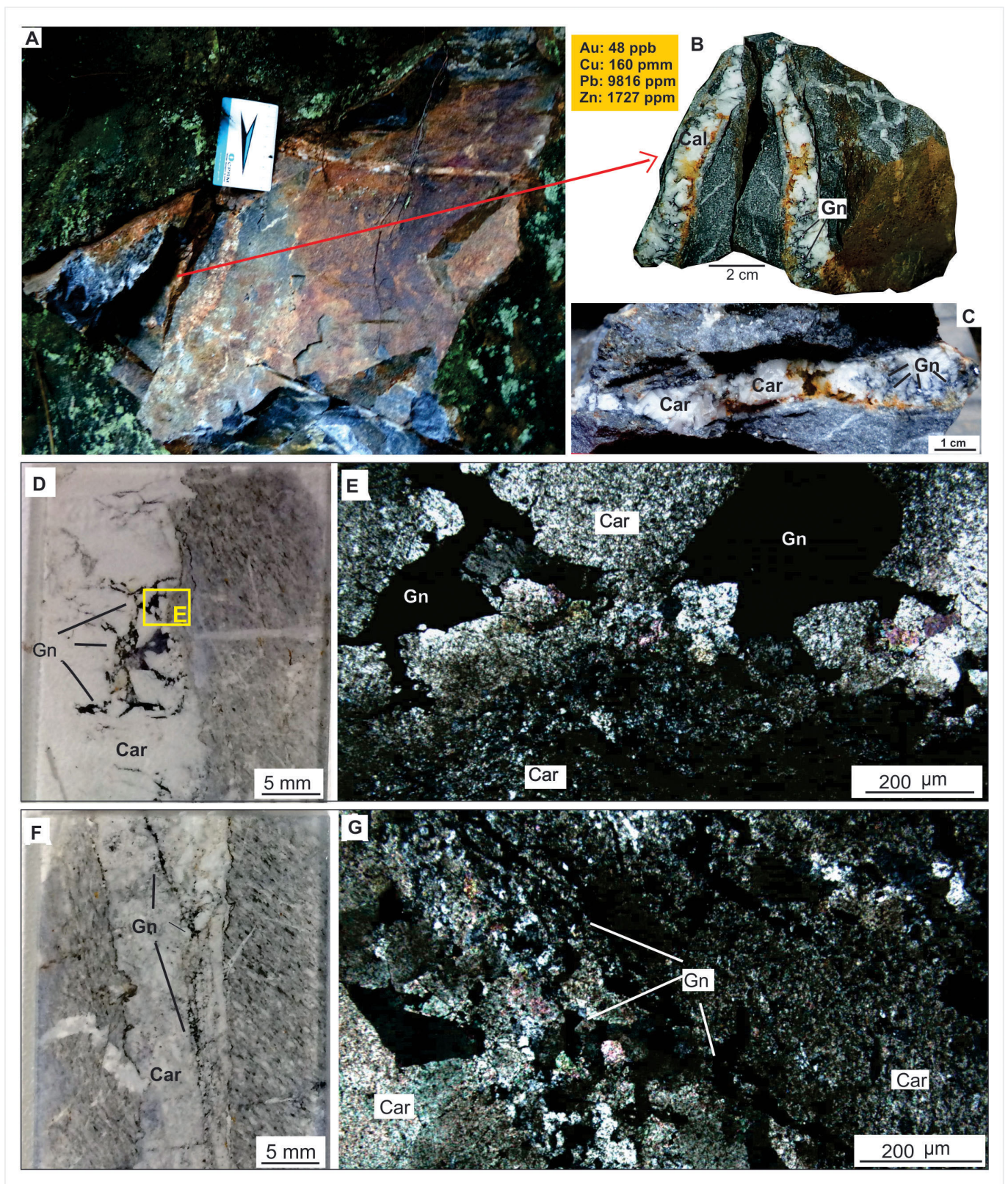


FIGURE 8. Carbonate veins in the outcrops around Rocha Mine (Água Clara Formation). A) Two orthogonal sets of carbonate veins in the host marble. B) Detail of (A) calcite vein with straight vein-marble contact and respective metal grades. C) Carbonate vein with dendritic fractures filled by galena. D) Thin section photography and E) Cross-polarized photomicrography of the vein-marble contact. Hydraulic fractures filled by galena and/or quartz. Quartz and carbonate hydraulic veinlets in the host rocks (arrows). In (E) galena filling these connected fractures and open space. F) Thin section photography and G) Cross-polarized photomicrography of quartz-carbonate vein cross-cutting a well-developed foliation (S) defined by quartz, carbonate and sulfide. Fractures parallel to the carbonate vein walls filled by galena. Hydraulic fractures in the host rock filled by carbonate, galena, and/or quartz. Mineral abbreviations: Qz – quartz, Car – carbonate, Gn – galena.

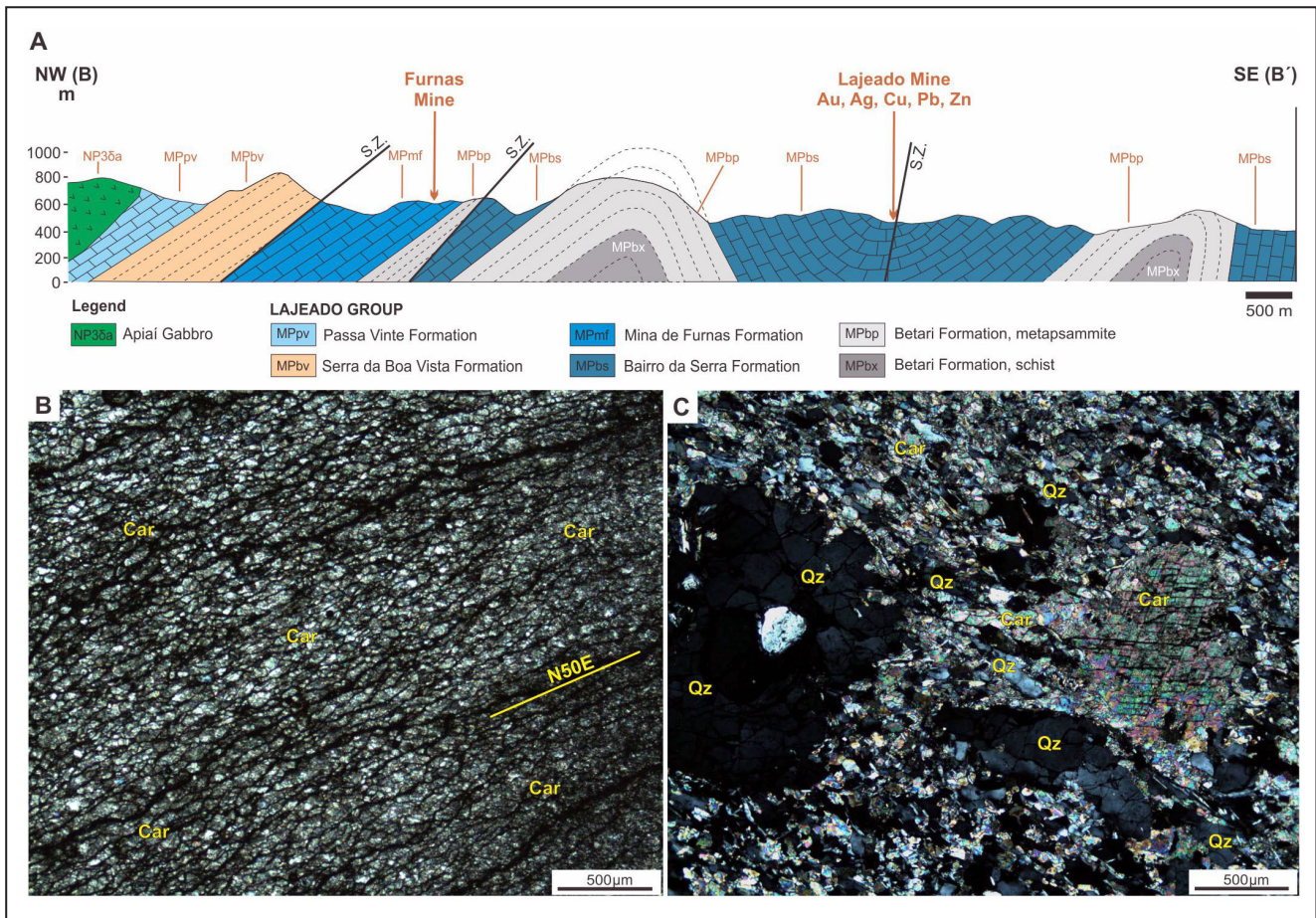


FIGURE 9. Lajeado Target. A) Geological profile of Lajeado target, highlighting the location of the Furnas and Lajeado mines in the regional geological structures (the location of the profile is shown in Figure 2) (geological database of Faleiros et al. 2012). B) Anastomosed and spaced foliation is defined by the preferred orientation of quartz and carbonate microlithons surrounded by micas and opaque minerals (cross-polarized light). C) Calcite veins and veinlets subparallel to the layers, and transposed to the mylonitic anastomosed foliation (cross-polarized light). Mineral abbreviations: Qz – quartz, Car – carbonate.

and the contacts with host rocks and ores are diffuse. The veinlets appear to fill hydrofractures, because of the randomly disposed orientation, as found in other mines.

6.2. Furnas Mine

Descriptions were made in a secondary gallery of the Furnas Mine, very close to the main gallery, which was blocked owing to the collapse of the entrance tunnel. It is a good place to characterize the relative chronology of the veins; however, in situ ore could not be found.

The metalimestone outcropping in the Furnas mine shows color banded texture, with alternating white and dark gray bands (Figure 12A and B), similar to that of the Lajeado mine. The dark gray bands are composed of very fine carbonate, and the white bands comprise very fine to fine carbonate.

The types of veins found in the Furnas mine are similar to the ones found in the Lajeado mine. The sulfide-quartz-carbonate veins are centimetric and composite veins, which, from the walls to the center, are composed of carbonate, sulfide films (mainly pyrite), and quartz (Figure 12A), arranged in crack-seal texture. These veins are folded in a recumbent fold with a sub-horizontal axis (038/20).

There are four phases of faults and veins relating to each other. Strike-slip fault zones (N84E/74NW) are characterized

by subhorizontal striae (N265/15) (Figure 12B) with steps that indicated right-hand movement. The fault cross-cuts the sulfide-quartz-carbonate veins, and hosts subparallel quartz veins. Other sulfide-carbonate-quartz crack-seal veins (ENE-WSW direction) are composed of carbonate in the outer zone and quartz and sulfides in the inner zones (Figure 12C). These veins are cut by later quartz veins with sulfides (Figure 12D). They are preferentially oriented in the E-W direction and dip between 40 to 80°.

7. Synthesis of the acquired data

Table 2 summarizes the integration of information collected in this work with the main characteristics of the mines. This information shows that almost all the ore is hosted by metalimestones and veins, either as massive sulfide veins or in fractures within carbonate veins, and only occasionally disseminated. Galena is the main ore mineral in most of the mines described, except for Panelas, where galena is associated with sphalerite and chalcopryrite traces. Galena veins mainly cut veinlets of pyrite and pyrrhotite. Sphalerite occurs only in the Panelas Mine, arsenopyrite occurs only in the Lajeado Mine, while chalcopryrite occurs in both of them. In the secondary Barrinha Mine, mineralization is quite different since its host rocks are phyllites and occur in

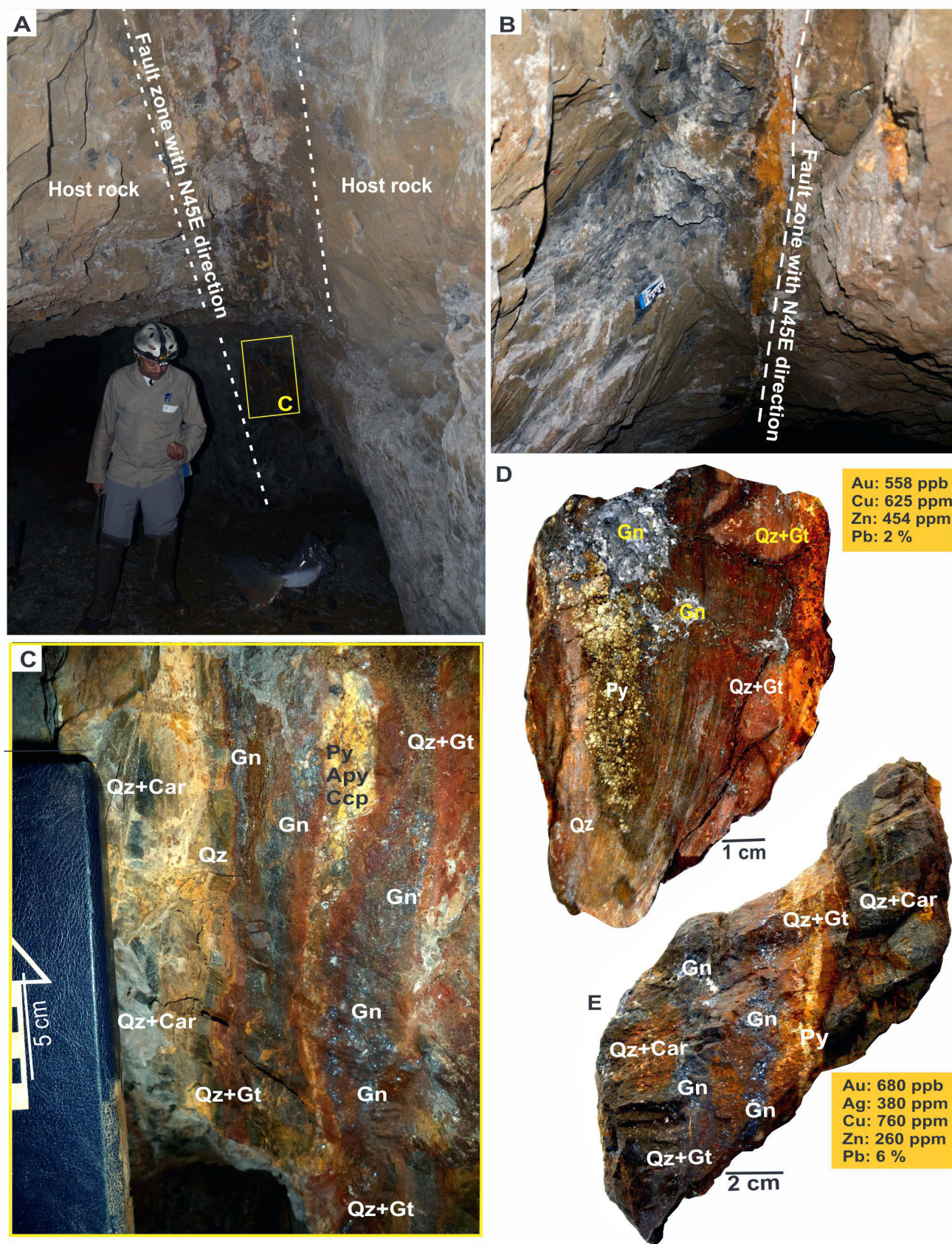


FIGURE 10. Ore features from the Lajeado Mine. A) The general aspect of the fault zone with N45E strike in metalimestone (inside the gallery). B) In the gallery roof, the ore vein is parallel and in the center of the fault zone. Both are continuous throughout the gallery. C) Detail of (A) sulfide-quartz-carbonate veins (pyrite, and traces of arsenopyrite, and chalcopyrite) in yellow, cross-cut by galena veins in grey, and quartz-carbonate veins in pale yellow. Note the goethite alteration in ochre. D) Sample of the sulfide-quartz-carbonate veins, with pyrite breccia fragments (embedded in a galena cement) which also fill fractures. Note the goethite and quartz alteration. E) Sample of the sulfide-quartz-carbonate veins intersected by galena veins. Mineral abbreviations: Gn – galena, Py – pyrite, Apy – arsenopyrite, Ccp – chalcopyrite, Gt – goethite, Qz – quartz, Car – carbonate.

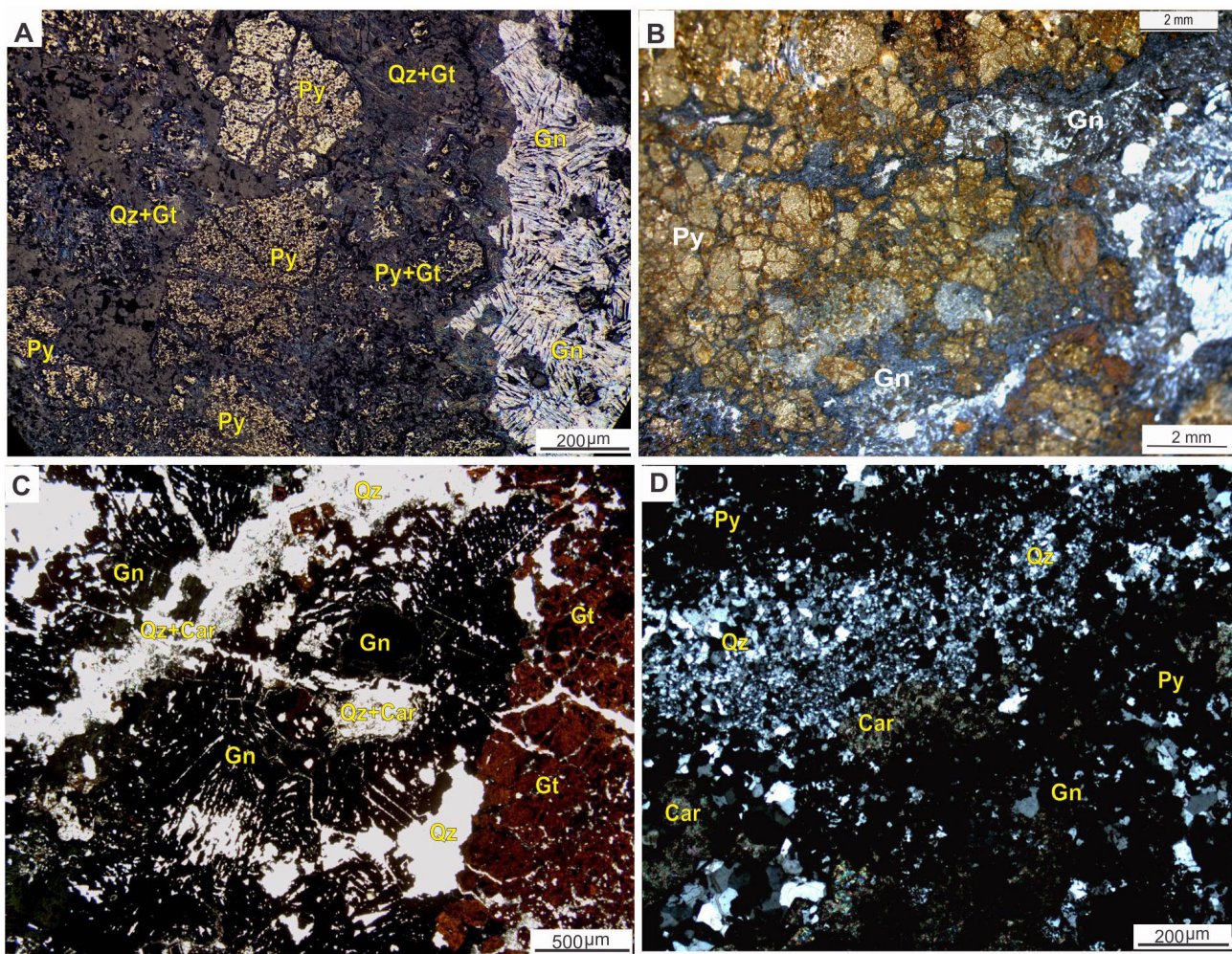


FIGURE 11. Photomicrograph of the ore from Lajeado Mine. A) Brecciated pyrite sub-idiomorphic grains being replaced with goethite and quartz. Galena veins are not brecciated and cross-cut goethitic pyrite (reflected light). B) Round pyrite breccia fragments with galena cement. Pyrite is partially or completely replaced with goethite (photomicrographs were taken using a stereo microscope). C) and D) Quartz-carbonate veins and veinlets cross-cut goethitic pyrite and galena (plane and cross-polarized light). Mineral abbreviations: Qz – quartz, Car – carbonate, Gn – galena, Py – pyrite, Gt – goethite.

association with quartz veins, and the sulfides are replaced by hematite and goethite, suggesting supergene enrichment in the deep water table. Also, mineralizations are always associated with high angle faults predominantly of NE-SW direction, and they present evidence of hydrothermal alteration, such as breccia zones, hydraulic fracturing, silicification, and sulfidation.

Geochemical analyses of ore samples collected in the Rocha and Lajeado targets from the massive sulfide veins, sulfide-quartz-carbonate veins, and the host rocks exhibit an ore composition dominated by Pb-Zn-Fe (Table 1). Copper and silver are important economic features of these deposits, with values reaching up to 1% of Cu and 564 ppm of Ag in the samples collected in the Panelas Mine. The ore presents high Au content, with values of 5,634 ppb in the secondary Barrinha mine. Figure 13 summarizes the distribution of the interest metals in each mine.

8. Discussion

The characteristics of the Lajeado Group mineralizations and host rocks presented in this work provide further insights into the similarities and differences among the

mines and established the ore formation controls in each of the deposits. In the Panelas Mine, the high values of Pb, Zn, Cu, and Ag are explained by the composition of the ore, which is dominated by galena (argentiferous), sphalerite, pyrrhotite, pyrite, and chalcopyrite. The highest grades occur in samples of this mine, except for Au (Figure 13). The high grades of Sn (up to 550 ppm), Sb (up to 400 ppm), As (up to 500 ppm), Cd (up to 180 ppm), and S (> 5%) are unique to the Panelas Mine (Table 1).

In samples from the Lajeado Mine, the ore is composed of galena (argentiferous), pyrite, arsenopyrite, and chalcopyrite. The maximum grades obtained were very significant, and the As grades, which reach 5,470 ppm, are noteworthy in this mine. There are high Sb grades (up to 93 ppm); however, they are significantly lower than those in the Panelas Mine.

In the area of the Barrinha Mine, new mineralizations were described in a secondary gallery, whose Au grades reached 5,630 ppb, associated with high levels of Bi (up to 125 ppm) and Te (up to 47 ppm). These uncommonly high values of Au could be explored as a byproduct, and this is the first report of the occurrence of such metal. The mineralization style differs from the one described in the Panelas and Lajeado mines. However, similar mineralizations were described in previous

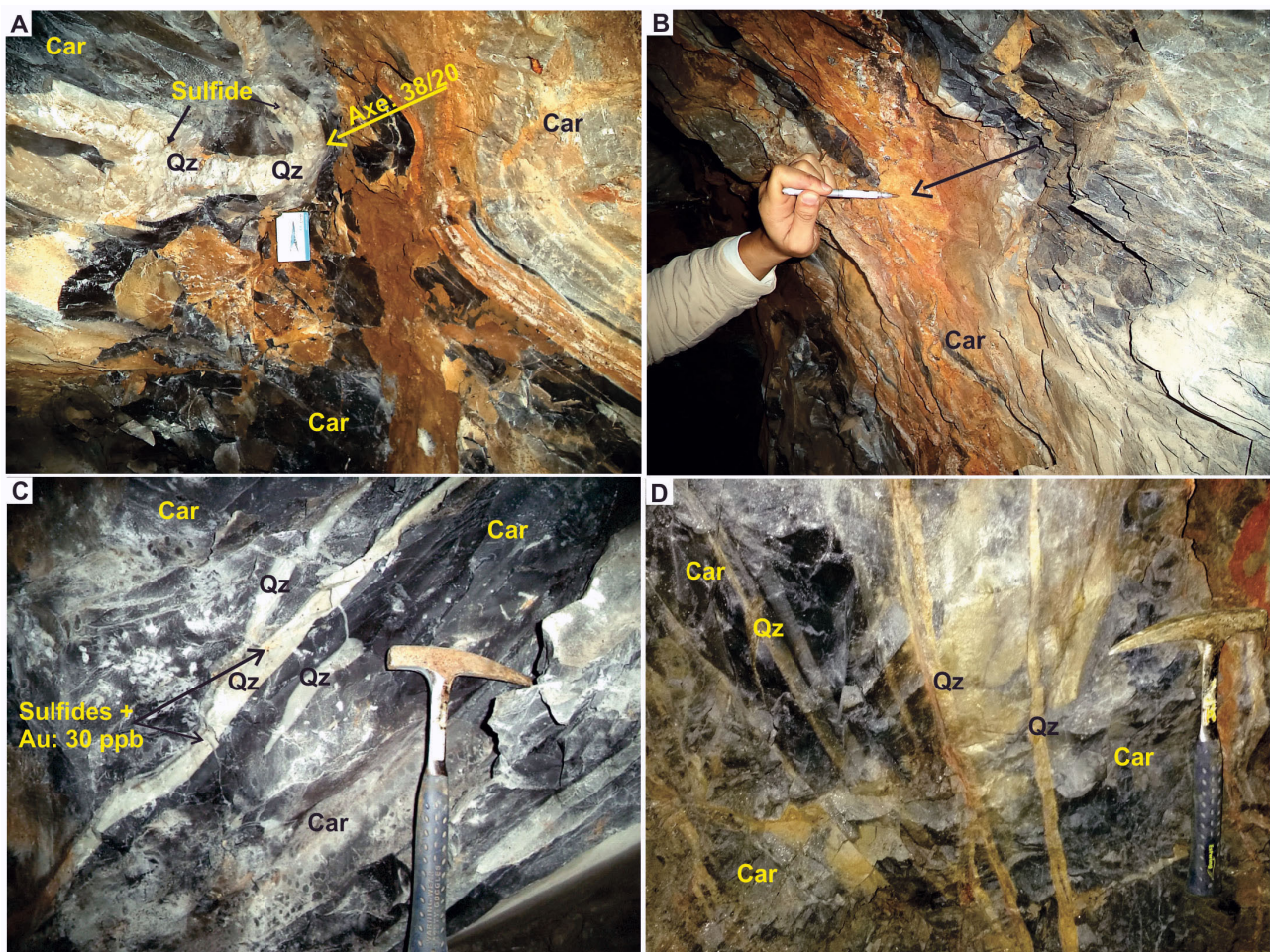


FIGURE 12. Hierarchy of veins in metalimestones inside the Furnas Mine sub-gallery. A) Composite sulfide carbonate-quartz vein, folded (recumbent fold with N038/20 axis). Sulfide levels occur between the carbonate and quartz interface. B) Detail of the N176/74 strike-slip fault zone, with N264/15 striae (indicated by the pen). C) Carbonate-quartz composite veins, with crack-seal texture (N333/61), cut by sulfide veinlets (indicated by black arrows) with the gold content. D) Subvertical quartz veins (EW direction) cross-cut previous structures. Mineral abbreviations: Qz – quartz, Car – carbonate.

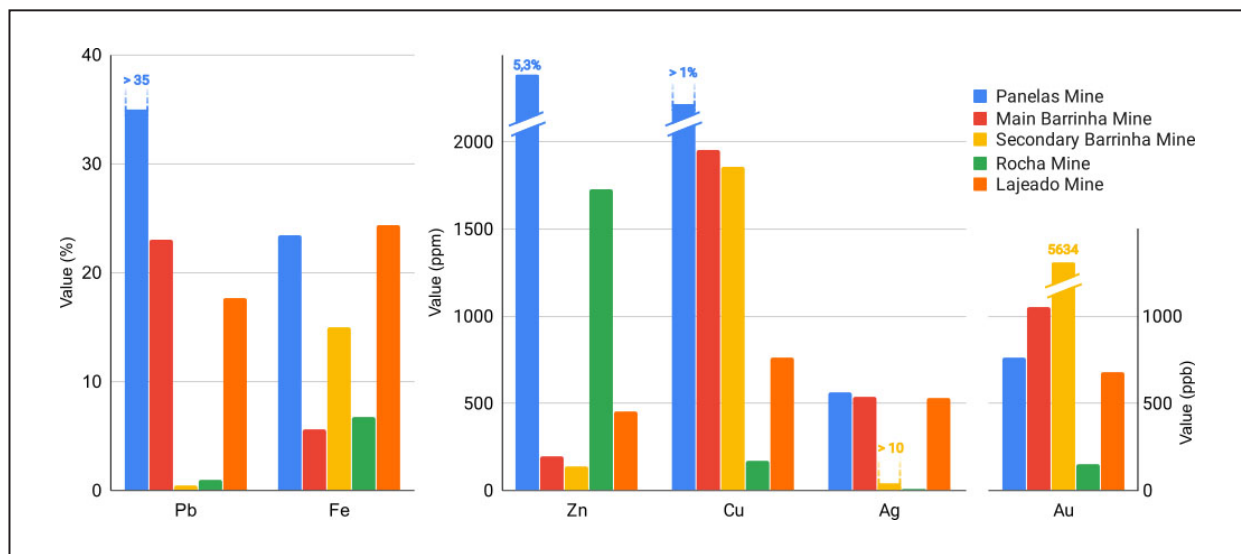


FIGURE 13. Geochemical results for elements of interest in each investigated mine. The dashed lines indicate that the result exceeded the maximum detection limit of the method employed; therefore, the grade may be higher than the one reported.

TABLE 2. Synthesis of the mineralization data described in each mine.

Mine	Host rock	Ore Occurrence	Structure control / hydrothermal alteration	Other Veins	Ore minerals assemblage	Stratigraphic host rock unit
Panelas Mine	Banded metalimestone	- Fault-fill massive sulfide veins	- High angle faults - Hydraulic fractures - Breccia Zone - Carbonate alteration	Carbonate Veins	- Galena, pyrite, sphalerite, pyrrhotite, and traces of chalcopyrite	Bairro da Serra Formation, Betari Formation (Lajeado Group)
Main Barrinha Mine	Met limestone lenses between phyllite	- Massive sulfide veins - Disseminated in host rock	- White mica-carbonate alteration - Breccia zone - Silicification - Sulfidation	Quartz-carbonate veins	- Pyrite, pyrrhotite - Pyrite veins - Galena veinlet	Bairro da Serra Formation sequence between Água Suja Formation sequences
Secondary Barrinha Mine Gallery	- Biotite phyllites - Phyllonites	- Quartz veins - Fault-fill massive sulfide veins	- Breccia zone - Silicification (vug-fill) - Hematite Goethite alteration	Quartz veins	- Sulfide altered to hematite/goethite	Água Suja Formation
Rocha Mine	Marble	-Fractures within carbonate veins -Disseminated in host rock	Hydraulic fractures silicification	1- Quartz veins 2- Carbonate veins 3- Galena veinlets	- Galena	Água Clara Formation, Água Suja Formation
Lajeado Mine	Banded metalimestone	- Fault-fill sulfide-quartz-carbonate veins - Galena veins	- Fault zone N45E strike -Silicification -Sulfidation	1- sulfide-quartz-carbonate veins 2- galena veins 3- quartz-carbonate veins	1- Pyrite, traces of chalcopyrite and arsenopyrite 2- Galena	Bairro da Serra Formation (Lajeado Group)
Furnas Mine	Banded metalimestone	No available data	-Fault zone (N84E/74NW) -Silicification	1- crack-sealed sulfide-quartz-carbonate veins, 2- carbonate and/or quartz oblique veins 3- subvertical quartz veins 4- sulfide veins	No available data	Furnas Formation (Lajeado Group)

projects in the main mine gallery, which is now collapsed and inaccessible. In this secondary gallery, there is ore in oxidized phyllonites, as well as in the fault zone. The different mineralization characteristics observed in this secondary gallery mine, associated with high values of Au, Bi and, Te, in opposition to the values observed in the other mines of the Lajeado and Rocha targets, could be an example of a different mineralization system that has affected the rocks of the Lajeado Group. In the ore samples of the drill cores of the previous projects developed in the Barrinha mine area (Fig. 7B and C), sulfides presented no relevant ore grades.

The host rocks where the mineralizations occur are mainly metalimestones, and they are usually banded. They are mostly found in the Mina de Furnas and Bairro da Serra formations (Lajeado Group) and the Água Clara Formation, units of the Açungui Supergroup, but they are not limited to any specific formation, only to rock type. The lithological control of the carbonate rock can be considered as one of the most important controls for the mineralization on both targets. Even for the ore hosted mainly in the siliciclastic rocks, e.g., the Main Barrinha Mine, it is concentrated in the carbonate lenses of phyllite. Silva et al. (1981) has also pointed out that there is lithological control in these mineralizations.

The occurrence of sulfides in metalimestones may be attributed to the high reactivity and alkaline pH of these rocks; therefore, when the mineralizing fluid passed through it, the metal ions precipitated in the form of galena, pyrite, etc. (Baker et al. 2004). The source of the metals present in the fluid may be the limestones themselves, as conjectured by Fleischer

(1976) and, in this case, the function of the fluid would be the remobilization of the existing metals and concentration in available open spaces, effectively characterizing ore formation. Therefore, lithological control results from a geochemical trap and from a source of metals, but, alone, it would not be enough to generate mineralization, and a combination with structural controls is needed.

The structural control of the ore mineralization in the Rocha and Lajeado targets is unequivocal. The structural data suggest an evolution of the veins in synchronicity with the regional deformation events. In both targets, sulfide-quartz-carbonate veins are sub-parallel or transposed to S0 and S1 foliations, and the main sulfides are pyrrhotite and pyrite. The compressive episode, responsible for S1 foliation, parallel to S0, has maximum strength in the NW-SE direction, characterized by thrust zones (of NE-SW direction), as suggested by Faleiros et al. (2011). The S1-related veins present a characteristic crack-seal texture, indicative of more than one open space, and mineral filling precipitation, as seen in the Barrinha and Furnas mines (Figures 6A, 12A). This texture characterizes variations in the fluid pressure regime as suggested by Cox (1995) and Sibson et al. (1988). This first generation of S1-foliation veins and S1 foliation are folded, developing recumbent folds, with axis 38/30 (Figures 12A), probably as the evolution of the thrust event, as pointed out by Faleiros et al. (2011). Another generation of carbonate-quartz crack-seal veins are not folded and probably developed in the axis of the recumbent folds. These veinlets are cut by sulfide veinlets, mainly pyrite with gold content (Fig. 12C). Again, the

crack-seal texture indicates fluid pressure fluctuations.

Another folding event developed kilometric open isoclinal folds, and turned the S0 layers and S1 foliation into the vertical position (Figures 3A and 9A). A S2 foliation developed as the axial plane of the folds. Later NE high angle strike-slip shear zones are responsible for a mylonitic foliation (S3) described as spaced anastomosed foliation (Figure 9B, 6D). The shear zones may coincide with the isoclinal fold axis, as in the Barrinha and Lajeado mines (Figures 3 and 9). High angle NE Fault zones host the main ore veins, called fault-fill veins by Robert et al. (1995). The main fault-fill ore veins are in the Panelas, Barrinha (secondary mine), and Lajeado mines (Figures 4A-B, 7A, and 12A-B). The faults are discontinuous structures (according to Fossen, 2016 and others), where there is a clear discontinuity between the host mylonites and the fault zone. Close to the fault zones, breccia zones and silicification may cut the mylonites, as in the Panelas (Figure 5D) and Barrinha mines. The cataclastic event breaks pyrite veinlets, leaving pyrite fragments in galena cement (Figure 11B). Galena veins and veinlets also cross-cut pyrite veins (Figure 10D and E), and fill microfractures and vug-fill in carbonate veinlets (Figure 8D-G). The breccia features suggest a post-ductile event, typically brittle, which superimposed on the mylonitic shear zones. In the Ribeira Shear Zone, Faleiros et al. (2007) also suggested a ductile deformation superimposed by a brittle deformation near the Panelas and Barrinhas mines.

However, many characteristics, such as crack-seal veins (Figure 10C) and hydraulic fractures (Figure 4D) in the fault zones and host rocks, suggest that these superimposed continuous and discontinuous structures may be the consequence of cyclic movements of high shear stress, shear zone failure, fault activation, fluid movement, and veins formation, as described in the fault-valve model (Cox et al. 1995; Sibson 1975, 1988; Faleiros et al. 2007, 2014). In this sense, all the structures can be developed at the same event, and could partially account for mineralization.

In summary, the collective data discussed here suggest that polymetallic mineralization is a syn- to post-transcurrence event. We do not discard the possibility that part of the ore has been formed in transtensional zones by reactivation of these strike-slip structures.

9. Conclusion

The data acquired from fieldwork, petrography, and litho-geochemistry provided a basis for improving the understanding of the sediment-hosted polymetallic mineralization, which was developed in a typical platform carbonate sequence of a passive margin, deformed during the Gondwana assemblage in the Brasiliano-Pan African orogeny. These are main advancements regarding each discussion topic:

- Lithological control of the carbonate rocks is extremely important in the area, as mineralization occurs almost exclusively in metalimestones or carbonate veins, irrespective of geological unit;

- Very high lead grades were identified in the Panelas and Lajeado Mines. They are higher than those reported in previous studies, and high gold grades that were previously unreported were identified in a secondary gallery of the Barrinha Mine. In this respect, a different ore style is suggested for the secondary gallery of the Barrinha Mine;

- The structural data suggest an evolution of the veins synchronous to the regional deformation events, from S1-foliation crack-seal sulfide-quartz-carbonate veins, S2-foliation quartz and carbonate veins, to S3-foliation quartz or carbonate veinlets with sulfide, and finally the fault-fill polymetallic ore veins;

- Structural control is also prominent as the massive sulfide veins are controlled by the NE high-angle strike-slip fault zones. Evidence for the occurrence of fault-valve processes is suggested owing to the presence of hydraulic fractures and crack-seal veins;

- Fault zones as the main control of the polymetallic veins is an innovative interpretation, increasing the perspectives for mineral exploration in the area.

Although these are small deposits, the data confirm that the mines in the region are not exhausted and potential exists even considering environmental restrictions. More expressive advancements could be obtained by detailed structural, isotopic, and fluid inclusion analysis which would allow a metallogenic approach, in addition to providing more grounded data for the discussion of the hypotheses presented in this paper.

Acknowledgments

We thank the Geological Survey of Brazil (SGB/CPRM) for providing the necessary infrastructure for the development of this work. We also thank the reviewers for their helpful comments, which contributed significantly to the quality of the manuscript.

Electronic supplementary file

Spreadsheet with geochemical results and sample location.

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