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$^{40}Ar/^{39}Ar$ AGES OF HYDROTHERMAL FLUIDS OF CABAÇAL Au-Zn-Cu DEPOSIT: IMPLICATIONS OF THE CACHOEIRINHA OROGENY ON MINERALIZATION EVENT IN SW AMAZONIAN CRATON

IDADES $^{40}Ar/^{39}Ar$ DE FLUÍDOS HIDROTERMAIS DO DEPÓSITO DE Au-Zn-Cu CABAÇAL: IMPLICAÇÕES DA OROGENIA CACHOEIRINHA NO EVENTO DE MINERALIZAÇÃO NO SUDOESTE DO CRÁTON AMAZÔNICO

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ABSTRACT - The Cabaçal deposit is located in SW Amazonian Craton, Mato Grosso State, Brazil, with important Au-Zn-Cu mineralization. The ore is hosted by the Alto Jauru orogenic rocks (1.79-1.74 Ga) comprised of felsic metavolcanic and metavolcanoclastic rocks and mineralizations occur as bands concordant with the mylonitic foliation, breccias, quartz-carbonate veins and rock-disseminated, and the polymetallic ore comprises chalcopyrite, pyrite, marcasite, pyrrhotite, sphalerite and galena. The mineralization is related to hydrothermal alteration and includes quartz, chlorite, carbonate, sericite and biotite. Host rocks contain garnet-sillimanite-plagioclase-quartz mineral association suggesting amphibolitic facies for the generation of the deposit. Six sericite grains from the hydrothermal zones yielded $^{40}Ar/^{39}Ar$ ages from 1521.3 ± 1.3 Ma to 1510.4 ± 1.2 Ga. These ages are evidence that hydrothermal solutions originated related to the Cachoeirinha orogen (1.58-1.52 Ga) cutting the Alto Jauru orogen (1.79-1.74 Ga) host rocks. Detailed geology and petrography indicate banded iron formation played an important role in the metal deposition as a chemical barrier for the mineralizing fluids.
Keywords: Cabaçal deposit. Amazonian craton. Hydrothermal solutions. $^{40}Ar/^{39}Ar$ ages.

RESUMO - O depósito de ouro do Cabaçal está localizado no SW do cráton Amazônico, no estado do Mato Grosso, Brasil onde ocorrem rochas do orógeno Alto Jauru (idades U-Pb de 1790 Ma a 1744 Ma). A mineralização é hospedada por rochas metavulcânicas e metavulcanoclásticas e ocorre como (i) bandas concordantes com a foliação milonítica, (ii) brechas, (iii) veios de quartzo-carbonato e (iv) disseminado. O minério é polimetálico e compreende calcopirita, pirita, marcasita, pirrotita, esfalerita e galena. A mineralização está relacionada à alteração hidrotermal e inclui quartzo, clorita, carbonato, sericita e biotita. Grãos de sericita das zonas hidrotermais foram datados pelo método ^{40}Ar / ^{39}Ar, utilizando *step-heating* a laser em grãos individuais, resultando em valores entre 1562 e 1502 Ma. Esses estudos revelam que o depósito de ouro do Cabaçal pode ser originado durante o orógeno Cachoeirinha (1.58-1.52 Ga) com geração de calor e remobilização de soluções hidrotermais que percolaram e depositaram os metais nas rochas do orógeno Alto Jauru (1,79-1,74 Ga). Geologia de detalhe e petrografia dos corpos de minério indicam que a formação de ferro bandado desempenhou um papel importante na deposição de metal como uma barreira química para os fluidos mineralizantes.
Palavras-chave: Depósito do Cabaçal. Cráton Amazônico. Soluções hidrotermais. Idades $^{40}Ar/^{39}Ar$.

INTRODUCTION

The southwestern part of the Amazonian craton is a multi-orogen region formed between 1.8 and 1.0 Ga which experienced effects of successive magmatism, metamorphism and deformation responsible for the origin of the mineral concentration in the region (Tassinari et al., 2000; Geraldes et al., 2001; Teixeira et al., 2015).

The main mineral deposits are the Expedito Zn-Cu deposits in the Aripuanã region (Neder et al., 2000); the Cu-Au Moriru deposit (Pinho, 2002); the Cabaçal Cu-Au deposit (Monteiro et al., 1986; Pinho, 1996); the Rondonian Tin Province (Bettencourt et al., 1999; Debowisky et al., 2019); and the Au deposits of Pontes e Lacerda region (Geraldes & Figueiredo, 1997; Fernandes et al., 2006). Several minor occurrences are described in the region, such as Au prospects in Rondonia and Mato Grosso states, and younger diamond deposits (Paleozoic) in Juína (MT) and Colorado do Oeste (RO) kimberlites and superficial concentrations in Morro do Leme Ni deposit originated from ultrabasic rocks (Angeli et al., 1997; Matos et al., 2004).

The Cabaçal gold deposit was explored during the 1980's for gold and during the 1990's for zinc. It is in the SW Amazonian craton, Mato Grosso state, Brazil, where the Alto Jauru orogenic rocks (U-Pb ages from 1790 Ma to 1744 Ma) and Cachoeirinha orogenic rocks (U-Pb ages from 1580 Ma to 1520 Ma) occur (Geraldes et al., 2001; Ruiz et al., 2004; Geraldes et al., 2004) and due the overprint orogenic events its genesis is still matter of debate. The mineralization is hosted within felsic volcanic and volcanoclastic rock of the Alto Jauru greenstone belt and the deposit origin processes are under debate.

The Cabaçal gold deposit is interpreted either as shear-related origin since the ore is parallel to tectonic foliation or syngenetic because the mineralization shows features related to the volcanic rock's formation (Pinho, 1996).

This work proposed new $^{40}Ar/^{39}Ar$ ages and petrologic studies in addition with the available geochronological U-Pb, Sm-Nd (Pinho, 1996; Pinho & Pinho, 1997; Geraldes et al., 2001; Ruiz et al., 2004), constituting a preliminary attempt to correlate the Proterozoic evolution of the Amazonian Craton with this important Au-Zn-Cu deposit.

The study stablishes correlations between the metallogenetic processes and tectonic/magmatic events in the southwestern Amazonian craton, and thereby provides constraints for base metals regional exploration.

REGIONAL GEOLOGY

Three major geochronological and tectonic provinces (Cordani et al., 1978; Teixeira & Tassinari, 1984; and Tassinari et al., 1997) are present in the SW part of Amazonian craton: Rio Negro/Juruena Province (1.75-1.55 Ga), Rondonian/San Ignacio Province (1.55-1.30 Ga), and Sunsas/Aguapeí Province (1.30-1.00 Ga; Geraldes et al., 2014; Teixeira et al., 2015). Volcanic rocks of Alto Jauru region (Figure 1) were described by Saes et al. (1984) as Quatro Meninas volcanic Complex and by Monteiro et al. (1986) as Alto Jauru greenstone belt (AJGB). Three metavolcanosedimentary belts (from E to W: Cabaçal, Araputanga and Jauru) are separated by granitic-gneiss terranes. These rocks were intruded by Proterozoic dolerites and granitoids and are covered by Middle Proterozoic Aguapeí Group continental clastic rocks.

Alto Jauru orogenic rocks

Monteiro et al. (1986) described the following sequence for the Alto Jauru greenstone belt: the lowest unit (basic volcanics) comprises massive amygdaloidal and variolitic metalavas and metavolcanic breccias, the latter enclosing lithic clasts from the upper lithologies. These are locally overlain by intermediate metavolcanics (andesites lavas and tuffs, interdigitate with felsic lavas, tuffs and metapelites). The next unit, acid metatuffs, comprises dacite-rhyodacite lavas, tuffs and epiclastics rocks which contain the main gold- and silver-bearing ore body explored between 1984 and 1990.

The acid metatuffs are overlain by metasediments, which include local quartz-sericite-chlorite schist. Interbeded of epiclastic debris are common, together with metacherts and garnetiferous magnetite bands (BIF's), the latter two are interpreted as chemical metasediments. Plutonic rocks of metatonalitic to metagranitic composition were described in Jauru region as coeval to volcanic rocks of AJGB. Carneiro et. al., (1992) described petrography and Sr isotopes in units called Pink Gneiss (sample 97-133), reporting a Rb/Sr isochron of 1734 ± 26 Ma and Geraldes et al., (2001) mapped an area between Cabaçal and Araputanga volcanic belts and described orthoderived gneissic (São Domingos granite-gneiss) which is intruded by Alvorada granite.

These authors also reported U-Pb results from metatuff collected in Cabaçal Mine. From the heavy concentrated four fractions of zircons were separated and yielded a U-Pb age of 1767 ± 24 Ma (Table 1) interpreted as crystallization age. The T_{DM} is 1868 Ma and $\varepsilon_{Nd(t)}$ is 2.4. U/Pb and Nd results of this sample indicate that the tuff protolith was derived from a source containing significant older crust or was contaminated by the supracrustal host rocks during volcanism. Banded silicic volcaniclastic metasediment (97-131) from the Cabaçal gold mine yielded zircons with a U/Pb age of 1746 ± 20 Ma interpreted as the crystallization age for the zircons (Table 1).

These results are consistent with volcanism and deposition about 1750 Ma. A second sample yielded U/Pb dating of three zircon fractions from this rock yielded an age of 1795 ± 10 Ma; most of the gneisses are Mesoproterozoic and are discussed below. Only one of the units mapped by Ruiz et al. (2004), the Aliança Gneiss (97-149), yielded a Paleoproterozoic U/Pb zircon age (1740 ± 27 Ma). Pinho (1996) reported SHRIMP U/Pb data for individual zircons from a metavolcanic unit in the area and obtained an age grouping at 1769 ± 29 Ma and a second grouping at 1724 ± 30 Ma. T_{DM} ages range from 1.92 Ga to 1.86 Ga (Geraldes et al., 2001), indicating that this belt probably represents juvenile material accreted to the SW Amazonian Craton about 1.80 to 1.75 Ga (Table 1).

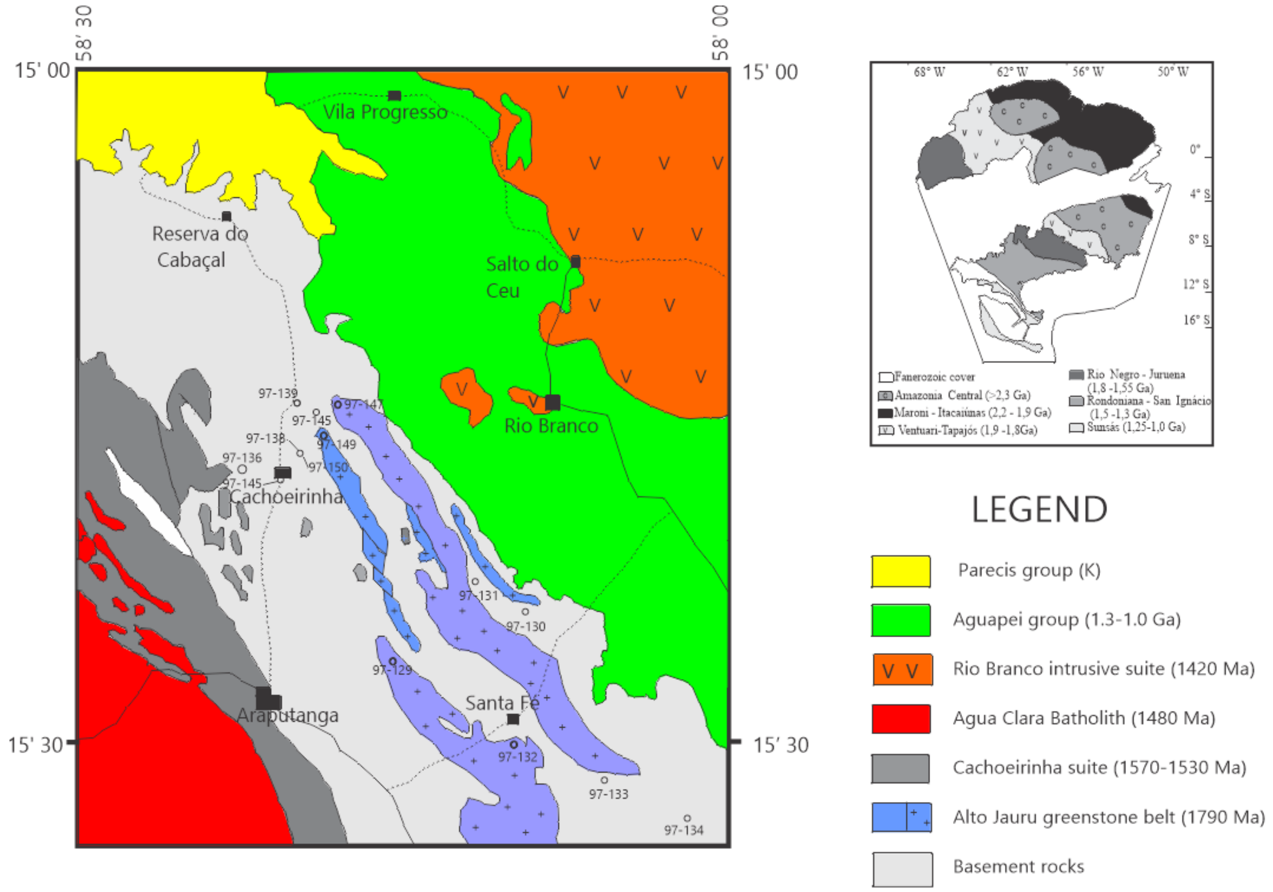

Figure 1 - Regional geologic map of the Cabaçal deposit region (according to Geraldes at al., 2001). Geochronological Provinces according to Tassinari & Macambira (1999).

Table 1 - U/Pb ages and Sm/Nd isotopic properties of samples from Paleoproterozoic rocks of Jauru Terrane. (A) Data from Geraldes et al. (2001). (B) Data from Pinho (1996).

Reference	Rock Description	U/Pb age (Ma)	$Nd_{(0)}$	$Nd_{(t)}$	T_{DM}
A	Metatonalite	1767±24	-17.7	2.8	1868
A	Granite Gneiss	1795±10	-18.1	2.2	1926
A	Granite Gneiss	1746±20	-11.9	2.0	1773
B	Metagranite	1769 ±29			
B	Metagranite	1724 ±30			

Cachoeirinha Orogenic Rocks

Another important rock generation event occurred between 1570-1530 Ma in SW Amazonian Craton border, located in Rio Negro-Juruena province according to Tassinari et al. (1997). This event formed arc-related rocks chemically compatible with a calc-alkaline suite, varying from tonalites to granites, which cut Paleoproterozoic continental crust. The basement rocks are represented, locally, by Alto Jauru greenstone belt (1.79-1.75 Ga) and located in the same geographic area, which limits are (Figure 1): North with the Cretaceous Parecis cover; South and east with the Brasiliano belt (Paraguai belt); West border occur Taquaruçu-Lucialva lineament and limit with rocks from Santa Helena Orogen (1.45-1.42 Ga).

Cachoeirinha Orogen rocks were initially described by Figueiredo et al., (1974) and Barros et al, (1982) as Xingu Complex. Carneiro (1986) and Carneiro et al., (1992) described the rocks in the region of São José do Quatro Marcos, suggesting at least two generations of rocks, the first represented by gray gneisses (Rb/Sr ages about 1.96 Ga) and the second comprising pink gneisses and granites from 1740 Ma to 1400 Ma (Rb/Sr ages). Granitoids of different compositions have been separated from the basement (Saes et al., 1984; Leite, 1989; and Ruiz, 1992) and time constrained by Rb/Sr ages from 1.70 to 1.40 Ga. Tassinari et. al. (1997) present U/Pb and Rb/Sr results constraining two major events from 1.8 Ga and 1.7 Ga (magmatic arc formed on Central Amazonian Province continental margin) and 1.6 Ga to 1.5 Ga (magmatic arc with reworking of the older one).

U/Pb geochronology (Van Schmus et al., 1998; Geraldes et al., 2001; Ruiz et al., 2004) constrained two events in the so-called Jauru region, the first defined as Alto Jauru greenstone belt (included in Rio Negro-Juruena Province 1.79-1.74 Ga) and the Cachoeirinha Orogeny, including anorogenic plutons. Tonalites, granodiorites and granites are described in Jauru river region as intruded in the gneissic basement. Tonalites are observed in São José dos Quatro Marcos (Carneiro et al. 1992) and Cachoeirinha cities region (Ruiz et al., 2004). The rocks are gray, equigranular, medium to coarse grained and maphic minerals define the foliation. Plagioclase, quartz, amphibole, and biotite comprise the main minerals. U/Pb ages in zircons Sm/Nd composition obtained in the samples Quatro Marcos tonalite and Cachoeirinha Tonalite yielded 1536 ± 11 Ma (T_{DM} =1.77 Ga and (Nd = +0.5) and 1549 ± 10 Ma (T_{DM} =1.83 Ga and (Nd = +1.0), respectively (see Table 2).

Granodiorites and granites are observed (Ruiz, 1992) in Santa Cruz batholith described as part of Cachoeirinha suite. They present lateral variations characterized by strong foliation and banding. The rocks analyzed by microscopy present a composition comprised of qz-feldspatic in felsic layers and biotite and amphibole-enriched in mafic layers. Ruiz et al., (2004) reported for Santa Cruz batholith a U/Pb age of 1587 ± 04 Ma (T_{DM} =2.05 Ga and (Nd = -0.8). São Domingos, reported as a granitic facies with gneissic feature yielded a U/Pb age of 1562 ± 36 Ma (T_{DM} =1.79 Ga and (Nd = +0.9). Granitic rocks with Cachoeirinha Orogen have a spread distribution on Jauru river region, with facies identified as Cachoeirinha granite (Ruiz, 1992) and Quatro Marcos granite yielded U/Pb ages from 1522 ± 11 Ma (T_{DM} =1.78 Ga and (Nd = +0.9) to 1537 ± 06 Ma (T_{DM} =1.75 Ga and (Nd = +0.5), respectively.

Orthognaisses from Cachoeirinha Orogen are observed surrounding Cachoeirinha city. They have gray color, granitic composition, and equigranular fabric (medium to coarse). Banding is folded, locally characterized by an aspect of migmatite.

The complex deformation resulted in irregular folds and discontinuous banding comprised of quartz feldspar-enriched and biotite-enriched layers. Granolepidoblastic quartz grains with irregular contacts with feldspar and mosaic fabric are interpreted as result of metamorphic recrystallization and biotite orientation along banding is due deformational process.

Younger plutons of granitic and granodioritic compositions are described as Granite Araputanga (Saes et al., 1984; Monteiro et al., 1986; and Matos et al., 1996). U/Pb results yielded 1485 ± 04 Ma (T_{DM} =1.77 Ga and (Nd = +1.7). Alvorada Granite (Monteiro et al., 1986; Toledo, 1997) yielded U/Pb ages of 1440 ± 06 Ma (T_{DM} =1.74 Ga and (Nd = -0.4).

Table 2 - U/Pb and Sm/Nd results on Cachoeirinha Orogeny rocks. Anorogenic granites are also included (Geraldes et al., 2001). U/Pb ages obtained in zircon by isotopic dissolution in monocrystal. (A) Data from Geraldes et al. (2001); (B) Data from Ruiz et al., (2004).

Reference	Description	U/Pb (Ma)*	$\varepsilon Nd_{(0)}$	$\varepsilon Nd_{(t)}$	T_{DM}
A	Quatro Marcos Tonalite	1536 ± 11*	-14.2	+0.5	1.77
A	Cachoeirinha Tonalite	1549 ± 10*	-14.7	+1.0	1.83
A	São Domingos Gneiss	1562 ± 36*	-20.2	+0.9	1.79
A	Quatro Marcos Granite	1522 ± 12*	-19.6	+0.9	1.78
A	Cachoeirinha Granite	1537 ± 06**	-22.2	+0.5	1.75
B	Santa Cruz Granite	1587 ± 04**	-15.0	-0.8	2.05
B	Araputanga Granite	1440 ± 06**	-20.2	-0.2	1.74

The Cachoeirinha Orogen rocks geochemistry analysis results display trends in major and trace elements variations diagrams interpreted (Geraldes et al., 2001) as result of a fractionating crystallization process. In general, tonalitic plutons have comparatively higher Na_2O and MgO; and are metaluminous. Granitic and granodioritic plutons have higher SiO_2 and K_2O, and lower CaO, Al_2O_3, and $FeO_{(total)}$, and MgO, and are peraluminous. The rare earth elements patterns are enriched in light ETR. Tonalites present Eu negative anomaly not observed in granodiorites and granites. Overall, they show calcalkaline trend and Y and Nb contents indicate syn-collisional granitoids. Oxygen isotopes (δO values from +5 to +3) data also indicated I-type granites as reported by Geraldes et al. (2008).

In this way, the Cachoeirinha magmatism took place within a short (50 Ma) time period and during a process of lithospheric convergence. It extended beyond the older continental margin represented by the Rio Negro-Juruena crust formed at 1,.79-1.75 Ga, including Alto Jauru orogenic rocks and the Alto Jamari Complex reported in Rondônia by Bettencourt et al (1999) and Roosevelt group (Rondônia and Mato Grosso states), both with U-Pb ages ranging from 1.76 ro 1.75 Ga. In general, the initial Nd isotopic composition of the most granitoids present very uniform ε_{Nd} values +1,7 to – 0.8 and T_{DM} model ages ranging from 2.05 to 1.75 Ga. Nd isotopic evolution diagram indicates that part of the samples present Nd isotopic initial and final composition are similar to the basement, i.e., they plot within the evolutionary path of the country rocks and thus probably represent material from the mantle with important participation of older crust.

The exposition of intrusive juvenile and reworked plutonic rocks and the lack of respective volcanic rocks allow suggesting that the Cachoeirinha Orogeny rocks represent the root of a magmatic arc formed on an older sialic crust which volcanic building was eroded, exposing the internal structure.

METHODOLOGY

The samples from the Cabaçal deposit were collected at different localities from open pits and from boreholes and two samples were selected for $^{40}Ar/^{39}Ar$ analysis resulting in six new ages. The micaceous rock samples were crushed and sieved at 30-60 mesh, and the sericite crystals were separated from quartz and oxides by handpicking under a binocular microscope. Three grains from each sample were placed into aluminum containers and irradiated, together with appropriate neutron flux standards, at the IPEN/CNEM IEA-R1 nuclear reactor. The standard used was the biotite GA-1550 (McDougall & Harrison, 1999), and the age adopted of 98.8 ± 0.5 Ma. The sealed vial is placed inside a 1.5 mm wall Cd-container (ensuring that the samples are not exposed to excessive heating during encapsulation), which was finally placed in a routable system to ensure that each position in the irradiation disks receives the same neutron dosage. This rod was placed in the irradiation position just outside the reactor core for 30 hours.

The argon extraction line is equipped with a home built fully automated noble gas extraction and purifications system as reported by Vasconcelos et al., (1999) at São Paulo University (USP). The system is composed of an optical table, where sample visualization and gas extraction by a 6-W continuous Ar-laser occurs, and a stainless steel ultra-high vacuum gas purification system equipped with a Polycold Cryocooler and two C-50 Fe-Ti-Zr SAES getters. The step heating procedure was used, in which laser output power is computer-driven to a predetermined value and maintained at that intensity for 30-60 seconds.

This procedure is repeated several times for a sample, at progressively higher laser output power. As result of this procedure, several fractions of the Ar gas contained in the sample are extracted at progressively higher temperature. Each Ar gas fraction obtained separately is analyzed in the mass spectrometer, yielding separated results, which are plotted in the apparent age versus % 39Ar released diagram. If 50% of the released gas yields the same age (within errors) is defined the plateau age. Integrated age comprises the average of the all-gas fractions released in each step-heating technique.

The analyses were done using the Mass Analyzer Products (UK) MAP-215-50 mass spectrometer with 15cm radius with extended geometry and 50mm 90o sector electrostatic analyzer equipped with a Nier-type source. The mass spectrometer houses two independent collectors, a Faraday collector positioned on the high-mass side of the optic axis and a Balzers 217 electron multiplier positioned on the low-mass side. The laboratory is fully automated through Mass Spec version 5.11, a Macintosh MS Basic software written specifically for $^{40}Ar/^{39}Ar$ analysis and data reduction. Blanks were measured between each step of the step-heating procedures.

RESULTS

Cabaçal ore deposit: local geology and petrography

The Cabaçal mineralization is enclosed within a sequence of metatuffs and metavolcanoclastic rocks, with layers of metachert and ferruginous metachert.

Around the ore body the main stratigraphic units of the Alto Jauru greenstone belt is the (i) Manuel Leme Formation comprised of metavolcanic and metapyroclastic rocks, (ii) the metatonalite and (iii) the metagabro, observed (Figure 2).

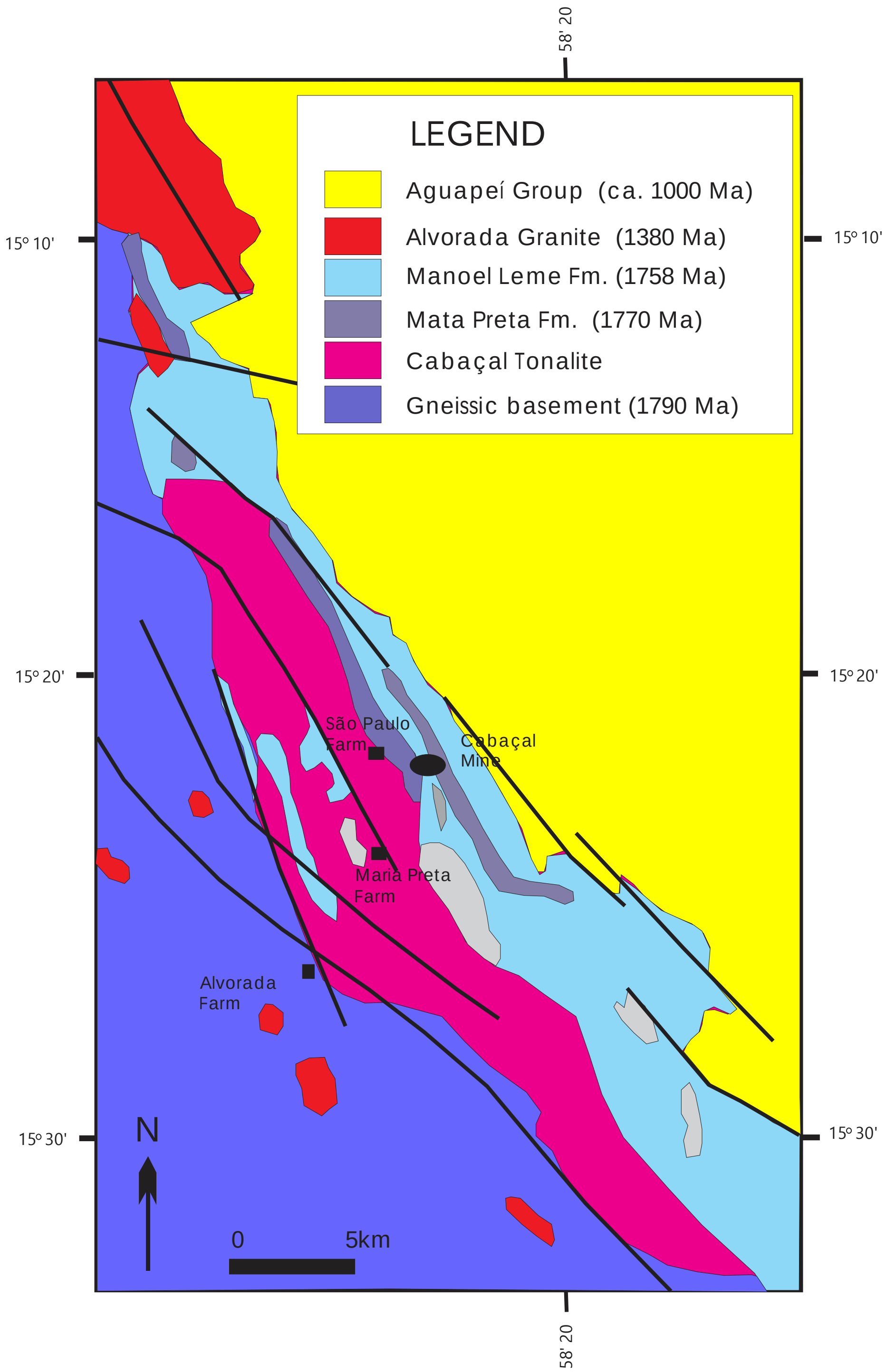

Figure 2 - Local geologic map of the Cabaçal Au-Cu-Zn Deposit and the main units described locally in the deposit context.

In addition, bodies of the Alvorada granite (Cachoeirinha Suite) are observed. The main ore body is limited by the metavolcanic-chemical unit (comprised of metachert and metatuffs intercalated with detrital and chemical meta-sediments) and a metavolcano-volcanoclastic unit (comprised of acid and basic to intermediate metavolcanic rocks). Lithologic types include quartz-sericite-chlorite (biotite schist, sericite-quartz schist, and chlorite-sericite-quartz schist.

Locally, relicts of compositional layering and graded bedding are observed. Generally, these structures are millimetric to centimetric and are parallel to the principal foliation plane

In the southwestern part of the mine site, intercalations of basic and acid metavolcanics occur. Basic to intermediate metavolcanic rocks are intercalated in the southeastern margin of the area, including pillow-lavas metabasalts (Figure 3 A). They are biotite-chlorite schist with epidote fragments interpreted as metatuffs and metabreccias with fine matrix rich in biotite, chlorite, epidote and quartz (Figure 3 B). The typical rock is light grey, and composed of plagioclase, quartz, biotite and sericite (Figure 3 C), with fine-grained porphyritic texture with folds (Figure 3 D), interpreted as dacitic lavas affected by metamorphism at the greenschist to amphibolitic facies.

Hydrothermal solutions in the Cabaçal deposit originated sericitic, biotitic, and chloritic alteration zones. Irregular-shaped ore zones of undulating outlines coincident with the principal foliation plane, and plunge towards in two different directions: SSW, with variable dip and SSE, dipping from 30º to 60º. Sericite and chlorite are common weathered minerals related to the concentration of sulfide ones.

Alterations consist of an inner chloritized core surrounded by an intermediate biotitic and a sericitic zone. Sericitic and chloritic alterations commonly occur associated with metavolcanic-hosted massive sulfide ores (Figure 4).

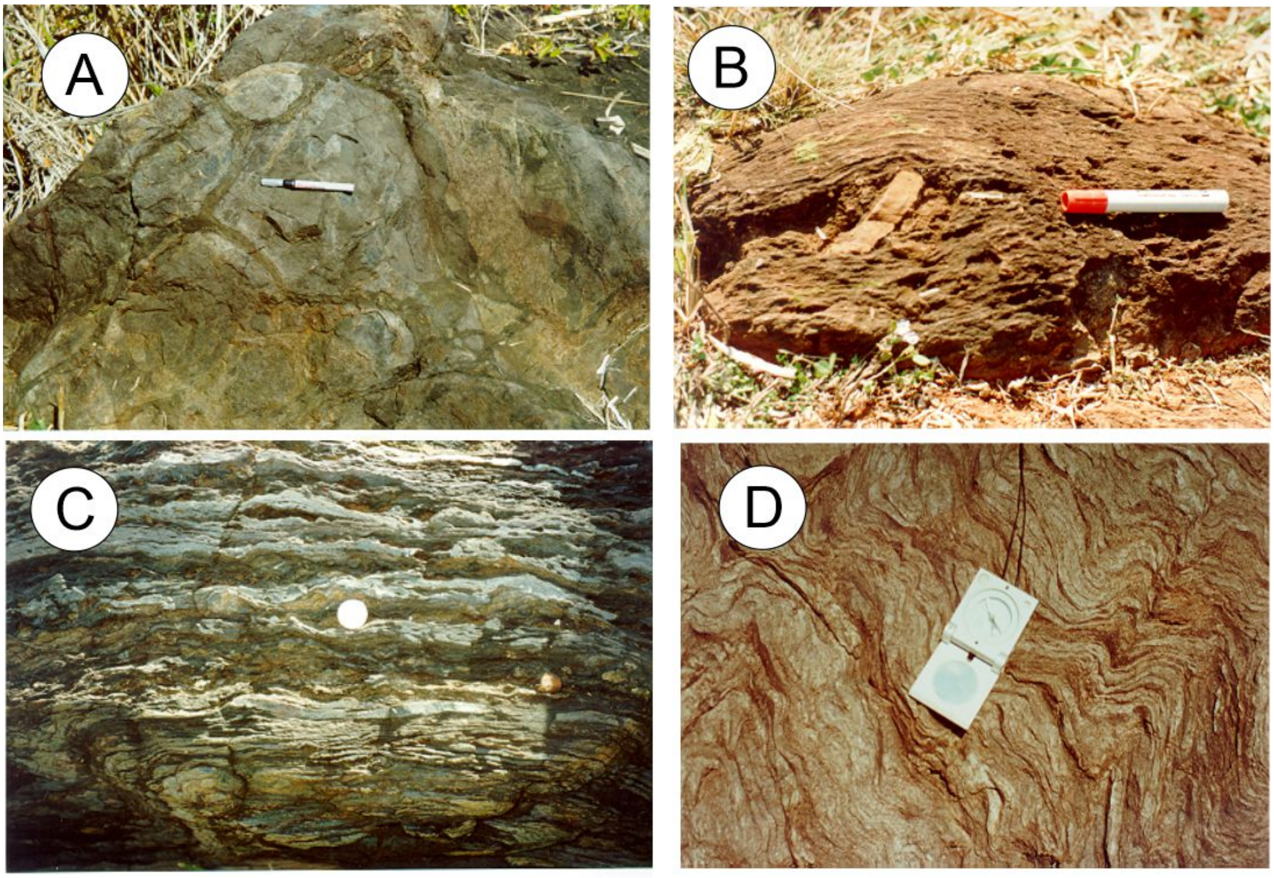

Figure 3 - Local rocks of Cabaçal Mine. (A) Metapillow lavas (basaltic composition); (B) meta-andesitic weathered lavas; (C) BIF and (D) Gneiss showing crenulation and parasitic folds.

Base metal and gold are hosted in the transition from the dacitic metavolcanic to tuffaceous sediments, pillow lavas, andesitic lavas and BIF. They are represented by concentrations of Cu-Au and Zn-Pb-Cu-Au, where sulfide and selenide minerals (Figure 5 A), native Bi (Figure 5 B), and Au-Ag and Au- Bi alloys (Figure 5 C) are important phases.

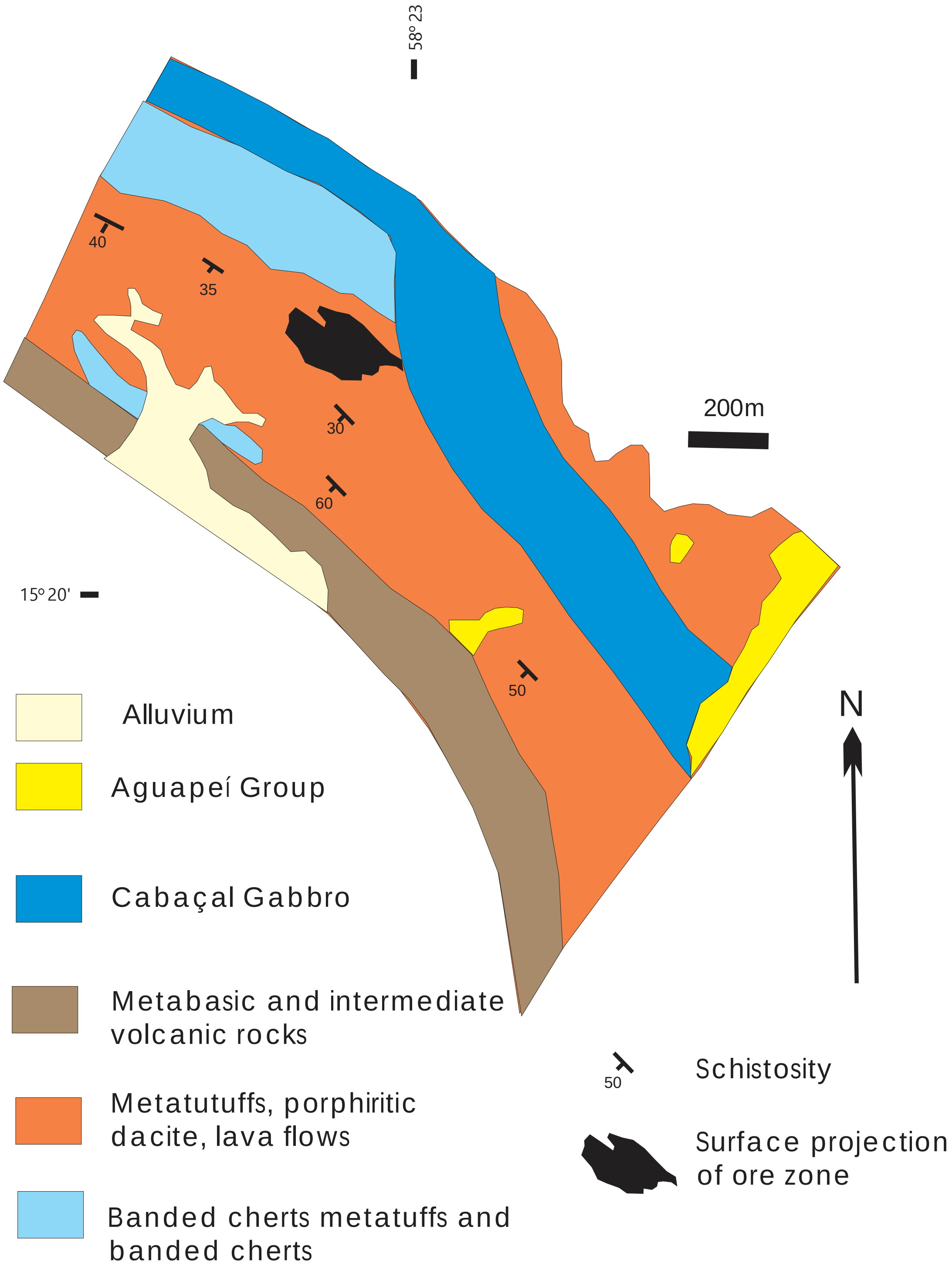

Figure 4 - Detailed geologic map of the Cabaçal Gold Deposit. Ondulating limits coincident with the principal foliation plane and plunge towards SSW, dipping about from 30º to 60º.

The ore occurs as disseminated, banded, veined, and massive types. The banded ore shows continuous laminae of sulfide minerals (chalcopyrite, pyrite, sphalerite, galena and pyrrhotite) coincident with foliation, and is usually associated with banded tuff, chert and the upper part of the chloritized zone, suggesting a volcanogenic origin. The veined ore is widespread in all over mineralized area and veins are composed chiefly of milky quartz but carbonate veins also occur. Two quartz vein generations are related to the mineral evolution (Figure 6 A and B) The brecciate ore is represented by fragments of chlorite zone (Figure 6 C), banded cherts, metatuffs, and quartz veins set in a matrix of sulfide minerals. Chalcopyrite is the most common sulfide, followed by pyrite, sphalerite, pyrrhotite, and visible native gold and Bi-Te minerals are common. The massive ore is restricted to the chlorite zone, comprised of chalcopyrite, pyrrhotite and lesser pyrite (Figure 6 D).

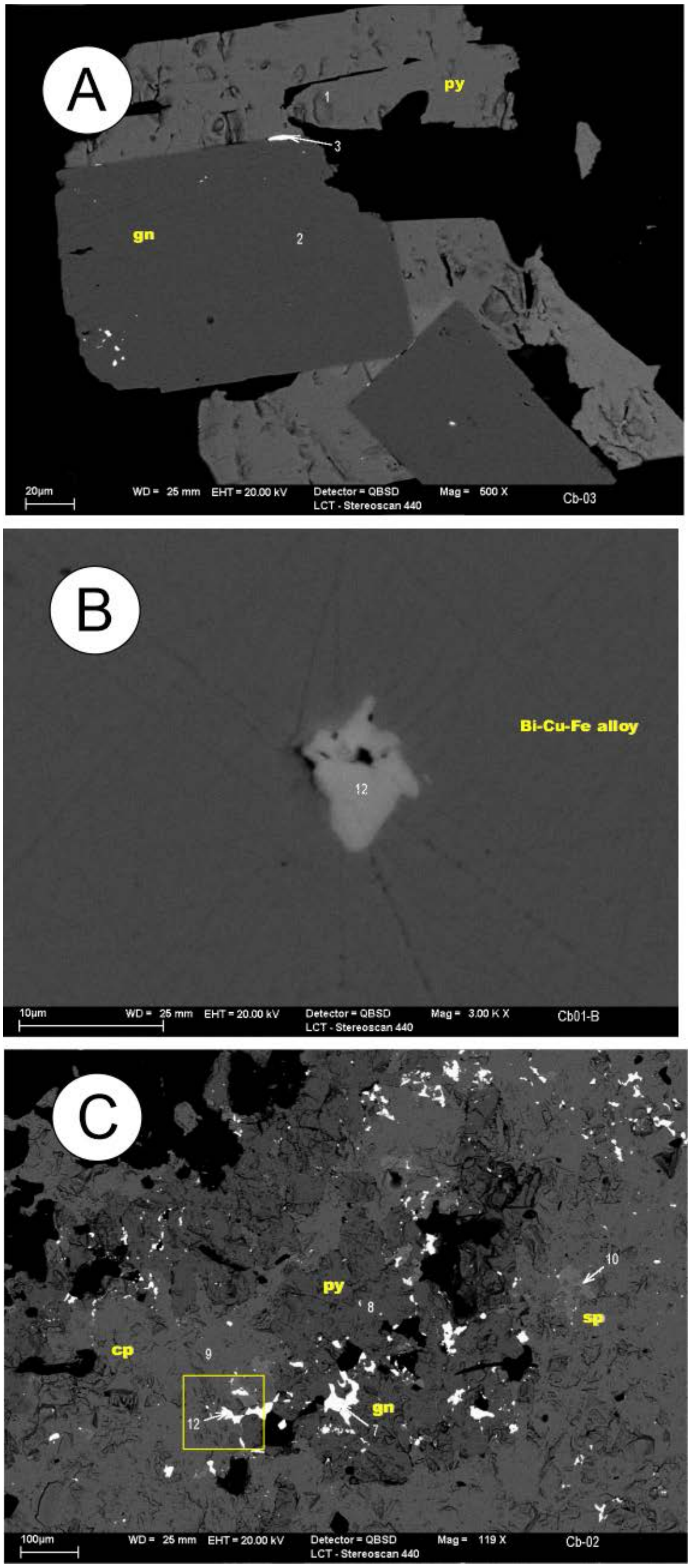

Figure 5 - SEM images of Cabaçal ore. (A) Minerals abbreviation are: py: pyrite; gn: galena; cp:chalcopyrite; sl: sphalerite. (B) Bismut+cooper+tellurium alloy. (C) Gold is observed in the square.

Petrographic studies of Cabaçal deposit ore allowed to identify the common mineral assemblage is comprised of sericite-biotite-garnet-quartz-staurolite, carbonate (Figure 6 E) and chlorite (Figure 6 F), locally with sillimanite which allowed Pinho (1996) to calculate the metamorphic peak to be in the range between 460^o and 490^{o}C. According to Pinho (1996) the second event originated asymmetric folds and the axial plane cleavage and/or crenulation cleavages were developed in the fold hinges. These plane strikes N-NW to S-SE and dips NW, but gentler than the first foliation. The third deformational event produced soft regional folds which axial planes strike W-NW and E-SE with a steep dip to N. Most of the sulfide concentrations are concordant with the first foliation, but when concordant with the second foliation, sulfides are Au-enriched.

However, Santos et al., (2016) presents petrography data associated with structural relations, which allowed to distinguish three metamorphic events: the first event, M1, contemporary to Sn is of lower green shale facies; the second event, M2, associated with the Sn + 1 phase is from green schist to amphibolite facies; and the third thermal event, M3, of hornblende hornfels facies, marked by the growth of garnet + sillimanite + plagioclase + quartz, resulting in amphibolitic facies and attributing temperatures above 550° C for metamorphism.

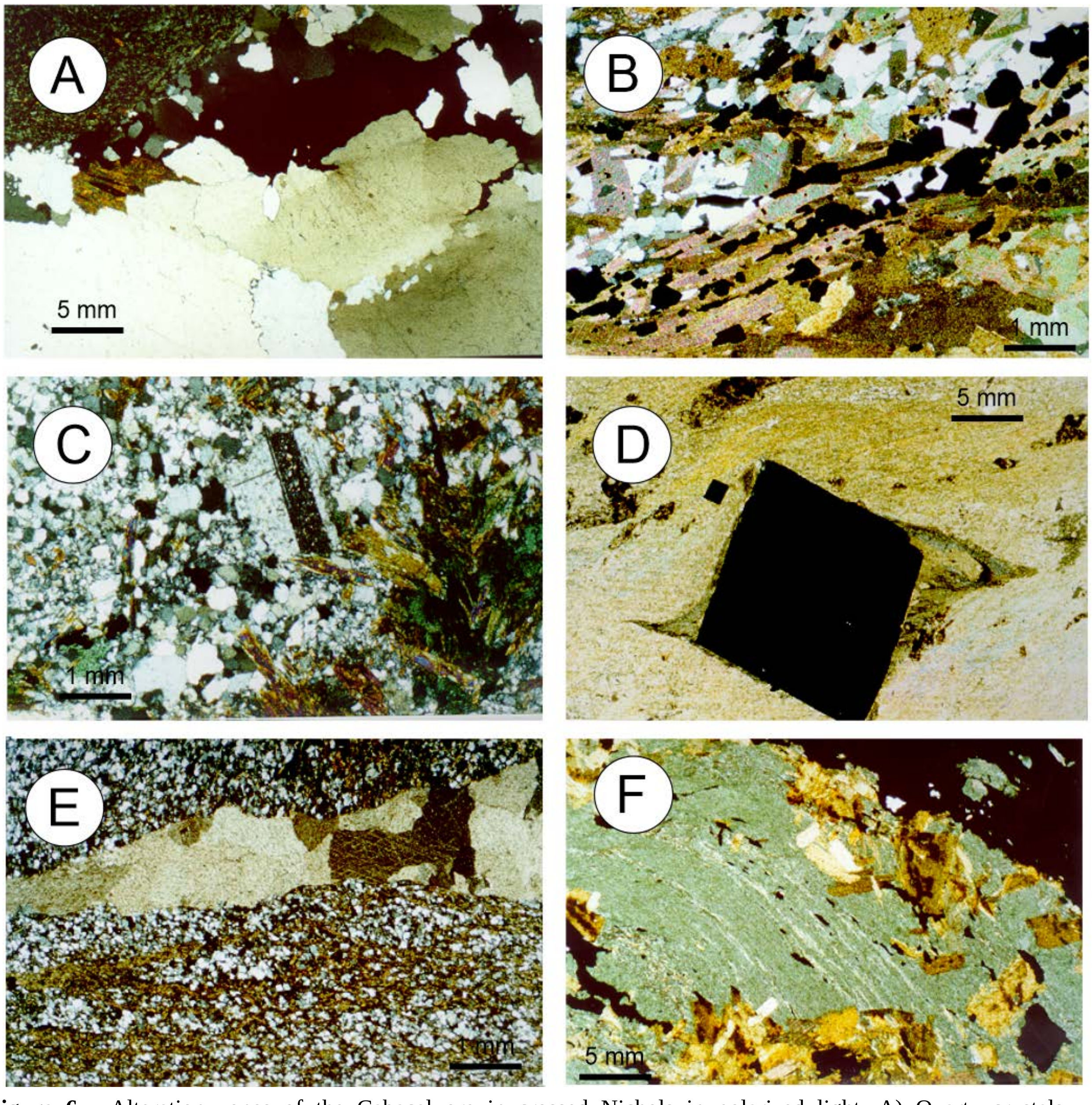

Figure 6 - Alteration zones of the Cabaçal ore in crossed Nichols in polarized light. A) Quartz crystals with recrystallization texture. B) Microlitic texture with plagioclase rips. C) Greenish chlorite with yellowish biotite. D) Oriented sulphide crystal showing rotation during deformation and strain shadow. E) Microcrystalline quartz showing recrystallization texture with carbonate; F). Greenish chlorite.

$^{40}Ar/^{39}Ar$ results

The samples from the Cabaçal deposit were collected from a borehole at different deep where the ore was cut by the drilling.

The grains were irradiated together with appropriate neutron flux standards, at the IPEN/CNEM IEA-R1 nuclear reactor and Ar isotope compositions were determined at CPGeo-USP $^{40}Ar/^{39}Ar$ laboratory and the results are presented in table 3.

The first sample was collected at 107.6 m and three grains were analyzed yielding ages of 1523 ± 13 Ma (plateau age); 1562 ± 17 Ma (integrated age); 1521 ± 11 Ma (plateau age).

The second sample was collected at 36.6 m and again three grains were analyzed yielding ages of 1513 ± 11 Ma (integrated age); 1498 ± 4 Ma (integrated age); 1502 ± 17 Ma (plateau age).

Table 3 - Ar isotope data for the sample analysed in this investigation.

Sample	40/39	38/39	37/39	36/39	40*/39	%rad	Laser (W)	Age (Ma)	erro (Ma)	Ar40 (mol	Age (Ma)	error (Ma)
113-107.6	69,08517	-0,00068	0,00000	0,01567	64,45194	93,30	0,20	1230	23,1	1,71E-15	1230	23,1
sericite	66,47346	0,01250	0,00000	0,00315	65,54151	98,60	0,40	1245	6,1	1,01E-14	1245	6,1
grain A	82,88496	0,00975	0,00000	-0,00081	83,12386	100,30	0,60	1471	3,1	3,79E-14	1471	3,1
	85,78199	0,01118	0,00000	-0,00017	83,83289	100,10	0,80	1503	3,2	6,52E-14	1503	3,2
	87,34697	0,01150	0,00000	0,00016	87,29786	99,90	1,00	1521	2,2	1,41E-13	1521	2,2
	87,51301	0,01082	0,00000	-0,00012	87,54823	100,00	1,20	1524	2,5	2,11E-13	1524	2,5
	87,49454	0,01092	0,00000	-0,00001	87,49549	100,00	1,50	1523	2,2	1,96E-13	1523	2,2
	86,79890	0,01120	0,00000	-0,00027	86,87785	100,00	1,80	1516	2,6	1,33E-13	1516	2,6
	86,41913	0,00969	0,00000	-0,00083	86,66440	100,30	2,20	1513	3,2	5,74E-14	1513	3,2
	85,60880	0,01009	0,00000	-0,00132	85,99679	100,50	2,60	1505	5	2,54E-14	1505	5
	84,86890	0,01146	0,00000	0,00081	84,63012	99,70	3,20	1489	5,8	1,45E-14	1489	5,8
	84,59068	0,01024	0,00000	-0,00352	85,63098	101,20	4,20	1501	11,0	8,82E-15	1501	11,0
	87,23477	0,01309	0,00000	-0,00066	87,42899	100,20	5,00	1522	10,0	7,54E-15	1522	10,0
113-107.6	62,96477	0,00772	0,00000	0,00825	60,52444	96,10000	0,30	1174	18,30	2,76E-15	1174	18,30
sericite	80,05247	0,01056	0,00000	-0,00114	80,38805	########	0,50	1438	3,90	2,85E-14	1438	3,90
grain B	86,00391	0,01111	0,00000	-0,00039	86,11823	########	0,80	1507	3,40	9,26E-14	1507	3,40
	87,25574	0,01066	0,00000	-0,00018	87,30858	########	1,00	1521	2,40	1,55E-13	1521	2,40
	87,16032	0,01128	0,00000	-0,00015	87,20358	########	1,20	1520	1,90	2,22E-13	1520	1,90
	87,23294	0,01209	0,00000	0,00006	87,21555	########	1,50	1520	2,00	2,34E-13	1520	2,00
	87,41080	0,01051	0,00000	-0,00040	87,52710	########	1,80	1523	2,80	8,78E-14	1523	2,80
	86,57913	0,01158	0,00000	0,00102	86,27663	99,70000	2,50	1509	3,00	4,75E-14	1509	3,00
	87,13342	0,01230	0,00000	0,00302	86,25900	99,00000	3,60	1508	7,90	1,67E-15	1508	7,90
	87,42941	0,01085	0,00000	-0,00049	87,55928	########	5,00	1524	4,00	2,18E-14	1524	4,00
113-107.6	76,62570	0,01648	0,02517	0,01829	71,22287	92,90000	0,30	1321	20,40	3,10E-15	1321	20,40
sericite	80,77782	0,12540	0,28296	0,00218	80,16934	99,20000	0,50	1435	4,90	1,90E-14	1435	4,90
grain C	86,61903	0,01190	0,01855	0,00074	86,40289	99,80000	0,80	1511	3,20	7,26E-14	1511	3,20
	87,22084	0,01166	0,00950	0,00045	87,08890	99,80000	1,00	1518	3,10	1,60E-13	1518	3,10
	87,38475	0,01156	0,01114	0,00027	87,30707	99,80000	1,20	1521	3,00	1,63E-13	1521	3,00
	86,38934	0,01088	0,00910	0,00033	86,29283	99,90000	1,50	1509	3,90	6,72E-14	1509	3,90
	86,14247	0,01353	0,21730	0,00220	85,52029	99,30000	1,80	1500	4,80	2,24E-14	1500	4,80
	85,65815	0,01750	0,00000	0,00352	84,61755	98,80000	2,50	1489	7,20	1,36E-14	1489	7,20
	86,12655	0,01643	0,52380	-0,00037	86,30546	########	3,60	1509	13,70	4,38E-15	1509	13,70
	91,67818	0,01781	0,00000	0,00045	91,54420	99,90000	5,00	1570	17,90	3,93E-15	1570	17,90
113/36,6m	81,78911	0,01733	0,00000	0,03762	70,67255	86,40000	0,20	1314	16,20	3,20E-15	1314	16,20
sericite	68,92926	0,01257	0,00000	0,00395	67,76035	98,30000	0,40	1275	9,00	1,27E-14	1275	9,00
grain A	79,21603	0,01182	0,00000	0,00005	79,20189	########	0,60	1423	3,80	3,86E-14	1423	3,80
	84,60061	0,01057	0,00000	-0,00001	84,60257	########	0,80	1489	3,50	9,88E-14	1489	3,50
	85,68396	0,01064	0,00000	0,00011	85,65217	########	1,00	1501	2,20	1,60E-13	1501	2,20
	85,35670	0,01249	0,00287	0,00025	85,28386	99,90000	0,20	1497	4,00	1,66E-13	1497	4,00
	85,41780	0,01070	0,00292	0,00038	85,30500	99,90000	0,50	1497	4,70	1,88E-13	1497	4,70
	86,36012	0,01125	0,00000	-0,00025	86,43418	10,10000	0,80	1511	2,60	1,19E-13	1511	2,60
	86,90835	0,01129	0,00000	0,00000	86,90292	########	2,20	1516	2,30	1,06E-13	1516	2,30
	87,24972	0,01150	0,01396	0,00042	87,12669	99,90000	2,60	1519	3,20	5,28E-14	1519	3,20
	87,48091	0,01278	0,17261	0,00080	87,26807	99,70000	3,10	1520	5,80	1,76E-14	1520	5,80
	85,27561	0,01643	1,01536	0,00458	84,05733	98,50000	4,20	1482	7,60	1,05E-14	1482	7,60
	88,74547	0,01089	0,35469	0,00081	88,55504	99,80000	5,00	1536	5,50	1,63E-14	1536	5,50
113/36,6m	75,90316	0,03931	1,38072	0,05610	59,49103	78,30000	0,30	1160	19,50	3,85E-15	1160	19,50
sericite	72,21935	0,01449	0,11892	0,00285	71,39135	98,80000	0,50	1323	5,00	1,66E-14	1323	5,00
grain B	78,98106	0,01272	0,00000	0,00092	78,70882	99,70000	0,80	1417	3,50	4,43E-14	1417	3,50
	85,29587	0,01107	0,00000	0,00035	85,19258	99,90000	1,00	1496	2,20	1,23E-13	1496	2,20
	86,94870	0,01124	0,02325	0,00014	86,90883	########	1,30	1516	2,10	1,88E-13	1516	2,10
	86,18093	0,01086	0,00000	-0,00013	86,21726	########	1,50	1508	1,90	1,99E-13	1508	1,90
	86,32341	0,01096	0,00000	0,00022	86,25829	99,90000	1,80	1508	2,10	1,43E-13	1508	2,10
	86,72060	0,01094	0,00000	-0,00038	86,83105	########	2,50	1515	2,30	1,11E-13	1515	2,30
	86,63615	0,00984	0,00000	-0,00046	86,77246	########	3,40	1515	4,20	3,42E-14	1515	4,20
	87,41394	0,01088	0,00000	-0,00012	87,44954	########	5,00	1523	2,30	9,89E-14	1523	2,30
113/36,6m	77,99292	0,01366	0,00000	0,00998	75,04190	96,20000	0,30	1370	6,10	1,30E-14	1370	6,10
sericita	75,43575	0,01208	0,00000	0,00424	74,18239	98,30000	0,50	1359	5,70	1,67E-14	1359	5,70
grain A	78,91716	0,01229	0,00000	0,00113	78,58324	99,60000	0,80	1415	4,10	4,73E-14	1415	4,10
	84,74281	0,01152	0,00000	0,00032	84,64711	99,90000	1,00	1489	3,10	6,83E-14	1489	3,10
	86,50585	0,01054	0,00000	0,00028	86,42339	99,90000	0,30	1510	2,90	1,25E-13	1510	2,90
	86,97992	0,01115	0,00000	0,00027	86,89919	99,90000	1,50	1516	2,20	1,35E-13	1516	2,20
	85,85138	0,01212	0,00327	0,00048	85,71030	99,80000	1,80	1502	2,80	1,57E-13	1502	2,80
	86,55464	0,01125	0,00000	0,00020	86,49380	99,90000	2,50	1511	1,90	2,05E-13	1511	1,90
	86,93016	0,01210	0,03077	0,00078	86,70413	99,70000	3,60	1514	3,40	1,38E-13	1514	3,40
	87,13524	0,01170	0,05281	0,00080	86,90669	99,70000	5,00	1517	2,20	1,14E-13	1517	2,20

Four grains of sericite from Cabaçal ore indicate a Ar/Ar age range from 1562 to 1513 Ma interpreted as cooling age of hydrothermal solutions.The trap temperature for $^{40}Ar/^{39}Ar$ in sericite is suggested from 330°C to 250ºC (McDougall & Harrison, 1999; Glasmacher et al., 2001)**.** Since the hydrothermal alteration at the Cabaçal deposit is dominated by quartz-carbonate-sericite-arsenopyrite assemblages, we interpret the ages here reported as the cooling age of the sericite and the hydrothermal fluids.

Two grains from sample 113 collected at 36.6 m yielded age of 1502 ± 17 Ma and 1498 ± 4 Ga (Table 4). This range of age is related to Santa Helena orogeny rocks formed at the Western limit of the Cachoeirinha orogenic rocks (Geraldes et al., 2001) with ages at about 1.46 Ga to 1.42 Ga. The heating from Santa Helena magmatism may have a important hole in the Cabaçal deposits, resulting in isotopic homogenization in sericite grains, as hypothesis proposed by Harbi et al. (2018).

Table 4 - Synthesis of the Ar/Ar obtained in this study.

Sample	Grain	Material	Age (Ma)	Error
113-107.6	1	sericite	1523	13
113-107.6	2	sericite	1562	17
113-107.6	3	sericite	1521	11
113-36.6	1	sericite	1513	11
113-36.6	2	sericite	1498	4
113-36.6	3	sericite	1502	17

DISCUSSIONS AND CONCLUSIONS

The Cabaçal gold deposit is located in the SW Amazonian craton, Mato Grosso State, Brazil, where the Alto Jauru orogenic rocks (U-Pb ages from 1790 Ma to 1744 Ma) and Cachoeirinha orogenic rocks U-Pb zircon age of the host-volcanic rocks is *ca*. 1790-1720 Ma. The Cabaçal Au-Zn Deposit is hosted by volcanic rooks of the Alto Jauru orogen and controlled by structural features. The gneissic rocks found hosting the ore contain metamorphic garnet-sillimanite-biotite paragenesis and indicate amphibolitic facies for the generation of the deposit. According to Santos et al. (2016), petrography and structural relationships indicate that orebody was affected by two deformational events, Dn and Dn+1, associated with Sn foliation (schistosity and gneissic banding) and Sn+1 (crenulation cleavage), and three metamorphic events (M1, M2 and M3): the first is contemporary with Sn in lower greenschist facies; M2 is associated with the second phase of Sn+1 under greenschist to amphibolite facies; the third thermal event of amphibolite facies resulted from intrusion of the Cabaçal tonalite.

In the Dn deformation phase, the foliation Sn stands out, which is represented by gneissic banding in the paragnaisses. As pointed out by Santos et al. (2016), tight folds to centimeter-scale isoclinals occur. The orientation of Sn foliation is generally East-West with dives to N or S. The main structure associated with the event Dn + 1 is represented by the crenulation cleavage Sn+1. This foliation is located in the axial plane of the Dn + 1 folds, which are open to tight, inclined with an inclination towards NE. The orientation of the foliation Sn + 1 is oriented N30º to 60ºW, and plunge towards SSW, dipping about 65 to 90º.

The mineralization is hosted by felsic metavolcanic and metavolcanoclastic rocks and occurs as (i) bands concordant with the mylonitic foliation, (ii) breccias, (iii) quartz-carbonate veins and (iv) disseminate. Detailed petrologic and geochemical investigations indicate that gold deposition is associated with metamorphic fluids migrating along regional shear zones. The ore is polymetallic and comprises of chalcopyrite, pyrite, marcasite, pyrrhotite, sphalerite, and minor galena, bismuth, selenides and tellurites. The mineralization is related to hydrothermal alteration and includes quartz, chlorite, carbonate, sericite and biotite.

Detailed petrologic investigations indicate that gold deposition was associated with metamorphic fluids migrating along regional shear zones (Figure 8). $^{40}Ar/^{39}Ar$ step-heating ages suggest 1.52-1.51 resetting (coeval to the Cachoeirinha orogen). We have analyzed sericites from the hydrothermal zones by the $^{40}Ar/^{39}Ar$ method, using laser step-heating dating in single grains. One sample is from a bore hole 107m deep and yielded a plateau age of 1521.3 ±

1.3 Ma. Another sample is 36.6 m deep and yielded a plateau age of 1510.4 ± 1.2 Ma (Figure 7). The same samples were dated by K-Ar method, and the ages obtained are 1643 ± 78 Ma and 1615 ± 65 Ma, respectively (Pinho & Pinho, 1997). These studies reveal that Cabaçal gold deposit may be originated during the Alto Jauru orogen (1.79-1.74 Ga) and later on underwent to an important remobilization process. With the available data is possible to define that the second event was related to the Cachoeirinha orogen (1.58-1.52 Ga)..

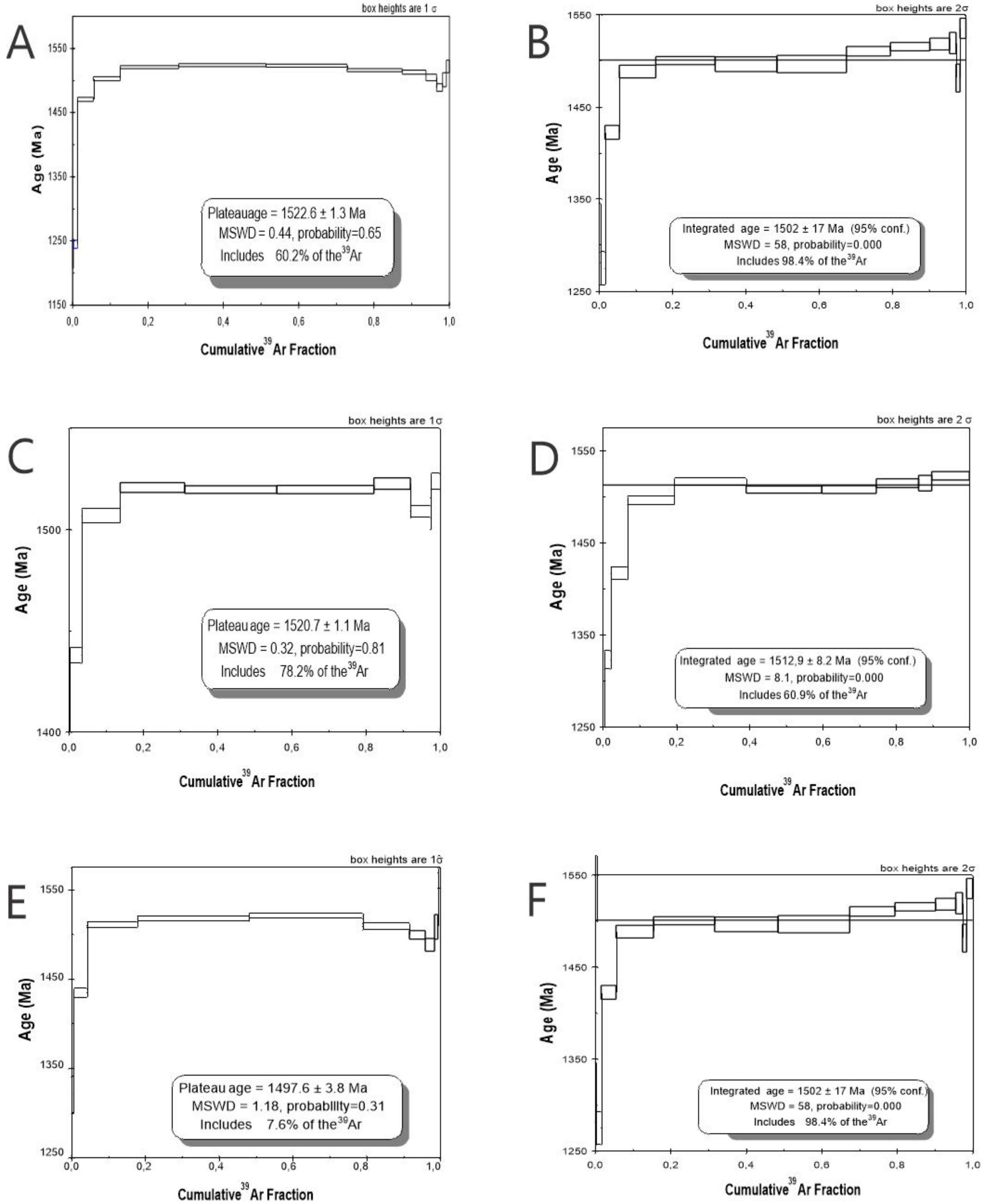

Figure 7 - Age (Ma*) versus* Cumulative ^{39}Ar fraction (A) for the 3 grains of sample 131-107.6; (B) for the 3 grains of sample 133-36.6.

The results here reported may be compared with the geochronologic data observed in the literature. The results here reported may be compared with the geochronologic data observed in the literature. Ar-Ar ages reported by Paulo (2004) show that the Cachoeirinha Magmatic Arc and Greenstone Belt Alto Jauru units have equivalent cooling ages (1.52 Ga), corroborating the hypothesis that both are part of the Jauru Terrain. Ruiz (2005) points out that the Cachoeirinha Orogeny (Calimmiana) evolved in two stages, the first, from 1590 to 1560 Ma, is dominated by of intraoceanic arc, and the second, from 1560 to 1520 Ma, is characterized by expressive granitic magmatism (batholiths Santa Cruz and Cabaçal) of continental magmatic arc.

The 40Ar-39Ar geochronological data point to a regional cooling of the domain around 1500-1450 Ma. The structural data indicate a regional compression with main transport from SW-W to NE-E. U-Pb zircon ages from older rocks of the Alto Jauru rocks obtained from a banded silicic volcaniclastic metasediment from the Cabaçal gold mine yielded a U-Pb age of 1758 ± 7 Ma, interpreted as the crystallization age for the zircons (Geraldes et al., 2001); this age is probably close to the depositional time of the metasedimentary sequence

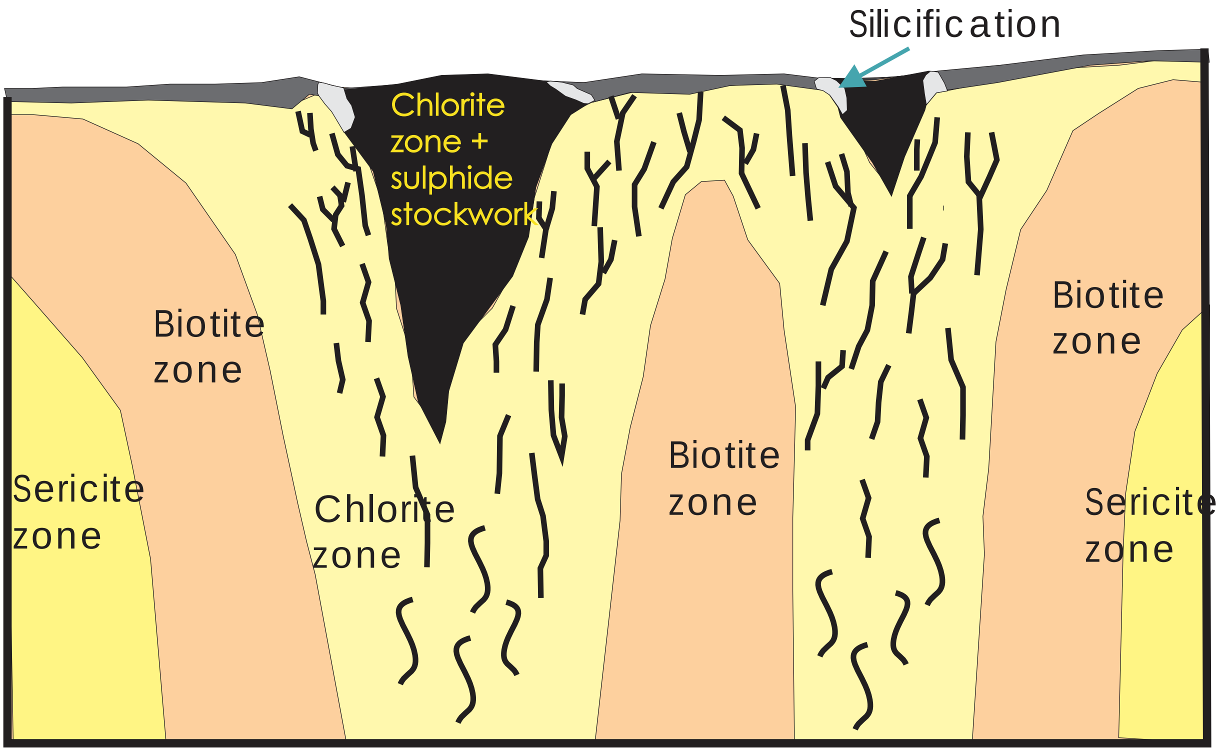

Figure 8 - Schematic model for Cabaçal gold deposit formation with host-rocks recording a strong shear zone responsible for hydrothermal alteration and rare metal deposition.

U-Pb SHRIMP data reported in the literature for individual zircons from a metavolcanic unit in the area yielded two ages grouping of 1769 ± 29 Ma and 1724 ± 30 Ma (Pinho, 1996) and 1819 ± 7 Ma (Santos et al., 2016).

These results are consistent with volcanism and deposition at ca. 1819-1750 Ma and could be related to the Alto Jauru Orogen evolution.

These studies reveal that Cabaçal gold deposit may be originated by volcanic process during the Alto Jauru orogen (1.81-1.75 Ga) and later underwent to an important remobilization by hydrothermal solutions.

The mineralization is related to hydrothermal alteration and includes quartz, chlorite, carbonate, sericite and biotite. Sericite grains from the hydrothermal zones obtained by $^{40}Ar/^{39}Ar$ method from a bore hole 107 m deep yielded a plateau age of 1521.3 ± 1.3 Ma. Another sample is 36.6 m deep, and yielded a plateau age of 1510.4 ± 1.2 Ga.

This evidence reveals that hydrothermal solutions originated related to the Cachoeirinha orogen (1.58-1.52 Ga) cutting the Alto Jauru orogen (1.79-1.74 Ga) host rocks.

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