Fluid inclusion and isotope (O, H, C, Sr) constraints on the orogenic gold mineralization at the Enche Concha and Tunel prospects, Gurupi Belt, Brazil

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Abstract

The gold mineralization at the Enche Concha and Tunel prospects, northwestern portion of the Gurupi Belt, is hosted in dacites and phyllites that belong to the ca. 2160 Ma-old metavolcano-sedimentary Chega Tudo Formation. These host rocks are variably deformed, from a spaced cleavage to schistose and mylonitic varieties. The hosting structures have previously been defined as produced in the Paleoproterozoic. The hydrothermal alteration processes include carbonatization, sericitization, sulfidation, and quartz veining. These processes are both pervasive and fissure-filling in style. Pyrite is largely predominant over chalcopyrite and sphalerite and gold occurs as a refractory phase in pyrite. Fluid inclusion, stable (O, H, C) and Sr isotopes studies indicate that the hydrothermal alteration and gold mineralization occurred between 260 and 370°C (mostly ~328°C), and 0.85 to 2.8 kbar, from a low-salinity (~5% NaCl), aqueous-carbonic (XCO2 = 0.03-0.13), relatively reduced (log fO2 = -32.1), and near neutral (pH = 5.0-8.2) metamorphic fluid (δ18O = +9.4 to +11.3‰, δD = -25 to -28‰). Contributions from deep-seated (lower crust and mantle) sources are suggested by a δ13C CO2 value of -7.6‰, and 87Sr/86Sr ratios between 0.702699 and 0.705141, which are lower than those found in the country rocks. Gold was transported by the Au(HS)2- complex and precipitation occurred in response to phase separation, identified by fluid inclusions, and fluid-rock interactions, given by the lowering of the δ13C CO2 values. The geological and genetic characteristics are equivalent to those of the orogenic gold system previously defined for the Gurupi Belt.

1. Introduction

The Gurupi Belt, in northern Brazil, contains shear-zone-hosted gold deposits that totalize over 158 t of gold (~5 Moz). These deposits, including Cachoeira, Chega Tudo, and Cipoieiro, have been defined as belonging to an orogenic gold system (Klein 2014), and formed at the late stages of an accretionary-collisional Rhyacian orogeny (Klein et al. 2020; Tavares et al. 2017). Enche Concha and Tunel are exploration targets (prospects, separated by ca. 2.4 km) located in the central portion of the Gurupi Belt (Fig. 1) and they have received intermittent exploration work. Unpublished company reports inform the presence of several mineralized intersections, most notably 3.5 m @ 0.82 g/t at Enche Concha, and 7.39 m @ 0.83 g/t (including 1 m @ 2.50 g/t) in the Tunel prospect.

Although the orogenic model is well-defined for the Gurupi Belt, no information on host rocks, hydrothermal alteration, and genetic aspects for several prospects, including Enche Concha and Tunel, is available. In this work, we discuss these aspects for both prospects, supported by fluid inclusions, stable isotopes (C, O, H), and provide the first Sr isotope compositions of hydrothermal calcite associated with gold mineralization in the Gurupi Belt. The results allow us to discuss the physico-chemical characteristics and sources of the mineralizing fluid, and make comparisons with known deposits in the Gurupi Belt and elsewhere.

2. Geological setting and gold metallogeny

2.1. Regional geology

The Gurupi Belt is composed of magmatic, sedimentary and metamorphic rocks that range in age from 2695 Ma to 549 Ma (Fig. 1, Klein et al. 2020, and references therein). The oldest rock is the Archean Igarapé Grande metatonalite (2695 ± 4 Ma), which forms part of the basement of the belt. Most of the rock units were formed during the Rhyacian period and include arc-related sequences, such as the orthogneisses of the Itapeva Complex (2167-2148 Ma), voluminous juvenile calc-alkaline granitoids of the Tromai Intrusive Suite (2174-2148 Ma) and Canoa quartz diorite (2162 ± 11 Ma), amphibolites (2166-2136 Ma), the juvenile metavolcano-
FIGURE 1. Location map (inset) and simplified geological map of the Gurupi Belt (modified from Klein et al. 2020), with location of the Enche Concha and Tunel prospects and main gold deposits: 1 – Cachoeira, 2 – Chega Tudo, 3 – Serrinha, 4 – Montes Áureos, 5 – Cipoeiro.
and Neoproterozoic rocks, with direction averaging N-S. The 
0.0 ºC). The precision was estimated at ± 0.5º C and ± 5ºC for 
600°C. The calibration was done with synthetic fluid inclusions 
heating-freezing stage with a temperature range of −196° to

All studies were performed in samples obtained from three 
Gurupi Belt. (1) D, is ductile, oriented predominantly to N40°-50°W, progressively folded by D1b, and 
and peraluminous, two-mica granites (Ney Peixoto and Pantoja granites) of 549 ± 4 
Ma (Klein et al. 2020, and references therein).

In terms of structural evolution, Tavares et al. (2017) defined 
three phases for the Gurupi Belt. (1) D, is ductile, oriented 
predominantly to N40°-50°W, progressively folded by D1b, and 
and the Igarapé de Areia Formation (younger than 2078 Ma) (Klein et 
al. 2020). All these Rhyacian units are part of an accretionary to 
collisional orogen, which continues to the north in the São Luís 
cratonic fragment (Klein et al. 2020, and references therein).

Neoproterozoic units comprise siliciclastic metasedimentary 
rocks younger than 1140 Ma (Gurupi Group) and 630 Ma (Piriá 
Formation), an anorogenic intrusion of nepheline-syenite (732 ± 7 
Ma), a calc-alkaline metatonalite (624 ± 16 Ma), and peraluminous, 
two-mica granites (Ney Peixoto and Pantoja granites) of 549 ± 4 
Ma (Klein et al. 2020, and references therein).

In structural terms, the Intrusive rocks are included in orogenic 
sequences, such as the Santa Luzia do Pará Formation (younger than 2140 Ma) and the 
Igarapé de Areia Formation (younger than 2078 Ma) (Klein et 
al. 2020). All these Rhyacian units are part of an accretionary to 
collisional orogen, which continues to the north in the São Luís 
cratonic fragment (Klein et al. 2020, and references therein).

4.1. Host rocks

 Petrographic investigation of drill cores down to 265 m in depth allowed the recognition of different rock types hosting 
hydrothermal alteration and gold mineralization. The rocks 
comprise an intercalation of dacite and phyllite, along with 
brecciated zones (Fig. 2).
The phyllite is a dark grey to greenish rock (Figs. 2 and 3A) composed of quartz, white mica, chlorite, and carbonate. This rock shows a penetrative and continuous cleavage, which gradually pass to a spaced foliation defined by the alternation of thin layers of mica and quartz. Locally, the rocks resemble schists, where the minerals are recrystallized and coarser-grained (Fig. 4). Porphyroclastic texture is also observed, with ovoid fragments of carbonate that are contoured by fine-grained micas and quartz (Fig. 4C). The variation in the planar structures may indicate progressive deformation (S1 followed by S1b, according to Tavares et al. 2017).

The dacites are light grey rocks with variable grain size, from aphanitic, to fine-grained and locally porphyritic (Figs. 2 and 3B). The granular varieties are composed of plagioclase (75%) and quartz (25%). The plagioclase is tabular and euhedral to subhedral (Figs. 3B and 4H), and partially replaced by carbonate (Fig. 4J). The quartz grains are anhedral and show subgrains. In the porphyritic varieties, which are also porphyroclastic due to deformation, the phenocrysts/plagioclase crystals made up 25% of the rocks, and comprise plagioclase (20%) and quartz (5%) set in a quartz-feldspathic matrix (Figs. 4K, 4L). The plagioclase is anhedral to subhedral, rather ovoid, and strongly replaced by sericite and carbonate (Fig. 4), whereas quartz is anhedral and rounded.

The fault breccia forms centimeter-thick layers that cut across the phyllite and dacite layers. The rocks are fragmentary, non-cohesive, and without evident planar tectonic fabric (Fig. 3C). The fragments consist of vein quartz, vein carbonate and phyllite (Figs. 4M, 4N), which range in shape from angular to rounded, immersed in a quartz-feldspathic matrix (20% of the breccia volume), which locally contains carbonate cement.
4.2. Hydrothermal alteration and gold mineralization

The hydrothermal alteration comprises four processes: carbonatization, sericitization, sulfidation, and quartz veining. These processes are both pervasive and fissure-filling, are distributed in all host rocks and have slightly different timing regarding deformation (Fig. 5).

Carbonatization is the main and more widespread alteration process observed in all lithotypes and along the entire investigated depths. The carbonate alteration comprises the formation of anhedral calcite, with grain-size ranging from 0.5 to 1.0 mm, and two types/stages are observed: (1) disseminated, by replacement of the magmatic plagioclase (Figs. 6A, 6B), and (2) crystallization in mm-thick veinlets (Fig. 6C). The veining is more intensive in the more deformed portions of the host rocks.

The sericitic alteration occurs predominantly in the dacites and is present in different forms. The alteration is mainly placed along the foliation planes (Fig. 6D), being syn-tectonic to S1 or S1b. Sericite in pressure shadows of pyrite (Fig. 6E) indicates crystallization during the late stages (S1b?) of foliation development (Witt 1993). Locally, the sericite flakes cut across plagioclase crystals, which are partially or completely replaced by carbonate (Fig. 6F). Disseminated patches and replacement of plagioclase are also common (Fig. 6G).

The sulfide alteration affects all host rocks, but is more abundant in the phyllites and quartz veins, being probably associated with the late stages of the ductile deformation. Pyrite is largely the predominant sulfide phase, with subordinate amounts of sphalerite and chalcopyrite occurring in spatial association with pyrite (Fig. 6H). Thin layers of pyrite are placed along the foliation planes or cut across this foliation (Figs. 6I, 6J), and isolated euhedral crystals associated or not with carbonate are also common (Figs. 6K, 6L).

Veins and veinlets of quartz and quartz-carbonate, with or without sulfides (Figs. 6I, 6K, 6L), crosscut all lithotypes.
These veins are mm- to a few cm-thick and are in general discordant to the foliation, but show deformation features, such as micro-folding and subgrain generation (Figs. 6L, 6M). The occurrence of thicker (up to 30 cm-thick), massive to laminated gold-bearing quartz veins, which have been mined by artisanal miners (indicating the presence of free-milling gold), has been informed by unpublished company report (Kinross).

Free gold particles have not been observed in our investigation. Gold was detected by scanning electron microscopy, ranging in grade mostly from 0.83 to 1.57%, but reaching higher grades (5-6%) in deformed pyrite crystals present in quartz veins.

5. Fluid Inclusions

The fluid inclusion study was carried out on quartz crystals from sulfide-bearing (mineralized) veins from the Tunel prospect, sampled from drill core JB08 at the depths of 73.2 and 74.5 m (Fig. 7A). Over 180 fluid inclusions have been analyzed microthermometrically.

5.1. Types and distribution

The quartz crystals that host fluid inclusions are anhedral, with irregular rims, and often forming subgrains (Fig. 7B).
FIGURE 7. (A) Sample of quartz-sulfide vein used for fluid inclusion study. (B) Photomicrography, on crossed nicols, of the quartz vein showing the characteristics of the quartz grains.

The fluid inclusions occur in clusters, in isolation, or in trails (Fig. 8). Necking down features are common in larger inclusions (>5 µm) from all types. These necked inclusions were not included in microthermometric studies. Microscopic investigation at room (22-24°C) and sub-zero temperatures allowed the identification of three types of fluid inclusions. One type is comprised of one-phase inclusions that did not show phase transitions during the microthermometric work. These monophasic inclusions are probably metastable or empty cavities and will not be further addressed in this paper.

The Type-1 consist of aqueous-carbonic fluid inclusions having two phases. These phases comprise liquid water plus liquid CO₂, or liquid water and gaseous CO₂ (Fig. B). The type-2 consists of aqueous fluid inclusions and is formed predominantly by two-phase (liquid + vapor) and subordinately one-phase (liquid) inclusions (Figs. 8C, 8D).

Type-1 fluid inclusions are less abundant than Type-2 and occur predominantly as isolated individuals, and subordinately in clusters (primary inclusions) and trails (secondary inclusions). The morphology is rounded to ellipsoidal, and they vary in size between 3 and 5 µm. The carbonic phase occupies 15 to 30% of the inclusion cavities.

The more abundant Type-2 occurs as clusters and intra-granular trails, and rarely in isolation. These inclusions are primary and pseudo-secondary in origin, and are rounded or polygonal, with sizes ranging from 2 to 5 µm. The vapor phase occupies 80% of the inclusion cavities, but some inclusions have 70 to 60% of the vapor phase.

When in clusters, Type-1 and 2 inclusions occur as an association, and no temporal (crosscutting) relationships could be established, suggesting that the two types were trapped at the same time and belong to a single Fluid Inclusion Assemblage (FIA – Goldstein and Reynolds 1994).

5.2. Microthermometric results

The following abbreviations are used in text and figures. TmCO₂: temperature of melting of the carbonic phase, ThCO₂: temperature of homogenization of the carbonic

FIGURE 8. Photomicrographs showing types and distribution of the fluid inclusions. (A) General view of a quartz grain with trails of fluid inclusions. (B) Large two-phase aqueous-carbonic (Type-1) fluid inclusion occurring in the same microscopic domain with Type-2 aqueous inclusions. (C) Large two-phase aqueous inclusion in spatial association with one-phase inclusions. (D) Cluster and trails of Type-2 inclusions.
phase, Tmclat: clathrate melting temperature, Tmice: final ice melting temperature, Teu: eutectic melting temperature, Tht: temperature of final/total homogenization. Considering the state of homogenization, L stands for liquid, and V for vapor.

Type-1 aqueous-carbonic fluid inclusions show TmCO2 values ranging from -56.6 and -57.3°C (Fig. 9A). The ThCO2 in the same type varies between 12 and 25.6°C (Fig. 9B), mostly to the liquid state, whereas Tmclat is in the range of 6.0 to 8.4°C (Fig. 9C). The Tht ranges from 251 to 370°C (Fig. 9D).

In the two-phase Type-2 fluid inclusions, only a few Tht have been observed, ranging from -24.5 to -20.0°C, and Tmice varies between -0.1 and -4.1°C (Fig. 9E). Tht is in the range of 167 and 342°C (Fig. 9D).

5.3. Density and composition

Density and compositional data were calculated based on the microthermometric results. The global and CO2 densities of the aqueous-carbonic fluid inclusions vary from 0.7 to 1.0 g/cm³, and 0.2 to 1.0 g/cm³, respectively (Bowers and Helgeson 1983). The salinity of these fluid inclusions are in the range of 4.4 to 5.3 wt.% NaCl equivalent (based on Collins 1979), and the small variation in the TmCO2 values in relation to the pure CO2 values, indicates only minor amounts (up to 5%) of additional components, such as N2 and/or CH4 in the carbonic phase (e.g., Van den Kerkhof and Thiéry 2001). The estimated XCO2 values range from 0.03 to 0.13. For the aqueous inclusions, densities of 0.7 to 0.9 g/cm³, and salinities of 0.2 to 6.3 wt.% NaCl equivalent are estimated according to Brown and Lamb (1986).

5.4 Origin of the fluid inclusions

Petrographic and microthermometric results have shown that the two types of fluid inclusions occur in association in the same microscopic domains of the hosting quartz, and that the two types homogenized broadly in the same range of temperatures (Figs. 9D, 10, and 11). These features suggest that the two types are coeval and belong to a single system. A few aqueous fluid inclusions with Tht of 300-350°C have been observed, ranging from -24.5 to -20.0°C, and Tmice varies between -0.1 and -4.1°C (Fig. 9E). Tht is in the range of 167 and 342°C (Fig. 9D).

6. Isotope geology

6.1 Stable isotopes

The stable isotope compositions were measured in hydrothermal minerals and fluids: oxygen in vein quartz; oxygen, and carbon in vein and disseminated calcite from the carbonate alteration; hydrogen in inclusion fluids hosted in quartz (Table 1).

The δ18O values of quartz from Enche Concha vary between +16.6 and +16.9‰ in mineralized veins and is +17.7‰ in a barren quartz vein, whereas mineralized samples from Tunel range from +15.3 to +16.3‰. The δD values of inclusion fluids from two mineralized samples are -28 and -25‰ in the Enche Concha and Tunel prospects, respectively.

The 87Sr/86Sr ratios are weakly radiogenic and range from 0.702699 to 0.705141 for the Enche Concha samples, and from 0.703055 to 0.705080 at Tunel. Therefore, no difference exists in the Sr isotopic composition in the two prospects.

7. Discussions

7.1 Physico-chemical conditions of mineralization (T-P-o2-pH)

The estimated temperature and pressure conditions of gold mineralization is based on the microthermometric results from fluid inclusions and isotope thermometry. The oxygen isotope compositions of the coexisting quartz-calcite pair from sample JB04_238.6 yielded a temperature of 328°C using the equation of Sharp and Kirchner (1994). This value is in line with the interval of total homogenization temperatures measured in the aqueous-carbonic fluid inclusions (~260-370°C).

For pressure estimations, we used the above temperature data, along with salinity, CO2 density, and isochores calculated according to Bowers and Helgeson (1983) for the system CO2-H2O-NaCl. These data yielded a pressure range of 0.85 to 2.8 kbar (Fig. 12A), implying 3 to 9 km in depth, assuming lithostatic conditions, which is compatible with the structural setting of mineralization.

For the calculated T-P-XCO2 range, a log fO2 value of -32.1 is estimated for the oxygen fugacity of the fluid using the method of Huizenga (2005). This value lies above the CO2-Ch4 buffer (Fig. 12B), which is in line with the fluid inclusion TmCO2 data, and indicates relatively reduced conditions during gold mineralization. Additionally, the presence of calcite and sericite in the hydrothermal alteration, together with the lack of K-feldspar, indicates a solution with near neutral to slightly alkaline pH (ca. 5.0 to 6.2; Romberger 1990; Hayashi and Ohmoto 1991).

7.2 Fluid composition and potential sources

The composition of the hydrothermal fluid was estimated from the stable isotope results, using relevant fractionation factors and temperature (328°C), and from direct measuring of the isotopic composition of fluid inclusions (Table 1). The
FIGURE 9. Histograms of the microthermometric results. (A) Temperature of CO$_2$ melting from Type-1 fluid inclusions. (B) Temperature of CO$_2$ homogenization from Type-1 fluid inclusions. (C) Temperature of clathrate melting in Type-1 fluid inclusions. (D) Total homogenization temperature for Type-1 and Type 2 fluid inclusions (V: vapor, L: liquid). (E) Final ice melting temperature for Type-2 fluid inclusions.
calculated and measured fluid compositions, along with the Sr isotope and fluid inclusion results, were then compared to those of potential sources.

The δ¹⁸O values of the water in equilibrium with quartz is +10.7 to +11.0‰ at Enche Concha, and +9.4 to +10.4‰ at Tunel (quartz-H₂O fractionation factor of Matsuhisa et al. 1979). Calculated for calcite the fluid δ¹⁸O values are in the range of +9.5 to 11.3‰ for the disseminated calcite, and is + 9.7‰ for the vein calcite in the Enche Concha prospect. At Tunel, the values are +10.0 and +11.4‰ (calcite-H₂O fractionation factor of Friedman and O’Neil 1977). As a whole, the fluid δ¹⁸O values have similar ranges in quartz and calcite from the two prospects (+9.4 to +11.4‰). These values, in combination with the δD values from inclusion fluids suggest a metamorphic source for the fluid (Fig. 13A).

The δ¹³C values of the CO₂ in equilibrium with calcite (calcite-CO₂ fractionation factor of Ohmoto and Rye 1979) range from -8.3 to -9.1‰ for the disseminated stage, and is -7.6‰ for the vein calcite at Enche Concha. The values for Tunel are -11.8 and -12.8‰. These CO₂ δ¹³C values are not diagnostic of a specific carbon source. Instead, the variation in the isotopic composition might indicate variable contribution of organic carbon from the carbonaceous schists and phyllites of the hosting Chega Tudo Formation, which is a common feature in the Gurupi Belt (e.g., Klein et al., 2005). In addition, the fluid δ¹³C value of the quartz-carbonate-sulfide is the highest among the studies samples (Fig. 13B), and this composition may be closer to that of the mineralizing fluid, indicating a deep seated source (Ohmoto and Rye 1979).

In closed systems, minerals with insignificant contents of Rb, such as calcite, which does not incorporate this element in its structure, preserve the initial ⁸⁷Sr/⁸⁶Sr ratio (Mueller et al. 1991). In consequence, the ⁸⁷Sr/⁸⁶Sr ratios of hydrothermal calcite may be used as an approximation to the Sr isotope composition of hydrothermal fluids, and in the investigation of changes that the fluids may undergo by interaction with regional rocks or with mineralized host rocks (Kontak and Kerrich 1995; Scanlan et al. 2018). Furthermore, even for carbonates that have recrystallized or re-equilibrated at low temperatures, the Sr and C isotopic systems are sufficiently resistant to preserve the original compositions (Kerrich 1987). The relatively low ⁸⁷Sr/⁸⁶Sr ratios...
TABLE 1 – Stable isotope (C, O, H) compositions of hydrothermal minerals and inclusion fluids.

| Target   | Sample | Mineral   | Stage       | δ²⁰⁸O (‰) | δ¹³C (‰) | δ²H (FI) (‰) |
|----------|--------|-----------|-------------|-----------|----------|--------------|
| Enche Concha | JB02_74 | Quartz Vein | Vein (barren) | +17.7     |          |              |
|          | JB02_100.9 | Calcite Dissemination | +14.3     | -10.6     |          |              |
|          | JB02_140 | Calcite Dissemination | +16.1     | -11.1     |          |              |
|          | JB02_149.5 | Calcite Dissemination | +15.5     | -11.4     |          |              |
|          | JB04_238.6 | Quartz Vein | +16.9     |          |          |              |
|          | JB04_238.6 | Calcite Vein (qtz-cc-sulf) | +14.5     | -9.8      |          |              |
|          | JB04_261 | Quartz Vein | +16.6     |          |          | -28          |
| Tunel    | JB08_51 | Quartz Vein | +16.0     |          |          |              |
|          | JB08_51 | Calcite Dissemination | +14.8     | -14.1     |          |              |
|          | JB08_73 | Quartz Vein | +16.3     |          |          |              |
|          | JB08_75 | Quartz Vein | +15.3     |          | -25      |              |
|          | JB08_96.15 | Calcite Dissemination | +16.2     | -15.1     |          |              |

FI: fluid inclusion water, qtz: quartz, cc: calcite, sulf: sulfide

TABLE 2 – Strontium isotope compositions of hydrothermal calcite from the disseminated carbonate alteration.

| Target   | Sample | Host rock | ⁸⁶Sr/⁸⁸Sr 2σ | ⁸⁷Sr/⁸⁶Sr 2σ | ⁸⁴Sr/⁸⁸Sr 2σ | ⁸⁶Sr/⁸⁸Sr 2σ | ⁸⁷Sr/⁸⁶Sr 2σ |
|----------|--------|-----------|-------------|-------------|-------------|-------------|-------------|
| Enche Concha | JB02_100.9 | Phyllite | 0.119183     | 0.000057     | 0.705141     | 0.000027    | 0.006739     | 0.000006    |
|          | JB02_149.5 | Phyllite | 0.117123     | 0.000052     | 0.702699     | 0.000028    | 0.006739     | 0.000006    |
|          | JB04_165 | Phyllite | 0.118589     | 0.000225     | 0.703110     | 0.000021    | 0.006739     | 0.000002    |
| Tunel    | JB08_51 | Dacite | 0.117549     | 0.000077     | 0.703160     | 0.000034    | 0.006739     | 0.000018    |
|          | JB08_56.8 | Phyllite | 0.118769     | 0.000058     | 0.703055     | 0.000028    | 0.006739     | 0.000002    |
|          | JB08_96.15 | Dacite | 0.119411     | 0.000114     | 0.705080     | 0.000025    | 0.006739     | 0.000004    |

FIGURE 12. Physico-chemical diagrams for the Enche Concha and Tunel prospects. (A) P-T plot showing the estimated conditions for gold mineralization (shaded box), using the isochores calculated to the range of XCO₂ of the aqueous-carbonic fluid inclusions. The vertical dashed line stands for the temperature obtained with the oxygen isotope thermometry, whereas the thick dashed line is the solvus for the CO₂-H₂O-NaCl system for 10 mol% CO₂ and 6 wt% NaCl equiv. (from Bowers and Helgeson 1983). (B) Aquous solubility of gold as a function of temperature and oxygen fugacity. The dotted-dashed lines are for the chloride complex [AuCl₂⁻], whereas the dashed lines are for the bisulfide complex [Au(HS)₂⁻]. The thick solid lines represent the limits of the stability fields of sulfides and iron oxides, and the dotted lines stand for other buffers (adapted from Romberger 1990, and Ohmoto and Goldhaber 1997).
(~0.7027-0.7051) measured in the hydrothermal calcite from Enche Concha and Tunel indicate a little evolved source with low Rb/Sr ratio. Comparing with the composition of orogenic gold deposits from different cratons and ages, we can observe that our results are lower than those of the orogenic deposits (Fig. 14). Our results are also lower than those presented by the regional Rhyacian rocks of the Gurupi Belt and adjoining São Luís cratonic fragment (Fig. 14). This indicates that the Sr present in the mineralizing fluid is externally-derived and that the regional rocks have not contributed with Sr to the fluid. Furthermore, the data indicate a probable deep source for Sr, such as the lower crust or mantle (Fig. 14).

7.3. Genetic constraints

Some interpretations about the genesis of the gold mineralization can be drawn for the studied prospects, based on the fluid inclusion and isotopic data. The physico-chemical characteristics of the fluid, the presence of pyrite as the main sulfide mineral, and the lack of significant amounts of base metals suggest the H₂S (alternatively HS⁻) as the main sulfur species in the fluid. This, together with the oxygen fugacity estimation indicate Au(HS)₂⁻ as the gold transporting complex (Fig. 12B). The destabilization of this complex and deposition of gold from solution might be ascribed to phase separation.

FIGURE 13. (A) Oxygen and hydrogen isotopic composition of the hydrothermal fluids at Enche Concha and Tunel compared with available data for orogenic gold deposits of the Gurupi Belt (Klein 2014). The fields for magmatic and metamorphic waters are from Sheppard (1986) and the meteoric water line is from Craig (1961). SMOW = Standard Mean Ocean Water. (B) Carbon and oxygen isotopic composition of hydrothermal calcite.

FIGURE 14. Strontium isotope composition of hydrothermal calcite from Enche Concha and Tunel compared to the isotopic compositions of orogenic gold deposits worldwide, and with potential sources. References: (1) this study, (2) Kontak and Kerrich (1995), (3) Scanlan et al. (2018), (4) Griesmann (2011), (5) Mueller et al. (1991), (6) Haebler (2002), (7) Rhyacian granitoids and gneisses of the Gurupi Belt and São Luís cratonic fragment, compiled from Hurley et al. (1968) and Klein and Moura (2003) and recalculated to the crystallization age, (8) large terrestrial reservoirs, compiled from Rollinson (1993). DM: depleted mantle, EMI: enriched mantle, N-MORB: normal mid ocean ridge basalts.
as documented by the fluid inclusion study, along with fluid-rock interactions, which is inferred from the carbon isotope data (reaction with organic carbon) and from the refractory character of gold, which is present in the structure of pyrite. Changes in the pH of the fluid by sericitization and removal of CO₂ of the fluid to produce calcite might have also contributed to the breakdown of the sulfur complex.

Our results and interpretations are similar to those described for other gold deposits in the Gurupi Belt (Klein 2014) and elsewhere, being consistent with the orogenic gold system (e.g., Goldfarb and Groves 2015, and references therein).

8. Conclusions

The Enche Concha and Tunel exploration targets (prospects) have gold mineralization hosted in dacites and phyllites that belong to the ca. 2160 Ma-old metavolcanic-sedimentary Chega Tudo Formation. Petrographic, fluid inclusion, and isotopic (O, H, C, Sr) data allowed the following observations and conclusions to be drawn.

(1) The hydrothermal alteration comprises the formation of pervasive and fissure-filling carbonate, sericite, and sulfides (pyrite and subordinate chalcopyrite and sphalerite), in addition to quartz (±carbonate, ±sulfides). Refractory gold occurs in pyrite.

(2) The alteration and mineralization are associated with previously defined Paleoproterozoic deformation phase.

(3) The hydrothermal alteration and gold mineralization occurred between 260 and 370°C, from 0.85 to 2.8 kbar, from an aqueous-carbonic, relatively reduced and near neutral metamorphic fluid, with contributions from deep-seated (lower crust and mantle) sources.

(4) Gold was transported by a sulfur-bearing complex and precipitation occurred in response to phase separation and fluid-rock interactions.

(5) The geological and genetic characteristics are equivalent to those of the orogenic gold system previously defined for the Gurupi Belt.

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