GEOCHRONOLOGY, ISOTOPIC SIGNATURE AND METALLOGENETIC MODEL FOR THE CÓRREGO PAIOL GOLD DEPOSIT, TOCANTINS STATE, CENTRAL BRAZIL

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RESUMO *GEOCRONOLOGIA, ASSINATURA ISOTÓPICA E MODELO METALOGENÉTICO PARA O DEPÓSITO DE OURO CÓRREGO PAIOL, TOCANTINS, BRASIL* O Terreno Almas-Dianópolis, embasamento do extremo norte da Zona Externa da Faixa de Dobramentos Brasília, hospeda ocorrências e depósitos de ouro, entre estes, o depósito Córrego Paiol, alojado em anfibolito com alto-Fe da Formação Córrego Paiol e metagabro. O depósito é de origem hidrotermal e foi formado sob condições de temperatura e pressão do fácies xisto verde. O anfibolito hospedeiro contém dois reservatórios de argônio, relacionados às orogenias Transamazônica e Brasiliana. Cálculos geotermobarométricos e as idades ^{40}Ar-^{39}Ar indicam que o evento mineralizante ocorreu durante o resfriamento, aproximadamente isobárico, que se seguiu a uma fase de descompressão isotermal do terreno hospedeiro, relacionados a uma trajetória P-T-t horária desenvolvida na fase final da Orogenia Brasiliana. Os isótopos de chumbo em pirita e rocha total indicam que dois reservatórios contribuíram com chumbo e ouro, por analogia, para o depósito Córrego Paiol: i) chumbo com desenvolvimento isotópico retardado, menores razões U/Th e elevadas razões $^{238}U/^{204}Pb$, originado na crosta inferior; ii) chumbo com maiores razões U/Th e elevadas razões $^{238}U/^{204}Pb$, proveniente da crosta superior. Os isótopos estáveis em carbonato sugerem a mistura de C e O de origem profunda, oriundos do terreno hospedeiro, com C e O provenientes das coberturas de rochas metassedimentares meso-neoproterozóicas. O depósito Córrego Paiol provavelmente fez parte de um evento metalogenético de escala cratônica, desenvolvido na margem oeste do Cráton São Francisco, com reflexos para o interior do cráton, ao qual estão relacionados outros depósitos de Au, e que retrabalhou, durante a Orogenia Brasiliana, reservatórios que também forneceram metais para depósitos de chumbo e zinco.

Abstract The Almas-Dianópolis Terrane (ADT) composes most of the basement of the northern segment of the External Zone of the Brasília Fold Belt and hosts several gold showings and small deposits as well. The most important is the lode orogenic-type Córrego Paiol lode gold mine, hosted by hydrothermally altered high-Fe amphibolite and metagabbro. The deposit was formed by mineralizing fluid under greenschist facies conditions. Host amphibolite retained two argon reservoirs, related to the Transamazonian (~2.0 Ga) and Brasiliano (~700 to ~535 Ma) orogenies. Geothermobarometric calculations and ^{40}Ar-^{39}Ar age spectra showed that mineralization (563±15 Ma) took place during near isobaric cooling stage that followed the isothermal decompression (started around ~700 Ma) of the host terrane, which are part of a collisional clockwise P-T-t trajectory developed during the Brasiliano Orogeny. Whole rock and pyrite lead isotopes indicate that lower and upper crusts contributed with lead and gold to the Córrego Paiol deposit. Stable isotopes in carbonate suggest a mixture of deep-seated carbon and oxygen, originated in the host terrane, and carbon and oxygen from Meso-Neoproterezoic metasedimentary cover. The isotopic, field and petrographic data gathered in this work, and compared with data from literature, allow for placing the Córrego Paiol gold mine as an element of a cratonic-scale metallogenetic event developed in the western margin of São Francisco Craton during Brasiliano Orogeny.

INTRODUCTION Isotopic dating is not available for the great majority of gold deposits in basement rocks, Meso-Neoproterozoic metasedimentary cover and in the Neoproterozoic juvenile arc systems located to the west of the Brasília Fold Belt, along the western margin of the São Francisco Craton. Only a few ages and structural correlation point out to a gold mineralizing event associated to the Brasiliano Orogeny (Araújo Filho & Kuyumjian 1996, 2000, Kuyumjian & Araújo Filho 2006). Also related to the Brasiliano Orogeny, are lead and zinc deposits hosted by the metasedimentary units (Natividade, Bambuí and Paranoá groups) that cover most of Brasília Fold Belt basement units and large cratonic areas. In this work, lead isotopic data of Córrego Paiol gold deposit ore pyrite and of whole-rock samples of host-amphibolite and surrounding granite-gneiss complexes of the Archaean-Paleoproterozoic Almas-Dianópolis Terrane (ADT) are discussed, aiming to constrain the local source rocks of lead and, by analogy, of gold. Additional carbon and oxygen stable isotopes in carbonate rocks of Córrego Paiol deposit ore, added to sulphur isotope from pyrite, helped in constraining a metallogenetic model for the deposit. Aiming to elucidate the time relationship between gold mineralization in Córrego Paiol gold deposit and regional metamorphism, ^{40}Ar-^{39}Ar dating was determined in one sample of hydrothermal muscovite and one sample of metamorphic amphibole of Córrego Paiol Formation amphibolite.

REGIONAL METAMORPHIC SETTING OF THE CÓRREGO PAIOL DEPOSIT The Almas-Dianópolis Terrane (ADT) consists of wide low-K calc-alkaline high- and low-Al TTG complexes (Cruz and Kuyumjian 1993, 1996, Thomsen and Kuyumjian 1994) and narrow intervening greenstone belts (Figure 1). Zircon and titanite SHRIMP U-Pb data indicate that the granitic bodies intruded the greenstone belts during the Paleoproterozoic (2.2 to 2.45 Ga), and oceanic lithosphere subduction is the most suitable geological process to yield both types of these granitic series (Cruz *et al.* 2003). The greenstone sequence, named Riachão do Ouro Group, comprises high-Fe and high-Mg metabasalts included in the lower Córrego Paiol Formation, and a sequence of phyllite, banded iron formation, quartzite, metachert, acid metavolcanic rock, and carbonaceous and conglomeratic levels grouped in the upper Morro do Carneiro Formation. The first deformational phase (Dn) was determined by the TTG complexes emplacement and high T/P greenschist to amphibolite facies metamorphism. Dextral N20°-30°E, N0°-10°E and N10°-20°W shear zones and retrograde albite-epidote facies conditions followed by greenschist facies conditions are related to the second deformational phase event (Dn+1). High-grade mineralized bodies of the Córrego

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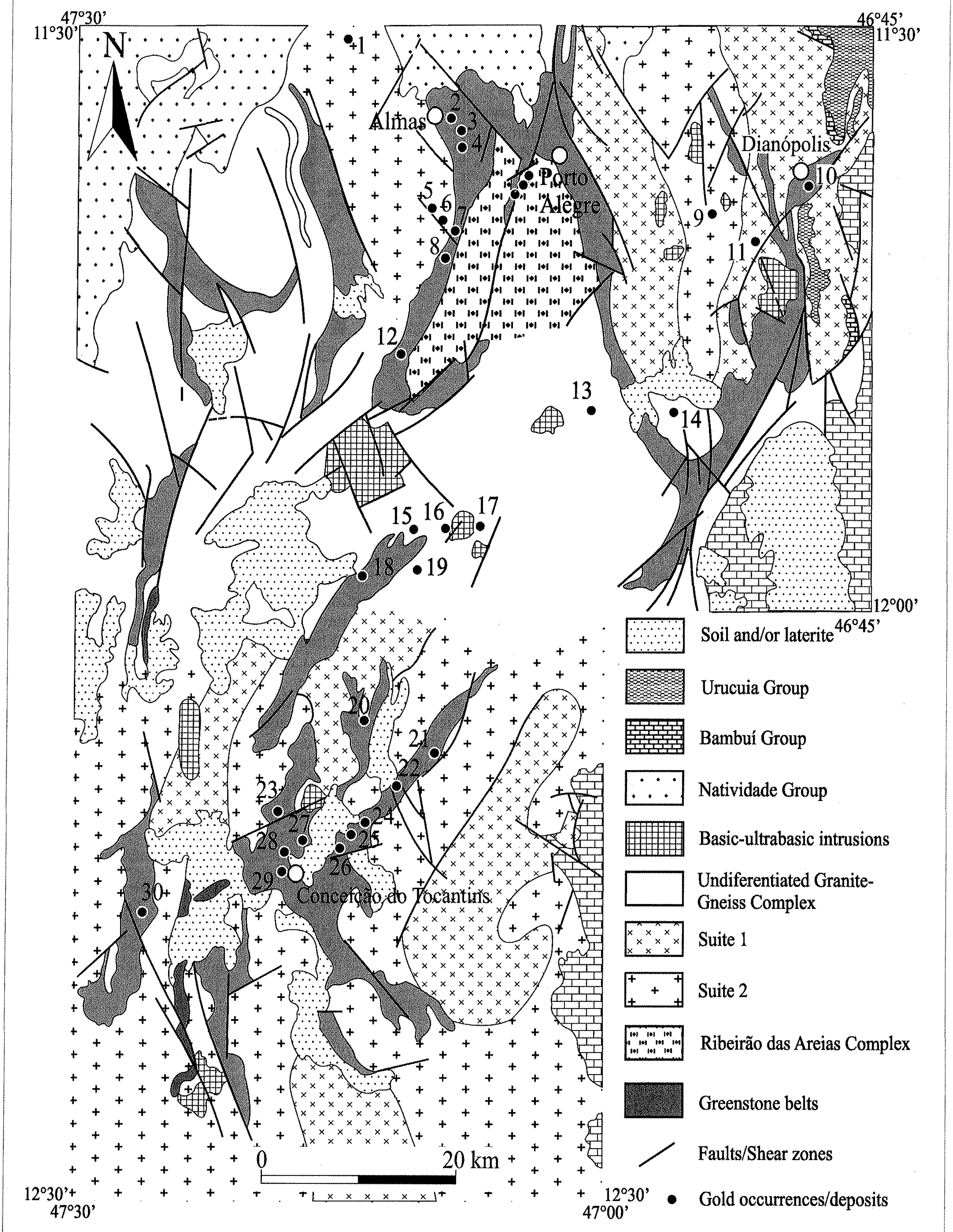

Figure 1 – Geological scketch map of the Almas-Dianópolis Terrane, after Padilha (1984), Cruz & Kuyumjian (1998) and Kuymjian & Araújo Filho (2006).

Paiol deposit display high angles with stretching lineations and are controlled by bends in the internal foliation of dextral N20°E/70°NW host shear zone. Hydrothermal assemblages of the deposit are coeval to retrograde greenschist assemblages and include chlorite, carbonate, sericite and sulphide, predominantly composed of pyrite. Ferrari and Choudhuri (2002,2004) state that homogenisation temperatures for coexisting primary and pseudosecondary inclusions associated with the sulphide –Au-quartz mineralization of Córrego Paiol are 210-410°C (high-salinity Type II) and 90-320°C (lower-salinity Type I). Temperatures of 320-440°C indicated by chlorite of the hydrothermally altered amphibolite and pressures around 2 kbars suggest that copper-gold mineralization of Córrego Paiol took place in the final stages of a clockwise P-T-t path typical of collisional setting (Cruz 2001) (Figure 2).

LEAD RESERVOIRS AND THE CÓRREGO PAIOL PYRITE LEAD Reinterpretation of previously published data led to the identification of the following lead reservoirs for the Córrego Paiol deposit pyrite lead: i) a lower crustal reservoir that has supplied lead with high $^{238}U/^{204}Pb$ (μ) and Th/U ratios, which is found in Bambuí Group, Type II lead of Babinski (1993), the most radiogenic galenas of Morro do Ouro, Morro Agudo and Vazante ores, and the least radiogenic galena of Monte do Carmo gold showings. This lead has a most likely Paleproterozoic age; ii) an upper crustal reservoir that corresponds to J-type lead of Bambuí Group galenas, Type III lead of Babinski (1993) and the least radiogenic galenas of Morro do Ouro, Morro Agudo and Vazante ores. This lead has a great dispersion on $^{206}Pb/^{204}Pb$ evolution curve and lower Th/U ratios due to an Archaean source; iii) Type I lead of Babinski (1993) found in carbonate rocks of Bambuí Group with high U/Pb ratios that had a post depositional evolution and may indicate deformational events, and; iv) Neoproterozoic mantle represented by galena of Zacarias Au-Ag-Ba deposit (μ of 9.56-9.61) located in the Goiás Magmatic Arc (Poll 1994). Most of the mentioned deposits are better explained by the mixture of lower and upper crustal lead, with the exception of Zacarias that has a mantelic lead. This mixture yields a linear array for the deposits. Lead isotopes of this large region are yet best explained by lead evolution of cratonic or continental environment of Doe & Zartman's (1979) plumbotectonic model, instead of the orogen curves of Stacey & Kramers (1975). U-Pb SHRIMP ages and whole-rock lead analyses of ADT granitoids were used to model initial μ values using Stacey & Kramer (1975) growth curve (Cruz 2001). Obtained μ-values were of 10.27 to 2.2 Ga metaluminous granitoids, 10.69 to 2.2 Ga peraluminous granitoids, and 10.77 to 2.45 Ga peraluminous granitoids. The Córrego Paiol Formation is intruded by 2.45 Ga granitoid, and if this minimum age is considered the obtained μ, fitted to whole-rock lead analysis, would be too low to be accountable by pyrite ore lead. All pyrite samples plot above Stacey & Kramer (1975) curve in uranogenic lead diagram with μ varying from 10.31 to 11.16 ($^{206}Pb/^{204}Pb$ = 15.830 to 17.414, $^{207}Pb/^{204}Pb$ =15.531 to 17.414). Model ages in the 1959-1120 Ma are much older than the age of mineralization of 535 Ma, as given by Ar-Ar dating in hydrothermal muscovite (Figure 3b). In the thorogenic lead diagram pyrite samples plot slightly above Stacey & Kramer's curve, what indicates a lower crustal reservoir (lower Th/U ratios, $^{208}Pb/^{204}Pb$ = 35.888 to 37.218) . Constructions of paleoisochrons of granite-gneiss complexes to 563 Ma indicate the 2.2 Ga peraluminous granitoids as the best candidate to local source of lead in pyrite. These rocks have isotopic ratios as low as those of pyrite and μ in the same range. The 2.45 Ga granitic plutons have a suitable μ, but its isotopic ratios are much higher than those of ore pyrite. However, the least radiogenic lead in pyrite has a lower crustal

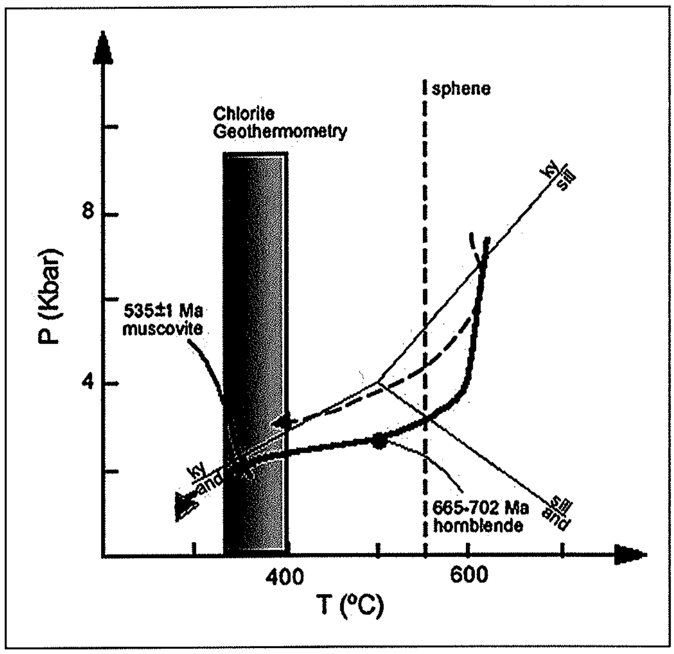

Figure 2 – The collisional setting clockwise P-T-t path of the Almas-Dianópolis Terrane.

signature (higher Th/U) suggesting that mineralizing fluids percolated through lower crust. Modeled μ (0.69-10.77) to source region of 2.2 and 2.45 Ga peraluminous granitoids indicate that the lower crust of ADT has $^{238}U/^{204}Pb$ ratios high enough to yield such signature. The generation of granulitic belt during the Transamazonian Orogeny (~2.1Ga) in adjacent basement terranes (São Francisco Craton and Porto Nacional Complex) may have depleted the lower crust of ADT in uranium. Therefore, the delayed isotopic evolution of Córrego Paiol deposit lead may be yielded by granulite facies metamorfism of ADT lower crust. Actually, granulitic enclaves are described amongst the ADT granite-gneiss complexes (Costa 1984). The more radiogenic lead of Córrego Paiol pyrite deposit may represent a mixture of upper crustal lead with local sources such as the 2.2 Ga peraluminous granitoids.

C, O and S ISOTOPES Ore ankerite of Córrego Paiol deposit was analyzed for C e O stable isotopes. $\delta^{13}C$ (PDB) values (-2.2 to –0.69‰) are similar of marine carbonate ($\delta^{13}C \sim 0$ ‰) and/or calcareous rocks ($\delta^{13}C$ = -2 a +2 ‰), and they are in agreement with those found in calcareous rocks of Meso-Neoproterozoic cover (Bambuí and Paranoá groups) that range from –2.6 to +16.1 ‰ (Babinski 1993, Santos *et al.* 2000), with the lowest values coming from the basal units of these groups. However, the unique enriched carbon contribution with provenance from Meso-Neoproterozoic sequences is not sufficient to generate negative values of $\delta^{13}C$. Thus, a mixture of C originated from a double source is plausible in order to explain the C isotopic composition of the Córrego Paiol mine. Therefore, a deep source can be both depleted in $\delta^{13}C$ and be enriched in $\delta^{13}C$, represented by the Meso-Neoproterozoic sequences. $\delta^{18}O$ (PDB) in Córrego Paiol ore ankerite (-17 to –16.64 %) displays little value variation and. Probably, it represents the isotopic composition of the mineralizing fluid. The obtained values are more negative than those of Meso-Neoproterozoic cover ($\delta^{18}O$ (PDB) = -13.9 to -0.2 ‰), a probable consequence of the higher deposition temperature of the hydrothermal environment, or due to oxygen mixing coming from Meso-Neoproterozoic sequences, the oxygen derived from deeper sources, *e. g.* base-

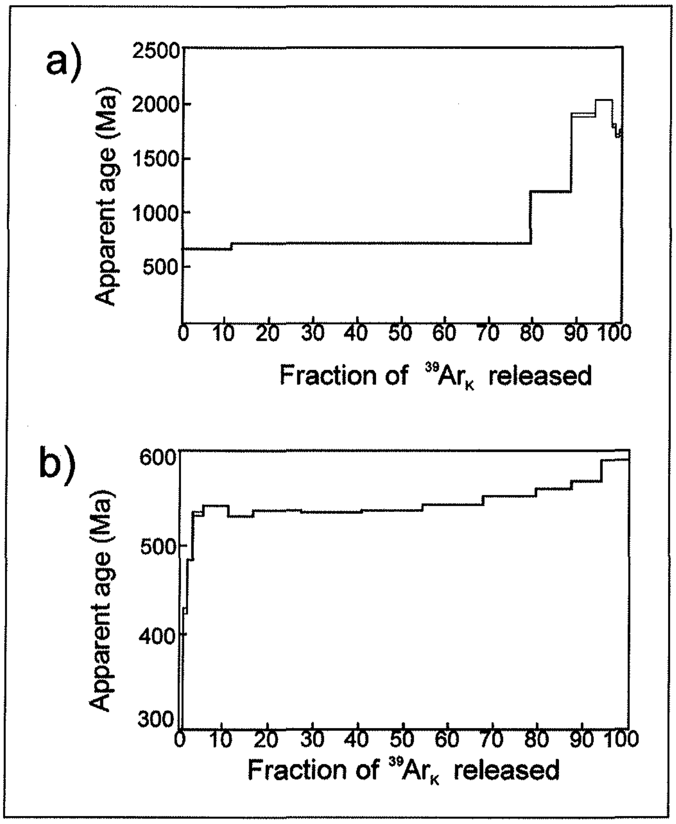

Figure 3 - ^{40}Ar-^{39}Ar geochronologic data of Córrego Paiol deposit obtained from (a) amphibole in amphibolite and (b) muscovite from hydrothermally altered amphibolite.

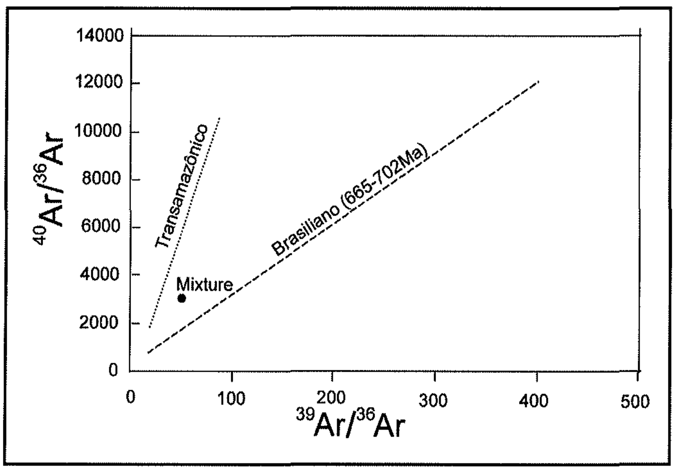

Figura 4- Isochron diagram indicating two argon reservoirs for the amphibolite of the Córrego Paiol Formation.

ment rocks. Therefore, stable isotopes are in agreement with lead results, indicating deep and upper crustal reservoirs. Values of $\delta^{34}S$ in pyrite from Córrego Paiol ore display a restricted variation from 1.83 to 2.12 ‰, not allowing to discriminate any type of reservoir to the S, due to such values being similar to the values assigned to granites, marine sediments, basic and intermediate volcanic rocks. Values of $\delta^{34}S$ in pyrite indicate a higher enrichment than the that of the mantle, MORB basalts and meteorites.

$^{40}Ar/^{39}Ar$ DATA AND THE TIMING OF GOLD MINERALIZATION ^{40}Ar-^{39}Ar geochronologic data of Córrego Paiol deposit were obtained from amphibole in amphibolite and in muscovite from hydrothermally altered amphibolite. The spectrum of amphibole separate sample (Fig. 3a) forms at lower temperature an initial step with the date of 665.0±1.1 Ma (11.2% of ^{39}Ar released at 800°C) followed by a plateau with the date of 702.4±0.9 Ma (68.2% of ^{39}Ar released at 950°C). The age spectrum then steps to the age of 2019.1±6.4 Ma. The $^{39}Ar/^{36}Ar$ vs $^{40}Ar/^{36}Ar$ plot (Fig. 4) shows two Ar reservoirs to this sample, one related to the Transamazonian Orogeny and the other to the Brasiliano Orogeny. The spectrum of hydrothermal muscovite (Fig. 3b) of Córrego Paiol deposit displays a plateau age of 535.4±0.7 Ma. This apparent muscovite age rises over the last 40% of ^{39}Ar released to up to 593.6±0.8 Ma. Geothermobarometric study of Córrego Paiol deposit and host amphibolite has shown that the onset of gold mineralization occurred after isothermal uplift and during cooling stage of a clockwise collisional P-T-t path (Fig. 2). Ar-Ar geochronology has constrained this evolution to the Brasiliano Orogeny. Furthermore, data show that metamorphic peak was reached earlier in the northern part of External Zone (665-702 Ma) than in the Internal Zone of Brasília Fold Belt (590-640 Ma). The late character of gold mineralization (535 Ma) in relation to the thermal evolution of Brasília Fold Belt is reinforced by the deformational and metamorphic history of host amphibolites.

CONCLUSIONS Isotopic data of Córrego Paiol deposit ore indicate that auriferous fluids percolated rock units of both lower and upper crust. Pb isotopic ratios suggest that a Pb reservoir with high initial $^{238}U/^{204}Pb$ ratios (μ) was depleted in U by granulitization during the Transamazonian Orogeny and, then, started a delayed decay evolution overprinted in the lower crust of ADT and São Francisco Craton. The $\delta^{13}C$ values points out to the participation of components from Meso-Neoproterozoic rocks in the auriferous hydrothermal systems and places a genetic link between the basement-hosted Córrego Paiol deposit and deposits hosted by Meso-Neoproterozoic cover units (Bambuí, Paranoá and Natividade groups). We propose that Dn+1 shear zones, developed late in the cooling stage of clockwise P-T-t trajectory, have acted as channelways to transport both metamorphic fluids generated in deeper crustal levels. Córrego Paiol gold deposit can be framed in a regional metallogenetic context related to the evolution of the Neoproterozoic Brasília Fold Belt, and comprising the western portion of the São Francisco craton.

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