

The Tocantinzinho gold deposit, Tapajós province, state of Pará: host granite, hydrothermal alteration and mineral chemistry

Depósito aurífero Tocantinzinho, província do Tapajós-PA: granito hospedeiro, alteração hidrotermal e química mineral

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ABSTRACT: This paper presents geological, petrographic and mineralogical data about the granite that hosts the Tocantinzinho gold deposit and aimed at contributing to the understanding of the hydrothermal processes related to the ore genesis. The host granite is a late to post-tectonic biotite monzogranite that fits in the oxidized sub-type of the ilmenite series. It was emplaced at depths of 6 – 9 km and reveals no deformation other than fracturing and brecciation. This intrusion has undergone mild to moderate hydrothermal alteration that generated two main rock varieties (salami and smoky), with no significant mineralogical or chemical differences, though quite distinct macroscopically. Several types of hydrothermal alteration have been recognized in the granitic rocks, greatly represented by filling veins and/or replacement of primary minerals. The hydrothermal history started with microclinization, during which the granitic protolith was in part transformed into the salami variety. This process was followed by chloritization when the temperature dropped to ~330 °C producing chamosite with X_{Fe} in the 0.55 – 0.70 range. Then it evolved to sericitization, at the same time that ore-bearing fluids precipitated pyrite, chalcopyrite, sphalerite, galena and gold. As alteration advanced, solutions saturated in silica and formed quartz veinlets. At the latest stage (carbonatization), aqueous and aqueous-carbonic fluids might have mixed, allowing Ca^{2+} e CO_2 to react to form calcite. Most sulfides are present in veinlets that crosscut the granite, some arranged as stockwork. Gold is normally very fine-grained and occurs mainly as sub-microscopic inclusions or along microfractures in pyrite and quartz. The Tocantinzinho deposit is very similar to the Batalha, Palito and São Jorge deposits, and to those of the Cuiú-Cuiú goldfield. Topologically, it has been classed as an intrusion-related gold deposit.

KEYWORDS: Tocantinzinho deposit; granitoids; hydrothermal alteration; intrusion-related deposit.

RESUMO: Este trabalho apresenta dados geológicos, petrográficos e mineralógicos referentes ao granito que hospeda o depósito aurífero Tocantinzinho e objetivou contribuir ao entendimento dos processos hidrotermais associados à sua gênese. O depósito ocorre em biotita monzogranito tardi a pós-tectônico, do subtipo oxidado da série ilmenita, que foi alojado a profundidades de 6 – 9 km. Esse granitoide encontra-se bastante fraturado e localmente brechado, tendo experimentado processos hidrotermais de grau fraco a moderado, os quais geraram duas principais variedades (salame e smoky) sem diferenças mineralógicas ou químicas importantes, porém macroscopicamente muito distintas. Vários tipos de alteração hidrotermal foram reconhecidos nas rochas granitoides, sendo representados principalmente por vênulas e pela substituição de minerais primários. A história hidrotermal teve início com a microclinização, durante a qual o protólito granítico foi em parte transformado na variedade salame. A temperaturas em torno de 330 °C ocorreu a cloritização, que produziu chamosita com X_{Fe} na faixa de 0,55 – 0,70. Seguiu-se a sericitização, durante a qual os fluidos mineralizadores precipitaram pirita, calcopirita, esfalerita, galena e ouro. À medida que a alteração progrediu, as soluções se saturaram em sílica e precipitaram quartzo em vênulas. No estágio mais tardio (carbonatação), provavelmente houve mistura entre fluidos aquosos e aquocarbônicos, de que teria resultado a reação entre Ca^{2+} e CO_2 e formação de calcita. A maioria dos sulfetos encontra-se em vênulas, algumas em trama stockwork. O ouro é normalmente muito fino e ocorre principalmente como inclusões submicroscópicas ou ao longo de microfraturas em pirita e quartzo. O depósito Tocantinzinho é muito similar aos depósitos Batalha, Palito e São Jorge, e aos do campo Cuiú-Cuiú. Tipologicamente poderia ser classificado como depósito relacionado a intrusões.

PALAVRAS-CHAVE: depósito Tocantinzinho; granitoides; alteração hidrotermal; depósito relacionado a intrusões.

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INTRODUCTION

The Tapajós gold province (TGP) is located in the central-southern portion of the Amazon Craton and presents a Paleoproterozoic geological evolution characterized by a succession of magmatic arcs that produced rocks which are mostly calc-alkaline in nature. The development of these arcs was followed by expressive intraplate volcanic-plutonic events, culminating with tholeiitic dyke swarms at the taphrogenic stage (Lamarão *et al.* 2002, Vasquez *et al.* 2002, Santos *et al.* 2004). It is a region of great interest for petrological, geotectonic, and mainly metallogenic investigations, since the geological environment proved to be favorable for the formation of gold deposits. Most of these deposits occur in granitoids, which have been studied since the late 1990s (Dreher *et al.* 1998, Coutinho *et al.* 2000, Klein *et al.* 2001, Juliani *et al.* 2002, Borges *et al.* 2009). Three genetic models have been proposed for these deposits: 1) orogenic lode type; 2) granitic intrusion-related; and 3) high and low sulphidation epithermal (Santos *et al.* 2001). Further, the occurrence of porphyritic deposits is postulated (Juliani *et al.* 2002).

Although the genesis of the Tocantinzinho deposit (Fig. 1) is attributed to a magmatic hydrothermal system, the granitic intrusion responsible for the mineralizing fluids is still unknown. It is an epigenetic deposit, hosted in a fractured and brecciated granitic body, which is aligned to other gold deposits (Palito, São Jorge, Battle,

Bom Jardim and Cuiú-Cuiú) within the NW-SE-trending Tocantinzinho lineament.

Gold deposits related to granites (Sillitoe 1991, Sillitoe & Thompson 1998, Lang & Baker 2001) are considered a distinct class within the hydrothermal category. Since they show many features similar to both orogenic gold and porphyritic Cu-Au and Sn-W deposits, further studies are recommended to establish more consistent genetic and exploration models for such deposits (Lang & Baker 2001).

This paper presents geological, petrographic and mineralogical data on the granitic host rocks of the Tocantinzinho deposit. It aimed at contributing to the understanding of the hydrothermal processes associated with its genesis and, by extension, to that of other deposits with similar characteristics.

MATERIALS AND METHODS

The study was made possible thanks to the logistical support and assignment of borehole samples by the Brazauros Resources Corporation and Unamgem Mining and Metallurgy Ltd. companies, the latter being a subsidiary of Eldorado Gold Corporation and current holder of the exploration rights. Good outcrops of granitic body are scarce, so the geological information was almost exclusively based on technical reports of these companies.

Petrographic analyses were performed on a Zeiss Axioplan microscope adapted with transmitted and

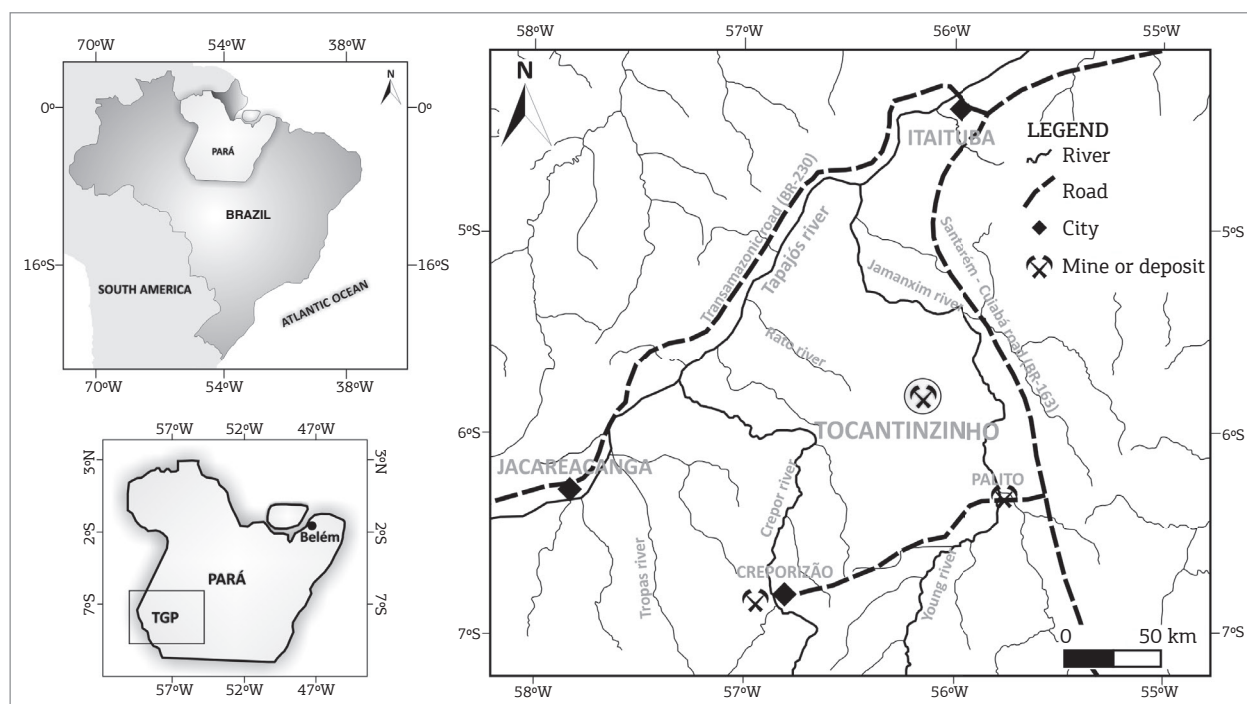


Figure 1. Location map of the Tocantinzinho deposit.

reflected light, and complemented in a scanning electron microscope (SEM) model LEO-1430, coupled with energy dispersive spectroscopy (EDS). The operations were conducted in the SEM with constant voltage acceleration of 20 kV, electron beam-induced current of 90 mA, working distance of 15 mm, beam diameter around 350 – 400 mm and counting time of 30 s for analyzing elements. The modal analyses were made on a Swift stitch counter, computing an average of 2,000 points per slide. The chemical composition of minerals was determined on a JEOL electron microprobe, model SuperProbe JXA-8600, under accelerating voltage of 15 kV, beam current of 20 nA, beam diameter of 5 mm and beam length of 10 s. Except for the electron microprobe, installed in IG-USP, all other analyses were performed in laboratories of IG-UFPA.

TAPAJÓS GOLD PROVINCE

Most of the TGP territory is included in the Tapajós Domain of the Ventuari-Tapajós (Tassinari & Macambira

2004) or Tapajós-Parima (Santos *et al.* 2006) geotectonic province. There is no consensus about its geotectonic evolution. Santos *et al.* (2001) distinguish five magmatic arcs based on geochemical and geochronological evidence (Fig. 2). In turn, Lamarão *et al.* (2002) and Vasquez *et al.* (2002) discuss the formation of a single magmatic arc that first evolved in a post-collision and subsequently in an extensional environment. Despite the differences, there are two distinct domains (Santos *et al.* 2001): to the west, the orogenic domain, consisting of back-arc sequences and oceanic basalts, besides calc-alkaline plutons of magmatic arcs; to the east, the anorogenic domain, characterized by intracontinental alkaline magmatism that resulted from the Uatumã event.

The first rock-forming events recorded in this province refer to the development of the Jacareacanga Group, which consists of metaturbidites deposited between 2.10 and 2.01 Ga (Santos *et al.* 2000), and to the granite-gneiss rocks of the Cuiú-Cuiú Complex, whose U-Pb dating (SHRIMP) yielded ages of 2.03 to 2.00 Ga (Santos *et al.* 2000). Lamarão *et al.* (2002 and 2005) described a set of

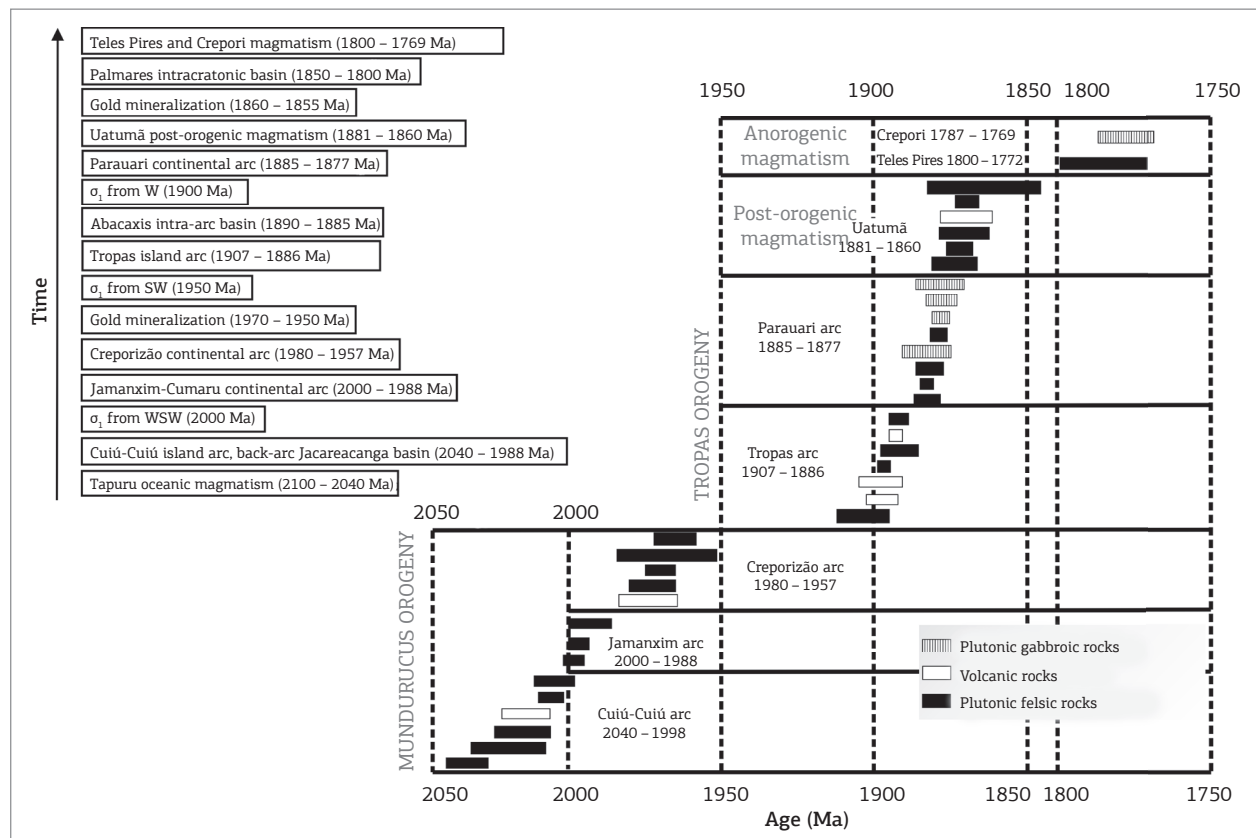


Figure 2. Summary of the geological evolution of the Tapajós domain. On the left, the sequence of formation of magmatic arcs and sedimentary basins is shown, besides the main events of deformation and gold mineralization. On the right, the timing of the Mundurucus and Tropas orogenies and their respective magmatic events are presented (Based on Santos *et al.* 2004). The mineralization event dating ~1.96 Ma is due to Coutinho *et al.* (2000). σ₁: direction of the deformation tensor.

intermediate to acidic calc-alkaline volcanic rocks typical of mature arcs and gathered them in the Vila Riozinho Formation (2000 ± 4 Ma and 1998 ± 2 Ma).

Protomylonitic syn- to late-orogenic granitoids make up the Creporizão Intrusive Suite (Ricci *et al.* 1999), which shows a medium- to high-K calc-alkaline nature and ages between 1997 and 1957 Ma (Santos *et al.* 2001). The Tropas Intrusive Suite also consists of calc-alkaline granitoids formed around 1.9 Ga (Santos *et al.* 2004). The Abacaxis and Sequeiros formations were deposited in intra-arc basins, whose detrital sources present ages of 1.89 Ga. At 1.88 Ga, an extensive late to post-tectonic calc-alkaline magmatism was recorded in the province and it is represented by the Parauari Intrusive Suite (Santos *et al.* 2000).

The igneous events were also characterized by mafic magmatism, especially the high-K calc-alkaline gabbroic rocks of the Ingarana Intrusive Suite (Santos *et al.* 2001). These rocks are interpreted to have resulted from underplating processes and are aged between 1887 and 1878 Ma.

Several intracratonic units were then formed and only affected by brittle deformation, among them the Iriri Group and the Maloquinha Intrusive Suite, both aged 1.87 Ga and related to the Uatumã volcano-plutonic event. The first is divided into the Salustiano and Aruri formations and comprises felsic volcanic and pyroclastic alkaline rocks, while the other consists of type-A alkaline granites. The Bom Jardim Formation (1881 Ma) is composed of volcanoclastic rocks, lamprophyres, andesites and dacites.

The installation of Paleoproterozoic continental rifts in the Tapajós domain culminated with the deposition of siliciclastic sedimentary covers corresponding to the Buiú Formation and the Palmares Group. The dikes and sills of the Crepori Diabase crosscut the Orosian basement and are aged 1780 ± 7 Ma, which, besides dating this magmatic event, indicates the minimum deposition age of the Paleoproterozoic sedimentary sequences. The troctolites of the Cachoeira Seca Intrusive Suite (1186 ± 12 Ma/U-Pb SHRIMP on baddeleyite crystals) mark the reactivation of the mantle under the Tapajós domain after a quiescent period of about 600 Ma. Santos *et al.* (2002) interpreted this event as a Stenian alkaline magmatism related to continental rifts, a reflection of the Sunsás orogeny.

The structural evolution of the TGP began with a ductile to ductile-brittle compressive event that imprinted a NE-SW-trending foliation in the rocks of both the Jacareacanga Group and the Cuiú-Cuiú Complex. A brittle-ductile to brittle compressive event was then superimposed, being easily recognized in radar and airborne geophysical maps. This event was responsible for the most prominent structures in the area, which are related to the development of sinistral NW-SE-trending transcurrent

megalineaments, which controlled the emplacement of the Creporizão, Tropas and Parauari suites, and probably the deposition of the auriferous ore, since most deposits are hosted in rocks of these suites. The subsequent extensional tectonics (E-W, NE-SW) would have been affected by the reactivation of old weak crustal zones or by the emplacement of the Maloquinha Intrusive Suite. The resulting structures are well characterized in the rocks produced during the Uatumã event, as well as in the Ingarana Intrusive Suite, and should have controlled the emplacement of rocks of both the Cachoeira Seca Intrusive Suite and the Buiú Formation.

Three classic types of gold deposits in the TGP have been defined according to mesoscopic features, microthermometric data and radiogenic and stable isotopes. Pb isotopic signatures of galena and pyrite suggest two mineralizing episodes around 1.96 Ga and 1.88 Ga (Coutinho *et al.* 2000), whereas Santos *et al.* (2001) consider there was only one episode of mineralization dated at 1.86 Ga (Pb-Pb on galena and Ar-Ar on muscovite). Klein *et al.* (2002), based on structural features of the deposits that lie in the southern portion of the TGP, suggest the occurrence of two distinct stages. The first one, between 1.97 and 1.95 Ga, is related to the NW-SE transcurrent regime that affected the Creporizão Intrusive Suite, fitting the model of orogenic deposits. The other, probably younger, would be related to the events of brittle reactivation of structures and would have favored the generation of intrusion-related deposits. The latter is consistent with the isotopic data of Santos *et al.* (2001) and Coutinho *et al.* (2000).

TOCANTINZINHO DEPOSIT

This deposit lies about 200 km SW from the city of Itaituba, state of Pará, and shows minimum dimensions of 150 m (width), 300 m (depth) and 700 m (length) with total resources estimated in 49 million tons of ore and average Au content of 1.25 g/t.

Geological Setting

The host granite is a NW-SE-oriented stock (Tocantinzinho granite), whose emplacement was controlled by the Tocantinzinho sinistral lineament. This stock is apparently intrusive into the bordering quartz monzonite rocks (Figs. 3A and B). In the area of the deposit, monzogranite rocks are dominant and have been mostly transformed into two hydrothermal varieties, informally referred to as salami and smoky. The former displays strongly reddish to pinkish coarse K-feldspar crystals associated with equally coarse milky quartz crystals in such an arrangement

that justifies its informal name. Although it does not show penetrative foliation, weak orientation of quartz crystals is observed. The other variety is distinguished by its greenish tone with gray to whitish hues. Subordinate granodiorite rocks, pegmatitic bodies and aplites, most likely co-magmatic, have been also recognized.

Hematitized monzogranite rocks occur involving the mineralized zone. The pinkish to reddish color they reveal resulted from the impregnation of potassium feldspar crystals with ferric oxide. These rocks show neither deformation nor brecciation, and are not mineralized. The quartz monzonite varieties are usually magnetic and cut by gold-free veinlets of epidote and pyrite. Some contacts with the hematitized rocks are marked by E-W faults, most likely related to the Tocantinzinho lineament.

Andesite dikes form a quite eroded body, which partially covers the mineralized zone and seems to taper and converge at depth to possible conduits that acted as magma feeders. This body was pervasively altered by sericitization, chloritization and carbonation, and cut by phengite-, chlorite- or calcite-bearing veinlets. Gold content is < 5 ppb, although rare values of 1 ppm may be recorded at the contact with the mineralized granite. The rhyolite dykes show porphyritic texture and represent the last magmatic event recorded in the deposit area (Fig. 3B), as indicated by the contact relationships between the various types of rock. Gold grade usually is < 5 ppb, but where brecciation and veining are intense, it may

reach 100 – 200 ppb. At depth, porphyritic quartz latite rocks were locally intercepted by drilling (Melo 2007). Most likely, even after the cooling of the Tocantinzinho granite, some magmatic chamber still remained active to generate these various kinds of volcanic rocks.

Structurally, although the mineralized granite does not show evidence of ductile deformation, brittle features are recognized in planar arrangements defined by NE-SW-trending, steeply-dipping sheeted veinlets containing chlorite and quartz. In addition, on surface mapping, a series of sinistral E-W faults were identified, mostly with up to tens of meters long (Juras *et al.* 2011).

Dating by the Pb evaporation method on zircon crystals from the host granite provided an average Pb-Pb age of 1982 ± 8 , which was related to an early magmatic manifestation of the Creporizão arc (Villas *et al.* 2013). The andesite and rhyolite dikes have not been dated yet, but Mello (2007) correlated them to the Vila Riozinho Formation.

The hydrothermal alteration affected all rock types with different intensities, so that many primary features of the host granite in the mineralized zone can still be recognized. The types of alteration described refer to sericitization, chloritization, silicification, carbonatization, hematitization and sulfidation, whose hydrothermal products are scattered throughout the rocky body or concentrated in veinlets.

According to Pereira (2006), the different styles of mineralization in the host granite comprise the

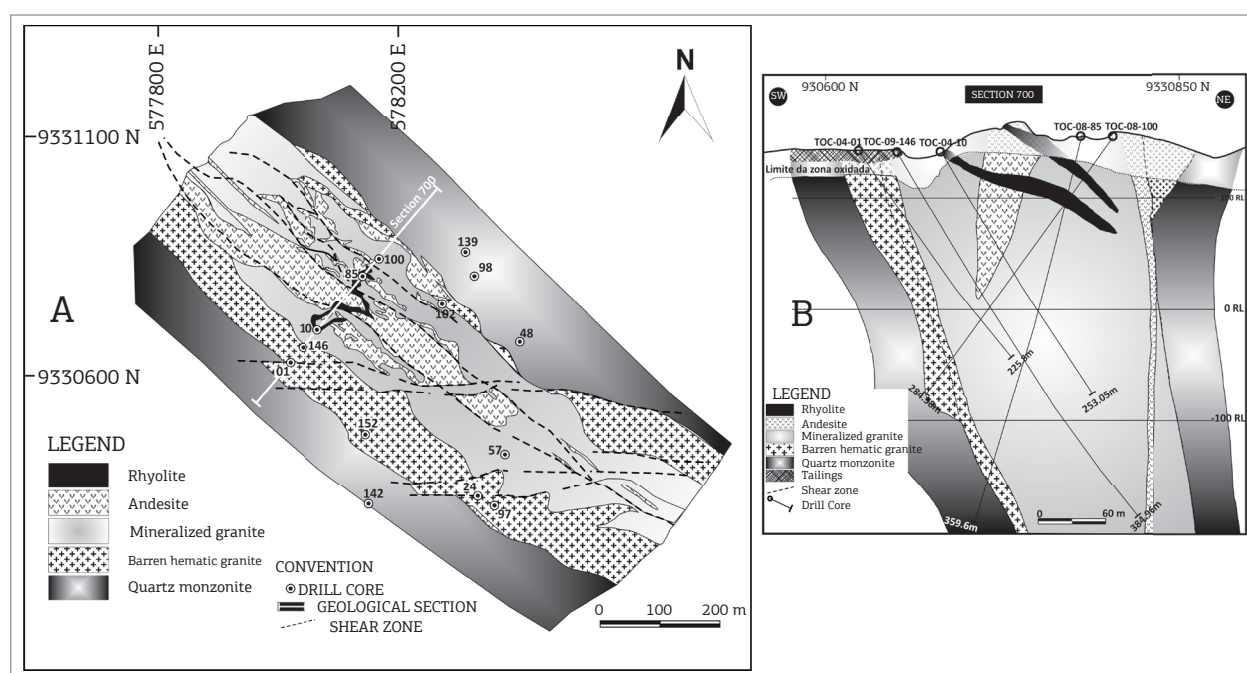


Figure 3. Geological map (A) and a SW-NE section (B) of the Tocantinzinho deposit. TOC 08-85 = borehole (Modified from Juras *et al.* 2011).

disseminations of sulfides, stockwork zones and sheeted-veinlets, the latter trending N20-30°E and N70-80°E, and represented mainly by (1) mm-thick veinlets with quartz-chlorite $\pm$ pyrite and (2) cm-thick veins composed of quartz-chlorite-carbonate-pyrite $\pm$ chalcopyrite $\pm$ galena $\pm$ sphalerite.

At least three stages of gold mineralization have been identified in the deposit (Geller 2004). In the first stage, fine gold particles filled fractures in pyrite crystals that are present in veinlets of quartz-pyrite $\pm$ chlorite. In the second and most important stage, gold occurs along fractures in pyrite, quartz and hessite crystals, which are disseminated in intensely fractured and brecciated zones, together with traces of chalcopyrite, sphalerite, galena, petzite, bismuthinite and native silver. Locally, gold occurs as inclusions in crystals of chalcopyrite, sphalerite and galena. A third stage is uncertain, because the presence of sulfides in veinlets of quartz-carbonate $\pm$ chlorite is rare. However, finely-grained gold crystals in fractures of veinlet quartz suggest that some gold may have been transported during the final stages of the hydrothermal event.

PETROGRAPHY OF THE GRANITOID ROCKS

Petrographic studies allowed to separate mildly altered granitoids (Fig. 4A) and moderately altered granitoids, the latter corresponding to the salami and smoky varieties (Figs. 4B and C). The first group is characterized for having 5 – 10% of hydrothermal products and little evidence of deformation, while the other exhibits > 10% of alteration minerals, rarely exceeding 50%.

Mildly Altered Granitoids

These hololeucocratic to leucocratic phaneritic rocks show a predominantly monzogranite composition, however alkali feldspar granite and granodiorite also occur (Tab. 1 and Fig. 5). The monzogranite variety has a pinkish color and is coarse to medium-grained, whereas the granodiorite variety presents whitish gray color and is medium-grained. In turn, the alkali feldspar granite is strongly reddish colored and coarse-grained. This study was only conducted with monzogranite rocks, the most representative ones in the deposit area.

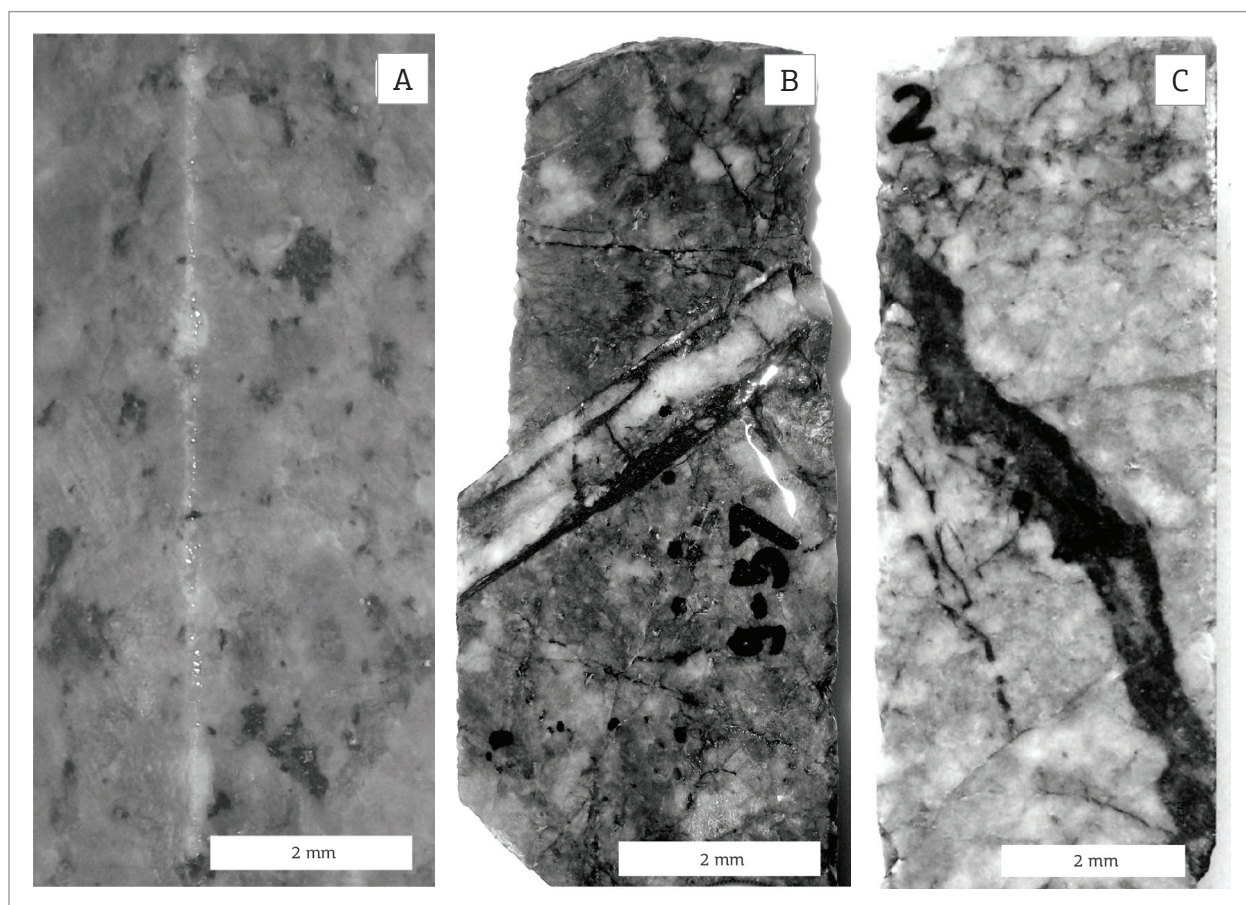


Figure 4. Photos of borehole samples from the Tocantinzinho deposit representing the mildly altered rock (A), the salami variety cut by quartz + hematite veinlet (B) and the smoky variety cut by quartz + chlorite veinlet (C).

In general, the monzogranite rocks reveal hypidiomorphic to allotriomorphic texture (Fig. 6A) with local development of poikilitic and rapakivi textures (Fig. 6B). Even though they are essentially isotropic, discrete deformational

features are locally observed. Potassium feldspar, quartz, and plagioclase are the essential minerals, while biotite and amphibole are varietal minerals. Zircon, magnetite, ilmenite, apatite, allanite, monazite, titanite and U-thorite, in

Table 1. Modal analyses (vol.%) of samples from the mildly altered granitoids that occur in the Tocantinzinho deposit

Rock	Biotite monzogranite						Amphibole biotite monzogranite	Biotite alkali-feldspar granite	Amphibole biotite granodiorite
MINERAL / SAMPLE	01 - 177	01 - 175	04 - 175	02 - 175	01 - 175B	04 - 178	08 - 177	09 - 177	05 - 101B
Quartz	27.6	33	28.7	21.1	34	22.6	12.3	29.7	23.6
Potassic Feldspar	41.4	41.8	42.4	46	38.1	29.7	45.9	64.1	6.6
Oligoclase	22.3	23.3	27.4	29.2	26.1	39.4	29.1	2.2	57.8
Biotite	6.6	1.3	1.2	3	1.5	7.6	8.4	2.3	8.3
Amphibole	-	-	-	-	-	-	2.1	-	0.9
Zircon	0.4	-	0.3	0.2	0.1	-	0.5	-	-
Apatite	-	-	-	0.1	-	-	-	-	-
Titanite	-	-	-	0.2	-	0.1	-	-	-
Magnetite	0.2	0.2	-	0.1	0.1	0.2	0.6	0.8	0.2
Ilmenite	0.2	0.2	-	0.1	0.1	0.4	0.9	0.8	0.2
$\Sigma M'$	7.4	1.7	1.5	3.7	1.8	8.3	12.4	3.9	9.6
Q	30	34	28	25	33	21	21	36	21
A	45	43	42	46	41	43	45	62	28
P	24	24	30	28	26	36	34	2	51

M' = biotite+amphibole+magnetite+ilmenite+zircon+apatite+titanite; (-): not observed.

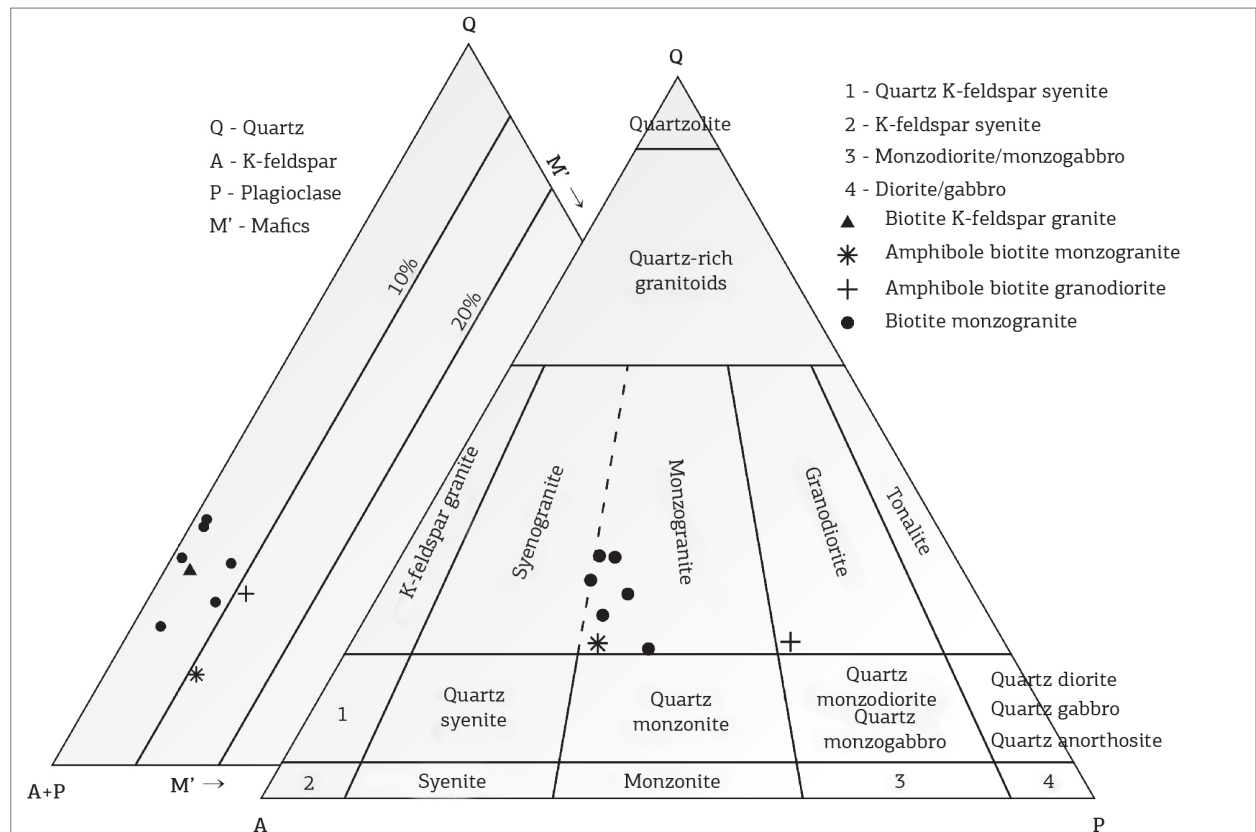


Figure 5. QAP and Q-(P + A)-M' modal diagrams (Streckeisen 1976) for the classification of studied samples.

this tentatively order of abundance, are the primary accessory phases.

Potassium feldspar is dominant (41 – 50 vol.%), forming fine to medium (0.15 – 1.10 mm) subhedral to rarely anhedral crystals that show gridiron structure and perthitic intergrowths of string (Fig. 6C) and patch types. Inclusions of plagioclase, biotite and quartz are commonly observed, lending to some potassium feldspar crystals a poikilitic character. Others show incipient replacement for phengite and clay minerals.

Oligoclase (An_{28-29}) amounts to 22 – 36 vol.% and reveals fine to medium subhedral crystals (0.15 – 1.10 mm), with dominant tabular habit, which present both albite and albite-pericline twinning. Another mode of occurrence is the micrometric to millimetric exsolution lamellae of albite in perthites. Possible oscillatory zoning is indicated by sericitized cores of some crystals (Fig. 6D). Locally, clay minerals and carbonates replace plagioclase.

Quartz makes up 21 – 33 % of the rock volume and generally exhibits fine xenomorphic crystals (0.15 – 0.50 mm). They show irregular wavy extinction and contain subhedral inclusions of oligoclase. Locally, their intercrystalline contacts are sutured, but straight with microcline and biotite crystals. Some crystals present microfractures filled by chlorite; others occur as inclusions in amphibole prisms.

Fine to medium (0.2 – 1.2 mm) subhedral flakes of biotite (1.5 – 8.0 vol.%) are normally altered to greenish chlorite along cleavage planes (Fig. 6E) and to a lesser extent to white mica. Even when brownish, the K_2O contents are ≤ 0.21 wt.% (Tab. 2), indicating to be in fact chlorite pseudomorphs, to which hematite and phengite are joined. Commonly, those flakes contain inclusions of zircon, monazite and magnetite.

The amphibole (Fig. 6F) has been identified as Fe-edenite. It essentially exhibits fine to medium (0.15 – 1.10 mm) subhedral tabular crystals, which account for 0 – 2% of the rock volume. Rare crystals show twinning or quartz and magnetite as inclusions.

Except for allanite and U-thorite, the accessory minerals occur as isolated crystals scattered in the granite or included in biotite. Zircon and apatite crystals reveal a subhedral and prismatic habit, whereas magnetite crystals are anhedral and almost completely replaced by martite. Allanite, in turn, reveals reddish brown crystals, in which concentric zoning can be seen (Fig. 7A). Evidence of metamictization is observed in zircon and allanite crystals. Ilmenite is present as anhedral crystals. Monazite and U-thorite display subhedral crystals, both having been identified by SEM-EDS (Figs. 7B and C). Some crystals with bipyramidal habit and completely replaced by carbonate and rutile have been described as titanite.

Among the secondary phases, phengite, clay minerals and carbonates are worth noting and resulted from the destabilization of feldspars. Chlorite was derived from biotite and it is also present in veinlets (clinocllore or chamosite).

Moderately altered granitoids

As the degree of alteration increased, the monzogranite changed into the salami and smoky varieties, of easy macroscopic distinction (Figs. 4A and B). In borehole samples, the former is dominant and recognized by the strong reddish or pinkish color of the coarse microcline crystals, contrasting with the associated milky quartz crystals. The latter displays grayish green color and seems to be less abundant. Veinlets and veins containing chlorite, quartz, sericite, carbonate and pyrite are common, especially in the smoky variety. Sulfides typically occur in veinlets together with quartz and chlorite (Fig. 4C), but are also disseminated in the rock and brecciated zones associated with sericite. On a microscopic scale, both varieties show remarkable textural and compositional similarities. The magmatic textures were masked in different intensities, especially in the cataclastic zones where evidence of intense fracturing, brecciation and comminution of crystals are very common. The breccia features are characterized by angular crystals of primary minerals, which are often surrounded by fine lamellae of sericite.

HYDROTHERMAL ALTERATION

The hydrothermal alteration at Tocantinzinho, although widespread, was mild to moderate, being more evident in places where brittle deformation was more intense and along some veins. Five main types of alteration have been recognized: microclinization, chloritization, sericitization, silicification and carbonatization.

The hydrothermal products are commonly formed at the expense of primary minerals present in the rock mass, but they also occur as constituents of monomineralic and polymineralic veinlets, whose spatial distribution locally characterizes the stockwork style.

Microclinization

This earliest type of alteration is the most distributed in the deposit, being responsible for the strong reddish hue of the altered granite and for the generation of the salami variety. Usually it occurs as continuous zones that gradually disappear at the same time the rock takes on a grayish to greenish hue, which typifies the smoky variety. This potassic alteration, where present, is pervasive and represented by hydrothermal microcline $\pm$ quartz $\pm$ hematite. The igneous

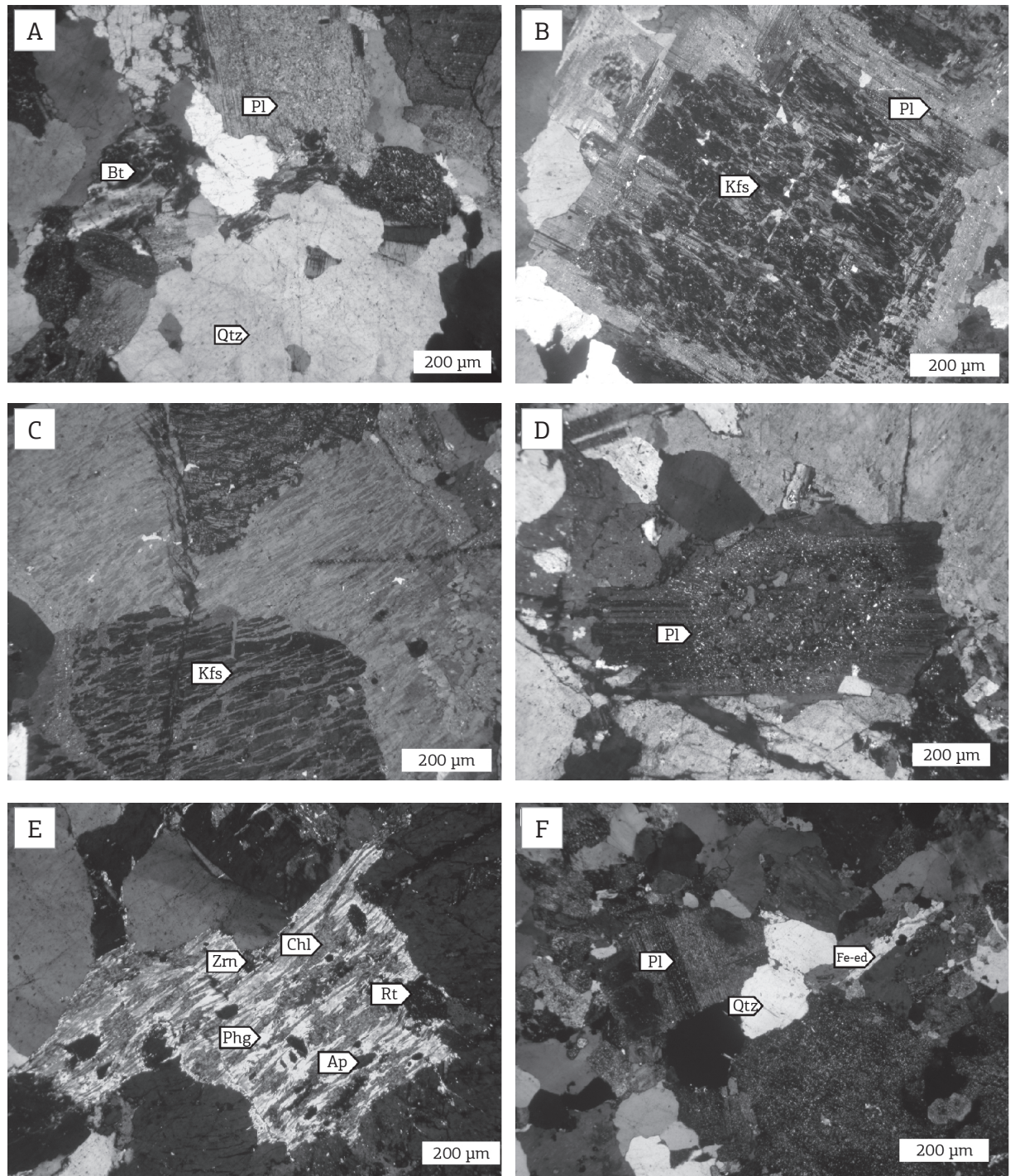


Figure 6. Photomicrographs of samples from the mildly altered granite viewed between crossed or parallel nicols. (A) Hypidiomorphic texture. (B) Rapakivi texture. (C) String-type perthite. (D) Concentric zoning highlighted by sericitized core. (E) Lamellae of chloritized biotite altered to phengite along cleavage planes showing inclusions of zircon, rutile and apatite. (F) Anhedral crystals of Fe-edenite, which are relatively rare in the monzogranites. (Ap: apatite Chl: chlorite, Fe-ed: Fe-edenite; Fks: K-feldspar; Mus: muscovite; Pl: oligoclase; Phg: phengite; Rt: rutile and Zrn: zircon).

potassium feldspar is commonly replaced by hydrothermal microcline, which lends it a mottled appearance (flames) in thin section, most evident on coarse crystals. Hematite occurs as very fine inclusions in hydrothermal microcline,

Table 2. Average compositions of the amphibole and microcline (% by weight and a.f.u.) present in granitic rocks of the Tocantinzinho deposit

Minerals/ Components	Fe-edenite	Microcline	
	Mildly altered	Smoky	Salami
SiO ₂	44.14	64.09	64.2
Al ₂ O ₃	6.39	18.23	18.4
TiO ₂	1.39	0	0.02
FeO	26.45	-	-
Fe ₂ O ₃	-	0.04	0.06
MnO	0.93	0	0.01
MgO	6.02	0	0
CaO	10.02	0.01	0.02
BaO	-	0.19	0.13
SrO	-	0.04	0.01
Na ₂ O	1.76	0.22	0.36
K ₂ O	0.71	16.79	16.45
Cl	0.08	-	-
F	0.26	-	-
Total	98.13	99.62	99.66
O=F	0.11	-	-
O=Cl	0.02	-	-
Total	98.0	99.62	99.66
Structural formula	23 oxygen atoms	32 oxygen atoms	
Si	6.93	11.96	11.95
Al ^{IV}	1.07	0.04	0.05
Al ^{VI}	0.12	3.97	3.98
Al _T	1.18	4.01	4.04
Ti	0.16	0	0
Fe ⁺²	3.47	-	-
Fe ⁺³	-	0.01	0.01
Mn	0.12	0	0
Mg	1.41	0	0
Ca	1.69	0	0
Ba	-	0.01	0.01
Sr	-	0	0
Na	0.54	0.08	0.13
K	0.14	4	3.91
Cl	0.03	-	-
F	0.13	-	-
Mg/(Mg+Fe)	0.29	-	-
(Ca+Na) _B	2.22	-	-
(Na+K) _A	0.68	-	-
	Final Member		
An	-	2.01	3.15
Ab	-	0.05	0.06
Or	-	97.93	96.79

Obs: the figures represent the average values for punctual analyses on several crystals of different samples; (-): not detected.

explaining the cloudy appearance this feldspar has under plane polarized light (Fig. 8A). The medium-grained and milky quartz crystals exhibit features of overgrowth (blebby quartz) and irregular contacts with hydrothermal microcline. Magnetite is commonly replaced by martite, and biotite is oxidized along its cleavage planes.

Chloritization

Chlorite was more abundantly formed early in the hydrothermal history of the deposit and kept on being formed, although subordinately, over the subsequent stages. Regardless of the stage, chlorite is generally derived from the partial or total replacement of primary biotite (Fig. 8B), when it reveals greenish color and composition of chamosite. It is also a constituent of monomineralic and polyminerallitic veinlets (quartz ± rutile ± carbonate ± pyrite ± chalcopyrite ± phengite). Rutile resulted from the alteration of biotite and possibly also titanite, in which case it is associated with calcite, forming rare crystals scattered throughout the rock. In these chlorite-rich zones, hydrothermal microcline is cut by veinlets of hematite. In the sericitization stage, chlorite occurs as aggregates of micrometric lamellae, especially where the rock is brecciated. During carbonatization and silicification, rare chlorite (chamosite) was precipitated, accompanying quartz and carbonate in veinlets. In the mildly altered rocks, clinocllore and chamosite were identified as alteration products of biotite or as veinlet constituents, but they were never observed in the same sample. It is possible that the occurrence of clinocllore reflects lower temperatures or increased interaction of the fluid with the andesitic rocks, which would have allowed the transfer of larger amount of Mg to it.

Sericitization

Like chlorite, white mica (identified as phengite) was formed continuously, but its most expressive generation coincided with mineralization. Among all the hydrothermal products, it is the second most abundant mineral. This mica replaces plagioclase and thin biotite lamellae along the cleavage planes. The association phengite + quartz + pyrite ± chalcopyrite ± sphalerite ± galena ± gold is commonly found in veinlets or as dissemination in the rock mass, especially when the destruction of plagioclase was more severe. Sericitization seems to have been greatly favored in brecciated and fractured zones, where the migration of fluids was particularly intensified. These zones, which are mineralized, exhibit plagioclase with deformed twinning planes (Fig. 8C) and are cut by a dense network of monomineralic (phengite) veinlets (Fig. 8D). Gold is intimately associated with pyrite in the sericitized zones. In the following stages,

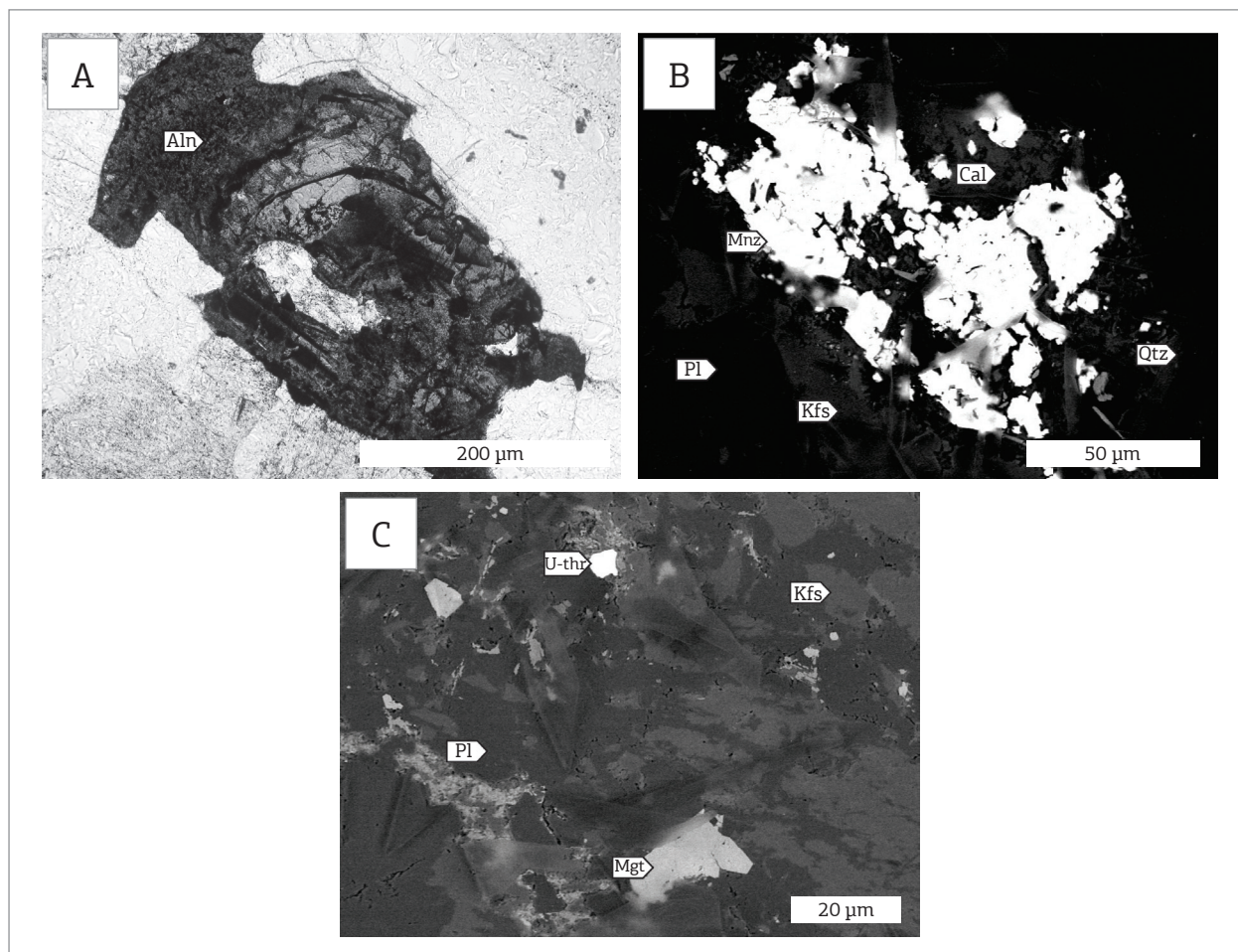


Figure 7. Accessory minerals. (A) Photomicrograph of allanite crystal (Aln) with concentric zoning (parallel nicols). Back-scattered electron images: (B) Aggregate of monazite crystals (Mnz); (C) Fine uranothorite (U-Thr) crystal with high reflectivity.

phengite has little expression and occurs on the walls of quartz veinlets (silicification) and of veinlets with quartz $\pm$ calcite $\pm$ chlorite (carbonatization).

Silicification

Although there has been an early generation of hydrothermal quartz, this mineral was largely precipitated in the stage that followed sericitization. Quartz occurs 1) in monomineralic veinlets exhibiting pseudo-hexagonal shapes, 2) in polymineralic veinlets (phengite $\pm$ chlorite $\pm$ rutile $\pm$ carbonates $\pm$ pyrite $\pm$ chalcopyrite) that cut brecciated mineralized zones (Fig. 8E), and 3) in the rock mass where it usually grows over pre-existing magmatic quartz. Silicification was more intense in cataclastic rocks (Fig. 8F), but quartz was also produced in lesser amounts during chloritization, sericitization or carbonatization. In the two latter stages it is mostly present in veinlets.

Carbonatization

This process marks the final stage of hydrothermal alteration recorded in the deposit. Monomineralic calcite veinlets commonly crosscut the sericitized zones (Fig. 8G). Other modes of carbonate occurrence are 1) in polymineralic veinlets accompanied by phengite $\pm$ chlorite $\pm$ quartz; 2) occupying interstices between pre-existing minerals; and 3) as monomineralic aggregates. Calcite veinlets are also common in the contact between the salami variety and andesite.

MINERALIZATION

The mineralization in the Tocantinzinho deposit is represented by gold, pyrite, chalcopyrite, sphalerite and galena, and, as already noted, it is closely associated with the sericitic alteration. Pyrite stands out as the

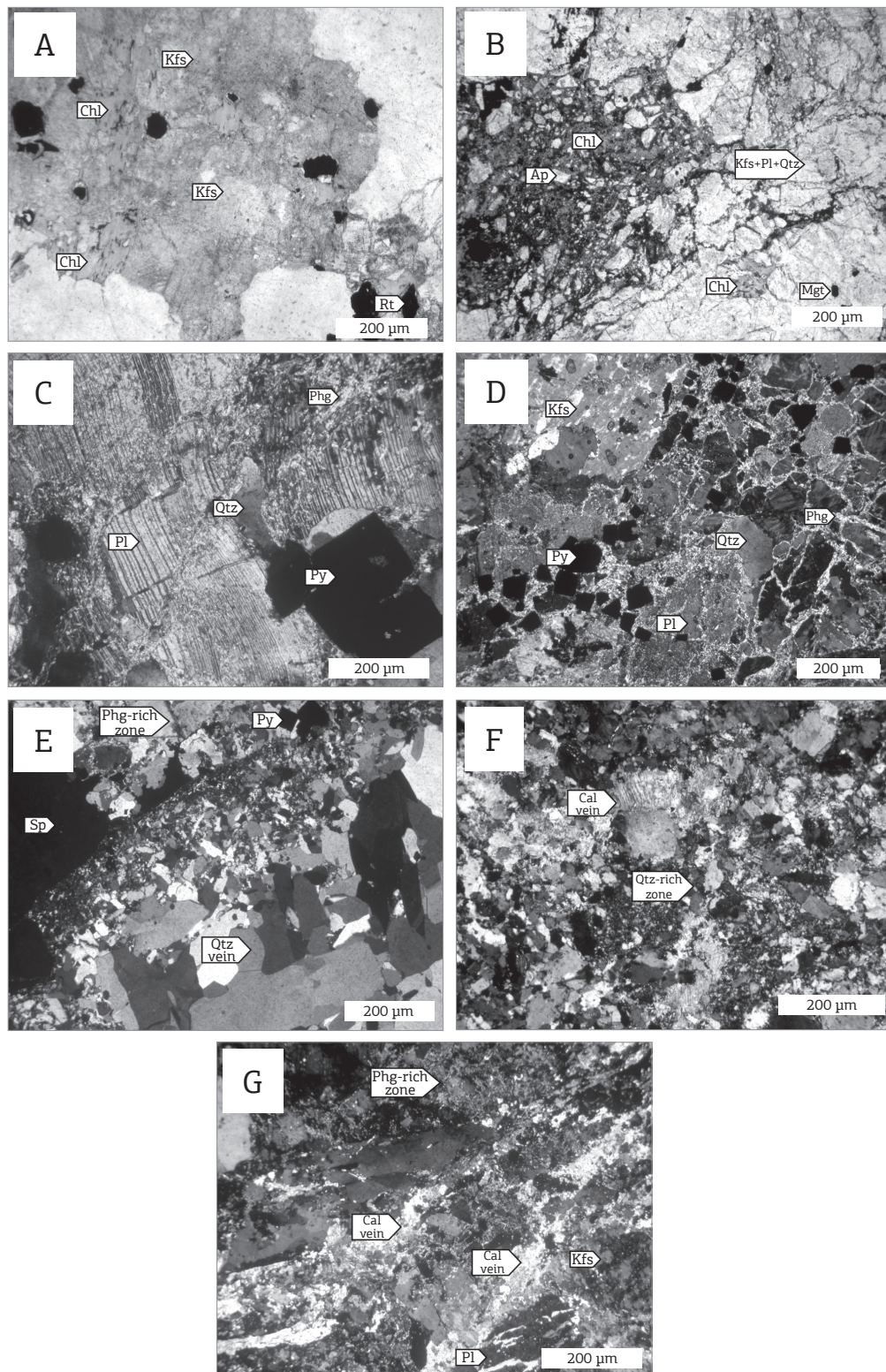


Figure 8. Photomicrographs of the salami and smoky varieties viewed between crossed nicols, except in A and B. (A) K-feldspar crystal with cloudy appearance containing chlorite and rutile inclusions; (B) Zones enriched in chlorite characterized by the abundance of this phyllosilicate either in veinlets or replacing biotite; (C) Plagioclase crystals with contorted twin planes partially replaced by pyrite and phengite; (D) Sulfide-rich brecciated zones densely cut by thin phengite veinlets; (E) Quartz ± chlorite vein cutting a sericitized and mineralized zone; (F) Quartz-rich cataclastic zone cut by calcite veinlets; and (G) Sericitized zone cut by calcite veinlet (Cal: calcite; Chl: chlorite; Fks: K-feldspar; Mgt: magnetite; Pl: oligoclase; Phg: phengite; Py: pyrite; Qtz: quartz; Sp: sphalerite).

most abundant sulfide. Its crystals are euhedral to subhedral, fine to coarse (0.09 – 1.50 mm), being present in polymineralic veinlets as disseminations in brecciated zones (Fig. 8D), or inclusions in sphalerite (Fig. 9A). Chalcopyrite occurs subordinately as exsolution lamellae in sphalerite (Fig. 9A), in polymineralic veinlets or replacing pyrite. Sphalerite is present as inclusions of brownish color and colloform habit (Fig. 9B) in crystals of pyrite and chalcopyrite of the salami variety, but the most common mode of occurrence are disseminated opaque crystals throughout the rock. Gold and galena occur as thin crystals, included or in fractures of pyrite, as well as disseminated in the rock, both having been identified by SEM-EDS analyses (Figs. 9C and D).

Figure 10 presents not only the temporal sequence of the different types of alteration, but also the main stage mineralization that was synchronous with sericitization. The exact paragenetic order of argentite,

Cu-bismuthinite, hedleyite, hessite, native bismuth and petzite is poorly constrained because these minerals are only minor.

MINERAL CHEMISTRY

Microcline

Only the microcline that is present in samples of the moderately altered granite was analyzed (Tab. 2). The composition averages for the salami and smoky varieties were $\text{Ab}_{3.15}\text{An}_{0.06}\text{Or}_{97.93}$ and $\text{Ab}_{2.01}\text{An}_{0.05}\text{Or}_{97.93}$, respectively (Fig. 11). There are, for all practical purposes, no chemical differences in the microcline of these two varieties, even in Fe_2O_3 , which could be accounted for the reddish color of the feldspar crystals in the salami variety.

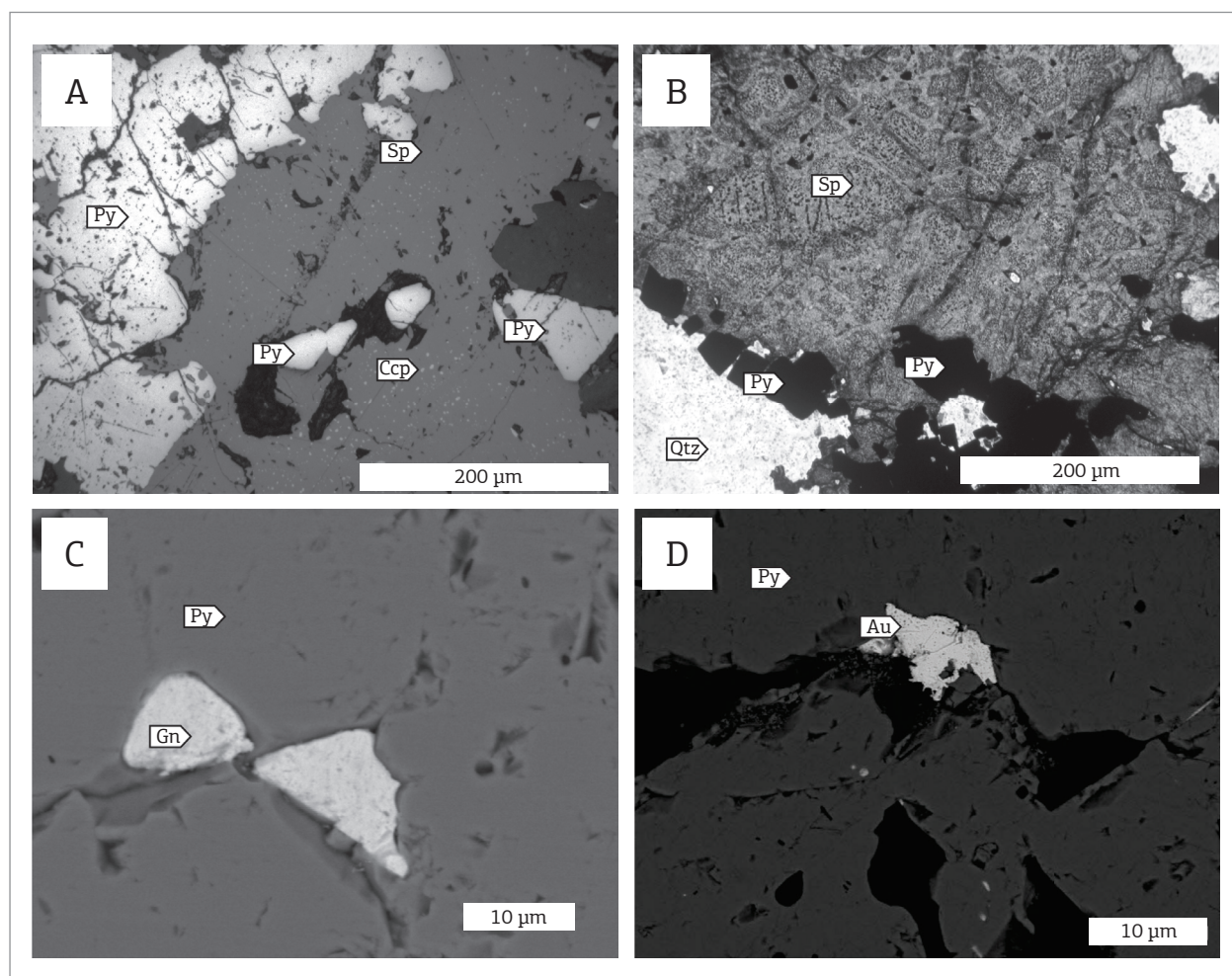


Figure 9. Photomicrographs of ore samples: (A) Pyrite inclusions and exsolution lamellae of chalcopyrite in sphalerite (crossed nicols and reflected light); and (B) Crystal of brownish sphalerite with colloform habit, bordered by pyrite and quartz (parallel nicols and transmitted light). Backscattered electron images of crystals of galena (C) and gold (D) included in pyrite. (Au: gold; Sp: sphalerite, Gn: galena, Py: pyrite, Ccp: chalcopyrite, Qtz: quartz).

Amphibole

The amphibole that occurs in the mildly altered rocks shows average composition of $(\text{Na}_{0.54}\text{K}_{0.14})(\text{Ca}_{1.69}\text{Mg}_{0.09}\text{Fe}^{2+}_{0.22})(\text{Mg}_{1.32}\text{Fe}^{2+}_{3.25}\text{Mn}_{0.12}\text{Al}^{\text{VI}}_{0.12}\text{Ti}_{0.16})(\text{Si}_{6.93}\text{Al}^{\text{IV}}_{1.07})\text{O}_{22}(\text{F}, \text{Cl}, \text{OH})_2$. The values of $(\text{K}+\text{Na})_{\text{A}} \geq 0.5$, $\text{Ti} < 0.5$ and $\text{Ca}_{\text{B}} \geq 1.5$ allow, according to Leake *et al.* (1997), the classification of this amphibole as a member of the edenite-Fe-edenite sub-group of the major calcic amphibole group (Fig. 12A). Compositionally, it corresponds to Fe-edenite (Fig. 12B), considering the average $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ ratio equal to 0.29 and Al_{T} between 1.22 and 1.11 with an average of 1.18 (Tab. 2). It is a Ca-deficient variety, since the B site is occupied by slightly less than 85% Ca; the remainder ~15% is filled with Fe^{2+} and Mg. Because the structural formula indicates electrical neutrality, i.e., $\Sigma_{\text{cation charges}} = \Sigma_{\text{anion charges}}$, it was inferred that Fe^{3+} is absent in the amphibole lattice.

White mica

Flakes of white mica that resulted from the replacement of plagioclase or that occur in veinlets cutting the mineralized zones were analyzed. The veinlet

white mica of the smoky variety is more enriched in FeO and MgO than that of the salami variety (Tab. 3). In comparison to the white mica that replaces biotite in the mildly altered rock, there is practically no

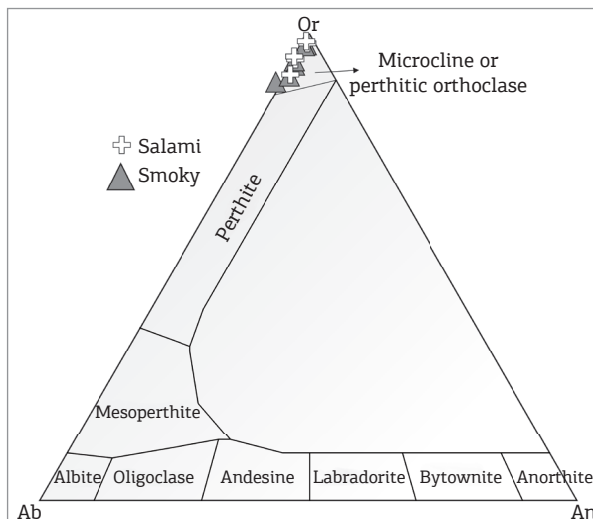


Figure 11. Ab-An-Or diagram illustrating the feldspar compositions present in the salami and smoky varieties.



Figure 10. Temporal relationships between the different types of alteration and a proposed paragenetic sequence for the ore minerals of the Tocantinzinho deposit.

difference concerning these components. White mica derived from plagioclase of the smoky variety and shows the highest TiO_2 contents (Tab. 3). The compositions of this phyllosilicate are concentrated in the upper half of the celadonite-muscovite line (Fig. 13) and can be represented by the average structural formula $(\text{K}_{1.91}\text{Na}_{0.05}\text{Ca}_{0.01}\text{Ba}_{0.01})(\text{Fe}^{2+}_{0.4}\text{Mg}_{0.44}\text{Al}^{\text{VI}}_{3.27}\text{Ti}_{0.02})(\text{Al}^{\text{IV}}_{1.57}\text{Si}_{6.43})\text{O}_{20}(\text{F}, \text{OH})_4$ with an average $\text{Fe}/(\text{Fe}+\text{Mg})$ atomic ratio of 0.53. It belongs to the phengite series (Rieder *et al.* 1998), whose chemical characteristics also meet the criteria of Cibin *et al.* (2008) for this classification.

Chlorite

Analyses were performed with chlorite, which was present in veinlets and replacing biotite from both the mildly and moderately altered granitoids (Tab. 4). Two compositional varieties have been identified (Fig. 14A): chamosite $[(\text{Mg}_{3.55}\text{Fe}^{2+}_{5.83}\text{Mn}_{0.12})(\text{Si}_{5.55}\text{Al}^{\text{IV}}_{2.45})\text{O}_{20}(\text{OH}, \text{F}, \text{Cl})_{16}]$ and clinocllore $[(\text{Mg}_{4.84}\text{Fe}^{2+}_{3.77}\text{Mn}_{0.12})(\text{Si}_{5.66}\text{Al}^{\text{IV}}_{2.34})\text{O}_{20}(\text{OH}, \text{F}, \text{Cl})_{16}]$. The former is the most common one, while the latter was only observed in the mildly altered rocks with very uniform $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio (0.42 – 0.44). In turn, chamosite occurs in all granite rocks, regardless of the alteration degree, and presents values of $\text{Fe}/(\text{Fe}+\text{Mg})$ between 0.57 and 0.68 (mean of 0.63). There is no chemical distinction between the chlorite derived from biotite and that occurring in veinlets of the mildly altered rocks. Conversely, the differences are significant when comparing these chlorite types in the salami and smoky varieties, particularly in the first one. The veinlet chamosite of the salami variety is, however, very similar in composition to the chamosite found in the mildly altered rocks, regardless of the mode of occurrence. On the other hand, if one

Table 3. Average composition (wt% and a.f.u.) of phengite from the Tocantinzinho deposit

Minerals/ Components	Phengite/ Veinlet		Phengite / Plg		Phengite / Bt
	Smoky	Salame	Smoky	Salame	Mildly altered
SiO_2	47.04	47.51	46.88	47.30	48.40
Al_2O_3	28.55	29.49	30.73	30.95	28.78
TiO_2	0.11	0.27	0.32	0.18	0.22
FeO	4.83	3.71	3.71	3.40	4.03
MnO	0.04	0.05	0.04	0.05	0.02
MgO	2.27	1.80	1.73	1.73	1.98
CaO	0.09	0.03	0.05	0.03	0.03
BaO	0.21	0.29	0.12	0.16	0.14
Na_2O	0.12	0.11	0.20	0.16	0.09
K_2O	11.06	11.02	11.14	11.14	10.75
Cl	0.02	0.03	0.00	0.01	0.00
F	0.18	0.09	0.16	0.14	0.26
Total	94.53	94.40	95.08	95.25	94.70
O=F	0.08	0.04	0.07	0.06	0.11
O=Cl	0.00	0.01	0.00	0.00	0.00
Total	94.45	94.35	95.01	95.19	94.59
Structural formula	22 oxygen atoms				
Si	6.41	6.50	6.49	6.41	6.60
Al^{IV}	1.59	1.50	1.51	1.59	1.40
Al^{VI}	3.35	3.26	3.37	3.35	3.22
Al_T	4.94	4.76	4.88	4.94	4.62
Ti	0.02	0.03	0.02	0.02	0.02
Fe^{+2}	0.39	0.42	0.35	0.39	0.46
Mn	0.35	0.00	0.00	0.01	0.00
Mg	0.01	0.37	0.32	0.35	0.40
Ca	0.00	0.01	0.01	0.01	0.00
Ba	0.01	0.01	0.00	0.00	0.01
Na	0.04	0.04	0.03	0.04	0.02
K	1.92	1.93	1.90	1.92	1.87
Cl	0.00	0.00	0.00	0.00	0.00
F	0.06	0.08	0.05	0.06	0.11
$\text{Fe}/(\text{Fe}+\text{Mg})$	0.53	0.54	0.52	0.53	0.53

(-): no data available; Bt: Biotite; Plg: Plagioclase.

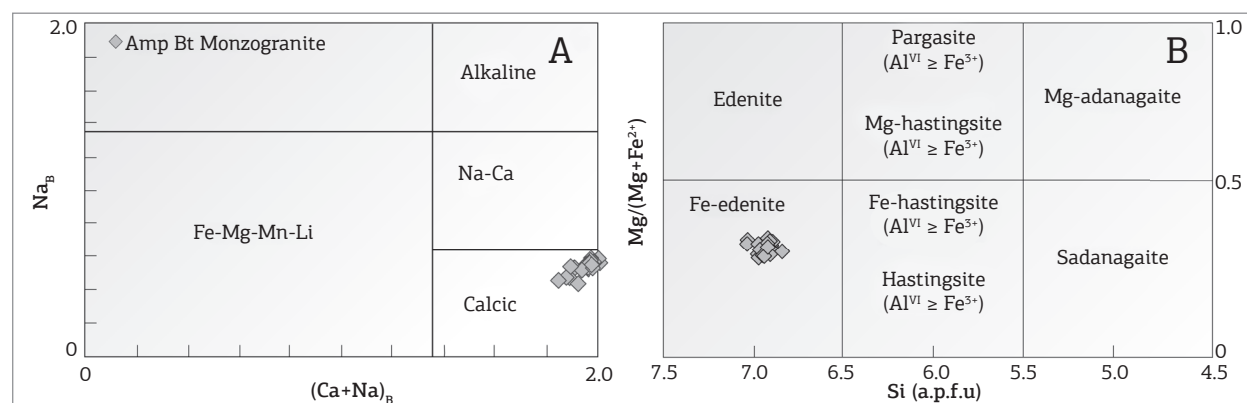


Figure 12. Compositional variations of the amphibole present in the mildly altered granitoid. (A) Diagram discriminating the four major chemical groups of amphiboles; and (B) Classification diagram of calcic amphiboles according to the parameters $\text{Ti} < 0.50$, $\text{CaB} \geq 1.5$ and $(\text{Na}+\text{K})\text{A} \geq 0.5$ (Based on Leake *et al.* 1997).

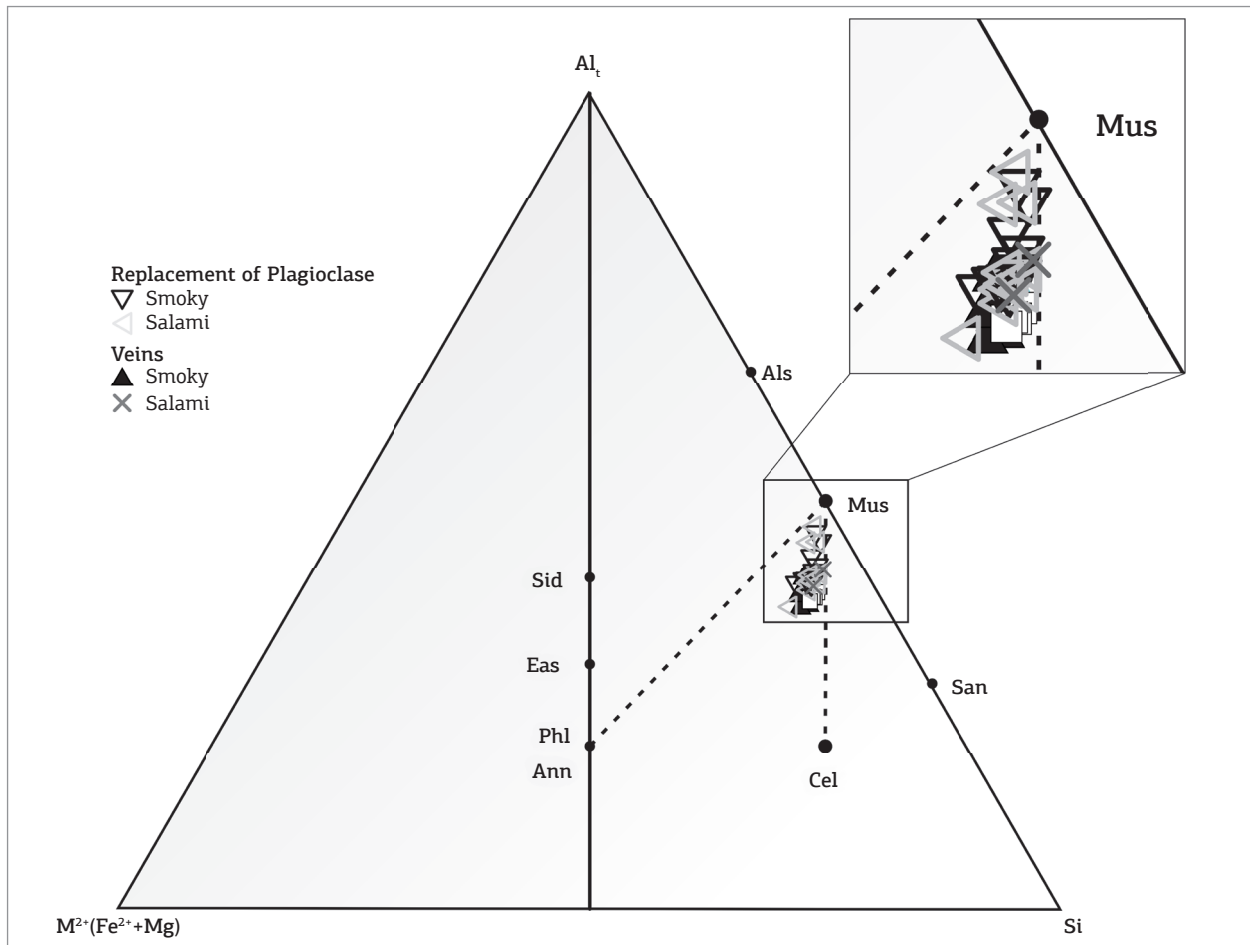


Figure 13. Compositional variation of the white mica from the salami and smoky varieties represented in an $AlT-M2^{+}-Si$ diagram. Analytical points are distributed along the upper half of the line that joins muscovite (Mus) and celadonite (Cel). Modified from Monier & Robert (1986).

considers only the chamosite derived from biotite, the decrease in the $Fe/(Fe+Mg)$ ratio from the mildly altered rock to the smoky variety is evident, passing through the salami variety (Fig. 14B).

DISCUSSION

Host Rocks

Granite rocks are dominant in the deposit area and make up a body that was probably emplaced at the final stages of the Cuiú-Cuiú orogenesis. This body, elongated in the NW-SE direction and coinciding with the Tocantinzinho lineament, shows evidence of brittle deformation caused by intense fracturing and brecciation, mainly in the mineralized zone. Features of ductile deformation have not been recognized so far in these rocks.

The mildly altered rocks show mostly the monzogranite composition, being associated with subordinate granodiorite and alkali-feldspar granite facies. Based on modal analysis, it was possible to infer, despite the alteration degree, that the salami and smoky varieties had the biotite monzogranite as protolith. From a macroscopic point of view, as noted, these varieties are quite distinct. Due to its reddish color, the salami variety was suspected to be richer in Fe_2O_3 ; however, in general the highest Fe_2O_3/FeO ratios are symptomatically detected in samples from the smoky variety. Recently, a study about mass balance pointed to a significant difference between these two altered rock varieties and mass gains were estimated to be greater in the smoky variety than in the salami one, especially in the sericitized zones (Santiago 2012).

The mineralogical composition of the monzogranites ($Qtz + Kfs + Olg + Hbl + Ttn + Bt + Ilm + Mgt$) is very similar to that considered ideal by many researchers to be used in geobarometry. In the present case, it allowed to obtain the data presented in Tab. 5. The results by

Table 4. Average composition (% by weight and a.f.u) of chlorite present in the Tocantinzinho deposit

Minerals/ Components	Clinochlore/ Ven	Clinochlore/ Bt	Chamosite/ Ven	Chamosite/ Bt	Chamosite/ Ven	Chamosite/ Ven	Chamosite/ Bt	Chamosite/ Bt
Mildly altered			Salami			Smoky	Salami	Smoky
SiO ₂	27.68	28.36	24.92	25.40	25.61	24.41	25.52	26.08
Al ₂ O ₃	18.46	19.19	19.75	19.69	17.98	19.75	18.78	18.42
TiO ₂	0.03	0.03	0.01	0.06	0.07	0.10	0.06	0.05
FeO	22.30	23.13	33.22	32.92	33.64	31.30	30.97	29.65
MnO	0.57	0.56	0.59	0.55	0.67	0.57	0.66	0.56
MgO	17.47	15.51	8.84	9.12	9.60	10.76	11.53	12.71
CaO	0.05	0.04	0.03	0.05	0.06	0.03	0.09	0.03
BaO	0.03	0.02	0.00	0.01	0.01	0.06	0.01	0.00
Na ₂ O	0.03	0.02	0.10	0.03	0.04	0.06	0.02	0.03
K ₂ O	0.02	0.63	0.01	0.37	0.08	0.13	0.06	0.08
Cl	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.02
F	0.22	0.24	0.13	0.13	0.11	0.08	0.08	0.16
Total	86.87	87.74	87.63	88.33	87.88	87.24	87.79	87.79
O=F	0.09	0.10	0.00	0.06	0.05	0.03	0.03	0.07
O=Cl	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
Total	86.78	87.64	87.58	88.27	87.83	87.21	87.76	87.72
Structural formula		28 oxygen atoms						
Si	5.81	6.05	5.52	5.57	5.68	5.39	5.57	5.65
Al ^{IV}	2.19	1.95	2.48	2.43	2.32	2.61	2.42	2.35
Al ^{VI}	2.38	2.72	2.67	2.66	2.37	2.53	2.41	2.36
Al _r	4.57	4.67	5.16	5.09	4.70	5.14	4.83	4.70
Ti	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.01
Fe ⁺²	3.92	3.77	6.15	6.04	6.24	5.78	5.66	5.37
Mn	0.10	0.12	0.11	0.10	0.13	0.11	0.12	0.10
Mg	5.47	4.84	2.92	2.98	3.17	3.54	3.75	4.11
Ca	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01
K	0.00	0.25	0.03	0.00	0.02	0.04	0.02	0.02
Cl	0.00	0.00	0.09	0.09	0.01	0.00	0.00	0.01
F	0.15	0.18	0.00	0.00	0.07	0.05	0.05	0.11
Fe/(Fe+Mg)	0.42	0.44	0.68	0.67	0.66	0.62	0.60	0.57

Bt: Biotite; Ven: Veinlet

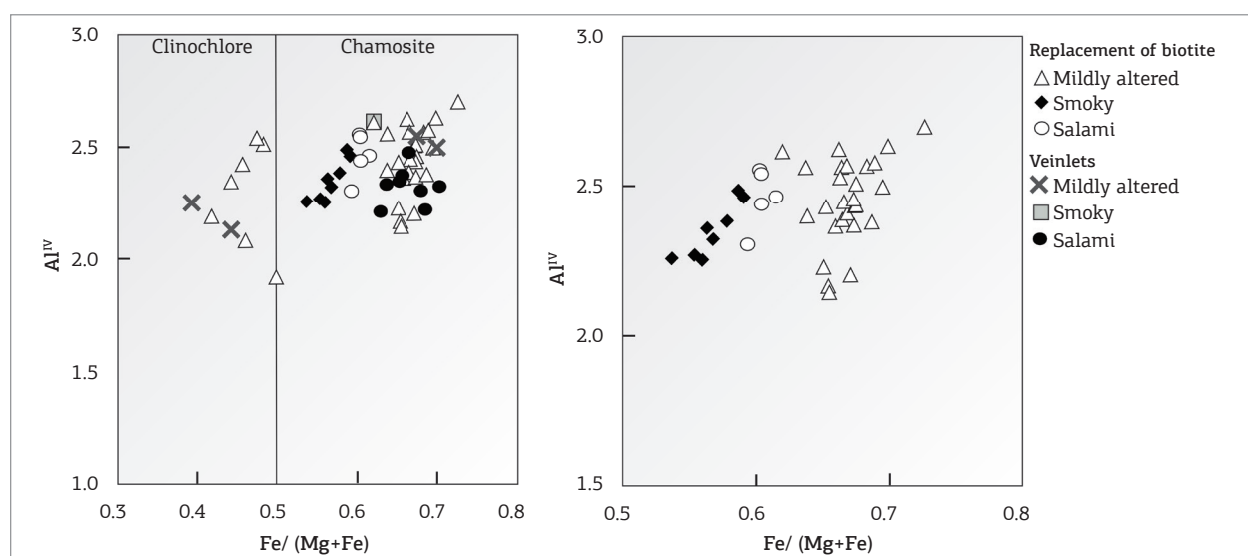


Figure 14. (A) Fe/(Fe+Mg) x Aliv diagram (Bailey 1988) in which are represented chlorite analyses from mildly and moderately altered granitoids. (B) Composition of chamosite derived from biotite, showing a decrease of XFe from the mildly altered rock to the smoky variety.

Hammarstrom & Zen (1986), Blundy & Holland (1990) and Schmidt (1992) are more reliable and yielded average pressures above 2 kbar, with minimum and maximum acceptable values of 1.9 and 2.8 kbar, implying depths of emplacement for those granitoids of 6–9 km.

With respect to the oxidation state of the magma that generated the monzogranites, the composition of Fe-edinite indicates mild f_{O_2} conditions (Fig. 15), which are consistent with the Fe_2O_3/FeO ratios in the total rock that range from 0.44 to 0.56. The presence of titanite and magnetite (< 0.2 vol.%), and the virtual absence of ilmenite in the primary accessory minerals would fit the Tocantinzinho monzogranites in the magnetite series granitoids (Ishihara 1981). However, in such a case, higher f_{O_2} should be expected. If the $Fe^{2+}/(Fe^{2+} + Mg)$ mole fraction of the mafic phases is a good indicator of the redox state of the magma, those granitoids would be best described as the oxidized subtype of the ilmenite series, as proposed by Takagi & Tsukimura (1997).

Hydrothermal Alteration

The alteration processes in granite rocks of the Tocantinzinho deposit were mild to moderate in intensity and generally caused few changes in their primary features. Microclinization, chloritization, sericitization, silicification and carbonatization were the main types of alteration, being the first three ubiquitous and the last two more selective and represented by filling veinlets, although silicification is also evidenced as overgrowth around primary crystals of quartz (blebby quartz).

The hydrothermal alteration history of the Tocantinzinho granite began with the transformation of the primary K-feldspar into hydrothermal microcline. Compositional factors play an important role in hydrothermal changes, even though in this case the formation of any of the two phases must have required high K^+ activities, in both the melt and aqueous solutions. The most important control should have been exerted by the relatively lower temperature of the fluid that favored the stability of the phase in which the chemical potential of the component $KAlSi_3O_8$ was lower. At this early stage, characterized by microclinization, the fluids should also have been oxidized (presence of hematite) and silica-rich to account for the overgrowth in pre-existing quartz crystals, typical of the salami variety. With decreasing temperature, mafic minerals were preferably destroyed and replaced

by chlorite with concomitant release of K^+ and H_4SiO_4 (eg. biotite + H^+ + H_2O $\rightarrow$ chlorite + K^+ + H_4SiO_4). The fluid, now richer in K^+ , moved through fractures and brecciated zones causing other minerals, notably oligoclase, to become unstable and be replaced by phengite. As a consequence, Na^+ , Ca^{2+} and silica were then transferred to the fluid (oligoclase + K^+ + H^+ + H_2O $\rightarrow$ phengite + Na^+ + Ca^{2+} + H_4SiO_4). This fluid, carrying base metals probably in the form of chloride complexes, in addition to gold, started precipitating pyrite $\pm$ chalcopyrite $\pm$ sphalerite $\pm$ galena in response to the increased pH (sericitization) and activity of the sulfur species. As the temperature decreased even more, dissolved silica precipitated as quartz in the rock mass and open spaces, characterizing the silicification stage of the hydrothermal alteration.

There is no study on fluids, but preliminary data reveal that aqueous and aqueous-carbonic fluid inclusions have been trapped in quartz veins (Joana Queiroz, personal communication). The aqueous fluid might be magmatic in origin and responsible for the microclinization, chloritization, sericitization and silicification, while the aqueous-carbonic fluid could be non-magmatic, but related to the shear zone. Somewhere these fluids must have been mixed so that Ca^{2+} , carried by the aqueous fluid, and carbonic species, transported by the aqueous-carbonic fluid, react to form calcite. The carbonatization stage was established and

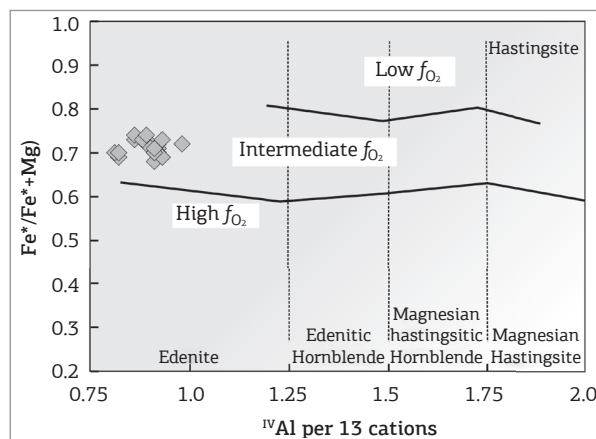


Figure 15. $Fe/(Fe + Mg) \times AlIV/13cations$ diagram with analytical data of amphibole crystals (sample 08-177) showing the f_{O_2} conditions under which the amphibole-biotite monzogranite crystallized (Based on Anderson & Smith 1995, Råmo *et al.* 2002 and Dall'Agnol *et al.* 2005).

Table 5. Crystallization pressures of the Tocantinzinho granitoid estimated with different geobarometers based on the hornblende AlT content

P ($\pm$ 3 kbar) Hammarstrom & Zen (1986)			P ($\pm$ 0.6 kbar) Schmidt (1992)			P (kbar) Blundy & Holland (1990)		
Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
1.5	2.24	2.03	1.89	2.63	2.42	2.12	2.82	2.62

the hydrothermal history of the Tocantinzinho deposit has come to an end. It should be emphasized, however, that despite the low solubility of CO_2 in felsic magmas, CO_2 -rich fluid inclusions have been interpreted in various granite intrusions as primary magmatic vapors (Löwenstern 2001). If so, a common magmatic origin could be instead envisaged for both the aqueous and aqueous-carbonic fluids.

The formation temperatures of chlorite were estimated with geothermometry equations by Kranidiotis & MacLean (1987), Cathelineau (1988) and Zang & Fyfe (1995). The data obtained with the Kranidiotis & MacLean's equation were found to be more suitable because the composition of chlorites studied by these authors is more similar (~70% of the analyses show $X_{\text{Fe}} = 0.4 - 0.64$) to that of the Tocantinzinho chlorites (0.57 – 0.68). The calculations indicated temperatures between 313 and 327°C for chamosite and 275°C for clinocllore (Tab. 6). The lower temperature may correspond to a sample that was collected near the contact of the intrusive body, when the isotherms were no longer elevated, and the flow of fluids was less intense, what would have favored the stability of the Mg-richer chlorite.

Considering the experimental data of Monier & Robert (1986), the Tocantinzinho phengite may have been formed in the range of 300 – 400°C and 2 kbar, although these authors underscore the poor accuracy of this phyllosilicate as a geothermometer in hydrothermal conditions. Significantly, however, there is consistency between that thermal interval and the estimated temperatures for the formation of the chamosite. The pressure range calculated by the hornblende geobarometer for the emplacement of the Tocantinzinho granite is also consistent.

In general, the low abundance of the alteration products is indicative that the Tocantinzinho hydrothermal paleosystem was dominated by the mineralogical environment, implying low fluid /rock ratios. In the particular case of chlorite, this ratio must have been less than 1 (De Caritat *et al.* 1993), and its composition largely controlled by the composition of the pre-existing biotite. As already pointed out, the X_{Fe} of the chamosite decreases from the mildly altered rock to the smoky variety, passing through the salami variety (Fig. 14B). Apparently,

biotite with high annite content tended to generate chamosite with the highest X_{Fe} , corresponding to the one that occurs in the mildly altered rocks. But as the hydrothermal alteration advanced, the fluid seemed to have become progressively Mg-enriched and exerted greater influence on the chlorite composition. Assuming a homogeneous composition for the primary biotite in the monzogranite rocks, the salami variety interacting with less Mg-enriched fluids than those of the smoky variety during chloritization could be an option. On the other hand, the chamosite that is present in veinlets that crosscut the granite rocks, irrespectively of their alteration degree, shows a quite uniform X_{Fe} (0.6 – 0.7). Such a narrow range also characterizes the chamosite derived from biotite of the mildly altered rocks (Fig. 14B). Plausibly, the fluid that initially altered the primary biotite was the same from which the veinlet chamosite was precipitated.

Table 7 summarizes the characteristics of the types of hydrothermal alteration recognized in the granitic rocks of the Tocantinzinho deposit in terms of mineralogical associations, style and mode of occurrence, and also temperature estimates under which they were developed.

Comparisons with other Tapajós gold deposits

The geological context of the Tapajós province was conducive to the formation of several types of hydrothermal gold deposits, as a result of both magmatic and metamorphic processes (Tab. 8). In terms of host rock, style of mineralization and hydrothermal alteration, the Tocantinzinho deposit is quite distinct from the Botica (V3) and Chapéu de Sol (V6) deposits, considered to be epithermal. Compared to the Patinhas and Ouro Roxo deposits, classified as metamorphogenic, the main differences are related with the style of mineralization and host rocks, besides the timing of mineralization that occurred after the peak of deformation in Tocantinzinho. The similarities refer to the types of hydrothermal alteration and metalliferous content.

With respect to Batalha, Palito and São Jorge, and those of the Cuiú-Cuiú ore field, the first two interpreted as porphyritic systems, the Tocantinzinho deposit generally presents similarities regarding the host rocks and styles of mineralization and alteration. All different types of alteration, except for the Na-metasomatism, not yet described in Tocantinzinho, are common to those deposits, as it is the contemporaneity of the mineralization to sericitization. The similarities are extended to the metalliferous content, although chalcopyrite, unexpressive and not associated with the main stage of mineralization in Tocantinzinho, appears as one of the main sulfides of the Palito and Batalha ores.

It is also noted that the host granite for the Tocantinzinho deposit, probably a precursor intrusion of

Table 6. Average temperatures of chlorite formation (ToC) obtained by the thermometric equations proposed by various authors

Rock type	Chlorite variety	Cathelineau (1988)	Kranidiotis & MacLean (1987)	Zang & Fyfe (1995)
Smoky	Chamosite	476	325	257
Mildly altered		323	327	249
Salami		467	313	249
Mildly altered	Clinocllore	388	275	232

the Creporizão Suite, is older than the ~1880 Ma granites that host the other deposits.

Possible Typology

Although information for the better understanding of the origin of the Tocantinzinho deposit is lacking, the data already available (Mello 2007, Juras *et al.* 2011, Santiago 2012, Villas *et al.* submitted) and those obtained in this work allow to envisage a genetic model for this deposit and set its preliminary typology.

The Tocantinzinho deposit is hosted in a granite stock, probably emplaced at the end or after the development of the Cuiú-Cuiú magmatic arc, at depths of 6–9 km under the influence of the sinistral, NW-SE-trending Tocantinzinho lineament. This intrusion is dominated by monzogranite rocks that crystallized under conditions of intermediate fO_2 . These rocks show high degree of fractionation ($SiO_2 = 67–76\%$), metaluminous to peraluminous character and affinity with the high-K calc-alkaline to shoshonite series (Santiago 2012). The hydrothermal products, whose abundance suggests low fluid:rock ratios, are ubiquitously distributed, but also occur as constituents of veins/veinlets. The mineralization coincided with the sericitization stage and is characterized by the Au-Cu-Zn-Pb-Te-Ag-Bi metallic association. Sulfides amount to less than 5%, being present in sheeted veins, stockwork and disseminations (Tabs. 7 and 8). The mineralizing fluids, still poorly investigated, have revealed the presence of carbon compounds and low to moderate salinity (Joana Queiroz, personal communication).

The aforementioned characteristics are consistent with magmatic-hydrothermal systems developed in subduction zone environments, like the oxidized (Seedorff *et al.* 2005, Robb 2006, Sinclair 2007, Sillitoe 2010) and reduced Cu-Au porphyritic deposits (Rowins 2000, Smith *et al.* 2012) or granitic intrusion-related deposits (Lang & Baker 2001, Baker

2005, Goldfarb & Hart 2005), all of them already described in TGP (Tab. 9). Concerning the intrusion-related deposits, besides the lack of consensus among researchers to represent a new class of epigenetic deposits, they were typically formed during the Phanerozoic, being rare in Precambrian times (Lang & Baker 2001).

The classical Cu-Au porphyritic deposits occur in less evolved rocks of intermediate composition, mainly derived from magmas with high fO_2 that were emplaced at shallow crustal levels (generally < 3 km). These rocks show their primary textures generally severely obliterated by the alteration processes that produced abundant magnetite, hematite and anhydrite/barite. Fluids are predominantly aqueous, saline and magmatic in origin. Many of these features are not consistent with those described for the Tocantinzinho deposit.

In turn, reduced Cu-Au porphyritic deposits reveal many similarities with their oxidized counterparts, but are developed in type I reduced granite rocks, which contain pyrrhotite and low copper content, being distal in relation to the porphyry system center (Rowins 2000).

The intrusion-related gold deposits commonly occur in Sn-W provinces, but Au is not necessarily associated with these metals (Thompson *et al.* 1999). They are hosted in relatively reduced and generally metaluminous type I granite rocks. The depth of the pluton emplacement ranges from < 1 to > 8 km, mostly between 4–6 km. Typically, they exhibit 1–5% sulfides, dominated by pyrite, and an anomalous metallic association (Au-Bi-Te-As-Sb-W), which may vary outwards the plutonic center (Lang & Baker 2001, Hart *et al.* 2002). The mineralizing fluids are weakly to moderately saline and CO_2 -rich with varying proportions of CH_4 , N_2 and H_2 .

Despite the similarities with the reduced porphyritic deposits, the anomalous metal association, the depth of pluton emplacement, the low sulphide content and the low fluid:rock

Table 7. Types of hydrothermal alteration present in the granite rocks associated with the Tocantinzinho deposit, highlighting the mineralogical associations, style, mode of occurrence and estimates of temperature

Types of hydrothermal alteration	Mineral associations	Modes of occurrence	Alteration styles	Formation temperature (°C)
Microclinization	Microcline+Hematite+Quartz	Mineral replacement	Pervasive	~600
Chloritization	Chlorite±Quartz±Rutile±Calcite±Phengite	Mineral replacement and veinlets	Pervasive to fissural	330
Sericitization	Phengite±Quartz±Chlorite±Calcite	Mineral replacement and veinlets	Pervasive to fissural	~300
Mineralization	Gold+Pyrite±Chalcopyrite±Galena±Sphalerite±Hessite±Cu-Bismuthinite±Molybdenite	Disseminated in rocks and veinlets	stockwork to disseminated	-
Silicification	Quartz±Chlorite±Phengite±Pyrite±Chalcopyrite	Veinlets	Fissural	-
Carbonation	Calcite±Chlorite±Phengite±Quartz	Veinlets	Fissural	-

(-): Not determined.

Table 8. Comparative data of gold deposits that occur in the Tapajós Province

Ore Deposits	Host rock	Host rock age (Ma)	Types of hydrothermal alteration	Mineralization styles	Metallic association	Fluid P and T conditions	Mineralization age (Ma)	Nature of fluids	Typology
Alvo V3 or Botica ^{9,12,15}	Felsic volcanics and volcanoclastics	1870 ± 8/ zircon U-Pb (SHRIMP)	Silica cap → Advanced argilic	Breccias pipes	Au+Ag± Cu±Mo	130 – 420°C	1869 ± 2 a 1876 ± 2/ alunite ⁴⁰ Ar/ ³⁹ Ar	Magmatic/ oxidized	Epithermal of high sulfidation
Alvo V6 or Chapéu do Sol ^{9,15,16}	Felsic volcanics and volcanoclastics	1870 ± 8/ zircon U-Pb (SHRIMP)	Sericitization with adularia → Propylitization with adularia → Argilic	Breccias	Py±Ccp± Mol±Au	350 – 410°C e 0.2 – 1.5 kbar	-	Magmatic/ oxidized	Epithermal of low sulfidation
Batalha ^{9,10}	Hornblende-biotite syeno- to monzogranite	1883 ± 4/ zircon U-Pb (SHRIMP)	Sodic → Potassic → Propylitization → Sericitization/ Mineralization	Stockwork to disseminated	Au+Py+ Ccp±Gn	115 – 290°C e 1.2 kbar	-	Magmatic/ reduced	Reduced porphyry or intrusion-related
Tocantinzinho ^{1,2,3,4,5}	Biotite monzogranite	1982 ± 8/ zircon Pb-Pb evaporation	Microclinization → Chloritization → Sericitization/ Mineralization → Silicification → Carbonatization	Sheeted veins, stockwork to disseminated	Au+Py±Ccp±Gn± Sp±Hes±Hed± Petz ±Arg± Cu-bis	-	-	Probably magmatic (?)/ reduced	Intrusion-related
São Jorge ^{6,7,8}	Amphibole Biotite monzogranite	1891±3/ zircon Pb-Pb evaporation	Propylitization → Sericitization/ Mineralization	Stockwork to disseminated	Au+Py±Ccp±Gn ±Sp±Cu-bi±Bi	280 – 350°C e 1.35 – 3.6 kb	-	Magmatic/ oxidized	intrusion-related or hybrid (orogenic with magmatic contribution)
Palito ^{10,11,12,13,14}	Granite	-	Potassic → Propylitization → Sericitization	Quartz veins, stockwork to disseminated	Ccp+Py+Au+ Cc+Ag-Cu-Au+ Po+Gn+Sp+Bi+ Cu-bi	101 – 400°C	-	Magmatic/ oxidized	Cu-Au Porphyry
Campo Cuiú-Cuiú ²¹	Tonalite/ Granodiorite	-	Cloritization-hematitization → Sericitization/ Mineralization Silicification → Carbonatization	Sheeted veins, breccias e stockwork	Py+Au±Ccp ±Gn±Sp	-	-	Probably magmatic	Orogenic (?)
Ouro Roxo ^{18,19,20}	Mylonitic Granodiorite e diorite	1894 ± 3 and 1897 ± 3/ zircon and titanite U-Pb (SHRIMP)	Propylitization → Sericitization → Carbonatization → Silicification	Quartz veins	Py+Ccp+Au ±Bi±Cu-bi	395°C and 2 – 4.2 kb	1900 e 1880/ zircon U-Pb (SHRIMP)	Magmatic/ reduced	Orogenic or hybrid (magmatic contribution)
Patinhas ^{9,17}	Hornblende gnaiss granodioritic	2033 ± 7 and 2005±7	Epidotization → caulinization	Quartz veins	Au±Py±Ccp	307 – 389°C and 2.1 kb	-	Metamorphic/ reduced	Mesozonal orogenic

Arg: Argentite; Au: gold; Bi: native bismuth; Ccp: chalcopryrite; Cu-bi: cupro-bismuthinite; Sp: sphalerite; Gn: galena; Hed: hedleyite; Hes: hessite; Mol: molibdenite; Petz: petzite; Py: pyrite; 1- Mello (2007); 2- Juras *et al.* (2011); 3- This paper; 4- Santiago (2012); 5- Villas *et al.* (submitted); 6- Borges (2010); 7- Borges *et al.* (2010); 8- Lamarão *et al.* (2008); 9- Santos *et al.* (2000); 10- Juliani *et al.* (2002); 11- Notto (2007); 12- Juliani *et al.* (2005); 13- Echeverri-Misas (2010); 14- Juliani *et al.* (2008); 15- Jacobi (1999); 16- Corrêa-Silva (2002); 17- Klein *et al.* (2001); 18- Keller & Couture (2006); 19- Veloso (2011); 20- Frantz *et al.* (2005); 21- Klein *et al.* (2004); 22- Almeida *et al.* 2000; 23- MacMahon (2011). (-) No data available.

ratio suggest that the Tocantinzinho deposit fits best in the class of the granite intrusion-related gold deposits. Although TGP is not recognized as a Sn-W province and presents a predominant Orosirian evolution, its tectonic context is equally favorable to the formation of intrusion-related deposits.

Mello (2007) first classified the Tocantinzinho deposit as an intrusion-related gold deposit, typology that was also defended by Juras *et al.* (2011). The new data presented here support this interpretation. However, any genetic model to be more consistent, further field investigations are necessary, as well as to obtain thermodynamic and isotopic data of the mineralizing fluids, in addition to determining the age of the mineralization.

Nevertheless, especially in situations in which granite emplacement is controlled by shear zones, one should

be very careful to distinguish between orogenic gold and intrusion-related deposits, given their geological convergence (Sillitoe & Thompson 1998).

CONCLUSIONS

The biotite monzogranite (1.98 Ga), host of the Tocantinzinho deposit, is an isotropic, late to post-tectonic stock, emplaced 6 – 9 km depths and crystallized under fO_2 intermediate conditions that enable its classification as an oxidized subtype of the ilmenite series.

This stock was subjected to mild to moderate hydrothermal processes, which generated two main varieties of altered rocks (salami and smoky), chemically and mineralogically similar, but quite different in macroscopic appearance. The

Table 9. Main characteristics of some of the largest granite intrusion-related gold deposits

Ore deposits	Location	Metallic association	Host Rock	Granitoid series	Saturation in alumina	Accessory minerals	Types of hydrothermal alteration	Mineralization styles	Emplacement depth (km)
Timbarra ^{1,2,4,5,6}	New England Fold Belt/ Australia	Au-Bi-Mo	Monzogranite	Magnetite/ Ilmenite	Meta to peraluminous	Magnetite, ilmenite, titanite, fluorite	Albitization, sericitization, chloritization and carbonation	Disseminated	~7
Kidston ^{1,2,4,5,6}	Queensland/ Australia	Au-Bi-Cu-Mo-W	Porphyritic rhyolite	Magnetite/ Ilmenite	Meta to peraluminous	Titanite, fluorite, magnetite, ilmenite, xenotime	Silicification, sericitization and carbonation	Breccia and sheeted veinlets	~3
Kori Kollo ^{1,2,4,5,6}	Bolivian Polymetallic Belt/ Bolivia	Au-Ag-As-Sb-Sn-Bi-Cu-Pb-Zn-W	Porphyritic dacite	Ilmenite	Meta to peraluminous	Titanite, magnetite, ilmenite	Silicification, sericitization	Breccias, sheeted veinlets and disseminated	< 2
Fort Knox ^{1,2,4,5,6,7,9}	Tintina Gold Belt/ Alaska	Au-As-Bi-Mo-W-Te	Granodiorite to granite	Ilmenite	Meta to peraluminous	Ilmenite, titanite, allanite	Potassic alteration, albitization, sericitization	Sheeted veinlets	1.5 – 9
Donlin Creek ^{1,2,4,5,6,7,8,9}	Tintina Gold Belt/ Alaska	Au-As-Ag-Bi-Cu-Zn-Te-Sb-Hg	Rhyolite	Ilmenite	Meta to peraluminous	Ilmenite, titanite, allanite	Potassic alteration, albitization, sericitization	Sheeted veins	~2
Dublin Gulch ^{1,2,3,4,5,6,7,9}	Tintina Gold Belt /Yukon Territory/ Canada	Au-Bi-Te-As-W-Sb-Pb-Cu	Biotite-hornblende granodiorite	Ilmenite	Meta to peraluminous	Titanite	Silicification, potassic alteration, sericitization, carbonation	Sheeted veinlets	~3.5

1- Lang & Baker (2001); 2- Thompson *et al.* (1999); 3- Maloof *et al.* (2001); 4- Hart & Goldfarb (2005); 5- Baker (2005); 6- Baker *et al.* (2005); 7- Baker *et al.* (2006); 8- Goldfarb *et al.* (2004); 9 - Goldfarb *et al.* (2000)

most important types of hydrothermal alteration were, in order, microclinization, chloritization, sericitization, silicification and carbonatization. The hydrothermal products occur when replacing primary minerals or in filling veinlets, and are represented mainly by microcline, chlorite (chamosite and clinocllore) and phengite. The mineralization was contemporaneous with sericitization, and locally features the stockwork style.

Microclinization marks the early stage of the hydrothermal alteration history of the Tocantinzinho granite, and it was responsible for the generation of the salami variety. At lower temperatures, around 330°C, primary mafic minerals were largely transformed into chamosite, setting forth the main chloritization stage. Farther from the major alteration zones, clinocllore was also stabilized, but at 275°C. The chemical differences observed in chlorite show that the temperature and the compositions of the destroyed minerals and fluids were the most important controlling agents in constraining chlorite composition. Sericitization came next, when base metal- and gold-bearing fluids precipitated pyrite ± sphalerite ± chalcopyrite ± galena ± gold in response to increasing pH and activity of the sulfur species. With progressive temperature drop, the aqueous solutions started precipitating silica mostly as veinlet quartz. At the latest stage, there was probably a mixture between aqueous and aqueous-carbonic fluids, causing calcite deposition that characterizes the carbonatization stage. The Tocantinzinho

deposit is very similar to the Batalha, Palito and São Jorge deposits, and to those of the Cuiú-Cuiú goldfield, but there are also significant differences. Geological, petrographic and chemical data of the Tocantinzinho deposits allow to indicate that it is probably an example of granite intrusion-related depo it within TGP, but a better constrain of its typology requires the dating of the mineralizing event, as well as isotopic and thermodynamic studies on the hydrothermal minerals and physical-chemical investigation of the mineralizing fluids.

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