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ARTICLE

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Gold deposits of the Tapajós and Alta Floresta Domains, Tapajós–Parima orogenic belt, Amazon Craton, Brazil

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Abstract The Tapajós region is one domain of a major Paleoproterozoic orogenic belt, named Tapajós–Parima and is discussed in the context of the evolution of the Amazon Craton. The orogenic belt is composed of a back-arc sequence, four volcano-plutonic arcs, intra-arc sedimentation and is limited to the east by the cratonic rocks of the Central Amazon Province. The evolution and timing of the main events is established by zircon, baddeleyite, and titanite SHRIMP U–Pb geochronology of 29 rock samples, while lead and argon isotopes are used to study the age and source of the gold mineralization. Based on the mesoscopic nature of the orebodies, and, in some cases, on microthermometric and stable isotope data, the Tapajós gold deposits are classified as (1) orogenic and (2) intrusion-related, and may be grouped into four deposit-type categories: (1) orogenic, turbidite-hosted: disseminated and quartz–pyrite veinlet deposits, hosted by metaturbidites (lower greenschist-facies, Jacareacanga Group) and emplaced in ductile structures; (2) orogenic, magmatic arc-hosted: disseminated and pyrite–quartz–carbonate vein deposits, hosted by metamorphic rocks (Cuiú-Cuiú Complex) and formed under a ductile–brittle regime, with the Ouro Roxo deposit as a type example; (3) intrusion-related, epizonal quartz-vein deposits: vertical to subvertical quartz-pyrite veins and pyrite disseminations filling extensional brittle faults; and (4) intrusion-related, epizonal, disseminated/stockwork deposits, the type-example being the Serrinha deposit. Gold mineralization of type 3 is similar to that of Korean-type, while type 4 mineralization shows some similarities to porphyry-type deposits. Galena Pb–Pb and muscovite Ar–Ar data indicate an age of ~1,860 Ma for the intrusion-related gold mineralization. Preliminary Pb isotope data on K-feldspar indicate that the fluid source was more likely to have been from within the Jacareacanga, Cuiú-Cuiú and Tropas units than the Creporizão, Maloquinha, and Iriri units. This study shows the existence of two main types (orogenic and intrusion-related) of gold deposits, which are related to specific tectono-magmatic events that occurred during a limited period of time in the orogenic belt evolution. This information may be useful as a guide for gold exploration along the orogenic belt.

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Introduction

The aim of this paper is to define the geological evolution of the Tapajós gold province and the nature and timing of the associated gold deposits.

Small-scale alluvial mining in the Amazon Craton has been the main source of gold in Brazil during the last three decades. Nilço Pinheiro discovered gold at the mouth of the Tropas River in 1958. This triggered the discovery of several other alluvial gold deposits during the 1960s (e.g. Cuiú-Cuiú, Porto Alegre, Patrocínio, Água Branca and Porto Rico). The Tapajós gold province became the main gold producer in Brazil in the 1970s into the 1990s. About 430 landing airstrips were cleared to support the work of 80,000 miners in a very remote region covered by jungle. The annual gold production during 1975–1990 was in the 60–80 t range, despite the fact that only a small portion of the gold being mined was officially reported by the Departamento Nacional da Produção Mineral.

The impressive gold production attracted the attention of several Brazilian companies. About 20 engineering and transportation companies created new mining subsidiaries to explore the Tapajós gold fields. None achieved success because of the adoption of a poor exploration philosophy that targeted only the alluvial deposits, which are usually high-grade but low tonnage deposits. Following exhaustion of some of the alluvial–eluvial deposits, small-scale mining switched to primary ores, with the discovery of a few hundred lode gold occurrences in the Paleoproterozoic Tapajós–Parima Province, mainly in the Tapajós and Alta Floresta domains. Mining companies have evaluated several deposits (Ouro Roxo, São Jorge, Serrinha, Abacaxis, Limão, Crepori and Castelo dos Sonhos). All these deposits have estimated reserves that vary from 5 to 60 t of gold.

The Brazilian Geological Survey has registered 178 sites of exposed primary ores; 140 in the Tapajós domain and 38 in the Alta Floresta domain. Normally, only the supergene zones above the fresh rock, approximately 15 to 120 m thick, are mined by open pit, although in a few cases, underground mining has been attempted. Underground mining has usually failed because of the lack of adequate investment, inappropriate technology, and excess underground water. Since 1995, several mining companies (e.g. Rio Tinto Zinc, Matapi, Barrick, Golden Star, Western Mining, Pegasus, and New Bullet) have explored the region, always surrounding a known mine site. In some areas, exploration has reached the drilling and deposit evaluation phase, as in the Limão, Ouro Roxo, São Jorge, Jutaí, Castelo dos Sonhos, Abacaxis and Serrinha gold deposits. New data collected from drill cores, combined with fieldwork and new geological and geophysical regional maps produced by the Brazilian Geological Survey (Almeida et al. 2000; Klein and Vasques 2000; Bahia and Quadros 2000), have provided the background information for this study.

Regional tectonic setting

The Tapajós gold province is located in the south-central part of the Amazon Craton (Fig. 1). Numerous structural, geochronological, and metallogenic similarities with the Peixoto de Azevedo (Mato Grosso state) and Parima (Roraima state) gold provinces led Santos et al. (2000) to include the three domains in the same orogenic belt, named the Tapajós–Parima orogenic belt. This belt is 1,900 km long and 180–280 km wide, and includes a fourth domain, named Uaimiri and is mostly covered by the Uaimiri–Atroari Indian Reservation. These four domains (Parima, Uaimiri, Tapajós and Alta Floresta) are separated by sedimentary basins and the K'Mudku mobile belt (Fig. 1). Despite the scarcity of geological data from the Parima and Uaimiri domains, the four domains show the same main features: (1) evolution mainly between 2,030–1,870 Ga (Orosirian Period of the Paleoproterozoic); (2) a prominent north–northwest trend; (3) mainly calc-alkalic, magmatic-arc rocks (with lesser metasedimentary rock sequences); and (4) comparable gold metallogeny.

The belt is bordered to the west by younger Palaeoproterozoic provinces that were accreted to the craton at ~1.85–1.70 Ga (Rio Negro and Rondônia-Juruena provinces). Underthrust rocks from the Tapajós–Parima belt may have been the partial source for the granitoids intruding the younger provinces, as indicated by Sm–Nd data (Santos et al. 2000).

The Tapajós–Parima orogenic belt represents new crust added to the Archean Central Amazon province (Archean) during part of the Palaeoproterozoic (2.10–1.87 Ga) (Santos et al. 2000). Accreted sedimentary rocks and oceanic basalts are present only in the western part of the belt. Calc-alkalic, arc-related granitoids generated mainly during four main magmatic pulses – 2.02, 1.96, 1.90 and 1.88 Ga (Santos et al. 2000; this work) – mainly dominate the orogenic belt. Intracratonic A-type granites of the Maloquinha (1.87 Ga) and Teles Pires (1.78 Ga) suites are intrusive into the rocks of the Tapajós–Parima orogenic belt.

Geology of the Tapajós and Alta Floresta Domains

The stratigraphy of the Tapajós and Alta Floresta Domains is summarized in Table 1. Bizzinella et al. (1981) proposed the subdivision of the basement (Xingu Complex of Santos et al. 1975) into four main units, with distinctive ages, geochemistry and metallogeny: (1) Jacareacanga Group, a metavolcano-sedimentary sequence, (2) Cuiú-Cuiú Complex, composed mainly of tonalite-gneiss and amphibolite, which are metamorphosed to amphibolite facies; (3) Parauari Intrusive Suite, comprising batholiths with irregular shape, ranging from tonalite to syenogranite and dominated by unmetamorphosed monzogranites and granodiorites; and (4) Ingarana Gabbro, representing augite gabbro that intruded the previous two units. Pessoa et al. (1977) considered that the gold mineralization was related to the two granitoid suites above, and that tin and niobium mineralization was associated with the subsequent Maloquinha intrusive suite.

The geologic knowledge of the Alta Floresta Domain is poorer than that of the Tapajós Domain, but four main units are interpreted as the same in both domains. Santos and Reis Neto (1982) integrated the Juruena Granodiorite (Alta Floresta Domain) into the Parauari suite, Moura et al. (1997a) and Valente (1998) recognized most of the Tapajós Domain units in the Alta Floresta Domain: Cuiú-Cuiú Complex, Parauari suite, Iriri Group and Teles Pires suite (Table 1, Fig. 2). Equivalent rocks to the Jacareacanga Group are locally present (Fabinho schist), but not shown in Fig. 2.

To improve the regional stratigraphy in a region lacking isotopic information, 32 mineral samples (zircon, titanite and baddeleyite) were dated by U–Pb to determine the age of all Proterozoic units of the province. SHRIMP investigations were undertaken at Curtin University of Technology, Western Australia, following the procedures of Smith et al. (1998). Other U–Pb and Sm–Nd data used to interpret the regional geology are from Sato and Tassinari (1997) and Santos et al. (2000).

Supracrustal rocks

The Jacareacanga Group is a metamorphosed volcano-sedimentary sequence with a north–northwest structural trend exposed in the westernmost part of the orogenic belt (Figs. 1 and 3). The main metamorphic minerals in the Jacareacanga sequence are sericite in the metasedimentary rocks and actinolite in the metabasalts, indicating greenschist-facies metamorphism. However, in the areas with higher strain, the metamorphic grade reached the biotite zone.

This unit was previously considered to be a greenstone terrain, possibly Archean in age (Bizinella et al. 1981). However, the geometric relationship between the supracrustal rocks and the syntectonic granitoids (Cuiú-Cuiú Complex) does not have the typical granitoid–greenstone dome-and-keel pattern, which is observed in the Trans-Amazonic and Carajás Provinces. Additionally, the volume of preserved basalts is small, leading Santos et al. (2000) to redefine the Jacareacanga Group as more probably an accretionary

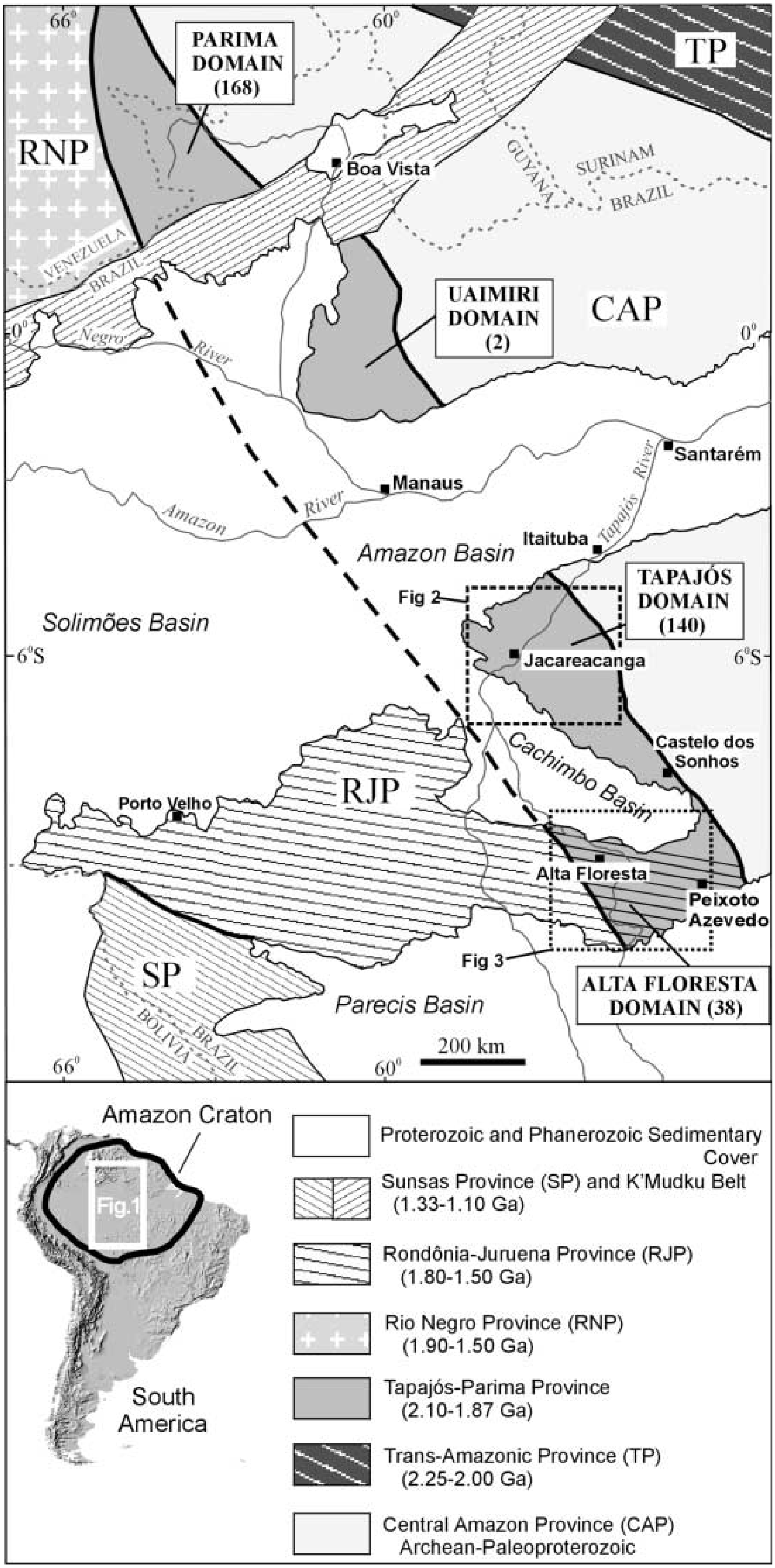


Fig. 1 The four domains of the Tapajós–Parima orogenic belt (*dark gray*). Other provinces of the Amazon Craton adapted from Santos et al. (2000). South America insert indicates location of craton (*black, bold line*) and of this map (*white rectangle*). *Numbers* of gold mines in parentheses for each domain

Table 1 Stratigraphic column and correlations between Tapajós and Alta Floresta domains

Period	Ma	Tapajós domain	Alta Floresta domain	Rocks	Environment
Stenian	1,189	Cachoeira Seca Gabbro		Alkali-gabbros and troctolites	Rifting
Statherian	1,760	Teles Pires Intrusive Suite	Teles Pires Intrusive Suite Teles Pires volcanic group[a]	A_1-type granites: orthoclase granites, rapakivi granites and associated volcanic rocks	Plume-related continental rifting
	1,789	Crepori Dolerite	–	Tholeitic dikes and sills	Continental break-up
Orosirian		Palmares Group	Beneficente Group	Continental sedimentation	Continental rifting
	1,870	Maloquinha Intrusive Suite	Maloquinha Intrusive Suite	A_2-type granites: orthoclase granites,	Post-collisional, underplating
	1,870	Iriri Group	Iriri Group	syenogranites, granophyres and related volcanic rocks	magmatism
	1,880	Parauari Suite	Juruena Granodiorite, Matupá Granite	Bimodal monzogranite–gabbro/anorthosite suite	Magmatic arc 4
		Abacaxis and Sequeiro Formations	–	Quartz wacke, siltstone and wacke	Intra-arc sedimentation
	1,898	Tropas Suite	Juruena Granodiorite	Tonalites, meta-andesites	Magmatic arc 3
	1,960	Creporizão Suite	Xingu Complex	Monzogranites	Magmatic arc 2
	2,010	Cuiú-Cuiú Complex		Tonalites, meta-andesites, metabasalts	Magmatic arc 1
Riacian	2,000/2,100	Jacareacanga Group	Fabinho schista[a]	Metaturbidites, metachert, BIF, metabasalt	Back-arc sedimentation and oceanic magmatism

[a] Informal name

sequence. The main lithostratigraphic units are: (1) metamorphosed oceanic basalts, more common in exposures in the western part of the group and interpreted as the lower sequence; (2) an upper metamorphosed turbiditic unit that crops out to the east; and (3) a metamorphosed chemical sedimentary unit, interlayered with turbidites, composed of massive to laminated chert and subordinate layers of banded iron formation. The small area of exposed accretionary sequences and the scarcity of oceanic basalts may be explained in two ways: (1) this group of rocks may be located to the northwest and west, beneath the Amazon and Cachimbo basins or, (2) a subsequent rifting event has removed the western part of the belt.

The Sai-Cinza metaturbidite has a clastic zircon population with ages in the 2,125–2,098 Ma range. These zircons are interpreted to be derived from early magmatic rocks formed in a back-arc environment, and constrain the maximum age of both the Jacareacanga Group and the orogenic belt.

Magmatic arcs

Two granitoid units, the Cuiú-Cuiú Complex and Parauari Intrusive suits, have been well recognized in the area since the 1970s (Pessoa et al. 1977; Bizzinella et al. 1981; Coutinho et al. 1998). The Parauari granitoids are intrusive into the Cuiú-Cuiú Complex. A third granitoid suite, Creporizão, was proposed by Ricci et al. (1999) to group protomylonitic granitoids with stratigraphic position intermediate between the Cuiú-Cuiú and Parauari units. The present U–Pb data and the data from Brito et al. (1999) show that the rocks related to the Parauari arc group into two distinct age clusters, which favours the Parauari Suite subdivision into the Parauari and Tropas Suites. The granitoid suites are the products of distinct magmatic arcs, migrating from west to east.

The ages of the four magmatic arcs do not overlap, indicating that there were long periods with minor or no magmatic activity. The ages within the older arc range from 2,033 ± 7 Ma (Cuiú-Cuiú type-area) to 1,995 ± 12 Ma (Jamaxim River). The Cuiú-Cuiú arc consists mainly of large, syn-tectonic, calc-alkaline tonalite bodies and associated tholeiitic metabasalts and meta-andesites (amphibolites). The metamorphic grade of the Cuiú-Cuiú Complex (first magmatic arc) is better determined from the associated metabasalts and meta-andesites, rather than from the granitoids. Metavolcanic rocks are composed mainly of hornblende–andesine–epidote, an assemblage diagnostic of amphibolite-facies regional metamorphism.

The batholiths are elongated north–northwest to northwest (Fig. 3) and commonly have prominent metamorphic banding parallel to the foliation of the Jacareacanga Group rocks. However, banding is not a definitive criterion to distinguish the Cuiú-Cuiú rocks from the younger magmatic arc rocks because it is lacking in some batholiths, such as the Jamaxim River (1,995 Ma) and Porquinho do Amana (2,020 Ma) batholiths.

The Creporizão Arc is composed of late-tectonic, calc-alkaline monzogranite and granodiorite plutons and related metamorphosed andesites and basalts that intrude the Cuiú-Cuiú granitoids. Creporizão Suite granitoids are protomylonitic and may locally be metamorphosed to lower amphibolite facies.

Creporizão andesitic and basaltic xenoliths are common within the Creporizão and Tropas granitoids. The intermediate-age arc (Creporizão) was generated from 1,974 ± 6 to 1,957 ± 6 Ma according to zircon U–Pb data. The Creporizão granitoids have been only recently identified (Ricci et al. 1999) and are not yet discriminated from Parauari granitoids on geological maps. The ages of the youngest arc (Parauari) indicate two clusters, with one made at 1,898 Ma (lower Tropas River, Ouro Roxo and São Jorge) and the other at 1,880 Ma (Rosa-de-Maio, Parauari type-area, Penedo, Caroçal, Uruá). The Parauari name is maintained for the younger group (1,880 Ma), which includes the Parauari Suite type-area (Rosa de Maio gold deposit). The name Tropas River is introduced to distinguish the older rocks, which are well exposed in the lower Tropas River channel.

These rocks were previously considered to be metamorphosed (Bizzinella et al. 1981; Faraco et al. 1996) and related to the Cuiú-Cuiú Complex, but the chemical composition of the biotites (Santos et al. 1997), particularly their high FeO/MgO ratios, indicates an igneous, not metamorphic, nature (Gokhale 1968; Nashit

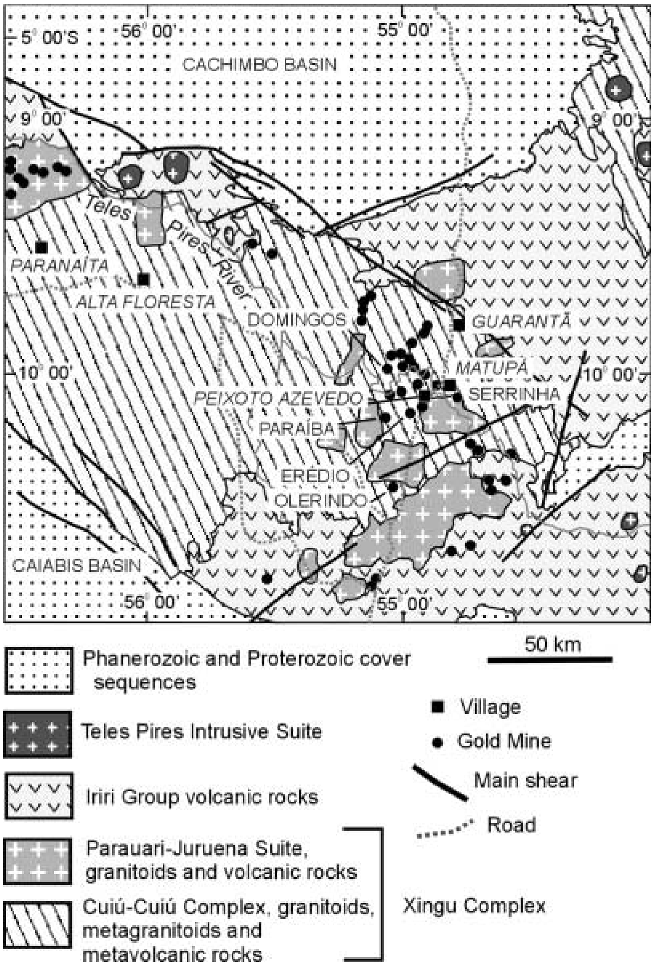


Fig. 2 Simplified geological map of the Alta Floresta Domain (modified from Moura et al. 1997a; Valente 1998) shows the location of Serrinha gold deposit and most of the other gold mines in the region

et al. 1985). The Tropas granitoids commonly enclose xenoliths of basalt and andesite, which are derived from the older Cuiú-Cuiú and Creporizão magmatic arcs. The calc-alkalic, felsic volcanic rocks related to the Tropas magmatism have a U–Pb age of 1,895 ± 7 Ma, obtained on sample JO-170 zircons.

Two intra-arc sedimentary formations (Sequeiro and Abacaxis), consisting mostly of siltstone and quartz-wacke, have clastic zircons from Tropas arc rocks with ages of between 1,909 and 1,895 Ma. They are intruded by the Parauari granitoids (sample DG2, 1,884 Ma). These units only have a local distribution in the Abacaxis and Maués mines and are not shown in Fig. 3. Inherited zircons with ages that correlate with the older granitoid suite are common, indicating that the partial melting of the older suites provided a source for the younger.

The Parauari Arc includes calc-alkalic, late-to post-tectonic gabbro (Ingarana), anorthosite (Jutaí) and monzogranite, with associated felsic volcanic rocks.

Almost all inherited ages (96 results, Table 2) from Cuiú-Cuiú, Creporizão, Tropas and Parauari magmatic arc rocks are Paleoproterozoic, only 20–140 million years older than the magmatic ages. This indicates that the Archean crust contribution to the arc generation was minimal or absent. The Sm–Nd data also indicate a juvenile nature for the granitoid suites above, having 'Trans-Amazonian' model ages in the 2,264–2,104 Ma range and ϵ_{Nd} (T = 2.01; 1.97 and 1.89 Ga) that is positive or slightly negative (–2.38 to + 1.83; Santos et al. 2000).

Post-collisional magmatism

Several units were formed under extensional, intracratonic conditions and are unmetamorphosed. These were affected only by brittle deformation (Table 3), enclosing the Uatumã Supergroup (~1.87 Ga), Palmares Group (> 1.79 and < 1.89 Ga), Crepori Diabase (1.79 Ga), Teles Pires Granite (1.76 Ga), Cachoeira Seca Troctolite (1.19 Ga), Piranhas Dolerite (0.51 Ga) and Cururu Diabase (0.18 Ga).

The Uatumã Supergroup includes the Iriri Group (felsic volcanic rocks, andesites, latites, tuffs and agglomerates) and the Maloquinha Intrusive Suite (orthoclase granites, alaskites, syenogranites, granophyres, quartz-syenites, hastingsite granites and riebeckite granites). The granitoids are A-type, peraluminous to alkaline, F-, Y-, and Nb-rich, and were emplaced at shallow depths of about 4–6 km. The more precise age for the A-type granites is 1,870 ± 4 Ma (type area of Maloquinha Granite, sample MA-32). The volcanic rocks associated with the Maloquinha plutonism have an age of 1,870 ± 8 Ma (Iriri Group, MM-36).

The more evolved monzogranites and syenogranites from the Parauari arc may have macroscopic similarities to the younger A-type Maloquinha granites.

The cratonic assemblage

Granites of the Maloquinha Suite show evidence for an origin related to the partial melt of an Archean continental source, as indicated by a population of inherited zircons with an age of 2,679 ± 10 Ma determined for sample MA32 (Table 2), and by Sm–Nd data. These granites have Archean Sm–Nd model ages (2,535–2,850 Ma) and ϵ_{Nd} (T = 1,870 Ma) as low as – 12.40 (Santos et al. 2000).

Andesites cutting Maloquinha Suite granitoids, and named Carapuça (Pessoa et al. 1977), are strongly altered by gold mineralizing fluids (as in the Mamoal and Joel mines). They have lamprophyric characteristics and were emplaced ~1,870 Ma on the basis of cross-cutting relationships (Klein and Vasquez 2000).

Structural evolution

The belts defined by rocks of the Jacareacanga Group show prominent metamorphic foliation along a north–north-west trend with a steep dip to the south–south-west. The primary bedding is subparallel to the foliation, suggesting strong transposition ($S_{0\text{-}m}$) along the sequence. The major structural feature within rocks of the Jacareacanga Group is interpreted as a succession of regional isoclinal folds, with axes trending parallel to the north–northwest foliation. The older granitoids of the Cuiú-Cuiú Complex show a similar style of deformation and the same regional trend, suggesting that both units were deformed under the same compressional regime with displacement towards ~070°. This early deformation did not affect the magmatic arc rocks of the Creporizão Suite (1,965 ± 9– to 1,974 ± 6 Ma, this work), indicating that the deformation is older than 1,974 ± 6 Ma (magmatic zircons U–Pb age) and younger than, or contemporaneous with the 2,005 ± 7 Ma magmatic zircon U–Pb age of the Cuiú-Cuiú Complex (this work). The early-stage deformation (D_1) may have been synchronous with the metamorphic peak because the metamorphic minerals biotite and hornblende are oriented along S_1. The whole rock Rb–Sr age (2,002 ± 18 Ma, Santos, unpublished data) for the Sai-Cinza metaturbidite probably reflects the resetting of the Rb–Sr system during metamorphism.

Santos (1997) reported a north–south, vertical transcurrent sinistral system that cuts D_1 features at the Maués gold deposit. This D_2 deformation may be the same as that which produced the > 1.9 Ga Ouro Roxo-Cantagalo shear zone in the Pacu gold district (Almeida et al. 2000; this work; Jacobi 2000). This shear zone has a northeast (10°E, dipping 75°SE) orientation, ductile–brittle nature, and is dominated by a transcurrent sinistral component. The D_2 deformation affected the 1,894 ± 3 Ma tonalite (Tropas Suite) at the Ouro Roxo deposit, but younger rocks that include

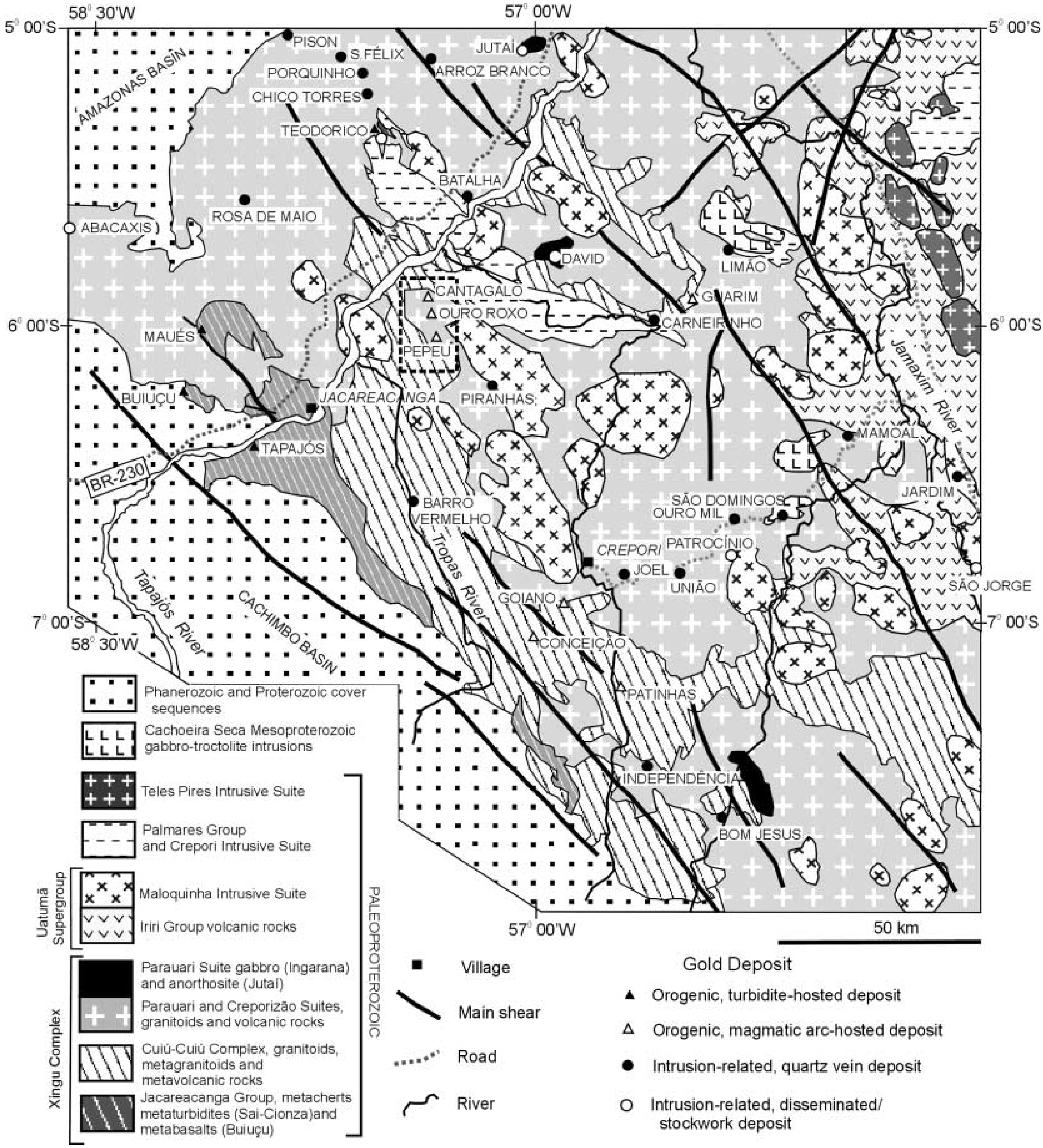


Fig. 3 Simplified geological map of the Tapajós Domain with location of most gold deposits mentioned in text and tables (modified from Faraco et al. 1996). Pacu district is *dashed rectangle* (Fig. 4)

banding-foliation and pluton-related brittle faulting. Most of the brittle deformation of the Creporizão and Parauari granitoids may have originated during the shallow intrusion of the younger, Maloquinha granitoids (Santos et al. 2000).

plutons of the Parauari suite (VP-24, 1,883 ± 4 Ma; Almeida et al. 2000) are not affected.

Deformation that is younger than D_2 is dominantly brittle. The Parauari (1.89 Ga) and Creporizão (1.97 Ga) granitoids are only locally affected by D_2. However, they commonly show magmatic

Synthesis

The combination of geochronological studies with fieldwork now allows a unified synthesis of the timing of the geological events (Fig. 4).

Table 2 Summary of the geochronological data of the main rock units in the Tapajós domain

Tectonic setting	Rock unit	Rock	[a]	Sample	Minerals[b]	U–Pb[c] Inherited age	U–Pb[c] Magmatic age	K–Ar (K) and Rb–Sr (R)
Mesozoic rifting	Cururu	Dolerite						179 ± 3[5]–K 148 ± 6[5]–K
Cambrian rifting	Piranhas	Dolerite		MP-10	B–Z	1,207 ± 16 to 2,238 ± 15 (6Z)	514 ± 14 (9)	
Sunsas rifting	Cachoeira Seca	Troctolite		MP-103	B		1,099 ± 28 (6)	1,043 ± 27[2]–K
Cratonic Volcano-plutonism II	Teles Pires	Granite		CC-21	Z		1,760 ± 12 (14)	
	Crepori	Dolerite		SD-45	B		1,782 ± 9 (12)	
		Gabbro		RO-98	P			1,694 ± 28[2]–K
		Gabbro		FB-355	P			1,365 ± 72[2]–K
Platform cover	Palmares	Subarkose		AL-9b	Z	1,879 ± 12 (10) 1,972 ± 13 (9) 2,029 ± 9 (1) 2,054 ± 14 (1)		
Cratonic Volcano-plutonism I	Maloquinha	Granites						1,770 ± 24 (15)[3]–R 1,732 ± 82 (8)[5]–R 1,650 ± 20[5]–R
		Granophyre		JO-169	Z	1,993 ± 9 (8)	1,864 ± 18 (7)	
		Alaskite	X	JO-3	Z	1,899 ± 25 (3)	1,877 ± 12 (5)	
		Alaskite	X	BV-1	Z	1,900 ± 18 (4) 2,207 ± 8 (1)	1,871 ± 8 (7)	
		Monzogranite	X	JO-199	Z	1,993 ± 18 (4)	1,874 ± 7 (19)	
		Monzogranite				2,223 ± 12 (2) 2459 ± 11 (4)[1]		
				MA-32	Z	1,999 ± 8 (2) 2,679 ± 10 (5)	1,870 ± 4 (12)	
	Iriri	Volcanic rocks						1,765 ± 16[5]–R
		Rhyodacite	X	MM-36	Z	1,996 ± 7 (1)	1,870 ± 8 (17)	
Magmatic arc IV	Ingarana	Anorthosite		JO-184	T		1,878 ± 8 (25)	
		Gabbro	X	JO-69	B–Z	2,007 ± 6 (1)	1,879 ± 3 (10) 1,873 ± 10 (15)	
	Matupá	Granite	X	MM-X	Z		1,870 ± 12	
	Parauari	Syenogranite	X	VP-24	Z		1,883 ± 4 (15)	
			X	JO-54	Z		1,880 ± 14 (4)[1]	
Intra-arc sedimentation	Abacaxis	Siltstone	X	JO-57	Z	1,895[1], 1,899[1] 1,902[1], 1,909[1]		
	Sequeiro	Quartz-wacke	X	JO-68	Z	1,895[1], 1,898[1] 1,901[1], 2,065[1]		
Magmatic arc III	Tropas	Tuff (rhyolitic)		JO-170	Z	1,977 ± 10 (2)	1,895 ± 7 (14)	
		Meta-andesite	X	JO-101	Z	1,972 ± 15 (3)	1,898 ± 5 (12)	
		Tonalite		JO-102	Z	2,009 ± 6 (2)[1]	1,894 ± 2 (3)[1]	
Magmatic arc II	Creporizão			JO-180	Z		1,957 ± 6 (12)	
		Monzogranite		JO-175	Z	2,006 ± 11 (4)	1,970 ± 12 (9)	
		Microtonalite	X	F21	Z		1,974 ± 6 (12)	
Magmatic arc I	Cuiú-Cuiú							1,800 ± 43[5]
		Granodiorite	X	MQ-102	Z		2,033 ± 7 (8)	
		Quartz diorite	X	JO-190	Z	2,040 ± 4 (2)	2,016 ± 5 (10)	
				JO-173	Z	2,046 ± 5 (1)	2,015 ± 9 (12)	

		Tonalite	X	JO-51	Z		2,011 ± 23 (4)[1]
			X	MA-44	Z		2,005 ± 7 (13)
Back-arc sequence	Jacareacanga	Meta-turbidite		JO-59	Z	2,098[1], 2,106[1] 2,125[1], 2,875[1]	

[a] Gold mineralization host rocks are indicated by an X
[b] B, Baddeleyite; P, plagioclase; T, titanite; Z, zircon
[c] All data from U–Pb SHRIMP, except when marked with superscript 1: conventional U–Pb from Santos et al. (1997). Numbers of analysis between brackets. All ages in Ma. Rb–Sr ages are whole-rock reference isochrons
[d] References: *1* Santos et al. (1997); *2* Pessoa et al. (1977); *3* Santos and Reis Neto (1982); *4* Basei (1975); *5* Tassinari (1997)

The Paleoproterozoic Tapajós–Parima orogenic belt was formed at ~2.10–1.87 Ga and is partly younger than the more extensive Transamazonian orogenic belt recognized throughout northern South America (2.25–2.00 Ga). Five successive granitoid events occurred during the Tapajós–Parima orogeny. The initial four formed distinct subduction-related magmatic arcs, whereas the youngest is associated with the partial melting of Archean crust of the Amazon Craton. Intracratonic magmatic activity, associated with crustal rifting, is identified at 1.76 Ga (rapakivi granites and tholeiitic intrusions), 1.18 Ga (alkali-basalts), 0.51 and 0.18 Ga (dolerite dike swarms).

Gold deposits

Background

The Tapajós–Parima orogenic belt includes the largest number of individual gold mines in Brazil. In the Parima gold domain, the mining activity lasted only 5 years (1988–1993), but, during this time, 168 alluvial and colluvial mines were active. Some of the mines are located inside the Ianomâmi Indian Reservation so the Brazilian government closed these in 1993. Alluvial gold was reported by Santos et al. (1974) in the Uaimiri domain, another region partially inside the large Uaimiri–Atroari Indian Reservation. Only one gold mine is now active in this domain (Anauá mine). Because of limited data, gold deposits in these two northern domains are not discussed in this paper.

All available data from primary deposits are from the southernmost gold domains, Tapajós and Alta Floresta, where 178 lode gold deposits are registered; mining companies have recently evaluated some of these gold deposits as large tonnage resources.

Types of gold deposits

An appraisal of the available data from the 178 gold deposits suggests that there are two main categories of lode gold deposits in the region. Table 4 presents the main geological attributes of 33 gold deposits, selected because more data are available for these than for other deposits. This partially reflects the fact that many of these are the larger and more important deposits discovered to date. Obviously, many of these deposits still lack precise information on ore composition, alteration mineralogy, extent of alteration haloes, ore grade, and elemental association, and this prevents classification of all deposits throughout the two domains. The ore grade and resource are only know for the Ouro Roxo (1 Moz @ 9.28 g/t Au) and São Jorge (2 Moz @ 2.4 g/t Au) deposits (Jacobi 2000).

The gold deposits of the Tapajós region belong to three main types: (1) mesozonal orogenic deposits (Groves et al. 1998), (2) epizonal, intrusion-centered (Sillitoe 1991) or intrusion-related (Sillitoe and Thompson 1998) and (3) palaeoplacers (Table 4). Based on the mesoscopic nature of the orebodies, structural control, and, in some cases, microthermometric and stable

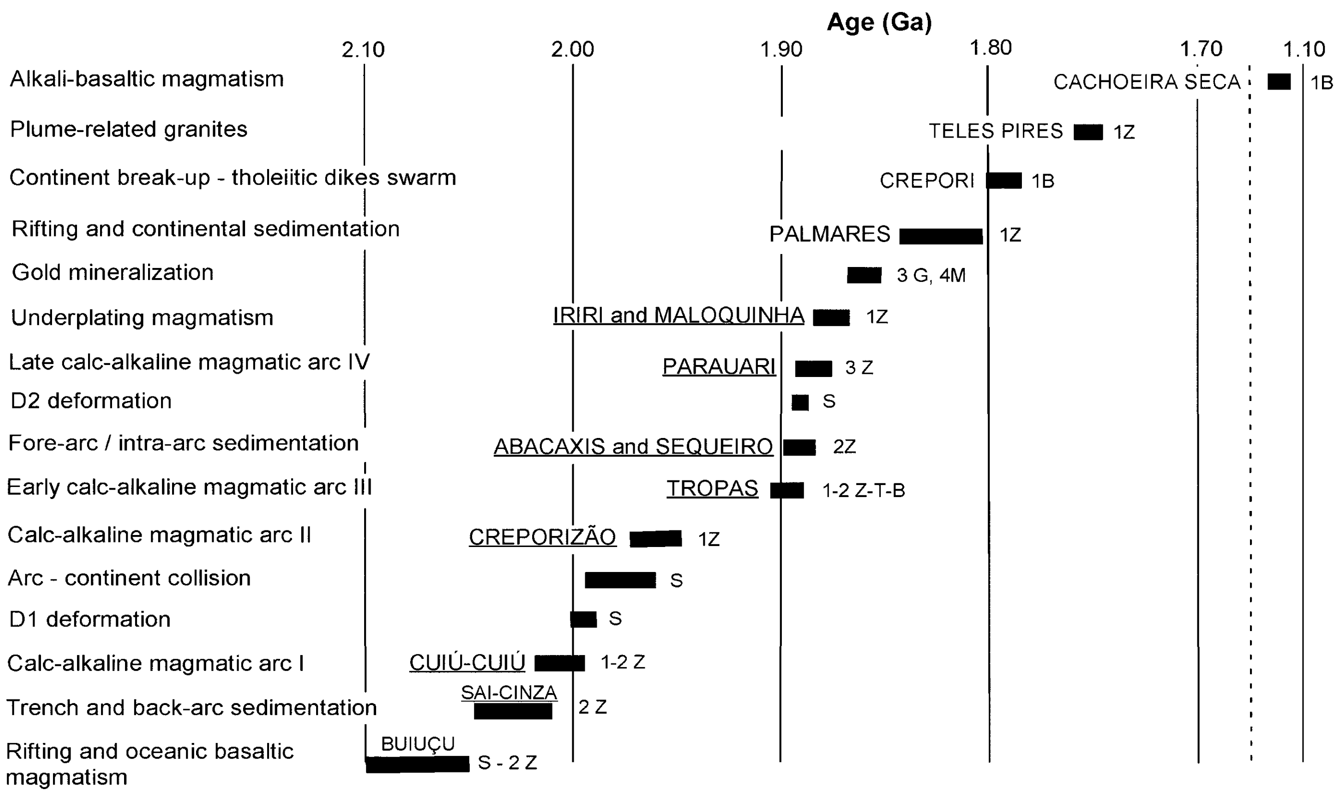
Table 3 Summary of the characteristics of rock-units post-dating the gold mineralization in the Tapajós and Alta Floresta domains

Stratigraphic unit	Structure	Age (Ma)[a]	Common features
Cururu Diabase	Dike of tholeiitic gabbro-diabase	± 180	Continental rocks, with no metamorphism and affected only by brittle shear
Piranhas Diabase	Dike swarm of tholeiitic gabbro-diabase	514 ± 15	
Cachoeira Seca Troctolite	Lacoliths and dikes of alkalic gabbro-troctolite	1,192 ± 13	
Crepori Diabase	Sills and dikes of tholeiitic gabbro-diabase and differentiated rocks (monzonite, granophyre, diorite)	1,778 ± 9	
Teles Pires Intrusive Suite	Stocks of A-type perthite granite, granophyre and rapakivi granite	1,783 ± 20	
Palmares Group	Synclines of fluvial braided and alluvial fan sedimentary rocks: quartz-sandstone, subarkose, red shale and conglomerate	1,879 ± 12[b]	

[a]All ages are SHRIMP U–Pb on zircon and baddeleyite, except for Cururu Diabase (K–Ar)
[b]Age of the youngest clastic zircon population

isotope data, the lode gold deposits can be classified as (1) mesozonal and (2) intrusion-related as described in Table 5. The orogenic gold deposits occur mainly in the western and south-western zones of the orogenic belt, whereas the intrusion-related deposits are dominant in the northern, eastern, and southeastern areas (Fig. 3). Two gold deposits, Ouro Roxo and Serrinha, are selected for description as examples of the two major types recognized in the region: mesozonal are magmatic arc-hosted and epizonal are intrusion-centred. Data for other deposits are limited and only a preliminary description of some of these is possible (Table 4).

Fig. 4 Evolution of the Tapajós–Parima Province based on geochronology: *1* SHRIMP U–Pb; *2* conventional U–Pb; *3* Pb–Pb; *4* Ar–Ar. *Z* zircon; *B* baddeleyite; *T* titanite; *G* galena; *M* muscovite; *S* interpreted age. Sai-Cinza and Buiuçu are informal names used in the Jacareacanga Group



Orogenic, turbidite-hosted deposits

Many of these deposits occur as disseminated gold or as auriferous quartz–pyrite veinlets, hosted by lower greenschist facies metaturbidites and metabasalts of the Jacarecanga Group. These deposits formed in ductile

Table 4 Summary of the characteristics of the most important primary gold deposits in the Tapajós and Alta Floresta domains

Gold deposit[a]	Host rock/unit[b]	Form	Metallic minerals[c]	Alteration[d]	Geochemical association[e]	Strike of host-rock	Ore spatial position	Reference[f]
Orogenic, turbidite-hosted deposits								
Buiuçu	Schist/J	Quartz veins	Py	Chl, ser	Au	N50°W/80°	N30°W/80°	4
Tapajós	Schist, metachert/J	Quartz veins	Py		Au	N70°W/47°	N70°W	4
Maués	Sericite schist/J	Quartz veins		Ser	Au	N20°W/80° and N–S vertical foliation	N20°W	1
Teodorico II	Talc-chlorite schist/J	Quartz veins	Py	Chl, ser	Au	N40°W/75°		
Domingos-AF	Talc-chlorite schist/J	Quartz veins	Py	Ser	Au (Cu)	N60°W		
Orogenic, magmatic-arc-hosted deposits								
Goiano	Granodiorite/CC	Eight quartz veins	Py		Au	N60°W	N50°E/90° N–S/90°	1,2
Patinhas	Granodiorite/CC	Quartz vein	**Py**, cpy	Epid, kaol	Au (Cu)	NW	N20°–30°E	6
Erédio-AF	Gneiss	Quartz vein	**Py**, cpy		Au (Cu)		N20°E/80°	
Ouro Roxo/Cantagalo	Metandesite, tonalite/CC-P	Dissemination in meta-andesite; quartz-pyrite and pyrite veins	**Py**	Ser, chl, car	Au (Cu)	N10–20°E/65–75°SE	N10–30°E/35°SE	1
Pepeu/Cantagalo	Metabasalt?/CC	Dissemination in mafic fragments; quartz veins	**Py**, cpy		Au (Cu)	N10°W/50°	N10°W/80°	1,2
Guarim (Cuiú-Cuiú)	Granitoid/CC	Quartz vein, hydrothermal breccia	Py, **cpy**, **bn**	Ser, chl, car	Au (Cu)	N20°E	N75°E/75°	5
Conceição	Metandesite, tonalite/CC	Quartz vein, dissemination in mafic enclaves		Ser, chl, car	Au	N40°W/55°	N55°E/75°	1
Intrusion-related, quartz-vein deposits								
Sequeiro/Maués	Quartz-wacke/S	Quartz veins	*Py*		Au			1
Chico Torres	Granodiorite/P	Quartz vein	*Py*	Ser, epid	Au		N6°W/68°	4
Patrocínio (Malaquias)	Protomylonite/CR	Quartz veins with 3–10% pyrite	**Py** (Gn, sl, apy)	Ser	Au		N40–50°E, subvertical	3
David/Bom Jardim	Gabbro/monzodiorite/I	Quartz vein	**Py, cpy, gn**, sl, bn	Alb, car, ser	Au (Cu, Pb, Zn)		N55°W/90°	1,4
Pista Nova (Morro João)	Monzogranite, acid volcanic rocks/P	Quartz veinlets and quartz-kaolinite stockwork	Py	Ser, chl	Au, Pb, Co, Cu and As	N45°–50°W cataclasites	N45°–50°W	3
Bom Jesus	Monzogranite/P	Three parallel quartz veins	Py, cpy, gn	Ser, feld	Au		E-W	2
Pison	Granophyre, tuff, acid volcanic/IR	Stockwork and quartz veins	**Py, sl, ccs,** bn	Kaol, ser, car	Au (Cu, Zn)		E-W/90°, N70°W/90°, N65°W/73°	1,2
Batalha	Syenogranite/M	Quatrz vein, stockwork	**Py, cpy, gn,** po, apy, bn	Ser, epid, alb	Au (Cu, Pb, As)		N45°W/70°, N60°W/90°	4
Limão	Syenogranite/M	Dissemination and mas-sive sulphide (30% py)	**Py, (cpy)**	Feld, ser, (car)	Au (Cu, Bi, Ag, Co)	N40°W	E–W	3

Table 4 Continued

Gold deposit[a]	Host rock/unit[b]	Form	Metallic minerals[c]	Alteration[d]	Geochemical association[e]	Strike of host-rock	Ore spatial position	Reference[f]
Porquinho	Monzogranite/CC	Quartz vein	**Py**, cpy, apy	Sil, epid	Au (Cu, As)		N40°W/90°	4
Mamoal	Andesite	Dissemination in mafic dike			Au (Pb)			1
Joel/Creporizão	Andesite	Dissemination in mafic dike		Ser, epid, adul	Au			1
Ouro Mil/Creporizão	Andesite?	Dissemination and stockwork in mafic dike			Au	N70°E		
Intrusion-related, disseminated-stockwork deposits								
Serrinha-AF	Monzogranite/Ju	Dissemination	Py	Ser, alb, chl	Au (Cu, Mo, Ag)			7
Patrocínio (Alcântara)	Monzogranite/P	Dissemination in 6–15 m thick K-feldspar rich zones, with 1–15% pyrite	**Py**, apy	Chl, ser and (car)	Au			3
Paraíba-AF	Granodiorite/P	Dissemination in mafic dike	Py, cpy	Car, ser	Au (Cu)		N10–30°W/90°	
Teodorico I	Gabbro/I	Dissemination, contact veinlets	Py	Sil, car	Au	N60°W/40°	N60°W/40°	4
Jutaí	Mt-gabbro/I	Dissemination and small veins	Py, mt	Chl	Au (Fe)			1,2
São Jorge	Monzogranite/P	Dissemination and stockwork	Py, cpy	Ser, chl, car	Au (Cu)			
Abacaxis	Siltstone, grd/A-P	Dissemination, quartz veins	**Py**, po	Ser	Au	NNW bedding, subvertical	NW dipping 45°NE; NS, 60°E	1,2
Palaeoplacer deposit								
Castelo dos Sonhos	Quartzite, metaconglomerate/U	Dissemination in conglomeratic quartzite and polymictic metaconglomerate	**Free gold**, gold inclusions in quartz (**hm**, py, cpy, po, tetraedrite)	Incipient ser	Au	NNW to NE bed-ding, dipping 14–35° to SE and SW. N30–65°E subvertical foliation	NNW to NE, dipping 14 to 35° to SE and SW	3

[a] Gold deposits shown in Fig. 3; AF-gold deposits located in Alta Floresta domain, shown in Fig. 2
[b] *J* Jacareacanga Group; *CC* Cuiú-Cuiú Complex; *CR* Creporizão Intrusive Suite; *A* Abacaxis Formation; *S* Sequeiro Formation; *T* Tropas Intrusive Suite; *P* Parauari Intrusive Suite; *Ju* Juruena Granodiorite; *I* Ingarana Gabbro; *IR* Iriri Group; *M* Maloquinha Intrusive Suite; *U* unknown
[c] *Py* Pyrite; *cpy* chalcopyrite; *bn* bornite; *gn* galena; *sl* sphalerite; *apy* arsenopyrite; *ccs* chalcosite; *po* pyrrhotite; *mt* magnetite. Predominant phases are in bold
[d] Alteration minerals: *Adul* adularization; *car* carbonatization; *chl* chloritization; *epid* epidotization; *feld* feldspathization; *kaol* kaolinization; *ser* sericitization; *sil* silicification
[e] Economic commodity listed first; those in parentheses are metal anomalies
[f] References: *1* this work *2* Santos (*1997*); *3* Araneda et al. (*1998*); *4* Almeida et al. (*1999*); *5* Klein and Vasques (*2000*); *6* Bahia and Quadros (*2000*); *7* Moura e al. (*1997b*)

Table 5 Comparison between intrusion-related and orogenic gold deposits in the Tapajós and Alta Floresta domains

	Intrusion-related	Orogenic
Structure	Secondary, vertical to subvertical brittle shears related to granitoid intrusions	Secondary, subvertical to gently-dipping ductile and brittle-ductile shears associated with regional shear systems
Host rock metamorphism	Absence of regional metamorphism	Amphibolite, greenschist facies or no metamorphism
Sulfides	Galena is common as a trace sulfide	Galena is very rare
Alteration minerals	Fe-carbonate (ankerite) is rare. Presence of adularia, calcite and fluorite in some deposits	Chlorite and carbonate are common. Absence of calcite, adularia and fluorite
Geochemical association	Au (Cu, Mo, Pb, Zn, Ag, As)	Au (Cu, As)
Fluids[a]	Low to high salinity, CO_2 very poor or CO_2 absent fluids, trapped under 240–320 °C (David) and 220–340 °C (Joel) and at < 1,500 m depth	Low- to moderate-salinity, aqueous-carbonic mineralizing fluids, trapped between 300–380 °C at > 2,500 m depth (Patinhas)

[a]Based on a few examples: Intrusion-related data from Dreher et al. (1998), Moura et al. (1997b) and orogenic data from Klein and Vasques (2000)

structures and the deposits are restricted to the westernmost part of the region: examples include the Buiuçu, Tapajós, Maués, Teodorico and Domingos gold deposits (Table 4, Fig. 3). According to Santos (1997), veinlets and disseminated ore zones at the Maués (or Espírito Santo) mine were generated during a period of transpression (N20°W). Orebodies were subsequently reworked by another episode of ductile deformation, which involved sinistral strike-slip movement (N–S/90°). These gold deposits may correspond to the type 15 of Robert et al. (1997): turbidite-hosted gold deposits in slate belts. The ductile tectonic regime and the metamorphic grade (lower greenschist to lower amphibolite facies) of the host rocks suggest that these deposits in the rocks of the Jacareacanga Group are the deepest gold deposits formed in the Tapajós and Alta Floresta domains.

Orogenic, magmatic arc-hosted deposits

Orogenic gold deposits, occurring as disseminated ores and pyrite–quartz–carbonate veins are hosted by metamorphic rocks (Cuiú-Cuiú Complex) and granitoids (Tropas Suite and Cuiú-Cuiú Complex). These lode deposits typically formed under a ductile–brittle regime in the western, southwestern, and southern areas of the orogenic belt, and include the Ouro Roxo, Cantagalo, Pepeu, São Jorge, Erédio, Patinhas, Goiano and Conceição deposits. The regional host rocks are foliated or banded granodiorite, quartz diorite and monzogranite of the Tropas Suite and Cuiú-Cuiú Complex. The main mineralization is disseminated in mafic xenoliths and roof pendants of meta-andesite and metabasalt and in sheared granitoids. In addition, the veins are concentrated in the mafic xenoliths, and along their contacts, although a few quartz–pyrite vein deposits also cut the granitoids distal to xenoliths (e.g. São Jorge and Guarim deposits; Klein et al. 1999a). Pyrite-rich quartz and pyrite-only veins are common, chalcopyrite is ubiquitous in small amounts, but other sulfide minerals are rare. The main alteration minerals are sericite and carbonate in the intrusive rocks, and pyrite, chlorite, epidote, albite and leucoxene in mafic xenoliths. The sericite–carbonate hydrothermal alteration halo is as broad as 22 m at the Ouro Roxo deposit (drill hole 21) and overprints the biotite- and amphibole-bearing metamorphic assemblage.

The lodes are in secondary shear zones in the rocks of the Cuiú-Cuiú Complex and Tropas Suite. They are mainly steeply-dipping strike-slip faults, connected to major, regional NNW–SSE (Guarim, Conceição, Goiano) and N10–20°E (Ouro Roxo, Pepeu, Cantagalo, Patinhas) striking reverse-sinistral shear systems. The gold-bearing pyrite–quartz veins and pyrite–gold disseminations occur along steeply-dipping (65–75°) to gently-dipping structures (35°), and are rarely vertical or subvertical.

Fluid inclusions studies of quartz veins in the Patinhas lode indicate low to moderate salinity, aqueous-carbonic mineralizing fluids, trapped between 300–380 °C and 1.5–4.8 kbar (Klein et al. 1999b). At the Guarim Goldmine (Cuiú-Cuiú village region), the estimated P–T conditions are 260–300 °C and 1.25–3.9 kbar (Klein et al. 1999a). These data provide evidence for deposition of the gold mineralization under lower epizonal to upper mesozonal crustal levels (4–10 km), which are consistent with many orogenic gold systems. Supporting evidence is provided by the Guarim gold deposit, which has characteristics of emplacement (Klein et al. 1999a) intermediate between those of orogenic and intrusion-related deposits.

The Ouro Roxo gold deposit

Located in the Pacu district, in the west-central part of the Tapajós domain, the Ouro Roxo deposit is the best studied orogenic gold deposit of the Tapajós–Parima orogenic belt. The Pacu district (Fig. 5) contains several gold mines (Ouro Roxo, Centrinho, Pepeu, Araújo, Samaúma, Matraca, Nova Brasília and Cantagalo), where the geology is dominated by a granodiorite-, tonalite- and quartz diorite-bearing batholith of the Tropas Intrusive Suite. This intrusive complex, named the Tropas batholith, is N–S elongated and approximately 40 km long. To the southeast and northeast, it

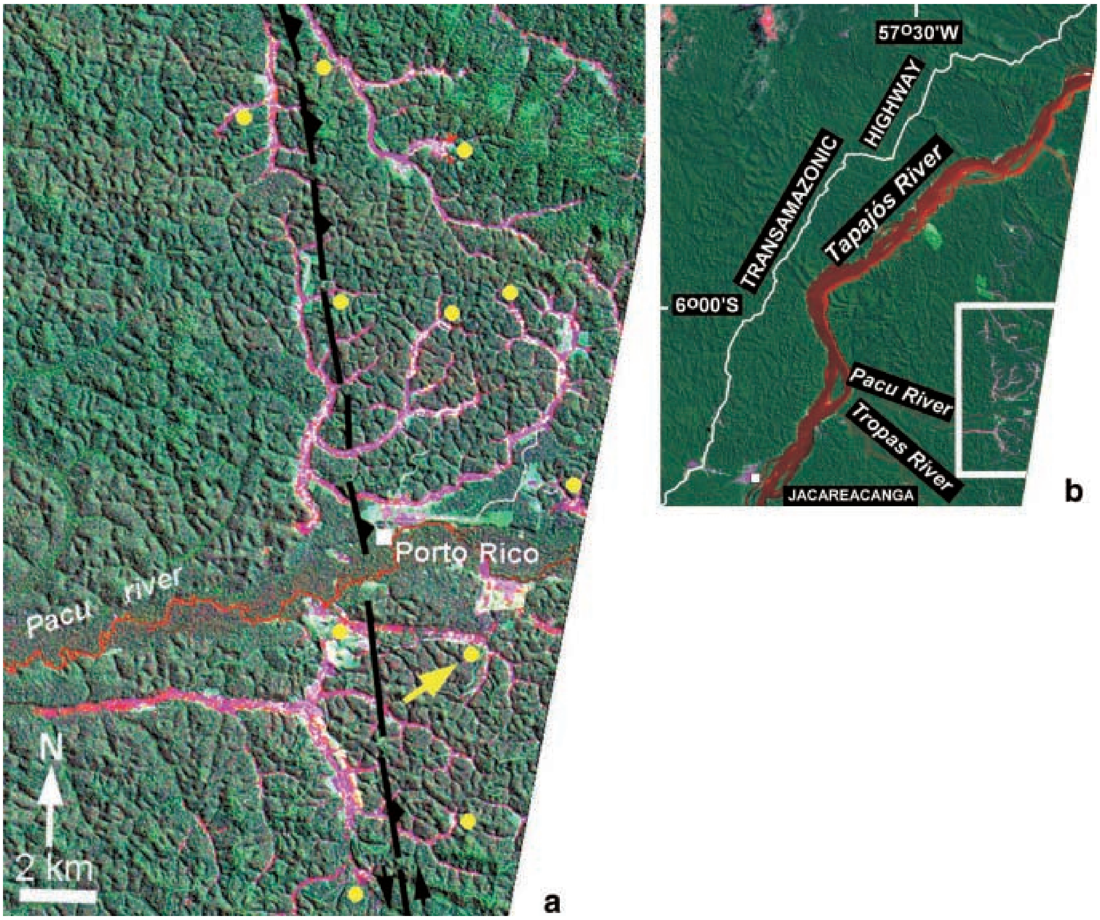


Fig. 5 **a** Landsat TM image (3R/4G/5B) from scene 229/64 shows the Pacu gold district. *Greenish colors* correspond to Amazon forest; *pinkish/magenta zones* along creeks mark exploited alluvials; *yellow circles* locate the primary gold mines; *yellow arrow* shows Ouro Roxo location; and the *black line* is the Centrinho-Cantagalo shear zone. **b** Landsat TM image (3R/4G/5B) from scene 229/64 gives location of **a** (*white polygon in the lower right area*) in the center-north region of the Tapajós gold province. *Bright red zones* along Tapajós River right margin represent suspended clay derived from alluvial mining on its tributaries rivers basins

intrudes the Cuiú-Cuiú Complex, but to the west it is intruded by a granite stock of the Maloquinha Suite. The banded or foliated granodiorites, quartz diorites and tonalites are mainly exposed along the Tropas and Pacu Rivers. The tonalites are the dominant rock type, having 53–58 wt% SiO2, K_2O <2 wt%, and low Y (<20 ppm), Nb (<10 ppm) and Th (<5 ppm), and can be classified as calc-alkalic, arc-related rocks (Thièblemont and Cabanis 1990).

The batholith is rich in mafic inclusions, which are xenoliths of andesite and basalt. They range from a few centimetres to hundreds of metres in length, are commonly elongated along a N–S trend, and are hydrothermally altered to chlorite, epidote, albite, leucoxene and pyrite. The relationship of the mafic rocks with the host rocks is poorly known because both rock types are strongly sheared in the region of the Ouro Roxo gold deposit, as well as in the other deposit exposures (Pepeu, Cantagalo and Centrinho). In the southern zone of the Pacu batholith, in the Tropas River region, mafic rocks are less altered and deformed, and have an angular shape and sharp contact with the host rock. The mafic rocks were initially interpreted as early dikes, which were deformed together with the Tropas granitoid host. The U–Pb SHRIMP data (Table 2) show, however, that the mafic fragments are older ($2{,}012\pm8$ Ma, sample JO-190, drill hole 8; $1{,}973\pm8$ Ma, sample JO-21, drill hole 21) than the tonalite-granodiorite host ($1{,}893\pm3$ Ma).

The Pacu district (Fig. 5) is cut by several shear zones, which contain mylonites and ultramylonites. These are brittle–ductile and trend from N10°W to N20°E. The main shear zone (Centrinho–Cantagalo) trends N10°W (Fig. 5) and is 1,000–2,500 m wide and at least 40 km long. There is a strong structural control on gold mineralization in the Pacu district, with deposits distributed mainly to the east of the main shear zone. The spatial distribution of the deposits suggests a structural link with the regional N–S shear zone. The orebodies are disposed along a succession of subparallel secondary shear zones that strike N10°E–N30°E. These brittle–ductile shears zones are as wide as 100 m and extend at least 3 km along a N10–20°E strike. They are sinistral-reverse with a 65–75°SE dip. The shear zones that host the orebodies, as intercepted by drill holes, are similar to the exposed shear zones, but display a lower dip of about 35°SE. They are probably the continuation of those exposed at the surface and represent favourable, low-angle dilational zones or Riedel-like structures into which the mineralizing fluids were focused.

The main controls on the mineralization are the low-angle zones in the secondary, N10–30°E-trending shear zones and the chemically reactive mafic xenoliths of the batholith. These flat, elongated mafic xenoliths provide planar anisotropies that favor shear zone development. The mineralized zones are notable by their chloritic alteration, disseminated pyrite, and quartz–carbonate–pyrite veins (Fig. 6). There is a strong correlation between pyrite content and gold abundance. Gold occurs as fine-grained (< 125 μm) inclusions in pyrite and as visible free gold. Massive pyrite veins have gold contents of > 50 g/t, and some ore intervals contain 1.0–1.5% copper. Two styles of mineralization are present. The first is early disseminated pyrite in the mafic rocks and fine pyrite veinlets (< 2 cm in width), which are generally of low gold grade, but reach 32.2 g/t Au in one 0.63-m interval, and parallel to foliation. The second is later pyrite-rich (50% pyrite by volume) quartz–carbonate veins, which are brecciated and cut the mineralization described above. The pyrite-rich veins are 10–80 cm thick, whereas the more economical intervals average 8.2 m in thickness and have a grade of 9.3 g/t Au. Sericite–carbonate–pyrite hydrothermal assemblage dominant in the granitoids, with haloes reaching 80 m in thickness in some drill hole intervals. The chlorite–carbonate–pyrite–leucoxene alteration assemblage is typically restricted to the metavolcanic rock pendants and xenoliths. Both alteration assemblages overprint earlier biotite–amphibole metamorphic assemblages.

Intrusion-related, quartz-vein gold deposits

This type of deposit is also mainly characterized by quartz–pyrite veins in potassic granitoids and disseminated gold in pyrite-rich, altered mafic dikes (Limão, Penedo, Joel, Mamoal, Batalha, David, São Domingos, Goiano and União). The felsic rocks are related to the Creporizão, Parauari and Maloquinha Suites and the younger andesites are part of the Carapuça unit (Pessoa et al. 1977). Quartz stockworks are associated with some deposits (São Félix, Pison, Carneirinho, Independência, São Domingos, Arroz Branco, Piranhas and Batalha), whereas other deposits (Carneirinho and Bom Jesus) are characterized by thin breccias. The quartz veins and breccias are vertical to subvertical, filling extensional brittle faults and dilational jogs, and are normally massive, although banded (Fig. 7); open-space filling and comb textures are also present (Robert 1996). Normally, the veins are less than 80 cm in thickness and 150 m in length, but they represent more than 85% of the known primary gold deposits in the region because they are so easily detected and exploited by prospectors.

Dreher et al. (1999) described quartz veins hosted by volcanic rocks (Iriri Group) with chalcedonic and crustiform textures. Based on fluid inclusion studies, Dreher et al. (1998) also showed that the hydrothermal quartz was formed at 240–320 °C (David Mine) and 220–340 °C (Joel Mine). In both deposits, CO_2 was not detected in the trapped fluid inclusions and the average salinity ranged from 0.43–1.15 wt% NaCl (Dreher et al. 1998). Chalcopyrite is always present in small amounts in the intrusion-related deposits, and galena and sphalerite occur in several mines. The quartz veins have variable strikes, lack structural compatibility with major regional faults and shear zones, and each pluton has its own system of fractures and veins.

The epizonal gold deposits of the Tapajós and Alta Floresta domains most closely resemble the Korean-type of intrusion-related deposits (Robert et al. 1997). Important critical features include the geological setting (abundant potassic granitoid intrusions), form of mineralization (quartz veins in brittle faults), main types of alteration (sericitization and chloritization, with limited carbonate), and the elemental association (Au–Cu–Pb–Zn–Ag, where Au:Ag > 5). This type of intrusion-related deposit is high-grade/low-tonnage, so gold is probably most exploitable by small-scale mining. Consequently, because of the lack of technology and the high cost of the Amazon mining operations, only deposits richer than 20 g/t Au are being mined.

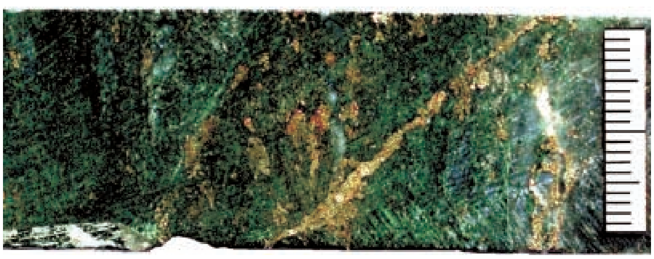


Fig. 6 Typical orogenic gold mineralization from Ouro Roxo gold deposit (drill hole 21,163.8 m). Au-pyrite and Au-pyrite–quartz–carbonate veins hosted by 1,973 ± 8 Ma Creporizão Suite metabasalt deeply altered to chlorite + carbonate + leucoxene + pyrite assemblage. *Scale bar* in cm

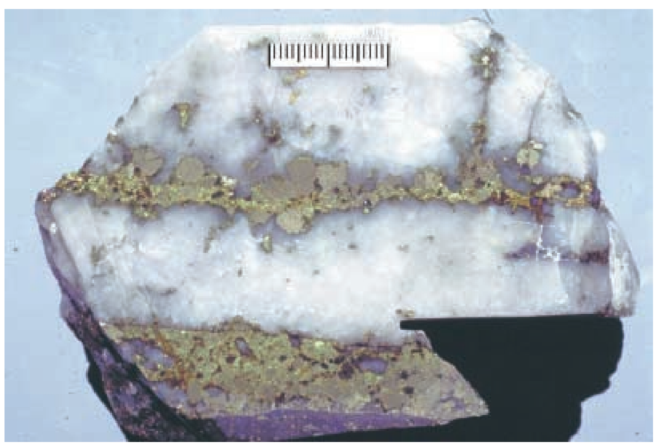


Fig. 7 Example of common intrusion-related gold mineralization from Chico Torres deposit (sample JH-15). Banded Au-pyrite–quartz vein, high-grade ore (~30 g/t Au). *Scale bar* is 2 cm

The presence of minor adularia in two of the intrusion-related gold deposits (Joel and David) led Dreher et al. (1998) to classify the gold veins as low-sulfidation epithermal (adularia-sericite type). However, the epizonal gold deposits of the Tapajós domain lack many of the characteristics of epithermal deposits (see Hayba et al. 1985; Henley 1991; Robert et al. 1997) as indicated in Table 6. The main distinctions are the apparent absence of any relationship to penecontemporaneous volcanic rocks, the restriction of alteration to a few meters from the ores, the scarcity of the adularia, the consistently low silver concentration, and the absence of native silver or silver sulfosalts. Only 7 of the 178 primary gold deposits in the Tapajós and Alta Floresta domains are hosted by subvolcanic felsic igneous rocks, a common ore host in epithermal systems. In these deposits, the volcanic rocks are hypabyssal and grade to granophyre in some places such as at Pison. These deposits are restricted to the northwestern part of the Tapajós domain (Pison, Quatá, Seta de Ouro, São Félix, 12 de Outubro, Chico Torres and Maranhense) and, despite the host-rock type, they lack all other characteristics typical of epithermal gold deposits.

Subaerial lava flows and pyroclastic units of the Iriri Group are largely exposed in the eastern and northeastern parts of the domain, where volcanic centers and calderas may exist. However, there is no epithermal gold mineralization known in these volcanic terrains.

Intrusion-related, epizonal disseminated/stockwork deposits

Some of the intrusion-related deposits are dominantly stockwork systems. These include the Jutaí, Paraíba, Serrinha, Alcântara, Carneirinho and Abacaxis South deposits. They have some similarities with the classic gold-bearing porphyry deposit types (Sillitoe 1991), such as style of mineralization (granitoid-hosted disseminated or stockwork) and the presence of hydrothermal magnetite. However, it is preferable to group these as intrusion-related (Sillitoe and Thompson 1998) because host rocks are not porphyries, hydrothermal alteration is not extensive, and Cu, Mo and Ag are sub-economic. Prospectors rarely discover this deposit type, and do so only when there are small, gold-rich quartz veins associated with the main stockwork and disseminated ore styles.

The Serrinha gold deposit

The Serrinha gold deposit is located in the extreme south-easternmost part of the Tapajós–Parima orogenic belt within Alta Floresta domain (Fig. 2). The Serrinha deposit is associated with the Matupá Granite, which intruded the Palaeoproterozoic Cuiú-Cuiú granitoids (Valente 1998). These units dominate the geology of the Peixoto de Azevedo–Matupá–Guarantã region, and were correlated with the Archean Xingu Complex of the Carajás Province (Silva et al. 1974; Sato and Tassinari 1997).

Two main groups of post-Cuiú-Cuiú granitoids have been distinguished in the Alta Floresta domain (Botelho and Moura 1998). The first comprises oxidized, I-type, calc-alkaline granitoids, which crop out between the towns of Matupá and Paranaíta. The granitoids vary from granodiorite to monzogranite and are the host rocks for gold mineralization at the Serrinha, Paraíba, Erédio-Melado, Olerindo and Waldomiro deposits. The second group is composed of oxidized alkaline granites, occurring as irregular or rounded bodies and assigned to the younger anorogenic Teles Pires-type Suite. Although some gold occurrences are spatially related to these granitoids, gold systems are controlled by regional lineaments and/or shear zones, and the genetic link

Table 6 Comparison of adularia–sericite epithermal gold deposits with the Joel and David intrusion-related deposits

Characteristic	Classic adularia–sericite gold deposits[a]	Joel deposit	David deposit
Geological setting	Complex subaerial volcanic environments, commonly in calderas. Associated subvolcanic intrusions	Hypabyssal	Hypabyssal
Host rock	Silicic to intermediate and alkalic volcanic rocks	Andesite dike cutting monzogranite	Gabbro pluton
Mineralogy	Argentite, tetrahedrite, tennantite, native silver and gold, selenides. Mn present in the gangue	Pyrite, chalcopyrite, galena, gold	Pyrite, chalcopyrite, galena, sphalerite, bornite, gold
Alteration	Propyllitic to argillic, supergene alunite, and abundant adularia	Sericite, chlorite, albite and rare adularia and fluorite	Chlorite, albite, sericite, adularia and carbonate
Temperature	100–300 °C	220–340 °C	240–320 °C
Source of fluids	Dominantly meteoric	Unknown	Unknown
Metal association	Au, Ag, electrum, As, Sb, Hg (± Pb, Zn, Te)	Au, Cu, Pb, Zn, Ag	Au, Cu, Pb, Zn, Ag
Au:Ag ratio	1:10 to 25:1	≥5:1	≥5:1

[a] Based on Hayba et al. (1985), Henley (1991) and Robert et al. (1997)

between the alkaline granites and gold mineralization in the Alta Floresta Domain remains speculative (Botelho and Moura 1998). The Matupá Granite is a batholith of about 280 km^2 in the northern Alta Floresta domain, which is correlated to Parauari Suite in the Tapajós Domain (Valente 1998). At the Serrinha gold deposit, it crops out as massive and undeformed blocks of 1.87 ± 12 Ga biotite monzogranite. The calc-alkaline Matupá Monzogranite is subsolvus, medium- to coarse-grained, pink, and equigranular to porphyritic (Moura et al. 1997a).

The tectonic and geochemical features of the Matupá Monzogranite are similar to those of the granitoids of the Parauari Suite. Its Pb–Pb zircon model age ($1{,}870 \pm 12$ Ma, Moura et al. 1997a) is comparable to the U–Pb ages of representative bodies of the Parauari Suite, such as the Penedo Granite ($1{,}883 \pm 4$ Ma), Ingarana gabbro ($1{,}879 \pm 3$ Ma) and Rosa de Maio adamellite ($1{,}879 \pm 11$ Ma).

In the Serrinha deposit, the Matupá Monzogranite was substantially modified by metasomatic processes, which generated different hydrothermal assemblages. The metasomatic zones are normally superimposed throughout the granitoid, precluding the definition of zones with a specific geometric pattern.

Magmatic plagioclase is transformed to albite, phengite, chlorite and epidote; microcline is altered to phengite and albite; and biotite is altered to chlorite, epidote, phengite, magnetite and/or titanite.

In the gold-mineralized zones, the plagioclase is completely albitized, there is no preserved biotite, magmatic titanite and apatite are absent, and phengite and chlorite are abundant. Different styles of alteration can be identified at the Serrinha gold deposit. The first gold-related alteration event formed albite, sericite, and chlorite. The albite occurs on the borders of K-feldspar or as individual crystals in the rock, which maintains its granitic texture. Sericitization is more widespread than chloritization, such that the gold-bearing granitoid was transformed to masses of fine phengite, quartz, microcline, and minor albite and chlorite. Locally, however, the predominant alteration phase is chlorite, which is very rich in manganese (as much as 6 wt% MnO).

Superimposed over these early alteration phases is a strong pyritization. It is mainly characterized by disseminated pyrite and pyrite infill of microfractures. Where disseminated, pyrite occurs together with another generation of albite, microcline, phengite and chlorite, whereas, in fractures, pyrite is associated with quartz, phengite, chlorite and/or calcite. The final hydrothermal event is carbonatization of some areas of the Serrinha deposit, where fractures in the metasomatic minerals were filled by calcite, in places associated with quartz, phengite, chlorite and/or pyrite.

Gold mineralization is disseminated and restricted to the most intensely hydrothermally altered monzogranite, with which pyrite, sericite, chlorite and/or albite are associated. Hydrothermal magnetite and rutile are ubiquitous within pyrite. Gold is in the native form and occurs as inclusions or filling fractures in pyrite crystals. Two generations of gold and three of pyrite have been identified by Moura et al. (1997b) based on textural and crosscutting relationships. The early gold, with a high Au/Ag ratio, occurs as inclusions in the first generation of pyrite. The second generation gold is generally more enriched in silver and fills fractures in the early pyrite or occurs as inclusions in second generation pyrite. The third generation pyrite is not related to gold and is restricted to a late microcline-rich zone.

The Serrinha ore has low grades of Ag, Cu and Mo, unlike some gold-porphyry deposits. The presence of pyrrhotite and magnetite inclusions in gold-bearing pyrite crystals suggests that the Serrinha deposit was formed on or above the pyrrhotite + pyrite + magnetite buffer (Moura et al. 1997b).

Sulfur isotope data for second generation pyrite ($\delta^{34}S = +1.3$ to $+3.5\%$, Moura et al. 1997b), together with fluid inclusion results (Moura et al., unpublished data), are consistent with a mineralizing fluid exsolved from a crystallizing magma.

Based on the petrographic and chemical characteristics of the Matupá Monzogranite, its hydrothermal alteration assemblages, the ore paragenesis and evolution of the mineralizing fluids, the Serrinha gold deposit was considered by Moura et al. (1997b) to be similar to disseminated deposits that are genetically related to oxidized, calc-alkaline, I-type granitic magmas (Burnham and Ohmoto 1980; Blevin and Chappell 1992) and are often classified as porphyry-style gold deposits (Sarkar et al. 1996; Sillitoe 1997). However, as stated above, we prefer to classify it as an intrusion-related gold deposit.

Paleoplacer deposits

The Castelo dos Sonhos deposit is the only recognized gold paleoplacer deposit in the Amazon Craton. The deposit is located 120 km south-east of the south-eastern limit of the Tapajós domain map (Fig. 1) and may not be related to the lode deposits in this domain. The mineralization is hosted by a mature supracrustal fluviatile sequence (quartzites, metaconglomerates and conglomeratic quartzites), which was metamorphosed (lower greenschist to upper amphibolite facies) and open-folded. The Castelo dos Sonhos sedimentary sequence has an undefined stratigraphic position, but it may be comparable to the mature fluvial sequences present in the post-orogenic sedimentary cover (Palmares Group). Following this hypothesis, the mineralization would be younger than 1.85 Ga (maximum age of the Palmares Group), having the primary orogenic and intrusion-related gold deposits as the source for the detrital gold.

The gold is either free (intergranular) or occurs as inclusions (5–200 μm in diameter) in quartz. The higher gold concentrations are hosted by metaconglomerates with a high proportion of clasts to matrix (Araneda et al.

1998). According to these authors, there is no relationship between gold grade and sulfide minerals.

Constraints on ages of gold deposits

Relative age constraints

Gold mineralization is hosted by a number of stratigraphic units, but no significant hydrothermal alteration, nor mineralization, occur in rocks younger than those of the Maloquinha Suite (Fig. 4). This suggests that gold mineralization pre-dates deposition of rocks of the Palmares Group.

Rocks of the Palmares Group are intruded by the 1,782 ± 9 Ma (baddeleyite U–Pb) Crepori gabbro–dolerite intrusions. The youngest population of clastic zircons in a Palmares subarkose sample has an age of 1,879 ± 12 Ma (Santos et al., unpublished data) and probably was derived from granitoids of the Parauari Suite. The age of the Palmares Group, therefore, is in the range of 1,879 ± 12 to1,782 ± 9 Ma, and would be the relative minimum age for the gold mineralization in the orogenic belt.

The two main types of lode-gold deposits have different host-rock units. The orogenic deposits are mainly hosted by rocks of the Cuiú-Cuiú Complex and the Tropas Intrusive Suite (and, to a lesser degree by the Jacareacanga Group). The intrusion-related deposits are mainly hosted by rocks of the Parauari and Maloquinha Intrusive Suites (and, to a lesser degree, by the Iriri Group and Creporizão Suite).

The Maloquinha Suite age was determined in six samples (Santa Rita Monzogranite, 1,874 ± 7 Ma; Iriri Rhyodacite, 1,870 ± 8 Ma; Pepita Granite, 1,872 ± 4 Ma; Barro Vermelho Granite, 1,873 ± 6 Ma; Maloquinha Granite, 1,870 ± 4 Ma; and JO169 granophyre, 1,864 ± 18 Ma). Considering only the five more precise results, ages for the Maloquinha Suite range between 1,881 and 1,862 Ma, with a weighted mean of 1,872 ± 2 Ma. Thus, the maximum age for some of the intrusion-related gold deposits is 1,862 Ma.

Zircons from five bodies of the Tropas Suite were dated by SHRIMP (Uruá felsic tuff, 1,895 ± 7 Ma; Abacaxis Granodiorite, 1,892 ± 6 Ma; and Tropas Andesite, 1,898 ± 7 Ma) and conventional U–Pb (Tropas Tonalite, 1,894 ± 2 Ma; and Ouro Roxo Tonalite, 1,894 ± 3 Ma; Table 2). The age range obtained for the Tropas Suite is 1,905–1,886 Ma, with a weighted mean of 1,894 ± 2 Ma. Thus, the maximum age for some of the orogenic gold deposits is 1,886 Ma.

At the Ouro Roxo deposit, zircons from two mafic xenoliths from drill holes were dated using SHRIMP (Table 1). The zircon U–Pb ages of 2,016 ± 5 and 1,974 ± 6 Ma are older than the host rock (1,898 ± 2 Ma, Table 2), confirming that they are not dikes. These two mafic rock ages correlate well with the ages of the two older magmatic arcs in the region: Cuiú-Cuiú (2,015 ± 9; 2,011 ± 26; and 2,005 ± 7 Ma) and Creporizão (1,970 ± 12 Ma), strengthening the interpretation that they are xenoliths derived from the older volcano-plutonic arcs.

Absolute ages of formation for intrusion-related gold deposits

Pb–Pb dating

Hydrothermal minerals were dated in order to determine the age of gold mineralization (Table 7). Analytical methods for chemical separation of lead from sulfide minerals follow standard procedures (Ho et al. 1994). Lead isotope analyses were performed on a VG354 multicollector mass spectrometer at the Curtin University of Technology, Western Australia.

Galena is the best mineral to establish the initial lead-isotope composition of ore systems because it is a lead-rich mineral having U/Pb = 0 (McNaughton and Groves 1996). The Tapajós intrusion-related gold deposits commonly have enough galena to be analyzed, whereas this sulfide mineral is rare or absent in the orogenic gold deposits of the region. Galenas sampled from four different intrusion-related deposits (David, Joel, Porquinho and Piranhas mines) were analyzed for lead isotopes (Table 7) and results were plotted on a $^{207}Pb/^{204}Pb$ diagram (Fig. 8). The initial Pb isotope composition of intrusion-related deposits varies in a linear trend (from Joel to Porquinho, Fig. 8), which reflects crustal heterogeneity during mineralization. Galena data plot on an 1,855 Ma Pb–Pb reference isochron (MSWD = 0.134), which may represent a crustal mixing line for the Tapajós gold province at ~1.86 Ga, whereas pyrite–chalcopyrite data scatter about the galena line (eight samples above and six below the line), suggesting that they are part of the same ore system (Fig. 9). The Pb–Pb model-ages for ten galenas range from 1,924 to 1,823 Ma, with a mean of 1,867 ± 17 Ma (Fig. 10). By adding 11 Pb–Pb model ages for ore-related pyrite to the same data set, the mean age is 1,869 ± 30 Ma.

The age of the orogenic gold deposits was not established by Pb–Pb dating. These deposits may be broadly synchronous with the intrusion-related deposits, but formed at deeper crustal levels within the evolving orogenic belt.

Ar–Ar dating

Hydrothermal muscovite from the ore (drill core DG1) of the Abacaxis intrusion-related gold deposit was dated by argon methodology using a spot-laser. Laser analyses were carried out by a laser-optical system, which includes an LTI-237/90 impulse infra-red laser and a Carl Zeiss LMA-1 microscope. Irradiation of the samples was carried out in the research reactor VVR-c (State Scientific Centre, Karpov Physical–Chemical Research Institute, Obninsk, Kaluga Region, Russia).

Table 7 Lead isotope data from ores (sulfides) and rocks (K-feldspar) of the Tapajós domain. Isotope ratios normalised to NBS-981. Analytical errors are ±0.15% (2σ)

Sample	Deposit	Unit/host-rock	Rock age (Ma, U–Pb)	Mineral[a]	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	Model age (Ma)	μ	Laboratories[b]
JO-69-2	David	Ingarana Gabbro	1,879 ± 3	Gn	15.946	15.532	1,875	10.95	1
JO-69-3	David	Ingarana Gabbro	1,879 ± 3	Gn	15.946	15.527	1,867	10.91	1
JO-69-5	David	Ingarana Gabbro	1,879 ± 3	Gn	15.955	15.529	1,864	10.91	1
JO-69-6	David	Ingarana Gabbro	1,879 ± 3	Gn	15.945	15.530	1,823	10.62	1
JO-69-7	David	Ingarana Gabbro	1,879 ± 3	Py	16.006	15.608	1,936	11.42	1
JO-69-8	David	Ingarana Gabbro	1,879 ± 3	Py	15.833	15.403	1,771	10.20	1
JO-69-9	David	Ingarana Gabbro	1,879 ± 3	Py	15.914	15.472	1,812	10.57	1
JO-69-10	David	Ingarana Gabbro	1,879 ± 3	Py	15.900	15.463	1,809	10.52	1
JO-69-11	David	Ingarana Gabbro	1,879 ± 3	Cpy	15.952	15.500	1,824	10.71	2
JO-67-1	Piranhas	Parauari Monzog		Gn	15.942	15.532	1,872	10.94	2
JO-67-2	Piranhas	Parauari Monzog		Gn	15.924	15.516	1,878	10.96	2
JO-66-1	Mamoal	Carapuça Andesite		Py	18.183	15.974	986	11.53	2
JO-66-2	Mamoal	Carapuça andesite		Py	16.197	15.762	2,001	12.26	2
JO-107-1	Joel	Parauari Monzog		Gn	15.876	15.505	1,840	10.55	2
JO-107-1	Joel	Parauari Monzog		Py	26.087	15.713	2,017	12.10	1
JO-107-1	Joel	Parauari Monzog		Py	15.903	15.494	1,853	10.74	1
JO-107-1	Joel	Parauari Monzog		Py	16.229	15.830	2,064	12.76	1
JO-107-1	Joel	Parauari Monzog		Py	16.580	15.812	1,804	12.00	1
JO-107-1	Joel	Parauari Monzog		Py	15.909	15.597	1,992	11.51	1
JO-107-1	Joel	Parauari Monzog		Py	16.462	15.753	1,806	11.75	1
JO-107-1	Joel	Parauari Monzog		Py	16.052	15.651	1,960	11.67	1
JH-29-1	Porquinho	Cuiú-Cuiú Monzog	2,020 ± 12	Gn	16.145	15.649	1,891	11.49	2
JO-3	Jardim	Maloquinha Syenog	1,873 ± 6	K-feld	16.036	15.532	1,807	10.81	2
JO-59		Jacareacanga	2,098	K-feld	15.764	15.388	1,803	10.19	2
JO-101b	Tropas	Parauari Metabasalt	1,898 ± 7	K-feld	15.723	15.396	1,847	10.31	2
JO-173		Cuiú-Cuiú Tonalite	2,015 ± 9	K-feld	16.030	15.635	1,954	11.58	2
JO-174		Cuiú-Cuiú Monzog	1,995 ± 15	K-feld	16.127	15.528	1,733	10.66	2
JO-175		Creporizão Monzog	1,969 ± 6	K-feld	16.556	15.634	1,575	10.84	2
JO-180		Creporizão Monzog	1,957 ± 6	K-feld	16.449	15.599	1,601	10.74	2
BV-1	Barro Vermelho	Maloquinha Syenog	1,871 ± 7	K-feld	16.330	15.487	1,518	10.16	2
CC-21-1		Juruena Tonalite	1,793 ± 6	K-feld	16.025	15.429	1,661	10.12	2
GM-10-1		Teles Pires Syenog	1,757 ± 16	K-feld	18.580	15.670	180	9.94	2
MM-36		Iriri Rhyolite	1,870 ± 8	K-feld	16.282	15.494	1,566	10.25	2

[a] *Gn* Galena; *py* pyrite; *cpy* chalcopyrite; *K-feld* K-feldspar
[b] Laboratories: *1* University of New Hampshire, USA; *2* Curtin University of Technology, Western Australia

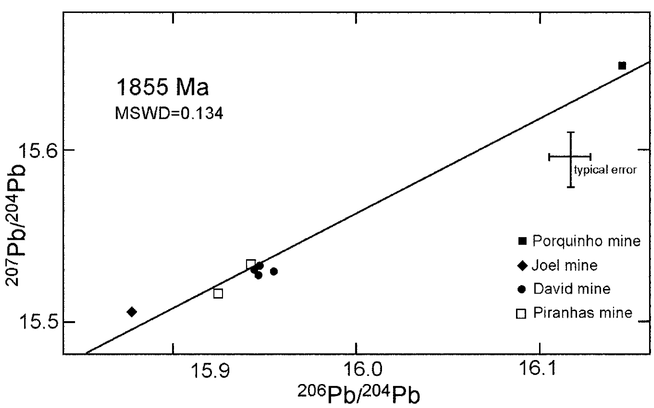


Fig. 8 Uranogenic common Pb diagram showing galena data for four epizonal gold deposits

Two muscovite flakes, each ~500 μm in diameter, were selected for analyses. The diameter of the obtained craters varies from 50–200 μm and is normally 100 μm. Six spots were placed in the two muscovite flakes and the oldest core age detected was 1,860 ± 13 Ma (Table 8). This result correlates well with the Pb–Pb age for mineralization in other intrusion-related gold deposits (see above) and indicates a regional hydrothermal event at ~1,860 Ma. The younger 1,749 ± 23 and 1,782 ± 6 Ma ages obtained on muscovite rims (Table 8) are interpreted as being caused by ^{40}Ar loss because of the younger Crepori magmatism (1,778 ± 9 Ma, Fig. 4).

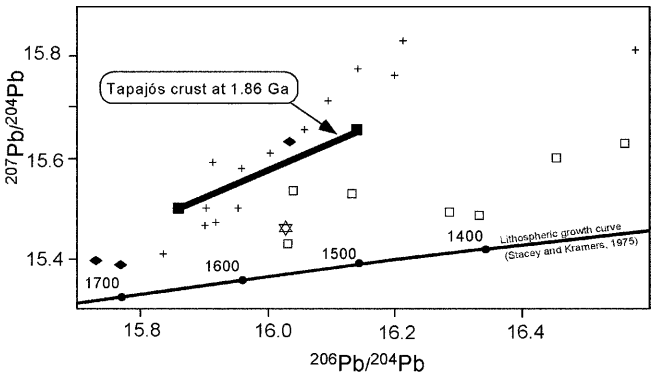


Fig. 9 Common Pb isotope plot comparing K-feldspar (*open squares* and *filled diamonds*) and pyrite data (*crosses*) to standard lithospheric growth curve (Stacey and Kramers 1975) and to the estimated composition of crustal rocks at ~1.86 Ga. *Open squares* are host-rocks to epizonal deposits and *filled diamonds* are host-rocks to mesozonal deposits. Possible Pb initial composition for the Maloquinha–Iriri magma indicated by the *star*

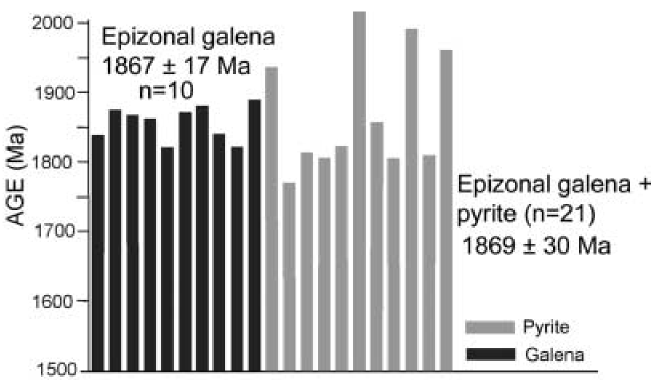


Fig. 10 Histogram for galena (10) and pyrite (11) Pb–Pb model ages

Discussion on sources of the gold

The source of lead in the mineralizing system was investigated by a reconnaissance study of lead isotopes on K-feldspars, combined with the Pb–Pb sulfide data. The K-feldspar was separated from the same host-rocks that were dated by SHRIMP U–Pb (Table 7), and the results plotted together with the galena and pyrite results (Fig. 9).

The host rocks (JO-101 and JO-59) to the orogenic deposits are less radiogenic than the host rocks to the intrusion-related deposits. One exception (JO-173) plots above the galena line, but it is a small xenolith and may have been affected by magmatic fluids. The K-feldspar from the host rocks of the orogenic deposits are less radiogenic than those of the galena, and plot close to the projection of the origin of the galena line. This indicates that these two host rocks could be a source for the ore fluids. The average of the least-radiogenic K-feldspars of the host rocks to the intrusion-related deposits yields an estimate of the initial lead isotope composition of the Maloquinha magma. This average composition is distinctly more evolved than the galena data and plots below the galena line (Fig. 9).

The first conclusion from these results is that the Maloquinha/Iriri rocks did not contribute lead to the mineralizing fluid. However, another possibility is that the Maloquinha/Iriri K-feldspar lead-isotope system was affected by late crustal heating, during younger magmatic activity (Teles Pires granites, 1.76 Ga; Piranhas dolerites, 0.51 Ga or Cururu dolerites, 0.18 Ga). The K-feldspar lead-model ages are significantly younger than the SHRIMP U–Pb ages, ranging between 1,733 and 1,518 Ma (Table 7, with one result from sample GM-10 of 180 Ma) clearly indicating lead resetting during the Mesozoic (Cururu tholeiitic magmatism). Even if Maloquinha/Iriri magmatism was not the source for the ore fluids, it is still possible that it provided the heat for hydrothermal fluid circulation based on available age constraints.

The orogenic gold deposits are restricted to the Cuiú-Cuiú, Creporizão, and Tropas magmatic arcs and are distributed for 1,400 km along strike (Fig. 1), providing the strongest evidence that they are related to the last stages of deformation and magmatism of the Parauari arc. The intrusion-related gold deposits are probably broadly synchronous with late-Parauari magmatism, or post-collisional granites, broadly similar to the Maloquinha Intrusive Suite granites. The westernmost post-collisional granitoids are related to the final stages of the fourth magmatic arc, and had the older arc rocks as the main source; therefore, they are not anorogenic and should be not grouped with the Maloquinha Suite. The true Maloquinha anorogenic magmatism, derived from Archean crust, is dis-

Table 8 Laser analyses for sample DG1 (muscovite), Abacaxis mine. All analyses were corrected for mass discrimination, decay (for ^{37}Ar and ^{39}Ar), interfering neutron-induced reactions on calcium. ($[^{36}Ar/^{37}Ar]_{Ca} = 2.64\times10^{-4}$ and $[^{39}Ar/^{37}Ar]_{Ca} = 7.43\times10^{-4}$), and line blanks

Sample	$(^{40}Ar/^{39}Ar)m$	$(^{40}Ar/^{36}Ar)m$	$(^{36}Ar/^{39}Ar)m$ $\times10^{-2}$	$(^{37}Ar/^{39}Ar)m$ $\times10^{-2}$	$^{40}Ar^*/^{39}Ar_{Ê} \pm \sigma$	Age, Ma $\pm \sigma$
DG-01a	77.85	28,833	0.27	10.1	77.1 ± 0.5	1,845 ± 11
J = 0.02310 ± 0.00005	74.91	5,428	1.38	8.5	70.8 ± 1.3	1,749 ± 23
	76.66	383,300	0.02	7.9	76.8 ± 0.1	1,840 ± 5
DG-01b	74.52	248,400	0.03	7.9	74.4 ± 0.1	1,804 ± 5
J = 0.02308 ± 0.00005	72.82	121,367	0.06	9.6	73.0 ± 0.2	1,782 ± 6
	78.75	34,239	0.23	8.5	78.1 ± 0.7	1,860 ± 13

tributed from the Parauari arc to the east for 1,600 km, until the border of the Carajás Province, comprising a large area where there are no known gold deposits. This is perhaps the best evidence that the gold deposits are not related to the anorogenic granitoids, but rather to synchronous arc-related rocks, as elsewhere in the world (e.g. Groves et al. 1998). This is also consistent with the K-feldspar lead-isotope data.

Summary and conclusions

The following are the major conclusions of this research:

1. The Paleoproterozoic Tapajós–Parima orogenic belt, particularly the Tapajós and Alta Floresta Domains, is a major gold province with most of its gold produced from alluvial placers, but with high potential for primary gold deposits.
2. The Tapajós–Parima orogenic belt has four discrete magmatic arcs (Cuiú-Cuiú, Creporizão and two Parauari arcs), which formed between 2,010 and 1,880 Ma and are all followed by late-orogenic and intracratonic magmatic activity (Maloquinha Suite and Iriri Group) that are associated with crustal rifting.
3. Gold mineralization of various styles is hosted by the amphibolite-facies rocks of the Cuiú-Cuiú Complex, greenschist-facies supracrustal rocks of the Jacareacanga Group, magmatic-arc granitoids of the Creporizão and Parauari Suites, granitoids of the Maloquinha Suite, and volcanic rocks of the Iriri Group. A total of 178 deposits are known.
4. The primary gold deposits are broadly subdivided into two major groups, mesozonal orogenic and epizonal intrusion-related deposits, each of which can be subdivided into two main categories. As judged by their size potential, the more important deposit types are the magmatic arc-hosted orogenic deposits and the intrusion-related stockwork and disseminated gold deposits.
5. Some orogenic, turbidite-hosted gold deposits are hosted in metaturbidites of the greenschist-facies of the Jacareacanga Group. These consist of pyrite-bearing quartz veins associated with hydrothermal sericite and chlorite in ductile shear zones. They are interpreted to be mesozonal gold deposits, formed at the deepest crustal levels of any of the gold deposits of the Tapajós belt.
6. Orogenic, magmatic arc-hosted gold deposits are mainly in brittle–ductile structures in the Cuiú-Cuiú Complex, although Tropas Suite granitoids may also be mineralized in the Pacu district. Both vein and disseminated-style deposits are present, mostly associated with sericite, chlorite, carbonate and epidote alteration minerals. The best studied example is the Ouro Roxo deposit, which contains pyrite-rich quartz-carbonate veins in ~2.01–1.97 Ga mafic xenoliths in a 1,898 Ma mylonitic tonalite. Ore zones may be more than 8 m thick and average about 9.28 g/t Au. Minor copper enrichment is associated with the gold concentrations.
7. Intrusion-related vein deposits comprising subvertical to vertical quartz veins and stockworks, are mainly sited in brittle shears in granitoids of the Parauari and Maloquinha Suites. Rocks of the Creporizão Suite and Iriri Group also host this style of mineralization. Alteration comprises mainly sericitization and feldspathization, although epidote, carbonate, kaolin and fluorite are present in some deposits. Deposits of this type resemble the Korean-type deposits of Robert et al. (1997). This is the most common type of gold deposit in the area, because the high grades allow for easy discovery by prospectors.
8. Intrusion-related, disseminated/stockwork style deposits occur mainly in Parauari Suite granitoids, in sedimentary rocks derived from these (Abacaxis and Sequeiro Formations), in the Juruena granodiorite, and in the Jutaí gabbro. Alteration is largely sericitization and feldspathization, with chlorite and carbonate also present. Gold is associated with minor anomalies of Cu, Mo, Ag and F in some deposits. Fluid inclusion and sulphur isotope studies at the Serrinha deposit suggest a magmatic fluid source for the gold mineralization.
9. Previous interpretations that type 2 deposits are sericite–adularia-type epithermal deposits are negated by the lack of adularia in most deposits, the relatively restricted widths of alteration zones, and the lack of penecontemporaneous volcanism in most cases.
10. The age of the intrusion-related gold mineralization is constrained between the age of the Maloquinha Intrusive Suite (1,874 Ma) and the maximum possible age for the Palmares sedimentary cover (1,850 Ma). This is consistent with the Pb–Pb isochron age of ore galena at 1,855 Ma and the mean galena Pb–Pb model-ages of $1,867 \pm 17$ for the mineralization. Core zones of hydrothermal muscovite, dated by laser Ar–Ar, have an age of $1,860 \pm 13$ Ma. All these data indicate that the epizonal mineralization was formed at ~1,860 Ma. The age of the orogenic gold mineralization is not established, but might be similar.
11. Gold mineralization in the Tapajós Domain is related to the last stages of arc magmatism and deformation, and the heterogeneous crustal rocks were the main source of the lead in the gold-carrying fluids. The post-collisional granites (Maloquinha type) may have provided the heat source for the hydrothermal fluid circulation.
12. There are two main types (orogenic and intrusion-related) of gold deposits in the Tapajós Domain related to specific tectonic-magmatic events, both of which occurred during short intervals in the history of the orogenic belt evolution. This information may be useful as a guide for gold exploration along the orogenic belt.

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