FRAGMENTAL ROCKS OF THE IGARAPÉ BAHIA CU-AU DEPOSIT, CARAJÁS MINERAL PROVINCE, BRAZIL

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Resumo *AS ROCHAS FRAGMENTÁRIAS DO DEPÓSITO DE Cu-Au DE IGARAPÉ BAHIA, PROVÍNCIA MINERAL DE CARAJÁS, BRASIL* O depósito primário de Cu-Au de Igarapé Bahia, situado na Província Mineral de Carajás, norte do Brasil, está hospedado em rochas fragmentárias hidrotermalmente alteradas que ocorrem no contato entre as unidades vulcânica e sedimentar do Grupo Igarapé Bahia. Este grupo está metamorfizado em fácies xisto verde inferior e é considerado parte do Supergrupo Itacaiúnas, uma sequência metavulcanossedimentar arqueana (~2,75 Ga) que abriga os mais importantes depósitos de Cu-Au e de ferro da Província Carajás. As rochas fragmentárias constituem uma camada aproximadamente concordante, de cerca de 2 km de comprimento e 30-250 m de espessura. Trata-se de rochas heterolíticas, em geral matriz-suportadas, compostas principalmente por clastos grossos, angulosos a arredondados, de basalto, *BIF* e *chert* envoltos por uma matriz fina, formada por magnetita, siderita, clorita ferrífera e calcopirita disseminada a localmente maciça. Anfibólio, quartzo, ouro e uma série de minerais acessórios contendo elementos como Co, Mo, W, F, P, U, Mn, Pb, Sn, Ag, B, Cl e ETRL também estão presentes na matriz. As metavulcânicas sotopostas às rochas fragmentárias são metabasaltos de derrames, autobrechas e hialoclastitos formados *in situ*, sem evidências de vulcanismo explosivo. A unidade metassedimentar da capa contém principalmente metaturbiditos com abundantes feições de *slump* e desagregação indicativas de um ambiente marinho profundo e tectonicamente instável. As rochas fragmentárias depositaram-se provavelmente após um período de estabilidade e quiescência vulcânica – como evidenciado pela presença de clastos de *BIF* e *chert*– marcando um evento extensional súbito relacionado a falhamento sindeposicional que resultou em aprofundamento da bacia. De acordo com este modelo, a camada de rochas fragmentárias representa um depósito de fluxo de detritos constituído de material que sofreu colapso e se acumulou numa depressão submarina adjacente à zona de falha.

Palavras-chave: Rochas fragmentárias, depósito de Cu-Au de Igarapé Bahia, Província Mineral de Carajás, Pará, falhamento sindeposicional, depósito de fluxo de detritos.

Abstract The Igarapé Bahia primary Cu-Au deposit in the Carajás Mineral Province, northern Brazil, is hosted by hydrothermally altered fragmental rocks that occur at the contact between the volcanic and the sedimentary units of the Igarapé Bahia Group. This group is considered as a low greenschist facies unit of the major Archean (~2.75 Ga) metavolcano-sedimentary Itacaiúnas Supergroup, which hosts the most important Cu-Au and iron ore deposits of the Carajás Province. The fragmental rocks constitute an extensive, approximately concordant layer 2 km long and 30-250 m thick. They are heterolithic, usually matrix-supported rocks, made up mainly of coarse, angular to rounded, basalt, BIF and chert clasts set in a matrix of fine magnetite, siderite, Fe-chlorite and disseminated to massive chalcopyrite. Amphibole, quartz, gold and a series of accessory minerals containing elements such as Co, Mo, W, F, P, U, Mn, Pb, Sn, Ag, B, Cl, and LREE are also present in the matrix. The footwall metavolcanic rocks to the fragmental unit are flow basalts, autobreccia and *in situ* hyaloclastite, lacking evidence of explosive volcanism. The hanging wall metasedimentary sequence contains mainly coarse and fine-grained metaturbidites showing abundant slump and disruption features indicative of a deep, tectonically active marine setting. The fragmental rocks were probably deposited after a period of stability and volcanic quiescence – as evidenced by the presence of BIF and chert clasts - and define a sudden extensional event related to syndepositional faulting that resulted in deepening of the basin. According to this model, the fragmental layer represents a debris flow deposit made up of collapsed material that accumulated in a submarine depression adjacent to the fault zone.

Keywords: Fragmental rocks, Igarapé Bahia Cu-Au deposit, Carajás Mineral Province, Brazil, syndepositional faulting, debris flow deposit.

INTRODUCTION The Igarapé Bahia Cu-Au deposit is located in the Carajás Mineral Province, northern Brazil, approximately 70 km west of the village of Carajás (Fig. 1). The deposit consists of an upper gossan-laterite zone from which prominent amounts of gold were extracted until recently by Companhia Vale do Rio Doce (CVRD). The lower part of the deposit contains primary Cu-Au mineralization hosted by a hydrothermally altered fragmental rock unit. This unit occurs within supracrustal rocks of the Igarapé Bahia Group, considered part of the major Archean metavolcano-sedimentary Itacaiúnas Supergroup (Docegeo 1988), which hosts important Fe, Mn and other Cu-Au deposits of the Carajás Province (Fig. 1).

With respect to composition and texture, the Igarapé Bahia fragmental rocks have traditionally been described (Tazava 1999, Almada & Villas 1999; Tallarico *et al.* 2000, Villas & Santos 2001, Dreher & Xavier 2001, Santos 2002) as heterolithic breccias, formed by coarse fragments of different rock types set in a fine-grained matrix mostly composed of magnetite, carbonate, chlorite and disseminated to massive chalcopyrite. The additional presence of Au and of a variety of accessory minerals containing elements such as Co, Mo, W, F, P, U, Mn, Pb, Sn, Ag, B, Cl and LREE has also been mentioned. However, the term "breccia" implies that the

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contained lithic clasts are all or mostly angular whereas they in fact range from angular to rounded. Accordingly, we chose the more general term "fragmental" to refer to these coarse, heterolithic, clastic rocks.

Concerning morphology, most of the above-mentioned authors describe the fragmental rocks of Igarapé Bahia as constituting a large and approximately concordant unit.

Regarding origin, however, there has been extensive debate, with researchers mainly divided between those who admit the fragmentals to be syndepositional rocks (Almada & Villas 1999, Villas & Santos 2001, Dreher & Xavier 2001, Dreher 2004) and those who believe they formed from later hydrothermal or hydraulic activity (Tazava & Oliveira 2000, Ronzê *et al.* 2000, Groves & Vielreicher 2001; Tallarico *et al.* 2005).

In this paper, besides adopting the term "fragmental" to the mentioned rocks, we explore a syndepositional model that links the generation of these rocks to growth-faulting in a rift environment. The event took place in the early development of the Igarapé Bahia basin during a period marked by rapid transition from a quiet, stable environment to a tectonically active, basin-deepening stage. The model is based essentially on careful logging and detailed petrographic description of drill cores of the Igarapé Bahia deposit (see investigated drill holes in Figure 2), with special emphasis placed on the constitution, stratigraphy and geological setting of the mineralized fragmental unit and its enclosing volcanic and sedimentary rocks.

GEOLOGY OF THE CARAJÁS MINERAL PROVINCE The Carajás Mineral Province is one of the most important mineral districts of Brazil comprising an extensive area in the eastern part of the Amazon Craton (Fig. 1). The oldest geological unit of the Carajás region is a gneissic-migmatitic basement known as Xingu Complex, which was metamorphosed at *ca.* 2.8 Ga (Machado *et al.* 1991). In the northern part of the province (Fig. 1) the Xingu Complex is overlain by a metavolcano-sedimentary sequence known as Itacaiúnas Supergroup, *ca.* 2.75 Ga in age (Trendall *et al.* 1998), which is in turn covered by a metasedimentary unit named Águas Claras Formation deposited between 2.75 and 2.64 Ga (Dias *et al.* 1996).

The Itacaiúnas volcanic and sedimentary rocks underwent metamorphism from lower greenschist to upper amphibolite facies and most researchers (*e.g.* Gibbs *et al*. 1986, Docegeo 1988, Olszewski *et al*. 1989, Lindenmayer & Fyfe 1992, Winter 1994, Villas & Santos 2001; Galarza *et al*. 2002) believe they were generated and deposited in an ensialic rift environment. The Águas Claras Formation is only slightly metamorphosed and is composed mainly of arenites of shallow-marine and fluvial settings.

The Itacaiúnas Supergroup hosts some of the most important mineral deposits of the Carajás Province, namely the Cu-Au deposits of Salobo, Igarapé Bahia, Sossego and Cristalino, the Cu-Zn deposit of Pojuca, the large oxide iron-formations known mainly near the village of Carajás (*e.g.* N1, N4 and N5), and the manganese deposits of Sereno and Buritirama (Fig. 1).

Deformed granites dated *ca.* 2.75 Ga and 2.57 Ga (Machado *et al.*1991, Barros *et al*. 2004), minor late-Archean mafic sills and dikes, and undeformed, anorogenic granites of 1.88 Ga (Tallarico *et al.* 2004) intrude the older metamorphic units and some of the deposits.

GEOLOGY OF THE IGARAPÉ BAHIA DEPOSIT The Igarapé Bahia Cu-Au deposit constitutes an erosive window in the younger, areally extensive Águas Claras metasedimentary rocks (Figs. 1 and 2). The upper part of the deposit comprised an approximately 150 m thick, gossan-laterite cap that constituted the

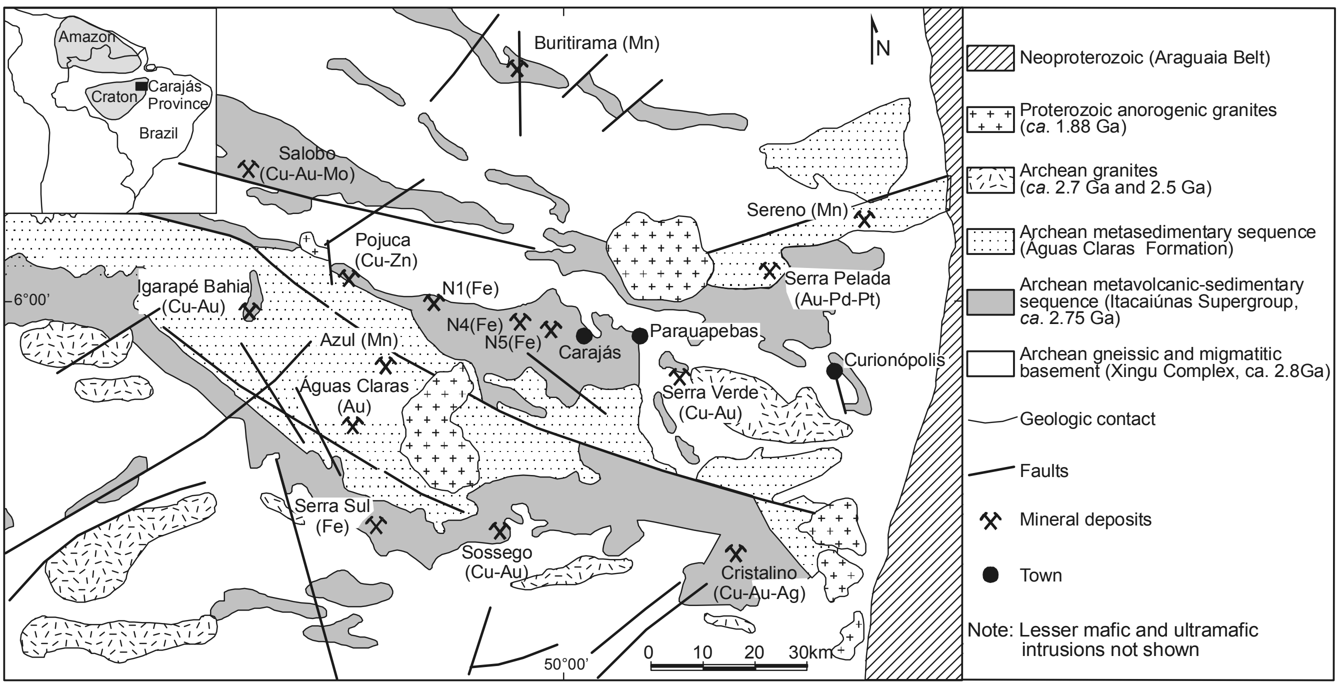

Figure 1 - Geological map of the northern part of the Carajás Mineral Province, Brazil (simplified from Docegeo 1988 and Tallarico et al. 2000).

Igarapé Bahia gold mine. Open pit mining by Companhia Vale do Rio Doce (CVRD) produced an average 10 t / year of gold from this deposit until 2002, when the operation was stopped. The mentioned gossan-laterite zone developed through the supergene alteration of rocks of the Igarapé Bahia Group, considered by Docegeo (1988) as a low greenschist-facies unit of the Archean volcano-sedimentary Itacaiúnas Supergroup.

The primary orebody, intersected by drilling down to 150-200 m, is a magnetite-chalcopyrite-rich fragmental layer that lies right at the boundary between a lower essentially mafic metavolcanic unit and an upper dominantly metasedimentary sequence (Figs. 2 and 3). The fragmental unit is a roughly tabular and concordant body about 2 km long and 30 to 250 m thick that was tilted to an upright position together with its enclosing rocks and later disrupted by various faults and mafic dikes. The three main segments of the fragmental body, known as Acampamento Norte (ACN), Acampamento Sul (ACS) and Furo Trinta (F30) dip steeply (about 80° NW, NE and SE, respectively) within a semicircular feature, as shown in Figure 2.

The so-called Alemão deposit (Barreira *et al.* 1999, Soares *et al.* 1999, Ronzê *et al.* 2000), situated immediately NW of Igarapé Bahia, below a cover of Águas Claras metasedimentary rocks, represents a particularly Cu-Au-enriched segment of the ACN orebody. According to Santos (2002), the Alemão consists of a concordant, almost vertically dipping, mineralized fragmental rock body, about 500 m long and 50 – 250 m thick (Figs. 2 and 4). Estimated resources for the Alemão segment have been quoted as 170 Mt @ 1.5% Cu and 0.8 g/t Au (Cordeiro 1999).

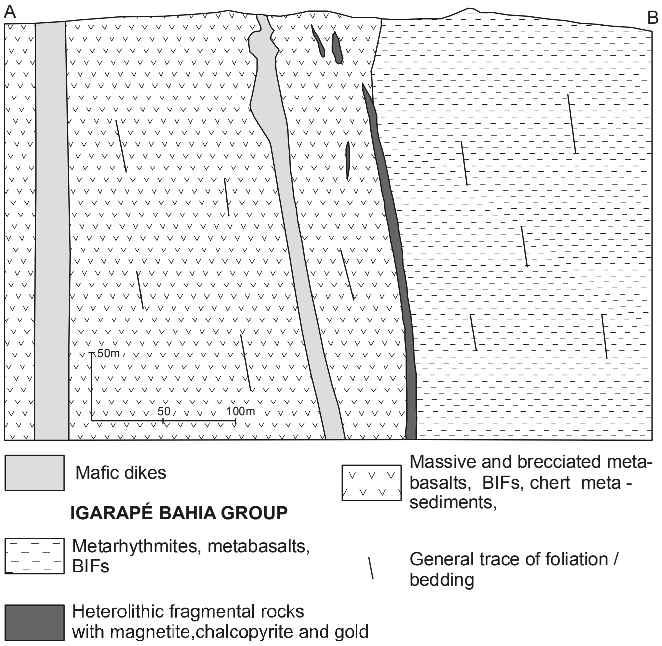

Figure 3 – Vertical section of the Furo Trinta orebody (slightly modified from CVRD 2000).

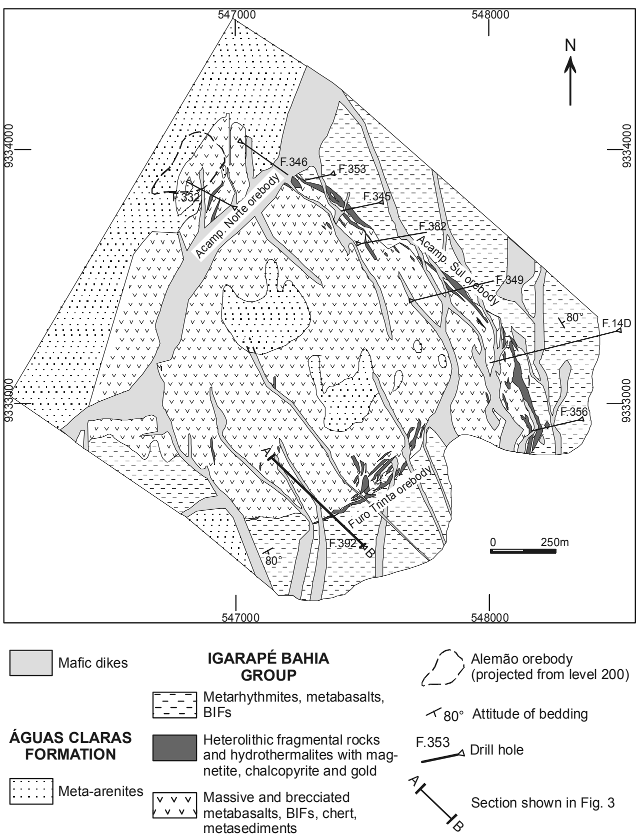

Figure 2 – Geological map of the Igarapé Bahia mine and investigated drill-holes (slightly modified from CVRD 2000).

Isotopic dating on zircons from the hosting metavolcanic and metasedimentary rocks of Igarapé Bahia produced similar ages of *ca*. 2.74 – 2.75 Ga (Galarza *et al.* 2002, Santos 2002, Tallarico *et al.* 2005). The unmetamorphosed mafic dikes that crosscut the Igarapé Bahia rocks as well as the Águas Claras metasediments (Fig. 2) have a maximum age of 2.67 Ga (Tallarico *et al.* 2005).

Mineralization is mostly confined to the matrix of the fragmental rocks and comprises disseminated to locally massive, fine-grained

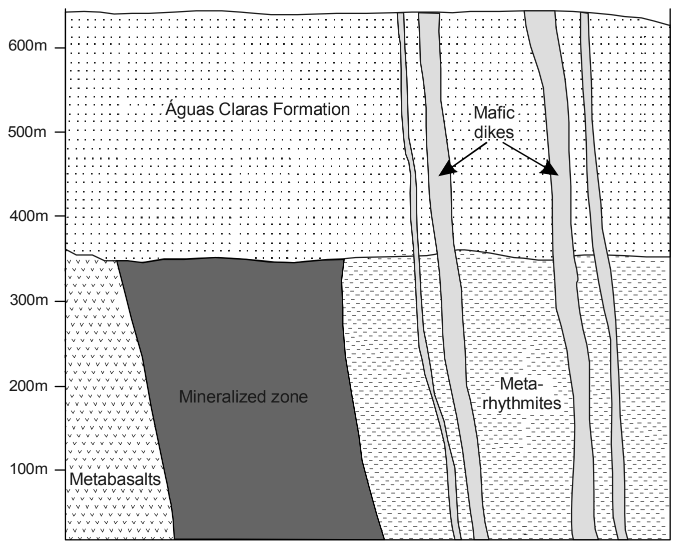

Figure 4 – Vertical section of the Alemão orebody (extracted from Santos 2002).

chalcopyrite with associated magnetite, gold, and minor other sulfides including bornite, cobaltite, molybdenite, digenite and pyrite. A massive sulfide intersection of about 40 m is referred to by Barreira *et al.*(1999) at the Alemão segment.

Fine-grained chalcopyrite also occurs as disseminations in some brecciated footwall metabasalts as well as in nodules and pore space and fracture fillings in thin sandstone layers of the upper metasedimentary rocks. Chalcopyrite is also present in coarse-grained, centimeter-thick, quartz-carbonate-sulfide veins that crosscut the fragmental layer, the hosting metavolcanic and metasedimentary rocks, as well as the younger Águas Claras meta-arenites. Chalcopyrite- and magnetite-bearing veins are also found occasionally cutting the mafic dikes, indicating that some, if not all, of the veins are younger than 2.67 Ga. The quartz-calcite-cemented hydraulic breccias registered by Santos (2002) in meta-arenites of the Águas Claras Formation that overlie the Alemão segment probably also belong to these late veining events that affected the Igarapé Bahia area.

Pb/Pb datings of chalcopyrite from three orebodies (ACN, ACS and F30) of Igarapé Bahia returned ages of 2,768 ± 29 Ma (Villas & Santos 2001) and 2,764 ± 22 Ma (Galarza *et al.* 2002a). According to the mentioned authors, these ages indicate that mineralization in the fragmental unit was syngenetic and approximately coeval with the enclosing volcanic and sedimentary rocks. However, Tallarico *et al.* (2005) argue that mineralization at Igarapé Bahia is epigenetic and approximately 175 Ma younger than its host-rocks based on a U-Pb age of 2,575 ± 12 Ma obtained in monazite from the fragmental rock matrix. Pb-Pb ages around 2.5 Ga were also obtained by Santos (2002) on sulfides and gold of the Alemão segment.

The lower metavolcanic rocks The footwall rocks to the fragmental unit of Igarapé Bahia are mainly metabasalts displaying massive, amygdaloidal and brecciated textures. Quartz-magnetite BIFs, chert, diabase and minor clastic sediments are also present. Geochemical studies by Sachs (1993) showed the presence of rare andesites and dacites among the basalts and indicated that volcanism at Igarapé Bahia is of tholeiitic affiliation.

The massive and amygdaloidal metabasalts constitute very fine-grained, stratiform units that indicate they belong to flows. These rocks are strongly chloritized and show slightly foliated structures under the microscope. The amygdaloidal basalts usually contain a few small vesicles suggesting, according to Ferreira Filho (1985), a low content of volatiles in the magma.

The massive and amygdaloidal metabasalts usually grade into brecciated basalts and an alternation of massive and brecciated rocks occurs in drill cores as the contact with the mineralized fragmental layer is approached. The brecciated metabasalts are both strongly chloritized and silicified and can be in most cases characterized as in situ hyaloclastites and autobreccias, formed by angular basaltic or volcanic glass particles (Fig. 5A). These rocks are considered as non-explosive volcanic products formed by quench fragmentation of lavas in contact with cold seawater (McPhie *et al.* 1993). Typical pyroclastic rocks, composed of crystal fragments, pumice, and/or glass shards, were not identified in this unit.

The mineralized fragmental rocks The Igarapé Bahia extensive unit of fragmental rocks is formed by heterolithic, mainly matrix-supported rocks, although clast-supported varieties are also present. Sorting and roundness are usually poor, with fragments ranging from one millimeter up to more than a meter across and showing angular to rounded shapes. Jigsaw-fit textures are rarely seen in these rocks and no layering is visible, although locally some clasts may be oriented and aligned.

The lithic clasts in the fragmental rocks consist mainly of basalt and quartz-magnetite BIF (Figs. 5B, 5C, 5D) with lesser chert (Figs. 5B and 5E), siliciclastic sediment and brecciated BIF clasts. The basaltic fragments show the same massive, fine amygdaloidal or brecciated textures of the footwall basalts. The presence of BIF fragments indicates that iron-formation layers covered the basic flows at Igarapé Bahia, which is a commonplace feature elsewhere in the Carajás region.

The matrix of the fragmental rocks is fine-grained, massive to slightly foliated, and composed mainly of Fe-rich minerals like magnetite, siderite, Fe-chlorite and chalcopyrite. Stilpnomelane, Fe-amphibole, apatite, quartz, cobaltite, molybdenite, tourmaline, epidote, bornite and digenite are locally important components. Less common phases are pyrite, chalcocite, covellite, fluorite, biotite, cassiterite, ferberite, ferropirosmalite, monazite, uraninite and ilvaite (Tazava 1999, Tallarico *et al.* 2000). According to Tallarico *et al.* (2005), the fragmental rocks may contain up to 15 g/t Au, 380 ppm U, and La and Ce contens of up to 1000 ppm each.

Gold usually occurs associated with sulfides like cobaltite and chalcopyrite (Daleffe 2001, Santos 2002) but may also be found as inclusions in other minerals. Magnetite in the matrix is often subhedral or anhedral and apparently corroded by chalcopyrite. Chalcopyrite is usually anhedral (Fig. 5F), suggesting that it crystallized late or was remobilized during metamorphism, as is usual for very ductile sulfides (Vokes 2000).

Matrix-rich fragmental rocks with diffuse banding and containing scattered, very small and partly replaced clasts also occur, particularly in deep reaches of the ACN and northern ACS orebodies. These rocks have been termed hydrothermalites by various authors (Ronzê *et al.* 2000, Tazava & Oliveira 2000, Santos 2002) and are made up of almost pure chalcopyrite and magnetite.

The lower greenschist facies metamorphism that affected the fragmental rocks produced chlorite and/or carbonate pressure fringes adjacent to the lithic fragments, a slight foliation in most of the rocks, and elongate chalcopyrite grains. These features are apparent in the matrix of many of the breccia varieties (Figs. 5C, 5D and 5E), particularly in samples from the Alemão segment (see photographs shown by Ronzê *et al.* 2000 and Santos 2002).

The upper metasedimentary rocks The rocks that overlie the fragmental unit are mainly interlayered clastic metasedimentary rocks like meta-arenites, metasiltites and meta-argillites. Less common rocks in this sequence include BIFs, metabasalts, chert, diabase and possibly tuffs. The clastic sedimentary rocks have been termed metarhythmites by Docegeo (1988) and are here interpreted as a turbiditic assemblage following Bocalon (1997).

The meta-arenites have pale grey or pale greenish-grey colors and commonly constitute centimeter-thick layers displaying sharp planar basal contact and well-defined graded bedding with upward transition into siltite or argillite. However, massive arenite beds up to meter-thick, with poor or no particle size grading and lacking internal stratification, are also present, mainly in the lower part of the hanging wall sequence. These rocks were possibly deposited rapidly, from high-density turbidity flows (Einsele 1991). The metasiltites and meta-argillites are usually darker than the arenites and occur more commonly towards the middle and upper parts of the hanging wall pile, although in the northern ACS orebody they

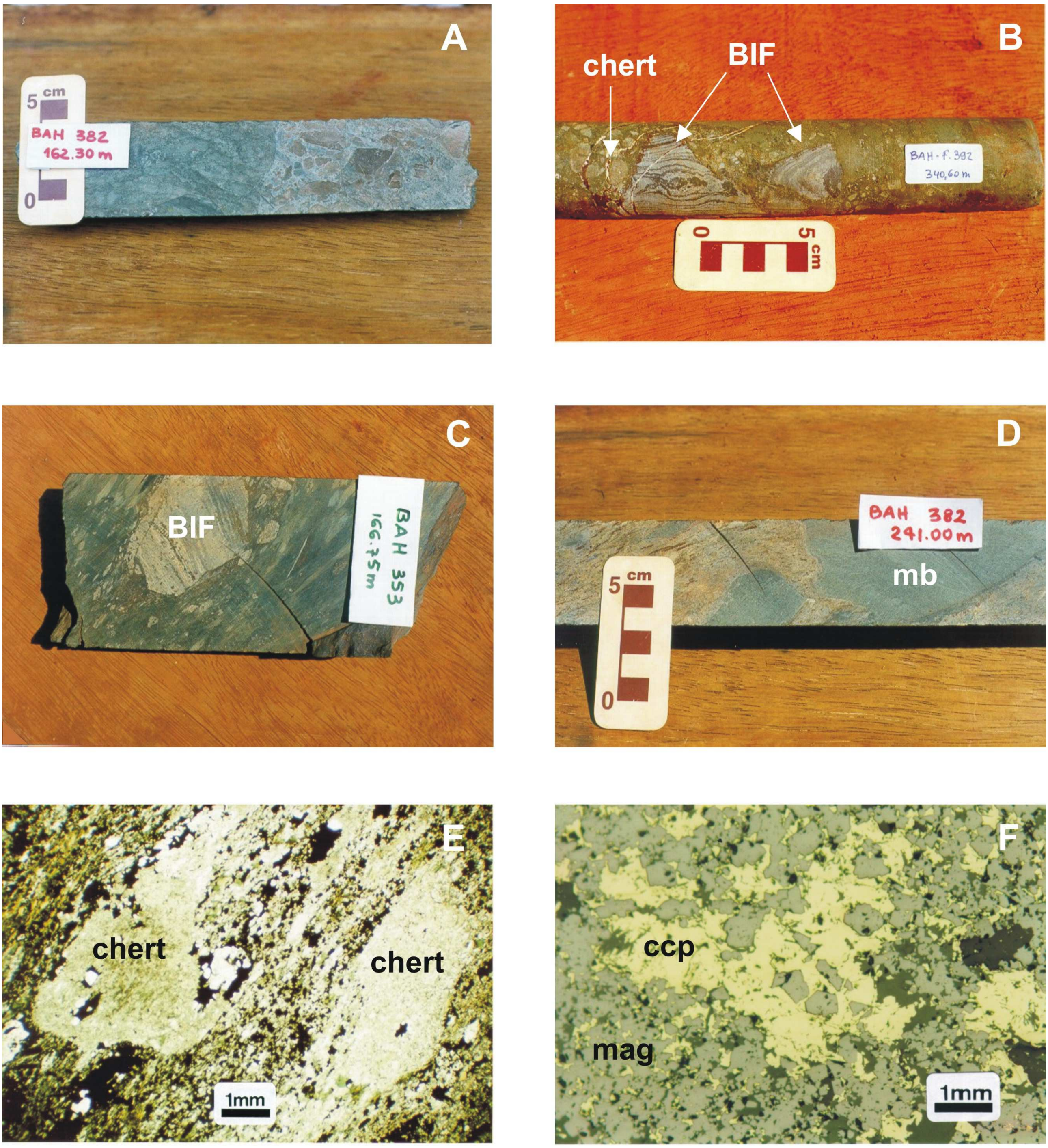

Figure 5 – Metavolcanic and fragmental rocks of Igarapé Bahia. (A) Footwall hyaloclastite showing a brecciated texture. Fragments are not well defined on the left half of the sample, but angular clasts can be seen on the right side, displaying a jigsaw-fit texture characteristic of quench fragmentation. Sample BAH382/162.30m. (B) Heterolithic, matrix-supported fragmental rock containing large angular BIF clasts and smaller, rounded chert particles set in a fine-grained matrix. Sample BAH392/340.60m. (C) Matrix-supported fragmental rock with a large BIF clast set in a fine, foliated matrix made up of Fe-rich silicates, magnetite and chalcopyrite. Sample BAH353/166.75m. (D) Fragmental rock formed of large, rounded, massive-textured metabasalt clasts (mb) surrounded by a slightly foliated, siderite-chalcopyrite matrix. Sample BAH382/241.00m.(E) Photomicrograph of a fragmental rock containing chert particles set in a foliated matrix made up of chlorite, carbonate and disseminated, elongate chalcopyrite grains (in black). Sample BAHF382/287.15m. Plane polarized light. (F) Photomicrograph of the matrix of a fragmental rock containing abundant, euhedral to anhedral magnetite (mag) and anhedral chalcopyrite (ccp). Sample BAH353/177.35m. Reflected light.

lie directly on top of the fragmental layer. They constitute millimeter-scale plane-parallel strata that alternate regularly with each other forming thick laminated sequences (Figs. 6A and 6B). These are usually interpreted as distal D-E turbidites (Bouma 1962), deposited from medium to low density currents.

The upper metasedimentary rocks are composed mainly of chlorite, sericite, angular to sub-rounded quartz grains and lesser feldspar and biotite. The meta-arenites usually contain somewhat rounded fragments of chert and basic to acid volcanic lithic grains. Elongate mudstone intraclasts dark grey in color contained in some of the arenites (Fig. 6C) were interpreted as flattened pumice fragments by Ferreira Filho (1985). We consider these to be rip-up clasts that resulted from erosion of pelitic layers by dense turbidity flows. Juvenile pyroclasts such as pumice or bubble-wall shards were not recognized in these rocks, implying that the latter are not syn-eruptive, but essentially detrital sedimentary deposits formed by reworking of volcanogenic material, as defined in McPhie *et al.* (1993). The only possibly primary pyroclastic rocks in the sequence are fine-grained laminated sheets of acid ash-tuffs that occasionally occur interlayered with the detritic metasediments.

Striking features of the upper metasedimentary rocks are their abundant slide, slump and disruption structures as well as the presence of breccia and conglomerate interbeds. These features occur in between apparently undeformed layers, suggesting that they formed mostly in situ and are related to repeated tectonic disturbances probably linked to growth faulting. The fine laminated siltite-argillite metaturbidites, as well as the occasional BIF horizons, usually display contorted bedding caused by folds or small-scale faults (Fig. 6B), which may indicate that the sediments were only partially lithified by the time of deformation. The coarser-grained arenite-metaturbidites in turn often show bedding disruption (Figs. 6C and 6D), possibly associated with liquefaction or fluidization processes (Lowe 1975), whereas breccia and conglomerate interbeds record yet more advanced deformation, involving

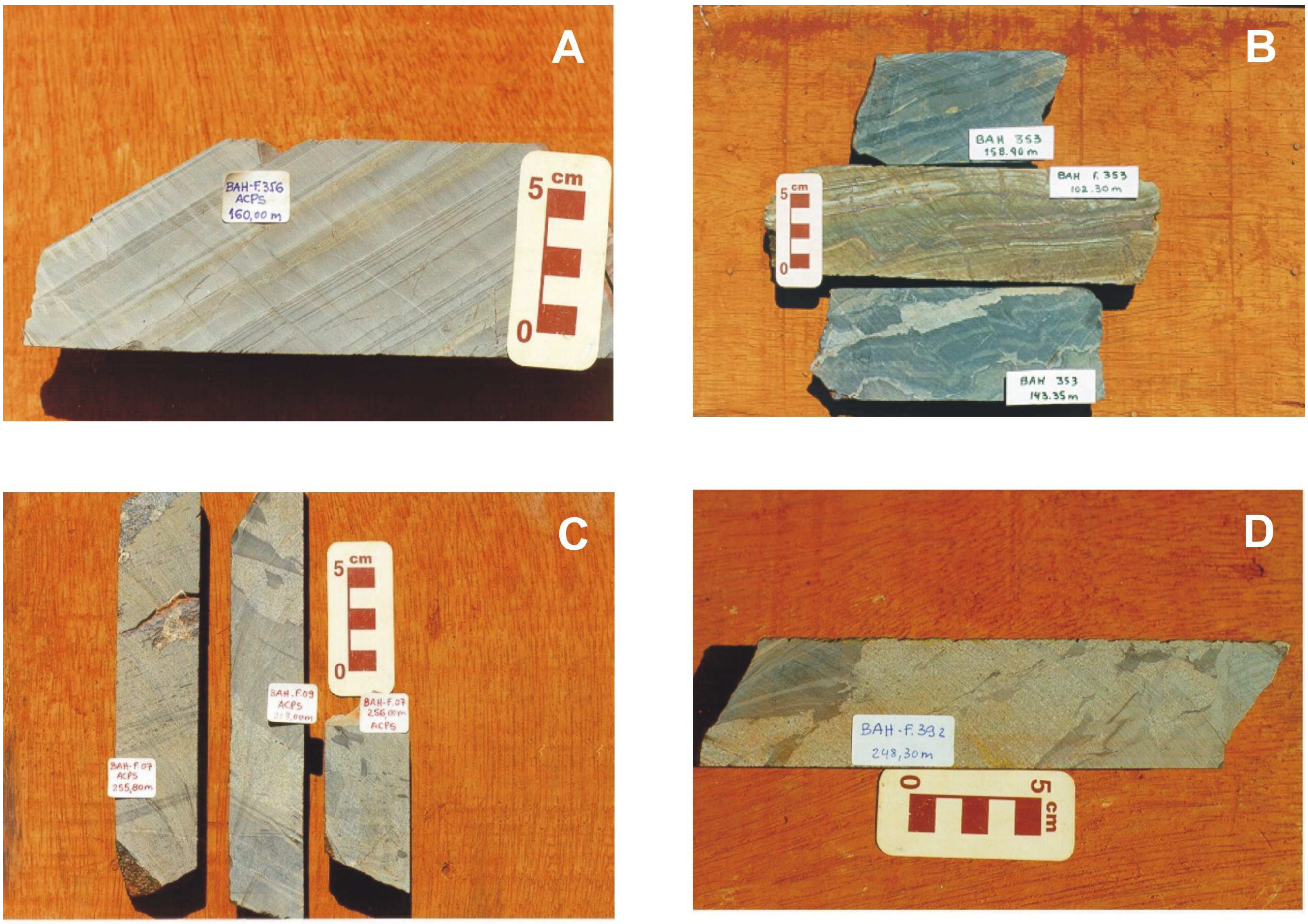

Figure 6 – Metasedimentary rocks of Igarapé Bahia. (A) Drill core sample of a metarhythmite from the upper metasedimentary unit showing an undisturbed laminated structure. Sample BAH356/160.00m. (B) Fine-grained argillite-siltite-metaturbidites or metarhythmites showing contorted bedding caused by folding and small-scale faulting. Samples BAH353. (C) The drill core sample on the left (BAH07/255.80m) consists mostly of meta-arenite containing dark, elongate and aligned argillite particles possibly derived from the erosion of argillite layers. The other samples on the right (BAH09/213.00m and BAH07/256.00m) display argillite clasts (dark grey) in arenite (light grey), possibly originated through liquefaction or fluidization processes. (D) Disrupted bedding in hangingwall metasedimentary rock. Disruption was probably caused by fault-related synsedimentary slump and dewatering processes. Sample BAH392/248.30m.

disaggregation and even reworking of locally-derived sediments.

DEPOSITIONAL SETTING OF THE IGARAPÉ BAHIA ROCKS The presence of BIF, chert, hyaloclastite and autobreccia associated with the mafic flows demonstrates that the rocks of the lower metavolcanic unit were formed in a submarine environment. Dreher & Xavier (2001) suggested a deep marine setting for the Igarapé Bahia volcanism based on the weak vesiculation in lavas and the absence of pyroclastic products among the basaltic rocks. However, according to Huston & Cas (2000), the mentioned features should not be considered as reliable indicators of any specific water depth. This notwithstanding, these features attest the essentially non-explosive character of the mafic volcanism at Igarapé Bahia. The BIF and chert layers among the mafic flows are diagnostic of periods of tectonic stability and volcanic quiescence that were suitable for chemical precipitation from hydrothermal fluids discharging onto the sea floor.

The predominance of basalt and BIF clasts in the fragmental rocks indicates that most clasts were derived from the immediate footwall rocks to the fragmental unit. From these data it can be assumed that the fragmental rocks of Igarapé Bahia represent an intraformational unit located at the base of the dominantly sedimentary upper sequence. With respect to their general matrix-supported, unlayered structure and concordant character, they are comparable to debris flow deposits, as previously noted by Almada & Villas (1999) and Dreher & Xavier (2001). According to Einsele (1991), debris flow deposits are commonly associated with sudden subsidence events related to active faulting.

The occurrence of turbidites, in turn, indicates that a deep marine environment prevailed during the deposition of the hanging wall rock unit. Thus, the general stratigraphy of the Igarapé Bahia sedimentary sequence comprises a thick basal fragmental or debris flow unit, overlain by deep-water turbidites displaying widespread slump and disaggregation textures. This assemblage is typical of the so-called gravitational or mass flow deposits (Tucker 1981, Einsele 1991) that commonly record events of extension and sudden collapse of part of the sea floor adjacent to a growth fault (Fig. 7). The siltite-argillite turbidites represent the subsequent, gradual infilling of the basin by finer-grained material, equally accompanied by recurrent tectonic activity along the fault.

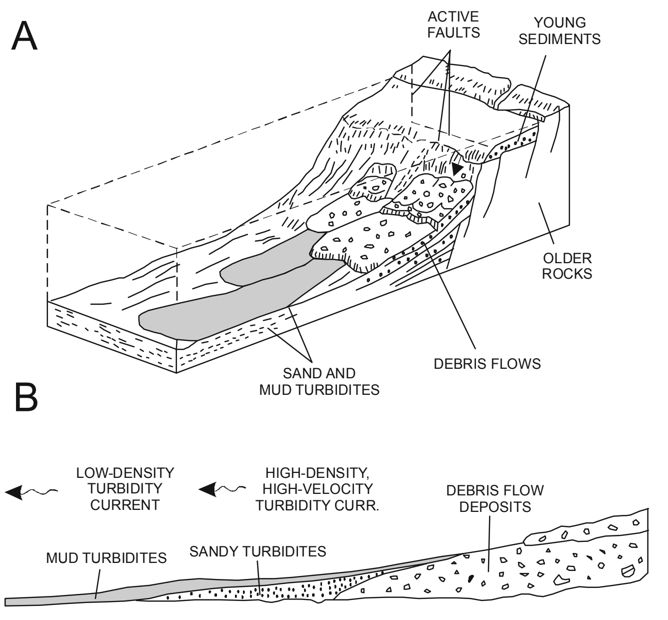

Figure 7 – Gravity or mass flow deposits. (A) Depositional setting adjacent to active faults; (B) Main features (modified from Einsele 1991)

MAIN HYPOTHESES ON THE ORIGIN OF THE FRAGMENTAL ROCKS The Igarapé Bahia Cu-Au deposit has been considered in many recent publications (Barreira *et al*. 1999, Tazava & Oliveira 2000, Ronzê *et al.* 2000, Groves & Vielreicher 2001, Tallarico *et al*. 2005) as belonging to the Fe-oxide-Cu-Au (or IOCG) class of deposits defined by Hitzman *et al*. (1992). This view takes into account the abundance of magnetite, the geochemical association of elements in the ore (*e.g*. Fe, Cu, Au, U and LREE) and the concentration of the ore in fragmental rocks described as hydrothermal or hydraulic breccias. Both ore and breccias are interpreted as epigenetic and formed simultaneously, being comparable to those occurring at the Proterozoic Cu-Au Olympic Dam deposit, in Australia. Ages of *ca.* 2.5 Ga for the ore, determined by Santos (2002) and Tallarico *et al*. (2005), are used to reinforce the epigenetic character of the breccias and associated mineralization.

However, our data obtained so far demonstrate that the epigenetic origin of the breccias is difficult to sustain, particularly with respect to the age of *ca*. 2.5 Ga determined for its formation. An important aspect refers to the concordant or strata-bound character of the fragmental unit, which occurs confined to the contact between the footwall metavolcanics and upper metaturbidites. Hydrothermal or hydraulic breccias would not necessarily be conformable and would more probably constitute an irregular body of rock crosscutting different units. The fragmental rocks of Igarapé Bahia also only very occasionally display jigsaw-fit textures, considered typical of hydraulic breccias and indicative of i*n situ* fragmentation processes. Other evidence shows that the Igarapé Bahia fragmentals are mostly foliated rocks that were formed prior to metamorphism and tilting to the present upright position of the Igarapé Bahia Group, and that were subsequently cut by undeformed mafic dikes, which have a maximum age of 2.67 Ga (Tallarico *et al.* 2005). Furthermore, the geological section presented in Figure 4, reproduced from Santos (2002), clearly shows that the mineralized fragmental rocks do not transect the Águas Claras Formation meta-arenites that overlie the Alemão segment, whereas the above-mentioned mafic dikes actually do. This demonstrates that the fragmental rocks must be older than 2.5 Ga.

Up to this moment, no rock specimen similar to the mineralized Igarapé Bahia fragmentals was found hosted in the Águas Claras unit. This reinforces the idea that the fragmental rocks were formed prior to the deposition of the Águas Claras sediments being consequently coeval with or very close in age to the Igarapé Bahia Group rocks.

Almada & Villas (1999) and Villas & Santos (2001) interpret Igarapé Bahia as a magnetite-Cu-Au deposit generated in a volcanic-exhalative system. The mentioned authors inferred the Igarapé Bahia fragmental rocks to be contemporaneous with their host rocks, and to have originated by a phreatic explosive event followed by later redeposition as a debris flow deposit. The evidences used by Villas & Santos (2001) for a syngenetic origin are in part the same mentioned in the preceding paragraphs, reinforced by datings on sulfides that yielded ages of 2.76 Ga, considered very close to the age of the hosting Igarapé Bahia rocks. However, the admitted explosive event that generated the fragmental rocks was certainly not related to a volcanic or phreato-magmatic event as there are no evidences of explosive volcanism at Igarapé Bahia. A purely phreatic event, on the other hand, is a more consistent possibility, although Almada & Villas (1999) and Villas & Santos (2001) should have stressed the need of a steep submarine slope to explain the considerable mass movement experienced by the ejected material and its accumulation as an extensive debris-flow deposit. In our view, the topography and instability associated with a growth fault explain the generation of the fragmental rocks without the need of a phreatic explosive event.

PROPOSED ORIGIN OF THE FRAGMENTAL ROCKS The alternative proposed in this paper is to consider the fragmental rocks of Igarapé Bahia as a syngenetic debris flow deposit, related to growth faulting (Fig. 8). The resemblance to debris flow deposits refers not only to the strata-bound character of the fragmental unit but also to its unlayered, predominantly matrix-supported structure and poorly selected, locally-derived clastic content.

The presence of ancient growth faults at Igarapé Bahia should be considered as highly probable, as such faults are inherent to rift settings, remaining active during most of the evolution of these environments. According to Sangster (1999), debris flow deposits can be used as a reliable evidence of the presence of primitive syndepositional faults, even in cases in which these faults can not be identified, due for instance to later igneous intrusions or tectonic reactivation.

Further evidence of the presence of ancient growth faults is given by the presence of turbidites - also considered as gravity flow sediments - and by the abundant slide and disruption structures shown by these rocks, indicative of tectonic instability. The high concentration of mafic dikes in the Igarapé Bahia mine area may equally indicate that the site contained major deep-penetrating faults that were reactivated from time to time, rendering the area a structurally permeable and adequate one to the emplacement of intrusions and channeling of mineralizing fluids (*e.g.* Hodgson 1989).

Fragmental rocks have an important role due to their porosity and permeability making them susceptible to mineralization by open-space filling and replacement processes. Evidences such as the confinement of the ore almost exclusively to the fragmental unit, particularly to its matrix, and the presence of apparently corroded and partly replaced lithic clasts strongly suggest that strata-bound replacement and infilling processes occurred at Igarapé Bahia (Dreher & Xavier 2001, Dreher 2004).

Fragmental rocks similar to the Igarapé Bahia ones are also reported from other sites in the Carajás region, as at the Pojuca Cu-Zn deposit (Winter 1994) and near the N4E iron deposit (Hoppe *et al*. 1987). The mentioned authors describe such rocks as intraformational breccias or conglomerates probably originated by growth faulting. The fragmentals at Pojuca, termed "rochas com fragmentos" (Winter 1994), are slightly mineralized and correspond to biotite-garnet schists and hornblende schists containing subrounded clasts of quartzitic rock derived from an underlying mineralized iron formation layer.

CONCLUSIONS The fragmental rocks of Igarapé Bahia constitute an extensive, approximately concordant layer situated between a lower, dominantly metabasaltic unit and an upper metasedimentary sequence, as previously defined by other authors (e.g. Almada & Villas 1999, Tallarico *et al.* 2000, Ronzê et al. 2000, Dreher & Xavier 2001, Santos 2002). The fragmental rocks correspond to heterolithic, mostly matrix-supported rocks composed of angular to rounded clasts mainly of basalt and quartz-magnetite BIFs derived from the lower unit.

The footwall metabasaltic rocks correspond to submarine flows and in situ hialoclastites and autobreccias, with no evidence of associated explosive volcanism. The presence of BIF clasts in the fragmental unit indicates that iron-rich chemical sediments were precipitated over the mafic flows during periods of stability and volcanic quiescence.

The upper metasedimentary unit is composed mainly of arenite and siltite-argillite turbidites showing abundant slide and slump features indicative of a deep, tectonically active subaqueous environment. The argillite intraclasts contained in some arenites were also produced in connection with this unstable setting.

The fragmental rocks of Igarapé Bahia are interpreted as a sedimentary syngenetic deposit that defines a sudden extensional

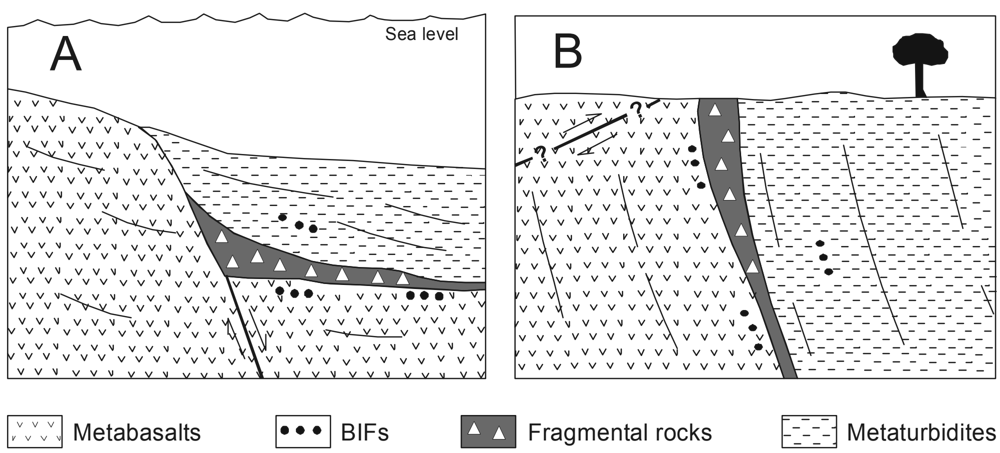

Figure 8 – Model for the generation and evolution of the fragmental rocks of Igarapé Bahia. (A) During Archean times. (B) Present situation.

tectonic event, related to active faulting that resulted in deepening of the Igarapé Bahia basin. The fragmental rocks very likely represent a debris-flow deposit, as originally indicated by Almada & Villas (1999), which accumulated in a submarine depression adjacent to the fault.

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