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Reactivation of Archaean strike-slip fault systems, Amazon region, Brazil

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Abstract: The Itacaiúnas Belt on the southeastern margin of the Amazonian Craton comprises two E–W-trending Archaean fault zones (Carajás and Cinzento strike-slip systems) developed sub-parallel to a broad zone of earlier ductile shearing. Older basement rocks display a pervasive E–W-trending mylonitic fabric, formed at high temperatures during sinistral transpression *c.* 2.8 Ga. A sequence of younger Archaean cover rocks was deformed under low greenschist facies conditions during a second phase of sinistral transpression associated with retrogression and reworking of basement fabrics. All these rocks are overlain unconformably by very low grade to unmetamorphosed volcanic and sedimentary rocks of Late Archaean–Early Proterozoic age. The Carajás and Cinzento strike-slip fault systems formed during subsequent regional dextral transtension (*c.* 2.6–2.7 Ga) which down-faulted cover sequence rocks into dilational fault jogs. Later sinistral transpression (>*c.* 1.9 Ga) partially inverted these dilation zones, producing oblique compressional faults and folds evident mainly in cover rocks. Renewed fracturing, regional emplacement of granitic plutons and swarms of dykes *c.* 1.8 Ga were followed by fault-controlled deposition of immature sandstones and conglomerates. Phanerozoic activity is limited, although some faults display evidence of minor neotectonic activity. The waning influence of the basement architecture and decreasing intensity of later reactivations is consistent with lithosphere-scale weakening with a finite life span.

Keywords: Brazilian Shield, Archaean, cratons, reactivation, strike-slip faults.

The Precambrian rocks forming the South American Platform in Brazil comprise a collage of Archaean cratons separated and internally disrupted by a network of large-scale shear zones or mobile belts (Cordani *et al.* 1984). Some regions were reactivated and reworked during well-known Proterozoic orogenic episodes (e.g. Costa *et al.* 1991), and basement structures are also known to strongly influence Phanerozoic events such as the opening of the present-day South Atlantic (Le Pichon & Hayes 1971; Costa *et al.* 1993). The role of reactivation during the Archaean is less well understood. The current study addresses this problem by examining the Precambrian rocks of the Carajás region (Fig. 1) that lie within a broad E–W-trending zone of Late Archaean ductile deformation, later low grade cover sequences and faults known collectively as the Itacaiúnas Belt (Araújo *et al.* 1988; Araújo & Maia 1991).

Regional geology

The Carajás region lies on the eastern side of the Brazil Central Shield, which forms the southern part of the Amazonian Craton (Fig. 1). The E–W-trending Itacaiúnas Belt is bounded to the east by the Late Proterozoic Araguaia Belt and is obscured to the west by an overlying sequence of Mid-Proterozoic cover rocks (Araújo & Maia 1991; Macambira *et al.* 1994). To the south, it is in contact with an Archaean granite-greenstone terrain, whilst to the north, it is covered by Palaeozoic and Cenozoic sediments related to the intracratonic Amazon Basin (Fig. 1).

The regional tectonostratigraphy of the Itacaiúnas Belt is based on the geological relationship of units to the main phase of basement deformation and associated high grade regional metamorphism. An Archaean Basement Assemblage is

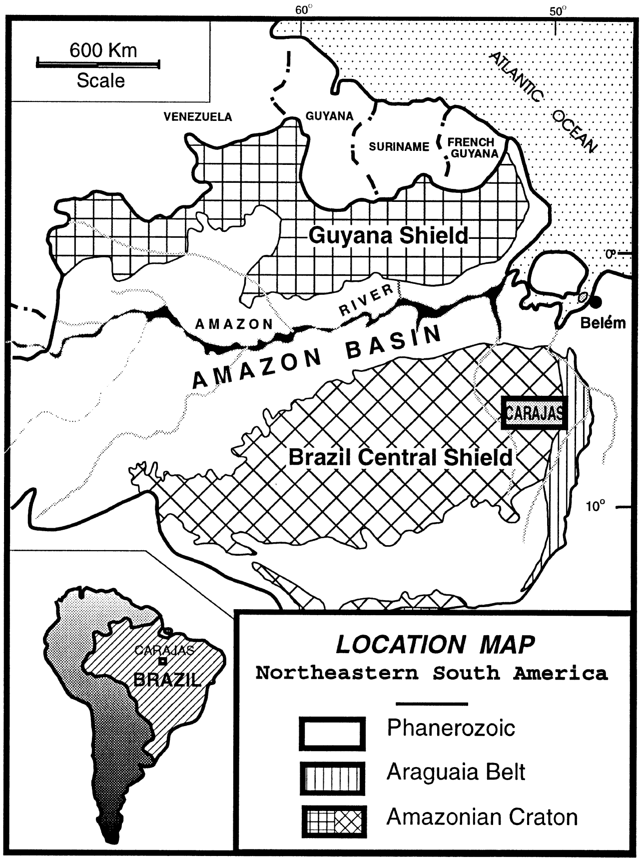

Fig. 1. General location map of the Carajás region in NE Brazil.

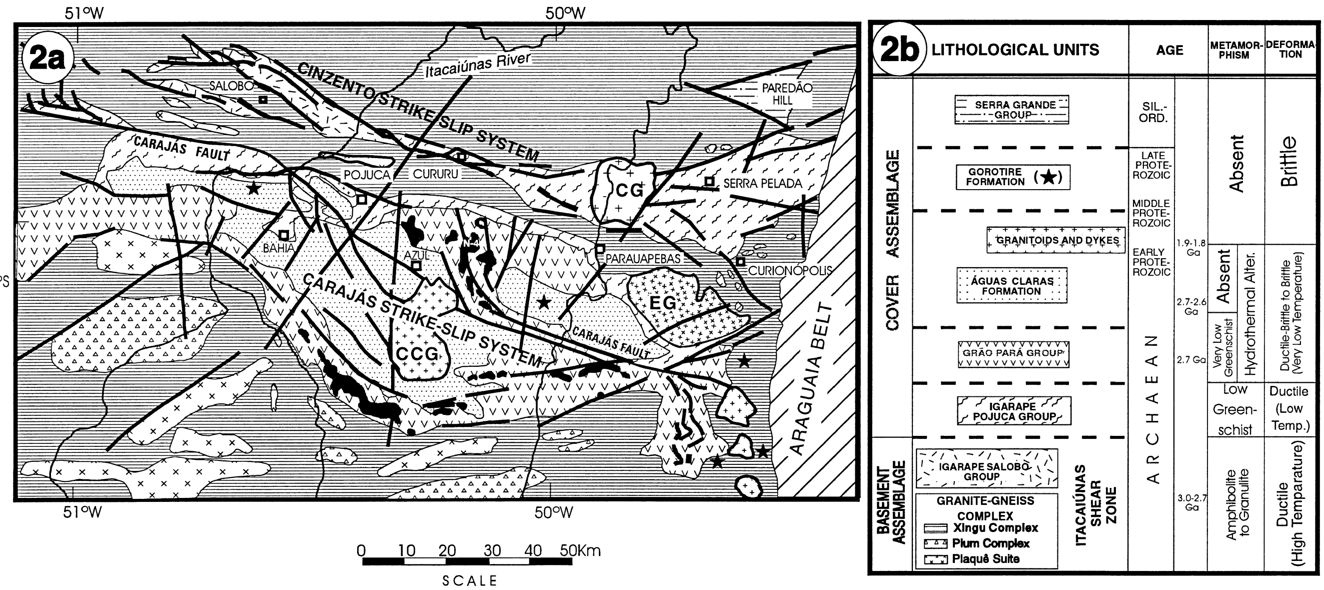

Fig. 2. (**a**) Simplified geological map of the Carajás region in the eastern part of the Itacaiúnas Belt based on the present work. '★' Gorotire Formation outcrops. CCG, Central Carajás Granite; CG, Cigano Granite; EG, Estrela Granite. Based on DOCEGEO (1988); Araújo & Maia (1991); Siqueira (1990) and Pinheiro & Holdsworth (1997). (**b**) Table summarizing the tectonostratigraphy of the Carajás region.

dominated by the Granite-Gneiss Complex (Fig. 2a and b), comprising older granulite facies orthogneisses (Pium Complex; *c.* 3.0 Ga; Rodrigues *et al.* 1992), younger upper amphibolite facies orthogneisses with migmatites (Xingu Complex; *c.* 2.9 Ga.; Machado *et al.* 1991) and syn-tectonic granitoids (e.g. Plaquê Suite; Araújo & Maia 1991). In addition, a younger supracrustal unit of high grade volcano-sedimentary rocks occurs in the north of the region (Igarapé Salobo Group; *c.* 2.7 Ga; Lindenmayer 1990; Machado *et al.* 1991; Fig. 2a and b). All these rocks are deformed in a broad braided zone of steeply-dipping, E–W-trending ductile shearing here termed the Itacaiúnas Shear Zone (Fig. 2b). A Cover Assemblage (Fig. 2a and b) is represented by low- to very low-grade volcanic and sedimentary rocks that are either known or are inferred to rest unconformably on rocks of the Granite-Gneiss Complex. A deformed Archaean sequence of greenschist facies clastic sedimentary rocks (Igarapé Pojuca Group; DOCEGEO 1988) are presumed to be unconformably overlain by less deformed volcanic and ironstone sequences that have suffered only very low grades of regional metamorphism (Grão Pará Group; *c.* 2.7 Ga; Wirth *et al.* 1986). All these rocks are unconformably overlain by an unmetamorphosed sequence of shallow marine to fluvial clastic deposits (Águas Claras Formation; Nogueira *et al.* 1996). The Estrela Granite Complex (Fig. 2a; Barros & Dall'Agnol 1996) is an intrusive granitoid emplaced into the Granite-Gneiss Complex and Igarapé Pojuca Group. The age of emplacement and deformation of this rock is thought to be *c.* 2.5 Ga as it has been correlated with a small, dated (*c.* 2.57 Ga; U–Pb zircon) granitoid at Salobo (Lindenmayer 1990; Barros & Dall'Agnol 1996). Both Cover and Basement assemblages are intruded by *c.* 1.8 Ga A-type granitic plutons and basic dykes, including the Central Carajás and Cigano granites (Fig. 2a and b; Wirth *et al.* 1986). All units are unconformably overlain by a thin, localized sequences of ?Mid–Late Proterozoic (Gorotire Formation; Barbosa *et al.* 1966) and Phanerozoic clastic sedimentary rocks (Serra Grande Group; Caputo & Lima 1984; Fig. 2a and b).

New regional mapping by the authors demonstrates that the high-temperature ductile fabrics in the basement rocks are post-dated by at least three cycles of brittle–ductile strike-slip reactivation at generally low metamorphic grades, leading to the formation of two major E–W-trending fault zones: the Carajás and Cinzento fault systems (Fig. 2a). The early ductile fabrics in the Basement Assemblage appear to significantly influence the geometry of these fault zones, which in turn control the location of Cover Assemblage outcrops and the distribution of later deformations.

High-temperature ductile deformation

The steeply-dipping, generally E–W-trending high temperature mylonitic fabrics defining the Itacaiúnas Shear Zone are thought to have developed under upper amphibolite facies regional metamorphic conditions (e.g. DOCEGEO 1988; Araújo & Maia 1991). A series of anastomosing high strain zones enclose lenticular pods of less deformed gneiss. Radiometric dating (zircon U/Pb) of the shear zones indicates that the metamorphism and deformation occurred toward the end of the Archaean (*c.* 2.8 Ga, Machado *et al.* 1991). According to previous studies, kinematic indicators suggest a regime of sinistral transpression with partitioning of deformation producing linked systems of ductile strike-slip and thrust-dominated shear zones (e.g. Araújo *et al.* 1988; Araújo & Maia 1991). Our studies in well exposed areas (e.g. Itacaiúnas River, Parauapebas–Curionópolis; Fig. 2a), reveal heterogeneous strain intensities with variable lineation orientations that are consistent with a transpressional regime. Synchronous sinistral and dextral shear sense indicators are preserved, with sinistral indicators being dominant regionally; all examples display a significant component of reverse movement.

Low-temperature ductile deformation: the Igarapé Pojuca Group

Clastic metasedimentary rocks of the Igarapé Pojuca Group crop-out in E–W-trending belts along the eastern part of the Cinzento fault zone and on the northern and western borders of the Carajás Strike-Slip System (Fig. 2a). These rocks display moderately to steeply dipping slaty cleavages in pelitic lithologies (e.g. Serra Pelada, Bahia Mine) and low-temperature protomylonitic to mylonitic fabrics in arenaceous-to-quartzitic units (e.g. Cururu, Itacaiúnas River) and basic metavolcanics (e.g. Pojuca Mine, Itacaiúnas River). Deformation textures and mineral assemblages in these rocks are consistent with low greenschist facies regional metamorphic conditions although the effects of hydrothermal alteration are also ubiquitous. The exact relationship between these rocks and the Grão Pará Group are uncertain and controversial (e.g. Araújo & Maia 1991) due to a lack of exposed contact relationships. We suggest that the two groups are separated by an unconformity on the basis that the Igarapé Pojuca Group is more pervasively deformed and that it displays consistently higher temperature mineral assemblages and fabrics compared to the Grão Pará Group. Deformation in the Igarapé Pojuca Group has produced close to isoclinal folding of the sequences on all scales and in well exposed sections (e.g. Serra Pelada), the folds display a consistent clockwise sense of cleavage transection that appears to be consistent with regional sinistral transpression (Pinheiro & Holdsworth 1996). This phase of deformation is presumed to be significantly younger than the Itacaiúnas Shear Zone as the temperatures of deformation are lower and as the Igarapé Pojuca Group is known to unconformably overlie rocks of the Basement Assemblage. Narrow low temperature ductile shear zones and an associated greenschist facies retrograde metamorphism are widespread in parts of the Granite-Gneiss Complex (e.g. Lindenmayer 1990; Araújo & Maia 1991) and may be the same age as the deformation and metamorphism affecting the Igarapé Pojuca Group.

The Carajás–Cinzento strike-slip fault systems

Later brittle faulting led to the formation of two regional, E–W-trending fault zones that are clearly visible on Landsat and radar images: the Carajás and Cinzento strike-slip systems (Fig. 2a). These steeply dipping structures display curved and braided patterns typical of strike-slip fault zones and preserve direct and indirect evidence for several phases of dextral and sinistral movement since *c.* 2.7 Ga. The orientations of the faults are strongly controlled by the trend of pre-existing ductile fabrics in the underlying Basement Assemblage. Where the high grade rocks are exposed, an important set of fractures with significant displacement always occurs sub-parallel to the foliation. On a larger scale, Cover Assemblage rocks are closely associated with the major fault strands and appear to be preserved adjacent to bends, offsets and splays (Fig. 2a). This has led several authors to suggest that the Cover Assemblage rocks were laid down in a series of small dilational jog or pull apart basins along the Carajás and Cinzento faults during a phase of dextral strike-slip movements (e.g. Araújo *et al.* 1988; Siqueira 1990; Araújo & Maia 1991). More recent sedimentological and structural studies (Nogueira *et al.* 1996; Pinheiro & Holdsworth 1996, 1997) have shown that a pull-apart basin model is inconsistent with the stratigraphic and facies patterns of the Grão Pará Group and Águas Claras Formation. All these rocks appear to have been laid down in sedimentary basins of regional extent *prior* to the onset of dextral strike-slip movements which then faulted down previously deformed (Igarapé Pojuca Group) and undeformed (Grão Pará Group; Águas Claras Formation) cover rocks into the basement in a series of dilational jogs along the major fault strands. It is difficult to ascribe individual structures in either basement or cover to this dextral event due to subsequent sinistral and dextral reactivations (see below). It therefore remains to some extent a conjectural episode, based on the distribution of the stratigraphic units in the region.

Sinistral transpression and inversion: the Carajás Fault

Low-temperature brittle–ductile to brittle deformation is highly localized along particular fault strands and pre-existing jogs along major structures, notably the Carajás Fault (Fig. 2a). Here, a narrow (<2 km wide) zone of complex folds and sinistral strike-slip faults is developed in the otherwise little deformed Águas Claras Formation adjacent to the Carajás Fault, whilst larger scale folding and partitioning of sinistral transpressional strains is associated with inversion of Cover Assemblage rocks buttressed against basement in pre-existing dilational jogs (e.g. N-4 mine; Pinheiro & Holdsworth 1997).

Later events

A series of A-type granitoids was emplaced following the sinistral transpression, including the Central Carajás Granite (U–Pb Zircon age of *c.* 1.88 Ga; Wirth *et al.* 1986) which cuts the Carajás Fault system (Fig. 2a). The granite carries mainly N–S-trending magmatic state deformation fabrics and, on the basis of limited exposures, appears to be formed from a series of coalesced N- or NNE-trending subvertical sheets. The form and location of this and other plutons (e.g. Cigano; Fig. 2a) is consistent with emplacement into dilational jogs during minor dextral movements along pre-existing major fault strands. Prominent N–S- and NE–SW-trending extensional and transtensional fracture sets are found throughout the Basement Assemblage (Figs 2 & 3a) and parts of the Cover Assemblage. These are thought to have formed during the Middle Proterozoic, together with similarly oriented basic dykes (Choudhuri *et al.* 1990) thought to be related to a regional NE–SW extensional episode recognized throughout the SE part of the Amazonian Craton (Costa *et al.* 1991). This correlation would imply that pre-existing E–W-trending structures in the Carajás region accommodated limited dextral displacements possibly acting as oblique transfer faults.

Apparently isolated outcrops of immature sandstones and boulder conglomerates (Gorotire Formation; Barbosa *et al.* 1966; Fig. 2b) have been recognized in a number of locations in the Carajás region (labelled '★' in Fig. 2a). These alluvial fan deposits carry clasts of all earlier rock types found in the region, including granitoids petrographically identical to the *c.* 1.8 Ga suite of plutons. The poorly sorted, immature character of the deposits may indicate highly localized derivation, possibly due to local faulting and pull-apart basin formation, although further mapping is required to test this hypothesis. Phanerozoic alluvial sandstones and siltstones of the Serra Grande Formation were down-faulted into the basement (e.g. Paredão Hill; Fig. 2a and b), possibly during the Mesozoic Atlantic opening. Minor displacements continue to the present day as neotectonic activity is indicated along the

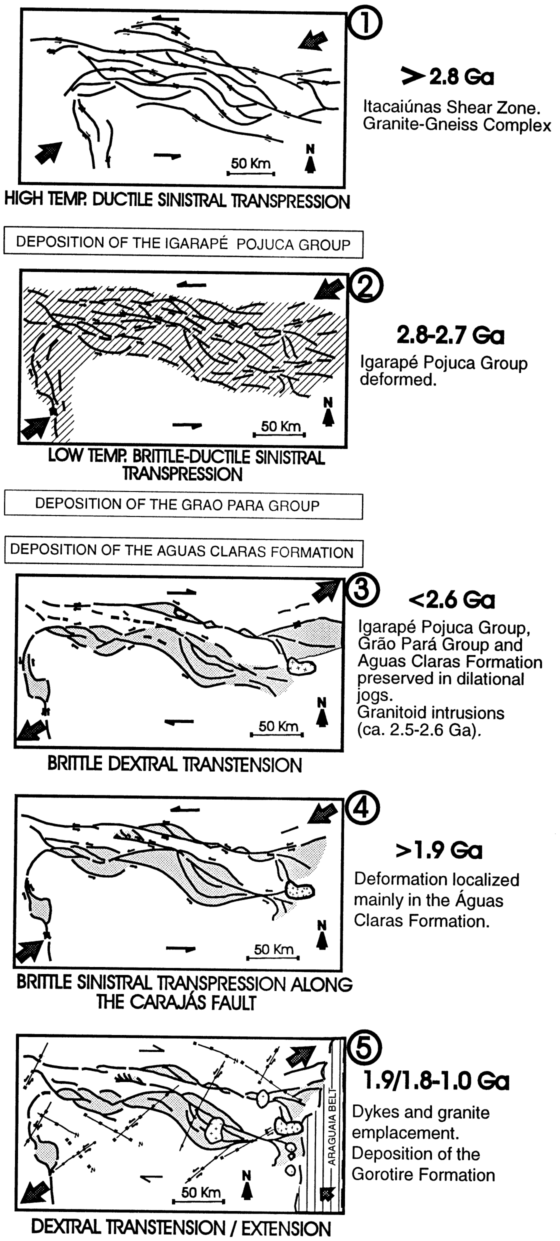

Fig. 3. Summary reactivation history of the Carajás region.

Cinzento Fault based on the occurrence of recent seismicity (Costa *et al.* 1993) and hot springs (e.g. Cururu; Fig. 2a).

Reactivation and weakening

There is good circumstantial evidence that the orientation of the regional basement fabrics has controlled the geometry and location of subsequent deformation events. Reliable criteria indicating reactivation in the Carajás region include: the occurrence of inversion geometries in the previously down-faulted cover sequences; the observed parallelism between successively lower temperature deformation fabrics and faults in basement outcrops, often with changes in shear sense; direct and indirect dating of early high temperature and later events using dated cover sequence unconformities and cross-cutting plutons; the occurrence of neotectonic activity along the fault zones.

The protracted reactivation history suggests that long-term weakening has occurred in the Carajás region. In exposures of the Basement Assemblage rocks, later low temperature ductile shear zones and/or brittle fractures are often seen to run parallel to pre-existing basement fabrics, especially in old high strain zones. This may suggest that geometric or fabric softening has influenced initial reactivation processes, but more obvious weakening effects are associated with the development of these later structures. In particular, the low-temperature brittle–ductile deformations are associated with the extensive retrogression, phyllonitization and hydrothermal alteration of rocks along and adjacent to faults and shear zones. These processes are almost certainly associated with the syn-tectonic influx of fluids and are likely to cause significant and permanent reaction weakening effects.

Conclusions

The structural history of the Carajás region, summarized in Fig. 3, reveals a number of important features concerning the reactivation of Archaean basement terrains.

(1) There is an overall decrease in temperature associated with deformation through time that is consistent with progressive exhumation of the crust. Similar embrittlement sequences are recognized in many other long-lived basement shear zones (e.g. Grocott 1977).

(2) The regional basement fabrics are steeply dipping and E–W trending. Subsequent deformations are wrench-dominated events possibly because the foliation orientation favours strike-slip, as opposed to dip-slip reactivation (cf. Etheridge 1986).

(3) The location of the younger Cover Assemblage rocks is structurally controlled by strike-slip faults. Most cover sequences occur in dilational jogs or offsets along major reactivated strike-slip fault zones. However, faulting entirely post-dates deposition and does not control basin formation.

(4) Strain intensity is often controlled by the location and geometry of pre-existing faults. Thus, deformation may be localized into narrow zones adjacent to major fault strands or into restraining bends or offsets. These local transpression zones may also display kinematic partitioning of strains due to basement buttressing effects or accommodation of different displacement components along differently oriented pre-existing fault sets.

These observations suggest that the Archaean rocks of the Carajás region preserve evidence for over 2.8 Ga of deformational activity during which time the original basement fabric has been reactivated thereby exerting a strong influence over the distribution, geometry and kinematic patterns of later deformations. The influence of the basement architecture and the intensity of later reactivations appears to wane after a time period of about 1.0 Ga following the initial high temperature deformation in the basement. This may indicate the existence of a weakening effect on a lithospheric-scale with a finite life span, possibly originating in the underlying lower crust or mantle. Similar reactivation time-limits may exist in other Precambrian basement terrains.

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