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The Archean-Paleoproterozoic structural evolution of the Caraíba Cu-Deposit, northern São Francisco Craton, Brazil: A historical review of its understanding coevally with the development of a high-risk mining project

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Abstract

The belt of basic-ultrabasic rocks within the Curaçá River Valley Province of the Bahia State, northeastern Brazil, has been known for enclosing several Cu-orebodies that helped sustain the industrial development of Brazil in the last five decades. Caraíba, Vermelhos, Surubim, Terra do Sal, Angicos, Sussuarana are the most prominent of these deposits. The Caraíba Cu-Orebody, so far the most important of all, is part of a body of Archean hypersthenites and norites that underwent poly-deformation and granulitization in the roots of the Paleoproterozoic Itabuna-Salvador-Curaçá orogen, which records the continental collisions responsible for building the São Francisco-Congo paleocontinent in Rhyacian times, ca 2.0 Ga ago. The Caraíba Mine setup happened during the 1970 decade, together with the rush to free the country's economy from the costs of importations, exactly when the first international oil crisis (1974-1978) was suffocating the economy in many countries. Although that time coincided with the boom of geological knowledge associated with the worldwide acceptance of plate tectonics, the study of high-grade metamorphic terrains was still embryonic. In particular, the meaning of the poly-phased tectonic structures in areas recording a high degree of plasticity during deformation remained unraveled. Due to the international economic crisis, everything necessary for running the Caraíba Mine was done under pressure. Nonetheless, the coeval geological studies required for deciphering the area's structural evolution and the mineralization controls, vital for the booming mining planning and profitable exploitation of the Cu ore, had to keep the academic standards for surviving the hurry.

Part of this text is a historical novel as it describes in detail how the convenient geological knowledge of the Caraíba-Cu Orebody could be achieved progressively in the years 1980-1990, well in the middle of the rush affecting everything and everybody working in the Caraíba Mine Project. We emphasize the detailed structural geology studies as the primary tool for guaranteeing timely technical accuracy during the ore's exploitation and profitability in the mine project. As such, it means a historical but profoundly scientific document necessary for those interested in academic and technical purposes related to large-scale mine projects everywhere. Moreover, it highlights the human drama lived by many fortunate professionals in that forgotten semi-desertic area of northeastern Brazil. The experience gained when studying several generations of tectonic structures and metamorphism at Caraíba transformed for the better and forever the lives of several geologists and other professionals equally in charge of operating the Caraíba Mine during those pioneer years.

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1. Introduction

1.1. Motivation for the Review

The need for high-tech metals like copper is increasing in the modern world, once they are strategic and critical commodities playing an essential role in the global shift toward renewable energy (Skirrow et al., 2013; Castro et al., 2022; Silva et al., 2024). According to Garcia et al. (2018), the Curaçá River Valley terrane was the second largest copper producer in Brazil. The Caraíba mine produced approximately 750,000 tons of copper until 2008, and the total reserve of the mine is estimated to be around 96 million tons of ore, containing 1.82% Cu (Teixeira et al., 2010c). Currently, the Ero Copper Company, through Mineração Caraíba S.A. (MCSA), manages the Caraíba Operations, including the Pilar and Vermelhos underground mines and the Surubim open pit mine (additional information can be accessed at

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the technical reports available at https://erocopper.com/operations/caraiba-operations).

It is essential to observe how fundamental is the role of structural geology in allowing successful mining operations of orebodies that have undergone polyphase deformation, especially those that experienced severe temperature conditions such as upper greenschist facies and above. As a live example of this concept, the geology of the Caraíba Copper Orebody (CCO) can provide valuable insights into copper mineralization models in other Precambrian areas, which constitute large part of the Earth's continental crust. The insights are particuly valid if applied to ore deposits in which the deformation was assisted by high amphibolite-granulite metamorphism typical of deeper parts of mountain belts, such as the CCO and the Curaçá River Valley terrane. This contribution is highly relevant because polyphase deformation is the case for many ore deposits (Cu, Pb, Zn, Au, and Ag, for instance) worldwide, regardless of the geological age. If so, it is also important in economic and geological terms.

1.2. Aims of the paper

This work summarizes the history of the geological knowledge at the CCO, which build up necessarily recalls the scientific and practical experience lived by the corresponding author during over thirty years (1977-2010) of engagement with the geology of the high-grade Curaçá River Valley terrane (Appendix 1; A1-1). Moreover, although readers can learn about the geology of the Caraíba orebody and Curaçá terrane (Fig. 1A) through a dozen published scientific papers which followed the works of D'el-Rey Silva (1984, 1985), with emphasis on D'el-Rey Silva (1992), D'el-Rey Silva et al. (1988, 1994, 1996, 2007) and D'el-Rey Silva and Oliveira (1999), by reading this historical review they can get aware of other relevant information that composed the Dissertation but has remained unknown until now, or was not reported conveniently in the published papers. By revealing this information in detail, this paper aims to clarify that the enormous responsibility of a group of specialized technicians for the survival of the mine project could only be satisfied because of the tools provided by structural geology as a key branch of the geological sciences. Moreover, this historical review is also timely, as it may help the mining companies' efforts to explore base metals in the Curaçá terrane.

2. Geological Setting of the Curaçá Valley Copper Province

2.1. Regional overview

2.1.1. The Rhyacian-Orosirian ISAC and Minas-Bahia orogens

Figure 1B introduces the Itabuna-Salvador-Curaçá orogen/belt (ISAC), one of the key lithotectonic units recording the Paleoproterozoic assembly of the São Francisco – Congo paleo continent precursor of the São Francisco Craton, eastern Brazil. According to Sabaté et al. (1990), Barbosa (1996), Aguilar et al. (2017), and Barbosa and Barbosa (2017), the ISAC orogen represents a collisional mountain chain stretching N-S between the Paleoarchean Gavião block, and the Mesoarchean Serrinha, and Jequié continental blocks, in the central-eastern part of the Bahia State (U-Pb age data from Barbosa and Sabaté 2004). In regional terms, the ISAC orogen constitutes part of the northern domain of the Minas-Bahia orogen, which southern part grew wider due to the accretion of continental and juvenile arc material (Teixeira et al. 2017; Barbosa and Barbosa 2017; Aguilar et al. 2017; Bruno et al. 2021).

Within the ISAC orogen, the northern part encloses the surroundings of Caraíba, and the southern part encloses the Ipirá-Lajedinho area. These parts are the most significant in regional geology summaries, such as, for example, in Ribeiro et al. (2021) and references therein.

Nevertheless, once this historical review addresses the geology of the Caraíba orebody, it concentrates on the ISAC´s northern part, which stretches between the Serrinha and Gavião blocks and is known as the Curaçá River Valley terrane (Fig. 2).

2.1.2. The northern Itabuna-Salvador-Curaçá orogen and the Curaçá Valley Copper Province

The ISAC orogen mainly consists of amphibolite to granulite facies tonalitic and charnockitic tectonites with basic-ultrabasic enclaves, as well as supracrustal tectonites, in both its northern and southern segments (Barbosa and Sabaté 2004), in which the latter corresponds to the Ipirá-Lajedinho area, about 300km South of Caraíba (Fig. 1B).

The Serrinha block consists of amphibolite-facies aged 2900-3500 Ma, ortho and paragneisses of granodiorite composition, migmatites and amphibolites (Barbosa and Sabaté 2004). Its eastern part encloses Paleoproterozoic greenstone sequences and arc-like orthogneiss and granites indicative of a Paleoproterozoic back-arc basin (Silva 1996). To the East, this block underlies Neoproterozoic metasedimentary rocks and, further East, the Mesozoic sedimentary rocks of the Tucano basin. The Itiúba Syenite stretches along a large part of the contact between the Serrinha Block and the ISAC orogen.

The Gavião block is mainly composed of gneiss-amphibolite associations, amphibolite-facies tonalite-granodiorite orthogneisses dated at 2800-2900 Ma, as well as greenstone belts and a 3200-3400 Ma trondhjemite-tonalite-granodiorite suite (Barbosa and Sabaté 2004). Its westernmost part is covered by metasedimentary rocks deformed in the Neoproterozoic Brasiliano orogeny and by Quaternary limestones. To the West of the town of Bonfim, this block also encloses the Campo Formoso Cr-bearing mafic-ultramafic layered body, a major Paleoproterozoic intrusion that is unconformably overlain by the Jacobina Group, being all intruded by the late Paleoproterozoic Campo Formoso granite (Silva 1996; Leite 2002). According to Silva (1996) and Santos et al. (2019), the Jacobina Group is part of a much longer Archean rift-like volcanic-sedimentary basin extending further to the South, between the Gavião and Jequié blocks (outside the Fig. 2 southern border).

2.2. Stratigraphy

2.2.1. Introduction

The lithotypes of the northern ISAC orogeny (or Curaçá terrane) are divided into the Tanque Novo-Ipirá and the Caraíba complexes and a complex of migmatitic gneisses and syn-tectonic granitoid intrusions (Jardim de Sá et al. 1982).

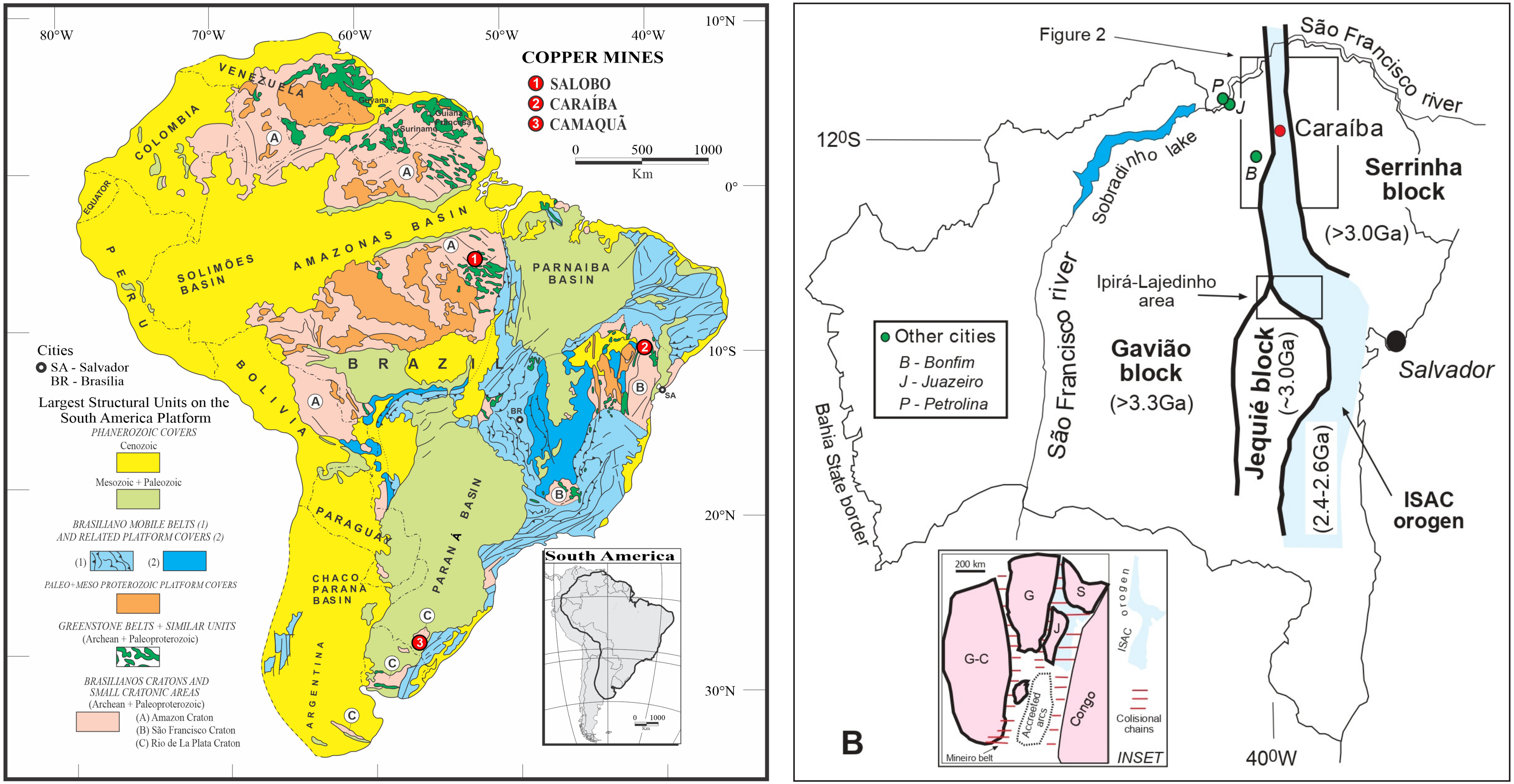


FIGURE 1 - The geological background for the Brazilian Copper Project. A – Summary map of the South American terrane East of the Andes emphasizing the main lithotectonic units in Brazil (based on Dardenne and Schobenhaus, 2001) with an indication of the three primary sources of Copper known in 1976-1978, when the Caraíba Mining Project was conceived. B – Summary diagrammatic map of the Bahia State territory highlighting the main lithotectonic units linked to the evolution of the Itabuna-Salvador-Curaçá (ISAC) and the site of Caraíba (adapted from D'el-Rey Silva et al. 2007; and references therein). The age data within brackets are discussed in the text. The diagrammatic map in the inset accounts for the geological data and interpretation in Aguilar et al. (2017), Bruno et al. (2021), and Barbosa et al. (2021) and represents the build up of the Rhyacian-age São Francisco–Congo paleocontinent precursor to the São Francisco Craton, according to the collision of Archean-Paleoproterozoic continental blocks (G = Gavião; S = Serrinha, J = Jequié, G-C = Guanambi-Correntina in Brazil, and Congo in Africa) and the anastomosed array of intervening collisional chains. The ISAC orogen is the northern part of the Minas Bahia orogenic chain which southern part comprises a great volume of acreted arc material.

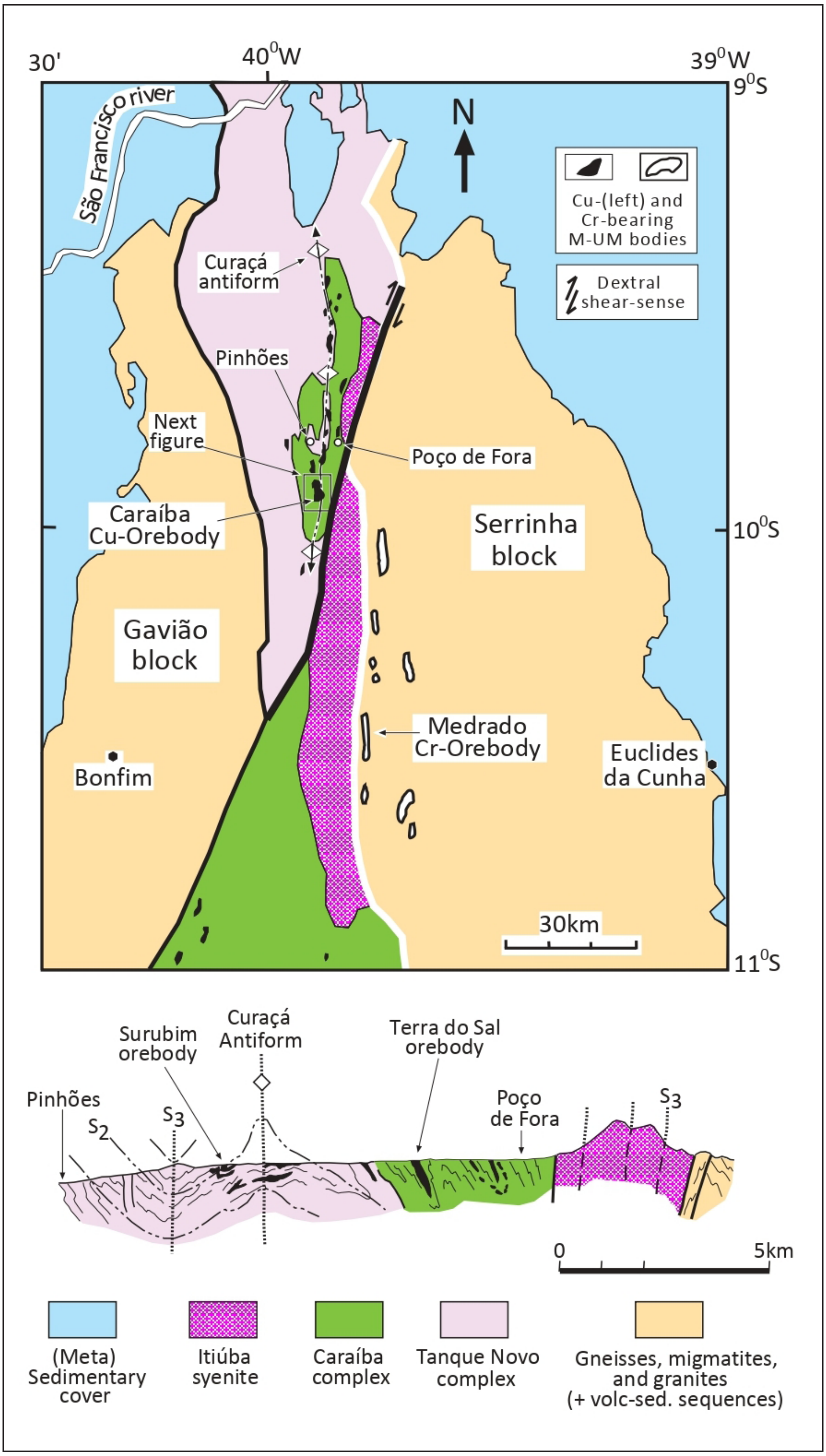


FIGURE 2 - Simplified map of the northern end of the Archean-Paleoproterozoic Itabuna-Salvador-Curaçá orogen (northern São Francisco Craton) emphasizing the Caraíba orebody and other occurrences of Cu-bearing mafic-ultramafic bodies (M-UM) of the Curaçá River Valley terrane (based on D'el-Rey Silva et al. 2007; and references therein). Bottom: vertical geological section across the eastern side of the terrane and boundary with the Serrinha Block, as seen along the road Pinhões-Poço de Fora (adapted from Hasui et al. (1982a, b); Sá and Reinhardt 1984).

Although rock units of these two complexes exist in the northern and southern parts of the orogen (e.g., Ribeiro et al. 2021), the text below focuses on the lithotypes constituting the Curaçá Valley Copper Province, where several bodies of Cu-bearing mafic-ultramafic rocks (including the Caraíba Cu-Orebody; Fig. 2). These bodies, which occur in both the Tanque Novo-Ipirá and Caraíba complexes, make up the scenario of economic mineral interest.

The 2084 Ma old Itiúba syenite separates the 2580 Ma old Curaçá Valley Copper Province to the west, from the 2085 Ma old Jacurici Valley to the east, where is the Medrado Cr-orebody. In addition to the ages above (all U–Pb SHRIMP zircon ages in Oliveira et al. 2004), the existence of reworked Archean rocks has been reported by several other researchers across the entire ISAC orogen (e.g., Leite 2002; Barbosa and Sabaté 2002, 2004; Oliveira et al. 2010; Piaia et al. 2017), including in the Curaçá terrane (Inda and Barbosa 1978; Lindenmayer 1981). The fact that rocks of the orogen and the three Archean continental blocks present distinct Sm-Nd characteristics has supported understanding an evolution in terms of collisional tectonics following the consumption of oceanic crust material (e.g., Leite 2002). Earlier, D'el-Rey Silva (1993) had documented the same structural-metamorphic evolution for both the Curaçá terrane and the Lajedinho-Ipirá area and interpreted the collision of the Jequié and Serrinha blocks with the Gavião block leading to a sinistral transpression, which is particularly evident during the younger event (D_3) of regional deformation.

2.2.2. The Tanque Novo-Ipirá Complex

The Tanque Novo Complex (or Sequence) comprises mostly quartz-feldspathic gneiss with thin intercalation of amphibolites, cordierite-sillimanite-garnet paragneiss, oxide-facies banded iron formation, calcsilicate rocks, marbles, olivine (forsterite) marbles, anhydrate-bearing marbles, and quartzites (Jardim de Sá et al. 1982; D'el-Rey Silva 1984, 1985). Slices of gneisses of the Archean-age crystalline basement likely occur intercalated with these rocks, although they are not easily identifiable due to the intense and very ductile polyphase deformation.

2.2.3. The Neoarchean Caraíba Complex

The mafic-ultramafic rocks form one of the three lithostatratigraphic units composing the substratum of the Curaçá terrane (Lindenmayer 1981; Jardim de Sá et al. 1982; D'el-Rey Silva 1984, 1985). They occur as isolated bodies within high metamorphic grade supracrustal rocks (Tanque Novo Sequence) and gneisses, migmatites, and metagranitoids composing the Caraiba Complex. These two units occur west of the Itiúba syenite and are also mappable in the vicinities of the Caraíba orebody (Fig. 3).

2.2.4. The assemblage of 2580 Ma-old mafic-ultramafic rocks hosting Cu deposits of the Curaçá Valley

Early regional studies (Delgado and Souza 1975) showed the direct association of Cu-sulphides with the mafic-ultramafic rocks that made the Curaçá River Valley an economically relevant metallogenetic area (the Curaçá Cu-District). Other studies showed that nearly three hundred bodies of such mafic-ultramafic rocks occur from Caraíba to the North in the Curaçá River Valley terrane. The Cu-bearing bodies consist of magnetite hypersthenites and or norites. On the other hand, the vast majority of the bodies consist of Cu-poor or Cu-barren gabbros, gabbronorites, and anorthosites. (Figueiredo 1981; Lindenmayer 1981).

Six other Cu-occurrences were characterized as smaller deposits with an average grade around 0.5-0.6 % Cu. Among these, the Surubim and Terra do Sal bodies, situated ~30 km and ~20 km North of Caraíba (see cross-section at the bottom of Fig. 2), and the Angicos body, are all being mined currently or have already be exhausted, in consequence of the elevated price of the metal. Finally, the deposit named Vermelhos, the biggest among those cited above, was the last to be mined for being situated ~90 km north of the concentration plant at Caraíba. It belongs now to the Ero Copper Company and will be addressed again in the very end of this historical review (item 6.7).

According to thousands of chemical analyses carried out during decades of mining operation, the Ni-content in the Cu-bearing rocks cited above is almost negligible, even in the ore concentrated at the Caraíba concentration plant (see also Mayer and Barnes 1996; Teixeira et al. 2010b). Nevertheless, slices of serpentinites bounding the Caraíba orebody on its eastern and western sides (D'el-Rey Silva 1984) permit stating that bodies of ultramafic rocks (precursor of serpentinites) more suitable for hosting Nickel deposits may occur regionally. This possibility justifies an ongoing program of diamond drilling searching for Nickel in the surroundings of Caraíba.

2.2.5. Syn-, late and post-orogenic granitoids, including the 2084-Ma Itiúba Syenite

The complex of syn-, late and post-orogenic granitoids mainly comprises migmatitic gneisses and syn-tectonic granitoid intrusions composing the G_1 and G_2 suites of gray tonalites and granodiorites (Jardim de Sá et al. 1982). In addition, all these lithotypes are intruded by reddish-pink, highly foliated K-rich granites G_3 suite. These rocks, which emplaced as lubricants during the D_3 progressive deformation, occur as N-S elongated bodies and comprise four sub-types around Caraíba (Fig. 3). Such granitic bodies, labeled G_{3a} to G_{3d} (D'el-Rey Silva 1984, 1985) resist erosion and commonly detach in the local topography as long ribbons standing a few meters above the surroundings.

The Itiúba syenite, which is also a syn-D_3 intrusion, occurs as an N-S trending, over 100 km-long and narrow body sustaining the Itiúba Range ~100m or more, above the flat topography of the flat valley (Fig. 4). It consists of highly foliated granitoids metamorphosed under amphibolite facies conditions, ca. 2.0 Ga ago (Rb-Sr data in Figueiredo 1976; Brito Neves et al. 1980). Several U-Pb SHRIMP ages of magmatic zircons indicate crystallization of the syenite 2,084 Ma ago, along the tectonic zone separating the Cu and Cr metallogenetic districts cited behind (Fig. 2; Oliveira et al. 2004).

2.3. Tectonic framework

2.3.1. Structure of the Curaça Valley as a whole

Lithotypes belonging to the Tanque Novo Sequence and Caraíba Complex, as well as the mafic-ultramafic rocks, all underwent a D_1-D_3 polyphase progressive deformation (mushroom fold interference patterns) assisted by large volumes of syn-tectonic G_1-G_3 granitoid intrusions and metamorphic events of amphibolite, granulite, and amphibolite facies, respectively M_1-M_3.

The Curaçá antiform is the regional fold, which hinge stretches all over the Curaçá River Valley (Delgado and Souza 1975). It is the preferred site of occurrence for the bodies of mafic-ultramafic rocks in the Curaçá terrane (Fig. 2). Nevertheless, the antiform was characterized as being an F_3 fold only after regional-structural studies carried out by Gáal (1982), Jardim de Sá et al. (1982), and Hasui et al. (1982a, 1982b).

2.3.2. Models postulated for its tectonic evolution

A vast amount of geology and structural data collected regionally, and also on the surface and underground sites of the Caraíba Mine and other small bodies, drove into the conclusion that the Cu-bearing rocks were originally plate-like features concordant with the bedding or emplaced sub-parallel to and coevally with the regional S_1 foliation (Lindenmayer

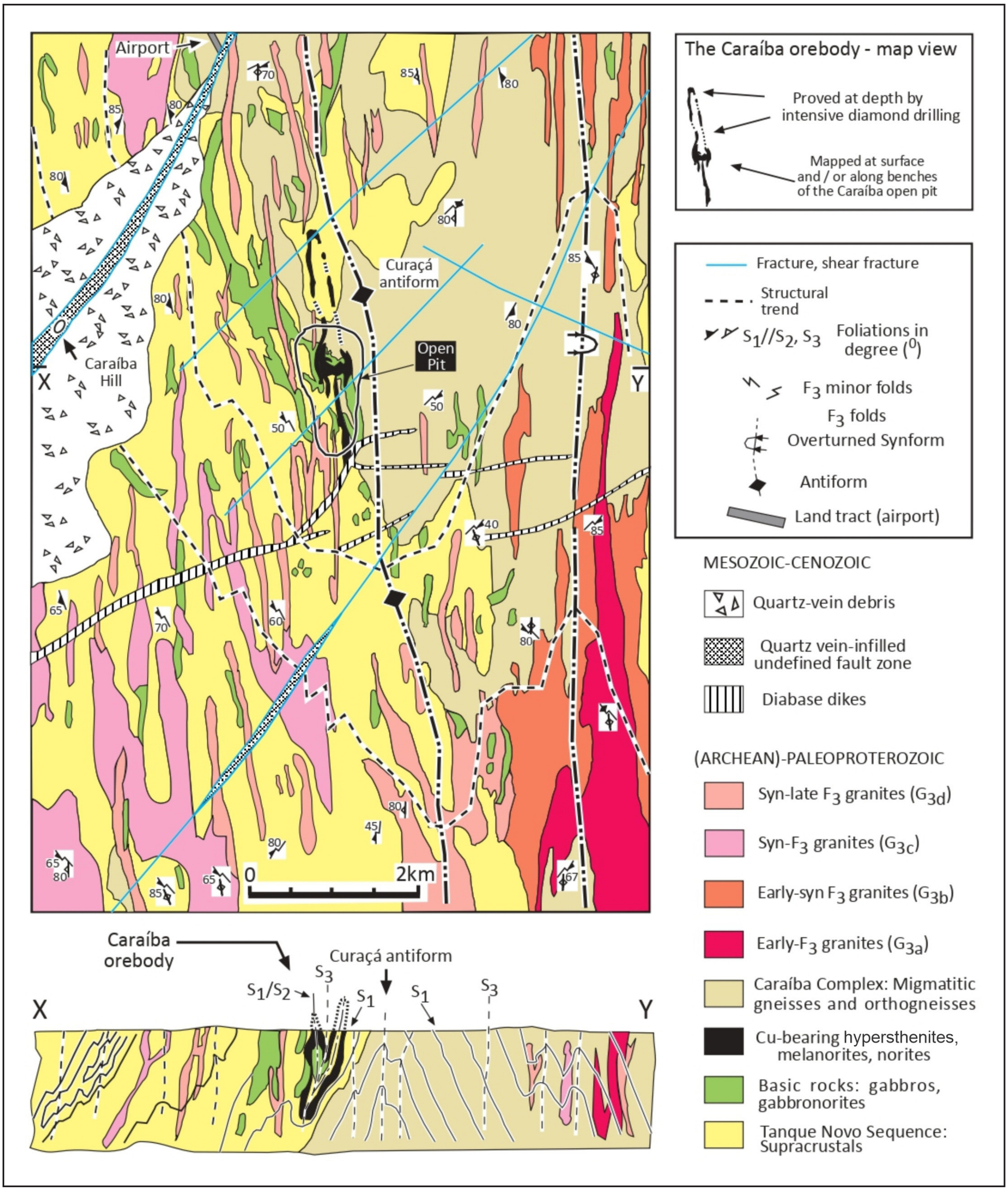


FIGURE 3 - Geological map of the Caraíba orebody and surroundings, simplified from the 1:10,000 scale geological map (see Fig. 9 in D'el-Rey Silva 1984). Note the Curaçá antiform, the open pite site, the airport´s land track, and the overall shape of the F_3 X F_2 mushroom in map and cross section views (bottom).

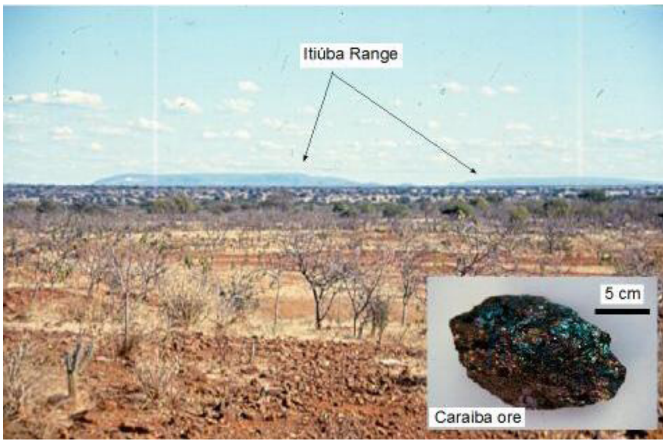


FIGURE 4 - Partial view of the Caatinga (the very dry Brazilian Savannah) in the Curaçá River Valley. The future Caraíba mine site is in the foreground, from where the ore (inset: Cu sulphides disseminated in dark brown hypersthenite) would be extracted. The N-S trending Itiúba Range (background) is practically the single topographical high in the generally horizontal terrain.

1981; Lindenmayer et al. 1984; D'el-Rey Silva 1984, 1985; Mayer and Barnes 1996; D´el-Rey Silva et al. 1988, 1994, 1996, 2007). The fact that Caraíba is a Cu-only (chalcopyrite and bornite-rich) deposit and is closely associated with deep-water chemical sedimentary rocks, such as banded iron formation and forsterite-anhydrate marble (former evaporites) is relevant for understanding the origin of the mineralized bodies in the northern part of the ISAC orogen.

Conditions for the granulite facies metamorphism were estimated around 850^0-720^0C (Jardim de Sá et al. 1982; Ackermand et al. 1987), or up to 1000^0C, with pressures varying from 8-10kbar (Leite 2002; Leite et al. 2005), all based on several geothermometers and sapphirine-bearing assemblages. The granulite facies metamorphism of the Caraíba Cu-bearing rocks is according to the change in the com of the oxides in the ore, due to equilibration with orthopyroxene displaying a typical metamorphic texture (Mayer and Barnes 1996).

The U-Pb isotopic data support an older-younger sequence of crystallization ages consisting of: 2580 Ma for a sample of Caraíba orebody norite (U-Pb SHRIMP data in Oliveira et al. 2004); 2,250 Ma for syn-D_2 tonalite in the Caraíba Airport outcrop; and 2051 Mafor syn-D_3 granite intrusive in the Caraíba orebody (U-Pb age data respectively from zircons and monazite; D´el-Rey Silva et al. 1996). For its structural-metamorphic-magmatic and geochronological importance, the structural and isotope geology of the Airport outcrop (D'el-Rey Silva et al. 2007) is summarized ahead and the implications for the origin of the orebodies further discussed.

3. The Caraíba Deposit

The 1:1,000 scale geological mapping of the Caraíba open pit lasted seven years (1978-1984) and demanded from the corresponding author the mapping of successive walls created for opening and progressively enlarge each of the four upper benches (440, 425, 410, 395; Fig. 5A). The original maps, important documents, attached in the original size in the MSc Dissertation by D'el-Rey Silva (1984), were reduced and redrawn using the FreeHand 10 software and are presented in a slightly simplified form in this historic review (Figs. 3 and 5A). For representing the part of the Caraíba orebody North of section 45, which belonged to DOCEGEO (target R-22), in the geological map of the Caraíba´s surroundings (Fig. 3), the corresponding author utilized detailed data obtained after the 1:5,000 scale mapping carried-out by Lindenmayer et al. (1984) with the aid of trenches and diamond drill holes.

3.1. The copper ore

The Cu-bearing and Cu-barren basic-ultrabasic rocks that constitute the Caraíba orebody occur interleaved with rocks of the Caraíba Complex and the Tanque Novo Sequence (Figs. 3 and 5A). The vast inventory of data obtained after such detailed mappings (Figs. 3 and 5A) as well as from the detailed mapping of the ramp and several galleries in the Caraíba underground mine, plus the information collected from kilometers of drill cores from boreholes of DOCEGEO´s drilling campaign (1977-1978) and boreholes perforated already under the responsibility of the CMSA´s Mine Geology Division (1979-1984), altogether drove (D'el-Rey Silva 1984, 1985) to the long list of conclusions ahead (1-12).

(1) G_3 granites occur as small-large elongated bodies controlled along the S_3 foliation and clearly intrude the rocks of the Tanque Novo Sequence, the Caraíba Complex and the basic-ultrabasic bodies, as well as G_1 and G_2 granites (Figs. 3 and 5A). **(2)** The Caraíba synform that controls the orebody´s geometry in cross sections is a km-sized F_3 fold parasite in the western limb of the regional-scale Curaçá antiform. The hinge of the Caraíba synform occurs as deep as 1,000 m, proved by diamond drill holes in vertical cross sections. **(3)** The very high concentration of Cu in the ore entrapped in F_2 hinges is according to field data and thousands of Cu-content chemical data (see more ahead). The occurrence of Cu-sulphides along the S_3 foliation is far less common, however. In reality, the leading role of deformation D_3 relates to the thickening of F_3 hinges at depth rather than to the migration of the sulphides towards surfaces of the S_3 foliation (more details in the following sections). **(4)** Within the open pit (Fig. 5A), the orebody stretches N-S for 1,600 m. Since the time of DOCEGEO´s studies (1977-1978), it has been divided into 34 vertical cross sections 45m apart from each other and labeled 13 to 45. **(5)** On a map view, it comprises the E-W trending central part, which is as wide as ~600m between sections 31 to 37; two steeply-dipping tabular bodies stretching south between sections 31 to 13; and two other tabular bodies stretching North between sections 37 to 45. The tabular bodies are much more distant one from the other in the northern (sections 37-45) than in the orebody's southern part (sections 37-45; Fig. 5A). **(6)** The easternmost tabular body from section 37 to the North is proved to exist at deeper parts by diamond drill holes in cross sections 37-45, but are absent on the four mapped benches of the open pit. **(7)** In these cross sections and others across the R-22 (the northern part of the orebody belonging to CVRD), the Cu-bearing rocks occur in contact with or intercalated within lenses of olivine marbles at depth. In addition, according to Lindenmayer et al. (1981, 1984), these rocktypes crop out in E-W trenches dug across the northernmost part of the orebody, which allow defining the hinge of the Caraíba F_3 syncline on the surface (Fig. 3). **(8)** In the Caraíba

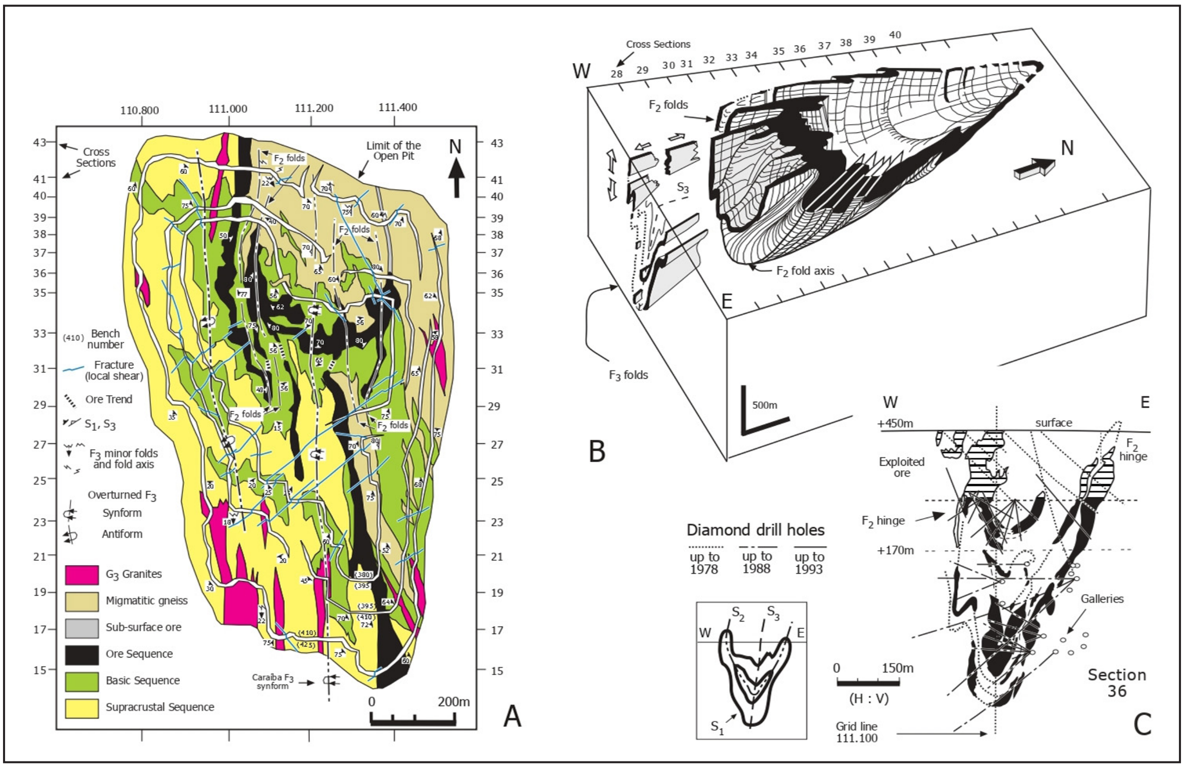


FIGURE 5 - Geology of the Caraíba mushroom. (A) - Simplified geological map of the Caraíba orebody showing some attitudes of the S_1 foliation, minor D_3 structures, and the axial trace of the leading F_2 and F_3 folds. The dip and slip direction of the (shear) fractures have been obtained from the original map in D´el-Rey Silva (1984). The ore trend line representing the orebody's eastern part continuing in the underground (North of section 35) means a new addition to the original map. (B) - Schematic 3-D representation of the Caraíba mushroom (simplified from D´el-Rey Silva et al. 1988). (C) – Geometry of the ore layers in cross-section 36 after diamond drilling in different years, as indicated. Adapted from D´el-Rey Silva et al. (1996) and D´el-Rey Silva and Oliveira (1999). The mushroom figures in the inset are typical for cross-sections 32-37, which refer to the central part of the orebody.

orebody, the Cu-bearing hypersthenites and norites occur together with Cu-barren hyperites, gabbros, norites and gabbronorites, and gradual contacts are common between these lithotypes, in both the open pit and underground mine, and in drill holes, too. **(9)** However, the detailed mapping showed the Cu-barren country rocks following an NNW trend, which clearly contrast with the N-S trending Cu-bearing rocks, being the discrepancy noticeable from the orebody's central part to the North (Fig. 5A). Although D'el-Rey Silva et al. (1996) already addressed such a relationship, it is further discussed ahead because of its importance for understanding the geology of the Caraíba Mine and the meaning of geophysical data (Teixeira et al. 2010b). **(10)** Two sets of long-and-straight fractures cut across the Caraíba area (Fig. 3). One set comprises four fractures trending NE, and the other is represented by one fracture trending NW. Two of the NE-trending fractures host mappable quartz veins situated North and South of the orebody. The northernmost vein constitutes the~30 m-high isolated peak named Caraíba Hill, which dominates the panorama Northwest of the open pit and produces a >1km-wide zone of colluviums. ENE to E-W vertical dikes of dark green, fresh, undeformed and very resistant diabase, supposed to be Mesozoic-Cenozoic in age, form long strips to the South of the open pit, characterized by trails of m-sized blocks in the field. Outcrops of the most prominent of such dykes occur very close to the paved road to Caraíba. **(11)** A larger population of NE- and NW-trending fractures was characterized in detail during the mapping of the four upper benches of the open pit (Fig. 5A). The NE-trending sub-vertical fractures, which traces are as long as 400m across, are far more common in the southern half of the open pit and generally contain striations suggestive of sub-horizontal shearing between the adjacent blocks. Some of these embryonic shear zones eventually displace minimally the orebody's layers and served as sites for preferred infiltration of K-rick fluids and minor metassomatism of the wall rocks. Along these fractures, the orebody's basic-ultrabasic rocks are locally transformed into a strongly foliated metasomatite (D'el-rey Silva 1984; 1985). **(12)** Finally, a longitudinal zone of high strain deforms the country rocks in the underground mine, running parallel-and-very close to the orebody's eastern margin. It consists of a West-dipping, steep-and-narrow zone of highly foliated, light green to yellowish-greenish to gray serpentinite representing retrometamorphism assisted by intense fluid infiltration into mafic-ultramafic rocks and also into olivine marbles. In parts of the narrow zone, the serpentinite is a massive and reddish-brown to red color rock due to the metassomatism imposed by a late entry of K-rich fluids, which is typical of the deformation event (D_3) in the Curaçá terrane. The existence of the narrow zone of serpentinite-marble tectonite, firstly noticed in diamond drill holes cutting across the eastern side of the orebody (Docegeo 1978), was confirmed by the ramp and first galleries of the underground mine.

Several near-surface galleries opened and studied by DOCEGEO (1977-1978) and hundreds of drill holes perforated by DOCEGEO and Caraíba from 1977 to 1989, all cutting across both the western and eastern margins of the orebody, plus field mapping, altogether demonstrate that the orebody-bounding eastern zone of high strain is unique and has no similar elsewhere in the whole open pit and underground mine, or in the orebody's surroundings.

3.2. Geometry of the Caraíba orebody

The Caraíba orebody became a ~ 2 km-long mushroom due to the interference of an N-S trending F_3 synform upon E-W trending F_2 folds (Fig. 5 and inset). The mineralization consists of disseminated Cu-sulphides, mainly chalcopyrite-bornite, and commonly occurs along the S_1 banding, which is penetrative in the mineralized rocks across the Caraíba Mine and country rocks, as well as in the other lithotypes found elsewhere in the Curaçá high-grade terrane.

Considering the orebody's size in the open pit and its northern continuation (R-22), the Caraíba mushroom is over 2,000 m-long in the N-S direction (Fig. 5B). Its wider central part, comprised between sections 31 to 36, is due to the amalgamation of several F_2 hinges. Due to re-folding, the originally sub-horizontal and E-W trending B_2 axes became vertical in the upper part of the mushroom, but the original sub-horizontal plunge is preserved around the hinge of the F_3 synformal at depth (D'el-Rey Silva 1984, 1985).

The tectonic structures at Caraíba are fundamental for demonstrating the D_1-D_3 regional deformation across the Curaçá River Valley terrane. The F_1 folds are far less common than the F_2 and F_3 folds. They are small-scale, rootless, and intrafolial relative to the metamorphic banding S_1 in migmatites and the S_0/S_1 planar anisotropy in the Tanque Novo metasedimentary rocks. Similarly, the F_2 folds are not very common, but specimens of dm-scale are easily recognized in several outcrops where they deform the metamorphic banding S_1 (S_0/S_1) and are deformed by the F_3 folds. The F_3 x F_2 folds interference in the Caraíba mushroom point to dam-hm scale F_2 folds verging to the North, with the axis B_2 originally sub-horizontal and trending E-W. The F_3 folds are extremely common, being commonly cm- to km-scale, up-right, tight to isoclinal, and occur associated with a pervasive axial planar foliation (S_3). The fold axis B_3 plunges gently-moderately, either to the North or to the South, across the Curaçá River Valley. B_3 plunges 20^0S in the surroundings of Caraíba. The S_2 and S_3 foliations are both marked by the preferential orientation of biotite, hornblende and highly flattened crystals of feldspar and quartz, but S_2 is also associated with granulite facies assemblages in G_2 granites, being the best example found in the Airport outcrop (Fig. 3) among others that Jardim de Sá et al. (1982) described elsewhere.

3.3. Models so far postulated for ore genesis

The original model, which asserts a magmatic origin for the Cu-mineralization across the Curaçá River Valley (Lindenmayer 1984) and, specifically, a volcanogenic origin for the Cu-ore at Surubim (Bello 1986), stands strong and continues to be valid. According to Teixeira et al. (2010b), the copper deposits have a mix of characteristics and are related to hydrothermal fluids of magmatic origin, but have also been affected by metamorphism. More recently, the copper deposits in the Curaçá Valley have been interpreted as IOCG-type mineralization by Garcia et al. (2018) and Hühn et al. (2014, 2020). Based on SHRIMP U-Pb zircon ages and sulfur isotope geochemistry carried out in the Caraíba, Sussuarana, Surubim, and Vermelhos orebodies, Garcia et al. (2018) conclude that the mineralization is in part Archean-age syn-magmatic, and in part related to hydrothermal alteration during the Peleoproterozoic deformation and high-grade metamorphism affecting the orogen's roots. They also established a Paleoproterozoic age of 2047± 11 Ma for a sample of norite from the Surubim deposit. Nevertheless, the precise structural control of the primary mineralization in hinges of F_2 and F_3 folds at Caraíba, as included in this historical review, leaves no doubt that such hydrothermal activity cannot be related solely to the last event (D_3-M_3) of deformation and metamorphism.

4. The Caraíba Project: A historical perspective

4.1. Introduction

The fact that the geological knowledge about highly migmatized areas as the Curaçá terrane was still on its first steps across the entire 1970´s in particular the incipient knowledge about deformation under highly plastic conditions, further contributed to challenging the team of geologists working for Caraíba. The reality is that the basic theory that is currently known about the controls of deformation in high-grade terranes started only after the classical paper by Passchier et al. (1990) and was still being erected worldwide when the Caraíba Mine entered in operation. Thus, the more mature geologists in charge since the beginning of the Caraíba Project searched for aid within the scientific community, particularly from the Brazilian universities and international consultants (Appendix 1; A1-2).

Nevertheless, the geologists at Caraíba had to carefully work things out on their own. They started observing that although the Curaçá terrain is adjacent to the Raso da Catarina, the wildest and driest area in Brazil, and the Caatinga seemed to be completely devoid of rock exposures (Fig. 4), there were several outcrops scattered around. Some of these outcrops displayed a flat-lying and amoeboid surface as large as hundreds of square meters, while others consisted of small blocks of rocks concentrated in a few meters-sized area. There were also some elliptical-shaped outcrops with the longer axis oriented N-S. Additionally, the geologists noticed large amoeboid areas characterized by a depressed topography covered by dark brown to black color argillaceous soil. These areas transformed into small lagoons during the rainy season.

Moreover, the pioneer geologists also realized that the most significant flat-lying outcrops correspond to well-banded paragneiss, orthogneiss, or migmatites; the outcroping small blocks usually consist of Tanque Novo supracrustal rocks, mainly paragneiss, olivine marbles, calc-silicate rocks and banded iron formation; the elliptical shaped exposures invariably consist of pink granites; and the argillaceous soil (locally named massapê) was in many cases the *in situ* product of weathering of mafic-ultramafic rocks, as proved by trenches and/or gravity and magnetism surveys carried out by the mining company, at that time named Caraíba Metais Sociedade Anômina (CMSA).

4.2. The historical background

Early in the decade 1970, the economy of the entire world was shaken by the countries exporters of oil, whose decision for a considerable increase in the international price of such commodity brought profound consequences, even for geologists in Brazil (Appendix 1; A1-3). Consequently, and similarly to what happened everywhere, mainly in the oil importers countries, the government in Brazil implemented several decisions aiming short- and long-term impacts on the country´s balance on external trading. Thus, the Caraíba Copper Project was born to introduce the industrial-scale production of copper in Brazil, as part of the government´s efforts to cut down the cost of importations in general. The Caraíba ore was discovered accidentally ~180 years ago due to the exposition of green copper oxide (malachite) on thesurface of the old Caraíba Farm. The CMSA team of regional exploration geologists re-studied it in 1978-1990.

So far, the Brazilian production of copper had been historically obtained from Cu-ore exploited of just three main ore deposits distant for over 2,000 km one from each other (Fig. 1A): the Salobo orebody, hosted in metasedimentary-volcanic rocks of the Salobo Sequence, part of the Archean-age Carajás Mineral Province (Pará State) inside the Amazon Craton (Lindenmayer and Teixeira 1999; Dardenne and Schobbenhaus 2001; Teixeira et al. 2010a); the Caraíba orebody, hosted in Archean meta-hypersthenites and metanorites found in the Curaçá River Valley terrane that is the northern continuation of the Archean-Paleoproterozoic Itabuna-Salvador-Curaçá amphibolitic-granulitic orogen in the São Francisco Craton, within the Bahia State (Fig. 1B; D'el-Rey Silva 1984; D'el-Rey Silva and Oliveira 1999; Oliveira et al. 2004; Teixeira et al. 2010b); and the Camaquã orebody, hosted in Neoproterozoic-EoPaleozoic siliciclastic sedimentary rocks (Remus et al. 2000; Dardenne and Schobbenhaus 2001; Toniolo et al. 2010) cropping out in the Precambrian window which forms part of substratum of the Rio Grande do Sul State, in the southernmost part of the country. Nowadays, the three historical mines are part of a group of two dozen Cu-ore deposits across the country, the majority of which is under operation or has been already mined (see names, ore reserves, and copper grades for nineteen of them in Silva et al. 2024).

Because Salobo had just been discovered in the early 1970´s (Dardenne and Schobbenhaus 2001) and despite Camaquã was producing copper in the early 1970's and decades before (Toniolo et al. 2010), the relatively small size of that orebody limited the production to an amount much lower than that of the country´s needs in tons of metallic copper per year. Thus, the government focused on the Caraíba orebody and its area of geographical and economic influence. However, there was a significant problem in the early 1970's because Caraíba was only a promise, not a real mine at that time. Even so, the government claimed back the property of the Cu deposits across the country so that the private owner of Caraíba (the Pignatary Group) sold the orebody to BNDE, the Brazilian official bank for financing economic development (currently known as BNDES, where the final S stands for Social).

For planning and controlling the Brazilian internal production of copper, the BNDE was assisted by the Caraíba Metais Ltda (CMSA), a federal state company created explicitly for implanting and running the Caraíba Copper Project. The Caraíba Project comprised a metallurgical plant located in the industrial district of Camaçari, situated very close to Salvador (capital of the Bahia State; Fig. 1B) and the Caraíba Mine, where the ore (initially supposed to contain ~1% Cu) would be transformed into a concentrated with up to 30-33% Cu and then transported by train for a distance of 510km to the melter at Camaçari. The construction of the metallurgical plant at Camaçari and all the mining facilities at Caraíba started early in 1977. At that time, the big dam of Sobradinho was also being built across the São Francisco River (Fig. 1B) as another significant federal investment.

In the end, the Caraíba Copper Project happened to be a success for a series of reasons. The most obvious is that the country now has its proper production of metallic copper. Moreover, because the Caraíba orebody lies in the semi-arid domain of northeastern Brazil (Fig. 4) and because the Curaçá River remains dry nearly 10 months each year, one of the first steps in the project setup was the construction of a ~85 km-long water pipeline (0.8m diameter) for bringing water from the São Francisco River, since a base station a few kilometers west of Juazeiro until Caraíba (Fig. 1B). The freshwater, initially necessary for running the whole industrial complex in the Caraíba Mine and for supplying the village of Pilar, which was specially built for housing the mine workers and their families, soon became also vital for the maintainance of tens of thousands of people living in small farms, villages, and small towns near Caraíba, since well before the start-up of the mining operations (Appendix 1; A1–4; A1-5).

Moreover, the gross economy in the area surrounding Caraíba, particularly in the cities of Bonfim, Juazeiro, Petrolina (Fig. 1B) and smaller localities much closer to the Caraíba Mine (such as Jaguarari, Uauá, Santa Rosa de Lima - not shown) benefited in a large scale from the huge amount of money shed into the region since 1977. In addition, the existence of the Caraíba Mine was one of the main factors that justified the construction of the Petrolina international airport (Appendix 1; A1-6), which, since the early 1980´s, has served as one of the main pillars supporting the area of Juazeiro-Petrolina as a large-scale producer of fruits which are exported to several parts of the world.

Therefore, we must conclude that the macro-political decision to implement the Caraíba Copper Project was correct, even because the current success enjoyed by the Ero Copper Company is only possible because of the existence of the village at Pilar, the water pipeline bringing water from a long distance, and the concentration plant at Caraíba. The continuity of the mining operations by the Ero Copper Company in other parts of the Curaçá River Valley means that the initial investment at Caraíba has been paid generously on both economic and social grounds.

Nevertheless, for some historical and geological reasons, the entire planning of the mine project already born with some significant uncertainties, so the production of copper from the Caraíba Mine meant, in the pioneer years between 1978 and 1990, an enormous and exciting professional challenge for a whole generation of Brazilian geologists, administrators, engineers (civil, mechanical, electrical and mining engineers) as well a whole sort of skilled professionals from abroad.

The main historical reasons were: the BNDE was institutionally a public financing bank, not an experimented mine owner; decisions taken by public institutions such as the BNDE were subjected to all sorts of political agreements, but these were not necessarily as deep and fast as a big mine generally requires; before the start-up of the Caraíba Project, until the end of the 1970´s, large-scale mining operations in Brazil had been restricted to the exploration of iron, manganese and alluminum orebodies which are characterized by huge ore reserves and higher ore grades, requiring only a minimal care during mining if compared to ore deposits of base metals, which are characterized by a much lower ore grade (Appendix 1; A1-7) and constitute investments of much higher risk of losses and are potentially hazardous during operation.

The main geological reason is that the orebody's geology was not conveniently known when the historic decision for making Brazil self-supplied in terms of copper came out suddenly and required, in a short time, a whole series of technical events necessary to implement the Caraíba Mine Project. The effects of such decision on the Caraíba Project are treated in detail below.

4.3. Basic engineering and economical aspects of the Caraíba Project

In its original version the whole Caraíba Mine Project included: the first draft of the mine itself, the choice for the mining methods and mining equipment, an estimative of the numbers of production, and arrangements to transport the concentrated ore to Camaçari, 500km away (see above). Thus, BNDE and CMSA contracted Milder Kayser, a reputed consultancy company heavily based on the experience of Canadian miners and international consultants. Simultaneously, as the study of the orebody had to be hurried up, CMSA contracted the DOCEGEO Company (Appendix 1; A1-8) to improve the geological knowledge of the Caraíba orebody in a couple of years and increase the level of confidence for the mine project.

DOCEGEO's geologists worked hard in 1977-1978 aiming to improve the geological knowledge of the Caraíba Cu-orebody, at the same time that Milder Kayser was already elaborating the final steps of the whole project and started to buy the mining equipment. In reality, in that couple of years, everything was happening simultaneously and in a hurry and or under pressure at Caraíba.

The mining project elaborated by Milder Kayser comprised the open pit and the underground mine; the concentration plant; and a series of concrete-made edifices used for maintenance of equipment, offices for technical, administrative, and security staff, and two restaurants, altogether characterizing a vast industrial complex (Fig. 6A). The underground mine implied the construction of the main ramp, galleries for transport, production and ventilation, the main shaft and auxiliary shafts for ventilation and vertical transport of the mined ore (Fig. 6B). According to the geological interpretation at that time (1977-1978), the shape of the orebody justified the choice for two mines.

Actually, by the time the government received back the property of Caraíba (1976), the technical staff of the Pignatary Mining Company (PMC) had already drilled a series of diamond drill holes plunging 45˚ east. The PMC's technical staff envisaged the central part of the orebody (Fig. 7) as a collage of closely-spaced, roughly continuous plate-like bodies of Cu-mineralized hypersthenites and norites dipping 60˚-70˚ West. Some blocks areas thick as 10´s meters and others even more significant, all interleaved within the country rocks (composed mainly by gneiss).

In 1977-1978, forced by the general lack of natural outcrops at Caraíba, DOCEGEO opened, mapped, and sampled a series of trenches and near-surface galleries, and produced a 1:2,000 scale geological map of the orebody (Fig. 8A) evidencing a wider central part and narrow segments to the North and South of this. DOCEGEO perforated tens of additional drill holes plunging 75^0 East, all distributed in E-W vertical sections, 45 metres apart one from another in the central part of the orebody and 90 m apart in both the northern and southern segments. Based on these additional drill holes, that Company elaborated vertical cross-sections preserving the Pignatary´s Group interpretation according to an orebody consisting of steeply-dipping table-like bodies of mineralized rocks (Fig. 8B; see also Townend et al. 1980) and produced 1:2,000 scale horizontal maps for different depths of the orebody, then building a 3-D maquette evidencing the wider central part and the collage of N-S trending mineralized lenses (Fig. 9A).

With such an understanding of the orebody´s central part, Milder Kayser engineers projected the open pit from the surface, situated 455 m above sea level, until a depth of 300 m below (Fig. 8B) and divided it into 19 benches, 15 m-high each, so that the bottom of the uppermost bench was 440 m and the bottom of the lowermost bench rested 155 m above sea level. To separate the two mines, Milder Kayser engineers left an 80 m-thick security slab untouched. The underground mine, originally planned to reach 450-500 m below the bottom of the security slab, required the opening of the main shaft with ~1000 m length in the vertical and diameter of 6 m, as it is actually.

By juxtaposing horizontal maps for different depths below the surface, DOCEGEO showed the 3-D shape of the orebody in a maquette (Fig. 9A) and calculated the ore reserves at Caraíba: 100 million tons of ore with an average grade around 1% Cu. Consequently, Milder Kayser established that runoff material from the open pit would be divided into ore, marginal ore, or simply waste, in which the copper grade was respectively ≥0.45% Cu, 0.20-0.45% Cu, or <0.20 Cu.

The general 3-D shape of the orebody and the geological cross sections displaying continuous table-like lenses of mineralized rocks opened the doors for Milder Kayser to envisage the homogeneous distribution of the copper content, both along strike and dip of the mineralized bodies, giving way to a quite optimistic expectative of continuous and problems-free production of ore containing a minimal of 1% Cu from the underground mine, counting with 5 levels of production, each one 90 m-high (Fig. 6B).

As established in the underground mine original project (Fig. 6B), a longitudinal gallery was opened on top of each level, aiming to connect the main shaft to the ramp and transversal galleries access the orebody. The ore would be extracted from vertical prisms of mineralized rocks, idealistically 90 m-high (see G; in Fig. 6B), and transported until a local shaft. There, the ore would fall to the deepest longitudinal gallery corresponding to the bottom of level 5 (see F in Fig. 6B). Along level 5, the ore would go to a primary crusher situated at the bottom of the main shaft (see H) and, from there, it would be transported until the surface by an elevator and then

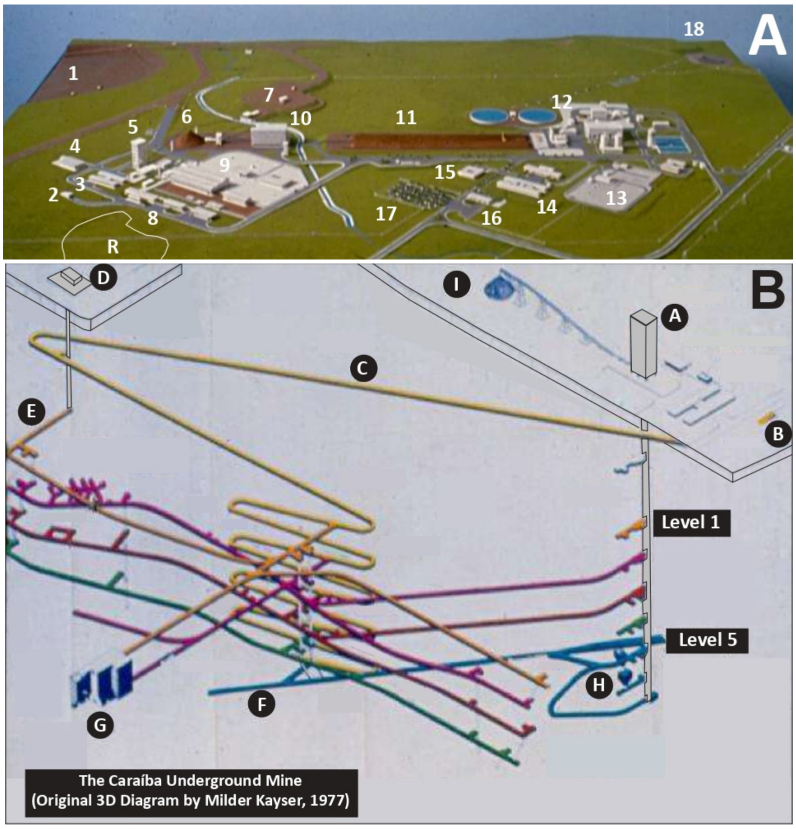


FIGURE 6 - Details about the Caraíba Mine Project.(A)- A maquette display of the industrial complex at Caraíba: 1 – The open pit; 2 – Entrance of the ramp to access the underground mine; 3 – Mine office; 4 – Deposit of diamond drill cores; 5 – Main shaft; 6 – Pile of ore from both the open pit and underground mine, after primary crushing; 7 – Primary crusher; 8 – Mine restaurant and Mechanic-Electrical Engineering offices; note the site of the Restaurant outcrop (R) which is discussed in the text; 9 – Heavy maintenance garage; 10 – Secondary crusher; 11 – Piles of homogenized ore after secondary crushing; 12 – Concentration plant; 13 – Chemistry laboratory; 14 – Main office; 15 – Main restaurant; 16 – Main entrance and Security office; 17 – Car park; 18 – Waste dam (partially shown, to the right). (B)–An idealized view of the underground mine as initially projected by Milder Kayser. A – Tower of the main shaft; B – Ramp entry; C – Ramp, plunging 17% North; D – Shaft for ventilation; E – Gallery for ventilation of Level 1; F – The lowermost gallery (Level 5); G – Blocks of the orebody, in this case, situated between levels 1 and 2; H – Primary crusher below Level 5; and I – On the surface, the pile of ore after primary crushing at depth (the same pile numbered 6 in Fig.6A).

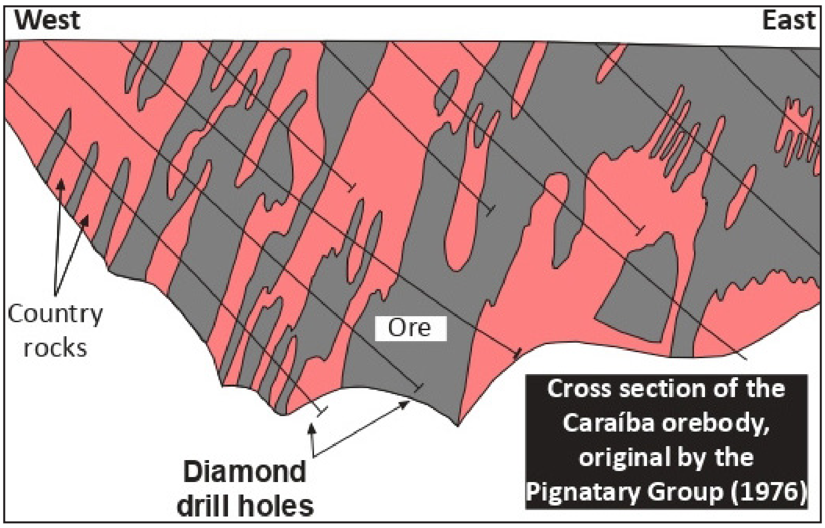
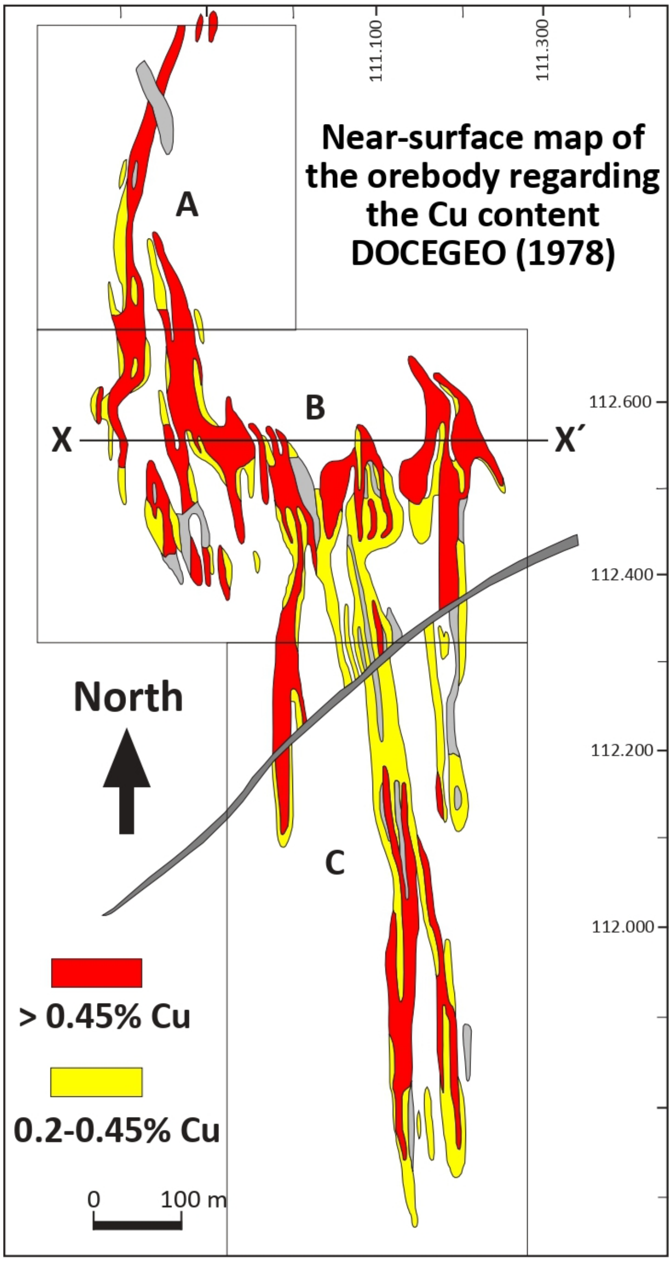


FIGURE 7 - Vertical geological section across the central part of the Caraíba Cu-orebody, as envisaged by the Pignatary Mining Company (1976).



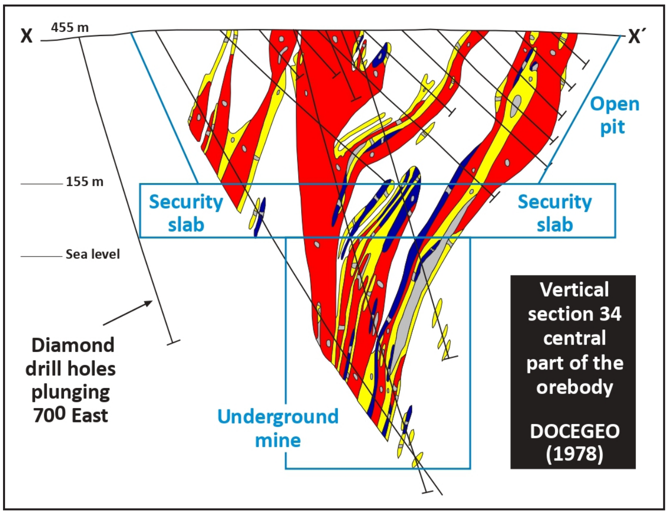


FIGURE 8 - Basic geology of the Caraíba Orebody in the early days of the Caraíba Mine Project (1978). A - Near-surface horizontal map of the Caraíba orebody, as envisaged after the soil layer's removal (adapted from Docegeo, 1978). Note the series of mineralized lenses trending N-S and the color scale for the Cu-content. Line XX' stands for the vertical section 34 (see B). B - Simplified vertical geological section across the central part of the orebody depicting Cu-content distribution in mineralized lenses represented in different colors. Note the limits of the Open pit, the Underground Mine, and the Security slab (blue lines) as projected by Milder Kayser.

transported by a conveyor belt until the pile of crushed ore (see I in Fig. 6B; the central part of Fig. 10 shows the real pile in the field).

Based on such a aproject, CMSA contracted in Sweden, already in 1977-1978 (therefore three-four years before the production of the Cu ore has started in the underground mine) the acquisition of a series of special trains and wagons envisaged for transporting the ore collected in the level 5 of the future underground mine until the primary crusher situated in the bottom of the main shaft (Fig. 6B).

As a pioneer in that front, the corresponding author witnessed in 1977-1978 a series of simultaneous events, including the open pit start-up (Fig. 9B); the early moments in the opening of the ramp and the main shaft (Fig. 9C-D); the rush in the construction of the village of Pilar, the concentration plant (Fig. 10) and all other buildings composing the whole industrial area, including the ~80 km-long pipeline destined to bring water from the São Francisco River. Altogether, these operations made of Caraíba and surroundings an anthill of workers from many parts of the world (Appendix 1; A1-9), and made of the dry Caatinga a bathtub into which millions of US Dollars were shed monthly by BNDE. Equally, in 1977-1978, CMSA started to contract geologists and mine engineers for the team that would be responsible for the production of copper.

While DOCEGEO was finishing its final report about the Caraíba orebody, only a few people working in the anthill were worried about the size of the technical drama concerning the lack of knowledge on the geology of the orebody. The worried people were basically some senior engineers of Milder Kayser and the three senior geologists (Appendix 1; A1-10) of the recently created CMSA's staff of geologists, as they knew the size of the responsibility for understanding the orebody and feeding the mining engineers with reliable information for planning the fundamental mining operations coming soon.

Four geologists among the DOCEGEO's staff also helped with their criticism upon the geometrical model assumed until 1978(Fig. 8). Two of these geologists (Appendix 1; A1-11) were

FIGURE 9 -The early days at Caraíba. A - Maquete displaying the 3-D shape of the Caraíba orebody (Docegeo, 1978). The next photographs were taken in the field by Luiz D'el-Rey (Dec/1977). The picture in (B) shows an electrical shovel loading a truck in the early days of 1978, during the opening of the uppermost bench of the open pit. (C - D) These pictures document the initial stage in the opening of the ramp and main shaft, respectively (underground mine).

FIGURE 10 - Construction of concentration and underground mine facilities in the early days at Caraíba. A looking-to-the-East view of the secondary crusher (to the left) and the tower of the main shaft (right), all still under construction in the early days of 1978, coevally with the first days of mine operation in the open pit. The stockpile seen in the middle grew up with the first loads of ore exploited from the open pit (bench 440 m), which was used for testing the primary crusher (further left, outside the picture, from where departs the inclined conveyor belt). The underground mine was not contributing with ore, at that time, yet.

only directly involved with the study of the target R-22 (northern end of the Caraíba orebody). In addition, all the younger geologists hired between 1979 and 1981 for composing the Caraiba´s technical staff (Appendix 1; A1-12) soon realized the reasons for worries and rapidly embraced the task to establish the basic routine with which the Mine Geology Division became capable of controlling the exploitation of ore with a minimal loss of Copper due to dilution during the mining works.

During the 1:10,000 scale geological mapping of the surrounding Caraíba Mine area (1982-1983), the corresponding author (the map's author) walked a minimal distance of 130 km distributed in eighteen E-W trending tracks opened for a CMSA's new campaign of geophysical survey in the orebody's neighborhoods. The tracks were 500m apart, one from each other, most of them marked every 100m, others marked every 50m, composing a frame (omitted for simplicity in Fig. 3) that was essential for providing accurate location of the outcrops. The outcrops existing between these tracks were located accurately with the aid of 50 m-long measuring tape.

During those pioneer years, the more systematic geological study of the Curaçá Valley terrane was being carried out simultaneously with the exploitation of ore from the uppermost four benches of the open pit and the opening of the ramp and galleries in the underground mine. The considerable amount of geology and structural data obtained during such studies allowed a better understanding of how heterogeneous the Caraíba orebody was and emphasized the need for much more care during mining should one avoid an undesirable level of ore dilution during explotation. Consequently, the original project envisaged by Milder Kayser and BNDE was heavily challenged, particularly the one for the underground mine.

Due to all the above, the initial engineering and economic principles in the Caraíba Mine Project ended up by putting on the shoulders of two tens of CMSA's geologists and mining engineers the direct responsibility for re-planning the underground mine in the period 1978-1984.

With the support of consultant engineers hired among Chilean experts on Cu mines, the CMSA's technical staff could succeed in pushing the production of copper into the expected route. Several modifications were introduced in the whole project, meanwhile the technicians worked under pressure, as they had to guarantee the monthly production of copper by running a large mine for which there was not a reliable project and the vast equipment (shovels, electrical drillers, out-of-road trucks, big tractors) that cost tens of millions of US Dollars showed themselves to be troublemakers, too. The most visible modifications concerned the underground mine planning, but not only. For example, mechanical and electrical engineers faced their own challenge trying to keep operating the fleet of mine equipment, for which the maintenance was made difficult beyond necessary because vital spare parts had to be imported and were always missing in the mining exactly when they were most required. In other words, the difficulties included a series of obstacles imposed by the federal bureaucracy concerning international trading in general (Appendix 1; A1-13).

Moreover, in the pioneer years (1977-1990), the value of a ton of metallic copper oscillated between US$ 1,700 and 2,000, never above, so everybody working for CMSA lived permanently scared by a ghost named low profitability. At that price of the metal, only Caraíba could be considered a mine among other Cu-bearing bodies of mafic-ultramafic rocks already known to exist in the Curaçá River Valley. In the following years, the private company which purchased the Caraíba Mine and its industrial complex from the federal government (1989-1990) largely benefited from the rising of international prices of copper after, particularly throughout the decade 2000-2010, in which the values oscillated above US$ 5,000, or as high as the US $ 7,000-8,000, making profitable other smaller deposits in the valley and turning Caraíba itself highly profitable.

Keeping in mind the historical, economic, and engineering aspects of the Caraíba Copper Project, as above, it is possible to understand the scale of the challenge at Caraíba and the value of structural geology for solving the problems concerning mining planning and saving hundreds of millions US Dollars.

5. Unravelling the 3D geometry of the Caraíba ore body

5.1. Characterizing the polyphase deformation in the host rocks of the Caraíba deposit

Beyond that point of knowledge, geologists first noticed evidence of polyphase deformation and metamorphism (e.g., Fig.11A) across the Curaçá terrane. However, before the area's complex evolution could be understood, they had to remove from mind the idea that all the layers dip steeply or were sub-vertical. Although wrong, such an impression was understandable because the high intensity and pervasiveness of D_3 shortening brought the layers and or the metamorphic banding S_1 towards parallelism with the N-S trending sub-vertical surfaces of foliation S_3 in many localities (e.g. Fig. 11B).

Nevertheless, as more and more outcrops were studied, the S_3 foliation and F_3 folds were shown to be equally common (Fig. 12) so that, after collecting data along field profiles, it became possible to realize that before the onset of F_3 folding, the layers' dip was much closer to the horizontal, as in the regional cross sections (Figs. 2-3). At this point, the reader is undoubtedly asking: if only the metamorphic banding S_1 and the mineral foliation S_3 are evident, what structures represent the D_2 event, how did they become apparent, and what does the D_2 deformation mean in the evolution of the Curaçá terrane?

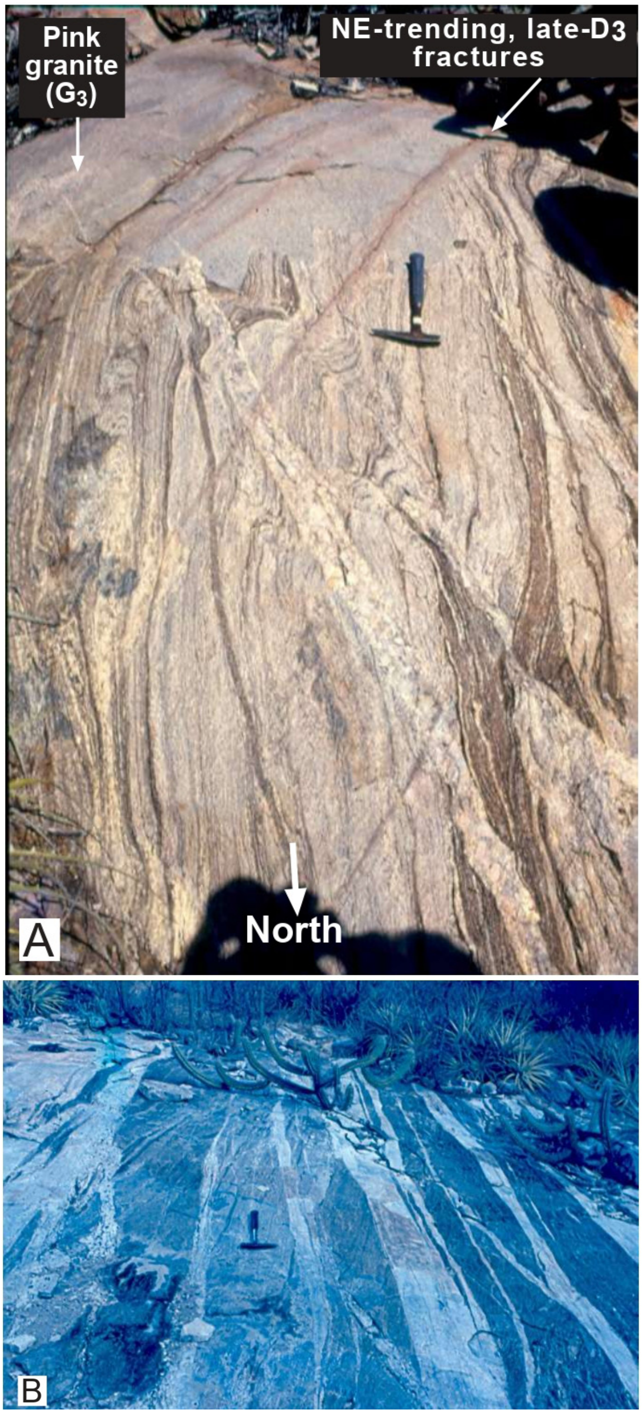


FIGURE 11 - (A) Typical flat-lying outcrop, in this case near the village of Poço de Fora, ~30 km North of Caraíba, displaying typical migmatite with a continuous metamorphic banding (S_1) deformed by folds which are transected by pegmatitic veins injected along dextral shear zones (close to the hammer). The whole set is invaded by a fine-grained pink granite (G_3) but the gradual contact evidences *in situ* partial melting and migmatization of the country rocks during D_3 deformation. A longer, SE-trending tabular granitic vein cuts across and supports the interpretation of sinistral transpression during D_3. The youngest features are NE-trending fractures, along which K-rich fluids imprinted the metasomatism typical of the D_3 event in the Curaçá terrane. (B) A looking-to-the-South view of a flat-lying outcrop situated East of Caraíba. N-S trending and sub-vertical strips of dark color migmatized amphibolite occur intercalated with sheets of G_3 pink granite exhibiting the strong mineral foliation (S_3) parallel to the contacts. The granitic sheets transect the earlier metamorphic banding (S_1) in the amphibolitic strips. S_3 also occurs in the darker strips but cannot be seen due to the photograph scale.

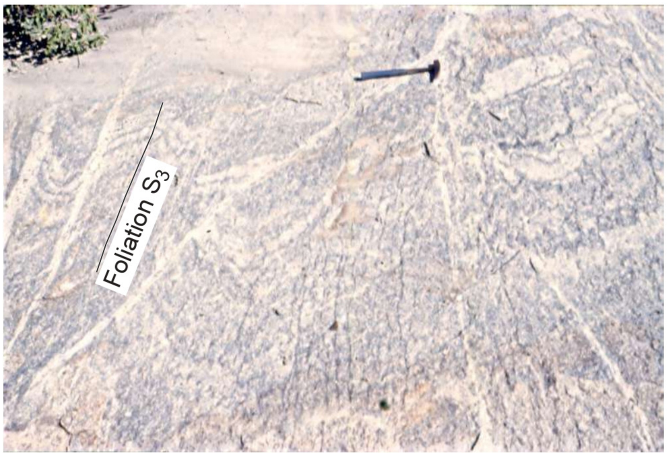


FIGURE 12 - Evidence of F_3 folds. Flat-lying outcrop of orthogneiss exhibiting a somehow diffuse metamorphic banding deformed by F_3 folds and cut across by the pervasive and sub-vertical biotite-hornblende mineral foliation S_3 which trends N-S and is associated with lit-par-lit injections of white to light yellow G_3 granitic material.

The answers to these questions constitute the heart of the contribution of the detailed structural analysis of the Caraíba orebody and surroundings.

The clues on the existence of the D_2 event were provided by the metamorphic banding S_1 affected by two distinctive folding events and the presence of three generations of granitic magmatism (G_1-G_2-G_3) respectively associated withD_1-D_2-D_3, as characterized by Jardim de Sá et al. (1982). By showing the mutual cross cutting relationships between these granites, other lithotypes and the tectonic structures, including the different conditions of metamorphism, these authors made possible to show the association between G_2 magmatism with the granulite facies metamorphism regionally (Fig. 13).

5.2. D1 fabric elements

Apart from G_2 and G_3 granitoids, the Tanque Novo Sequence and Caraíba Complex lithotypes and the mafic-ultramafic rocks exhibit the regional metamorphic banding (S_1), which is a generally a continuous planar composite structure developed under high-amphibolite facies metamorphism associated to pervasive migmatization.

In the Tanque Novo Sequence, S_1 is sub-parallel to the sedimentary layering (S_0) and is noticed because m-thick layers of amphibolite occur intercalated with cm- to m-thick layers of quartz-feldspar paragneiss, quartzite, banded iron formation, calc-silicate rocks, and olivine marbles. This is observed mainly in the Pinhões dam and in outcrops along

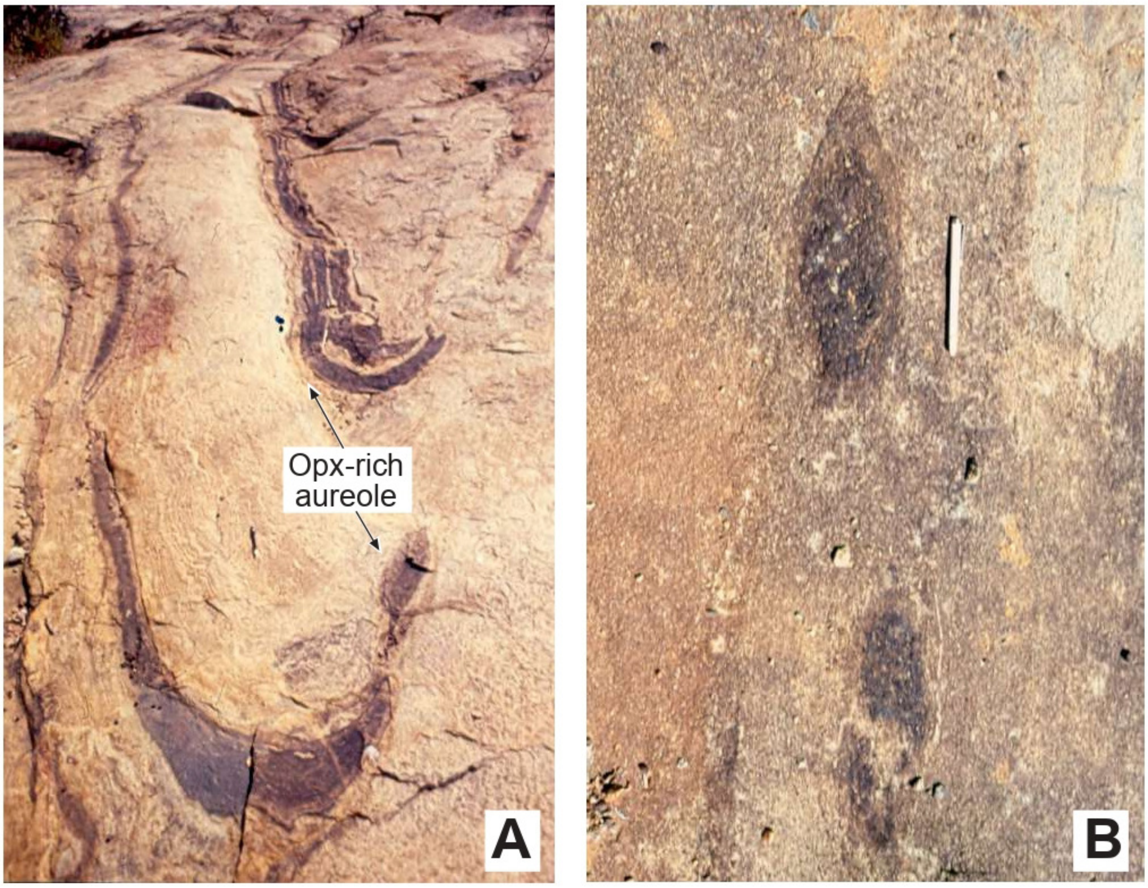


FIGURE 13 - Granites G_2 and granulite facies metamorphism. A - Outcrop (~15 km NW of Caraíba) exhibiting layers of dark brown amphibolite with internal banding (S_1) and contacts parallel to the diffuse banding (S_2) seen in the light brown tonalitic orthogneiss (G_2). The intrusion of G_2 resulted in a cm-thick hallo of orthopyroxene (Opx) along the limits of the amphibolite layers. The F_3 folds deform the contacts and the hallo, plus S_1 and S_2. Note the black pen in the fold´s core. B – Detailed displays amphibolites boudins surrounded by the Opx-rich hallo and foliation S_2 parallel to the 12 cm-long white pen. The North and the amphibolite facies mineral foliation (S_3) are both along the vertical.

the profile Pinhões - Poço de Fora (Fig. 8; Hasui et al. 1982a, 1982b; Jardim de Sá et al. 1982), as well as in the NW quarter of the Caraíba open pit and surrounding area (D'el-Rey Silva 1984) or in trenches across the target R-22 (Lindenmayer et al. 1984). In the paragneiss, the crystals of quartz and feldspar occur strongly flattened and elongated together with biotite and hornblende, primarily, as well as garnet, cordierite, and sillimanite. In metabasic rocks (e.g., amphibolites), S_1 consists of cm- to dm-thick bands displaying alternated dark and light colors and respective composition of more mafic (hornblende and biotite) or more felsic minerals (feldspars and quartz, mostly) and may occur enhanced by mm- to cm thick bands of leucossome and granitic material injected lit-par-lit (see example inside the darker layers; Fig.11B). The common occurrence of boudins of calc-silicated rocks and olivine marbles in strips of D_1 migmatites invaded by sheets of G_3 granite (e.g.Fig. 14) places the Tanque Novo Sequence at the bottom of the lithostratigraphy. Such field-based interpretation has been further improved by evidence of D_2 deformation (D'el-Rey Silva 1984) and isotopic Sm-Nd and U-Pb geochronology data (D'el-Rey Silva et al. 2007; summary ahead).

5.3. D_2 structures

The detailed litho-structural mapping of the four upper benches of the Caraíba open pit (D'el-Rey Silva 1984) took part from 1978 to 1984. Right in the beginning, and counting only with the diamond drill holes perforated until 1978-1980 (Pignatary's and DOCEGEO's drilling campaigns), but pushed by his professional duties (Appendix 1; A1-14) and the boom of evidence for two different generations of folds (F_2 and F_3) affecting the metamorphic banding (S_1) everywhere around Caraíba (e.g. Fig. 15 A-C), that author produced in 1978-1979 a set of vertical cross sections containing the first interpretation of the whole Caraíba orebody in terms of a poly folded tabular body of Cu-bearing mafic-ultramafic rock with overall geometry controlled, in all the cross-sections, by a single and tight F_3 synform with axial surface strongly inclined to the West (Appendix 1; A1-15), being inspired by a particularly beautiful natural specimen (Fig. 16).

FIGURE 14 - Syn-D_1 ductile flow. A trail of boudins of calc-silicated rocks and olivine marble (to the right of the hammer) inside a strip of migmatitic amphibolite, indicating differential ductile flow during D_1 migmatization Sheets of pink granite cut the whole set sub-parallel during D_3 migmatization. Same outcrop as in Fig. 11B.

As a consequence of these new cross sections and the corresponding author being a senior geologist in the mine and also the Manager in the Mine Geology Division, he had to assume the responsibility for guiding all the steps for mine planning based on a complexity folded orebody, having done this simultaneously with the construction of the industrial complex predicted in the original project (Fig. 6) and relying solely upon the tools of structural geology.

In the new interpretation of the Caraíba Cu-deposit (Fig. 5B), the geological sections across the central and more prominent part of the orebody (sections 32 to 37), required the existence of some F_2 folds refolded by the main F_3 synform and its parasites. Nevertheless, the decision for the type 2 of F_3 x F_2 folding interference pattern (mushrooms and boomerangs; Ramsay 1967) could only be achieved with confidence only after completion of the mapping of the open pit (D'el-Rey Silva 1984) and after much academic discussion (Appendix 1; A1-16). Because D_3 flattening was so strong and melt-assisted, the real geometry of some of the 10cm- to 1m-scale figures of F_2X F_3 fold interference pattern seen in the field (e.g. Fig. 15 A-B) is obscured, once the hinges may occur partially obliterated by extreme ductile thinning or melt injection or a combination of these factors.

Furthermore, other outcrops evidencing the stiffness of the mafic-ultramafic rocks during D_3 deformation, relative to the country rocks, triggered the alarm of danger, as they strongly suggested that the mineralized rocks at Caraíba likely underwent the same kind of disruption or boudinage during their structural evolution, indicating the strong probability that, in contrary to what was previously assumed by Milder Kayser, the Cu content would not be homogeneously distributed in space.

Since then, and even after some necessary professional arguments (Appendix 1; A1-17), the Mine Geology Division held direct control upon the set of operational steps needed for the definition of the Cu-content in the run-off-mine material before a decision could be made whether to send every truck coming from the open pit to the primary crusher or to the piles of waste or marginal ore. In reality, such a decision was a game involving millions of US Dollars one or more times every week.

5.4. D_3 structures

The F_3 folds are non-cylindrical, cm- up to km-sized, generally tight, asymmetric, generally up-right or E-verging, with N-S trending axial planes dipping 85^0-75° W. Fold axes (B_3) are sub-horizontal and plunge to northerly or southerly directions, such as the Curaçá Antiform. S_3 is a typical mineral foliation primarily defined by biotite, hornblende, and strongly flattened quartz and feldspars. Commonly the latter two display a prolate geometry representing a penetrative L_3 mineral stretching lineation parallel to B_3.

5.5. Fold Interference patterns

The walls of the four upper benches (Fig. 17) were mapped (1978-1984; 1:1,000 scale) simultaneously with the opening of bench 395m (bottom 380m above sea level) so that the Cu-orebody could be tracked in great detail in successive exposures every 10-20m along- and across-strike, blasting after blasting. The study of these benches in the open pit, new galleries in the underground mine, the core of new diamond drill holes, and outcrops in the surroundings of the mine (Fig. 3),

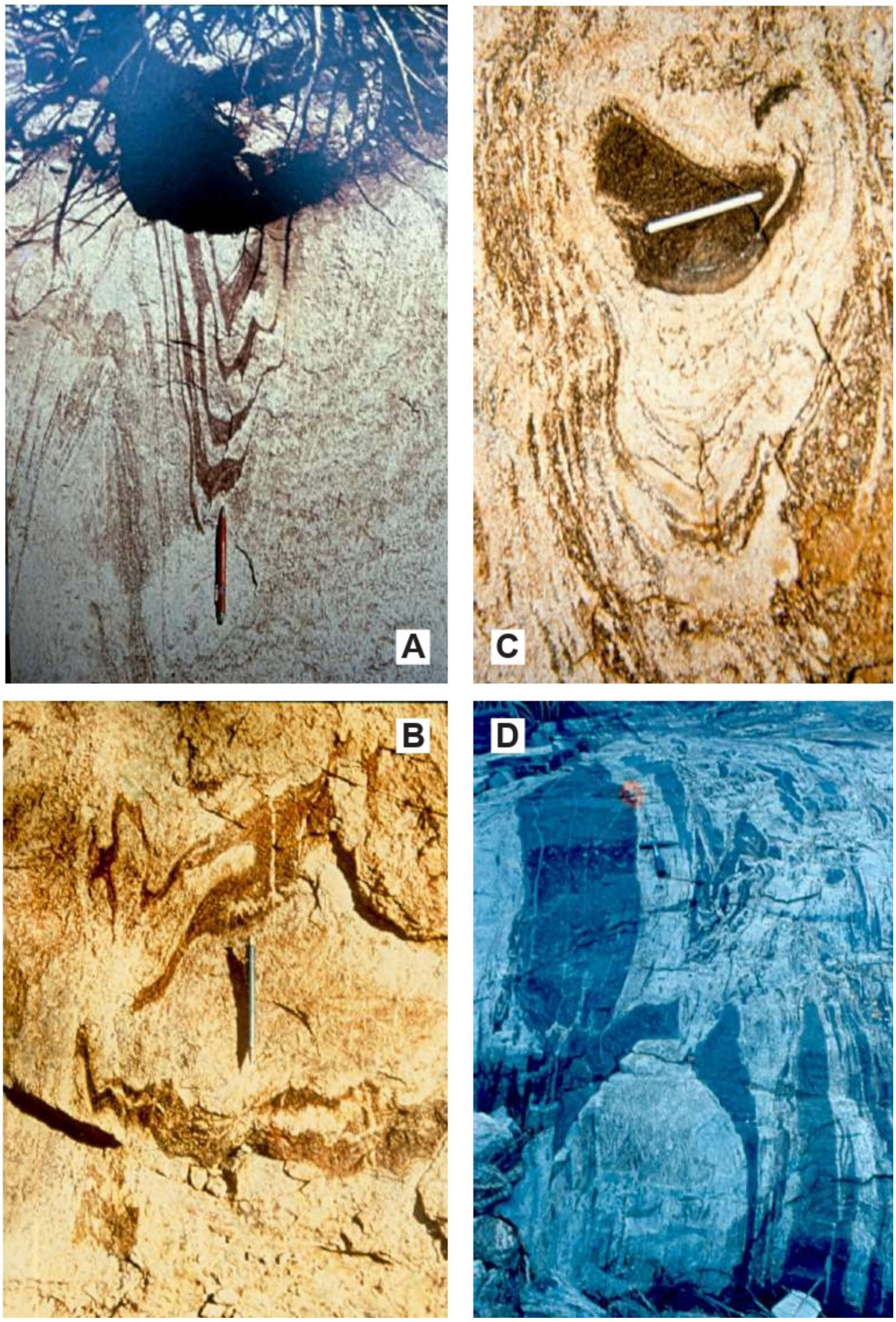


FIGURE 15 - Examples of F_2 x F_3 refolding. All features are from different outcrops around the Caraíba Mine. A-C - Evidence of two foldings events (F_3 x F_2) deforming the metamorphic banding (S_1). The N-S trending trace of foliation S_3 is evident along the vertical in all the pictures. D - A typical syn-D_1 migmatite evidences the stiffness of the mafic-ultramafic rocks, which occurs folded and disrupted around the F_3 hinge (center of the picture). In contrast, the thinner layers of the same rock visible a few centimeters above behave ductilely (right to the hammer).

provided essential information for understanding the geology of the Caraíba Cu-deposit and the Curaçá terrane as well.

The sequence of five vertical walls in the open pit (Fig. 18) allowed D'el-Rey Silva (1984) to follow several geological and structural features in 3-D from the surface to a depth of over 70 metres. The data led no doubt that zones of more intense deformation occur associated with the sub-vertical surfaces of the S_3 foliation (detail in Fig. 16) and the infiltration of K-rich fluids along S_3 and even along the sub-vertical contacts between mineralized layers and country rocks.

More detailed observations permitted to emphasize: (a) - the clear existence of richer and poorer zones of mineralization within the orebody (Fig. 19); (b) – the fact that the metamorphic banding S_1 could be easily seen in both the Cu-barren and Cu-bearing mafic-ultramafic rocks in the open pit, and was folded (Fig. 20); (c) - the preference of the Cu-sulphides for

FIGURE 16 - An inspiring example. The first specimen of a typical F_3 fold was collected in the early days of operations in the open pit (beginning of 1978). Placed on a heavy wooden base, this block and the fold remained for at least 20 years in the headquarters of the Mine Geology Division, serving as the mine geologists' inspiration. The F_3 fold deforms the S_1 metamorphic banding in the migmatitic gneiss, one of the country rocks. Note the surface of transposition parallel to the strong sub-vertical mineral foliation (S_3).

FIGURE 17 - The Caraíba open pit by the end of 1982, in which the lowest bench (the fourth from the surface) was just in the first stages of opening, in the open pit's center.

the magnetite-bearing bands of hypersthenite relative to the bands of norite, even when the magnetic bands were no more than 1 cm-thick, confirming what had already been noticed in drill cores (Fig. 21).

Thus, with the attitude of S_1 documented on several walls, successively exposed one few meters from each other, blast after blast during the mining operation, the lithostructural mapping could be done in the desired detail in the mafic-ultramafic rocks as easily as it was in the gneiss, migmatites, and supracrustals also existing in the open pit. These geological and operational facts largely helped to follow the contacts between mineralized layers and the trend of S_1 banding in all the lithotypes, guaranteeing the great degree of precision achieved in the geological map of the open pit (Fig. 5A). For example, the enlargement of bench 395 would result in N-S and E-W adjoining walls in the open pit's central part, which would allow to follow the trend of S_1 and the folds deforming it in space (Fig. 22).

5.6. The 3D geometryof the Caraíba mushroom is finally depicted

The day-after-day geological mapping of the 3-D block (bench 395) showed that, in the central part of the orebody (Fig.22), both the contacts and the S_1 banding in both the mineralized and country rocks strike E-W and dip steeply to the North. In contrast, the country rocks along the southern contact change the dip gradually towards the South. In that part of the orebody, such a change in the dips, which is a consequence of the layers turning around the large-scale F_2 hinges, also forced a shift to the N in the original S-plunge of the B_3 fold axes, as illustrated in the figure.

At that height of the happenings, when the structural confidence acquired with the observation of the S_1 banding led to understanding the orebody as a polyfolded mass of Cu-

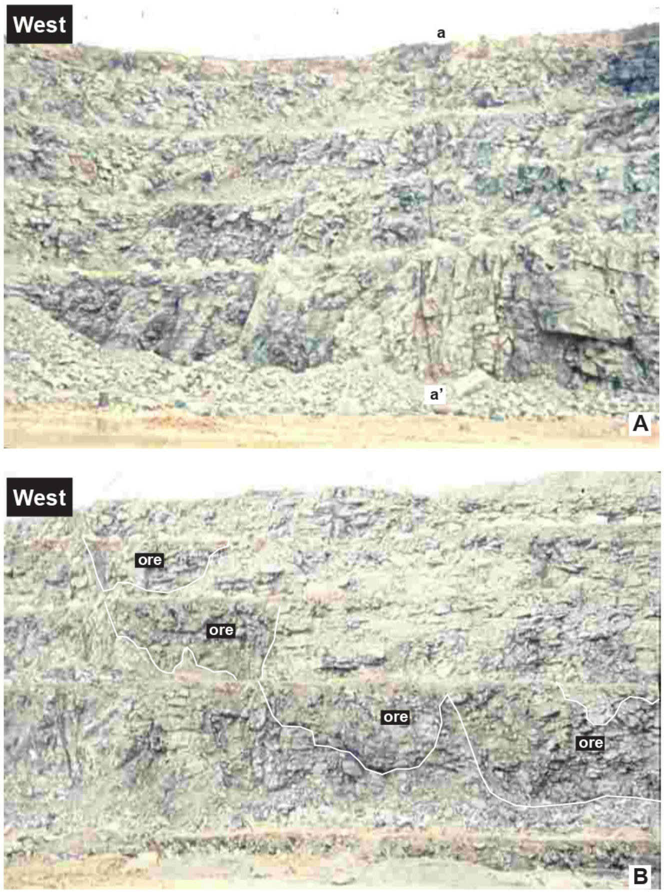


FIGURE 18 - Key structures in the vertical walls of the uppermost five benches of the mine. A - A sub-vertical transposition zone of high strain can be followed (a-a') for at least 75 m vertically. B - The darker color of cu-mineralized hypersthenites and norites detaches from the lighter shadeof the country rocks, allowing visualization of the F_3-folded contact.

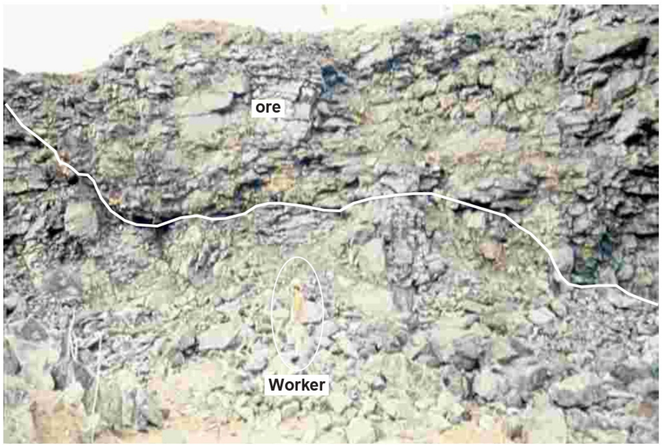


FIGURE 19 - A closer view of the F_3-folded lower contact of the ore layer, which rests above, enclosing several yellow patches due to a higher concentration of chalcopyrite in the ore. Note the worker for scale (inside the white ellipse).

abundance of type 2 folding interference pattern (mushroons and boomerangs; Ramsay 1967) in and around Caraíba, when compared with other parts of the Curaçá terrane, and also the crucial evidence of F_3 folds deforming both the S_1 banding and F_2 folds in the vicinities of the mine (Fig. 24) or deforming both S_1 and the E-W trending S_2 foliation, such as described in the Restaurant outcrop (Fig. 25), a large flat-lying exposure of orthogneiss existing just 150 m East of the entrance of the underground ramp (Appendix 1; A1-18). These structures and their most feasible explanation (Fig. 26 and Appendix 1; A1-19) left no doubt that an E-W trending foliation formed in rocks of the study area, in a time post-S_1 and pre-D_3 deformation, and on the N-S strike of D_1 and D_3 structures across the surroundings of the open pit. (3) After the seven years of detailed mapping, the geological map of the open pit showed the complete similarity between the geometry of the mineralized layers (metapyroxenites/norites) and the shape of the orebody as defined by the isolines of Cu content or each of the upper four benches (Appendix 2, A2-1; and more details ahead).

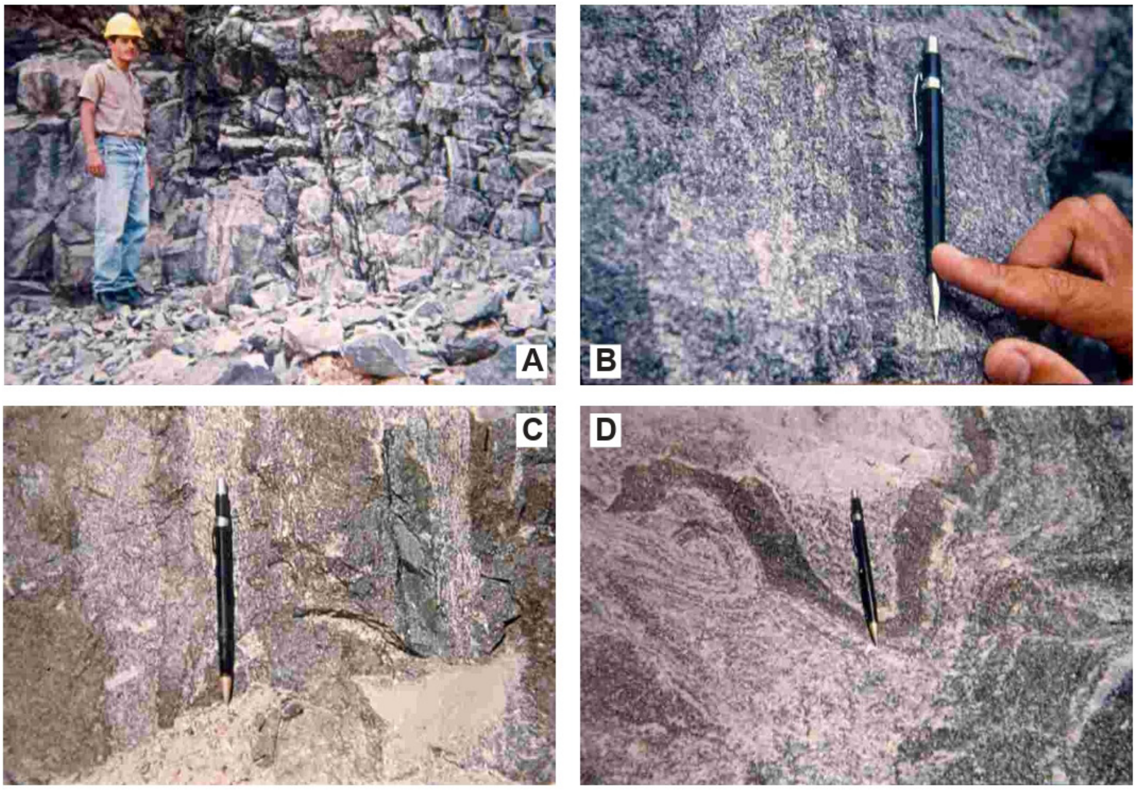


FIGURE 20 - Observing tectonic structures in the open pit. A - Remarkable visibility of the metamorphic banding S_1 in the Cu-barren mafic-ultramafic rocks migmatized during D_1 (left half of the picture) and in the Cu-bearing melanorite (right half). See details of the latter in B-C. The photograph in (D) displays a re-folded specimen of the S_1 banding in mineralized melanorite, consisting of intercalated strips of hypersthenite and norite or (less commonly) gabbronorite. Although this structure may represent an early deep crust phenomenon of magma mingling, its abundance in the drill cores (see examples in Fig. 21 A-B), the parallelism with the S_1 metamorphic banding in adjacent country rocks (paragneisses or migmatites, for example) in the drill cores, and the structural control exerted by the F_3 folds upon the S_1 banding already affected by F_2 folds in the field and cross-sections, altogether point to the predominant role of regional deformation in creating the metamorphic banding in the Cu-bearing and country rocks, such as discussed ahead in this text.

bearing rocks, the level of confidence was pushed upper by other critical data collected during the first years of mapping in the Cu-mine and surroundings.

(1) The detailed logging of cores from many diamond drill holes provided abundant evidence of S_1 banding, similarly to what was observed in the field (Fig. 23). (2) The relatively high

As such, the four maps (Appendix 2, Fig. A2-1) also demonstrated: (a) - the non-uniform distribution of the copper sulphides within the mineralized layers; (b) - the longer axis of the Cu-bearing lenses, in general tens of meters-long, clearly following along the metamorphic banding; (c) – in particular, the map pattern of the lenses on the surface of each bench

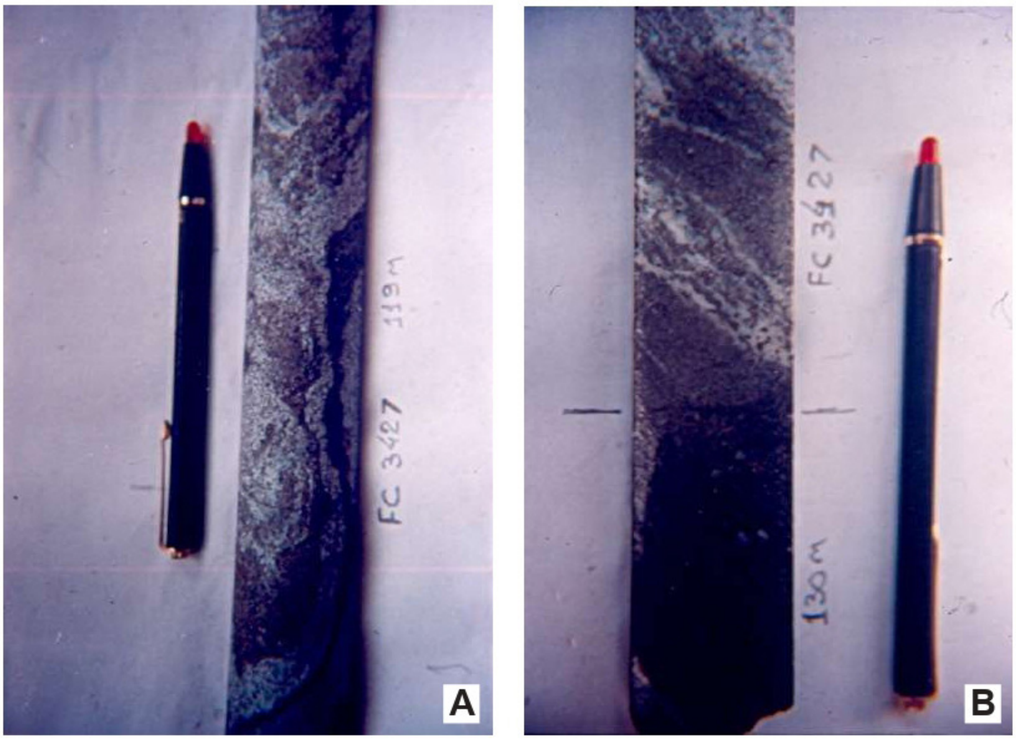


FIGURE 21 - Folliation S_1 in drill cores. The metamorphic banding S_1 in mineralized rocks, as seen in drill cores of the Caraíba Mine. The example in (A) shows S_1 in folded layers of melanorite, depth of 119 m, drill hole FC 3427. The one in (B) is from a depth of 130 m in the same drill hole (discussed in the text).

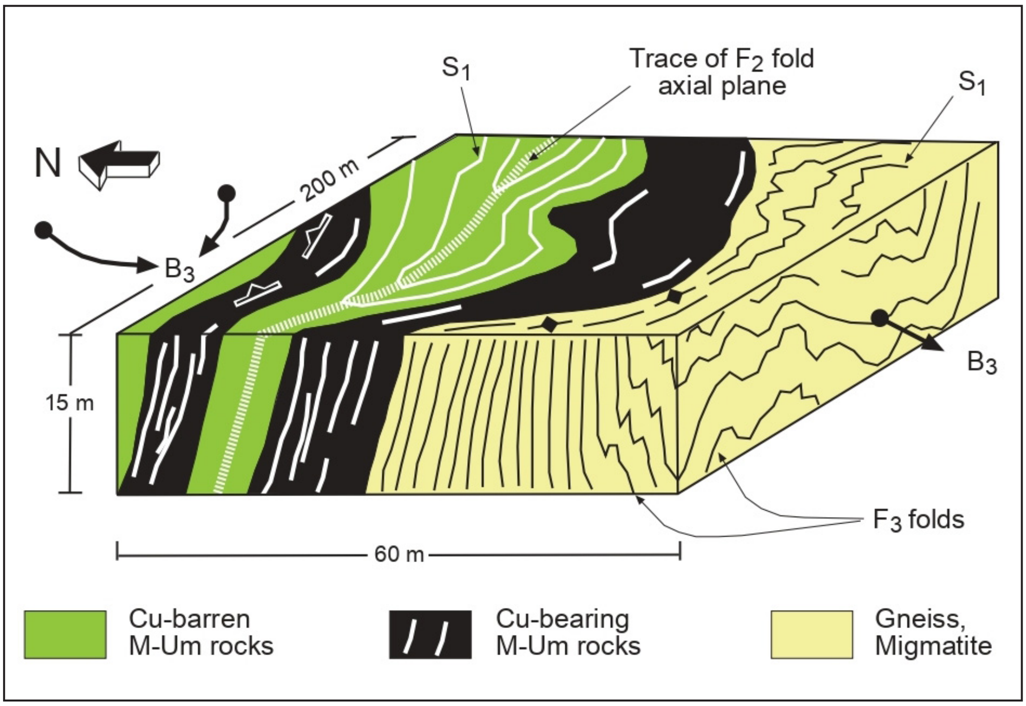


FIGURE 22 - Block diagram summarizing the structural features and relationships in the central part of the Caraíba orebody, bench 395 (adapted from Fig. 14b in D'el-Rey Silva 1984). Note the changing dips of layers and plunges of F_3 fold axes around the larger F_2 hinges in the central part of the orebody.

resembled very well the E-W trend of the orebody´s central part; and (d) –the most substantial concentration of copper in vertical bodies coincident with the main F_2 hinges control the geometry of the mineralized layers in the geological map and inside theCaraíba F_3 synform (Fig. 5A-B).

The four maps of Cu-% isolines (D'el-Rey Silva 1984) are a consequence of the efforts of the Caraíba Mine geologists in pursuinga desirable degree of accuracy in the classification of slabs of rocks as ore, marginal ore, or waste, before and after each blast in the open pit (see also below).

5.7.Further detailed data from the Mine

The profitability of the metallic Copper production based on the exploration of the Caraíba open pit depended on how many times would be repeated, every day of every week through a year, a mining cycle comprised of six main steps. The amount of cycles in a working shift, or throughout a day, gives an idea about the performance of the mining equipment, reflected in the number of travels of out-of-road trucks in and out-the-mine. In other words, a mining cycle (steps 1-6 in Appendix 2, A2-2) evaluates the mining operations' efficacy and constitutes a vital tool in mining management.

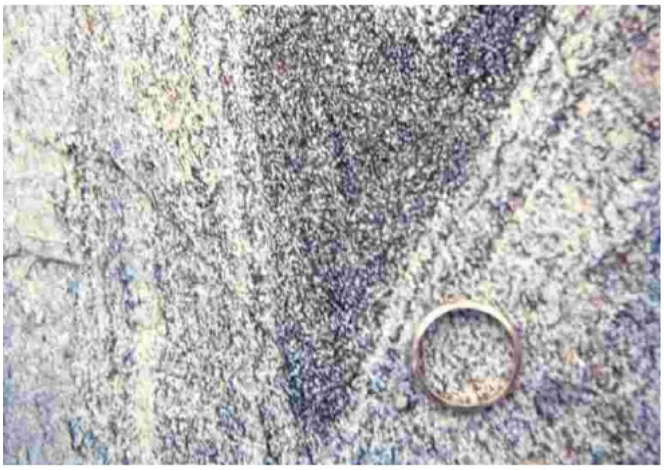


FIGURE 23 - D_1-D_3 evolution recorded in banded gneiss of the Restaurant outcrop. The metamorphic banding S_1 is deformed around an F_2 hinge that is the SW-pointing termination of an m-scale F_3 x F_2 mushroom-like structure. Both the F_2 hinge and S_1 are cross-cut by the strong S_3 mineral foliation defined by biotite and flattened crystals of quartz, feldspar and hornblende, all aligned top left to bottom right (details in and around the 2 cm-big wedding ring).

Because of the geologists´ professional feeling about the orebody's heterogeneity and the risks for mining if such heterogeneity could be overlooked, the Mine Geology Division claimed the direct responsibility for defining the copper content in every slab of blasted rocks. Such a task included the topographic survey of the position of each hole in the field, before drilling; sampling the pulverized rock in the cone of powder surrounding the mouth of each drilled hole; transport of the samples to the Chemistry Laboratory; and, after the results were known, the production of a map displaying the different materials (regarding the Cu content) in the bench slab before the "fire" (Fig. A2-3, Appendix 2), and finally, defining the physical borders between ore, marginal ore, and waste, before and after the blasting.

The fact that the huge mine equipments always implied great danger of mixturing Cu-rich and Cu-poor material during the operation gives an idea about the importance of controlling the Cu content in the blasted material (Fig. 27). As such, it required indication of the slices of different average Copper grade with the aid of colored banners placed along the upper border of the bench (Fig. 27A) so that the shovels' operators could see even during the night shifts and could inform the truck drivers about the type of material being loaded in their trucks. Thus, by knowing the Cu content in thousands of points of a (3m x 3m) tight grid covering each bench, the orebody's geometry could be followed with great precision, bench after bench (Appendix 2, A2-1).

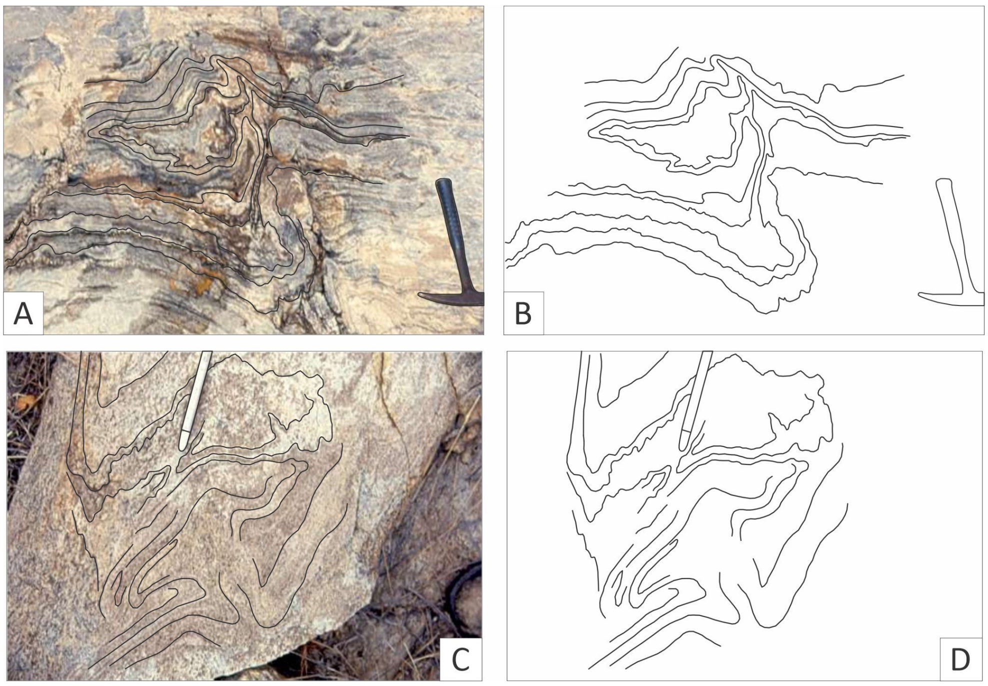


FIGURE 24 - More evidence of type 2 of the F_2 x F_3folding interference pattern.These two examples of F_3 and F_2 folds (A and C; respective line drawings in B and D) deforming the metamorphic banding (S_1) were found in outcrops closer to the Caraíba Mine, respectively NW and SW of the open pit area. The example in (A) means an asymmetric boomerang structure in banded gneiss, and the one in (C) represents a typical mushroom structure in orthogneiss (see also the Photo 34 on page 148 of the MSc Dissertation by D'el-Rey Silva 1984)

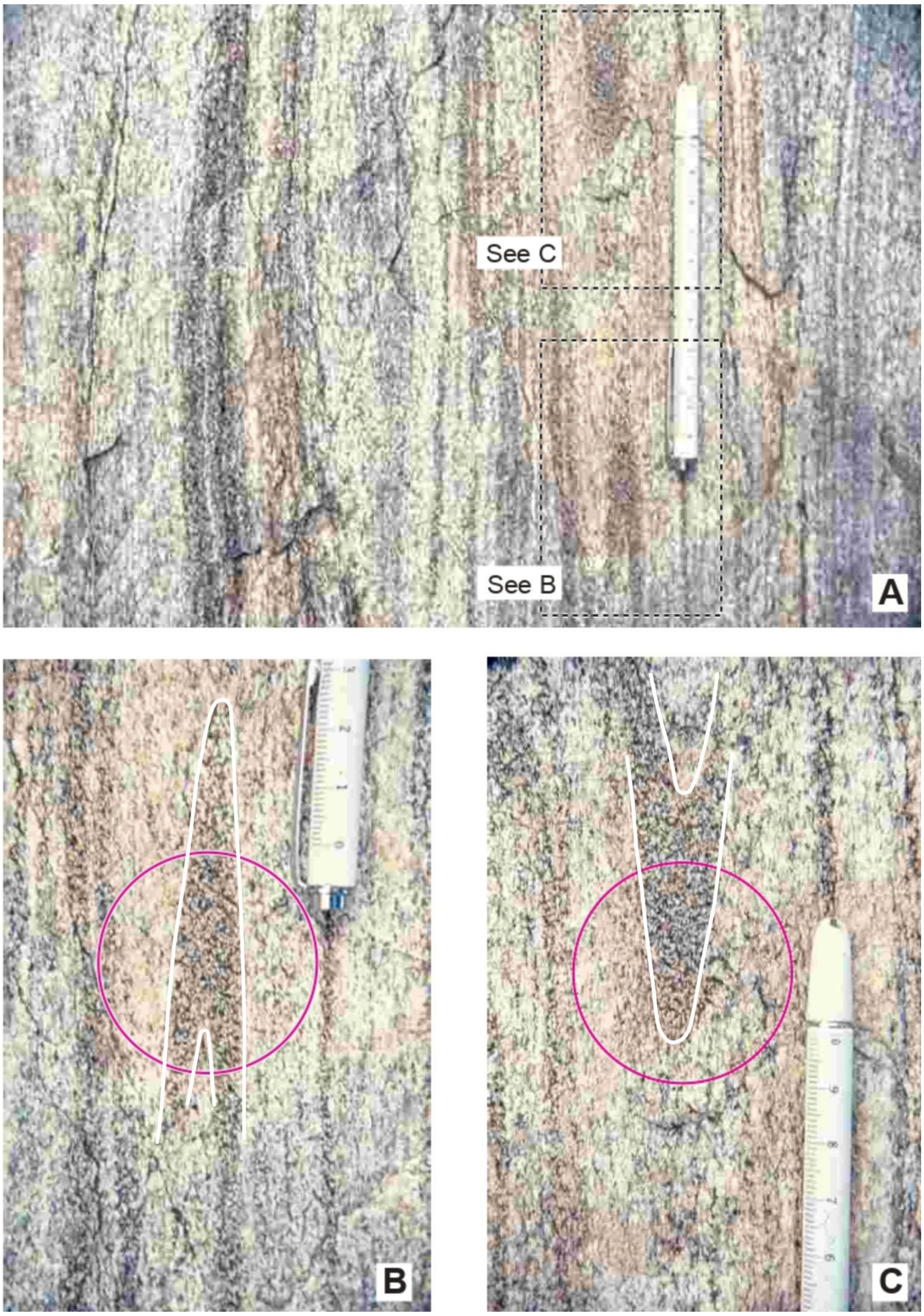


FIGURE 25 - Evidence of S_1, S_2, and S_3 foliations in orthogneiss of the Restaurant outcrop. The head of the scaled white pen points North. A - The evident metamorphic banding S_1 is affected by two intrafolial rootless F_1 folds (just left to the pen). The details (B-C) allow observing the S_2 foliation transecting the two hinges (highlighted by white lines) and being crenulated by the North-striking S_3 foliation (similarly oriented as S_1). The E-W original trend of foliation S_2 is preserved across the hinges (inside the ellipses). Outside the hinges, and due to the strong E-W shortening (D_3), foliation S_2 rotates into gradual parallelism with S_1 and S_3. Same photographs 23-25 in the corresponding author´s MSc Dissertation.

5.8.The Caraíba Airport outcrop

The Airport outcrop is an easily accessed flat-lying exposure of tonalitic orthogneiss with an ameboid surface of nearly 1,000 m^2 of area, situated very close to the northern end of the land track of the Mine airport, being part of the western limb of the Curaçá antiform, close to this fold hinge (Fig. 3). The outcrop used to be visited by groups of geologists between 1980 and 1982, a time when drones did not exist, yet. However, only a one day-long exercise of detailed litho-structural mapping (Appendix 1; A1-20) could unveil the geological importance of the outcrop in the resulting geological map, which was an essencial component of the cited MSc Dissertation (Fig. 15 in D'el-Rey Silva 1984). Such a map is reproduced here with additional information (Fig. 28) obtained after geochronological studies carried out in the period 2000-2007 (D'el-Rey Silva et al. 2007).

The Airport outcrop tonalite contains a yellowish-gray well-banded orthogneiss composed of oligoclase-andesine, hornblende, biotite, orthopyroxene, clinopyroxene, minor microcline, and quartz, with garnet, magnetite, apatite, and zircon as accessory phases. It encloses tens of dm-sized boudins of amphibolite displaying an internal and quite strong S_1 metamorphic banding that is interrupted abruptly along the contact with the tonalite, which typically displays the S_2 foliation. Foliation S_2 is a quite homogeneous granulite-facies

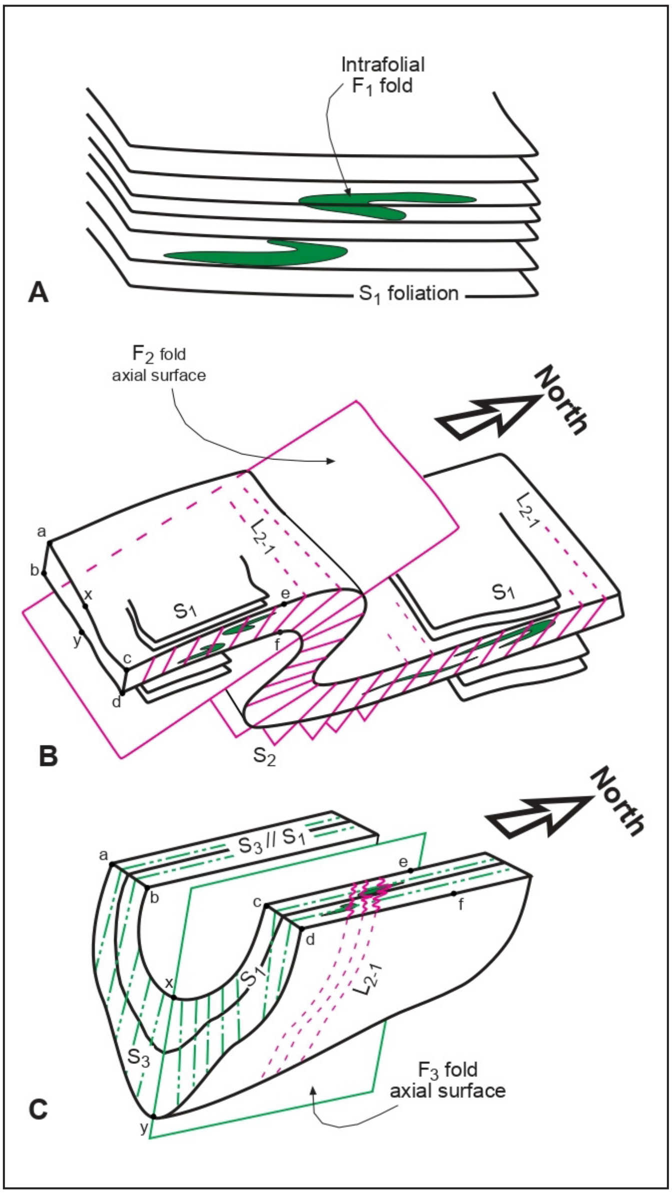


FIGURE 26 - Diagrammatic explanation of the structures in Figure 25. A - The S_1 foliation and the F_1 intrafolial rootless folds represent the deformation event (D_1) and record conditions of high amphibolite facies metamorphism. B - D_2 event was characterized by E-W trending, highly asymmetric F_2 folds, and the South-dipping foliation S_2 developed under granulite facies metamorphism. C - The D_3 shortening further tightened (under high amphibolite facies metamorphism) the F_1 hinges in the limbs of the up-right F_3 folds and crenulated the S_2 foliation cutting across the F_1 hinges. For reference, see points a-f and x, y (in B and C). The rectangle limited by c, d, e, and f (in C) represents the photograph shown in Fig. 25.

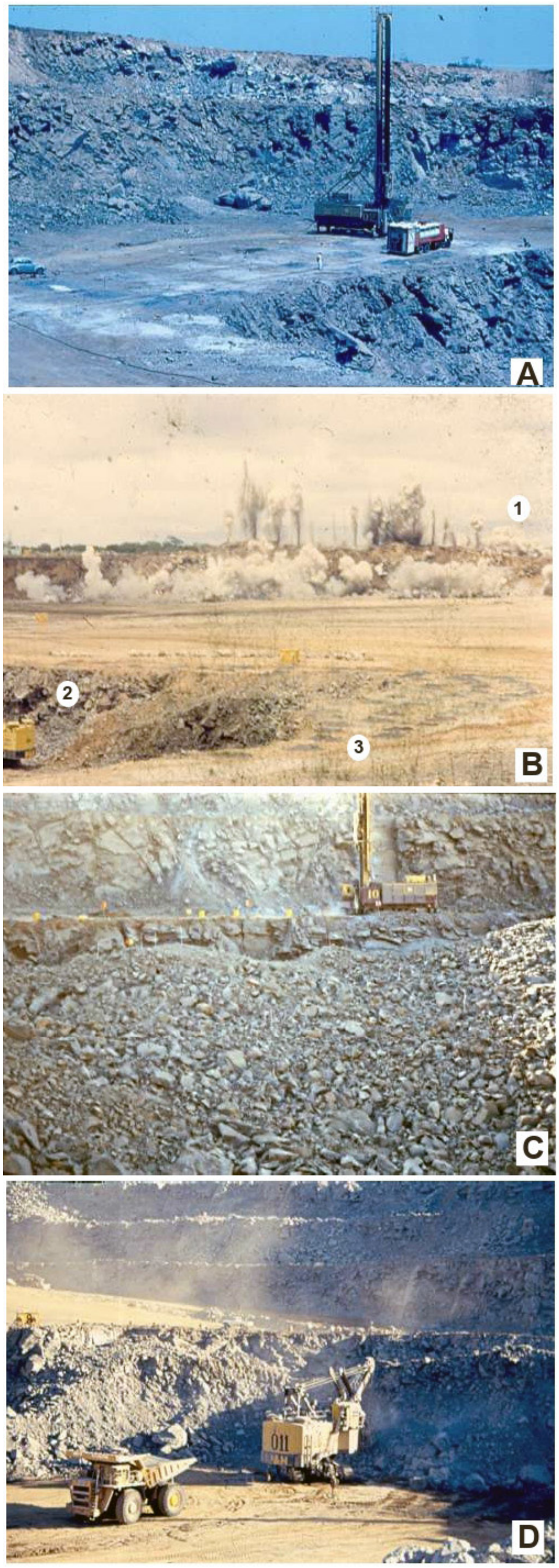


FIGURE 27 - Details of the mining operation in 1978-1980. (A) A bench slab was drilled, and the holes were loaded with semi-liquid explosives from a truck, whereas the electrical driller was still drilling the last hole. Note the cone of rock powder surrounding each hole´s mouth; (B) Viewing an explosion (1), a pile of exploded rocks not yet removed from the lower bench (2) and, in the foreground (3), another slab already drilled but still in situ; (C) Although barely visible in the photo, red and yellow colored banners were used on the bench edge for indication of corresponding areas of ore and marginal ore in the pile of blasted material visible in the foreground; (D) An electrical shovel collecting material for loading the huge truck.

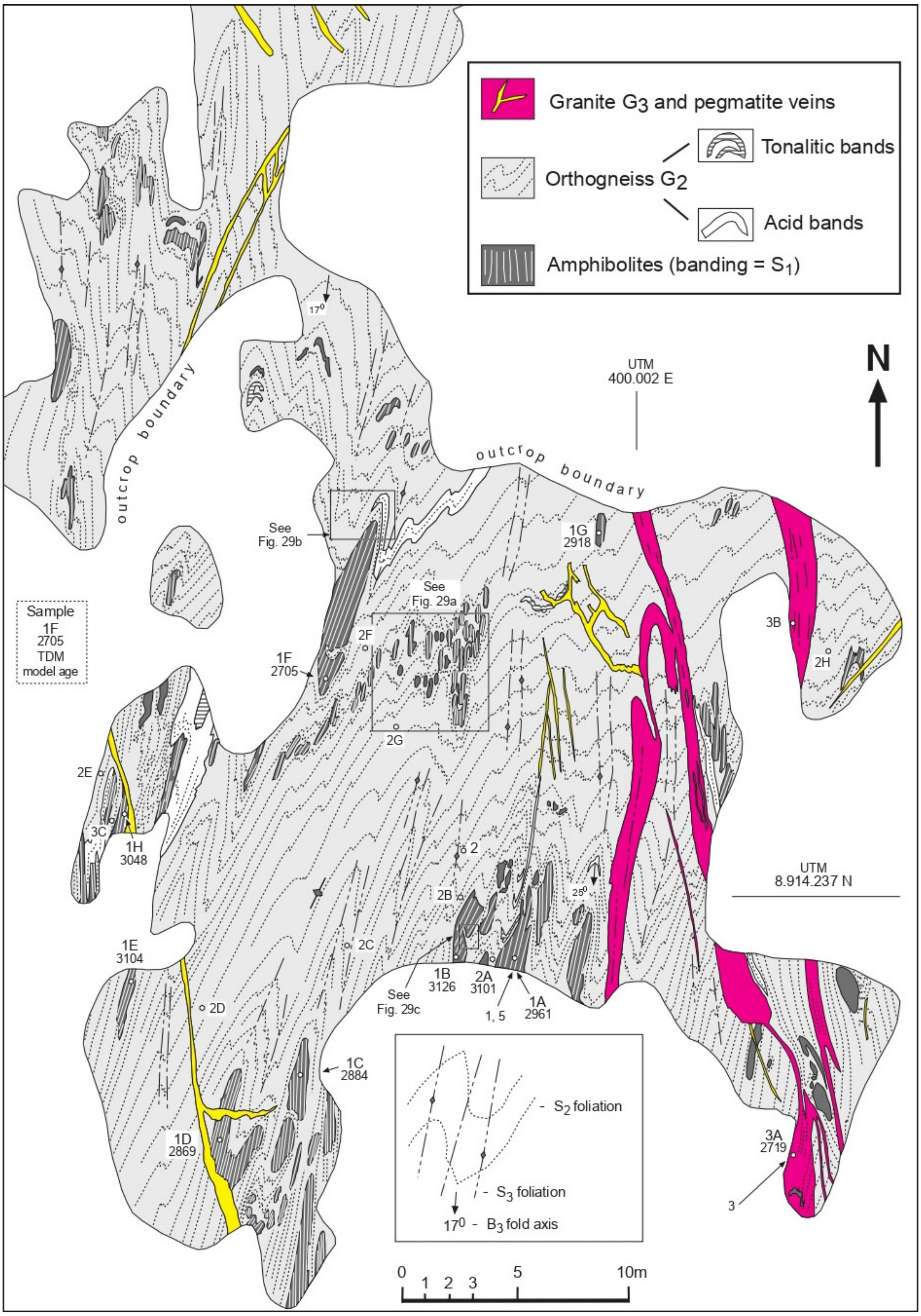


FIGURE 28 - Geological map of the Caraíba Airport outcrop, adapted from D'el-Rey Silva (1984). Note the sites for sample collection and the sample´s T_{DM} - Epsilon Neodymium Model Age, as in D'el-Rey Silva et al. (2007; see their tables 1 and 2). Note the sites from where the photographs in Fig. 29 a-c come.

metamorphic banding consisting of ≤1cm-thick bands of flattened crystals of feldspar, quartz, minor biotite, intercalated to ≤1cm-thick bands of pyroxene, hornblende, plus biotite, and is also marked by some cm- to dm-thick and >2m-long bands of acid composition, as well as <1m-sized lenses of non-porphyritic granitoid, all affected by uncountable, 0.5-2.0m-scale, very tight F_3 folds. These folds are associated with a sub-vertical, N-S striking penetrative mineral foliation (S_3), which is mostly marked by biotite and flattened crystals of hornblende, quartz, and feldspar. Fold axes B_3 plunge ≤25^0 South.

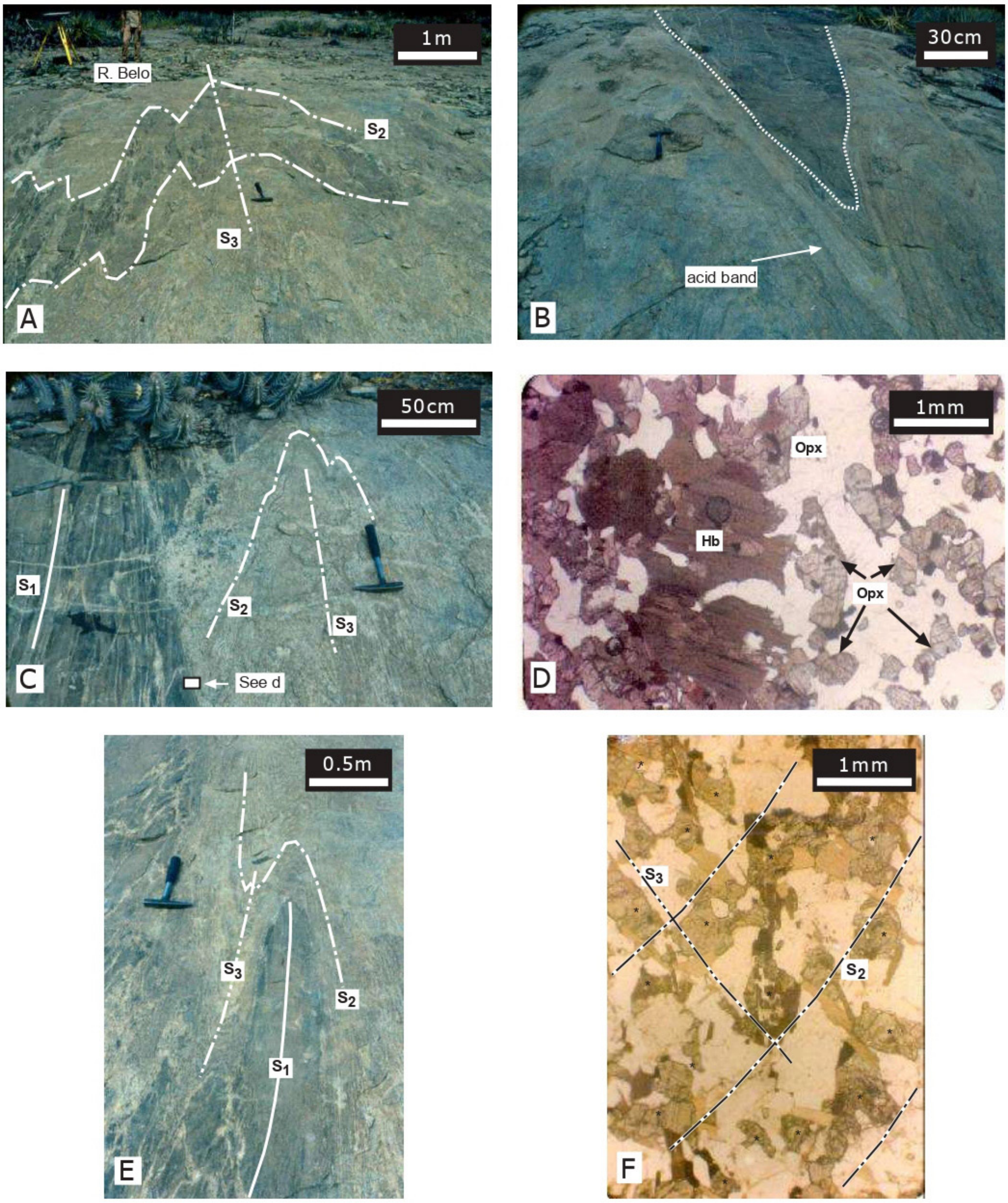


FIGURE 29 - Geological aspects of the Airport outcrop as seen in thin sections. Four view-to-the-South photographs (A, B, C, E) and two photos taken from oriented thin sections (D, F) compose the figure. The alignment of boudins in the central part of the outcrop (A) defines a layer striking E-W before F_3 folding. The longer axis of the boudins parallels the S_3 axial planar foliation and the hammer; B – An F_3 hinge deforms the grey tonalite and a 10cm-thick acid band, which turns around the head of the largest boudin in the outcrop (outlined by the dotted white line). See and compare to the map in Fig. 28; C – Relationships between the F_3 folded tonalite and the eastern side of the boudin from which sample 1A was collected. Note the felsic pegmatoid along the amphibolite-tonalite contact marked by ≥1cm-large crystals of orthopyroxene; D – Detail of a thin section cut in a sample collected at the boudin-tonalite contact (in C). Large crystals of hornblende (Hb) dominate in the left half of the picture and occur together with plagioclase and some crystals of orthopyroxene (Opx), whereas the latter dominates in the right half, together with larger crystals of plagioclase. Opx crystals grew at the expense of the Hb crystals along the margin of the boudin; E – Detail of an F_3 fold affecting the metamorphic banding S_2 with a boudin of amphibolite entrapped in the hinge. The traces of S_1 (inside the boudin) and S_3 are both parallel to the boudin´s long axis, and F – A thin section cut across one F_3 hinge. Crystals of pyroxene (some indicated by a black asterisk) and plagioclase occur along the S_2 banding, and ribbons of biotite and flattened crystals ofplagioclase define the mineral foliation S_3.

After the detailed mapping, all the main geology features in the Airport outcrop appeared together on the map (Fig. 28), such as they would appear in a large photograph taken from a drone in the air. Thus, as the boudins trails nearly trending E-W became evident, they permitted an insight into ancient tabular bodies of amphibolite affected by F_3 folds and evidencing a more complex evolution. In reality, the data indicate that during D_2 ductile flow the tonalite (G2) intruded E-W continuous layers of S_1-foliated amphibolite and acquired the granulite-facies S_2 banding, whereas the amphibolite layers underwent boudinage. Meanwhile, the metamorphic banding S_2 experimented intense shortening during D_3, assisted by the intrusion of G3 granitic sheets. During the shortening, the amphibolite boudins rotated nearly 90° around a vertical axis so that their longer horizontal axis became systematically oriented N-S and entrapped along F_3 axial surfaces (Fig. 29 a, b, and e). The facts that the boudins are systematically nested in the F_3 hinges and their long axis rest parallel to the North-trending traces of S_1 and S_3 strongly support interpreting that: (1) the S_2 foliation formed sub-parallel to S_1, both trending E-W in that part of the Curaçá terrane, before D_3 deformation. (2) the G2 tonalite is a syn-tectonic intrusion which formed sheets parallel to the limbs of the E-W trending F_2 folds;(3) the D_1-D_3 deformation was rather progressive; (4) the regional shortening D_3 rotated all surfaces which composed the D_1-D_2 anisotropy (layers, S_1 and S_2) to steep dips and N-S trends.

5.8.1. U-Pb geochronology of zircons from the Airport outcrop amphibolite

On top of the field and structural evidence for such a detailed evolution, in 2000 the corresponding author collected ten samples of rocks in the airport outcrop, aiming to obtain U-Pb and Sm-Nd age data and further constraining the evolution of the Curaçá terrane.

The data (tables 1 and 2 in D'el-Rey Silva et al. 2007) indicate: (1) The isotopic data of the G2 tonalite (sample 2A: T_{DM} = 3101 Ma; $\varepsilon Nd_{(t)}$ = -6.79) and G3 granite (sample 3A: T_{DM} = 2719 Ma; $\varepsilon Nd_{(t)}$ = -9.87) suggest partial melting of Mesoarchean continental crust, likely to be the continental part of the basement of the Tanque Novo supracrustals; (2) Plotted in a single $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ isochronic diagram (Fig. 8 in D'el-Rey Silva et al. 2007), the data from the eight samples define two alignments of points respectively corresponding to an older age of 2603 ±110 Ma, with $\varepsilon Nd_{(t)}$ values close to zero, interpreted as the age of crystallization of the igneous protolith of the amphibolites, and the age of 2022 ± 290 Ma with negative $\varepsilon Nd_{(t)}$ values consistent with late isotopic re-equilibration of the Nd isotopic system and partial re-equilibrium during regional metamorphism. This process of re-equilibration could have been theoretically related (McCulloch and Black 1984) to contaminating fluids with low Sm/Nd ratio, or loss of Sm relative to Nd during metamorphism; (3) The values obtained for the Nd isotopes of individual samples of amphibolites indicate a heterogeneous isotope distribution reflected in varied T_{DM} ages and variable values of $\varepsilon Nd_{(t)}$, most likely related to the size of the boudins, mainly.

For example, samples with values of $\varepsilon Nd_{(t)}$ close to zero or slightly positive (1A, 1C, 1D, and 1H, all from large boudins; Fig. 29) indicative of preservation of the igneous protolith´s isotopic composition provide T_{DM} model ages around 2.7-2.8Gy, whereas T_{DM} model ages around 2.9-3.1Ga correspond to samples (1B, from the border of a boudin; 1E and 1G from small boudins) with more fractioned Sm/Nd ratios and most negative values of $\varepsilon Nd_{(t)}$ that reflect more significant isotopic interaction with the hosting rocks. Sample 1F (from the largest boudin in the outcrop) has its original composition best preserved and the highest positive value of $\varepsilon Nd_{(t)}$.

6. Mine development: validation of the Caraíba mushroom

6.1. Importance for the mining operations

Elaborating reliable geological cross-sections is fundamental for mining planning in the short and middle term and for guiding mine geologists during new drilling campaigns. Therefore, even with relatively little information at depth, the corresponding author was encouraged to re-interpret the orebody's cross sections of 1984, due to the confidence in the structural evolution according to multiple phases of folding.

The continued exploitation in the open pit and new diamond drill holes perforated from the surface or inside the underground mine, in the incoming years 1985-1988, allowed for improving the vertical cross-sections in D'el-Rey Silva (1984) with the addition of some F_2 fold hinges for controlling the geometry of the mineralized layers in more detail, beside the tight-isoclinal Caraíba F_3 synform (Appendix 2, A2-4). The new data demonstrated that the hinge of the Caraíba Synform, which reached the maximum depth of 1000 m in section 29, becomes progressively shallower in sections to the North, as exemplified by sections 35, 38, and 41 (Appendix 2, A2-4).

Even though the northern part of the orebody had not been adequately drilled yet, within the part belonging to Caraíba, the re-interpretation accounted for the plunge of the B_3 fold axis (~18^0 South; Fig. 3) and for the fact that, at that time, DOCEGEO had already drilled the very shallow synformal hinge, further North, in the R-22 target (Lidenmayer et al., 1984). The mining operation relied on these cross sections (Appendix 2, A2-4) until the first half of 1988, when the corresponding author was ordered to return to the Mine Geology Division (Appendix 1, A1-21) and lead the group of Mine geologists in re-evaluating the Cu-ore reserves to face BNDES's growing interest in privatizing the Caraíba Company.

The re-evaluation exercise demonstrated the level of scientific care that invariably involved the geologists at Caraíba and, after a productive discussion (Appendix 1; A1-22), the geology data existing in the second half of 1988 allowed the construction of a horizontal map showing the geometry of the mineralized layers on a surface ~300 m below the deepest bench of the open pit in 1984, on the topographic level 129 meters above sea level (Appendix 2, A2-5A). The central part of such a map accounted for the information provided by a tight fan of four horizontal diamond drill holes (DDH) and new galleries on the same sub-level (Appendix 2, A2-5B). The new data allowed characterizing the typical pattern of boomerangs and mushrooms (interference of F_3 and F_2 folds), demonstrating the remarkable similarity between the geometry of the mineralized layers at depth and the geological map of the open pit (Fig. 5A), all in agreement with the very accurate maps of ore content on each of the four upper benches at Caraíba (Appendix 2, A2-1).

The findings from the new data were not merely supportive; they were transformative. They provided compelling evidence for the Caraíba mushroom, prompting a deliberate and radical change in the conception of the vertical geological sections for the central part of the orebody but guaranteeing that the realignment of the spatial geometry of the layers with the predicted boomerang and mushroom theoretical pattern (Appendix 2, A2-6) mirrors the same procedure adopted in the cross-sections accounting for the data existing in the previous period 1984-1988.

The radical change in the vertical cross-sections was simply because evidence of F_2 hinges became more numerous in the cross-sections of 1988 than they were availabe in 1984. Here, the extent of the modification introduced in the second half of 1988 is exemplified by section 35, where new boomerangs were interpreted in the same place of the cross-section where, four years before, they had not been predicted due to the limited amount of information (compare the cartoons A and B in Fig. A2-6; Appendix 2). This further underscores the transformative effect of the new data on our understanding of the orebody, inviting us to delve deeper into these intriguing findings. Therefore, a 3-D view of the entire Caraíba mushroom was finally achieved, according to the block diagram first published by D'el-Rey Silva et al. (1988) and reproduced in Fig. 5B. The next years in the mining operations would show that the new interpretation was quite fortunate (see more below).

The example above invites geologists to remember that working in mines enhances their responsibility. Especially where the orebody is complexly deformed, such as at Caraíba, this responsibility is not solely enormous but must be professionally faced no matter the personal consequences. This sense of professional responsibility is fundamental because nobody else in the mining company must understand the real meaning of geological data and their implications for mining planning (worse, if these are structural geology data). If so, when wrong decisions are made in the geological model, the inevitable inaccurate mining planning will undoubtedly reduce profits. A predictable economic disaster will put in risk the job of everybody in the company, but there is nobody else to blame other than the geologists.

The need for a sudden change in the interpretation of the vertical sections across the central part of the orebody in 1988 (no changes were necessary for the cross sections of the southern and northern parts of the Caraíba mushroom; Fig. 5C) demonstrates the enormous challenges that the tectonic structures impose to structural geologists if they want to work with facts, not only with models (Appendix 1, A1-23). That is a strong reason supporting the need of this historical review, as it records the legacy of the learnings with structural geology and the importance of structural geology at Caraíba, not only for things that are relevant but only understandable by geologists (geology as a science), but also for things that are pretty real for the whole society and everyone appreciates when going right, for example a well-applied public investment of nearly 2 billion US$ Dollars almost 50 years ago (values of 1970-1980).

After all, the new cross-sections produced in 1988 were the starting point for updating the horizontal maps displaying the mineralized layers for each 15m of the open pit and each 20m of the underground mine so that the orebody became sliced in 3-D, being the documents included as part of the ore reserves re-evaluation report. Combined, those cross-sections and horizontal maps became the primary tool for mining planning from 1988 onwards.

6.2.The Caraíba mushroom intensively mined (1988-1996)

The addition of more F_2 folds to the cross sections of the orebody's central part in 1988 allowed an increase of about 20% in the ore reserves. Furthermore, the efforts of the whole team of geologists at Caraíba came to be strongly compensated because the new cross-section interpretation continued to be successfully proved by more and more geology data in the years to come. The great confidence in the spatial geometry of the orebody drove geologists in the Mine Geology Division to exclude from the total ore reserves the amount of Copper supposed to exist by the geostatistic method in blocks not coinciding with a mineralized layer in the corresponding geological cross-section (Appendix 1, A1-24).

In fact, from 1988 to 1994-1996, as the underground mine production consolidated, floods of new geology data from many galleries opened for mining the ore directly and tens of boreholes executed for short-term mining planning proved the continuity of the orebody's map pattern at even more profound levels of the underground mine, according to the example 320 m below the surface (Fig. 30).

As the exploration front went deeper on both mines and moved further North in the underground, it required an intensive program of drilling and opening of new galleries between 1989 and 1996, which inevitably tested the validity of the 3-D geometry of the layers in the orebody's central part and beyond to the North. The newly interpreted F_2 hinges of 1988 were proved in sections 34-36 (Fig. 31A-D), and from there until the northern border of the orebody's central part (sections 37-39; Fig. 32A-C). Moreover, still according to the theoretical predictions, the F_2 hinges became progressively smaller in the latter sections and simply disappeared from section 40 (Fig. 32D) until the legal limit of the property (section 45).

To date, several diamond drill holes executed in those years proved the hinge of the Caraíba F_3 synform at a maximum depth of ~1100 meters below the surface in section 36 (Fig. 31D). They also demonstrated the F_3 hinge's disruption and the infilling of voids by G_3 granites (not shown in the section), similarly to the relationship noticed in the open pit since when the mine was mapped in detail (1978-1984; D'el-Rey Silva 1984; Fig. 5A).

Moreover, the short-time mining control required that some fans of short drill holes were perforated, between 1989 to 1994, through the remaining volume of rocks in the open pit, starting at stations situated on the bottom of the open pit in 1988 (see red lines in Fig. 31C-D). They demonstrated how important was the radical change introduced in the cross sections at 1988 for the profitability of the mining project (Appendix 1, A1-25).

In reality, all the cross-sections elaborated since 1988 were carefully checked against new data derived from the mine exploration and against the attitude of the S_1 foliation data in all the drill cores (e.g. in Fig. 21). As illustrated in Fig. 33, the F_3 synform interpreted in the upper part of the central orebody in sections 34 and 35 of 1988 (see yellow dots in Figs. 31 A-B) was proved to exist by fans of drill holes executed until 1994 in the cross-sections located 22.5 and 45.0 meters to the North (Figs. 31 C-D).

As detailed by D'el-Rey Silva et al. (1996), for precaution against the lack of control upon rotated drill cores, a simple but safe technique was adopted for further checking to fold hinges in cross-sections, which was possible only where each drill hole cut the mineralized layer perpendicularly (Fig. 33).

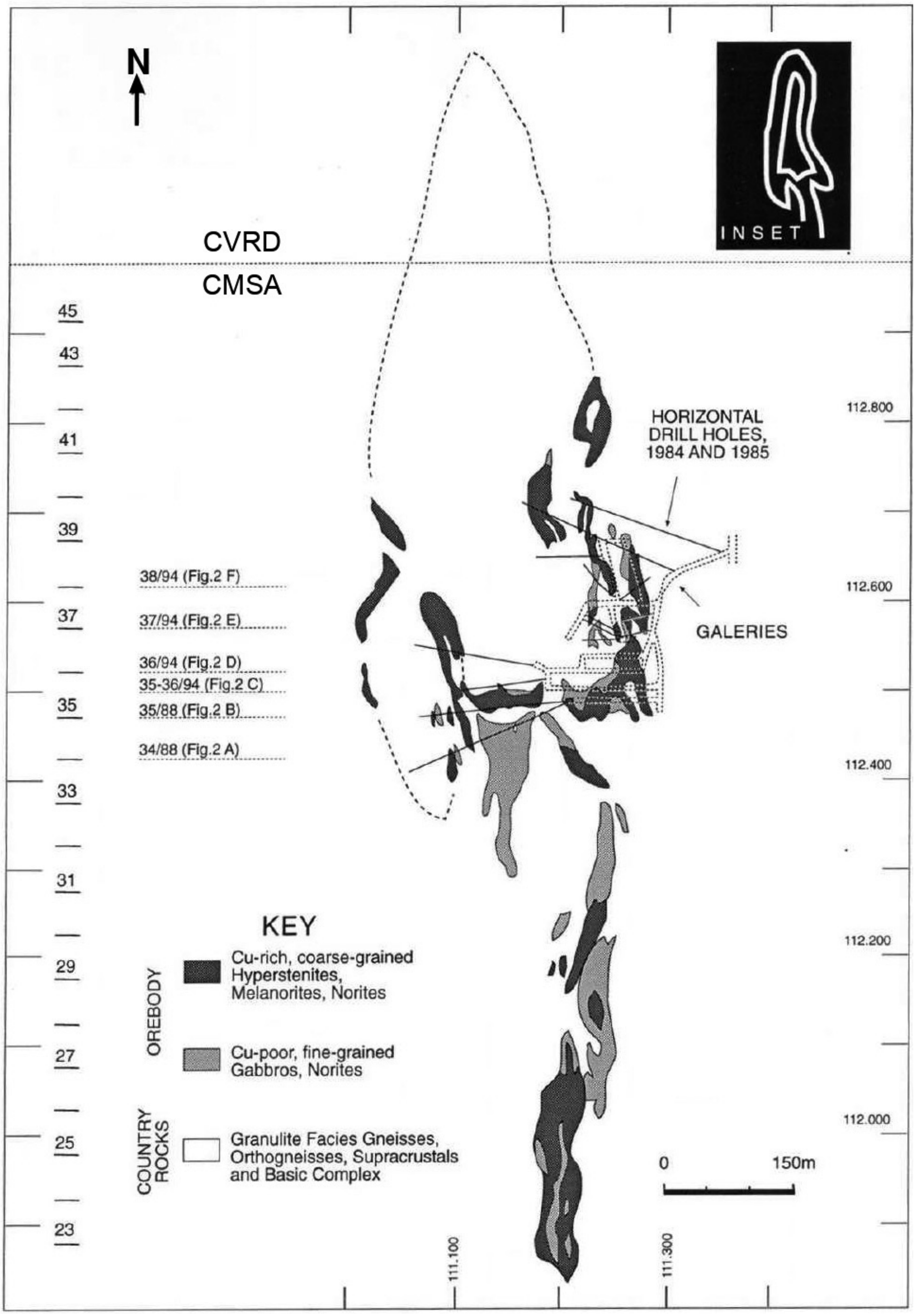


FIGURE 30 - Horizontal map of the Caraíba orebody 320 m below surface, corresponding sub-level 1 in the underground mine, in other words a depth of 84 m above sea level (D'el-Rey Silva et al. 1994). The dashed lines that complete the shape of the Caraíba mushroom (see also the Inset) are based on data from vertical cross sections in the southern and northern parts of the orebody, including the part belonging to CVRD (or it's subsidiary, DOCEGEO).

The technique, which consisted in observing the S_1 foliation in the drill cores and plotting the measured angle of it with the axis of the drill core, allows defining the edges of the cone of theoretically possible positions of S_1 on the plane of section. If the angle between S_1 and the core´s axis is close to 90°, the interval of possibilities (in other words, the cone´s angle) is very narrow and, in this case, the average position of S_1 must be very close to the real position of the layers on the plane of the section, no matter how much the core rotated in space during drilling. The same is valid when sub-horizontal drill holes cutting sub-vertical limbs (e.g., Fig. 32 C-D).

7. Discussion

7.1.The tectonic relevance of the Caraíba orebody

The greater confidence acquired with the geological sections checked until 1994, as above, permitted elaborating

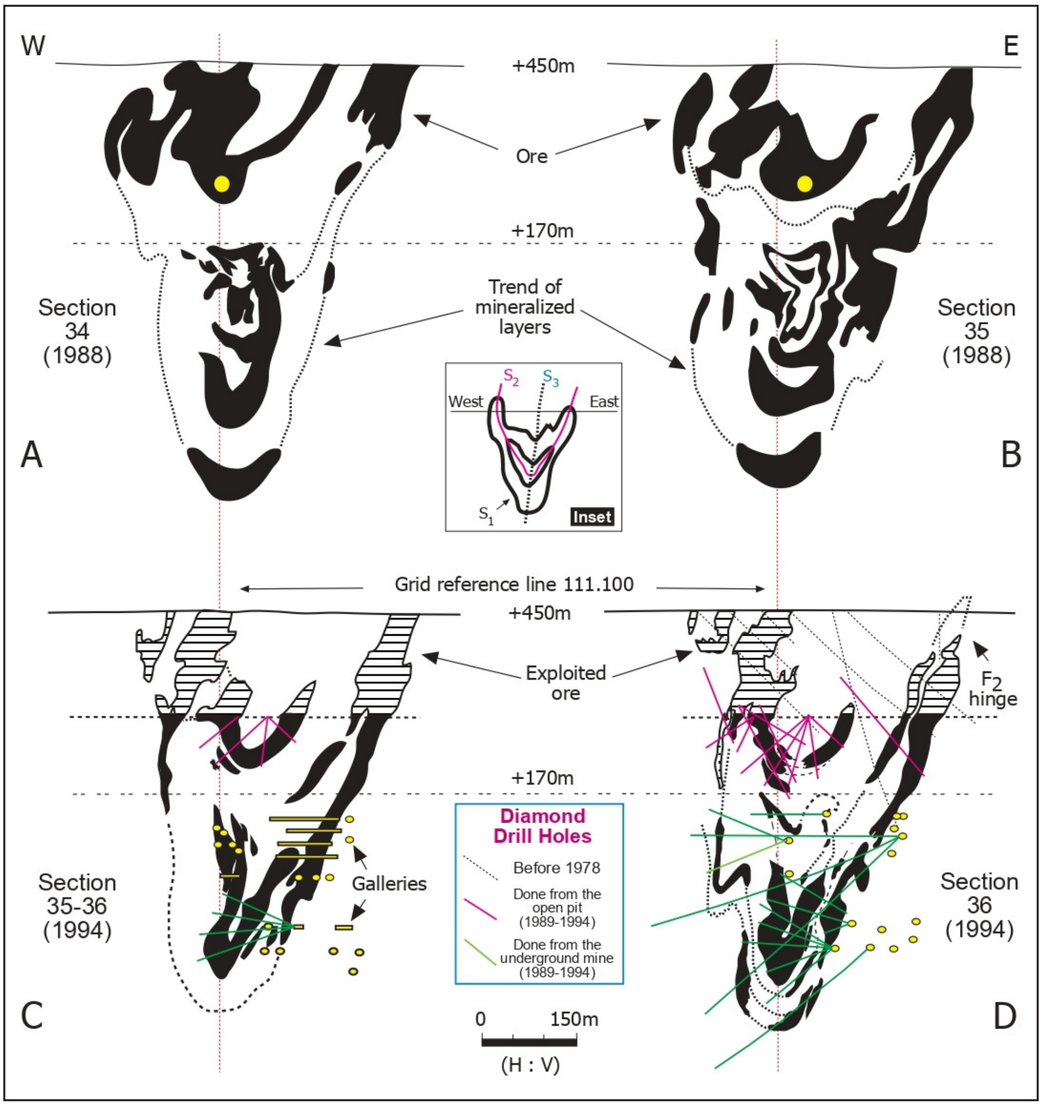


FIGURE 31 - The central part of the Caraíba orebody viewed in cross-sections of 1988 and 1994 (A-B and C-D, respectively). The drill holes, which for simplicity were omitted in sections 35 and 36 of 1988 (A-B; D'el-Rey Silva et al. 1988), are extensively shown in sections 35-36 and 36 (C-D; D'el-Rey Silva et al. 1994). The yellow dots in A and B mark F_3 hinges and are reference for further discussion in the text.

a new 3-D maquette for the Caraíba ore body (Appendix 2, A2-7). From 1994 to 2000, the reserves of Cu-ore in the open pit were progressively exhausted, leaving behind a 300 m-deep conical hole, ~3 km-long on the surface of the Caatinga in northern Bahia (Fig. 34) and an enormous legacy in terms of data, which strongly constrain the tectonic evolution of the northern part of thel SAC orogen.

The enormous inventory of data reported in the literature and summarized here allow characterizing the Caraíba Cu-deposit as a ~1000 m-high, tight and non-cylindrical F_3 synform gently-moderately plunging to the South, a simple parasite of the regional Curaçá Antiform. The Caraíba orebody acquired the shape of an N-S trending mushroom (Fig. 5A-B) due to the interference of the F_3 synform with several mesoscopic F_2 folds.

The tectonic importance of the Caraíba orebody rests in the preservation of crucial structural evidence exactly where the ISAC orogen was squeezed to its narrowest map expression and is particularly more evident when one realizes that the same D_1-D_3 structures and their field relationships are more abundant on the orogen's larger parts. An example is the Ipirá-Lajedinho area, which is primarily protected by the northern margin of the Jequié block (Fig. 1B). In such an area, a whole set of data including abundant m- to hm-scale and E-W trending F_2 folds associated to mappable, ductile, D_1-related lateral ramps, plus N-S trending D_3 transcurrent structures, as well as F_2 x F_3 mushrooms and boomerangs, some as large as the Caraíba mushroom, altogether justifies interpreting the ISAC orogen as the result of a long-lived, oblique collision-related sinistral transpression (D'el-Rey Silva 1993; Barbosa 1996).

The intensity of D_3 shortening is maximum around Caraíba for three reasons: (1) being 300km far from the Jequié block (Fig. 1B) the Caraíba surroundings were not protected; (2) the intrusion of the large Itiúba syenite, a D_3-related event, most likely added for further squeezing the Caraíba area and for tightening and hiding, even more, the E-W trending D_2 structures existing there; (3) the conditions for high plasticity in the Curaçá River Valley terrane were largely favorable throughout D_3 deformation, as deductible from the abundance of G3 magmas, in map or outcrop scale.

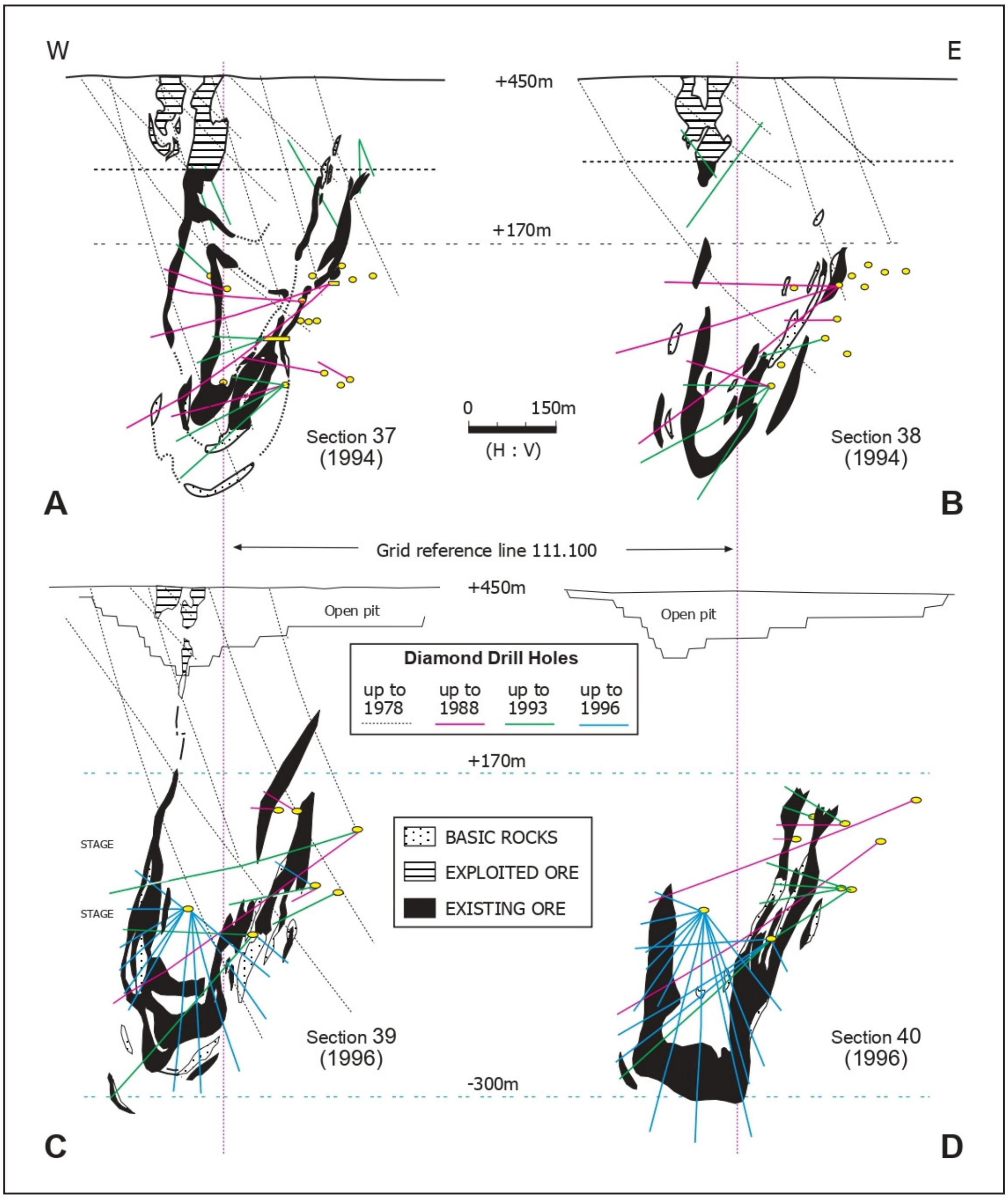


FIGURE 32 - The northern part of the central Caraíba orebody viewed in cross-sections of 1994 and 1996 (A-B, as in D'el-Rey Silva et al. 1994; and C-D, as in D'el-Rey Silva et al. 1996). Note how many diamond drill holes perforated the deepest hinge zone of the Caraíba F_3 synform. The white space corresponds to Cu-barren rocks, such the Tanque Novo Sequence supracrustals and other lithotypes (same pattern as in all the cross-sections of this review).

Nevertheless, the F_3 x F_2 co-axial pattern (type 3 by Ramsay 1967) is also argued to exist in the surroundings of Poço de Fora, about 30 km North of Caraíba (Fig. 3; Sá and Reinhardt 1984), the same area where the mushroom-and-boomerang F_3 x F_2 interference pattern was well characterized by Jardim de Sá et al. (1982). In reality, both types of interference may have well co-existed. D'el-Rey Silva et al. (1988) postulated that the Caraíba F_3 x F_2 mushroom might be explained by syn-D_2 or early-D_3 rotation of the F_2 folds during the progressive deformation so that the B_2 axes became oriented E-W, and such a rotation fits well in different velocities of the layers going into the subduction zone that likely existed, according to the geodynamic scenario proposed in section 7.2.

The subduction zone environment makes such rotation and the mushroom type of interference understandable even in a scenario of regional transpression, in which all the folding phases produced a large majority, perhaps a totality, of nearly N-S trending folds. This is because, considering that the regime of intense plasticity during deformation in the high-grade terrane likely facilitated differential intensities of ductile flow, along the length of the subduction zone, during D_1-D_2 deformations, leading to the rotation of relatively rigid bodies such as the Caraíba orebody as a whole. Moreover, because the differential movement happened most likely at all scales, F_2 boomerangs and mushrooms could form in outcrop scales (e.g., Fig. 24) and remain preserved in a domain of steep-dipping layers, such as it is the Curaçá River Valley terrane at first glance.

If so, geologists may realize why different patterns of folding interference co-exist regionally, or even in the same outcrop, and realize that types 2 and 3 of folding interference

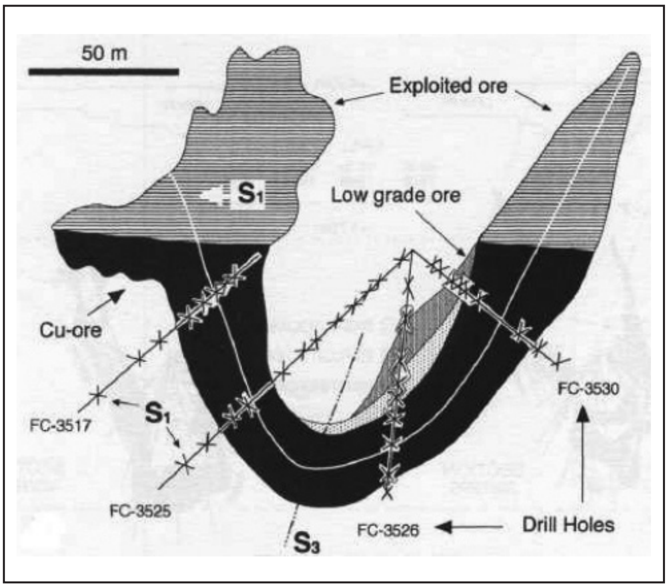


FIGURE 33 - A careful check on cross-sections of Caraíba based on the attitude of S_1 foliation in drill cores. The example is for sections 35-36 (see D'el-Rey Silva et al. 1996). The continuous while line marks the average trace of foliation S_1. See text for details.

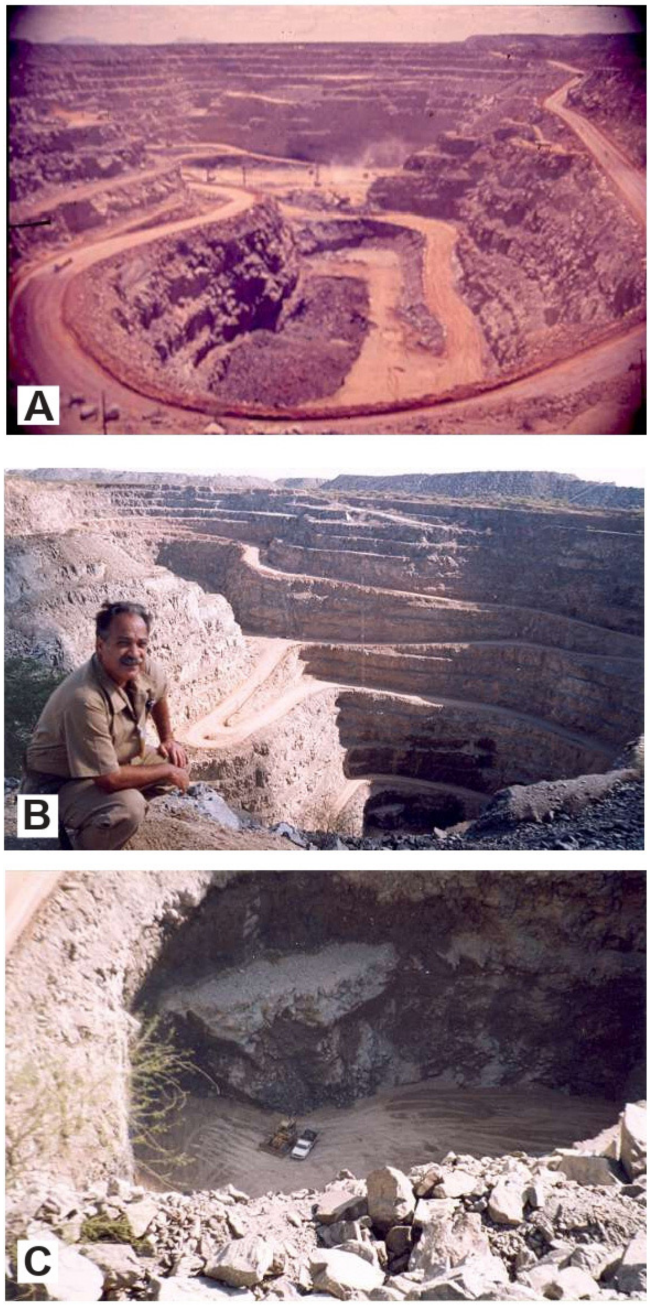


FIGURE 34 - Progressive deepening of the Caraíba open pit. The photographs, taken from the surface of the Caatinga, show (in A; looking North) 14 benches of the Caraíba open pit in 1994 and, in (B), the end of the mine in 2000, which was witnessed by the corresponding author. The photo in (C) shows a tractor and a truck seeming children´s toys in the bottom of the mine, zoomed from the original surface of the Caatinga, ca. 300 m above.

patterns in the Ipirá-Lajedinho area (D'el-Rey Silva 1993) and further north, particularly along the Pinhões-Poço de Fora profile (Fig. 2), such as summarized above, all fit well in the ISAC´s regional geology.

7.2. Polyphase evolution and a sound geodynamic scenario for the Curaçá Terrane

The polyphase structural-magmatic-metamorphic evolution of the Curaçá terrane can be summarized as in Figure 35. The lack of metasediments in contact with the boudins of amphibolite in the Caraíba Airport outcrop suggests the airport amphibolites as remnants of a Neoarchean oceanic lithosphere. In addition, the amphibolite´s protolith (potentially similar to oceanic crust basalts; see Sm-Nd and U-Pb data and discussion in D'el-Rey Silva et al. 2007) may well have been the same for the basalt flows destined to become the amphibolites intercalated with metasediments of the Tanque Novo Complex.

Contamination due to interaction with ancient sialic crust and/or partial opening of the isotopic system during metamorphism would modify the protolith´s Sm-Nd system to the real one existing in the amphibolites. Alternatively, if the protolith derived from an enriched mantle, the amphibolites would also display negative values of $\varepsilon Nd_{(t)}$ and, therefore, both hypotheses demand new geochemistry data to be accepted (D'el-Rey Silva et al. 2007). Nevertheless, according to these authors, the age of 2600 Ma may be assumed for basin sedimentation/volcanism, at least for the basin precursor of the northern part of the ISAC orogen.

The above interpretations drive our attention to the results of detailed and independent geochemistry studies that pushed Lindenmayer (1981) to define a tholeiitic signature for the primeval magma of the Curaçá Cu-bearing bodies, in general, and Bello (1986) to conclude that the hypersthenites and norites constituting the Surubim orebody record an ancient volcanic suite.

D'el-Rey Silva et al. (2007) interpreted that the Caraíba orebody´s protolith could have been: (a) a basaltic rock of layer 2 of the oceanic crust; (b) basalts shed as flows within sediments in the Tanque Novo Sequence; or (c) a gabbroic sill intruded into the Tanque Novo sequence. They were supported by the strongly similar ages of 2580 Ma for norites at Caraíba (Oliveira et al. 2004) and 2600 Ma for the Airport amphibolite.

In reality, and despite of further geochemistry and petrology studies being required to demonstrate whichever the protolith´s origin among the three possibilities in the last paragraph, the

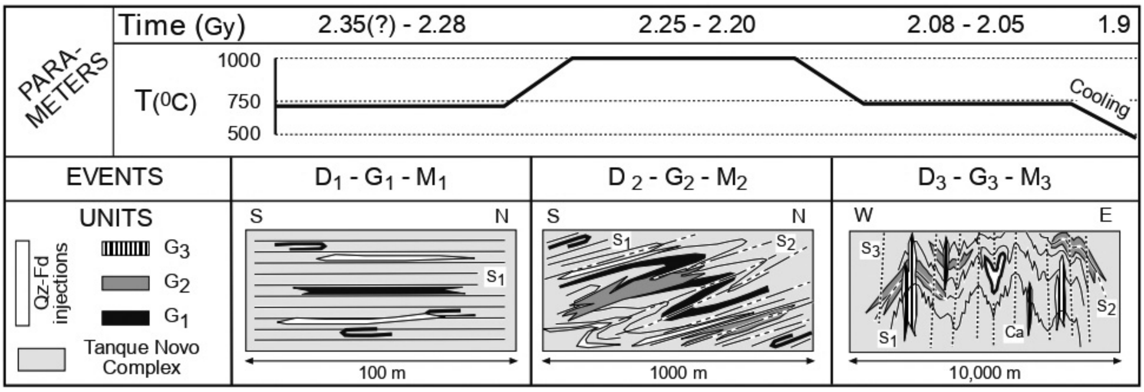


FIGURE 35 - Summary diagram depicting the tectonic evolution of the Curaçá terrane (from D'el-Rey Silva et al. 2007). An estimative of parameters such as time and temperature is indicated on the upper part. Structures are observed at varied scales in the field, from cm- to dm-size up to the scale indicated in the bottom of each diagram. The leftmost diagram displays G1 conformable bodies of amphibolite emplaced in the Tanque Novo Complex. These include the 2.58 Ga old body of mantle-derived rocks (Oliveira et al. 2004), protolith of the Caraíba orebody. The central diagram displays the previous units and structures affected by the S_2 foliation, asymmetric F_2 folds, and syn-tectonic G2 intrusions. The rightmost diagram displays D_1-D_2 units and structures affected by up-right tight F_3 folds associated with the S_3 foliation and syntectonic G3 intrusions, all affected by the M_3 amphibolite facies metamorphism. The typical boomerang shape of the Caraíba orebody is depicted in the center, just to the left of the F_3 Curaçá antiform (Ca).

abundant structural data reported here strongly recommend that, before D_1 deformation, the protolith was a conformable body in the same sub-horizontal position of the Tanque Novo volcanic-sedimentary pile, so that the amphibolite protolith and the country rocks came to experience together the same D_1-D_3 structural/metamorphic evolution. Thus, as the structural and field geology data fit all three possibilities (a-c above), there is a considerable way open ahead for testing each one of the hypotheses, which will certainly be accomplished with the aid of much detailed laboratory studies (petrography, petrology, isotopes, microprobe, geochronology) on the mineralized rocks of the Caraíba orebody or elsewhere.

Despite the U-Pb data admitting other regressions in the Airport outcrop, D'el-Rey Silva et al. (2007) accepted the U-Pb age of 2.6 Ga for the amphibolite protolith because it is the highest value obtained; the derivation from the population of clean zircons; the residence of the U-Pb age within error of the Sm-Nd isochronic age obtained for the same amphibolites; and the similarity with the SHRIMP age obtained for the Caraíba norite by Oliveira et al. (2004). In addition, since metamorphic zircons in the Airport amphibolite yield an age between 2.3 and 2.2 Ga, this is regarded as the time interval in which, most likely, the isotopic system in the amphibolites was disturbed by incoming fluids derived from the G2 tonalite. If so, the interpretation that M_1 metamorphism predates 2.3-2.2 Ga is supported because the G2 tonalite is a syn-D_2 tectonic intrusion and the pristine zircons from the airport G2 tonalite provided an age of 2248 ± 36 Ma (D´el-Rey Silva et al., 1996), emphasizing the significance of this early Paleoproterozoic D_2 event.

Once the field relationships in and around the Caraíba orebody indicate a polyphasic evolution and because G2 granitoid intruded syn-tectonically, then remains valid to interpret that the structural and metamorphic evolution of the Curaçá terrane happened between 2300-2250 and 2050Ma ago. Considering the age data in Tables 1 and 2 by D'el-Rey Silva et al. (2007) it is possible to figure out a more detailed scenario (Fig. 35): M_2 granulite facies conditions peaked in the 2250–2200My interval, and M_3 amphibolite facies conditions peaked 2080–2050 Ma with cooling conditions lasting until 1900Ma (according to Rb-Sr, Sm-Nd and Pb evaporation data; see D'el-Rey Silva et al. 1996; and references therein).

Three similarly important facts make the Curaçá terrane a classical orogen, for which the understanding of a sound geodynamic scenario emerge, but only after combining accurate field geology, structural data, and geochronology studies upon samples with well-known structural control. Firstly, the significant errors associated with the ages of the Airport amphibolites indicate opening and heterogeneous modification of the U-Pb and Sm-Nd isotopic systems in the igneous protolith. The difficulty of dating mafic rocks in a high-grade terrane resides in that such rocks present small amounts of minerals suitable for high precision age determination (Appendix 1, A1-26). Moreover, because their isotopic systems were affected at varied intensities during extreme conditions of metamorphism, the study of these systems will indicate varied levels of complexity, no matter if the terrane´s tectonic evolution was polyphase or polycyclic (see several references in D'el-Rey Silva et al. 2007).

Secondly, the older cratonic blocks in the São Francisco Craton present different isotopic backgrounds (Fig. 1B) acquired in the Archean so that the ISAC orogen may be hiding evidence for the involvement of the margins of the Gavião and Serrinha Mesoarchean blocks in a polycyclic evolution due to Neoarchean and Paleoproterozoic subduction events.

Actually, in the area extending to the south of the Itiúba syenite, Teixeira (1997) mapped the Caraíba and Tanque Novo (or Tanque Novo-Ipirá) complexes folded/tectonically imbricate together with the São José do Jacuípe Suite, the latter consisting of norites, gabbro-norites, gabbros, peridotites, and pyroxenites. Moreover, based on the results of detailed petrology/geochemistry studies, Teixeira (1997) concluded that part of the Caraíba Complex defines a magmatic arc and parts of the Tanque Novo and Jacuípe suites match the characteristics of an oceanic crust. In addition, U-Pb SHRIMP age data (quoted in Delgado et al. 2003) indicate a Neoarchean age for such a magmatic arc, and they may suggest a similar age for the intervening oceanic crust material. The Neoarchean arc fits in the data favorable to the existence of the 2600 Ma old oceanic crust possibly represented by the amphibolites in the Airport outcrop.

The third fact is that the long-lived transpression-like tectonics recorded in the ISAC orogen has a great potential to transform a single suture into a stack of sub-vertical suture segments, and the traces of these segments may spread over a wider field area than a single suture zone may have been originally. In the case of polycyclic evolution, a transpression-like tectonics could have stacked segments of two collision sutures, thus creating a geological puzzle that demands multidisciplinary studies until each puzzle piece can rest identified and placed in the accurate position.

Combining their results with the results of previous workers, D'el-Rey Silva et al. (2007) proposed the following geodynamic scenario: (1) The protoliths to the amphibolites in the Caraíba Airport and Tanque Novo sequence both formed 2.6 Ga, when a large ocean separated the Gavião and Serrinha blocks; (2) the Caraíba Complex was evolving in this ocean as an island arc above an east-dipping subduction zone that plunged below the Serrinha Block (Leite 2002); (3) sometime between 2.35 and 2.25 Ga the rocks of the Tanque Novo Sequence and Caraíba Complex entered in the subduction zone, then underwent layer-parallel shearing and acquired D_1 structures associated with M_1 amphibolite facies metamorphism at ~750 ^{0}C; (4) D_2 Structures developed when the rocks were buried further and underwent granulite facies metamorphism (M_2) peaked at 2.25-2.2 Ga, which fits in the 2.2-2.1 Ga interval that Leite (2002) indicated for amalgamation of the island arc to the Serrinha Block and also suggests a back-arc scenario for part of the Tanque Novo sequence as well as for the amphibolites and the Cu-mineralized orebodies. The E-W fold axes (F_2) formed in consequence of a kind of embayment pointing–down to the east, inside the N-S trending subduction zone; and (5) Closure of the ocean at ~2.1 Ga resulted in the formation of a foreland basin to the west (Leite 2002) inside which the rocks of the Jacobina Group likely evolved. Moreover, (6) the roots of the orogenic chain started to be uplifted when the Gavião Block began to enter into the subduction zone and the ultimate Gavião – Serrinha continental collision (2.08 Ga ago, such as in Leite 2002) caused D_3 deformation under M_3 amphibolite facies metamorphic conditions, which peaked at 2.08-2.05 Ga.

7.3.Testing the geodynamic scenario

The existence of a Neoarchean magmatic arc (comprising the Caraíba Complex and São José do Jacuípe Suite) has been demonstrated by U-Pb SHRIMP age data obtained more recently, as well as the Paleoproterozoic amalgamation of the Archean continental blocks leading to regional deformation/metamorphism (Oliveira et al. 2010; Piaia et al. 2017). Moreover, Aguilar et al. (2017) have described a similar scenario for the Quadrilátero Ferrífero and the Mineiro belt (or the Minas-Bahia orogen) which composes part of the southern São Francisco Craton and is the southernmost continuity of the ISAC orogen.

However, Oliveira et al. (2010) obtained U-Pb SHRIMP ages of 2574 ± 6 Ma and 2074 ± 14 Ma, respectively, for the core and metamorphic rims of zircons from the same G2 tonalites at the Caraíba airport outcrop, for which D'el-Rey Silva et al. (1996, 2007) presented the less precise U-Pb age of 2248 ± 36 Ma mentioned earlier. Based on the SHRIMP ages above, Oliveira et al. (2010) argued for: (1) the Caraíba airport tonalites crystallized at ~2570 Ma during the construction of the Caraíba Complex as a possible Andean-type magmatic arc along the eastern margin of the Gavião block; (2) the build-up of the northern part of the ISAC orogen resulted from the 2.09-2.07 Ga collision of the Caraíba-Gavião superblock with the Serrinha block, during which the Caraíba arc was reworked to granulites, locally at ultrahigh-temperature conditions; and, (3) the interval 2082 ± 17 to 2074 ± 14 Ma is probably the best for the high amphibolite-granulite facies metamorphism in the northern ISAC orogen.

It is practically consensual in the literature that the age of regional high-grade metamorphism in the orogen is no older than 2080-2090 Ma, which matches the 2100 Ma age of regional metamorphism in the Mineiro belt (U-Pb ages of monazites and titanites; Aguilar et al. (2017). Nevertheless, the lack of a combination of zircon ages with detailed structural-metamorphic evidence prevails in the literature, apart from the study presented for the Caraíba Airport outcrop (see item 5.6.3), which evolution still asks for more detailed attention (see below).

If so, we come to this point being able to envisage that, at a particular moment during the Paleoproterozoic subduction of the oceanic lithosphere, the Archean-age Airport tonalite (part of the Caraíba magmatic arc) underwent shearing for acquiring the granulite facies S_2 metamorphic banding and was sliced together with the layers of G1 amphibolites (which had already become a foliated-S_1tectonite under amphibolite facies metamorphism) so that S_2 and S_1 parallel to each other. These structures allow demonstrating the F_2 folding episode described in the Airport outcrop. Later, the packet comprised of G1 and G2 meta-igneous rocks was affected by the numerous F_3 normal folds coevally with the intrusion of syntectonic amphibolite-facies G3 pink granites. Ages of syntectonic granitoids (G3) across the ISAC orogen vary from a maximum of 2098 ± 1 Ma for the São Felix syenite (not mentioned before in this text) and 2084 ± 9 Ma for the Itiúba syenite (U-Pb SHRIMP data in Barbosa and Sabaté 2004; Oliveira et al. 2004, respectively) which is an amphibolite-facies syntectonic body never related to any granulite facies metamorphism in the literature, until the minimum age of 2027 ± 16 Ma obtained for a pink granite hosted along with the axial plane of F_3 folds in the Airport outcrop (U-Pb SHRIMP data in Oliveira et al. 2010). Moreover, intermediary ages of G3 granites are also reported, for example the 2078 ± 6 Ma Capela quartz-monzonite of the Caraíba Complex (U-Pb SHRIMP data; Oliveira et al. 2010); the 2064 ± 6 Ma Bravo granite of the Ipirá-Lajedinho area (Fig. 1B; U-Pb SHRIMP data; Barbosa et al. 2008); and a 2051 ± 16 Ma G3 granite body intrusive in the Caraíba orebody (D'el-Rey Silva et al. 1996, 2007).

After all above, and considering the 2574 ± 6 Ma (U-Pb SHRIMP) crystallization age for the Airport G2 tonalite, as in Oliveira et al. (2010), we must conclude that the ages of G3 granitoids indicate the interval 2100-2027 Ma when referring to the M_3 metamorphism (Fig. 35).

The fact that the granulite facies metamorphism was instead an event of regional importance which affected the huge plate-like body of Cu-mineralized hypersthenites and norites (the Caraíba orebody) and well beyond, plus the fact that the 2074±14 Ma SHRIMP age obtained for the metamorphic rim of zircons in the G2 tonalite (Oliveira et al. 2010) is the same age for typical G3 granites, altogether leave open the need for a more precise age determination for M_2 and M_1 metamorphisms in parts of the northern orogen. That is the fairly central idea in D'el-Rey Silva et al. (2007).

Not occasionally, the 2082 ± 17 Ma age obtained from the rim of four zircons in the Archean São José do Jacuípe Suite (Oliveira et al. 2010) is the same for M_3 metamorphic zircons (2084± 4 Ma) extracted from the ~2570 Ma G1-M_1 amphibolites in the Caraíba airport outcrop (D'el-Rey Silva et al. 2007) and is precisely the exact age of the amphibolite facies Itiúba metasyenite.

Despite the U-Pb age of 2248±36 Ma initially interpreted as the crystallization age of the G2 tonalite (D'el-Rey Silva et al. 1996, 2007) has to be replaced by the more precise SHRIMP age of 2574± 6 Ma in the zircons' core (Oliveira et al. 2010), it is not strange in the tectonic setting of B-subduction and arc amalgamation which likely prevailed in the ISAC and Mineiro orogenic entities since about 2.3 Ga, respectively (Leite 2002; Aguilar et al. 2017). Moreover, the noticed disturbance in the Sm-Nd isotopic system of the G1 amphibolite in the Airport outcrop (the 2022±290 Ma Sm-Nd isochronic age in Fig. 2 by D'el-Rey Silva et al. 2007) argues for care before one considers as meaningless the U-Pb age of 2248±36 Ma found in zircons from the airport outcrop G2 tonalite.

Finally, whichever is the age of the M_1 and M_2 metamorphisms and no matter if the 2248 ± 36 Ma age quoted above is meaningless or not, future accurate scientific investigations could not disregard the possibility that the Archean zircons found in the G2 tonalite (Oliveira et al. 2010) may be inherited crystals. Despite such possibility being extremely low, and it is not being defended here, the fact is that it cannot be 100% ruled-out, for the sorrow of all of us geoscientists, even respecting the Caraíba Complex as an Archean unit and considering the presence of Archean zircons in the São José do Jacuípe Suite, far to the south of Caraíba (Oliveira et al. 2010; Piaia et al. 2017).

7.4.Matching the Caraíba orebody with geophysical data

According to Teixeira et al. (2010b), the processing and interpretation of available aeromagnetic data have shown the area which surrounds the Caraíba Cu-orebody as dominated by expressive and penetrative magnetic trends in the N-S direction and transected by a set of discrete aeromagnetic lineaments trending SW-NE (Fig. 36). Moreover, Teixeira et al. (2010b) interpret that because the lineaments are seen on images of the total magnetic field and in the vertical derivate of the total field, their magnetic signature may derive from deep sources. If so, the geophysical data in Teixeira et al. (2010b) ask for an immediate explanation and matching against the Cu-orebody and the Curaçá Valley terrane geology.

For the sake of the truth, the SW-NE magnetic lineaments correspond to the NE-trending fractures, which are the most numerous and longer among those initially mapped in the surroundings of Caraíba (Fig. 3) and the open pit (Fig. 5A). Furthermore, in and out of the open pit, NE- and NW-striking

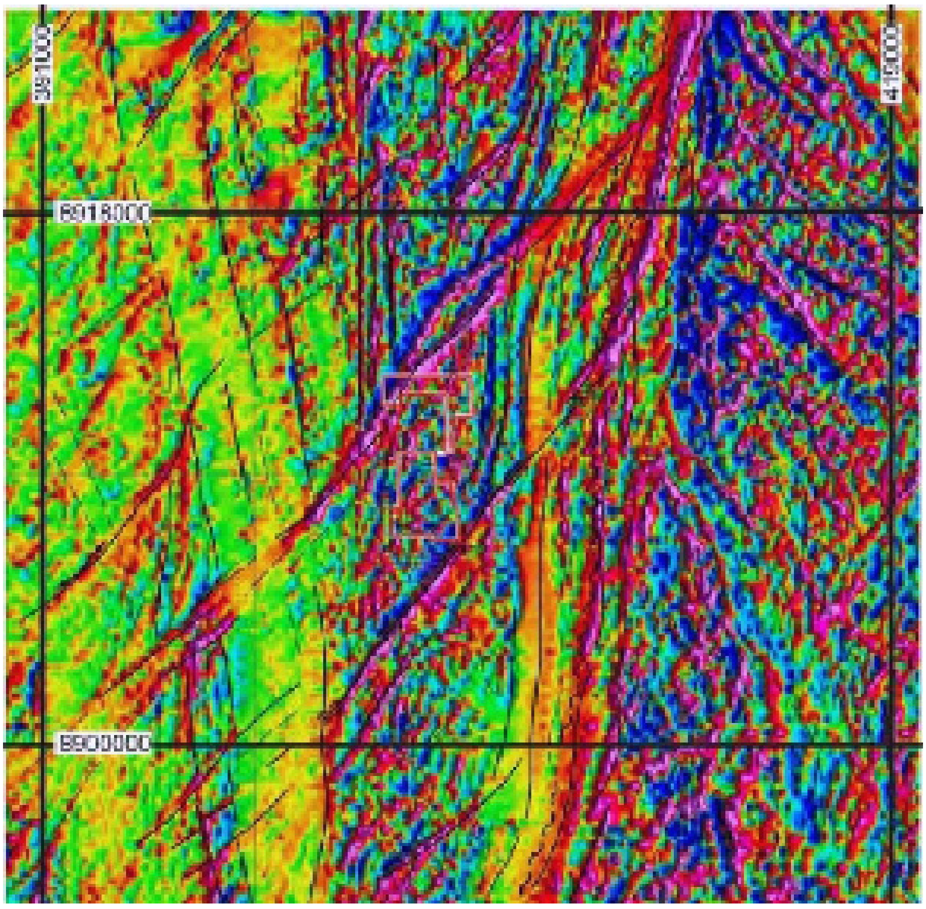


FIGURE 36 - Map of the first vertical derivate of the total magnetic field (Figure 16B in Teixeira et al. 2010b) showing the more significant structural traces in the surroundings of Caraíba. The UTM coordinates refer to Datum WGS84 and Zone 24 South

fractures form a typical conjugate pair compatible with the E-W orientation of the maximum compressive stress σ_1 active during event D_3 in the Curaçá terrane. This interpretation is reinforced by the fact that the fractures commonly appear regionally as sharp surfaces of rupture associated with narrow zones of K-rich and pink-color metasomatic fluids typical of D_3 deformation event (e.g., Fig. 11A).

The N-S penetrative aeromagnetic lineaments are, in fact, the expression of the generalized mylonitic foliation which dominates in the Curaçá terrane, such as interpreted by Teixeira et al. (2010b). Nevertheless, such foliation corresponds to the composite anisotropy (e.g., Figs. 14 and 25) which formed during the three stages of deformation, not only during D_3. In the initial stage, the generalized syn-D_1 layer-parallel shearing that affected the Tanque Novo rocks and G1 syn-tectonic intrusives developed foliation S_1, a metamorphic banding/mylonitic foliation originally in a sub-horizontal position. The emplacement of the Caraíba sill happened during the D_1 sub-horizontal shearing of crustal scale, so far the most significative regionally. In addition, intense inter-layer shearing occurred during the second stage (D_2 event; see ahead). In the last stage, S_0, S_1, and S_2 all became sub-vertical and mostly striking N-S, resulting from the intense regional shortening D_3 assisted by the development of foliation S_3 parallel to $S_0/S_1/S$.

Moreover, since the Mine has been mapped in detail, D'el-Rey Silva (1984) drew attention to the fact that, as a whole, the Caraíba mushroom trends N-S whereas the Cu-barren mafic rocks and gneisses outside the mushroom trend slightly different (Fig.5A). The sub-vertical layers of Cu-barren rocks abut against the SE corner of the central orebody whereas, relative to the NW corner, they trend NW. Such field situation, represented schematically in Fig.37A, was firstly explained (D'el-Rey Silva et al. 1996) in terms of the structural evolution of the orebody itself, considering the vast amount of data evidencing that the layers in the mineralized body and Tanque Novo volcano-sedimentary sequence acquired the same S_1 metamorphic banding since before or at least during the very early moments of D_2 event (Fig. 37B). If so, a system formed by a frontal ramp and a lateral ramp (Fig. 37C) provides the template necessary for the generation of the different trends of the rocks after F_3 folding (Fig. 37A).

The E-W trending frontal ramp (Fig. 37 B-C) matches well with the suitable place for developing E-W trending F_2 folds and syn-D_2 multiplication of thicknesses. In addition, the N-S trending lateral ramp may have well developed due to the contrast of competence existing along the eastern margin of the sill-like original body, which was in contact with marls transformed into olivine marble (see conclusion number 7 in section 3.3.1). These D_1 tectonites (sheared marls) were probable lubricant layers during D_2 deformation. If so, the mechanical weakness along the (lateral ramp-like) eastern margin of the orebody could accommodate differential movements during D_2 thrusting-and-folding, and the sub-vertical N-S trending lateral ramp was in a most suitable position for future reworking during D_3. It is not occasional the occurrence of highly sheared calc-silicated rocks exactly and solely along the eastern border of the central orebody (see item 3.3).

Thus, although the geophysical lineaments may suggest the intrusion of the Caraíba orebody along ductile shear zones (Teixeira et al. 2010b), these existed but were rather sub-horizontal syn-D_1 features and, even though the evolution of

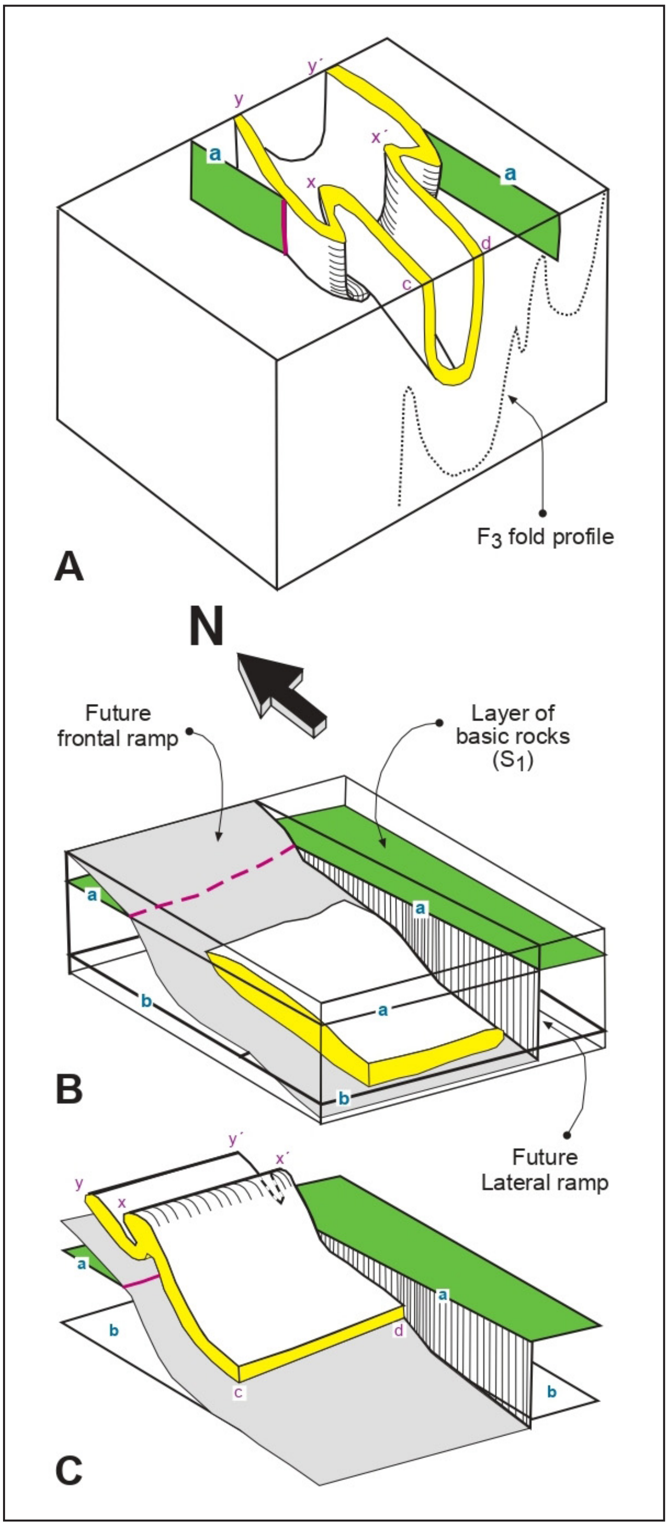


FIGURE 37 - Out-of-scale cartoons aiming to explain the different trends of the Caraíba Mushroom (yellow) and the country rocks represented by surfaces labeled a and b (the green color stands for basic rocks). The block diagram in (A) shows the orebody and country rocks in space and illustrates the map pattern to be explained. Note the reference points c, d, x, x', y, and y'. By the end of event D_1 (B), all the rocks at Caraíba had already acquired the S_1 metamorphic banding, and the orebody (resting between layers a and b) was just to be displaced to the North (event D_2), along the future frontal and lateral ramps indicated. After D_2 thrusting (C), the orebody and country rocks acquired the F_2 folds with E-W sub-horizontal fold axis. The tight folding superimposed upon these D_2 tectonites during event D_3 (back to A) accounts for the map pattern exhibited by the orebody and country rocks.

the Curaçá terrane has taken place under transpression, as previously mentioned in this text, there is not the possibility that the Caraíba orebody could have intruded along vertical shear zones during D_3.

Any eventual cause for the intrusion of the orebody during the transpressive D_3 event would require the opening of space within a sinistral, N-S trending transcurrent system (by the way, the sense of movement is not relevant here) and, in such a tectonic situation, intrusions would have occupied voids in releasing bends or voids created by moving apart the walls of the several vertical fractures which are theoretically predicted to form in vertical shear zones (Fig. 38). Some of these voids would be hypothetically folded straightforwardly or firstly rotated and then folded. However, these F_3 folds would have vertical axes, unlike the gently double plunging F_3 folds affecting the Caraíba orebody.

Even assuming that the orebody intruded syn-F_3 as a vertical body folded as above, why the G3 granites (syn-F_3 intrusions (always sub-vertical, sheet-like, and N-S trending everywhere in the Curaçá Valley) are never folded? Why should there be one mode of emplacement for the hypersthenites and another for the G3 granites if they are both contemporaneous with F_3 folds? Why there is not, in all the space of the Curaçá terrane, a single E-W trending, sub-vertical, unfolded layer of hypersthenite or G3 granite?

In addition, the 2051 ± 16 Ma old G3 granites cross-cutting the hinge zone of proven 100 m-scale F_3 folds deforming the mineralized layers at Caraíba and also intruding the hypersthenites in other orebodies far to the north in the Curaçá Valley (Surubim and Vermelhos) also demonstrate that the bodies of hypersthenites and norites were emplaced well before the F_3 folds and G3 granites.

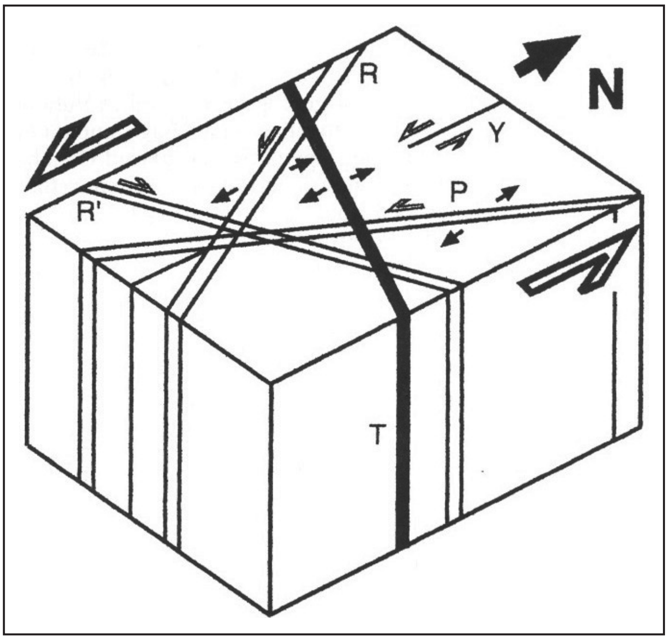


FIGURE 37 - Out-of-scale 3-D diagram which D'el-Rey Silva et al. (1996) used for denying the possibility that the Caraíba orebody could have intruded syn-tectonically along a hypothetical sinistral shear zone during the D_3 event in the Curaçá terrane. Vertical surfaces labeled R, R', P, and Y stand for Riedel, anti-Riedel, P, and Y (or PDZ) shear fractures, whereas T stands for tension gashes. As the small arrows indicate, all these surfaces would potentially open as hybrid fractures during progressive deformation (more details in text).

For the sake of all the data described in detail earlier in this text, the Caraíba orebody was emplaced as a sub-horizontal plate-like body sub-concordant with the Tanque Novo supracrustals. Together with the Tanque Novo rocks, it underwent D_1 interlayer shearing followed by D_2 and D_3 folding events, all in Paleoproterozoic times. Therefore it is not a surprise that Oliveira et al. (2004) obtained the 2.54 Ga U-Pb SHRIMP age for the mineralized norites at Caraíba.

7.5. Ending the saga

This historical review consolidates in a single text the results of studies carried out by independent researchers on the evolution of the Curaçá River Valley terrane and, in particular, on the results obtained during the thirty-two years (1978 to 2010) when the corresponding author was involved with the geology of the Caraíba Cu-orebody.

In reality, the efforts to understand the geology at Caraíba represent the first half of a real scientific saga. The second half, which is based on new data from more recent research focusing on other Cu-orebodies in the Curaçá Copper District (Vasconcelos et al. 2018; Ero Copper 2022), matches the results obtained in the saga's first half and supports extending the structural evolution at Caraíba for the entire Curaçá River Valley terrane. Here, it is worth saying that the geological conclusions in Ero Copper (2022) are mainly based on Frugis (2017) and Desrochers et al. (2020), whose respective reports constitute unpublished internal documents.

The saga's second half comprises the detailed geophysical study carried out by Vasconcelos et al. (2018), who point to the geometry of orebodies in the Angicos farm as tight up-right folds similar to the D_3 phase Caraíba Synform (see their Figure 6, among others). It also includes the multidisciplinary studies summarized by Ero Copper (2022), which combine data from geological mapping, geochemistry and geophysics with data obtained from diamond drill holes and galleries, altogether composing the scenario of an exhaustive database, all similar to the one presented here for the Caraíba orebody.

According to Ero Copper (2022), the geometry of the Pilar orebody, which is situated South of Caraíba, is controlled by a tight synform very similar to the D_3-phase Caraíba Synform (see Fig. 10.6; page 123 in Ero Copper 2022). Moreover, the geometry of the Vermelhos orebody in both geological maps and cross-sections (see Fig. 7.6, page 73; and Fig. 10.9, page 126; Ero Copper 2022) reproduces the pattern of F_2 x F_3 folding interference described here in every detail for the Caraíba Cu-Orebody.

The saga ends with necessary considerations regarding modern attempts to associate the geometric controls of the Cu-orebodies in the Curaçá terrane with shear zones. For example, Frugis (2017) refers to a geological section transversal to the regional trend in the northern portion of the Curaçá Valley, which comprises west-verging thrust faults to the west and east-verging thrusts to the east, as evidence of transpressional flower structure characterized by a double vergence of F_3 folds. Although the double vergence of thrusts and folds is not observed along the Poço de Fora field profile described further south (Hasui et al. 1982b; Reinhardt and Paixão de Sá 1982; see Fig. 2), the interpretation of transpressive tectonics in Frugis (2017) matches the regional evolution reported by D'el-Rey Silva (1993), Barbosa (1996), D'el-Rey Silva et al. (1996, 2007), according to which the tectonic structures in the ISAC orogen derive from the oblique collision of Archean landmasses. Anyhow, although transpressive tectonics is always charming for many geologists, it implies just a generic evolution of the orogen and does not provide a tool for determining the geometry of the mineralized layers at Caraíba or any other orebody in the Curaçá copper province, which is ultimately the critical goal for mining companies interested in profitable operations (Appendix 1; A1-25).

A last attempt to postulate a role for shear zones in controlling the mineralized layers at Caraiba came from Hühn et al. (2014). These authors described an iron oxide copper-gold (IOCG) prospect in the Neoproterozoic Riacho do Pontal orogen, which defines the border of the São Francisco Craton, Northwest of the Curaçá River Valley. According to them, new geological data derived from the Caraíba underground mine are inconsistent with the proposed structural control as summarized in this historical review. Those authors claim that Fráguas (2012) referred to newer drill holes intercepting a fault zone cutting the mineralized body in the deep hinge of the F_3 Caraíba Synform earlied defined by D'el-Rey Silva (1984). However, considering the lack of links between the Archean-Paleoproterozoic geology in the Curaçá terrane with the Neoproterozoic evolution of the Riacho do Pontal Belt, and the fact that Fráguas (2012) based his summary work on geological cross-sections already published for Caraíba (see Figs. 31D and 32D) and did not refer to any fault cutting the hinge ot F_3 Caraíba Synform, we consider the proposal in Hühn et al. (2014) as unlikely.

In summary, the following three aspects constrain in definitive what we understand that realy controls the mineralization at Caraíba. (1) Despite faults and shear zones were readily mapped in the open pit of the Caraíba Mine and surroundings in the pioneer years (e.g., Figs. 5A and 3) and in underground sites, they do not exert any control upon the geometry of the mineable lenses composing the orebody. Moreover, the attention paid to a ductile lateral ramp as a feature required for explaining the contact relationships between the orebody and the country rocks (see Fig. 37; or Fig. 11 in D'el-Rey Silva et al. 1996) demonstrates the profound care taken by the geologists at the Caraíba Mine for understanding the geometry of the Caraíba orebody, which involved a realistic and robust scientific basis. (2) Although the contact with the country gneisses on both the W and E sides is generally sub-vertical and is commonly marked by zones of intense ductile deformation and migmatization (Fig. 37), and the orebody and country rocks were cut-across by NNW- and NNE-trending zones of ductile shearing (Fig. 5A) developed late in the evolution of the area, whereby the narrow pyroxenitic layers were retrometamorphosed into biotitites and Cu-sulfide minerals remobilized to a minimal extent into shear zone-controlled small veins. The mining works at Caraíba evidence that the shear zones cited above did not imply any large displacement that could justify another interpretation for the geometry of the mineralized layers different from what had been proposed and carefully checked in D'el-Rey Silva (1984, 1985) and D'el-Rey Silva et al. (1988, 1996). (3) If there was a significant content of Copper remobilized along the shear fractures mapped since 1978-1984 (see also the original Figs. 9 and 10 in D'el-Rey Silva 1984), the 3m x 3m tight grid of samples aiming to define the Cu-content for every blasting in the Caraíba open pit (Appendix 2, A2-3) would have captured a straight linear trend in the percentage of Copper cutting the orebody. Instead, that grid of samples enhanced exactly the role of superposed foldings in controlling the geometry of the mineralized layers in successive maps of the orebody at depth (Appendix 2, A2-1).

In light of the comprehensive analysis presented, it is crucial to reiterate that without substantial and new data, the current understanding of the structural control of the Caraíba Mine and other Cu-deposits in the Curaçá Valley terrane, as outlined in this scientific-historical document, will remain unaltered.

8. Conclusions

This historical review consolidates the geological facts that permitted a group of pioneer geologists to unravel the Archean-Paleoproterozoic geological evolution of the Curaçá terrane in the northern part of the São Francisco Craton, NE Brazil. It is a timely initiative considering the successful continuity of mining operations in the Curaçá Valley.

The authors hope that this scientific-historical document drove the reader towards a clear understanding of the importance of detailed multidisciplinary studies headed by the structural geology analysis carried out in the context of the singular challenges faced during the stressful startup of a cost and high-risk mining project like the Caraíba Mine Project. The results at Caraíba were only possible due to a definitive belief in the strong power which structural geology has when it is based on detailed, comprehensive studies.

Furthermore, as the boomerang-and-mushroom fold interference pattern established for the overall architecture of the Caraíba Cu-orebody is also applicable to the evolution of the other deposits throughout the Curaçá terrane, the geological data derived from the intensive studies carried out in the last four decades ultimately constrains the efforts for understanding the metallogenetic processes involved in the generation of the Curaçá Valley Copper Province, Bahia, Brazil.

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Authorship credits

Author	A	B	C	D	E	F
LJHDS						
AMS						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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