Revista Brasileira de Geociências 12(1-3): 463-474, Mar.-Set., 1982 - São Paulo

GEOLOGY AND COPPER MINERALIZATION OF CURAÇÁ RIVER VALLEY, BAHIA

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ABSTRACT The high grade terrains of the N – S trending polycyclic belt known in Northeastern Bahia have been investigated along the Curaçá Valley region, as important copper mineralizations (180 millions tons of ore with 1,0% Cu, mostly in the Caraíba district) were discovered. The Curaçá Valley region is essentially formed by granodioritic to tonalitic gneisses (older basement?), Archean metasediments (quartz-feldspathic gneisses, leptynites, cordierite-sillimanite-garnet-biotite gneisses, quartzites, magnetite quartzites, calc-silicate rocks), and associated mafic-ultramafic intrusions. This lithologic assemblage was affected by metamorphism of granulite facies and tight folding apparently related to the Jequié event, and was reworked later during the Transamazonian event (retrometamorphic transformations, migmatization, granitization, deformation). The mafic-ultramafic intrusions (hyperstenite-norite-gabbro-anorthosite) are interpreted as being derived from differentiated tholeiitic magma and host well known mineralizations (magnetite-chalcopyrite-bornite-ilmenite, some pyrrhotite and pyrite, scarce pentlandite, violarite, millerite, tetrahedrite, hematite).

INTRODUCTION The copper deposit of Caraíba was discovered over a century ago, but the pioneer studies began only in 1944 when the National Department of Mineral Production (DNPM) made the first evaluation (Melo Jr. and Puchain, 1962) which revealed the existence of 10 millions tons of oxidated mineral with 1% of copper. Since then, various surveys have been executed, aiming not only at this deposit, but at other nearby areas as well which today constitute the copper District of the Curaçá River Valley extending for about 1,700 km^2 in the municipalities of Juazeiro, Curaçá and Jaguarari in the State of Bahia. These reserves are estimated at 180 millions tons of copper sulfides at 1.00% average grade and 5 millions tons of oxidate ore with 0.6% copper, the second largest in Brazil.

Today there exists an underground and an open-pit mining complex in this area, and a concentration plant designed to produce 150-180 millions t/per year of concentrate with 32%-34% copper.

Although the geological picture still lacks clear-cut definition, the knowledge of mineral concentrations was well developed in the last decades. The regional geologic studies began in the decade of the 60's, leading to a characterization of the Curaçá River Valley as constituted by gneissic-granulitic rocks, more or less migmatized and deformed, enclosing the mafic-ultramafic bodies with dissemination of copper sulfides.

During the last twenty years or even more of geologic studies, there has been a great advance in regional knowledge and in the investigations of several mafic-ultramafic bodies. However, many are still depending on detailed investigations, involving petrographic, stratigraphic and structural aspects of the lithologic sequences and the thermotectonic processes which developed during the Archean and Proterozoic ages (Transamazonian Event).

PREVIOUS WORKS After the first evaluation of the Caraíba deposit concluded in 1945 (Melo Jr. and Pouchain, 1962), Leinz (1948) described the host rocks of the mineralization and the parageneses of the copper minerals. This author estimated the copper sulfide formation temperature to be between 800 °C and 450 °C, considering it compatible with the magmatic origin.

These pioneer studies centered mainly on the Caraíba deposit, and in the 1960's the geological investigations were extended throughout the Curaçá River Valley. In 1964, Barbosa *et al.* conceived the Caraíba Group as a migmatite body of amphibolitic paleosomes, leptynites, calc-silicates, granites, granodiorites and tonalites. In this paper published in 1970 the copper mineralization was described as having a magmatic origin and associated to the intrusive pyroxenites. In 1969, Ladeira and Brockes Jr. carried out the first mapping of the area, raising the Curaçá to the category of a Supergroup, and dividing it into two groups: the lower Rio Curaçá Group, and the superposed Tanque Novo Group.

These authors also distinguished the existence of granitoid rocks, metasomatites and diaphtorite associates, and suggested that "the lithologies of the mafic-ultramafic sulfide-bearing sequence, would be relevant to an igneous 'suite' of the initial magmatism related to a geosynclinal subsidence".

In the decade of the 70's the investigations of the Curaçá River Valley received a new impetus bringing to light new considerations and concepts. Delgado and Souza (1975), completing the geological mapping begun by Ladeira and Brockes Jr. (1969), again used the denomination Rio Curaçá Group, dividing it into the Rio Curaçá and Tanque Novo sequences of lithologic character without stratigraphic conotation. As for the origin of the host rocks of copper, two possibilities were considered: they were "either

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pure and impure iron-calcium magnesium sediments or successive submarine volcanic eruptions of basic ultrabasic nature intergrown on the primitive sedimentary sequence". Thereafter they added (Delgado and Souza) that there exists a regional "substratigraphic" control for the mineralized mafic-ultramafic rock, the metamorphic structure of host rocks, the granitization, folding, hydrothermalism and metasomatism. Figueiredo (1976) studying the Poço de Fora region, admitted that the metamorphic rocks could be of sedimentary origin, in a platformal environment and of Archean age. He admitted furthermore the migmatization to be prior to the granitization and that the mafic-ultramafic rocks were volcanic.

Likewise in 1976, Jardim de Sá *et al.* studying the geochronological data of the region, designated the Caraíba Group as the Caraíba Complex.

Recently, Figueiredo (1980) studying the geochemistry of the Jacobina and Curaçá River Valley region, considered the Caraíba Complex to be formed of gneisses of a meta--sedimentary origin intercalated to the iron formation, calc-silicate and basic tuffs. A volcanic origin of chemical composition similar to Archean tholeiitic liquid and Mg--rich/basalts was attributed to the mineralized mafic-ultramafic rocks. Finally, in 1980, Lindenmayer defined the region as an Archean gneissic granulitic terrain reworked during the Transamazonian Event. The host rocks of copper mineralization were considered to be pre-tectonic intrusives and to have originated in a previously differentiated tholeiitic basalt liquid.

GEOLOGICAL SETTING The northeastern Precambrian region of Bahia State includes a mobile belt, mostly developed during the Lower Proterozoic in the northeastern border of the Archean Paramirim Craton (Almeida, 1979). In the eastern portion of this mobile belt is found the cratonic nucleus of Serrinha (Mascarenhas, 1976; Pedreira *et al.*, 1977) which includes a granitic-gneissic complex and volcanic sedimentary sequences of low to medium metamorphic facies, generically denominated as "Serrinha Greenstone Belt" by Mascarenhas (1973) (Fig. 1).

To the west, there is a metasedimentary sequence essentially of detrital origin, designated the Jacobina Group and attributed to the Lower Proterozoic.

The Curaçá Valley region includes a part of this mobile belt and is characterized by Archean gneissic-granulitic areas belonging to the Caraíba Complex (Jardim de Sá *et al.*, 1976). As will be described later, the rocks of this sequence were deformed by a polycyclic evolution, and were affected by the thermo-tectonic processes of the Jequié and Transamazonian events.

These high grade metamorphic belt were established and transformed into a stabilized cratonic terrain, adjoined further west to the Chapada Diamantina Group in the Middle Proterozoic. During the Upper Proterozoic they have integrated the São Francisco Craton, forming its northeastern portion together with the metasediments and metavolcanics of the Sergipano Fold Belt.

LITHOLOGICAL UNITS Three lithological units occur in the gneissic-granulitic complex of the Curaçá Valley. These units are constituted by sub-meridian belts of great petrographic complexity. Related to these belts are copper mineralized mafic-ultramafic sequences. Several granite bodies are associated with these units, but only one is large enough to be shown on the regional geological map (Fig. 2).

The units I and II show some resemblance to the Rio Curaçá and Tanque Novo Groups (Ladeira and Brockes Jr., 1969). These lithological sequences were described in detail by Lindenmayer (1980) under the name of Domains. Unit III corresponds to migmatitic gneisses, which developed in favorable structural zones modifying the original lithological sequences (units I and II).

The biotite-hornblende-gneisses and syenite gneisses of the eastern part of the area, are not described in this report. Therefore the following chapters refer to the western three-quarters of the area in Fig. 2.

UNIT I. Unit I includes the central part of the Curaçá Valley, where isolated outcrops occur as inselbergs in the flat valley surface. It consists of gray gneisses, conspicuously banded, of granodiorite-tonalitic to quartz monzonite composition, often containing hypersthene. Gabbroic intercalations are observed with an apparent thickness of several meters. The unit is folded, transposed and intruded by granitic rocks and pegmatite veins.

The gneissic sequence includes biotite gneisses, biotite hornblende gneisses, biotite clinopyroxene-gneisses and biotite-hypersthene-gneisses, closely related and intercalated. Mutual gradations are common due to the mafic mineral variations.

The gneisses show in thin section mafic bands bearing biotite, hornblende and hypersthene. Hypersthene occurs partially substituted by biotite and clino-pyroxene, and encircled by green-brown hornblende. The felsic bands bear microcline, plagioclase (An_{12} to An_{49}) and quartz. Chlorites, white mica, epidote and calcite are alteration minerals frequently observed in these rocks.

UNIT II. Unit II is a continuous outcropping to the west of the Curaçá River and discontinuous to the east. In the central part of the Valley the rocks of this unit occur subordinately, forming intercalations with the gneisses of Unit I. The outcrops are individualized boulders, the best expositions being found in the small rivers.

The principal lithologies are quartz-feldspar-gneisses, leptynites (with garnet and graphite), cordierite-sillimanite--garnet-biotite-gneisses, amphibolites, quartzites, magnetite-quartzites and calc-silicate rocks.

The mineralogical composition and probable origin of this sequence are shown in Table I.

The petrochemical and petrographic characteristics of Unit II suggest a supracrustal pelitic-chemical origin for this sequence (Lindenmayer, 1980) with probable volcanic components (Figueiredo, 1980).

UNIT III. Unit III is formed by migmatitic gneisses, with tonalitic to granitic composition occurring in the south of the Curaçá Valley, and in discontinuous outcrops in the north-south trend.

Contact between Unit III and gneissic rocks of the other sequences, is transitional and diffuse. Frequently it is possible to observe the nuclei of gneisses enclosed by migmatitic rocks. The migmatitic gneisses which included sillimanite-gneisses, leptinites and diopsidites, have a variable mineralogical composition. But where this migmatite included granitic and tonalitic rocks, the mineralogical compositions are homogeneous.

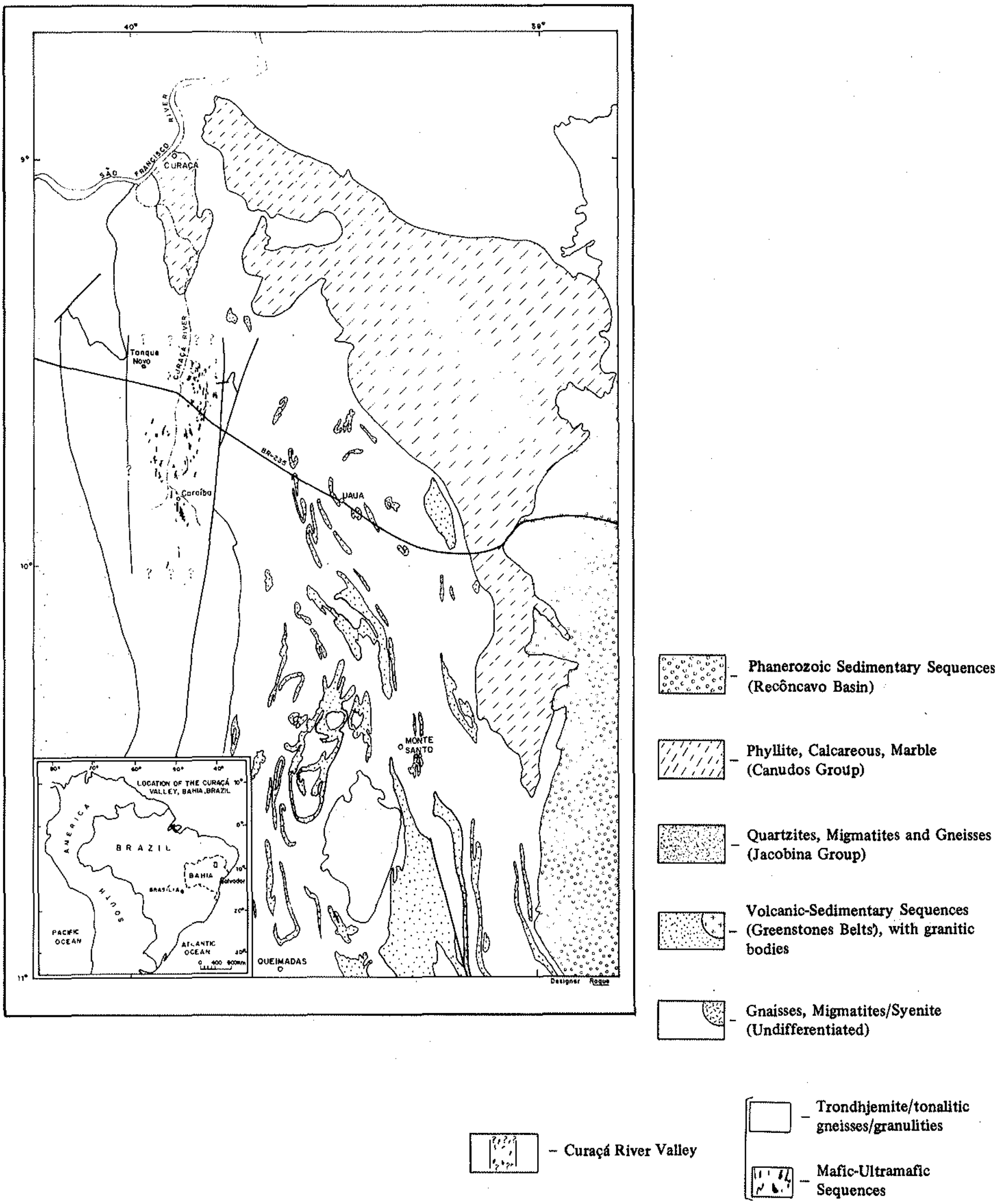

Figure 1 – Simplified geological map of northeastern São Francisco Craton, showing volcanic-sedimentary sequences and granulite-gneissic terrain of Curaçá Valley (Geology after Pedreira et al., *1976; Inda and Barbosa, 1978, modified)*

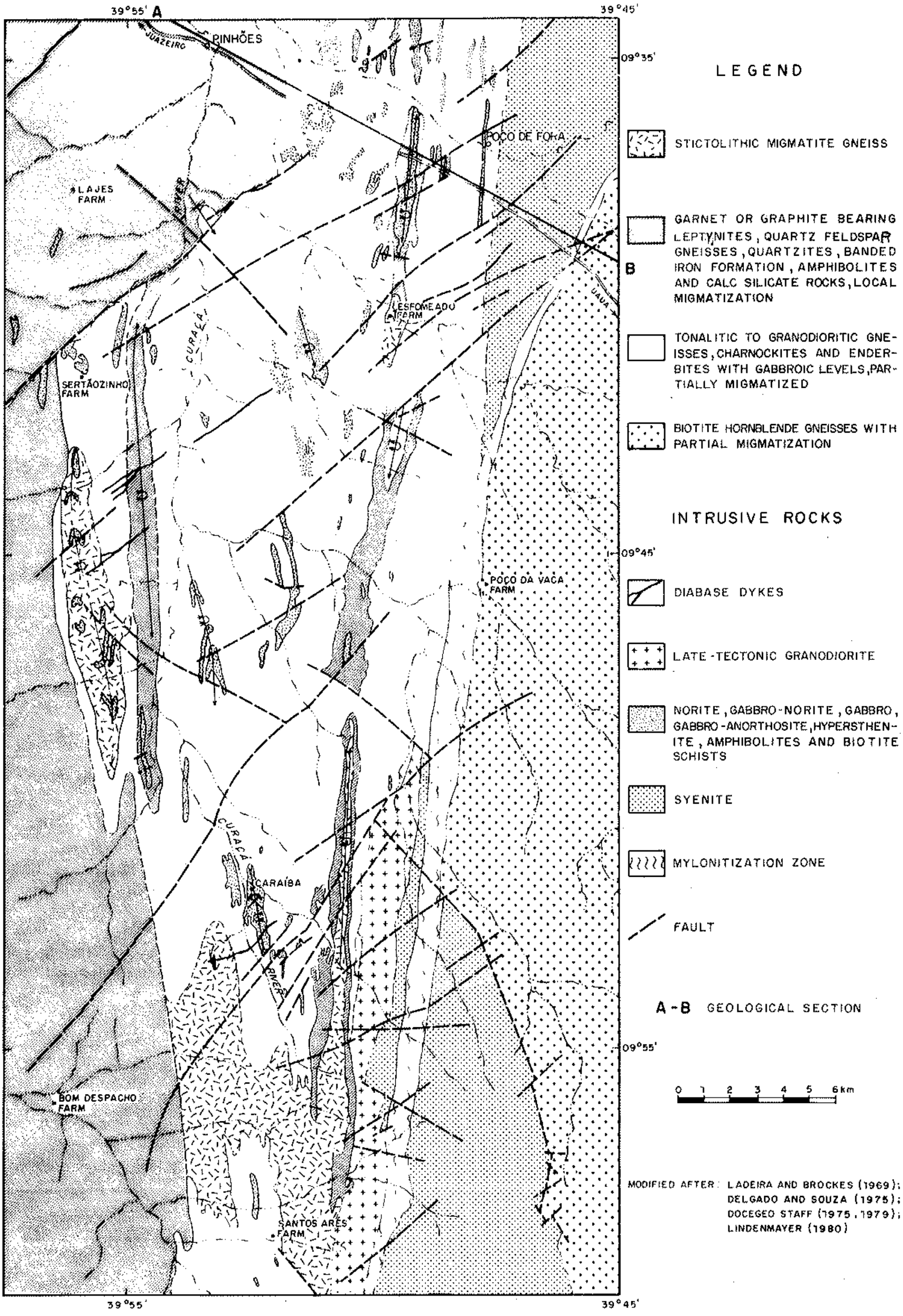

Figure 2 – Geological map

Table 1 – Lithological Association of Unit II (petrographic data by Lindenmayer, 1980)

Lithologies	Mineralogical associations	Probable origin
Leptynites Quartz, Feldspar-gneisses	Microcline perthitic, quartz, plagioclase, garnet, hypersthene, clinopyroxene, biotite	Graywackes and/or andesites-dacites
Cordierite-sillimanite gneisses	Cordierite, sillimanite, plagioclase, microcline, biotite	Pelitic and aluminous sediments
Calc-silicate rocks	Diopsides, plagioclase, forsterite, flogopite, hornblende, quartz, apatite, (anhydrite), etc.	Silicic-dolomites sediments with evaporitic layers
Quartzites, magnetite-quartzites	Quartz, magnetite	Iron-formation (Archean type)
Amphibolites	Hornblende, plagioclase, hypersthene (quartz)	Andesites

The contact aspects and the existence of two mineralogical groups of migmatitic rocks, indicate them to be rocks from Unit III derived from migmatization, feldspathization and granitization of lithological sequences belonging to units I and II

Common in these migmatitic gneisses are the stictolitic textures (Mehnert, 1968), where aggregates of garnets (or hornblende) occur in pegmatitic veins or feldspathic-quartz lenses of pink or white colour. These textures are believed to be generated through mafic mineral aggregation, which varies in composition, according to the original rock, without any satisfactory genetic explication.

Normally the migmatites are formed under the high temperature conditions of the amphibolitic facies, where we find orthoclase instead of muscovite, and where sillimanite-almandine-orthoclase is the characteristic mineral association. These characteristics are observed in gneissic migmatitic rocks belonging to Unit III.

INTRUSIVE SEQUENCE

Amongst the intrusive rocks outcropping in the Curaçá River Valley, there are granitic and quartz-monzodioritic and mafic-ultramafic rocks.

Granitic Rocks The granitic rocks and granitoids show fairly diversified types. They have a gray or pink color, porphyroblastic gneissic and equigranular textures. Internal foliation, in general, is conformable with the surrounding gneissic sequence, however unconformities are observed locally. They form elongated bodies or ptigmatic veins, with evidence of folding, and also can show granite enclaves. These aspects indicate several granitic generations. But it is not yet possible to establish the evolutional stages of this rock.

The most common types are granular granites and porphyroblastic granodiorites, the granular granites being more frequent. They have a very characteristic pink coloration, and intrude into the gneissic belonging to units I or II. They are stratiformal granites, with a thickness of about 80 m. They are composed of microcline, orthoclase, plagioclase (An_{17-20}) quartz and biotite.

Porphyroblastic granodiorite forms an extensive body to the east of Itiúba-Poço de Fora syenite in the east-southeastern part of the area. They have a dark gray coloration and are intensively foliated. Their porphyroblasts are of microcline, orthoclase, up to 3 cm long, in a matrix of microcline, orthoclase, quartz, plagioclase and biotite.

Finally, several bodies of quartz-monzodiorite can be mentioned. They form small and irregular intrusions, in a north–south direction, and appear intruded in the porphyroblastic granodiorite.

Mafic-ultramafic rocks The mafic-ultramafic rocks are sub-divided into three types: *a*) dunitic-peridotitic bodies; *b*) gabbroic bodies; and *c*) norite-hypersthenite sequences with copper mineralizations.

a) Dunitic-peridotitic sequences form small bodies, with a thickness of less than 20 m. They are distributed on the left side of the Curaçá River and are elongated in the north-south direction. There are diverse lithological types with a predominance of dunites, wehrlites, and harzburgites.

b) Gabbroic bodies are related to tonalitic gneissic, with which they form sharp contacts and occur with aspects of tabular dykes. They are composed of hornblende, hypersthene, clinopyroxene, plagioclase and quartz. They are foliated and folded together with the surrounding gneissic rocks. Lindenmayer (1980) compared these rocks with the basic deformed dykes of the Exterior Hebrides (Watson, 1973). The basic dykes marked crustal evolution steps in Greenland and the Hebrides, and enable the establishment of Precambrian stratigraphy. This aspect has not yet been studied in the Curaçá Valley area, and the origin of these gabbroic rocks remains unclear.

c) Norite-hypersthenitic mineralization sequences are formed by a suite composed of hypersthenite, norite, gabbronorite, amphibolites, and, very rarely, anorthosite. These mafic-ultramafic rocks host copper mineralization, and are formed of lenticular or, very rarely, tabular bodies, sheltered concordantly or subconcordantly in the lithologic units (I, II, III). They generally form elongated and folded bodies in a north-south direction. Their intrusive character is suggested by the shear and sharp contact with the gneissic and calc-silicate rocks belonging to Unit I and II. The rocks of these sequences show a stratigraphical disposition with the hyperstenites and copper sulfide in the basal parts. On the tops of the sequence norite, gabbro-norite and anorthositic rocks are present.

The hypersthenites are formed of hypersthene and clinopyroxene partially transformed in biotite, and subordinately by plagioclase, apatite, zirconite, magnetite, ilmenite and copper sulfides. They show variable quantities of biotite, and gradations between them and the biotite-schist are very common.

The norites are composed of hypersthene and clinopyroxene, biotite, hornblende, and plagioclase (An_{32-47}). These rocks can be banded, always showing the biotite and hornblende foliation. The gabbro-norites and gabbros are composed of greenish monoclinic pyroxene, partially substituted by green hornblende, hypersthene partially transformed into red biotite, plagioclase (An_{38-68}) and apatite, zirconite, magnetite, and ilmenite.

Amphibolitic levels still occur in the mafic-ultramafic bodies, generally showing remains of monoclinic pyroxene partially transformed into hornblende, and anorthositic layers formed by andesine and rare biotite.

METAMORPHISM The mineral paragenesis described in the three units and in the mafic-ultramafic rocks indicate granulitic assemblages. Figueiredo (1980) estimated with garnet-clinopyroxene and garnet-orthopyorene geothermometers the temperature of granulitic metamorphism as between 750 °C and 850 °C.

Beyond this metamorphic event, and as described previously, the replacements of granulitic facies minerals by hydrated minerals with lower metamorphic degrees are a constant in the area. Thus, the extensive retrogression of hypersthene in the region can be accounted for metasomatic reactions associated to migmatization and granitization. The transformations of granulitic assemblages such as hypersthene, plagioclase, clinopyroxene and red hornblende into green hornblende, biotite and quartz form the passage of granulitic facies to amphibolitic and the transformations of green hornblende into blue-green hornblende form the transition between high amphibolite facies and low amphibolite or epidote-amphibolite.

The migmatitic rocks, as described, show paleosome of high amphibolitic facies and the same diaphthoretical substitutions as the other units. Substitutions of the granulitic or amphibolitic paragenesis by green schist paragenesis, still appear locally, along the intense fault zone and in any lithological unit type. These low metamorphic mineral assemblages are, usually, composed of chlorite, white mica, quartz, albite and actinolite-tremolite.

From what was described, it can be verified that the regional metamorphism of the Curaçá River Valley rocks attained the low granulitic facies where anhydrous and hydrated mineral co-exist. It can also be verified that these granulites suffered later rehydration, migmatization and intrusion by granitoid rocks in conditions of high amphibolite facies, followed by retrometamorphism to paragenesis diagnosed as low green schist and amphibolite facies.

STRUCTURES The structural information was obtained from the observation of outcroppings with the objetive of defining general patterns for the individual features and superposition models. Furthermore, the structural features are represented in geological profile developed along the BR-235 road (Fig. 3).

Structural features The essential structures observed in the area are foliations, folds and discontinuities (Fig. 4).

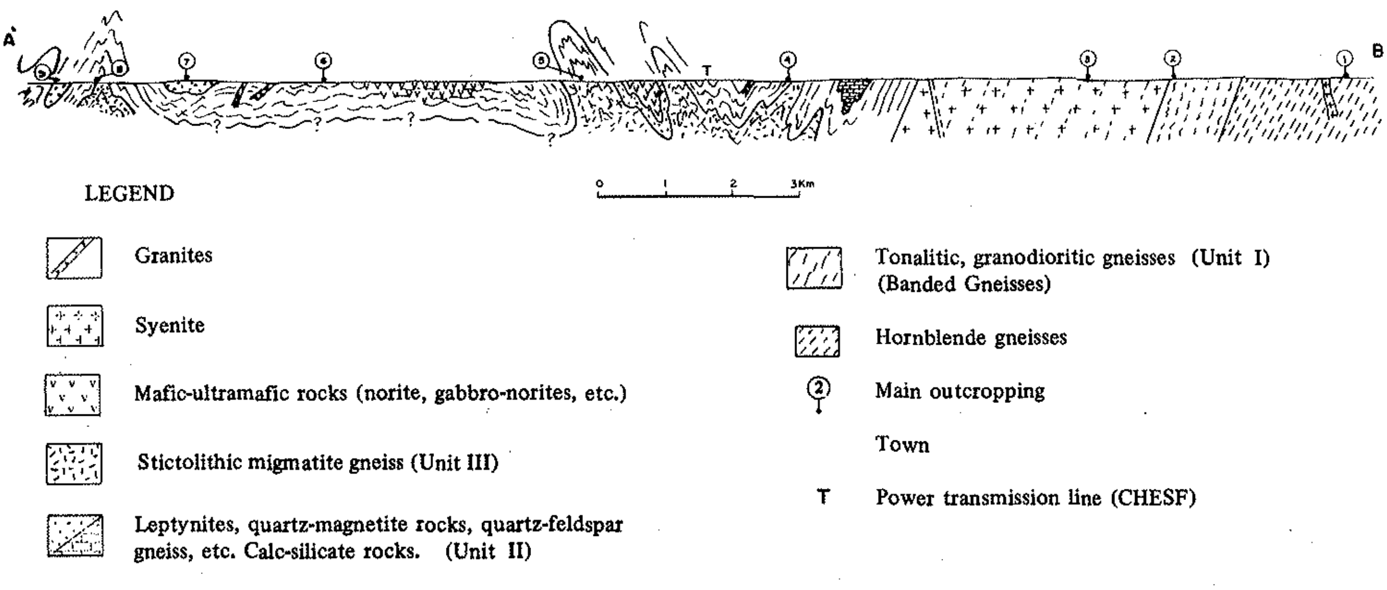

Figure 3 – Geological section A-B

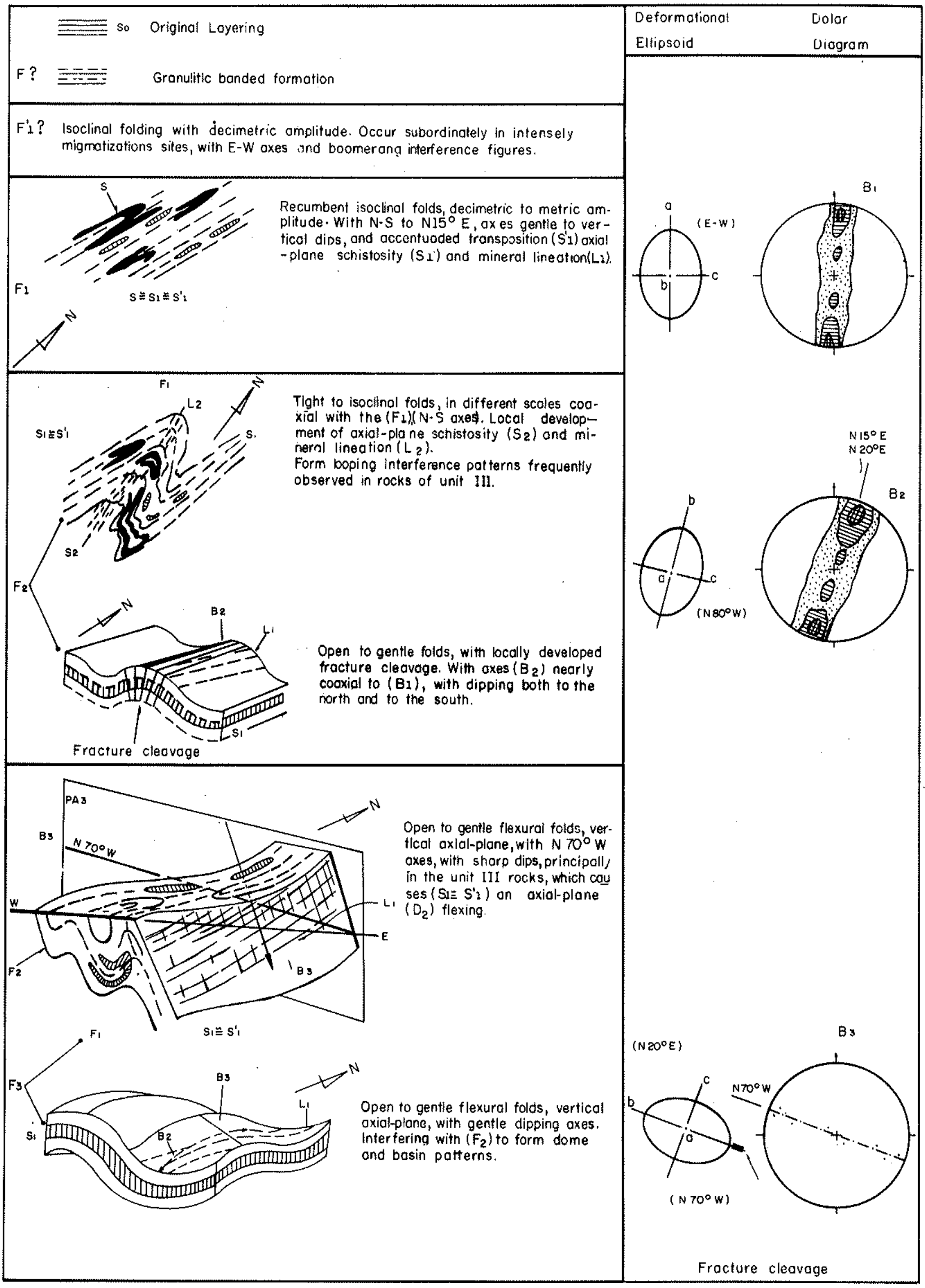

Figure 4 – Deformational events and related structural features

There are intrafolial folds (D_1) up to several meters of extension and they are characterized by their design of a pre-existing banding and by the development of axial plane schistosity (S_1).

The origin of banding (S) has not yet been clearly defined. One possibility is the development during a deformational phase. The schistosity (S_1) is penetrative and marked by planar disposition of micas and other minerals as flattened quartz. One mineral lineation (L_1) is frequently observed, parallel to the fold axes indicating stretching according to their direction. These intrafolial folds are characterized by greatly thickened hinges, and they could belong to the classes 2 or 3. They appear isolated or in groups of several successive folds. In both cases the recomposition of the major structures is not possible. Frequently these folds are observed isolated in transposed zones (S'_1), where the banding (S_1) and the schistosity, are found in parallel.

Fig. 5*a* shows measurements of L_1 and B_1 made in outcroppings along the BR-235 road, showing that the axes have a general NNE direction, with variable dips from horizontal to sharply inclined. This variation is not only a consequence of refoldings, but also of the non-homogeneous character of the deformations which originated these folds.

The second type of fold (D_2) consists of ondulations affecting the above cited features (S, S_1, S'_1, L_1). They are folds with large to medium interflank angles in Unit I, and medium to small ones in units II and III. Frequently these folds can even be isoclinal ones. In the narrowest folds the hinge thickening is more accentuated, and a second axial plane schistosity develops (S_2), not penetrative and restricted to the axial zone. They extend up to several meters and their asymmetric aspects enable the reconstitution of the major structures.

The folds (D_2) have submeridian axes and axial planes strongly inclined to the east or the west. Usually the axes are sub-horizontal, but they are not rectilineous and their curves tend to be sharply inclined. These ondulations of the axes are not due to later folds, but can be explained as non-homogeneous deformations.

Fig. 5*b* presents the attitudes of B_2 observed in the outcrops along the BR-235 road, showing that the general orientation is N-S with horizontal to vertical dips. The measured axial planes, are few but appear sharply inclined in a generally submeridian orientation.

The relation between the folds D_1 and D_2 is of co-axiality, the folds D_1 originally being of recumbent character. The resulting superposition model is the type 3. However, evidences of non-coaxiality have been observed locally between these phases of deformation, and therefore other figures of intermedial interference pattern developed. This can be seen locally in outcrops showing accentuated sign of migmatization (Esfomeado, Tanque Novo), where small interference patterns of the type 2 are observed. Some authors noticed this model of deformation and they believed in the existence of an earlier E-W deformational phase (Fig. 4). However, there is no structural feature found in the Curaçá Valley which could prove the development of such E-W deformational phase. These features might have been formed due to the movement of the D_1 folds, before the incidence of the phase F_2 in the plastic zones (migmatitic zones).

Folds of a third type (D_3) consist of very gentle ondulations, with vertical axial planes inclined and oriented around an EW-N70 °W axis. Their axes have E-W orientation, but their dips are variable depending on the attitude of the referencial surfaces (S, S_1, S'_1, S_2). These ondulations appear sparsely and, do not introduce important modifications in the resulting geometry of the anterior folding. Associated with them, in more competent layers, there is a fracture cleavage with N70 °W direction and variable dips (as a fan). Fig. 5*c* shows the B_3 attitudes measured in the outcrops along the BR-325 road, distributed in a WNW vertical plane which corresponds with the average attitude of the axial planes (AP_3).

The faults, fractures and joints and pegmatite veins represent the disruptive tectonic phase. The faults always have sharp dips and directional rejects. Frequently orientations are near N10-20E. The most important is the Itiúba Fault (Fig. 2), with a somewhat sinuous path approximately N-S/N10 °E, having an extensive cataclastic belt measuring up to 1 km thickness, including breccia, protomylonites, mylonites, and ultramylonites. The developed cataclastic foliation is steeply dipped, and faulting of the subhorizontal slickenside indicates a transcurrent character. Apparently the movement was dextrogyrous and the reject came up to several kilometers. The Poço de Fora-Itiúba syenite shows conjugate shear (N70 °E/N20 °E) and fracture (N40 °E), apparently developed contemporarily with the Itiúba faulting.

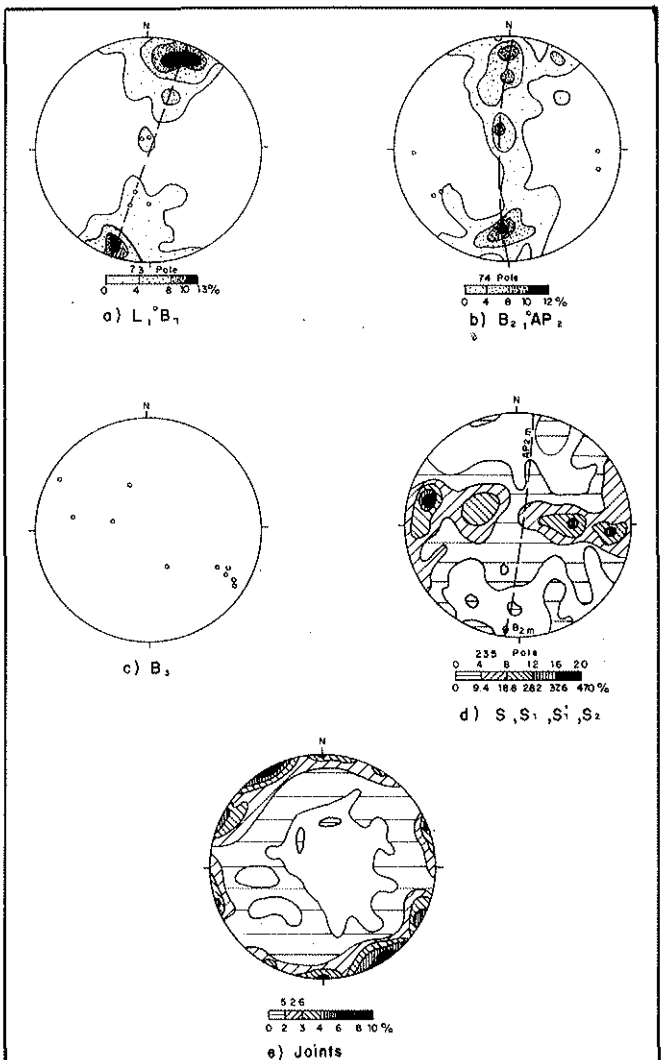

Figure 5 – Integrated stereogram measurements in outcropping along Serrote do Souza-Tanque Novo (BR-235 road)

The joints frame four cross-cutting sub-vertical families, observed in all the outcrops, although unequally developed. Generally they present a N30 °E, E-W, N60 °E, and N20 °W orientation, the first two seem to correspond to shear joints (Fig. 5*e*). The joints truncate the folds and faults, representing the latest discontinuities.

DEFORMATIONAL EVENTS Three folding events (D_1, D_2 and D_3) developed as can be seen in the Curaçá River Valley area. Even though the first one (D_1) had affected the whole area and even involved considerable crustal shortening (as evidenced by generalized transposition of S and by the types of folds) it was probably not very meaningful in terms of geometrical modification of the lithological sequence, as a whole.

The D_2 phase causes the geometrical configuration of the lithological bodies by submeridian elongated forms and by their localization in the through and nuclei of folds. Although the D_2 folds by themselves aren't indicative of great crustal shortening, this must have occurred to configurate synclinal and anticlinal structures of various orders with great modifications in the geometry of the lithological sequence. The D_3 phase is not of great importance in the general geometry and seems to have evolved progressively to the ruptural stage. Figs. 4 and 6 show the general pattern resulting from the three folding phases.

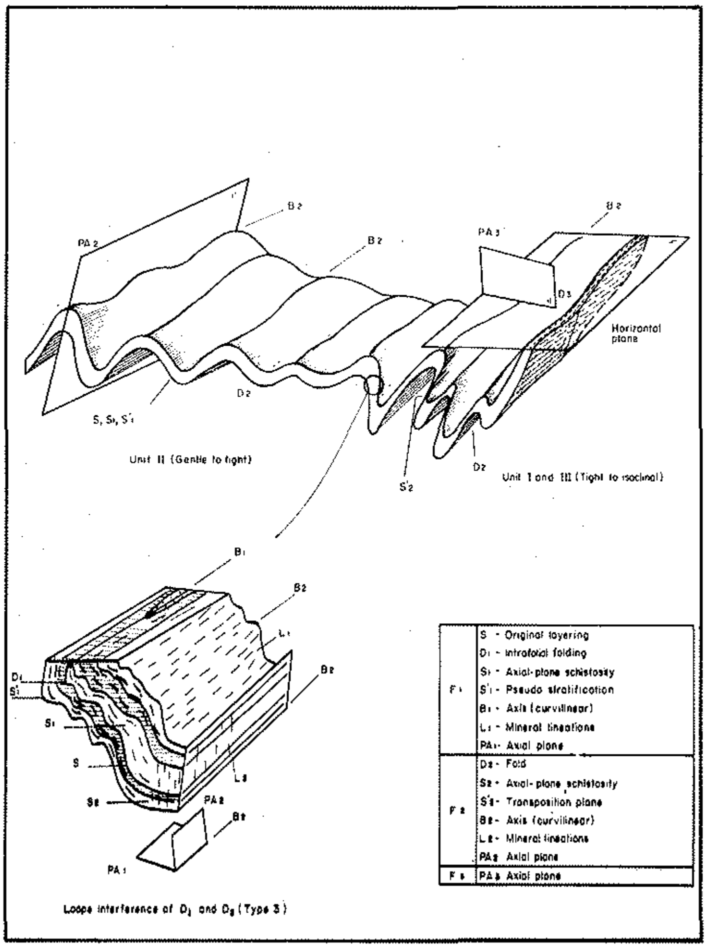

Figure 6 – General schematic diagram of interference patterns of F_1-F_2-F_3

The principal foliation attitudes (S, S_1, S'_1 and S'_2) are extensively dispersed, as can be seen in Fig. 5*d*. It can be seen, however, that the geometrical configuration of the lithological bodies, was developed during phase F_2. This is proved by the E-W guirlande (Fig. 5*d*) and by the ondulations in the litho-structural profile (Fig. 3).

Following the folds, disruptive tectonic events developed with faults and fractures as well and finally, the pegmatitic veins which penetrated, filling up the previously formed discontinuities.

GEOCHRONOLOGY The Rb-Sr data from the lithologies of Curaçá Valley define two reference isochrones. The first one of 2,850 ± 200 My. (I.R. – 0.704) refers to the granulite and charnockite rock and probably is indicative of the granulitic metamorphism (Cordani, 1976). The second isochrone at 2,160 ± 50 My. (I.R. – 0.706), indicates the reworking age of the rocks belonging to Unit I or II.

The granite isochrones indicate a Transamazonian age, but there is a need for more geochronological information in order to explain the history of granitic intrusions. Finally, examination by the K-Ar method indicates a minimum age of 1,518 My., as related to rocks indicating diaphthoretic alteration (greenschist facies).

Therefore the available datings indicate the ages of 2,850 ± 50 My. for the amphibolitic facies, and the first phase of folding. The age of 1,500 My. probably reflects the minimum age of deformational events, and is related to the disruptive tectonic events (Fig. 7).

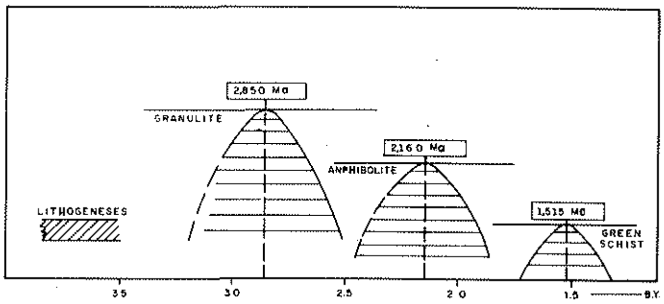

Figure 7 – Main deformational and metamorphical events

COPPER MINERALIZATION Aspects of mineral deposits The Curaçá Valley Copper Deposits are related to the mafic-ultramafic intrusions, which form elongated bodies in a north-south orientation (Fig. 8). The copper sulfides are mainly distributed in the base of the intrusions and are intimately related to pyroxenite and noritic rocks.

Apparently the copper deposits of the Curaçá area have these similar characteristics: structural setting (mainly in synclinal throughs), host rocks, and distribution and parageneses of sulfides. However, they are very different in the following ways: relative quantities between pyroxenitic and noritic rocks, metasomatic alteration intensity and the size and copper grade of the mineralized bodies. Bearing in mind these characteristics, the copper deposits and occurrences in Curaçá Valley, should be classified in four types.

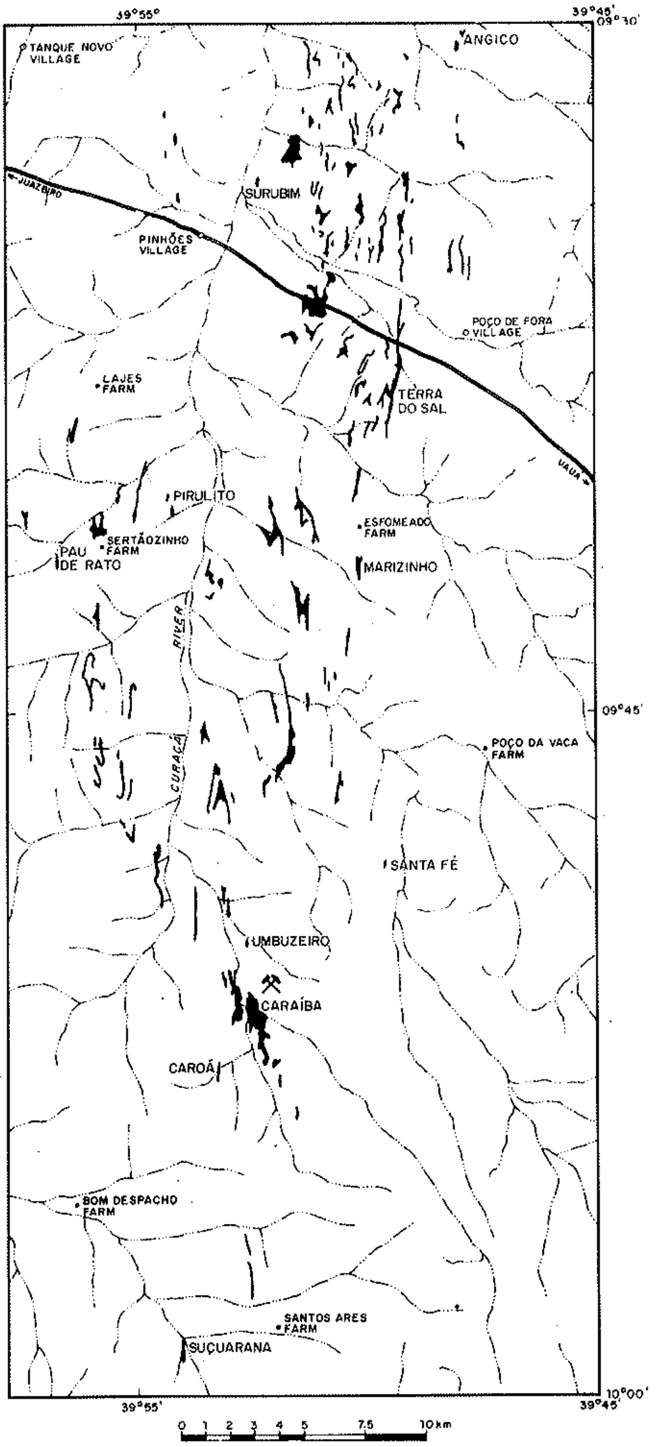

Figure 8 – Location map of the main mafic-ultramafic bodies

I – Deposits with sulfide distribution along the entire mafic-ultramafic sequence, constituted by massive sulfide associated with hypersthenite, which grades to noritic rocks with bands of pyroxenite. In these bands there is a weak to medium dissemination of copper sulfide. At the top of this sequence occur gabbro and gabbronorite without expressive copper mineralization.
Caraíba Deposit (Geologic reserves: 140 millions tons/1% of copper)

II – Small-scale copper mineral deposits, constituted by sulfides in alternating bands of pyroxenite and norite.
Angico, Pirulito and several others (deposits of medium reserves the 2.5 millions and medium copper grade varies from 0.6% to 0.8%).

III – Poor dissemination of copper sulfides in gabbro-norite rocks, which in general, do not form economically viable copper deposits.
Terra do Sal, etc.

IV – Copper deposits related to mafic-ultramafic sequence partially or completely biotitized. The distribution of sulfides are generically similar to type I, although in this deposit the principal copper concentrations are related to biotite-schist.
Surubim Deposit (Geologic Reserves: 14 millions tons/0,8% of copper).

Mineral parageneses The parageneses common to the first type of copper deposits at Curaçá Valley are formed by (in order of abundance) magnetite-chalcopyrite-bornite-ilmenite. Pentlandite, violarite, millerite, tetrahedrite, and hematite occur in lesser quantities. The pyrrhotite is of little importance as long as the pyrite occurs in rocks suffering diaphthoretic alteration of the green schist facies.

The sulfide-oxides when associated with hypersthenic rocks show granular textures intermixed with hypersthene resulting from the metamorphism of granulite facies affecting the host complex (deposits of types I, II, and III). In the metasomatic alteration zones of these deposits and in the partially or totally biotitized mineralized bodies (type IV deposits), the sulfides are lenticular or platoid, accompanying the phases of foliation delineated by the biotite.

On the whole the mineralized bodies appear in a layered position reflecting the original arrangement, the sulfide concentrations being associated with the ultramafic basal portions. However, this feature is greatly modified by phases of plastic deformation which provokes the development of sulfide concentration in the hinge thickenings, and the formation of lenses or elongated bodies along the fold axis (north-south). The rearranging of the sulfides during the rigid phase is local, with the filling-in of centimetric fractures and the dislocation of mineralized bodies without affecting the overall geometrical aspects of mineralized bodies.

Control of mineralization The distribution of copper sulfides can be seen to be closely related to the stratigraphy of the mafic-ultramafic sequences both the massive and strong disseminated sulfides associating with the hypersthenites and the weak disseminated sulfides related to norites and gabbro-norites. The principal host rock of copper sulfide is the pyroxenite; it also occurs in the bands of pyroxenite intercalated in norite rocks. There is a clear connection between the sulfide-magnetite and hypersthene. The inverse relationship occurs with the assemblage clinopyroxene and plagioclase, that is, gabbronorite and gabbro are either barren, or carry a low content of iron sulfide.

The chemical and mineralogical composition of the mineralized and weakly mineralized bodies, their parentage to Fe and Ti-enriched tholeiitic basaltic liquid, besides their high FM ratios (above 56) seem to suggest that they have originated from some previously differentiated liquid (Lindenmayer, 1980) and that the stage of differentiation which the liquid underwent when it reached the crustal level, had determined the formation of barren or mineralized bodies.

The close relationship of copper sulfides to magnetite-ilmenite also suggests that the mineralization is due to the separation of immiscible liquid sulfides (Lindenmayer, 1980).

In this context, one of the conditioning factors in the control of mineralization could be the differentiation stage of the tholeiitic melt. Liquids which bear the hypersthene-norite-gabbro crystallization, would give place to larger and higher-grade cupriferous deposits while the greatly differentiated liquid responsible for association with norite-gabbro would not form exploitable copper concentrations (Lindenmayer, 1980).

GEOLOGICAL EVOLUTION The geological and geochronological data shown by the Curaçá Valley led to a concept of the geological evolution steps and of the copper mineralization context.

The region is composed of gneisses ranging from granodioritic to quartz-dioritic compositions with gabbroic intercalations generically known as Unit I. It is suggested that this unit has been the basement of a sedimentary and volcanic sequence generically known as supracrustal sequence or Unit II. As far as we know, however, there is a lack of field data to support this idea. The occurrences of granitic and mafic-ultramafic sequence, underwent metamorphic conditions of granulite facies, reaching temperatures of 750 °C-850 °C (Figueiredo, 1980). Thereafter, retrometamorphic transformations into amphibolite facies took place. With the tectonic movements active again both the granitic melts and the fluid liberated during the metamorphic reactions, were mobilized favoring a deformation of the lithological sequences.

The silicate melts and the presence of alkaline aqueous fluids caused potassic metasomatism in the mafic-ultramafic rocks along with the formation of biotite-pyroxenite and biotite schist and remobilization of the copper sulfide concentrations. Related to this phase, feldspathization and migmatization of the gneissic rocks have also been registered.

Geochronological data seem to indicate extension of the Jequié Event (2,500-2,900 Ma) to the area. This would appear evident by the isochronic age of 2,500-2,900 Ma indicative of the development of a granulite facies metamorphism (Cordani, 1976). Thus, the gneissic basement, supracrustal sequence and mafic-ultramafic lithology, formed before the granulite facies metamorphism, must be Archean. The Transamazonian event shows extensive imprints in the area being represented by the isochronic age of $2{,}160 \pm 50$ Ma attributed to potassic metasomatism and granulitization (Cordani, 1976). The amphibolitic metamorphism which occurred after the granulitization, associated with the granitization and migmatization and concomitant with the three last deformational phases to which the region was subjected, is related to the Transamazonian Event.

Structuration of the area took place through folding phases followed by the development of disruptive phase features. The first folding phase (F_1) contemporaneous with granulitic metamorphism probably occurred in the Archean. This involved accentuated crustal shortening but probably did not affect the geometry of the lithological complexes and mineralized bodies.

The second folding phase (F_2) still in the amphibolitic facies gave the general configuration to the area, forming anticlinals and synclinals of various sizes.

The third phase (F_3) introduced gentle local ondulations and apparently was immediately succeeded by the rigid tectonic stage which generated the faults and fractures. The latter metamorphic transformations occurred in the greenschist facies, and geochronological measurements for rocks presenting mineralogical alterations related to this phase have indicated the minimum age about 1,500 Ma.

The lithologies as well as the enumerated events, show an extreme similarity between Curaçá Valley Region and those high-grade Archean terrains as described in geological literature. These terrains can be found well-preserved in the North Atlantic Craton and, in general, tend to become mobile belts through posterior re-working (Watson, 1973; Bridgwater *et al.*, 1973; Sutton, 1976; Windley, 1977) as seen in the evolution of the Curaçá River Valley in the Lower Proterozoic.

In the Archean granulitic-gneissic terrains, one can frequently find differentiated gabbro-norite-anorthositic or mafic-ultramafic intrusives associated to the tonalitic gneisses or the supracrustal sequence. In the Curaçá River Valley the differentiated rock intrusion are also found in the supracrustal sequence or in the tonalitic gneisses, exhibiting compositions varying between hypersthenite-norite-gabbro and norite-gabbro. The poorness of the ultramafic olivine bearing rocks in relation to copper deposits, the high value of their FM ratio, and the chemical characteristics of the host rocks indicate that these intrusions have originated from a liquid basalt already differentiated in depth.

The existence or inexistence of copper deposits would be determined by the stage of differentiation which the liquid is changed into, while emplacing in the supracrustal sequence.

The present data enable us to place the Curaçá River Copper deposits and occurrences among those of magmatic segregation formed by the separation of an immiscible liquid sulfide in differentiated intrusions.

Acknowledgments The Authors are indebted to Mrs. Zara G. Lindenmayer; the discussions and her's improvements during many field trips and meetings were very important for the development of this study.

Thanks are also due to Mr. Francisco Baptista Duarte for his careful revision and to Mr. Allan Drew Kobrin for his help in translating the manuscript.

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Recebido em 31 de julho de 1982