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THE METALLOGENESIS OF THE SOUTH AMERICAN PLATFORM

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The main objective of this review is to describe the most pertinent aspects of the metallogeny of the South American Platform, aiming to define the most important metallogenic units that developed during its evolution in the way of economically significant mineral provinces, and illustrating these with selected examples. The South American Platform represents, together with the Patagonia Platform and the Andean Belt, one of the principal tectonic divisions of the South American Continent. The consolidation of the South American Platform was completed by the end of the Neoproterozoic (Almeida *et al.*, 1976) (Figs. 1 and 2).

The constraints imposed by the space in which to adequately treat the far-reaching nature and diversity of the subject have necessitated that the selected models be described only in synthesis. Thus the opportunity for a more profound scientific discussion was reduced. For similar reasons the references cited are restricted to those considered to be wider in scope and in which additional references on the specific matter are cited.

The geochronological divisions adopted follow the recommendations of the International Commission on Stratigraphy (ICS/IUGS). However, for the Proterozoic we have preferred to adopt a three-part division, with boundaries at 1.8 Ga and 1.0 Ga, in line with the Tectonic Map of South America (Almeida, 1978). On the other hand the Proterozoic-Cambrian boundary is placed at 544 Ma, following the suggestion of Bowring *et al.* (1993).

THE GEOTECTONIC FRAMEWORK OF THE SOUTH AMERICAN PLATFORM

The South American Platform forms the nucleus or core of South America. It covers an area of about 15 M km^2, some 40% of which is exposed in three Precambrian shields: Guiana, Central Brazil (or Guaporé) and Atlantic. About 34% of the continental crust exposed in these shields was formed in the Archean, 80% was formed during the late Paleoproterozoic by the end of the Transamazonian Cycle, and about 98% at the end of the Neoproterozoic Brasiliano cycle (Cordani *et al.*, 1988;Cordani and Sato, 1999). At the end of the Neoproterozoic the South American Platform consisted of several plates or independent cratonic nuclei, most of which were still aggregated to their African counterparts. Between *c.* 650 and 540 Ma, the final amalgamation of these terranes (Fig. 3) was performed by a series of collisions during the Brasiliano (PanAfrican) Orogenic Cycle. The most important Brasiliano cratons of the South American Platform are the Amazonian, São Francisco, and Rio de La Plata cratons, in addition to smaller continental fragments. The basement of these cratons consists essentially of medium and high-grade metamorphic rocks, including associations of the granite-greenstone belt type and numerous granitoid plutons. Fragments of Archean medium to high-grade metamorphites occur as inliers in the Proterozoic mobile belts.

Geochronological data show that the evolution of the Amazonian Craton involved the addition of juvenile material performed by a number of tectonic events during the Archean, the Paleoproterozoic and the Mesoproterozoic, as well as the reworking of older continental crust. In the high-grade terranes (granulite and gneiss) some Archean protoliths occur in the Imataca Complex, Venezuela with U/Pb and Sm/Nd ages between 3.7 and 3.4 Ga (Sidder and Mendoza, 1995; L.A. Bizzi, pers. com.).

In the State of Amapá, Brazil, tonalitic rocks gave U/Pb and Sm/Nd ages between 3.1 and 2.94 Ga, whereas granulites showed Rb/Sr ages between 3.35 and 2.45 Ga (Lafon et al., 1998). In the Province of Carajás, Brazil, it seems that the principal time for the formation of continental crust is constrained between 3.0 and 2.8 Ga. However, zircon crystals aged up to 3.7 Ga have been reported in Paleoproterozoic granite and in sedimentary rocks. (Rio Maria granite-greenstone terrane). (Tassinari and Macambira, 1999). The oldest rocks found so far in South America occur in the Gavião Block of the São Francisco Craton, yielding Sm/Nd T_{DM} model ages up to 3.7 Ga (Cordani and Sato, 1999). In general, the majority of the radiometric results from this craton are of Neo-Archean age, between 2.9 and 2.5 Ga, and they are most prevalent in granite-greenstone terranes.

Archean granite-greenstone terranes or similar sequences form extensive areas in the interior of ancient cratons of the South American Platform. These include; (a) the Province of Carajás (Central Brazil Shield); (b) the Gavião Block and the Quadrilátero Ferrífero of the São Francisco Craton and; (c) the Crixás area of the Central Goiás Massif. Some of these granite-greenstone associations show Paleoproterozoic ages of about 2.2-2.1 Ga, such as the Rio Itapicuru region (São Francisco Craton) and an extensive belt in the NNE of the Guiana Shield. Banded iron formation units (BIF) of the Superior Province type (Paleoproterozoic), the Carajás type (Archean), and the Algoma-type (Archean) as well as sediments of the Witwatersrand type are also found in some of the cratonic areas.

With the close of the Brasiliano Orogenic Cycle, a network of mobile belts may be distinguished separating the cratonic areas. On the Atlantic side these mobile belts are especially well represented by the Brasília, Araçuai,

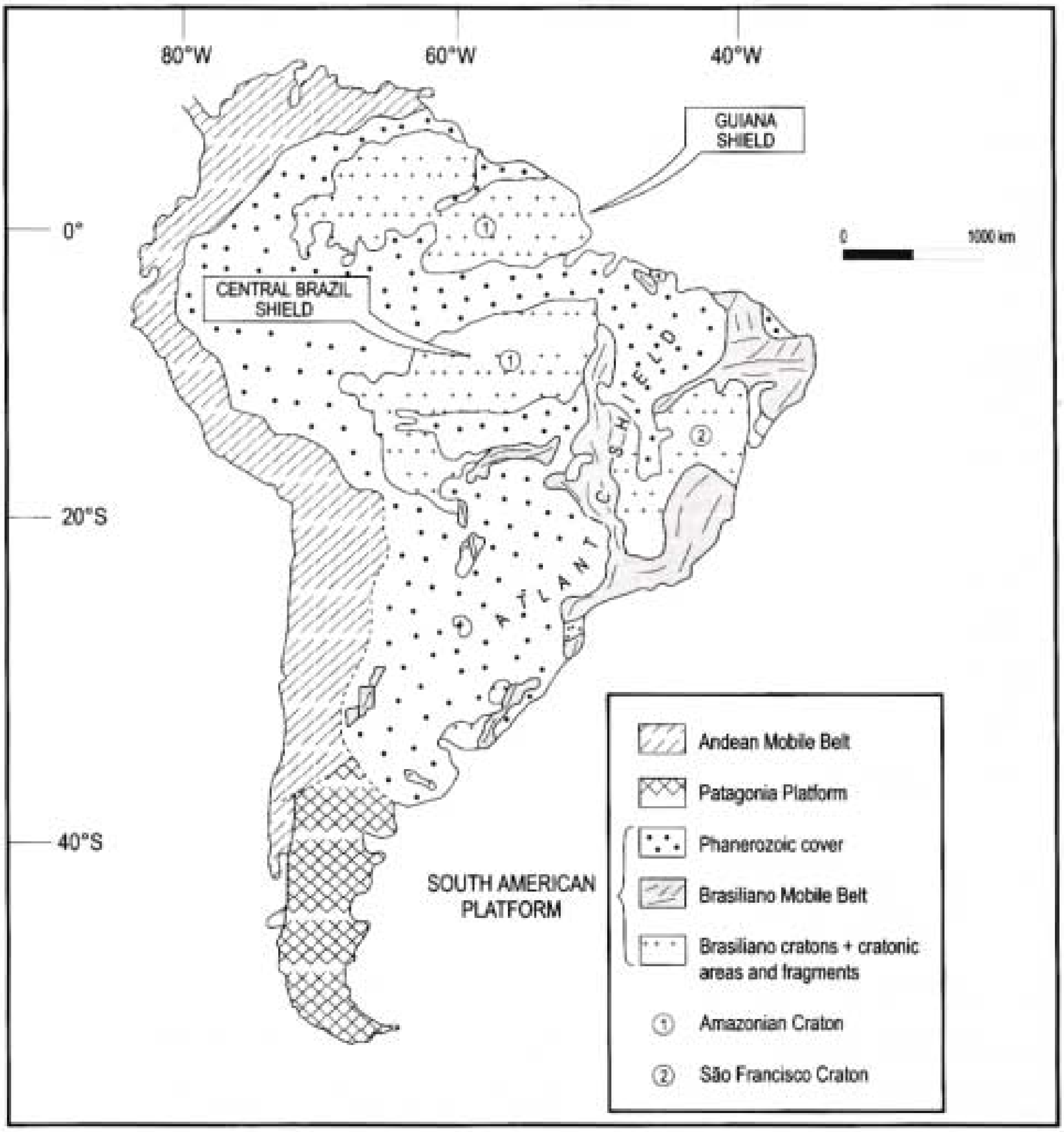


FIGURE 1 - Tectonic division of the South American Platform (modified after Almeida et al.,1978)

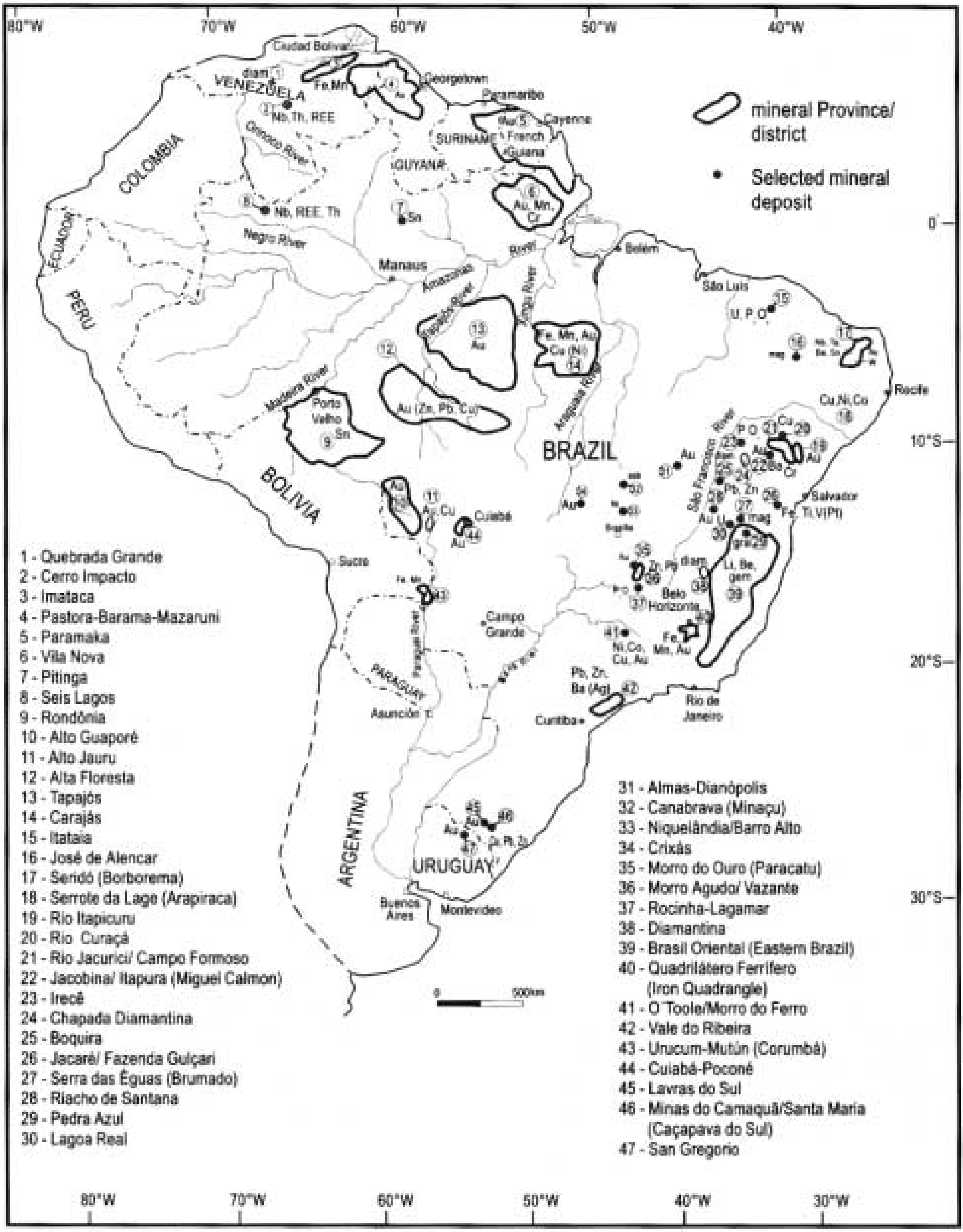


FIGURE 2 - Distribution of main Precambrian mineral provinces and selected mineral deposits of the South American Platform. Sources are cited in text. Abbreviations: asb - asbestos; diam. - diamond; gem - gemstones; gra. - graphite; mag - magnesite; REE - Rare Earths.

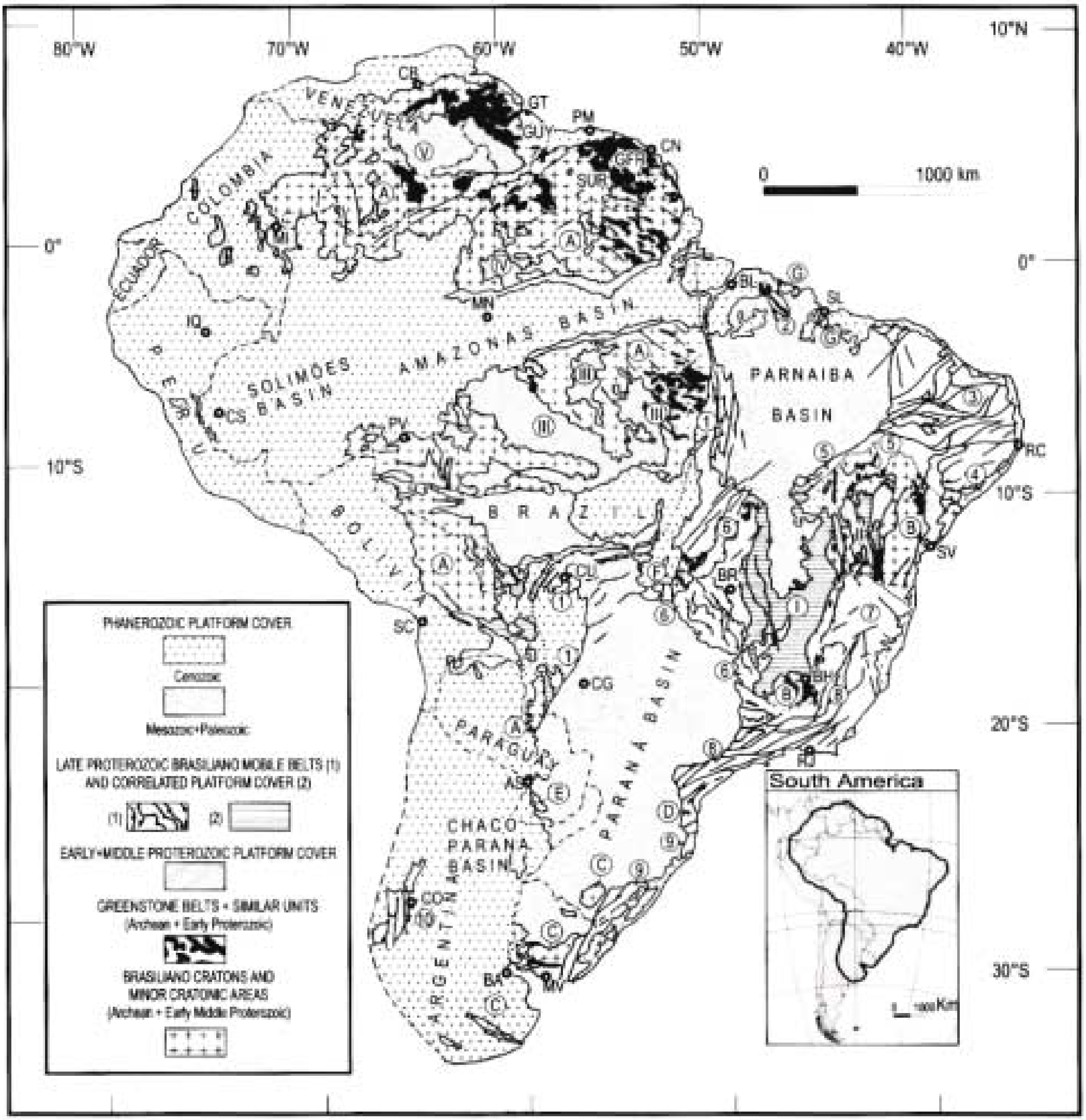


FIGURE 3 - Major structural units of the South American Platform. Brasiliano cratons and minor cratonic areas: Amazonian (A), São Francisco (B), Rio de La Plata (C), Luís Alves (D), Tibicuary (E), Central Goiás (F), São Luís (G). Selected Proterozoic platform cover: Bambuí (I), Chapada Diamantina (II), Beneficente-Iriri-Teles Pires and others (III), Urupi-Iricoumé (IV), Roraima-Surumu (V). Brasiliano mobile belts: Paraguai-Araguaia (1), Gurupi (2), Borborema Province (3), Sergipe (4), Rio Preto-Riacho do Pontal (5), Brasília (6), Araçuaí (7), Ribeira (8), Dom Feliciano (9), Sierras Pampeanas Orientales (10). Modified after Schobbenhaus and Campos (1984), Almeida et al. (1978) and others sources cited in text.
AS: Asunción, BA: Buenos Aires, BH: Belo Horizonte, BL: Belém, BR: Brasília, CB: Cuidad Bolivar, CN: Cayenne, CO: Córdoba, CS: Cruzeiro do Sul, CU: Cuiabá, GFR: French Guiana, GUY: Guyana, GT: Georgetown, IQ: Iquitos, MI: Mitu, MN: Manaus, MV: Montevideo, PM: Paramaribo, PV: Porto Velho, RC: Recife, RJ: Rio de Janeiro, SC: Santa Cruz de la Sierra, SL: São Luís, SUR: Suriname, SV: Salvador.

Ribeira, Dom Feliciano belts and by the Borborema Province. In central Brazil, the Paraguay-Araguaia Belt, over 2500 km long, extends into Bolivia and Paraguay. The relationship between the Paraguai-Araguaia Belt with the Sierra Pampeanas Orientales Belt, situated in the southwestern extremity of the Platform in the interior of Argentina, is not clear. Along the western margin of the Rio de la Plata Craton, there occurred during the Brasiliano Cycle, in early Cambrian times, a collision with the Pampia Terrane, that resulted in the Sierras Pampeanas Orientales mobile belt (Ramos, 1988). The Brasiliano mobile belts usually contain metasediments and metavolcanic rocks of low to medium metamorphic grade, and high metamorphic grade, locally. Many different types of granitoid pluton intrude these rocks. In part, these belts include older reworked rocks. The Borborema Province is different to the other mobile belts. It consists of branching system of orogens developed around a number of small cratonic nuclei, mostly Paleoproterozoic terranes, or rarely, Archean terranes.

The characteristic feature of the Amazonian and São Francisco cratons is the extensive platform cover consisting of sediments and volcanic rocks, mainly of Mesoproterozoic or Neoproterozoic age. These rocks have undergone little or no deformation, and generally contain well-preserved primary structures. This is probably the largest exposure of this type of cover in the world. In the Amazonian Craton this platform cover was deposited between *c.* 1.95 and 1.0 Ga, and was subsequently intruded by anorogenic granitoid plutons. The most important phase of magmatism (*c.* 1.95-1.8 Ga) is represented by calc-alkaline acid to intermediate volcanism of the Uatumã type, the rocks of which are overlain by mature sediments typical of continental and shallow-water marine deposition (Roraima/Beneficente type). Over the São Francisco Craton there are observed large exposures of platform cover consisting of terrigenous clastic and carbonate rocks of Mesoproterozoic and Neoproterozoic age (Espinhaço, Chapada Diamantina, Arai and Bambuí types). Anorogenic magmatism, associated with the opening of diverse continental rifts (Espinhaço-Arai) occurred in this craton at the beginning of the Mesoproterozoic between 1.77 and 1.70 Ga.

Fragmentation of the cratons and the development of Brasiliano oceanic basins started to occur at the beginning of the Neoproterozoic between 1.10 Ga and 950 Ma, involving extensive areas of the proto-South American Platform. The closure of these basins during the Brasiliano Orogenic Event resulted in the amalgamation of several cratons and smaller cratonic areas or terranes, a process that continued up to the beginning of the Paleozoic, and terminated with the consolidation of the present-day South American Platform.

The Precambrian basement of the South American Platform is partially covered by: (a) five large Paleozoic intracratonic basins: Solimões, Amazonas, Parnaiba, Paraná and Chaco-Paraná, the last-named being covered by extensive (Milani and Zalán, 1999) Cenozoic deposits; (b) several smaller Mesozoic/Cenozoic basins situated along the Atlantic coast (Cainelli and Mohriak, 1999) and; (c) the subandean basins in the extensive Andean foredeep (Llanos, Beni, Chaco, Pampas) lying along the margin of the Andean Cordillera, and almost totally covered by Cenozoic sediments.

From the end of the Brasiliano Orogenic Cycle this extensive Precambrian landmass was almost unaffected by tectonic events. Platform reactivation only occurred in the Mesozoic with the opening of the South Atlantic (South Atlantic Event) and continued up to the beginning of the Tertiary. Mainly during the Cretaceous there occurred the eruption of enormous volumes of basaltic lava and the intrusion of a number of alkaline-carbonatite complexes and kimberlitic pipes. The generation of sedimentary rift basins along the Atlantic coast is likewise related to this geotectonic event (Schobbenhaus and Brito Neves, 1996).

THE AMAZONIAN CRATON

The Amazonian Craton is one of the largest cratonic areas in the world, and has a surface of about 4.3 M km^2. It stabilized at the end of the Mesoproterozoic (Almeida *et al.*, 1976; Cordani *et al.*, 1988). Geographically, the Amazonian Craton is separated into two blocks by the Solimões-Amazonas basins (Fig. 3): the Guiana Shield and the Central Brazil (or Guaporé) Shield (Fig. 3).

According to the model proposed by Cordani and Brito Neves (1982), Lima (1984), Teixeira *et al.* (1989), Tassinari (1996), Tassinari and Macambira (1999), Cordani and Sato (1999), the geotectonic evolution that led to the cratonization of the Amazonian region resulted from a process of progressive crustal accretion from a more ancient nucleus that stabilized at the end of the Archean at about 2.5 Ga (Macambira and Lafon, 1995). Mobile and/or geochronological belts that succeeded each other in time and space surrounded this more ancient nucleus. In accordance with this concept, the Amazonian Craton was divided into six geochronological provinces (Fig. 4): Central Amazonia (>2.3 Ga); Maroni-Itacaiúnas (2.2-1.95 Ga); Ventuari-Tapajós (1.95-1.8 Ga); Rio Negro-Juruena (1.8-1.55 Ga); Rondônia-San Ignácio Belt (1.55-1.3 Ga) and Sunsas Belt (1.3-1.0 Ga).

Each of these provinces consists of specific plutonic, volcanic and sedimentary associations having distinct lithological, geochronological, geochemical and isotopic characteristics. The progressive stabilization of the Amazon region occurred during the Proterozoic through successive manifestations and ruptile intracratonic tectonics as can be seen through the development of rift mechanisms with associated volcanism, continental and marine sedimentation and the migration of anorogenic plutonism. These events terminated at the end of the Mesoproterozoic at about 1.0 Ga, at which time the Amazonian Craton was juxtaposed along its southern and eastern margins to the Paraguai-Araguaia Fold Belt.

The Guiana Shield

The Guiana Shield extends from the Atlantic Ocean at the northern and northeastern ends of the South American Platform to the Amazon sedimentary basin to the S (Fig. 5). In its western part this shield consists of the basement of the Andean foreland basins. Geological maps at adequate scales and/or systematic geochronological studies are

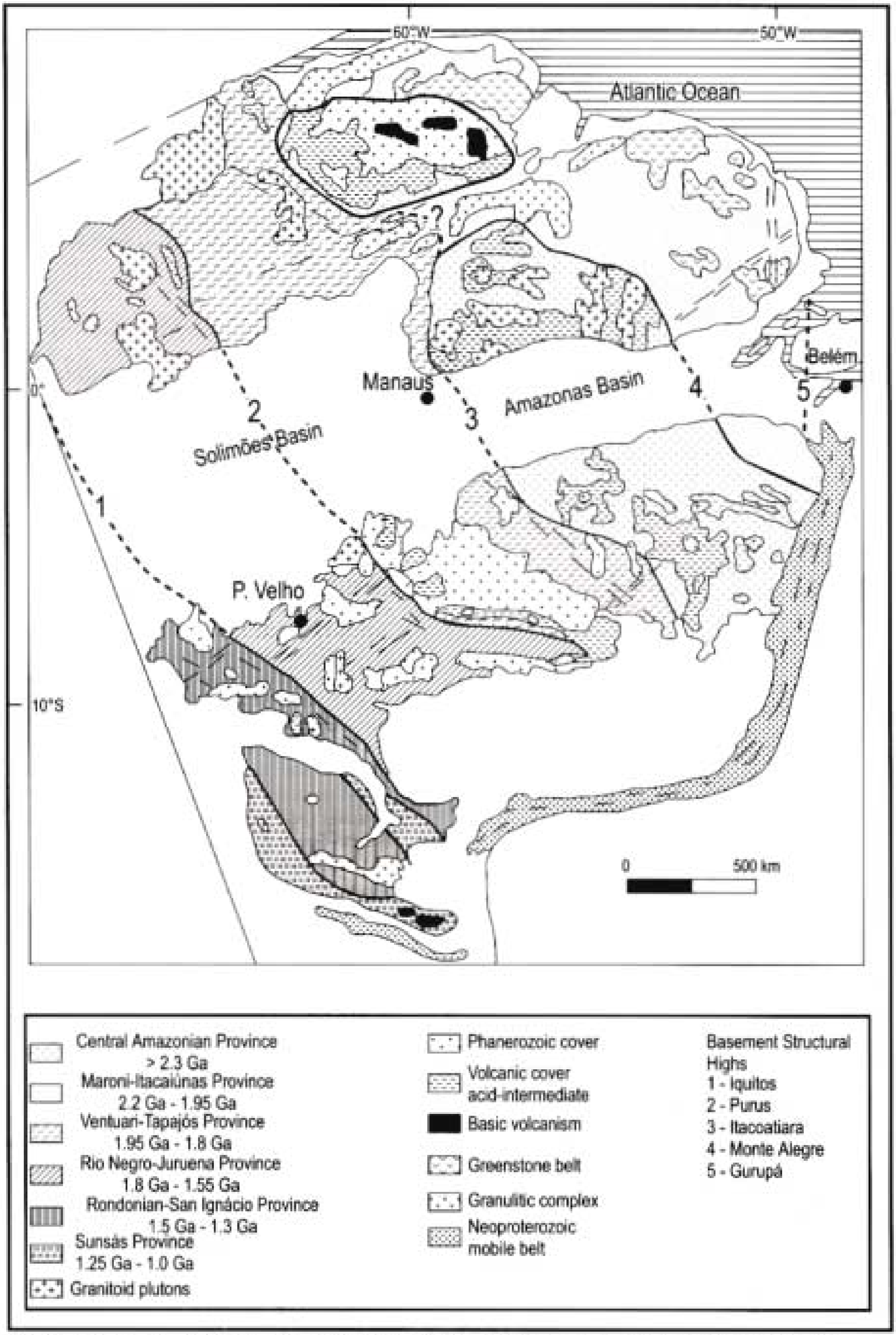


FIGURE 4 - Schematic map of Amazonian Craton, showing the distribution of geochronological provinces (modified after Teixeira et al., 1989; Tassinari, 1996; Tassinari and Macambira, 1999).

restricted to specific areas and are practically non-existent in the largest part of the shield.

The Guiana Shield may be divided into (a) a terrane consisting of granulite and gneiss in the western region of Venezuela as an Archean protolith (Imataca Complex); (b) a Paleoproterozoic granite-greenstone terrane some 300 to 400 km wide, lying along the Atlantic margin; (c) a non-differentiated terrain consisting of granite and gneiss and; (d) a central and western part with extensive cover of Paleoproterozoic felsic volcanic rocks and Mesoproterozoic continental sediments. Additionally, there occur Mesoproterozoic or younger dykes, sills and mafic flows besides alkaline complexes, also of Mesoproterozoic age. Paleoproterozoic events occurring at about 2.0 Ga (Transamazonian Orogenic Event) involved metamorphism, deformation and granitic magmatism, manifest in the Imataca Complex, the granite-greenstone terranes and to some extent the non-differentiated terranes consisting of granitic rocks (Gibbs and Barron, 1983).

In the extensive regions of the Guiana Shield underlain by non-differentiated granite and gneiss terranes and by granite-greenstone terranes, Tassinari and Macambira (1999) defined several geochronological provinces such as those referred to in the previous item (Fig. 4).

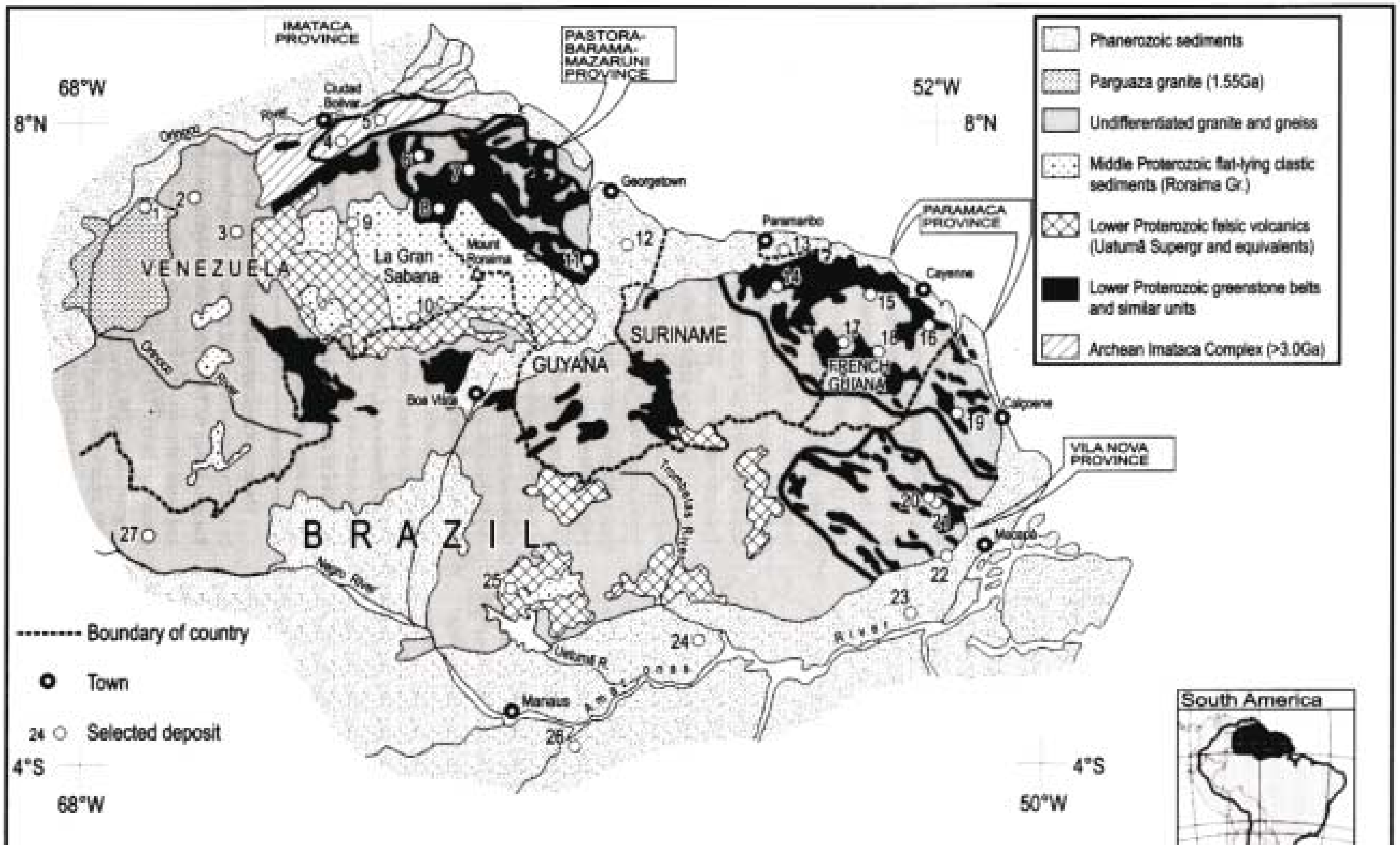
Terranes underlain by rocks of defined Archean age are rare in the Guiana Shield. The area having the largest exposures is that occupied by the Imataca Complex with ages between 3.7-3.4 Ga (U/Pb, Sm/Nd). The granulite and gneiss of the Imataca Complex are the oldest rocks of the shield, and display faulted contacts with the surrounding Precambrian rocks. At about 3.4 Ga this complex formed a stabilized continental nucleus. Between the various rock-types, of note are the intercalations of iron formation units, to which the origin of an important metallogenic province is related. Intrusion of granitic rocks and development of migmatite (Cerro La Ceiba migmatite) define a tectonomagmatic event between 2.8 Ga (zircon age/SHRIMP) and 2.7 Ga (Rb/Sr WR age) in the Imataca Complex (Sidder and Mendoza, 1995; Gibbs and Barron, 1993; L.A. Bizzi, personal communication). This event is known as the Aroense Event (Martin-Bellizzia, 1972). An extensive granite-greenstone province of Paleoproterozoic age and predominantly auriferous, lies along the Atlantic margin of the shield from Venezuela to Brazil. These units also include supracrustal formations that differ from the greenstone belt sequences in their relative paucity of volcanic rocks, and in some cases, by their younger stratigraphic position. Geochronological data, including that for U/Pb isochrons in zircon, Sm/Nd and Rb/Sr, suggest that the volcanic rocks of greenstone belt sequences and granite associated with the provinces under discussion were formed between about 2.25 and 2.10 Ga. In French Guiana, recent dating showed ages between 2.14 and 2.09 Ga for the Paramaka Volcanics (Carte Geologique de la Guyane Française, 1:500 000, in press). In general, the greenstone belt rocks of the Guiana Shield show the same typical characteristics as their Archean counterparts in other parts of the world. However, they contain smaller amounts of ultramafic rocks and larger amounts of clastic sediments. The granite-greenstone terranes represent the most important metallogenic unit of the shield, principally on account of the associated gold mineralization. Three different provinces may be distinguished: (a) Pastora-Barama-Mazaruni, in Venezuela and Guyana; (b) Paramaka, in Suriname, French Guiana and Brazil (State of Amapá) and; (c) Vila Nova, on the divide between the states of Pará and Amapá in Brazil.

In the central part of the shield in Brazil, Guyana and Suriname, excluding the areas referred to above, there occur exposures of volcano-sedimentary supracrustal rocks that underwent medium to high-grade metamorphism during the Transamazonian Event. In Brazil, these supracrustal rocks include the Cauarane Group.

Late Paleoproterozoic calc-alkaline continental volcanic rocks of acid to intermediate composition, locally associated with clastic sediments, can be observed over much of the central and western regions of the shield. These volcanic rocks are associated, in part, with granitic to granodioritic intrusions (*c.* 1.85 Ga), locally of sub-volcanic nature. This volcano-plutonism, to which the collective name of Uatumã has been assigned (Gibbs and Barron, 1983, 1993) is widely distributed throughout the Guiana Shield. However, Reis and Fraga (1996) consider that the cogenetic character of the Uatumã plutonic and volcanic rocks is inconsistent, taking in account the clear geochemical incompatibility of both. Indeed, the Uatumã volcanic rocks are more compatible with those observed in the post-orogenic suites related to the Transamazonian Event. The volcanic rocks of the Uatumã type occur at shallow crustal levels, suggesting that these might have been affected by the Transamazonian Event, and for this reason were interpreted as being related to a late or post-collision phase of this tectonic event (Bosma *et al.*, 1983; Reis and Fraga, 1996).

Several regional names are applied to the volcanic rocks of the Uatumã Supergroup: Surumu and Iricoumé in Brazil, Cuchivero in Venezuela, Burro-Burro and Kuyuwini in Guyana, and Dalbana in Suriname. U/Pb determinations in zircon from rhyolite from the Surumu and Iricoumé formations gave ages of 1.96 Ga, and samples of ash flow from the Cuchivero Group collected near Santa Helena de Uairén were dated at 1.98 Ga (Brooks *et al.*, 1995). A granite intrusive assigned to the Iricoumé Group at Pitinga situated to the NE of Manaus was dated at about 1.8 Ga by U/Pb (Lenharo, 1998). This type of granite hosts important tin mineralization in addition to other elements.

The units of the Uatumã Event are overlain discordantly by continental sediments of the early-Mesoproterozoic Roraima Group (*c.* 1.8 Ga), intruded by dykes, basic sills and small subordinate intrusives of continental tholeiite (Avanavero Suite). The most precise date for this tholeiitic magmatism is 1.789 Ga (U/Pb in baddeleyite) (Norcross, 1998; *apud* Santos *et al.*, 1999). The Roraima platform cover extends over much of the western part of the shield. It represents the most important unit of continental sedimentary rocks in the Guiana Shield that form tablelands (*tepuis*) typically represented by the Mount Roraima, at the triple divide between Brazil, Guiana and Venezuela, where this group attains a thickness of about 2500 m. The Roraima Group consists of orthoquartzite, arkose, conglomerate and smaller amounts of shale and tuff with jasper, deposited in fluvio-deltaic and lacustrine environments. It is believed that the conglomerate units



1. Los Pijiguaos (Al), 2. Quebrada Grande (Diamond), 3. Cerro Impacto (Th, Nb, REE), 4. San Isidro Iron Quadrilateral/Cerro Bolívar (Fe), 5. El Pao (Fe), 6. El Callao/ Lo Increible(Au), 7. Botanamo (Au), 8. Las Cristinas (Au), 9. San Salvador de Paúl (Diamond), 10. Icabarú (Diamond), 11. Omai (Au), 12. Berbice and Demerara (Al), 13. Moengo/Onverdacht/Paranam (Al), 14. Gross Rosebel (Au), 15. St Elie (Au), 16. Camp Caiman (Au), 17. Yaou (Au), 18. Dorlin (Au), 19. Laborrie Siboa/Salamangone (Au), 20. Amapari (Au), 21.Serra do Navio (Mn), 22. Igarapé do Breu (Cr), 23. Almeirim/Mazagão (Al), 24. Oriximiná/Porto Trombetas (Al), 25. Pitinga (Sn, Zr, Nb-Ta, REE), 26. Fazendinha (K), 27. Seis Lagos (Nb, REE)

FIGURE 5 - Schematic geological map of the Guiana Shield (modified after Gibbs and Barron, 1993; Bellizzia et al., 1981; Bardoux et al., 1998; Carvalho et al., 1995; Faraco and Carvalho, 1994; Gray et al., 1993; Brooks et al., 1995; Sidder, 1995)

intercalated in the sediments of the Roraima Group are responsible for the extensive alluvial and eluvial diamond mineralization that occurs regionally (Fleischer, 1998). The youngest of the Mesoproterozoic manifestations of granitic intrusion in the Guiana Shield is the Parguaza Batholith (1.55 Ga), situated near the margin of the Orinoco River in Venezuela (Fig. 5). Most of the Parguaza-type granites show rapakivi textures, anorogenic characteristics, and bear tin mineralizations. A good example example is the Surucucus Granite (1.551 Ga, U/Pb; Santos *et al.*, 1999), situated along the boundary between Brazil and Venezuela. Overlying the Parguaza Batholith there developed important supergene concentrations of bauxite. In Brazil there are syenite intrusions of normal and alkaline composition to which an age of about 1.5 Ga has been assigned. Examples are Cachorro, Serra do Acari and Mapari. Along the frontier between Brazil and Guiana there occurs the Mutum alkaline intrusion dated at *c.* 1.0 Ga. In the interior of the Guiana Shield there is evidence for faulting, reworking and the closing of isotopic systems in mica besides igneous intrusions at the end of the Mesoproterozoic and the beginning of the Neoproterozoic. These events are probably related to more intense activity at the margin of the shield between 1.3 and 1.1 Ga. Most of these faults strike NE-SW, and are associated with mylonite and pseudotachylite. This event has been referred to as Orinoquense, K'Mudku, Nickerie or Jari-Falsino. It is possible that these faults involved significant reactivation along zones of weakness, and as such could play an important role in the concentration of gold.

The igneous activity at the end of the Neoproterozoic includes the intrusion of alkaline complexes and volcanic mafic and felsic suites. The youngest Precambrian magmatic events observed on the Guiana Shield are those that refer to the Quebrada Grande diamondiferous kimberlite in Venezuela, dated at 710 Ma (Channer *et al.*, 1998), and to basic dykes in French Guiana that strike NE-SW and NW-SE, dated at 800 Ma (Carte Geologique de la Guyane Française, 1:500 000, in press). The alkaline complexes of Cerro Impacto, Venezuela and Seis Lagos, Brazil, still undated, may also be of Neoproterozoic age.

Swarms of tholeiitic diabase dykes intruded between the end of the Triassic and the beginning of the Jurassic, with strike N-S and NW-SE are very prevalent in the northeastern region of the shield and are related to the opening of the Atlantic Ocean.

The most important mineralizations on the Guiana Shield are described below, with emphasis on gold deposits along with those of iron, manganese, tin, chrome, niobium, tantalite, zircon and diamond. Most of these deposits were enriched significantly by tropical weathering processes.

The Imataca Province

Banded iron formation units (BIFs) with important iron mineralization are associated with the granulite belt of the Imataca Complex. This complex strikes NE-SW and forms a mountainous chain at least 510 km long from the Aro River to the Orinoco Delta at the northern limit of the Guiana Shield (Fig. 5). The protolith of the complex with an age between 3.7-3.4 Ga, consisted of clastic and chemical sedimentary rocks, sub-aerial volcanics of siliceous and calc-alkaline composition, and smaller amounts of plutonic rocks. These rocks were intensely folded and submitted to metamorphism that varies in grade from that of the granulite facies (two pyroxenes) to the amphibolite facies. They consist of orthogneiss, paragneiss, granulite, charnockite and metamorphosed BIF, along with smaller quantities of manganiferous sedimentary rocks, marble, dolomite and anorthosite. Regional metamorphism, deformation and granitic intrusion occurred during the Aroense Event at about 2.8-2.7 Ga. Between 2.1-2.0 Ga, during the Transamazonian Event, they underwent metamorphism in the amphibolite and granulite facies with granitic intrusions (Sidder and Mendoza, 1995).

The banded iron formation units represent less than 1% of the rocks of the complex, and their average thickness varies from a few centimetres up to about 200 m. Several enriched BIF deposits such as Cerro Bolivar and San Isidro are amongst the largest in the world. The iron reserves before mining exceeded 1855 Mt at 63% Fe, and 11 700 Mt at about 44% Fe. The proto-ore of the BIF units consists of an oxide facies assemblage in which magnetite and hematite are the main mineral species. The iron-rich beds are interstratified with siliceous beds containing quartz and metamorphic iron-rich minerals. These deposits are similar to the iron formation units of the Superior Province, notwithstanding some units of the Algoma-type or Carajás-type may also occur. The precious metal content of these rocks is seemingly low.

The majority of the iron ore deposits strike E-W, following the principal structural trend of the complex. The Cuadilatero Ferrifero of San Isidro (San Isidro Iron Quadrilateral) contains the largest reserves known in the complex. The district is underlain by amphibole-pyroxene gneiss, granitic gneiss and amphibolite. The ore was formed as the result of chemical precipitation of volcanic exhalative origin. The average grade of the iron ore is 61% to 68%. At the Cerro Bolivar Deposit the weathered ferruginous laterite is a friable ore formed typically from very fine-grained iron formation. Hematite, magnetite and quartz are the principal minerals. Silicate minerals, mainly sodic amphibole and pyroxene are the most common mineral phases of the iron formation units. The Cerro Bolivar Deposit is hosted in a thick stratigraphic section of iron formation units (220 m) that is repeated by tight folding and by imbricated reverse faulting. Weathering was an important factor in the enrichment of the Cerro Bolivar ore body. This produced an iron oxide cap composed of ferruginous laterite consisting of grains of primary hematite and a hard porous matrix of secondary goethite. The El Pao Deposit occurs intercalated in hypersthene granulite and quartz-feldspathic gneiss. Three types of ore are present: siliceous ore (hematitic gneiss), high-grade hard massive ore, and canga. The first two ore-types consist of lamellar hematite (specularite) in which the crystals are orientated and strongly deformed.

Beds of secondarily enriched manganese are interstratified with migmatitic gneiss, amphibolite and granulite of the Imataca Complex. These rocks form part of a sequence consisting of gondite, quartz-biotite schist, amphibole schist and dolomitic marble, the thickness of which is about 500 m.

The individual manganese beds are generally less than 10 m, with along strike extensions of more than 20 km. There are arguments in favour of the non-volcanogenic sedimentary model as well as the volcanogenic model to explain the genesis of the manganese deposits (Bellizzia *et al.*,1981; Sidder and Mendoza, 1995; Gray *et al.*, 1993).

The Pastora-Barama-Mazaruni and Paramaka Provinces

Geological setting

The Guiana Shield has been proven to host large gold deposits. Taking into account that the production from alluvial deposits overlying the shield in the last century was about 150 t, it is estimated that the remaining gold resources of the shield exceed 700 t of gold. Most of the occurrences show grades of 1.5 g/t Au (Bertoni *et al.*, 1998).

The Pastora-Barama-Mazaruni and Paramaka provinces contain the most important greenstone belt gold producers in the Guiana Shield (Fig. 5). Altogether, the largest mines in these provinces contain about 20 Moz of gold. These greenstone terranes extend for about 1500 km along the Atlantic coast. In Venezuela, the Pastora-Barama-Mazaruni Province comprises the Pastora and Botanamo groups, and in its extension to northern Guyana the Barama-Mazaruni Supergroup (Barama, Cuyuni and Mazaruni groups) represent it. The Paramaka Province occurs in Suriname as the Marowijne Supergroup and the Matapi, Paramaka and Armina groups. In French Guiana it has as its equivalent the Maroni Supergroup and the Paramaka, Bonidoro and Orapu groups. In Brazil (Amapá), the Paramaka Province is represented by the Serra Lombarda Group (Ferran, 1988) and by the Tartarugalzinho gold district in its southeastern extremity. Granitic plutons, domal batholiths, gneiss and migmatite separate the units of the greenstone belts in branching synclinoria. The units of the greenstone belts in the two provinces cited above were deposited mainly in marine environments. In general, the greenstone belts of the Guiana Shield consist of: (a) a marine sequence of mafic volcanic rocks of tholeiitic composition; (b) basalt (tholeiitic to calc-alkaline in composition), andesite, dacite and rhyolite and; (c) a sequence consisting of turbiditic greywacke, volcaniclastic rocks, chemical sediments and pelite. There also occur beds of metaconglomerate, derived mainly from volcanic rocks with associated sediments. Metamorphosed manganiferous and ferruginous sediments, chert and carbonate units are also present. In the several belts there also occur sub-volcanic intrusive rocks of felsic composition. The metasediments include many varieties of tuff, volcaniclastic conglomerate, greywacke and shale units derived from the associated volcanic rocks. In Guyana, the stratigraphic thickness of the greenstone belt is estimated at between 8 to 10 km. The provenance of these metasediments is not known.

Basalt with pillow structures and showing evidence for chemical alteration and mineralogy consistent with submarine spilitization dominates the lower part of the greenstone belt sequence. In the middle part of the sequence there occurs a larger amount of porphyritic andesite, dacite, rhyolite, submarine and possibly sub-aerial lava flows, siliceous sediments and tuffaceous interflow beds. Ultramafic rocks constitute 1% to 2% of the igneous rocks of the greenstone belts of the Guiana Shield, generally forming layered mafic-ultramafic complexes (Sidder and Mendoza, 1995).

Mineralization

The rock chemistry of these sequences has not been studied systematically. The original chemical composition of the igneous rocks has been changed by weathering and hydrothermal alteration (spilitization and potassic metasomatism) as well as by regional metamorphism in the greenschist and amphibolite facies. Trends of tholeiitic and calc-alkaline differentiation are common in the volcanic rocks. The main rock-types are tholeiitic basalt, sub-alkaline and with low K content, in addition to basaltic andesite. The volcanic rocks were mainly extruded in submarine conditions, and have chemical characteristics similar to those published for modern oceanic basalt, island arc rocks and rocks associated with continental arcs. Isotope studies have revealed that the volcanic rocks were derived by mantle melting and do not contain any contribution from Archean continental crust (Sidder and Mendoza, 1995).

The gold mineralization of the Guiana Shield can be related to several epizonal environments including calc-alkaline intrusives (Omai, St. Elie, Yaou, Dorlin, Sophie, Eagle Mountain), deformed terrigenous sediments (Gross Rosebel, Camp Caiman, Regina, Changement, Esperance), metasomatic volcanites and/or intrusive rocks (Las Cristinas, Dorlin) and semi-massive sulphide mineralization (Paul Isnard, Increible, St. Elie). Most of the gold occurrences are hosted in rocks affected by ductil-ruptile deformation in the vicinity of large shear structures (Bertoni *et al.*, 1998) in which developed shear-zone hosted with low sulphide gold-quartz veining.

Native gold, pyrite and smaller amounts of tetrahedrite, chalcopyrite, bornite, molybdenite, scheelite and sphalerite are the most typical metallic minerals present in quartz veins. Carbonate (usually ankerite) in quartz veins and evidence for carbonatization >30 m into the wall rocks is common in some gold districts such as El Callao in Venezuela. In addition to the carbonate alteration, the wall rock shows intense silicification, sericitization and propylitization (replacement of wall rock minerals by epidote and chlorite) many dozens of metres from the veins (Sidder and Mendoza, 1995).

In the Serra Lombarda Group predominates mineralization of the hydrothermal vein-type hosted in gneiss with amphibolite relicts, biotite schist, BIF, and metachert, regarded as the remnants of greenstone belt sequences. In the Tartarugalzinho District, the main gold mineralization is associated with quartzite beds, banded iron formation units and schist (Carvalho *et al.*, 1995; Ferran, 1988).

Large ductile shear zones have not been described in the literature of the Guiana Shield to any extent. One of the largest shear features in the Guiana Shield is related to the so-called Sillon Nord-Guyanais (Milesi *et al.*, 1995) situated in the N of French Guiana, and associated with the Transamazonian Tectonic Event. Several important gold deposits are related to this shear zone, extending from W to

E: Regina, Tortue, Camp Caiman, Changement, Boulanger, St. Elie, St. Pierre, Paul Isnard and Guyanais in the central region of French Guiana, and representing a shear zone striking ESE-WNW (Bardoux *et al.*, 1998). This structure appears to extend to the central region of Guiana, crossing Suriname. Amongst the gold deposits occurring in the vicinity of this megascopic features the following may be cited: Yaou, Dorlin, Sophie, Repentir, Antino, Benzdorp, Omai, Salamangone and Labourrie Siboa (Yoshidome). When analyzed as a whole, it can be noted that the majority of the gold occurrences, until now discovered in the provinces in question, are found in the vicinity of large structures such as that cited above. All the magmatic and sedimentary rocks of the greenstone belts that host gold mineralization in the provinces of Pastora-Barama-Mazaruni and Paramaka underwent at least one phase of ductile deformation. Shear zones and foliation of the first phase of deformation were affected by the structures of a second phase, generally less penetrative. The second phase may be genetically related to the K'Mudku or Nickerie Event (*c.* 1.2 Ga). Thus, only the structures related to the first phase are regarded as being true Transamazonian structures, and the majority of gold occurrences described up to now seem to relate this to a phase of remobilization along the structures of the second phase (Bardoux *et al.*, 1998).

Most of the intrusive rocks together with the Paramaka and Mazaruni volcanics as well as the sedimentary rocks of Armina were deformed concomitantly by a phase of intense ductile deformation. This event has been dated at about 1.99 Ga at Omai and St. Elie, setting the approximate absolute age of the Transamazonian Tectonic Event throughout the Guiana Shield (Lafrance *et al.*, 1999). U/Pb ages obtained on rocks from intrusive bodies from different parts of the Pastora-Barama-Mazaruni and Paramaka provinces suggest that there occurred at least three distinct intrusive events at 2.154 Ga (Las Cristinas), 2.125 Ga (St. Elie) and 2.09 Ga (Omai) (Fig. 5). When examined individually, it can be noted that the majority of these intrusive bodies underwent at least one phase of intense deformation that in many cases is synchronous with the mineralization. Data from Omai and St. Elie show that the mineralization occurred more or less contemporaneously in these deposits at about 1.99 Ga. It also showed that the gold was trapped several dozens of millions of years after the intrusive event (Lafrance *et al.*, 1999).

In summary, the characteristics of the gold occurrences in the Pastora-Barama-Mazaruni and Paramaka provinces are as follows: (a) the host rocks are variable, but volcanic rocks predominate; (b) structural control is the norm, although the types and styles vary; (c) the proximity to intrusions seems to be important, but not always so; (d) most of the deposits may be related to a stronger phase of deformation; (e) the majority of the gold occurrences observed are hosted within or very close to quartz veining, which is syn-tectonic to late-tectonic; (f) most of the occurrences are also hosted in discrete zones or regional shear zones; (g) the gold is generally associated with the sulphide minerals (pyrite, chalcopyrite and pyrrhotite), especially pyrite (Bardoux *et al.*, 1998).

The largest gold deposits in the Pastora-Barama-Mazaruni Province are those at Omai (4.2 Moz) in Guyana, and a set of deposits including Las Cristinas (8.6 Moz), El Callao, Lo Increible and Botanamo in Venezuela. Besides gold, the Las Cristinas deposits contain exploitable reserves of copper (Minérios & Minerales, ed. 225, 1998). In the Paramaka Province the most important deposit is that at Gross Rosebel (2.4 Moz) in Surinama; Paul Isnard (2.2 Moz), Camp Caiman (1.1 Moz), Yaou (0.8 Moz), Dorlin (0.35 Moz) and St. Elie in French Guiana; and Salamongone/Laborrie Siboa (0.35 Moz) in Brazil. The Omai Deposit in Guyana is the largest gold deposit known to date on the Guiana Shield, and one of the largest in South America.

The Vila Nova Province

The Vila Nova province is situated on the southeastern margin of the Guiana Shield to the W of Macapá, Brazil and extends to the international frontier with French Guiana. This province is underlain by volcano-sedimentary sequences of the greenstone belt type (Vila Nova Metamorphic Suite or Vila Nova Group) enclosed in medium to high-grade metamorphic complexes (Ananai and Guianense metamorphic suites). On the other hand, the metamorphites of medium to high-grade may have been derived from the same units that appear as lower grade rocks of the adjacent greenstone belts (João *et al.*, 1978; João and Marinho, 1982; Lima *et al.*, 1974; Gibbs and Barron, 1993). Radiometric data show intense reworking during the Transamazonian Tectonic Event (Tassinari and Macambira, 1999), involving older Archean rocks of high metamorphic grade. The Vila Nova Group occurs as discontinuous elongated and narrow belts that strike NW-SW, forming metamorphic belts of low to medium grade and consisting of broad folds with vergence to the NE. This group is considered to be an integral part of the various volcano-sedimentary sequences of the Guiana Shield dated between 2.25-2.10 Ga. The stratigraphy of the Vila Nova Group is best defined in the area of Serra do Navio. At the base there is a thick sequence of ortho-amphibolite (Jornal Formation) in contact with the Ananaí Suite (Scarpelli, 1966). The ortho-amphibolite is overlain by a parametamorphic sequence consisting of aluminous schist containing lenses of manganiferous proto-ore and beds of quartzite (Serra do Navio Formation). The schist sequence occurs in the quartzose, biotitic and graphitic facies. In the quartzose facies there occur lenses of calc-silicate marble, and in the graphitic facies zones of manganiferous marble with rhodochrosite can be observed. The absence of felsic volcanic rocks in the Vila Nova Province is a characteristic that differentiates this province from the Paramaka and Pastora-Barama-Mazaruni provinces.

In the Serra do Ipitinga, the southern part of the Vila Nova Province, the Vila Nova Group consists essentially of mafic-ultramafic basal metavolcanic rocks, and smaller amounts of metaplutonic rocks, rocks containing cordierite-anthophyllite and quartz-chlorite. Chemical sediments consisting of BIF (oxide and silicate facies), in addition to continental clastic metasediments (quartzite, *metapelite and metagreywacke) overlie these rocks.* The basal metavolcanic unit represents oceanic tholeiite with a subordinate komatiitic chemical lineage. In the Serra do Ipitinga occur three types of deposits: (a) sulphide mineralization of the syn-depositional hydrothermal volcanogenic type hosted, preferentially, in the quartz-chlorite rocks, and more rarely, in low grade metamorphites (pyrrhotite-pyrite-chalcopyrite and subordinately sphalerite with Au and Ag associated); (b) lode-type deposits in sheared quartz veins containing chalcopyrite, pyrite and covellite; (c) rocks altered by supergene processes such as gossan and laterite (Faraco, 1990, 1997; Faraco and McReath, 1998).

In the region of the rivers Santa Maria and Cupixi there predominate quartzite beds and sericite schist, intercalated with BIF units, and subordinately, metaconglomerate. This unit overlies the Bacuri mafic-ultramafic complex, in which there occurs chromite mineralization (Faraco and Carvalho, 1994).

Furthermore, in the Vila Nova Province occur intrusive rocks of the Mapuera Suite (biotite-alkaligranite and riebeckite-granite) and the Falsino Suite (granodiorite), as well as several bodies of the Mapari alkaline intrusive having Paleoproterozoic to Mesoproterozoic ages (Rb/Sr). On the southwestern margin of the Vila Nova Province the Mapari Intrusive Suite consists of two alkaline-carbonatite complexes (Maecuru and Serra do Maracanaí), with titanium and phosphate mineralization.

From the metallogenic point of view, the Vila Nova Province shows a widespread distribution of gold occurrences. Including the Amapari gold deposit, there are about 100 gold known occurrences. Also of note is the Serra do Navio manganese deposit, and the chromite at Bacuri, also known as Igarapé do Breu. Gold mining has been carried out at *garimpos*, generally in colluvial and placer deposits. In general, the primary gold mineralization is of the hydrothermal vein-type, associated with schist, quartzite and amphibolite. Gold is also found in metaconglomerate. The Mapuera Granite contains disseminated cassiterite; and gold, columbite and tantalite in quartz veins (Carvalho *et al.*, 1995; Faraco and Carvalho, 1994).

The Bacuri (Igarapé do Breu) Chromite Deposit

The chromite deposits are associated with the Bacuri mafic-ultramafic complex (Matos *et al.*, 1992) situated to the W of Macapá, which is intrusive into granite-gneiss medium to high-grade metamorphic terranes, associated with the Vila Nova Group. According to Spier and Ferreira Filho (1999), the Bacuri mafic-ultramafic complex that includes amphibolite, serpentinite, tremolite, and chromitite was deformed and metamorphosed in the amphibolite facies. These rocks include amphibolite, serpentinite, tremolite, and chromitite. They have a stratiform differentiated character defined in function of the magmatic layering of the cumulate and the chemical characteristics of the textures observed. The principal layer of massive chromitite, having an average thickness of 12 m, is situated in the interface between the mafic and ultramafic rocks. Thinner layers of massive and disseminated chromite (up to 3 m), are observed intercalated in the ultramafic rocks. The chromite crystals are euhedral, and their size is uniform (average 0.2 mm). The intense lateritic weathering exceeds depths of 120 m in the topographically elevated localities, permitting the classification of the ore into three categories: lateritic ore, very hard and cemented by iron oxide and hydroxide; friable ore cemented by clay minerals; compact ore cemented by tremolite, chlorite and rarely by orthopyroxene and olivine.

This complex hosts 11 deposits of stratiform chromite with before-mining reserves exceeding 9 Mt of chromitite, of which 2 Mt were mined between 1989 and 1997.

The Serra do Navio Manganese Deposit

The manganese deposits of Serra do Navio have a strike length of 10 km that trends N30°W. They are associated with the volcano-sedimentary sequence of the Vila Nova Group. This sequence has been highly folded, sheared and metamorphosed in the amphibolite facies. At the base occurs a thick sequence of mafic metavolcanic rocks (amphibolite), overlain by a predominantly schistose unit (biotite schist, graphite schist, quartz schist) intercalated with manganiferous layers and quartzite beds in the upper part (Rodrigues *et al.*, 1986).

The manganiferous zones that constitute the proto-ore of the queluzite-type, are intercalated with graphitic schist, consisting preferentially of rhodochrosite amounting to between 50% to 90% of the rock. In the more impure zones the manganese silicate minerals such as tefroite, spessartite and rodonite may predominate to form true gondite. The Mn grade of the proto-ore varies between 19% and 36%. Some sulphide minerals such as pyrrhotite, molybdenite, chalcopyrite and galena are found associated in small amounts in the proto-ore. On account of the equatorial climate, the laterite weathering profile may reach a depth of 100 m, causing the transformation of the carbonate and silicate minerals in the manganese-rich rock to oxide such as cryptomelane, pyrolusite and manganite, resulting an oxide ore richer in manganese up to 56% Mn.

The open-pit working began in 1959 in the oxide ore and continued for decades until 1997 at an output of 52 000 tpa, or a total production over the period amounting to 50 to 60 Mt MnO_2. During the final years of operation, the carbonate-rich proto-ore was mined at about 150 000 tpa, equivalent to a total production of about 3 Mt of manganese ore at an average grade of 35% to 38% Mn.

The Amapari Gold Deposit

The Amapari gold deposit was found recently (AngloGold) some 12 km to the E of Serra do Navio (Borges, 1999). The deposit is hosted in the volcano-sedimentary sequence of the Vila Nova Group, and it is regionally related to a transcurrent shear zone that underwent intense hydrothermal alteration. From the base to the top, there occur the following units: granite-gneiss basement; a volcanic unit (metabasic rocks and amphibolite); a chemical sedimentary unit composed of carbonate rocks, calc-silicate and oxide, silicate and oxide-silicate facies; banded iron formation units, silicate and oxide-silicate; a clastic-chemical sedimentary unit consisting of quartz-amphibole schist and amphibole schist; a unit consisting of pelitic clastic sediments including muscovite-quartzite and micaschist.

Throughout the area occur pegmatite intrusions in the form of elongate bodies, the thickness of which varies from some metres to more than 100 m. The pegmatite is syn-

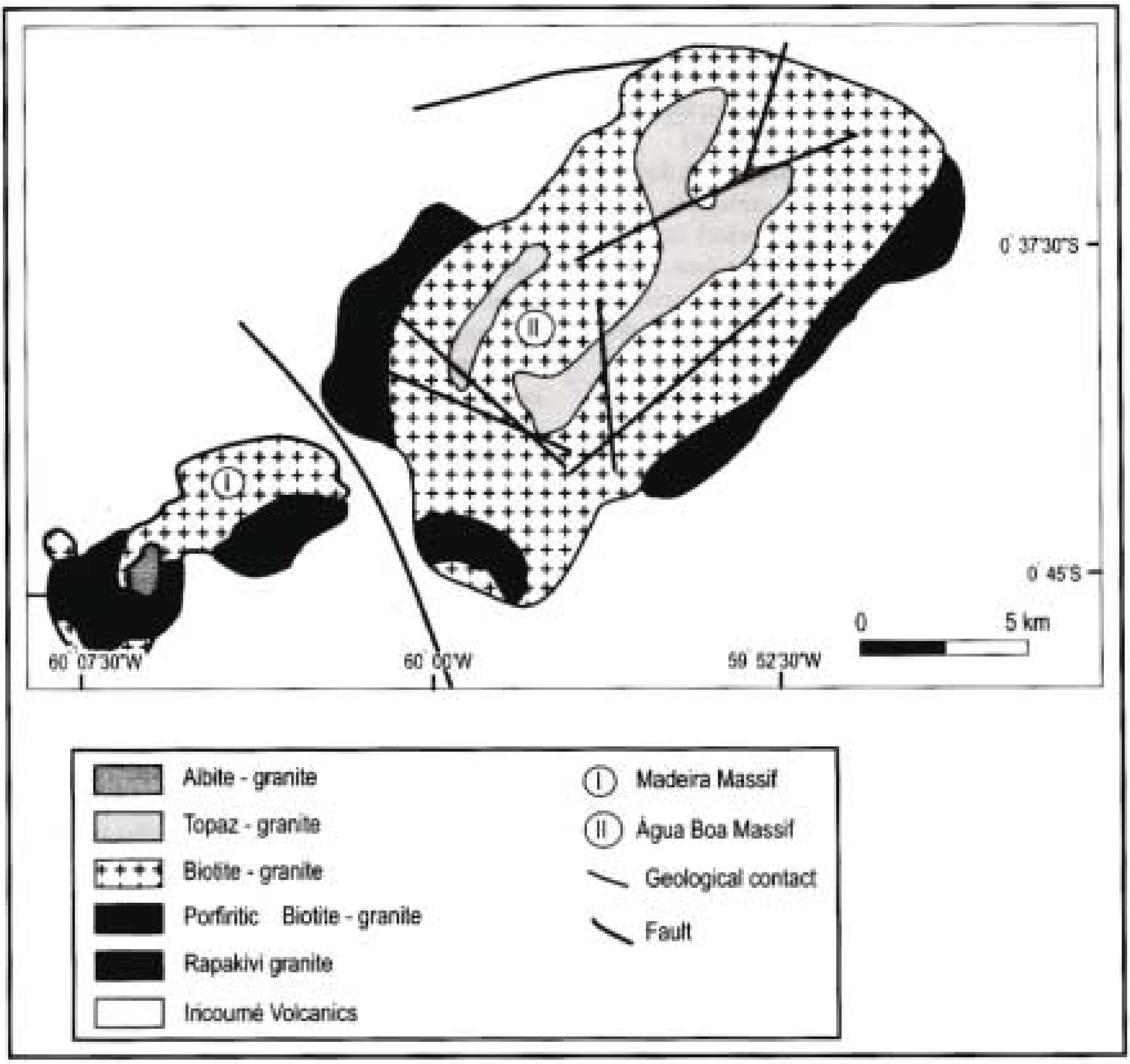


FIGURE 6 - Geological map of Pitinga Mine (modfied after Lenharo, 1998). For situation see Figure 5

tectonic and generally associated with shear zones with strike similar to the wall or country rocks.

The Amapari gold deposit has been classified as a contact metasomatic deposit or a skarn-type deposit (Meinert, 1988 *apud* Borges, 1999) in which the hydrothermalism was controlled structurally by a sinistral, high-angled transcurrent shear zone striking NNW-SSE. Amapari represents a gold deposit that resulted from a combination of factors: lithology (reactive rocks) and favourable structures (shear zones), the latter being the more important. The interaction between the rock-types and structure favoured the gold concentration, both by contact metasomatism as well as by hydrothermal solutions that percolated along the shear zone resulting in intense hydrothermal alteration (principally silicification, sulphidization and carbonatization) in reactive rocks such as BIF units, amphibolite, carbonate beds and calc-silicate. The highest gold grades occur preferentially in the BIF units (oxide, oxide-silicate and silicate facies), with intense hydrothermal alteration manifest as silicification and sulphidization (pyrrhotite and pyrite). The gold-bearing rocks have a brecciated aspect and intense transposition caused by shearing. There also occur carbonate rocks (calcareous marble), amphibolite and calc-silicate. These rocks are quite reactive in the presence of mineralizing hydrothermal and metasomatic fluids that percolated along the shear zone, concentrating the gold in favourable structures in the host rocks. The gold seems to be related to the structure of the sulphide minerals (pyrrhotite and pyrite). Chalcopyrite, sphalerite, arsenopyrite, galena and marcasite also occur in small amounts. However, with the exception of chalcopyrite, these minerals do not seem to be directly related to the gold mineralization.

The mineralization occurs in the zone of weathering as well as in the sulphide-bearing bedrock, where it follows the shear planes at depth. The primary mineralization occurs along a N-S strike-length some 7 km long, associated with zones of hydrothermal alteration in skarn. The weathering profile attains depths exceeding 100 m.

The evidence for considering a part of this deposit as a skarn-type gold deposit is based on the mineralogy, geological setting and the sulphide mineralogy, which may be compared to that of gold-skarns worldwide. The typical skarn minerals are garnet, pyroxene (diopside-hedenbergite), vesuvianite, apatite, titanite, actinolite, epidote and hornblende. There also occurs pyroxene rich in manganese. The sulphide species are pyrite and pyrrhotite. The origin of the mineralizing fluids may be explained in terms of the hypothesis that the deposit came about as the result of metasomatic fluids laden with gold and other elements that were channeled along fractures opened by the pegmatite intrusions. Seeing that the pegmatite is syn-tectonic, it is probable that the mineralizing fluids were also channeled along the shear zone (Borges, 1999).

However, the hypothesis that stands up best in the light of field observations and that best explains the gold concentration of the deposit is that which involves hydrothermal solutions associated with the shear zone.

The mineable reserves of colluvial and oxidized material, for a cut-off grade of 2.13 g/t Au, are about 30 000 kg/Au (*c.* 1.0 Moz Au). There is a considerable potential for primary gold mineralization as sulphide ore that is still being evaluated. Regional geochemical anomalies show anomalies for copper, lead and zinc (Borges, 1999).

The Pitinga Tin District

In the southern part of the Guiana Shield there is important tin, rare metals (Zr, Ta, Y and REE) and cryolite (Na_3AlF_6) mineralization, associated with the granitic massifs of Água Boa and Madeira at Pitinga (Figs. 5 and 6). These granitic rocks are considered to be anorogenic, intraplate and to have originated at high crustal levels. The age of the intrusion into the Iricoumé volcanic rocks is given as 1.8 Ga (Lenharo, 1998). Two types of tin mineralization have been defined:

a) Tin mineralization associated with greisen of the Água Boa Massif. According to Daoud (1988) and Lenharo (1998), the Água Boa Massif is a multiple intrusion consisting of three distinct phases: Rapakivi Granite, Biotite Granite and Topaz Granite. The tin mineralization is associated with post-magmatic processes of hydrothermal alteration in the form of vertical veining of mica-topaz-quartz greisen containing cassiterite, opaque minerals and tourmaline in fractures striking N50°W. The associated minerals are allanite, opaque minerals, zircon, fluorite, siderite, beryl, and sulphide minerals such as sphalerite, pyrite and chalcopyrite. Intense albitization of the granitic wallrock preceded the greisenization.

b) Tin mineralization associated with albite granite of the Madeira Massif. According to Daoud (1988) and Lenharo (1998), the Madeira Massif shows three distinct facies: Rapakivi Granite, Biotite Granite and Albite Granite. The tin mineralization associated with albite-granite is the disseminated type, being composed of cassiterite, zircon, columbite-tantalite, pyrochlore, xenotime and cryolite. The fresh rock contains: 0.176% Sn; 0.223% Nb_2O_5; 0.028% Ta_2O_5; 0.030% U_3O_8; 0.80% ZrO_2. This disseminated mineralization is enriched in the weathered mantle that is about 30 m thick and which is depleted with respect to cryolite. At a depth of about 150 m, the cryolite forms two massive bodies at the nucleus of the albite granite. In 1997, the production was *c.* 11 693 t Sn from 21 700 t of cassiterite concentrate with 53.88% contained Sn. The perspectives for the next fifteen years are to mine 13 M tpa of ore corresponding to the equivalent of 13 000 t/Sn, in adition to 800 t of columbite concentrate with 35% Nb_2O_5 and 3,5% TaO_2.

Diamond in the Guiana Shield

Three distinct diamond-generating epochs may be defined on the Guiana Shield: Dachine, Roraima and Quebrada Grande.

Dachine: This is a new type of occurrence that has recently been described in the Dachine area of French Guiana. The host rock is a volcaniclastic komatiite, an unusual volcanic rock found in the Paleoproterozoic Inini greenstone belt of the Paramaka Province. In the Inini greenstone belt there predominates calc-alkaline andesite and rhyolite and immature sediments. These rocks are intruded by granitoid plutons including tonalite and trondhjemite, suggesting an island arc setting. The ultramafic rocks that host the Dachine diamonds form part of a volcanic sequence in which most of the rocks have been transformed into albite-carbonate-chlorite-talc schist. Primary volcanic texture have been well-preserved locally. The diamond population consists mainly of micro-diamonds. The largest stone recovered was c. 4.6 mm in diameter. The discovery of diamond in ultramafic schist, such as the Dachine Schist, provides an explaination for diamond occurrences from unknown sources in other parts of the Guiana Shield, in addition to elsewhere on the South American Platform (Capdevila *et al.*, 1999).

Roraima: With the notable exception of the Quebrada Grande area, most of the known diamond placers in the Guiana Shield are in areas underlain by the Roraima Group, or are in areas downstream from exposures of this group. Diamond placers associated with the rocks of the Roraima Group form the second group of occurrences on the Guiana Shield. Although no diamond occurrence within the Roraima Group has ever been found, there is a pronounced spatial association between the alluvial diamond deposits and the outcrops of the Roraima Group. The most important occurrence is San Salvador de Paúl. The total historical production exceeds 2 M carats. The monthly production is estimated at 2000 carats. The high percentage of gem-quality diamonds and the absence of other minerals typical of a kimberlitic association that are more resistant to transport suggests a distal source or more than one sedimentary cycle or both (Gray and Orris, 1993). Another important locality for diamond placer deposits is Icabarú. Icabarú occurs at the southern margin of the Roraima Group, near to the frontier of Venezuela and Brazil (Brooks *et al.*, 1995). Likewise, in this area the diamonds are mined from conglomerate derived from the Roraima Group. The main alluvial diamond mining areas occur around or in the interior of the Pakaraima Mountains in Venezuela, Guyana and Brazil. These alluvial diamonds are generally regarded has having been derived from Pre-Roraima kimberlite and preserved in the conglomerate of the Roraima Group. In Venezuela, most of the areas that have been worked are situated in the drainage of the Caroni, Paragua and Icabarú in the eastern part of the State of Bolivar.

Quebrada Grande: The only diamondiferous kimberlite in South America occurs at Quebrada Grande, a tributary of the Guaniamo River, in the State of Bolivar, Venezuela. Placer diamond deposits were discovered in the Guaniamo region in 1968, and since then some 20 to 25 M carats have been recovered, including stones exceeding

40 and 60 carats. In 1982, highly diamondiferous kimberlitic dykes and sills were discovered. These intrusives have been dated at 710 Ma (Kaminsky *et al.*, 1998; Channer *et al.*, 1998). The emplacement of this kimberlite represents the youngest Precambrian event thus far observed on the Guiana Shield. The kimberlite cuts biotite-lamprophyre dykes dated at *c.* 850 Ma (Nixon *et al.*, 1992). The diamond production from this kimberlite by formal mining methods is expected to be 450 000 carats per year. It should be noted that the current production from the entire Guiana Shield is estimated at *c.*250 000 carats per year (L. A. Bizzi, personal communication)

The Carbonatites of Cerro Impacto and Seis Lagos

The Cerro Impacto is a structural feature in the State of Bolivar, Venezuela, that was first observed in radar images. Preliminary studies showed anomalous values for niobium, thorium, barium and other metals besides REE. Although fresh rock has still not been found, the mineralogy of the products of chemical weathering and leaching suggests that the original composition of the proto-ore was a carbonatite (gorceixite, goyasite, florencite, bastnaesite, monazite etc.). The carbonatite is associated with a ring structure, oval on shape, and approximately 10 km in diameter. The weathered cap that is at least 200 m thick does not contain any fragments of the original carbonatite rock. The laterite is enriched in Fe, Mn, Al, Ba, Th, Nb, REE (Ce, La, Nd), Ti, Zn, Pb and other elements.

This body has been emplaced near the intersection of large NE-SW and NW-SE fractures. These fractures may be related to those into which was intruded the Quebrada Grande Kimberlite. The age of the carbonatite is not known. A Proterozoic age is suggested by a possible relationship with the Quebrada Grande Kimberlite at 710 Ma (Bellizzia *et al.*, 1981; Sidder, 1995, Sidder and Mendoza, 1995; Channer *et al.*, 1998).

The Seis Lagos Carbonatite is situated in the headwaters of the Negro River, Brazil, near the frontier with Venezuela, and it consists of three alkaline-carbonatite pipes, mineralized with respect to niobium. In likemanner to the Cerro Impacto the age of this intrusion is not known. The very intense laterite weathering resulted in the development of a weathered cap exceeding 200 m thick in which the pyrochlore was destroyed, and the primary niobium minerals have been neomorphosed to rutile and niobiferous brookite. The reserves at Seis Lagos have been estimated at 2.898 billion t of ore at 2.81% Nb_2O_5 (Justo and Souza, 1986).

The Central Brazil Shield

With the exception of the Maroni-Itacaiunas Belt that is for all practical purposes restricted to the Guiana Shield, the Central Brazil Shield clearly shows a geotectonic zoning developed from E to W around an Archean nucleus by the accretion of successive magmatic arcs between 1.95 and 1.5 Ga, resulting in the formation of a vast continental juvenile crust. From 1.5 Ga to 1.0 Ga, the evolution of this southwestern part of the shield occurred in an ensialic environment.

The nature and distribution of the mineral deposits found on the Central Brazil Shield reflect this geotectonic evolution permitting the definition of several mineral provinces as follows:

- The Carajás Province with gold deposits in Rio Maria granite-greenstone terrane and with deposits of Fe, Mn, Au, Cu, Zn, Cr and Ni associated with the volcano-sedimentary sequences of the Grão Pará, Igarapé Bahia, Pojuca, Salobo groups, and the sediments of the Águas Claras Group;
- The Tapajós and Alta Floresta provinces with gold deposits mainly associated with intrusive granite of the Maloquinha, Serrinha do Matupá and Teles Pires types as well as others, in addition to the Cu-Pb-Zn mineralization related to the sedimentary (volcanic) cover of the Beneficente Group;
- The Alto Jauru Cu-Au District with deposits associated with volcano-sedimentary sequences;
- The Alto Guaporé Province with gold deposits formed during the Sunsas Event and Ni deposits associated with post-orogenic mafic-ultramafic complexes such as that of Rincón del Tigre in Bolivia;
- The Rondônia Province with tin deposits associated with youngest anorogenic granites.

The Carajás Mineral Province

The Carajás Mineral Province (Fig. 7a, b) (Santos, 1983) consists of two sets of Archean rocks of distinct age: the older Rio Maria region, and the younger Serra dos Carajás region.

The Rio Maria region is situated in the SE of the State of Pará and occupies the oldest part of the Archean Amazonian nucleus. These rocks have been assigned to the Rio Maria Granite Greenstone Complex, the evolution of which occurred in an interval between 3.0 and 2.8 Ga (Souza *et al.*, 1996, 2000). The volcano-sedimentary sequences (2.98 to 2.90 Ga) occur in series of irregular belts (Andorinhas, Gradaús, Inajá, Rio Novo and Sapucaia) known as the Andorinhas Supergroup, and are intruded by granodiorite of the Rio Maria type at 2.87 Ga (Pimentel and Machado, 1984; Macambira and Lancelot, 1992). At 2.87 Ga the region underwent an important tectono-metamorphic event, correlative with the Xingu Granite-Gneiss Complex.

The consolidation of sialic crust is taken to have occurred following the development and deformation of the Rio Maria greenstone belt sequence and its associated plutonism. On this sialic crust developed the volcano-sedimentary sequence of the Grão Pará Group, dated at 2.76 Ga (Machado *et al.*, 1991; Gibbs *et al.*, 1986, Wirth *et al.*, 1986). This sequence is correlative with the Igarapé Bahia, Pojuca and Salobo groups, which are overlain by the sediments of the Águas Claras Group, also of Archean age (>2.645 Ga). Several generations of mafic and ultramafic intrusions dated at 2.67 Ga (Machado *et al.*, 1991) and 2.645 Ga (Dias *et al.*, 1996) as well as granitic bodies assigned to the Sossego/Cristalino (2.74Ga), and Plaquê/Old Salobo (2.57 Ga) suites occur in the province (Dall'Agnol *et al.*, 1987). The deformation and the regional metamorphism associated with regional shear zones occurred between 2.58 and 2.5 Ga (Machado *et al.*, 1991; Pinheiro and Holdsworth, 1997), constraining the final stabilization of the area. At the

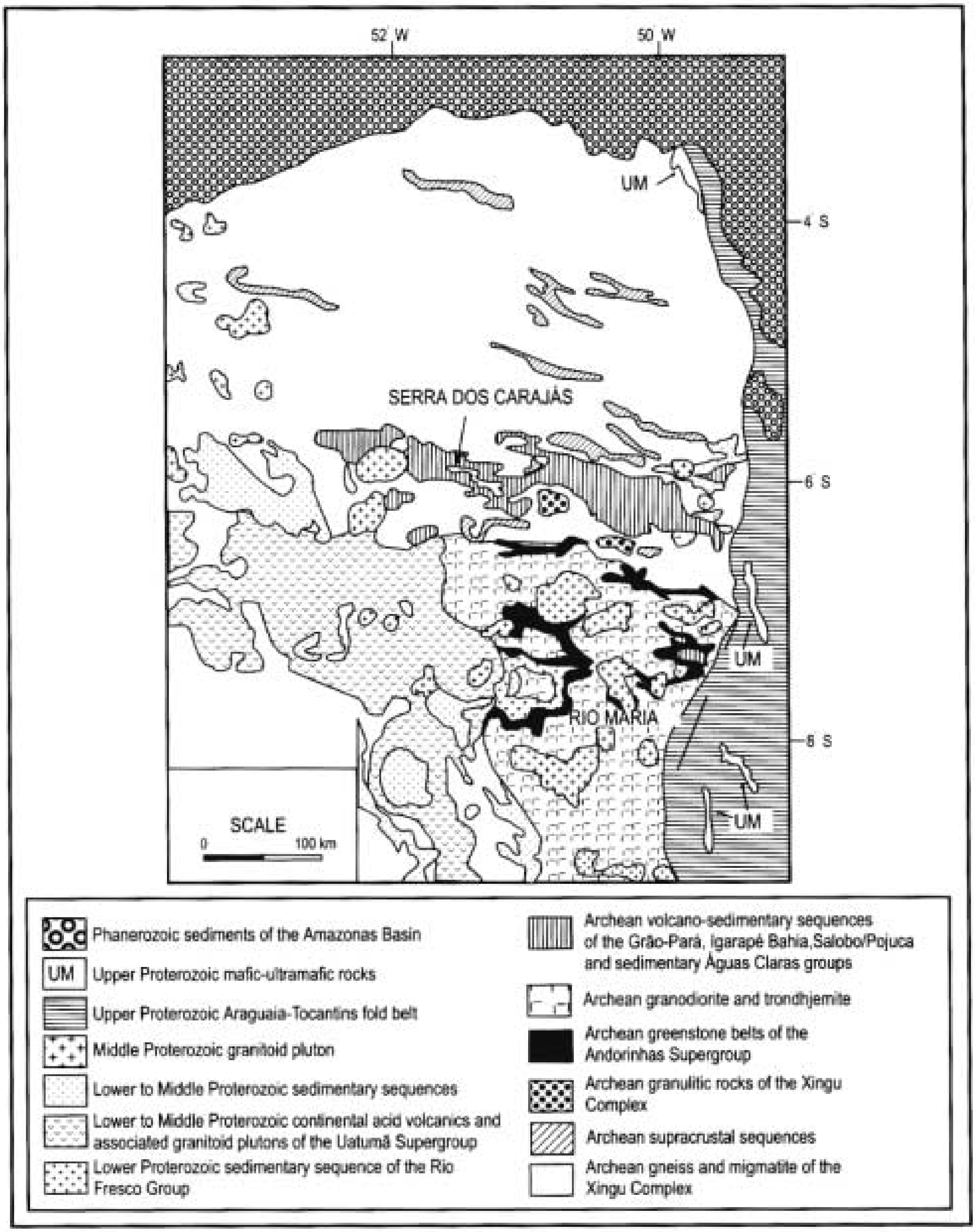
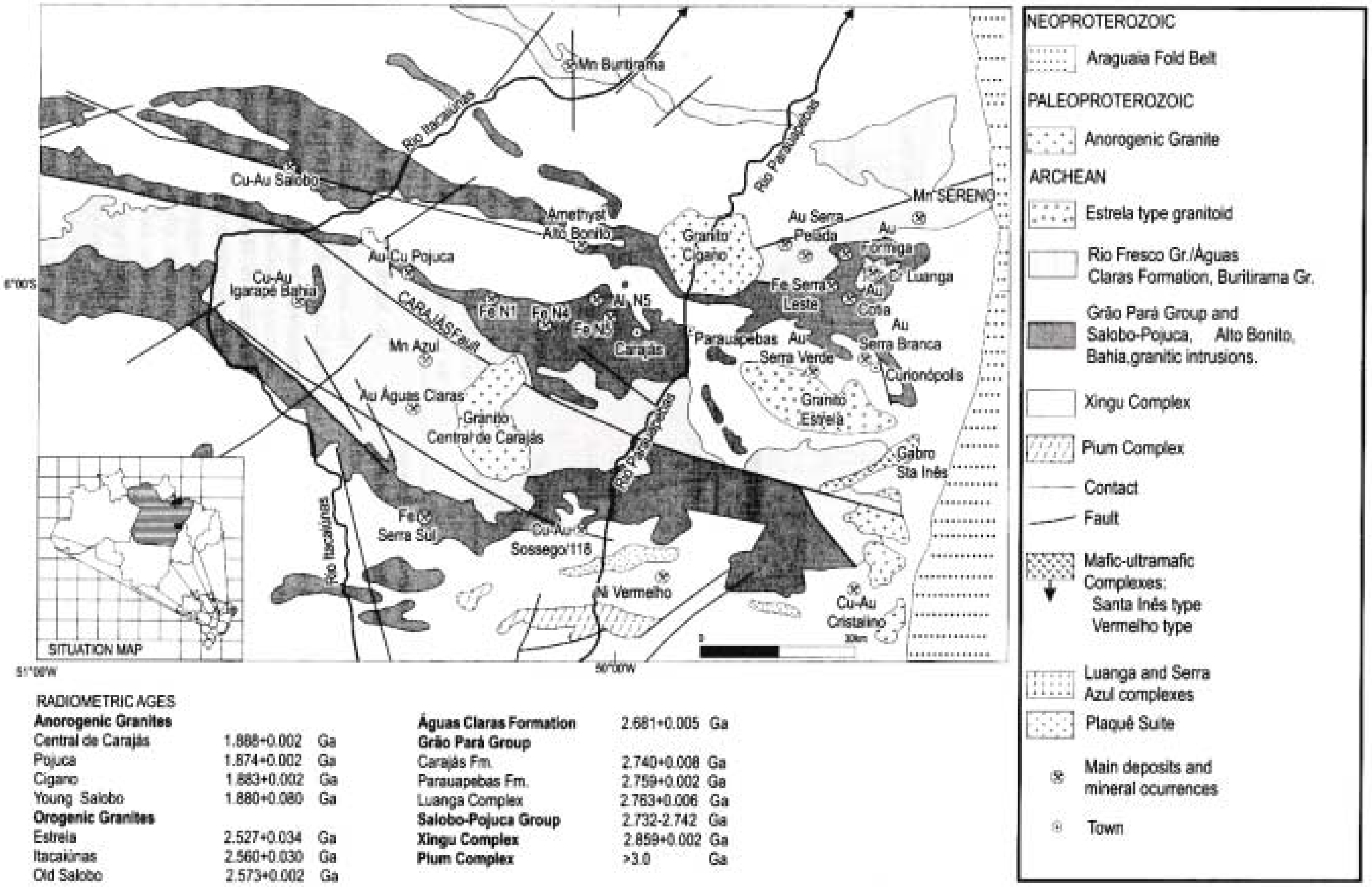


FIGURE 7a - Geological map of the eastern sector of the Amazonian Craton (modfied after DOCEGEO, 1988; Araújo and Nilson, 1988).



RADIOMETRIC AGES

Anorogenic Granites		
Central de Carajás	1.888+0.002	Ga
Pojuca	1.874+0.002	Ga
Cigano	1.883+0.002	Ga
Young Salobo	1.880+0.080	Ga
Orogenic Granites		
Estrela	2.527+0.034	Ga
Itacaiúnas	2.560+0.030	Ga
Old Salobo	2.573+0.002	Ga

Águas Claras Formation	2.681+0.005	Ga
Grão Pará Group		
Carajás Fm.	2.740+0.008	Ga
Parauapebas Fm.	2.759+0.002	Ga
Luanga Complex	2.763+0.006	Ga
Salobo-Pojuca Group	2.732-2.742	Ga
Xingu Complex	2.859+0.002	Ga
Pium Complex	>3.0	Ga

FIGURE 7b - Geological sketch map of the Carajás Region (modfied after DOCEGEO, 1988).

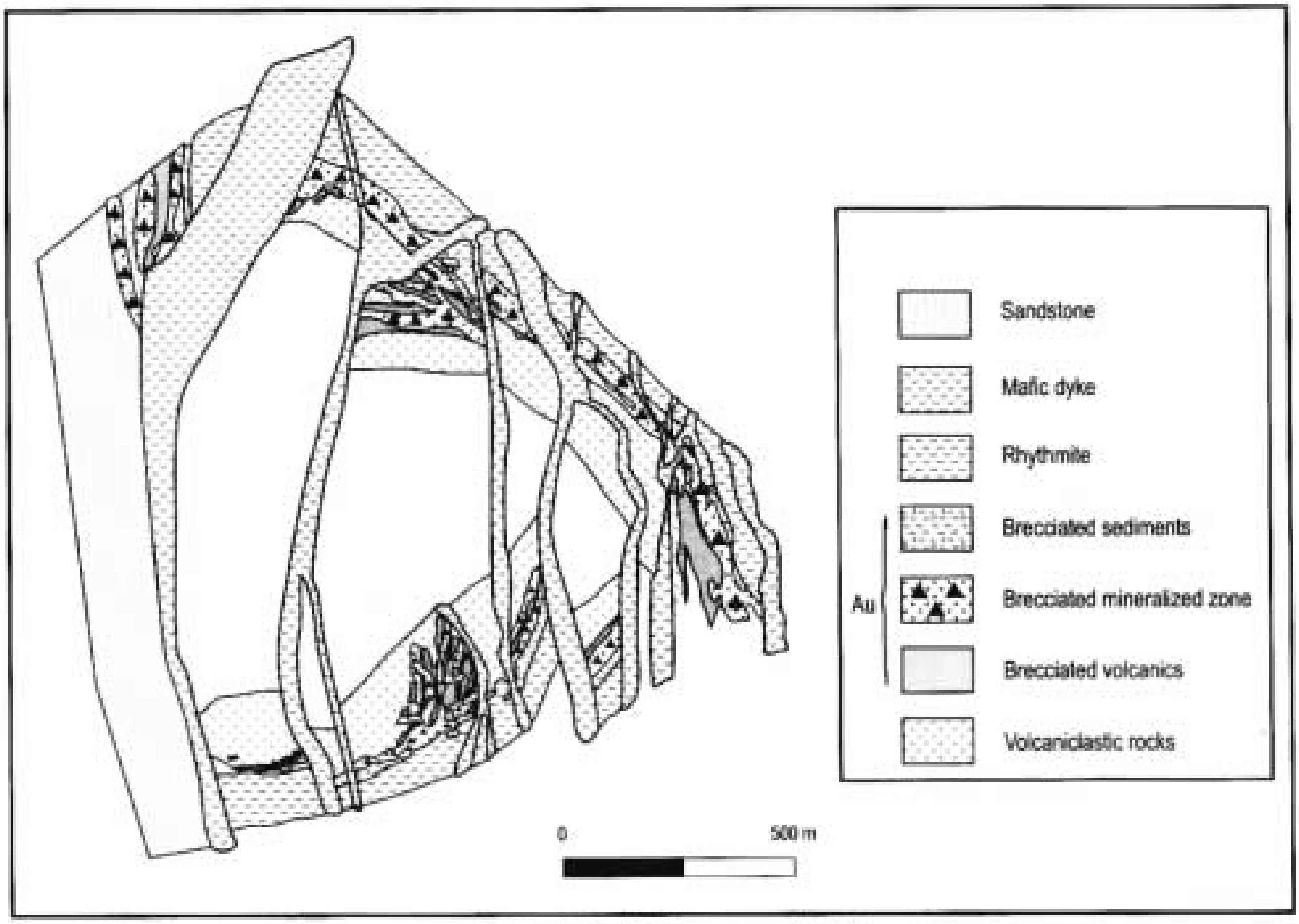


FIGURE 8a - Geological sketch map of Cu-Au Igarapé Bahia Deposit (modfied after Soares et al., 1999).

beginning of the middle Proterozoic (1.88 Ga), occurred in the region several anorogenic intrusions such as the Central Carajás Granite/Young Salobo Suite.

These units are associated with Cr, Fe, Cu-Au, Mn, Au and W mineralization that define the Carajás polymetallic province.

Lode-type Gold Deposits

Several small deposits and numerous gold showings are found in pyrite-rich quartz veins that developed as the result of intense hydrothermal alteration associated with regional shear zones that cut the rocks of the volcano-sedimentary sequence. The best known deposits are the Diadema in the Sapucaia greenstone belt (Oliveira *et al.*, 1995; Oliveira and Leonardos, 1990; Nascimento and Biagini, 1988) and Babaçu/Lagoa Sêca in the Andorinhas greenstone belt (Huhn, 1991; 1992; Souza *et al.*, 1990; Silva and Cordeiro, 1988).

Au-Cu-Bi-Mo Deposits of the Porphyritic Lode-type

The Cumaru gold deposit (Leonardos *et al.*, 1991; Santos, 1995; Santos *et al.*, 1998) is associated with a stockwork of quartz veins and veinlets, rich in pyrite, and related to a late-tectonic granodiorite intrusion dated at 2.87 Ga (Lafon and Scheller, 1994; Lafon and Macambira, 1990). The association of the metals Au-Cu-Bi-Mo, and the geochemical and isotope data, in addition to the fluid inclusion studies, led these authors to propose a mixed origin for the gold mineralization, classifying the deposit as a porphyritic lode-type exhibiting both magmatic and structural controls: The Cumaru Granodiorite is defined as I-type calc-alkaline intrusion of volcanic arc affiliation, similar to porphyry systems, that was affected by metamorphic aquo-carbonic fluids, which have circulated in the shear zone on the southern flank of the Gradaús greenstone belt.

The Serra dos Carajás Iron Ore Deposit

The Carajás Formation is an intermediate unit of the Grão Pará Group (Tolbert *et al.*, 1971; Beisiegel *et al.*, 1973) intercalated between two mafic volcanic units, and consisting of jaspilite which represents the proto-ore of the iron ore deposits. This jaspilite has as its main characteristic the alternation of bands rich in hematite/magnetite and bands of jasper, with numerous sedimentary structures such as cut-and-fill structures, spherulites, intraformational breccia, slump structures, and dehydration nodules and veins (Meirelles, 1986; Meirelles and Dardenne, 1993; Macambira and Silva, 1995). Geochemical studies on the jaspilite showed a positive anomaly for Eu and intermediate Cu and Zn values in relation to the values for BIF of the Algoma and Lake Superior types. The REE spectra are very similar to those of the mafic volcanic wall rocks. The set of geological and geochemical data indicate a volcano-sedimentary origin in a rift environment for the formation of the jaspilite in the Carajás Formation.

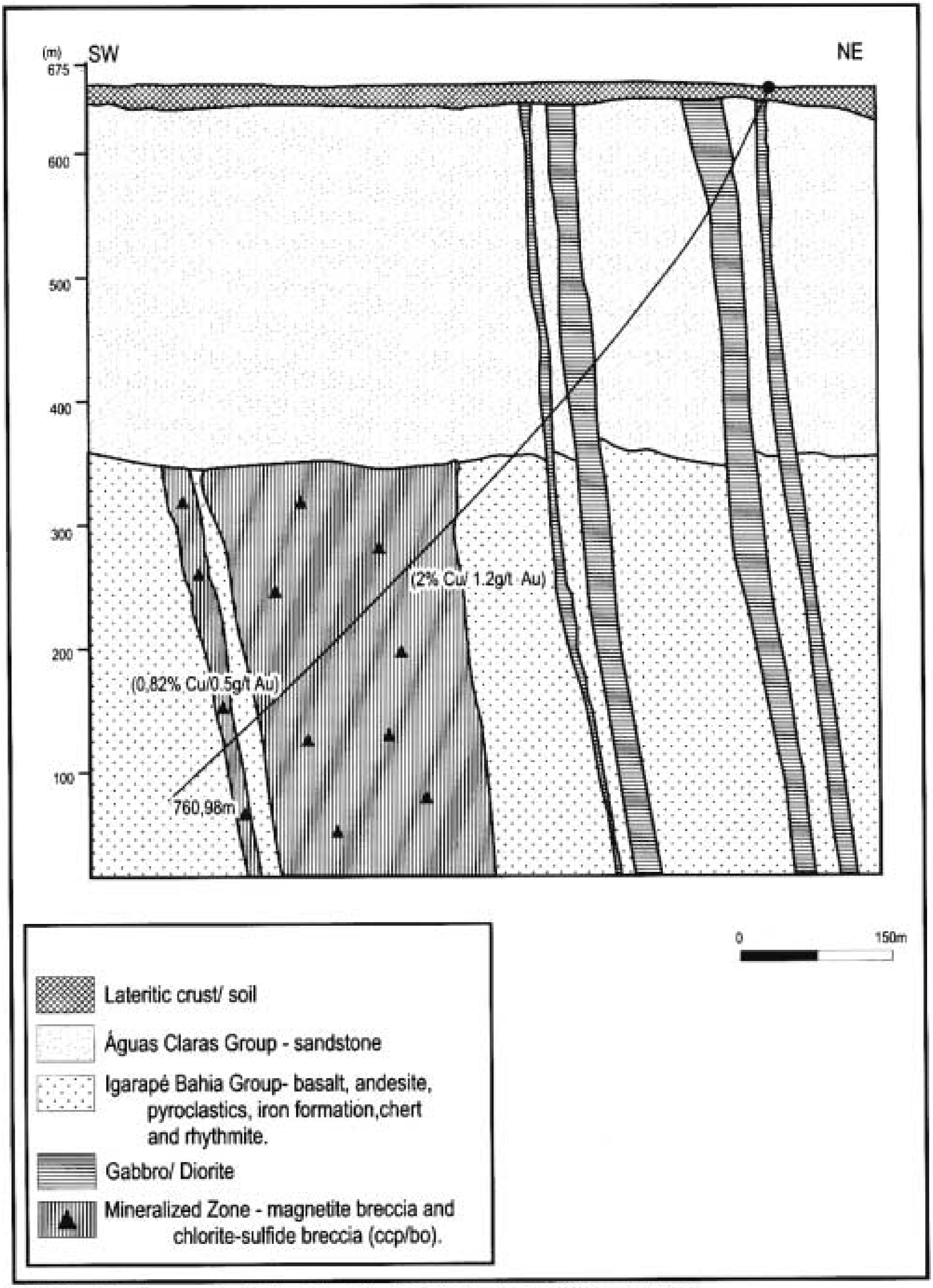


FIGURE 8b - Schematic cross-section of the Alemão Deposit (modified after Barreira et al., 1999; Soares et al., 1999)

These iron formation units cannot be classified either as the Algoma-type or as Superior-type. Moreover, they seem to be a unique type: the Carajás-type. On one hand, the strict relationship between the jaspilite of the Carajás region with volcanic rocks permits a comparison with the Algoma-type. On the other hand, the iron formation units occur only in the oxide facies suggesting similarities with the depositional environment of the Superior-type (Meirelles, 1986; Hoppe and Schobbenhaus, 1990; Meirelles and Dardenne, 1993).

The iron ore presently being worked in open pits at the huge Carajás Deposit came about as a result of laterite weathering that caused the supergene leaching of the silica in the jaspilite and the residual concentration of hematite (Costa, 1997). The reserves of the Serra dos Carajás have been estimated at 18 billion t of ore at 60% to 67% Fe. At the N4E area the mineable reserves are about 1.251 billion t of ore at an average grade of 60.9%Fe (Coelho, 1986). In 1998, the production was about 54 Mt of iron ore.

The controversy over the Carajás iron deposit involves the geotectonic context that preceded the development of the rift; (a) the basaltic volcanism is intraplate and of the Paraná Basin-type (Wirth *et al.*, 1986; Gibbs *et al.*, 1986; Lindenmayer, 1998) and the high-K values are related to the percolation of hydrothermal fluids (Lindenmayer *et al.*, 1998); (b) the basaltic volcanism associated with the jaspilite is defined as high-K with shoshonitic affinities (Meirelles, 1986; Meirelles and Dardenne, 1991; Dardenne *et al.*, 1988; Teixeira, 1994; Teixeira and Eggler, 1994) that developed as a mature magmatic arc, dominated by subduction mechanisms.

The Luanga Chrome Deposit

The stratiform bodies of massive and disseminated chromitite are associated with the orthopyroxenite of the mafic-ultramafic layered and differentiated complex of Luanga, intruded at 2.76 Ga (Machado *et al.*, 1991) at the base of the Rio Novo greenstone belt, thus being contemporaneous with the volcanism of the Grão Pará Group. This complex of mafic tholeiitic association is composed of a set of cumulate rocks, beginning with dunite and peridotite at the base, grading to orthopyroxenite with zones of chromitite, and transitioning to norite and leuconorite in the upper part (Hirata *et al.*, 1982; Medeiros and Meireles, 1985; DOCEGEO, 1988; Suita, 1998; Suita and Nilson, 1991). According to Suita (1996), the massive chromitite is enriched in PGE, with grades attaining 3.2 g/t PGE + Au and 3.0 g/t Pt + Pd.

Cu-Au Deposits

Grouped under this heading are the Igarapé Bahia/Alemão, Pojuca and Salobo deposits, in addition to new targets presently in phase of economic evaluation such as the deposits of Sossego, Cristalino, S118, etc. All these deposits have as their main characteristic the association iron oxide Cu-Au (-U-REE).

The Igarapé Bahia and Alemão Cu-Au deposits

Associated with the volcano-sedimentary sequence of the Igarapé Bahia Group, these two deposits (Figs. 8a and 8b) represent, for all practical purposes, a single mineralized entity. The Alemão Deposit, which was discovered by geophysics (Barreira *et al.*, 1999) is the along-strike extension in subsurface of the Igarapé Bahia Deposit. Three types of mineralization are known: volcano-sedimentary, hydrothermal and supergene.

- Volcano-sedimentary mineralization: this type of mineralization was known before the others as the result of drilling. It occurs in the form of disseminated chalcopyrite and pyrite associated with chlorite, principally in the sedimentary rocks and rhythmite beds in the form of banded iron formation units composed of magnetite, fluorite and chalcopyrite (Ferreira Filho, 1985; Ferreira Filho and Danni, 1985; Althoff *et al.*, 1994). Up to the present, this type of mineralization is not of economic interest.

- Hydrothermal mineralization: this type of mineralization was investigated by drilling and described at Igarapé Bahia by Ferreira Filho (1985); Althoff *et al.* (1994), Lindenmayer *et al.* (1998), and Tallarico *et al.* (2000b); and at Alemão by Barreira *et al.* (1999), and Soares *et al.* (1999). There are two types of ore: vein ore and brecciated ore.

The vein ore occurs in the form of small veins (0.7 to 2.7 cm thick) which cut several rock-types, and are surrounded by a chlorite envelope consisting of an association of calcite-quartz-chalcopyrite; quartz-magnetite-chalcopyrite; and quartz-chalcopyrite. Molybdenite and digenite (Althoff *et al.*, 1994), as well as uraninite (Angélica *et al.*, 1996) and fluorite have been described in the area.

The brecciated ore is found in association with hydraulic breccia that is situated preferentially at the contact of granophyre intrusions with sedimentary rocks and mafic volcanic rocks,. The ore is composed of fragments derived from the wall rock of the iron formation units. The matrix is rich in magnetite and quartz, and cemented by chlorite and calcite in addition to chalcopyrite-pyrite-chalcocite-covelite. The gold is mainly associated with chalcopyrite. The mineralization is accompanied by intense hydrothermal alteration represented by the assemblage of chlorite-quartz-albite-carbonate (Ferreira Filho, 1985; Ferreira Filho and Danni, 1985).

At Alemão, the reserves of primary sulphide ore are estimated about 170 Mt of ore at 1.5% Cu and 0.81 g/t Au (or 113Mt of ore with 1.98% Cu and 0.94 g/t Au).

According to Lindenmayer *et al.* (1998), the fluids responsible for the general chloritization and for the mineralization were rich in CO2, U, REE, Cu, Ag, Mo, F end Cl, as well as being highly saline. For these reasons Lindenmayer *et al.* (*op. cit.*) proposed that these fluids came from a magmatic source associated with the anorogenic granite intrusions dated at 1.88 Ga. However, other workers such as Huhn and Nascimento (1997), Oliveira *et al.* (1998), Tallarico *et al.* (1998, 2000 b) related the installation of the hydrothermal system to Archean dioritic intrusions, thus enabling a comparison with the Olympic Dam Deposit in Australia. The Igarapé Bahia was classified as a Fe oxide Cu-Au (-U-REE) deposit.

- A good argument in favour to the second hypothesis is the geological observation that the brecciated mineralization does not cut the Águas Claras sediments that unconformably overlie the Igarapé Bahia volcano-sedimentary sequence.

- Supergene mineralization at Igarapé Bahia: the ore is of lateritic origin (Zang and Fyfe, 1993; Costa *et al.*, 1996; Costa, 1997) consists mainly of hematite, maghemite, goethite with gibbsite, and subordinate kaolinite and quartz. This assemblage formed in the thick weathered zone (20 to 50 m) that developed over the veining rich in chalcopyrite. The gold grains found in the lower part of the ferruginous zone are almost pure. The deposit contained before mining reserves of about 12 Mt of ore at 5 g/t Au, and in 1999 the production was about 10 t of gold.

The Pojuca Cu-Zn-Au deposit

This deposit is situated on the northern side of the Serra dos Carajás (Fig. 7b). The Pojuca volcano-sedimentary sequence that hosts the Cu-Zn-Au deposit consists of a thick sequence of ortho-amphibolite intercalated with banded iron formation units, and overlain by beds of metamorphosed sandstone and siltstone. This sequence is intruded by dykes and sills of metagabbro and metadiabase (Farias and Saueressig, 1982; Farias *et al.*, 1984; Medeiros Neto and Villas, 1985; Medeiros Neto, 1986). The volcano-sedimentary sequence was intruded at 1.88 Ga by the Pojuca anorogenic granite. According to the workers cited above, three types of mineralization can be observed at this deposit.

- Mineralization associated with iron formation units: this type occurs as banded and disseminated sulphide, as massive sulphide, and as siliceous breccia. Although this type of mineralization has been considered as stratiform and of volcano-sedimentary origin, the mineralization associated with siliceous breccia is very similar to the hydraulic breccia of hydrothermal origin described at Igarapé Bahia.

- Mineralization associated with hydrothermal veining of quartz-feldspathic composition: this type of mineralization cuts all the rock-types of the volcano-sedimentary sequence, and is accompanied by propylitic alteration that is symmetric with respect to the axis of the veins. The main minerals are quartz, fluorite, calcite, tourmaline, albite and microcline together with chalcopyrite, pyrrhotite, sphalerite and bornite, besides molybdenite, ilmenite, pyrite, marcasite, cobaltite, hematite, mackinavite, cubanite and pentlandite. These quartz-feldpathic veins seem to be related to remobilization brought about by the intrusion of the Pojuca anorogenic granite at 1.88 Ga. In the vicinity of the Pojuca Granite, the same type of mineralization has been described as that related to the intrusion of the Gameleira Granite, dated at 1.88 Ga (M. Pimentel and Z. Lindenmayer, personal communication).

The Salobo Cu-Au deposit

The Salobo Cu-Au deposit was discovered by DOCEGEO in 1977 (Farias and Sauesserig, 1982). The deposit is situated some 30 km to the N of the Serra dos Carajás (Fig. 7b), and is hosted in a homonymous volcano-sedimentary sequence, the attitude of which is vertical. The rocks consist of quartzite, amphibolite, metagreywacke and iron formation units rich in magnetite to which is associated the copper mineralization (Fig. 9a,b). The deposit is limited by extensive shear zones, the strike of which is WNW-ESE, and is intruded by syn-tectonic granite, foliated and mylonitized (OSG), and dated at 2.57 Ga. At the beginning of the middle Proterozoic, at 1.88 Ga, this sequence was intruded by an anorogenic quartz-syenite (YSG) that caused contact metamorphism and intense hydrothermal potassic and propylitic alteration. The ore of the Salobo Deposit, studied mainly by Lindenmayer (1990, 1998), Lindenmayer and Fyfe (1994), Réquia *et al.* (1997) consists mainly of disseminated or massive bornite and chalcocite, always associated with lenses of magnetite. The other minerals present are chalcopyrite, molybdenite, uraninite, gold, ilmenite, graphite, safflorite, Co-pentlandite, covelite, digenite, hematite and native copper. The ore is hosted in the siliceous and aluminous iron formation units that are tectonically foliated and even mylonitized. This deformation reaches the lenses of magnetite-bornite-chalcocite, which show a plastic flux texture, mylonitization and brecciation. With the intrusion of the anorogenic quartz-syenite (YSG), the iron formation units and the mineralization underwent contact metamorphism in the pyroxene hornfels facies (750°C), followed by potassic alteration (650°C-550°C; 2.5 kbar) and by intense propylitization (350°C-270°C) manifest in a generalized chloritization of the iron formation units by the paragenesis almandine, biotite, hastingsite, titanite, rutile, greenalite in association with fluorite and uraninite, and by the development of veining with stilpnomelane, fluorite, molybdenite, allanite, chalcopyrite, cobaltite, gold and quartz.

The Salobo Cu-Au deposit was initially thought to be a VMS-type deposit of volcanogenic origin. It was successively defined by Lindenmayer (1990) to be volcanogenic; and then of mixed origin: exhalative for copper and epigenetic for Au-Mo-U (Lindenmayer and Fyfe, 1994). Later, it was considered to be porphyritic for Au (Lindenmayer, 1998, 1999), and finally as a deposit of the Fe-oxide Cu-Au (-U-REE) type associated with anorogenic granitic intrusions at 1.88 Ga by Lindenmayer *et al.* (1998) or with Archean granitic intrusions (Huhn and Nascimento, 1997; Huhn *et al.*, 1999). According to the contrasting views of Siqueira (1996), the Salobo Deposit is of hydrothermal origin, entirely related to a shear zone. A fundamental point to be clarified is the observation that the magnetite-chalcopyrite-bornite massive bodies have been affected by the Archean deformation as described initially by Lindenmayer (1990).

The reserves of the Salobo Deposit are estimated at 789 Mt of ore at 0.96% Cu, 0.52 g/t Au and 55 g/t Ag.

The Sossego-Cristalino/S118 Cu-Au deposits

The new discoveries of Cu-Au deposits known as Sossego-Cristalino-S118 are situated to the S of the Serra dos Carajás (Fig. 7b). According to Huhn *et al.* (1999), these deposits are associated with diorite and quartz diorite intrusions, dated at 2.74 Ga, in the volcano-sedimentary sequence of the Grão Pará Group. The attitude of these rocks is vertical and metamorphism has occurred in the greenschist to amphibolite facies. The mineralization occurs in brecciated and hydrothermalized zones, forming stockworks both in the volcanic wall rock as well as in the diorite. The mineralization is accompanied by a distinct enrichment in magnetite, apatite and allanite in addition to varied types of hydrothermal alteration including

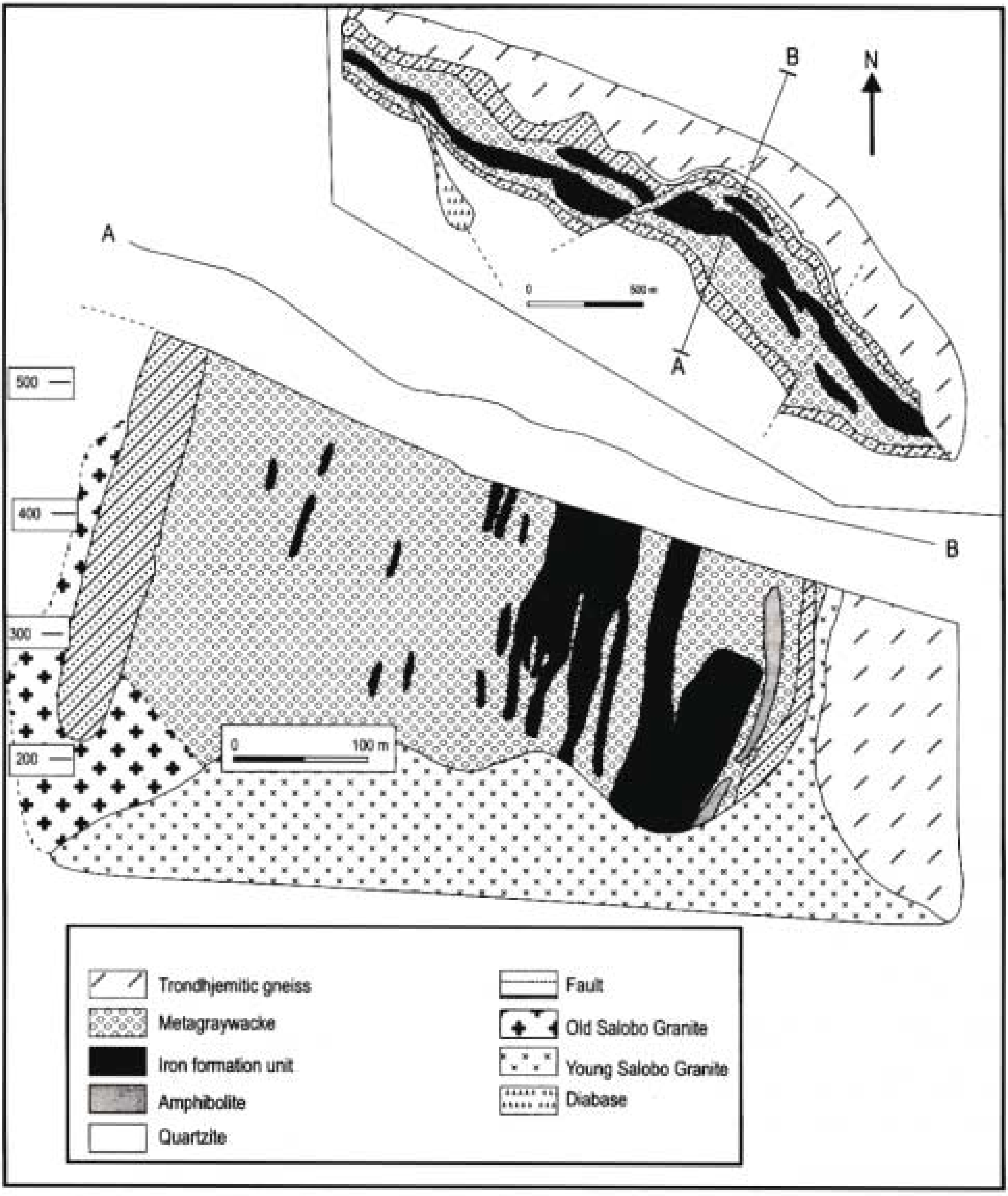


FIGURE 9a,b - Schematic geological map and cross-section of the Cu-Au Salobo Deposit (modfied after Lindenmayer,1998).

microclinization and biotitization (potassic alteration), albitization and scapolitization (sodic alteration), chloritization and carbonatization, silicification and tourmalinization. The ore consists of chalcopyrite, pyrite, magnetite, bravoite, willerite, cobaltite, vesite and gold. Mineralized intersection from the first drillholes showed grades of 1.4% Cu and 0.25 g/t Au, and the potential is estimated to exceed 200 Mt of copper ore. The partial reserves of the Sossego Deposit have been estimated at about 219 Mt of ore with 1.14% Cu and 0,34g/t Au. Huhn *et al.* (1999) consider that these new discoveries show features that are also common to the Cu-Au deposits of Alemão, Bahia, Pojuca and Salobo, and suggest these deposits will fall into the Fe-Cu-Au-U-REE model of Hitzman *et al.* (1992), in line with the initial view proposed by Huhn and Nascimento (1997).

The Azul Mn deposit

The Azul manganese deposit (Coelho and Rodrigues, 1986; Beisiegel *et al.*, 1973; Bernadelli and Beisiegel, 1978; Bernadelli, 1982) is associated with the lower member of the Águas Claras Group (Nogueira *et al.*, 1995) and dated indirectly at 2.645 Ga. In the Serra dos Carajás area the denomination Águas Claras Group has substituted the former Rio Fresco Group (Barbosa *et al.*, 1966). The lower member of the Águas Claras Group consists of argillite with subordinate siltstone and sandstone, deposited on a marine platform. The primary mineralization, or manganese proto-ore (Bernadelli and Beisiegel, 1978; Valarelli *et al.*, 1978) is found intercalated in the pelitic sequence in the form of two manganiferous units consisting essentially of rhodochrosite, quartz, phyllosilicate, feldspar and organic material. The ore, of lateritic origin, developed from the alteration and supergene enrichment in or on the lower manganiferous unit in the form of cryptomelane. In 1996 the mineable reserves were estimated at 54.36 Mt of manganese ore. The annual production was 1.1 Mt of metallurgical-grade ore and 70 381 t of manganese dioxide.

The Azul manganese deposit may be compared to sedimentary deposits developed at the margin of stratified and anoxic basins (Force and Maynard, 1991).

The Buritirama manganese deposit, isolated to the N of the Carajás Mineral Province may represent a metamorphic equivalent of the Azul sedimentary sequence or the Pojuca/Salobo volcano-sedimentary groups.

The Serra Pelada/Serra Leste Au Deposit

The Serra Pelada/Serra Leste gold deposit (Meireles *et al.*, 1982; Meireles and Silva, 1988) is hosted in the sediments of the Águas Claras Group, that form a regional synclinal structure, and is associated with a dextral transtensional system the strike of which is NNE-SSW, developed between regional shear zones the strike of which is ENE-WNW (Freitas-Silva, 1999). In this dilational environment the mineralizing fluids deposited gold in manganiferous and carbonate-rich tectonic breccia. The gold is free and rich in palladium (1% to 8% Pd) and platinum. The ore also contains silver (*c.* 0.5% Ag), iron (between 0.5%-1% Fe) and copper (*c.* 0.5% Cu). According to Tallarico *et al.* (2000 a) the ore bodies are found in the contact between the carbonate-rich siltstone and dolomitic marble and are surrounded by intense silicification. Quartz, dolomite, chlorite, actinolite, biotite, muscovite, magnetite, calcite, tourmaline, hematite, pyrite, chalcopyrite, molydbenite, galena, digenite as well as uranium-bearing minerals and rare earths accompany the Au-Pd-Pt mineralization. A hydrothermally-altered dioritic intrusion is known to occur underneath the deposit to which can be related the epigenetic mineralization.

The deposit has been highly weathered, and is known for the development of large nuggets (weighing up to 6 kg of massive gold) as well as huge gold agglomerates having dendritic and skeletal habits weighing between 26 and 62 kg. The deposit was discovered in 1977, and became famous on account of the number of *garimpeiros* (over 40 000) that worked there. Between 1980 and 1984 the Serra Pelada Deposit produced about 32.6 t of gold. The oxidized mineralization is known to a depth of 300 m.

The Águas Claras Cu-Au Deposit

The Águas Claras Cu-Au deposit is associated with shear zones and normal faults, the attitude of which is N20° to N40°E/70°NW, which cut the sediments of the Águas Claras Group, consisting of siltstone, sandstone, and sills and dykes of diabase. According to Soares *et al.* (1994) and Silva and Villas (1998), the primary mineralization is of hydrothermal origin. The first phase consisted of the development of massive quartz veins with cassiterite and wolframite accompanied with silicification of the mafic rocks and the tourmalization of the sediments. Chloritization and sericitization, intense brecciation of the quartz veins and the precipitation of sulphides mark the second phase of hydrothermal mineralization. The dominant sulphide species are chalcopyrite, pyrite and arsenopyrite; subordinate species are pyrrhotite, sphalerite, stannite, cobaltite, bismuthinite and galena, besides magnetite. The gold, rich in silver (*c.* 25% Ag), appears as irregular grains (0.01 to 0.26 mm) in the contact between pyrite and chalcopyrite crystals, as inclusions in arsenopyrite, and as isolated grains in chalcopyrite. The origin of the Au-Cu-Sn and W mineralization may be related to the Central Carajás granite intrusion dated as 1.88 Ga. The reserves of the deposit have been estimated at 9.5 Mt of ore at 2.43 g/t Au (Silva and Villas, 1998).

The lateritic weathering resulted in the formation of gossan at the surface (Angélica *et al.*, 1996), and the secondary mineralization in the form of gold nuggets is associated with goethite, limonite, hematite and martite, besides quartz, kaolinite and tourmaline. This weathered cap is worked for support of the industrial gold complex at the Igarapé Bahia Mine.

The Pedra Preta W deposit.

The Pedra Preta wolframite deposit (Cordeiro and Silva, 1986; Rios *et al.*, 1998) is associated with the Musa anorogenic granite intrusion (1.88 Ga) (Dall'Agnol *et al.*, 1994). The mineralization is contained in quartz veins with strike N80°W/subvertical, which cut the volcano-sedimentary sequence. Together with the quartz, there occur besides wolframite, topaz, muscovite, tourmaline, pyrite,

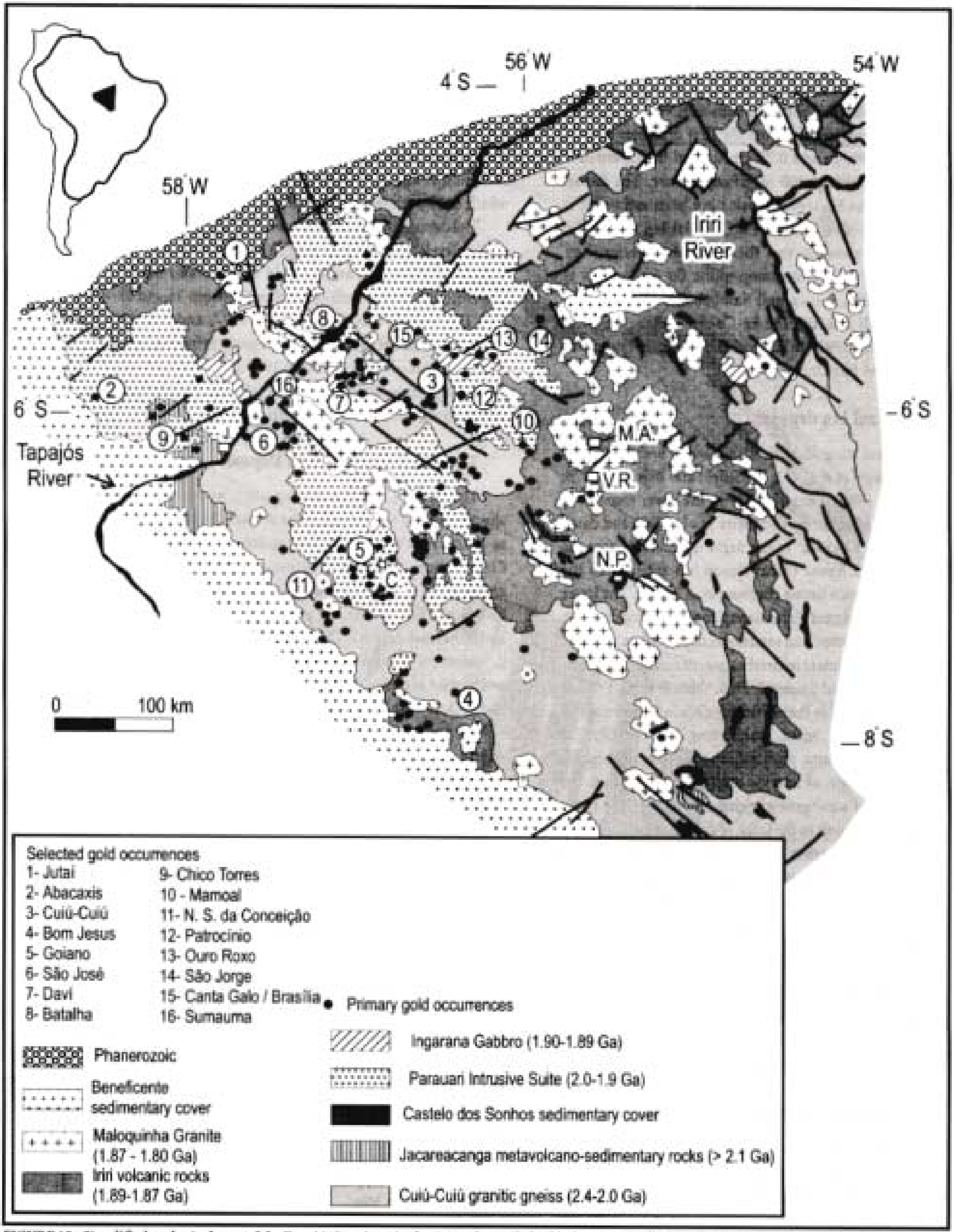


FIGURE 10 : Simplified geological map of the Tapajós Province in the Central Brazil Shield, showing the distribution of primary gold occurrences. Sources: Faraco et al (1996); Robert (1996). J.= Jacareacanga; M.A.= Morais Almeida; N.P.=Novo Progresso; V.R. = Vila Riozinho; C.=Creporizão

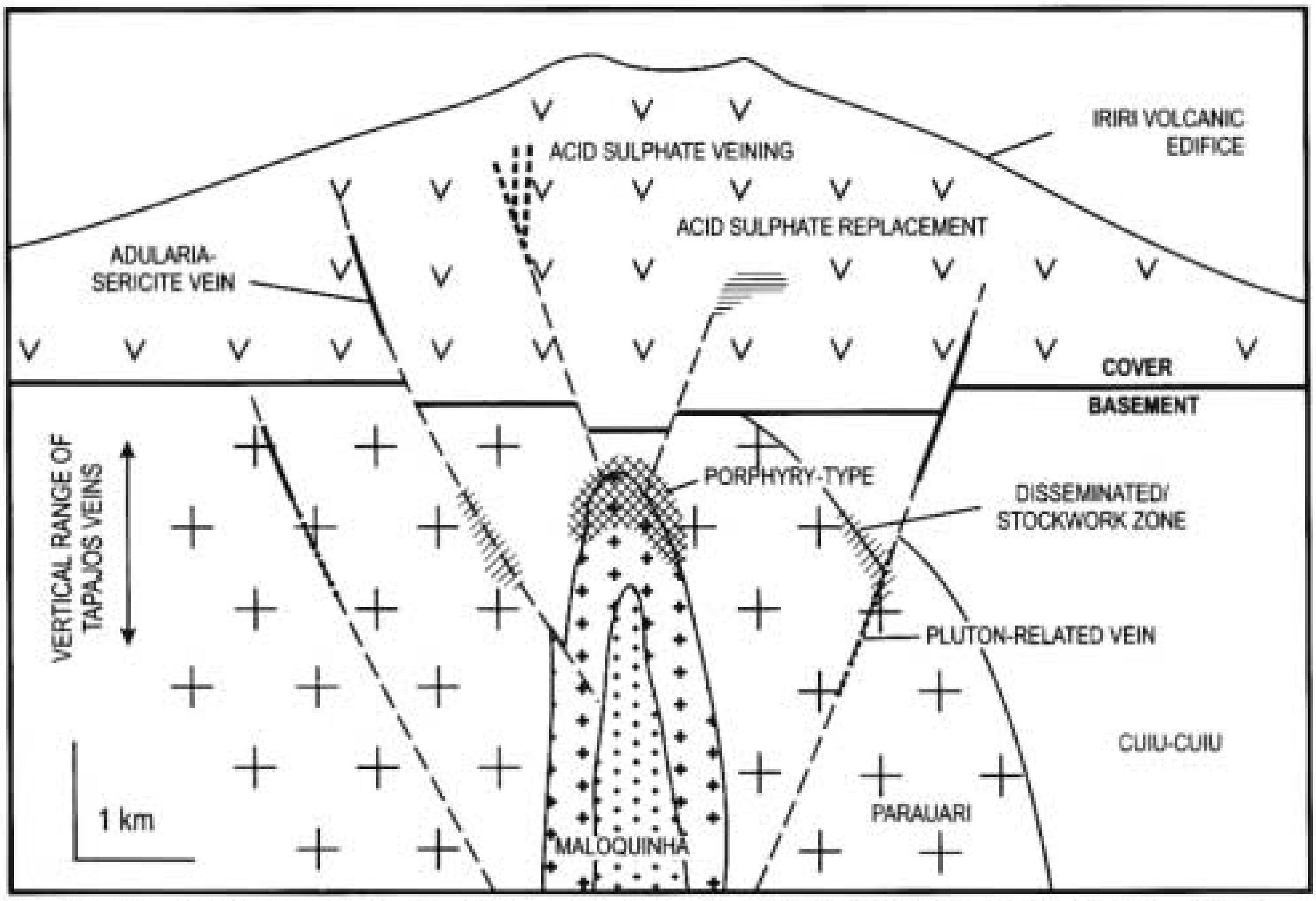


FIGURE 11 - Schematic geological model based in an intrusion - centered hydrothermal gold system applied to the Maloquinha Granite in the Tapajós Province (modfied after Sillitoe, apud Robert, 1996)

pyrrhotite and chalcopyrite. In the contact with the thicker veins, the wolframite is also disseminated in the intensely silicified wall rock. The ore reserves have been estimated at about 322 753 t at an average grade of 1.03% WO3.

The Tapajós Province

Geological context

Tapajós is the largest gold province in Brazil. It is situated in the central region of the Central Brazil Shield between the Tapajós River and the headwaters of the Crepori and Jamanxim rivers, the Serra do Cachimbo and the Iriri River (Fig. 10). The basement of this province consists of two main units: the Cuiú-Cuiú and the Jacareacanga Metamorphic suites of possible Paleoproterozoic age (>2.0 Ga). The Cuiú-Cuiú Suite consists of gneiss, migmatite, granitoid and amphibolite whereas the Jacareacanga Suite represents a supracrustal volcano-sedimentary sequence that has been metamorphosed and deformed in the high greenschist facies. The relationship of this unit with the Cuiú-Cuiú Metamorphic Suite is not known. Both these metamorphic suites were intruded by granodiorite and monzodiorite plutons and batholiths of the Parauari Suite considered to be syn to late tectonic (2.0-1.9 Ga). The Parauari Granitoid is calc-alkaline in composition, and often displays a rapakivi texture. All these units form the basement over which was deposited an extensive cover of sub-aerial volcanic rocks of acid to intermediate composition known as the Iriri Group (1.89-1.87 Ga), and an anorogenic co-magmatic intrusive suite, the Maloquinha Suite (1.87-1.80 Ga). The magmatism of the Iriri-Maloquinha rocks occurred during a geotectonic regime that was mainly extensional. The volcanic rocks and their sub-volcanic plutons are not penetratively deformed. The volcanic rocks with pyroclastic units and subordinate sediments have low dips, except in the proximity of faults. Clastic fluvial sedimentary rocks of the Castelo dos Sonhos Formation, underlie the Iriri Formation. These sediments generally form elongate quartzite ridges. An intrusion known as the Ingarana Gabbro Intrusion (1.90-1.89 Ga) cuts the Parauari Intrusive Suite and the Cuiú-Cuiú basement sequence. All these units are overlain discordantly by a sedimentary cover, locally with volcanic rocks of taphrogenic character assigned to the Beneficente Group. Basic sills and dykes of the Crepori unit intruded these rocks at about 1.69 Ga, as well as the mafic-ultramafic rocks of the Cachoeira Seca unit, dated at between 1.2 and 1.1 Ga (Robert, 1996; Faraco *et al.*, 1996).

The late stage Maloquinha Granitoid of alkaline to sub-alkaline affinities intrudes the Parauari Suite and the Iriri volcanics. These younger granitoid plutons are more fractionated than those of the Parauari Suite with Rb/Sr >1, and high Nb/Zr and Gd/Yb ratios. The Maloquinha intrusive rocks were emplaced at a very shallow depth. They have a porphyritric texture, and they are frequently reddish in colour. In addition to these characteristics they are anomalous with respect to F, Zr, REE, Y, Sn, Au and Cu, and play an important role in the mineral economy of the Tapajós Province (Jacobi, 1999).

Gold Mineralization

Primary gold occurrences are found mainly in the western part of the province in rocks of the basement units as well as in the Maloquinha intrusions. There are relatively few occurrences in the volcanic rocks of the Iriri cover. This distribution of the gold deposits (Fig. 11) may reflect the influence of the level of erosion in as much as these may expose certain styles of gold mineralization (Robert, 1996; Coutinho *et al.*, 1998).

Of the diverse occurrences of primary gold, two main styles of mineralization are present: (1) gold in quartz veins and (2) gold as disseminations in zones and stockworks. Quartz veining is the most common style of mineralization and can be observed at many localities including Abacaxis, Bom Jesus, Goiano, São José, Davi, Batalha, Chico Torres, Mamoel, Cuiú-Cuiú and at N. S. da Conceição. In general, the gold occurs in narrow discontinuous zones. Very often the gold is visible forming high-grade concentrations. The hydrothermal alteration is restricted to the veins and is never pervasive. Disseminated gold mineralization can be observed at Jutaí and Abacaxis.

The principal characteristics of the quartz veins may be summarized as follows: (a) they are polymetallic and generally contain pyrite, along with variable amounts of chalcopyrite, galena, sphalerite, pyrrhotite and molybdenite. Some veins contain alkaline feldspar, amethyst, and fluorite; carbonate is common; (b) at the occurrences there may be observed massive quartz to banded quartz structures (or comb quartz structures), and structure filling open spaces are also common; (c) the associated alteration consists of proximal sericite-pyrite (Bom Jesus) or K-feldspar (Batalha) or peripheral mineral assemblages of chlorite-epidote-calcite (Bom Jesus, Davi) or chlorite/sericite-sulphide-carbonate (Ouro Roxo); (d) the veins are associated spatially with ruptile faults, and there is some evidence that, locally, the veins may have been emplaced in active brittle faults (Bom Jesus, Goiano). These characteristics are typical of veins that have formed in relatively shallow crustal levels and indicate an *epithermal affinity for the veining of the Tapajós Province; (f)* the quartz veins occur in a variety of host rocks: granitic basement (Goiano), Maloquinha Granite (Bom Jesus) and non-metamorphosed feldspathic sandstone (Abacaxis); (g) the absence of penetrative deformation and significant metamorphism of the Maloquinha intrusives and of the sandstone at Abacaxis may indicate that the veining formed at shallow crustal levels, a view that corresponds to the inferred environment of the veins; (h) in spite of the diversity of the different types of host rock and their ages, the similarity of the characteristics of the veins suggests that the quartz veins have similar ages. Consequently, the veins are contemporaneous or younger that the Maloquinha intrusives (Robert, 1996).

The absence of primary gold occurrences in the Beneficente Group suggests that the veining is older than this group. Based on available data, the most likely interpretation is that the quartz veins were formed during the magmatic event that resulted in the Maloquinha intrusions at the end of the Paleoproterozoic (1.87-1.80 Ga). A possible exception is the veining at São José where the veins are parallel to the penetrative foliation in basement granitoid, and which form boudins along the foliation planes. The implication of this boudinage is that the veining was developed during the phase of basement deformation and is therefore older (2.4-2.0 Ga), this is to say at the base of the Paleoproterozoic. This fact raises the important possibility that there occurred two events that brought about the gold veining in the Tapajós Province: one that affected the basement rocks consisting of mesothermal veins in the lower Paleoproterozoic, and a second phase of veining in the younger Paleoproterozoic. Additional work is required to examine these two possibilities. Finally, it is important to note that the quartz veining is related to the Iriri-Maloquinha magmatic event. These veins are not abundant in the Iriri volcanic cover. The tendency is for these to occur in rock-units below this cover and within the Maloquinha intrusions.

The presence of disseminated auriferous sulphide mineralization in the Abacaxis Granodiorite and in weak to moderate fracture stockworks at Jutaí and São Jorge is highly significant in spite of the fact that this mineralization is not ore-grade. It shows that the disseminated stockwork mineralization, generally associated with the porphyritic environment (Sillitoe, 1991; Robert, 1996) could constitute a valid exploration target for the Tapajós Province. At Abacaxis, the granodiorite hosting disseminated sulphide mineralization intrudes non-metamorphosed sandstone and siltstone beds that are believed to be coeval equivalents of the Iriri volcanic rocks. This also implies that the granodiorite belongs to the Maloquinha Intrusive Suite, and that the diseminated mineralization may possibly have the same age as the quartz veining.

As mentioned above, the quartz veins have epithermal affinities. Specifically, these show several common characteristics with the epithermal deposits of the adularia-sericite type (Heald *et al.*, 1987; Robert, 1996). These include K-feldspar/sericite/chlorite alteration; weak sulphide mineralization in veins (sphalerite, chalcopyrite, and galena); and hematite and adularia (Dreher *et al.*, 1998) in some veins, and an absence of hypogene alunite, enargite-tenantite and a high degree of argillization. However, in the Tapajós veins *there occur a few instances in which the veining diverges from* the classical model of the adularia-sericite-type: the veins occur predominantly in the basement rather than in the volcanic cover; many veins are polymetallic, and as emphasized by Robert (1996) and Buchanan (1981) do not show a vertical separation of the basic and precious metals. The veins have some similarities with what Sillitoe (1991) and Robert (1996) referred to as plutono-related veining. These are transitional in character between adularia-sericite epithermal and mesothermal veins that occur at a slightly greater depth as compared to the epithermal veins. Figure 11 shows the position of the vein-types within a hypothetical hydrothermal system centered on an intrusion, and provides a plausible geological model for the gold deposits of the Tapajós Province.

More than 90% of the gold produced in the Tapajós Province was mined from thousands of placer deposits. Production figures show that about 159 t of gold were mined between 1959 and 1996. *Garimpos* of the Cuiú-Cuiú, Canta Galo, Abacaxis and Patrocinio types are classical examples of these large Recent placer systems. Gold is also found in Tertiary paleoplacers, some 10 to 20 m below the

Recent surface (Nova Brasilia) or in paleoplacers above the present surface (Sumaúma) (Robert, 1996; Dreher *et al.*, 1999; Martini, 1998; Costa and Carvalho, 1999; Coutinho *et al.*, 1998; Jacobi, 1999)

The Alta Floresta Province

Geological Context

The Alta Floresta Province is also essentially auriferous, in like manner to the Tapajós Province. It lies between the Serra do Cachimbo to the N and the Serra dos Caiabis and the Chapada dos Dardanelos to the S. To the E it is limited by the Peixoto de Azevedo/Matupá region, and by the Aripuanã River to the W (Fig. 12).

With the exception of some studies in specific areas the level of geological knowledge of the Alta Floresta Province is limited for the best part to geological mapping at 1:1 000 000 scale. Presently, geological mapping at 1: 250 000 scale is being carried out by the Geological Survey of Brazil. According to Tassinari (1996) the Alta Floreta region corresponds to the limit of two geological provinces or tectonic belts: the Ventuari-Tapajós Belt (1.9-1.8 Ga) to the N, and the Rio Negro-Juruena Belt (1.8-1.55 Ga) to the S, both defined by this author mainly on the basis of geochronology, supplemented by geological data. The limit between these two provinces passes approximately along a line between the towns of Matupá – Alta Floresta – Paranaita – Apiacás (Fig. 12). These two geochronological provinces or tectonic belts were interpreted by Tassinari (1996) and Teixeira *et al.* (1989) as having developed in magmatic arcs originating by collision directed against a continental block situated to the NE (Central Amazonian Province) (Fig. 4).

The basement of the Alta Floresta Province consists essentially of granitoid plutons of granitic to monzogranitic composition and gneiss of granitic to tonalitic composition. There also occur schist and mafic and ultramafic rocks, banded iron formation units, migmatite and other rock-types. In the basement of the Alta Floresta Province occur large batholiths (Juruena-type granitoid) that are isotropic to foliated banded and monzogranitic to granodioritic in composition (Paes de Barros, 1994; Paes de Barros *et al.*, 1999). The batholiths of the Juruena-type have not been adequately mapped yet. Recent U/Pb dating of a number of samples of basement granitoid, collected between the towns of Apiacás and Peixoto de Azevedo, show ages between 1.9 and 1.8 Ga for these intrusive rocks (JICA/MMAJ, 2000). On the other hand, a dozen samples of granite collected from the areas of Apiacás and Paranaita, dated by K/Ar, showed that these rocks have been reworked isotopically between about 1.35 and 1.10 Ga (JICA/MMAJ, 1999).

Overlying the above-mentioned basement occur acid to intermediate volcanic rocks with calc-alkaline affinities, including pyroclastic rocks (Teles Pires Group). There are few reliable dates available for this volcanism correlated by some authors to the Iriri Group. U/Pb dates collected near the town of Apiacás to the NW, and to the N of Matupá, showed ages of 1.78 Ga (JICA/MMAJ, 2000) and 1.8 Ga (C. Schobbenhaus, personal communication), respectively, for the Teles Pires Volcanics. About 400 km to the W of Apiacás, in the Moreru area, an ignimbrite sample presents an U/Pb age of 1.81 Ga for this volcanism (Pinho *et al.*, 1999). These dates indicate that the Teles Pires volcanism is about 100 Ma younger than that of the Iriri volcanic rocks exposed in the Tapajós Province. The Teles Pires volcanic rocks are cut by granitic intrusions (Teles Pires Granite) that are generally circular in plan, and similar in this respect to the Maloquinha Intrusive Suite, occurring associated with sub-volcanic rocks with alaskite affinities. U/Pb age determination for this granite gave *c.*1.76 Ga (J. Orestes Santos, personal communication). Mesoproterozoic sediments of the Beneficente Group, the thickness of which exceeds 1000 m, cover the volcanic rocks and granite intrusives of the Teles Pires Group. These sediments were probably deposited between 1.8 and 1.5 Ga in a continental rift, the strike of which was NW-SE. Morphologically, they form an extensive plateau known as the Chapada do Cachimbo. The Beneficente Group consists of continental and marine sediments intercalated with pyroclactic rocks. Sedimentary rocks from this group revealed Rb/Sr ages of 1.4 Ga, interpreted as the diagenetic age of the sediments (Tassinari *et al.*, 1978). In the Aripuanã region there occurs associated sedimentary and volcanic rocks of low metamorphic grade that are also correlative with the Beneficente Group. K/Ar and Rb/Sr ages of *c.* 1.5 Ga and 1.45 Ga, respectively, for diabase and alkaline rocks intruded into the sediments represent minimum ages for the sedimentation The southern limit of the Alta Floresta Province is marked by two important physiographic features: the Serra dos Caiabis and the Chapada dos Dardanelos in which there occur continental sedimentary sequences known as the Dardanelos Formation. This formation overlies the volcanites of the Teles Pires, the Beneficente Group and the basement. Alkaline basalt flows intercalated in the Dardanelos Formation gave K/Ar ages of between 1.4-1.2 Ga. To the NW of the Alta Floresta Province, in the region of the Sucunduri Dome, continental sediments of the Prosperança Formation, of possible Neoproterozoic age, overlie the Beneficente Group (Iwanuch, 1999).

Gold Mineralization

Gold is the most important mineralization related to the Alta Floresta Province. In second place occurs base metal mineralization. Gold mineralization, whether this be in secondary alluvial deposits or primary deposits, is widespread throughout the province for more than 500km, and especially along the southern margin of the Cachimbo Graben that strikes WNW-ESE. Most of the gold occurrences have received little study. Mining began in 1966 following the discovery of gold by *garimpeiros* along the Juruena River. Official production figures and estimates of the production from small workings in alluvial deposits between 1982 and 1995 (DNPM) are 112 and 148 t of gold, respectively (Peixoto de Azevedo, Colider, Matupá, Terra Nova do Norte, Guarantã do Norte, Alta Floresta, Apiacás, Paranaita and Aripuanã areas).

Paes de Barros *et al.* (1999) divided the occurrences of gold mineralization into four districts: Peixoto de Azevedo, Teles Pires, Cabeça and Aripuanã. According to these authors, in the Peixoto de Azevedo area that extends from the vicinity of the town of Peixoto de Azevedo to the vicinty of the town of Alta Floresta, important gold mineralization

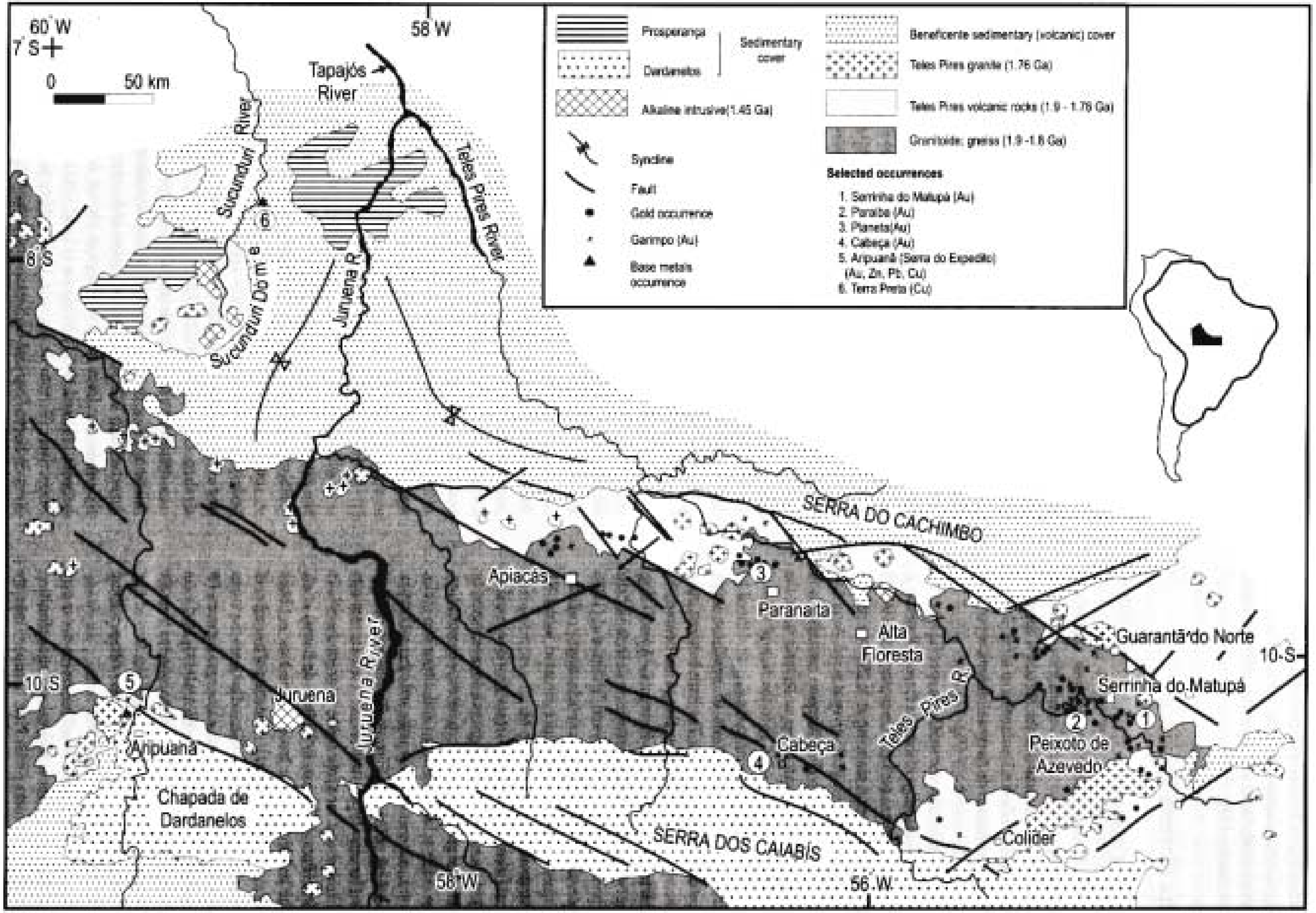


FIGURE 12 : Simplified geological map of the Floresta Province in the Central Brazil Shield. Sources of information: JICA-MMAJ (1999), Carvalho and Figueiredo (1982), Paes de Barros et al. (1999), and others.

is hosted in shear bands and in extensional structure that strike NNW-SSE and WNW-WSE. The ductile shear zones have as their main characteristic, continuous lineaments representing quartz-mylonite with the development of extensive pervasive hydrothermal alteration including silicification, chloritization, sericitization, epidotization and propilitization. Dozens of occurrences are hosted in shear fractures, including those at the Paraiba, Cubu, Pezão, Edu, Edson, Goiano, Mineiro workings and others. At the Serra do Guarantã occurrence, vein mineralization can be observed hosted in talc-chlorite schist that form mega-enclaves of ultramafic nature. Deposits related to granitic apophyses and stocks are frequently related to the Teles Pires magmatism. These may be observed as veins, veining and in stockworks, as for example, at the Pé Quente, Trairão, Aluizio, Naiuram *garimpos* and others. The Teles Pires area (Paes de Barros *et al.*, 1999) lies in a belt, over 200 long, that strikes E-W to NW-SE extending from Paranaita, passing through Apiacás to the Juruena River and reaching the area of the Moreru River. In general, the mineralization of this region is related to pre-Teles Pires magmatism represented by granitic batholiths, the rocks of which consist of equigranular biotite-monzogranite, light grey in colour. In the vicinity of the mineralized zones occurs a facies showing a higher degree of hydrothermal alteration with large bluish quartz crystals associated with an epidote, chlorite and pyrite paragenesis. The gold mineralization occurs associated with sulphide in quartz veins and as disseminations hosted in closely-spaced multiple shear bands. Gold also occurs associated with sub-volcanic acid rocks in pockets and in disseminated pyrite with grades exceeding 10 g/t Au. In the Cabeça region the gold mineralization occurs associated with a probable volcano-sedimentary sequence that underwent several phases of cataclasis, and which is locally intruded by the Teles Pires Granite. This volcano-sedimentary sequence is conditioned by a ductile shear zone, the strike of which is N70°-80°W. Thin gold-bearing veins with high-grade ore strike N20°-30°E and N5°-15°W.

The primary gold mineralization of the Alta Floresta Province may be divided into three types: (1) shear zone-hosted quartz vein type; (2) porphyry or disseminated type; (3) stockwork type. Examples of each of these three types are Paraiba, Matupá and Nova Planeta, respectively (Fig. 12).

The gold mineralization of the shear zone-hosted quartz vein type is related to a ductile shear zone that has the regional strike NW-SE, which cuts the entire province. This shear zone may be several kilometres wide, and includes some dozens of important gold veins and hundreds of zones with smaller gold veins.

This type of mineralization is best seen at the Paraiba underground mine, which has been considered to be the most important working in which veining is hosted in a shear zone. Reserves are given as *c.* 4.3 t of gold. The zones with quartz veins and veinlets have the preferential strike N20°-60°E, NNE, N30°-60°W and E-W. The Paraiba lode consists of a network of quartz veins with gold and copper displayed in parallel bands with variable sulphide content (Siqueira, 1997; Paes de Barros, 1994; JICA/MMAJ, 1999).

The gold mineralization of the porphyry or disseminated-type is associated with calc-alkaline granitic Type I plutons, of which the Serrinha do Matupá Granite is the best example (Botelho *et al.*, 1997; Moura, 1998; Botelho and Moura, 1998). The age of this granite (1.87 Ga, Pb/Pb), together with its geochemical characteristics are favourable indicators for gold prospecting in the region. The gold in this granite occurs in small high-grade vein-type deposits as well as in disseminations in wide hydrothermally-altered zones with sericitization, feldspathization, and pyritization. The association of gold with oxidized Type I granite and the hydrothermal alteration style are analogous to the associations present in world-class porphyry-type deposits (JICA/MMAJ, 1999). The Serrinha do Matupá Massif is a homogeneous, non-deformed monzogranite, with equigranular to porphyritic texture. The geochemical characteristics are similar to those formed in volcanic arcs as well post-collisional bodies, formed in association with oceanic lithosphere.

The stockwork-type gold mineralization is observed in the Teles Pires Intrusive Suite. It is controlled by regional lineaments or shear zones, and best observed in the area of Nova Planeta around the periphery of a monzogranite of the Teles Pires type. Here the strike is E-W, a direction that also coincides with that of a prominent shear zone. This monzogranite is intruded in basement granitoid as well as in volcanic rocks of the Teles Pires Group, as shown by the presence of dykes and apophyses of the intrusion (JICA/MMAJ, 1999; Veiga, 1988).

Base Metals Mineralization

In the Aripuanã region (Fig. 12), low metamorphic acid volcanic and pyroclastic rocks, problably related to the Teles Pires volcanism, host hydrothermalized polymetallic Zn, Pb, Cu, Au and Ag deposits. At the Serra do Expedito *garimpo*, situated to the NW of Aripuanã, the country rocks are metasiltstone that has been correlated to the Beneficente Group, and the mineralization resembles a gossan. There also occurs in this area polymetallic mineralization of the stratabound type related to the intersection of shear zones, striking E-W, in carbonate-rich pelite of the Beneficente Group. The mineralization occurs as massive, disseminated and veined sulphide with pyrite, pyrrhotite, sphalerite galena, and subordinately, gold and silver. Gold mineralization is also associated with the periphery of sub-outcropping intrusives (Neder *et al.*, 1998; Paes de Barros *et al.*, 1999).

In the Moreru area on the Aripuanã River, situated about 250 km NNW of Aripuanã area, Pinho *et al.* (1999) refer to hydrotermalized acid volcanics (1.81 Ga) and pyroclastic rocks with Au mineralization associated with pyrite, chalcopyrite, galena and ilmenite. Sulphides occur as disseminated form or in massive bands in subvolcanic bodies and in quartz-carbonate-chlorite veins cutting rhyolite. These rocks are related to the Teles Pires magmatism.

At Terra Preta, on the Sucunduri Dome (Fig. 12), the Beneficente Group bears copper mineralization (chalcopyrite and bornite) in beds of sandstone, argillite, calcareous sandstone and limestone. The mineralized zones are 7 to 12 m thick and contain copper grades of about 0.35% Cu (Carvalho and Figueiredo, 1982).

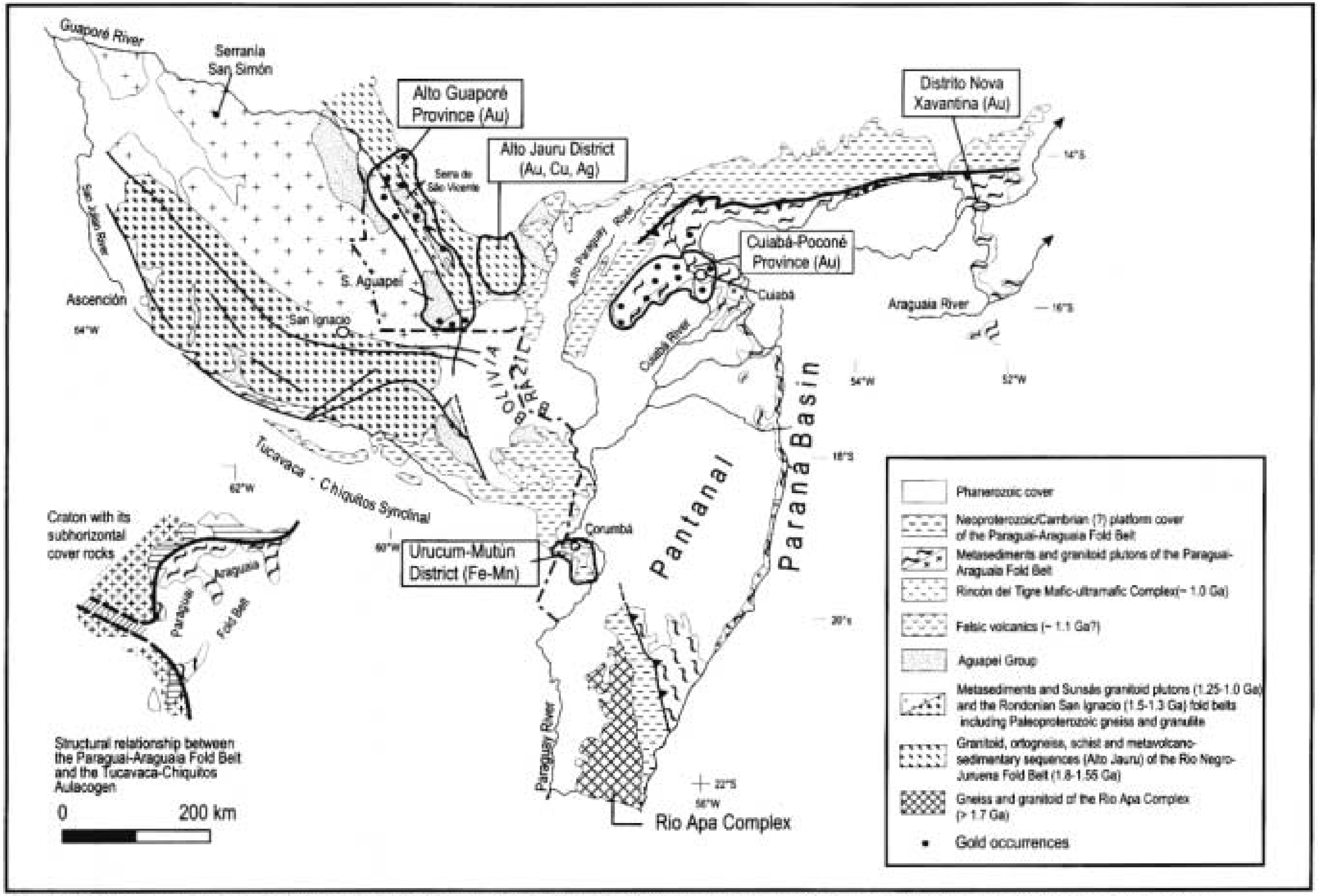


FIGURE 13 - Schematic geological map of the southwestern area of the Amazonian Craton and part of the Paraguai-Araguaia Fold Belt, showing the location of the Alto Guaporé and Cuiabá-Poconé provinces and the Alto Jauru, Nova Xavantina and Urucum-Mutún districts. Modified after Trompette (1994); Litherland et al. (1986); Tassinari and Macambira (1999); and other sources cited in text.

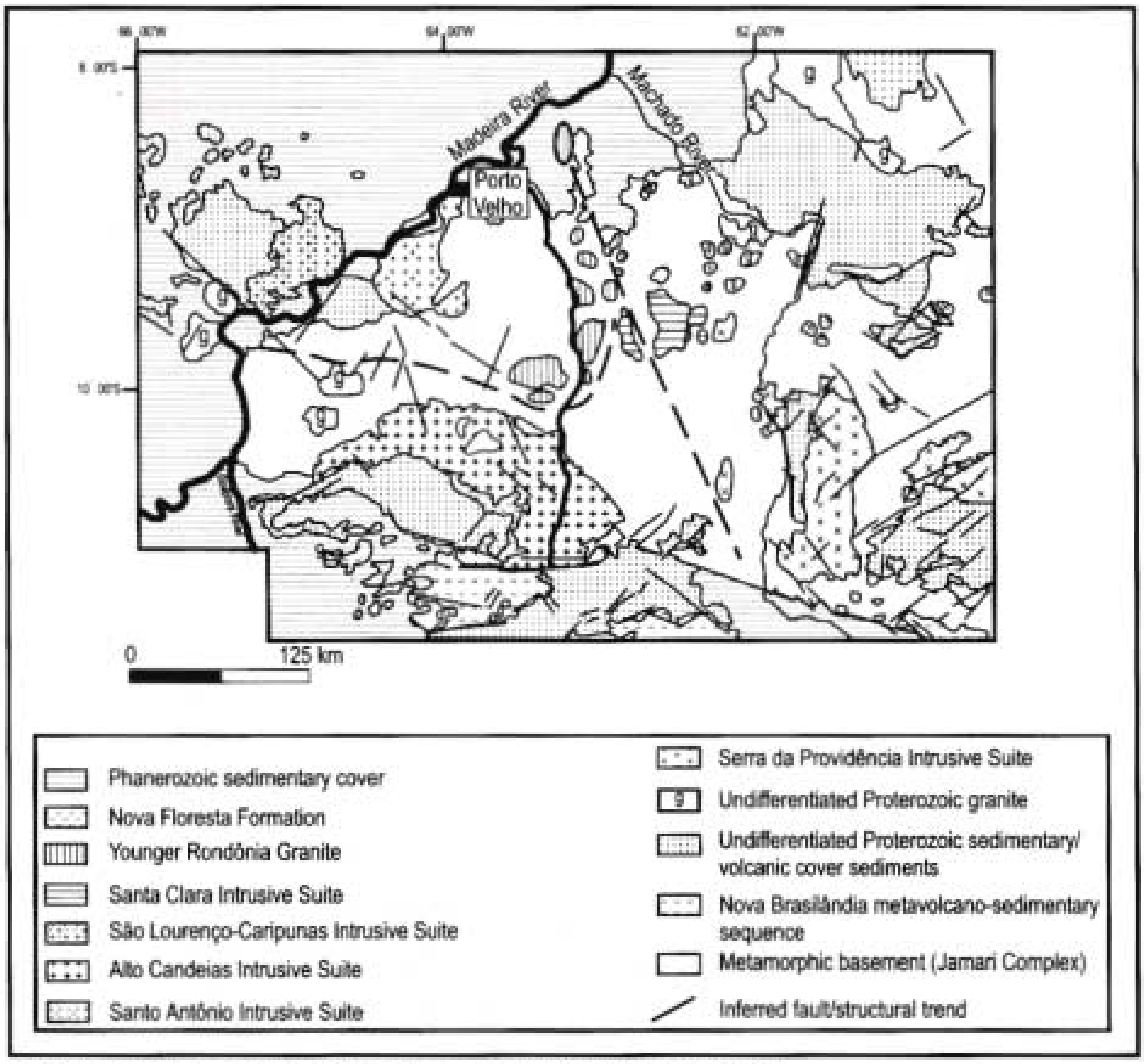


FIGURE 14 - Geological map of the Rondônia Tin Province (modified after Bettencourt et al., 1997).

The Alto Jauru District

The Alto Jauru gold district is situated in the State of Mato Grosso, Brazil, at the southeastern extremity of the Alto Guaporé Gold Province (Fig. 13) and is included in the Rio Negro-Juruena Belt (1.8-1.5 Ga). It consists of three volcano-sedimentary belts striking N25°W, separated by bands of granite-gneiss known from E to W, as Cabaçal, Araputanga and Quatro Meninas, constituting the Alto Jauru Greenstone Belt (Monteiro *et al.*, 1988). There is a Au-Cu-Ag deposit at Cabaçal. The volcano-sedimentary sequence may be divided into three units: (1) a basal unit consisting of mafic-ultramafic volcanic rocks of the Mata Preta Formation; (2) an intermediate unit consisting of acid volcanic rocks of the Manoel Leme Formation; (3) an upper sedimentary unit assigned to the Rancho Grande Formation. Gneissified plutonic rocks of tonalitic composition intrude this sequence. The age of these rocks was determined to be between 2.0 and 1.7 Ga (Geraldes *et al.*, 1996; Pinho, 1996). The Cabaçal gold deposit is associated with a volcano-sedimentary belt that developed in an island arc setting (Pinho *et al.*, 1997). It hosts a sequence of tuff units and intercalated volcaniclastic rocks with chert zones of the Manuel Leme Formation (Monteiro *et al.*, 1988). Three main types of mineralization have been recognized: associated with a shear zone; volcanogenic massive sulphide (VMS) type; and disseminated mineralization in tonalite (Pinho *et al.*, 1997). The third type is disseminated, banded, veined, brecciated and massive, and is composed of sulphide species such as chalcopyrite, pyrite, pyrrhotite, marcasite, sphalerite, cubanite, galena and molybdenite. In addition, there are minerals with selenium, tellurium, Au-Ag and Au-Bi compounds (Pinho, 1996; Pinho *et al.*, 1997). The total reserves of the Cabaçal Deposit are about 1.9 Moz Au, 0.6 Moz Ag and 43 000 t Cu (Souza, 1988), partially mined during the last decade. The mine is now closed.

The Alto Guaporé Gold Province

This province is situated on the boundary between Brazil and Bolivia in the upper reaches of the Guaporé River, in the southern part of the Amazonas Craton (Fig. 13). There occurred between 1.2 and 1.0 Ga the development of the Sunsas passive margin, representing a zone of oceanic expansion between Amazonia and Laurentia, as well as the development of the Aguapeí Aulacogen by intracontinental rifting (Sães and Fragoso Cesar, 1994; Sães, 1999). The closure of this basin by intercratonic collision of the Amazonian Craton and the Grenville Province brought about the formation of the Grenville-Sunsas collision belt, the inversion of the Aguapeí Rift, and the amalgamation of the Rodinia Supercontinent at 1.0 Ga.

The tectonic deformation related to the Sunsas Event is reflected by the development of an extensive shear belt of dextral character striking N20°W, which affected especially, the central zone of the Aguapeí Rift, to which are associated the main gold deposits and occurrences.

The gold mineralization is associated with quartz veining: Laurinha, Pau-a-Pique, São Francisco Xavier and São Vicente, constituting the Alto Guaporé Gold Province (Sães *et al.*, 1991; Silva and Rizzotto, 1994; Geraldes *et al.*, 1996; Sães, 1999). This veining generally occurs at the contact between the sediments of the Aguapeí Group and the granite-gneiss of the basement, and locally in the rocks of the Aguapeí sequence. The gold ore consists of quartz, pyrite and gold, accompanied by magnetite, chalcopyrite, galena and arsenopyrite. The hydrothermal alteration associated with the mineralization involved silicification, chloritization and sericitization which has been dated at between 960 and 910 Ma by K/Ar. The deposits are small with grades between 0.6 and 20 g/t Au, and reserves amounting to some tonnes of gold. Gold mining in the Serra de São Vicente has been going on for almost a century. The gold occurs in placer deposits formed from the erosion of sediments and quartz veins of the Aguapeí Group. The total reserves in alluvial-coluvial material are given as 0.14 Moz at an average grade of 0.14 g/m^3 Au. The gold reserves of the Alto Guaporé Province exceed 90 t Au.

In this province there also occurs mineralization associated with volcano-sedimentary units of the San Ignacio Group. However, the most important occurrence is situated to the NW, outside the province at Serrania San Simon, Bolivia, near the Guaporé River (Fig. 13). At this locality the gold mineralization is associated with the San Ignacio tectonic event (1.4-1.3 Ga) and occurs in hydrothermal gold-quartz space-filling lodes in greywacke, sandstone and conglomerate beds of the low-grade metamorphic San Ignacio schist belt. It is estimated that some 4 t of gold have been mined from vein and secondary deposits (Litherland *et al.*, 1986).

The Rondônia Tin Province

According to Bettencourt *et al.* (1997) cassiterite was discovered in 1952 in the then Territory of Rondônia, and has since been intensively mined by *garimpeiros* and mining companies. The total production up to 1995 has been estimated at about 220 000 t Sn. Present production is about 7500 tpa from the still active Bom Futuro and Santa Bárbara mining districts.

In the Rondônia Tin Province (Fig. 14) the Sn deposits and associated metals (W, Nb, Ta, Cu, Zn, Pb) are spatially related to the final phases of the rapakivi anorogenic granite intrusives of São Lourenço-Caripunas (SLC: 1.3 Ga) and the Younger Rondônia Granites (YRG: 950 Ma). These two suites are correlated with the development of the Sunsas-Aguapeí Orogen that occurred between 1.30 Ga and 900 Ma. The SLC is related to an extensional phase that preceeded the orogenic phase, whereas the YRG are interpreted as a distal manifestation of the orogenesis.

The YRG occur mainly in the Massangana, Ariquemes, São Carlos, Caritianas, Pedra Branca, Santa Bárbara and Jacundá massifs, situated in the central part of the province. The intrusive suite displays three distinct intrusive granite phases:

(a) an early phase, only observed at the Massangana Massif, consisting of coarse-grained biotite syenogranite with subordinate hornblende and accessory minerals that include zircon, apatite, ilmenite, magnetite and fluorite.

(b) an intermediate phase consisting essentially of fine to medium-grained syenogranite and alkali-feldspar granite with biotite, and locally with hornblende. The most common accessory minerals are zircon, monazite, ilmenite and fluorite.

(c) A late phase consisting essentially of topaz, Li-mica-albite granite and topaz-quartz-feldspar porphyry.

The tin mineralization and associated metals are spatially associated with the two last phases, occurring mainly in the form of Li-mica-albite granite with disseminated cassiterite and less abundant quantities of columbite-tantalite; pegmatite with topaz, beryl, cassiterite and subordinate columbite-tantalite; greisen bodies with cassiterite; quartz veins with cassiterite and wolframite; and quartz veins with Cu-Pb-Zn-Fe sulphides.

THE SÃO FRANCISCO CRATON

The São Francisco Craton (Fig. 15) (Alkmin *et al.*, 1993; Almeida, 1977) started its evolution in the Archean and ended at the close of the Mesoproterozoic. It is delimited by Neoproterozoic mobile belts related to the Brasiliano Cycle: Brasilia, Rio Preto, Riacho do Pontal, Sergipano, and Araçuaí (Fuck *et al.*, 1993).

The São Francisco Craton may be divided into three main compartments (Barbosa, 1997) the strike of which is broadly N-S: Eastern, Central and Western that are exposed over extensive areas of the states of Bahia, Minas Gerais and Goiás. The limits of these compartments correspond to large tectonic features, also with N-S strike: the tectonic limits of the marginal coastal basins; the Contendas-Jacobina Lineament, the Espinhaço Lineament; and the limit of the São Francisco Craton with the Brasília Belt.

These three compartments contain important deposits, of which the most important are associated with:

- Granite-greenstone terranes: Au and Mn of the Rio das Velhas greenstone belt (Quadrilátero Ferrífero); gold of the Rio Itapicuru greenstone belt; magnesite of the Brumado greenstone belt; barite of the Mundo Novo greenstone belt;
- Mafic-ultramafic complexes: Fe-Ti-V of the Jacaré and Campo Alegre de Lourdes sills; chrome at Rio Jacurici and Campo Formoso, and copper at Rio Curaçá/Caraíba;
- Exhalative sedimentary sequences: Fe of the Minas Supergroup (Quadrilátero Ferrífero); Pb-Zn at Boquira; Fe-Mn at Urandi-Licinio de Almeida;
- Sedimentary sequences: Au-U-Py at Jacobina and Moeda; diamond at Diamantina and on the Chapada Diamantina.

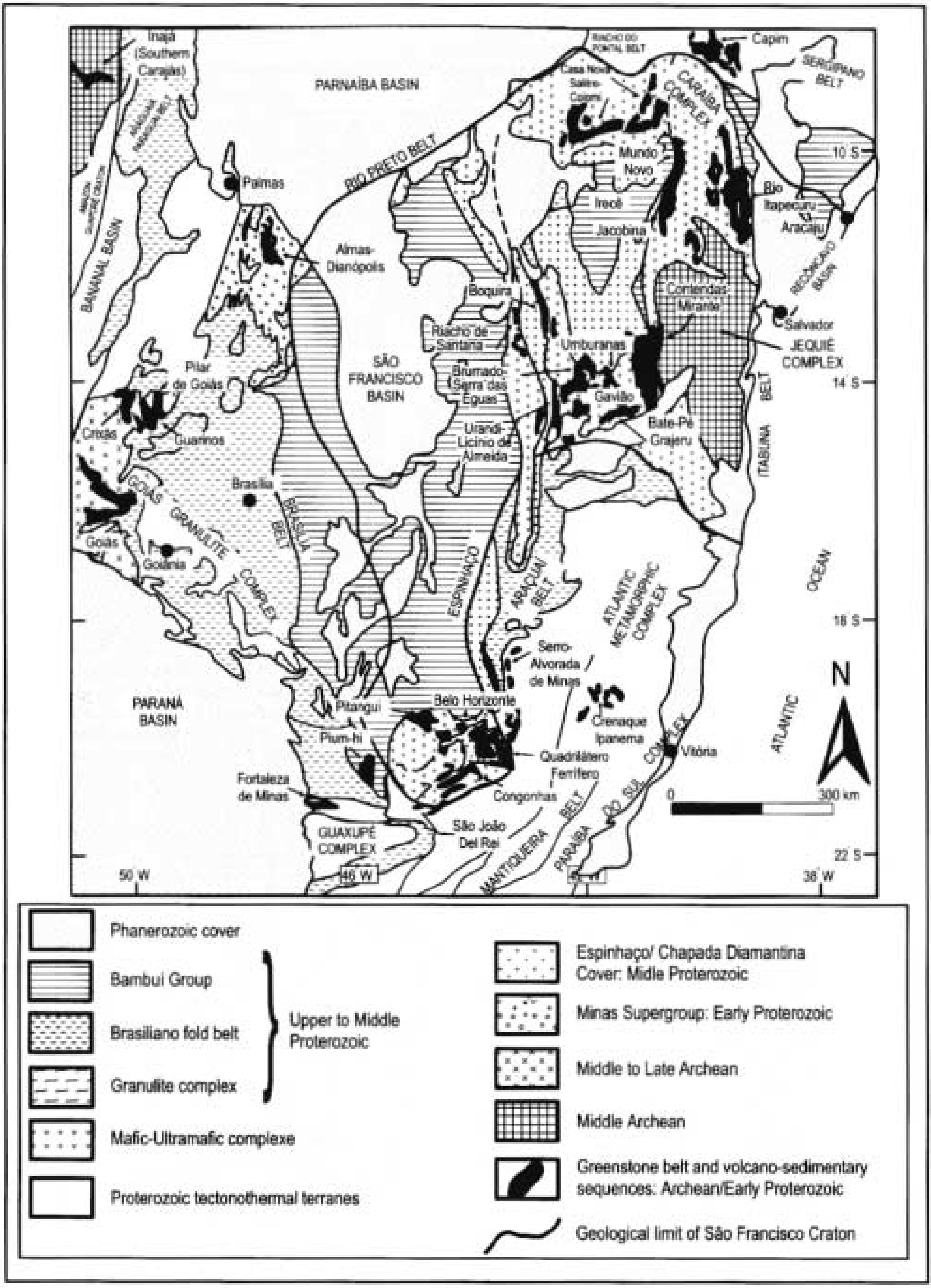
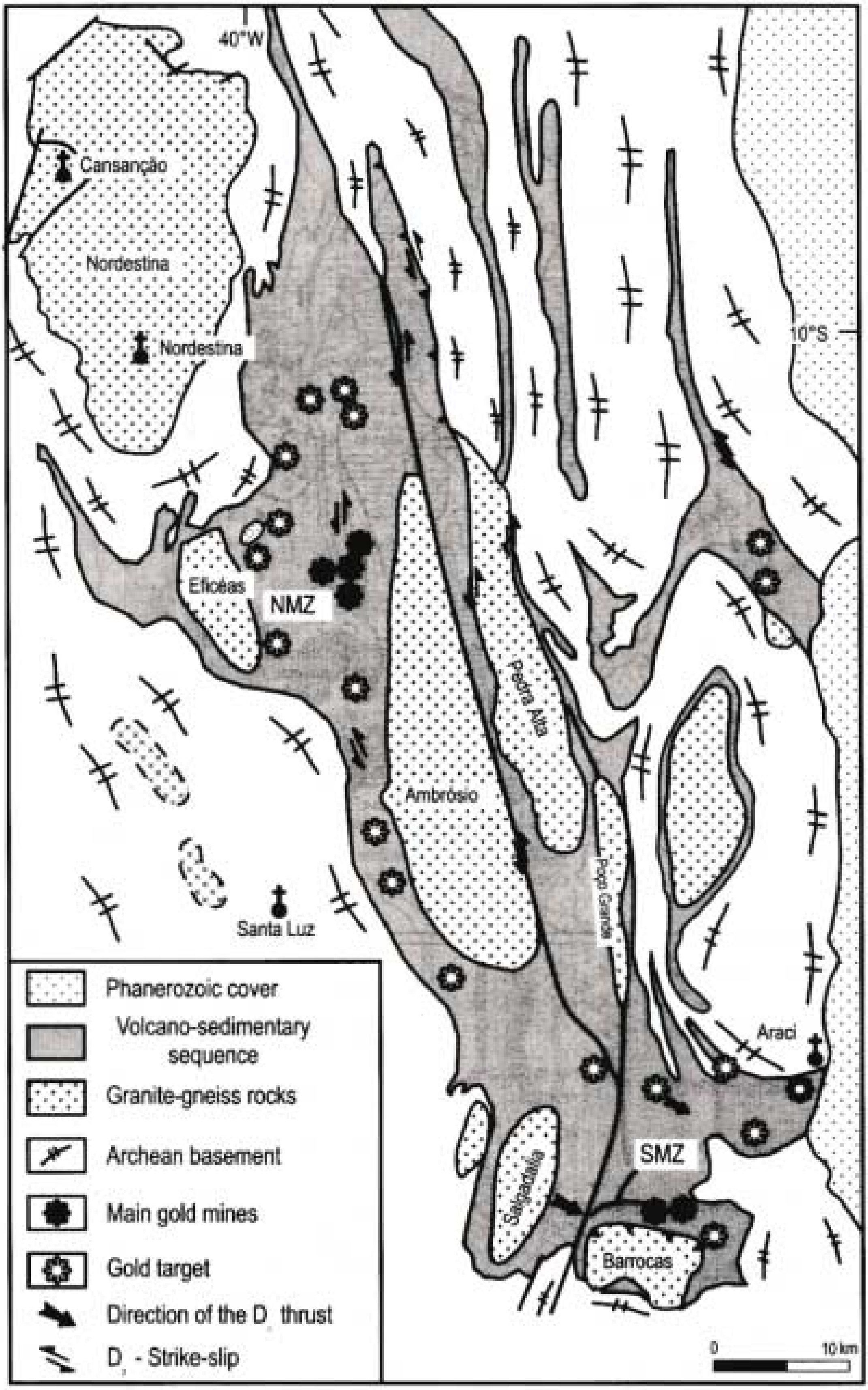


FIGURE 15 - Geological map of the São Francisco Craton and surrounding areas.



FIGURES 16 - Simplified geological map of the Rio Itapicuru Greenstone Belt. The North Mineralized Zone (NMZ) and the South Mineralized Zone (SMZ) are indicated (modified after Silva and Villas, 1998)

The Eastern Compartment

The Eastern Compartment includes the Jequié and Serrinha blocks with extensions into the Macururé Domain of the Sergipano Belt, the Itabuna and Curaçá-Salvador belts, as well as with the Jacobina rift sequence.

The Itapura Barite Deposit

The Itapura barite deposit (Castro *et al.*, 1997) is situated near the town of Miguel Calmon and is not well known. It occurs as hydrothermal veins that cut the metasedimentary unit of the Mundo Novo greenstone belt. However, one can observe banded iron formation units and zones with stratiform barite, intercalated with beds of chert, which favour the hypothesis of an exhalative origin of a distal facies of a volcano-sedimentary sequence. In the Mundo Novo greenstone belt, defined by Mascarenhas and Silva (1994), also occur some gold showings and those of base metals (Cu-Pb-Zn) at Fazenda Coqueiro where disseminations and zones of massive sulphide (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena and associated gold) can be observed in mafic and felsic volcanic rocks, intercalated with pelitic and chemical metasediments.

Rio Itapicuru Gold Province

The Rio Itapicuru greenstone belt (Fig. 16) (Davison *et al.*, 1988), metamorphosed in the greenschist facies, is hosted in the Serrinha Block, which is represented by the Santa Luz Complex. This complex of Archean age consists of gneiss, granodioritic orthogneiss, amphibolite and intrusions of differentiated mafic-ultramafic complexes containing chromite associated with the Pedras Pretas Deposit, situated near the town of Santa Luz. The volcano-sedimentary sequence consists of a basal mafic volcanic unit of tholeiitic composition of ocean-floor origin; an intermediate to felsic calc-alkaline volcanic unit, having the characteristics of a continental arc; and an upper sedimentary unit consisting of turbidite beds, chert and BIF units. It is intruded by syn to late tectonic Type I granitoid plutons. The evolution of the supracrustal and granitoid rocks occurred between 2.2 Ga (basalt) and 2.0 Ga (syn-tectonic granitoid) as determined by Sm/Nd, Pb/Pb, U/Pb geochronology in zircon, and by Rb/Sr (Silva and Cunha, 1999). Important gold concentrations are found in the Fazenda Maria Preta District to the N of the Rio Itapicuru greenstone belt and in the Weber Belt, situated to the S of the Rio Itapicuru greenstone belt (Kishida *et al.*, 1991).

The Fazenda Maria Preta deposits (Coelho and Freitas-Silva, 1998; Alves da Silva *et al.*, 1998) are found in three second order sinistral shear zones, the attitude of which is N-S/50°70°W. These zones lie parallel to the main shear zone farther to the E that affected the Maria Preta unit, which consists of andesitic lava flows intercalated in pyroclastic rocks and metasediments. The main mineralized zones are associated with quartz veins parallel to the mylonitic foliation and to breccia and stockworks of the wall rock. Pronounced veining, silicification and carbonatization attest to the intense circulation of hydrothermal fluids along the shear zone, resulting in the growth of quartz, carbonate, albite, and the precipitation of sulphides (pyrite, arsenopyrite, pyrrhotite), besides sericite and chlorite. The gold is free in the quartz and in the sulphide minerals. The deposits of the Fazenda Maria Preta district are not important economically. The reserves are estimated at 12.5 t of gold. The deposit was mined by open-pit methods to a depth of 100 m.

The deposits of the Weber Belt (Santos *et al.*, 1988;Teixeira *et al.*, 1990; Reinhardt and Davison, 1990; Alves da Silva *et al.*, 1998) are found to the S in an E-W bend that corresponds to a zone of overthrusting, resulting in the overturning of the stratigraphic units, which from S to N are: the Incó unit, consisting of carbonate-chlorite schist representing basalt; the Fazenda Brasileiro unit, bearing the most important gold mineralization; the Canto unit, containing pelitic-carbonaceous sediments intercalated with pyroclastic volcanic rocks; and the Abóbara unit, consisting of a thick sequence of basalts with thin sedimentary intercalations.

The Fazenda Brasileiro unit consists mainly of two zones of quartz-chlorite-magnetite-schist (magnetic schist) which host the gold mineralization. The upper magnetic schist zone is overlain by a sequence of graphitic schist. The magnetic schist zones have a thickness of 20m and 3m, respectively. Both magnetic schist zones are separate by an intermediate sequence of sericite-chlorite-carbonate-schist and plagioclase-actinolite-schist, the latter representing altered gabbroic bodies.

At the Fazenda Brasileiro Mine, the reserves of which are estimated at about 150 t of gold at 7 to 8 g/t Au, the mineralization is associated with zones of more or less graphitic quartz-chlorite-magnetite schist. The mineralized bodies may be up to 500 m long and 40 m wide, and they contain several generations of quartz veins with associate sulphide, locally forming a sulphide alteration halo with pyrite, pyrrhotite, arsenopyrite, carbonate and albite. Arsenopyrite is the most important sulphide species on account of the fact that it is always associated with gold. However, at the other mines in the Weber Belt, the gold may be associated preferentially with pyrrhotite. The gold is free, and occurs in the intergranular contacts, microfractures, and as fillings in sulphide. The circulation of hydrothermal fluids that gave origin to the mineralization of the Weber Belt are related to D_2 and D_3 events, and were for the best part channeled along shear zones resulting from the D_1 deformational phase.

The Rio Jacurici and Campo Formoso Chromite Districts

The chromite deposits of Medrado and Ipueira, situated in the Valley of the Jacurici River are associated with a mafic-ultramafic complex, some 7 km long and 300 m thick, intruded into the Salvador-Curaçá Belt. These deposits were initially interpreted as a stratified sill (Barbosa de Deus and Viana, 1982) in the contact between quartz-feldspathic granulite at the base, and a metasedimentary sequence at the top consisting of serpentinite-marble, diopsidite and metachert, forming a large synform the axis of which strikes N-S. The sill consists mainly of dunite, harzburgite, pyroxenite and gabbro (Fig. 17) in which there is intercalated a zone of cumulate chromite having an average thickness of 5 to 8 m, locally attaining 15 m. The chromite grains are subhedral and fine-grained, having an average diameter of 0.4 mm. The chromite is rich in chrome (48.8% Cr2O3) with a low Cr/Al ratio of about 3.2. According to Marques (1999), the cryptic variation of the minerals along the sill suggests injections of a primitive magma during the formation of the main chromite zone. The chromite reserves of the Ipueira-Medrado Sill are estimated at about 8 Mt (Mello *et al.*, 1986).

The Campo Formoso Complex is about 40 km long and 900 m wide. It is intruded into the granulitic rocks of the Mairi Block, and cut by the Campo Formoso Granite, dated at 2.0 Ga. The complex is covered discordantly by rocks of the Jacobina Group. From base to top it consists of actinolite gneiss, tremolite-actinolite serpentinite and serpentinite-chlorite-carbonate-talc schist; the two upper units contain seven chromitite beds with massive, disseminated and stringer ore (Barbosa de Deus *et al.*, 1982). The chromite grains are euhedral, and have an average diameter of 1 mm. They display a network texture, and locally an olivine-fill texture. The chromite is rich in Cr_2O_3 (up to 60%), and has high Cr/Al (*c.* 6.5) and Cr/Fe (*c.* 3.0) ratios.

The emerald deposits known in the Campo Formoso area are associated with a granite intruded at 2.0 Ga into the ultramafic rocks of the complex (Giuliani *et al.*, 1993).

The Rio Curaçá Copper District

The Caraíba copper deposit (D'el Rey Silva and Oliveira, 1999; Lindenmayer, 1981) is situated in the valley of the Curaçá River. It is associated with a mafic-ultramafic intrusive complex in the high-grade metamorphic Curaçá-Salvador Belt generated by the collision of the Serrinha and Mairi continental blocks at about 2.0 Ga. The sequence consists of gneiss with intercalations of amphibolite, paragneiss, BIF units, calc-silicate rocks, olivine marble and quartzite at the base; gabbro, gabbronorite, leucogabbro, peridotite, olivine-pyroxenite, hypersthenite rich in Cu, melanorite and norite in the intermediate unit; and migmatitic gneiss with syn-tectonic granite intrusions (tonalite and granodiorite) in the upper unit. The structure of the complex is vertical following polydeformation and polymetamorphism, in addition to shearing along ductile structures striking NNW-SSE and NNE-SSW. The mineralization consists essentially of chalcopyrite and bornite, which are disseminated or form massive irregular bodies in the coarse-grained hypersthenite, concordant with the mafic and metamorphosed sequence of the wall rock. The mineralized sill is attributed to successive intrusions of mantle-derived material before or during the D_1 deformation. The entire tectonic evolution is - considered to have occurred between 2.2 and 1.9 Ga. Mining since 1978 in open-pit and underground workings, the Caraíba Deposit has produced up to 1998 about 600 Mt of ore at 1.6% Cu.

To the N, in the Macururé Block, the Serrote da Laje Cu-Ni-Co deposit, situated in the proximity of Arapiraca (Alagoas), shows Cu-Ni-Co sulphide mineralization (Figueiredo, 1992; Horbach and Marimon, 1988).

The Jacobina Au-U-Py Deposit

The Jacobina gold deposit (Fig. 18) was mined continuously between 1973 and 1996. The ore-zone is hosted in a thick sequence of clastic metasediments assigned to the Jacobina Group of vertical attitude overlying the basement consisting of older granite-gneiss. The Jacobina Group is divided into three formations: The Serra do Córrego at the base, consisting of conglomerate and quartzite beds that host the gold-bearing zones; followed by an intermediate unit known as the Rio do Ouro Formation, consisting mainly of quartzite; and the Cruz das Almas Formation at the top, formed mainly of pelite beds. The Au-U-Py mineralization is associated with the conglomerate beds of the Serra do Córrego Formation. The more important zones are known as the Basal Reef, Main Reef, João Belo and Canavieiras, in which the gold grade varies between 2 and 100 g/t Au (Cox, 1967; Molinari, 1982; Molinari and Scarpelli, 1988; Scarpelli, 1991). The gold is associated with pyrite and may constitute up to 30% of the matrix of the conglomerate and with brannerite/uraninite. The most common accessory minerals are tourmaline, zircon, thorite, magnetite and chromite. The gold mineralization is considered to be a paleoplacer of the Witswaterrand-type and has been strongly affected by metamorphism and by percolating waters along shear zones, following the classification of a paleoplacer-type, modified as proposed by Ledru and Bouchot (1993).

The Central Compartment

In the Central Compartment are included the Gavião and Paramirim Blocks with extension to the N into the Sobradinho Domain; the Umburana, Ibitira-Ubiraçaba, Brumado, Guajeru and Contendas-Mirante granite-greenstone terranes; the Boquira and Licinio de Almeida-Urandi sedimentary-exhalative sequences, as well as the Mesoproterozoic cover of the Chapada Diamantina and of the Northern Serra do Espinhaço.

The Gold and Base Metals Occurrences Associated with Archean Greenstone Belt Sequences

In the Gavião Block occur several supracrustal volcano-sedimentary sequences of the greenstone belt-type: Umburana (UGB), Ibitira-Ubiraçaba, Brumado (BGB), Guajeru. The Contendas-Mirante (CMGB), which is situated in the ambit of the Jacobina-Contendas-Mirante Lineament is here incorporated in the Central Block in the interests of clarity. Numerous gold and base metals showings (Cu, Pb, Zn) are known in the UGB and CMGB, which are being prospected (Silva and Cunha, 1999).

The Jacaré Sill Fe-Ti-V-Pt Deposit

The stratified Jacaré Sill, dated at 2.9-2.8 Ga (Brito *et al.*, 1999) or 2.4 Ga (Marinho, 1991) is intruded into the Contendas-Mirante greenstone belt along the Jacobina Lineament (Galvão *et al.*, 1986; Brito, 1984), and represents

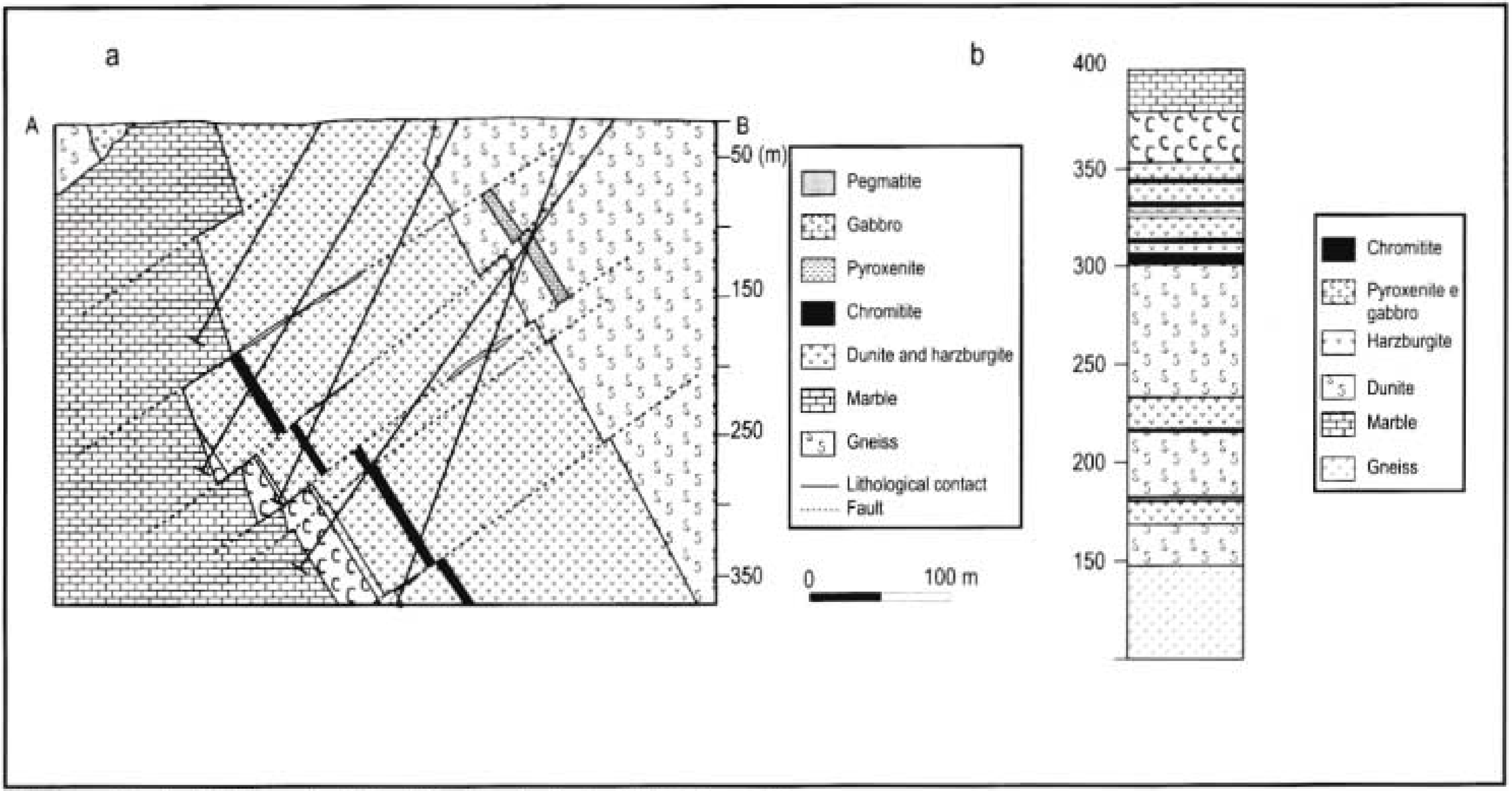


FIGURE 17 - a - Schematic geological cross-section of Ipueira Sill; b - Stratigraphic column (modified after Marques,1999).

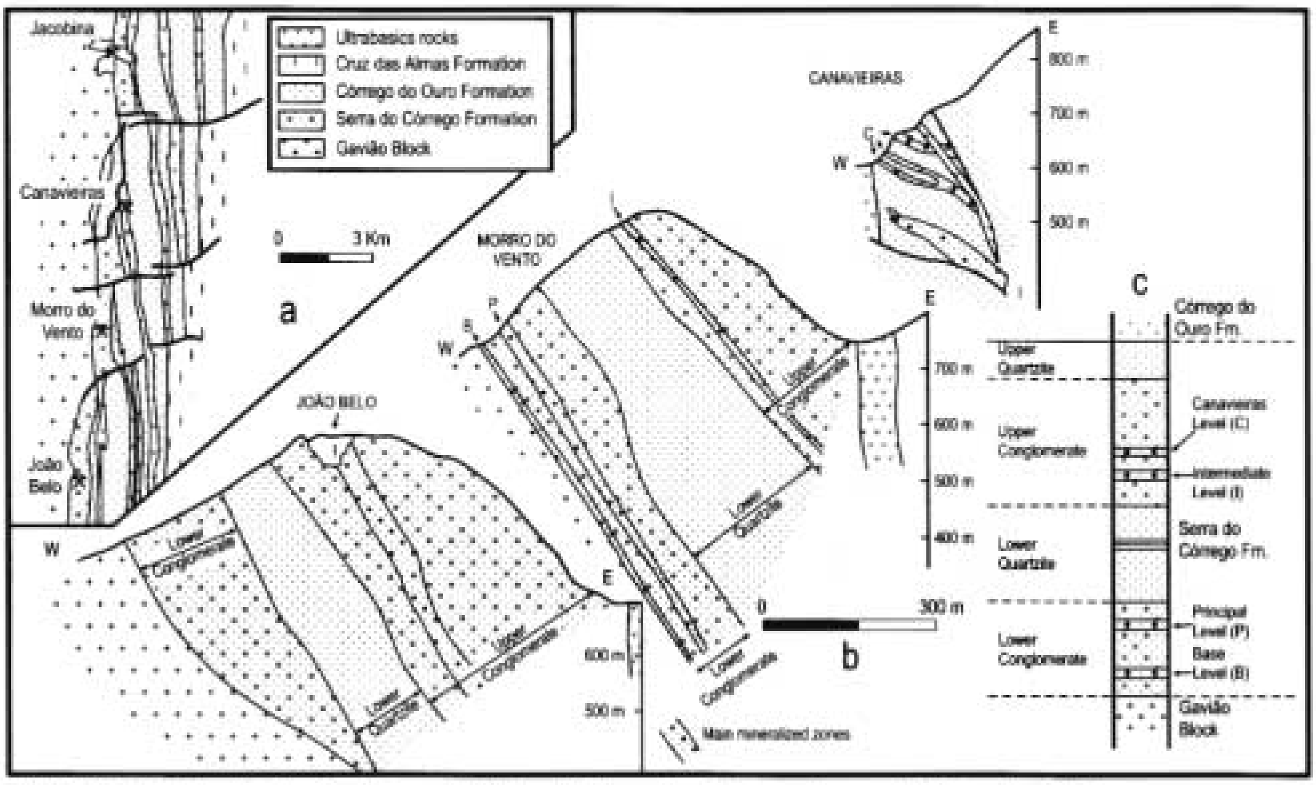


FIGURE 18 - Gold mineralization of Jacobina. a - simplified geological map; b - main cross-sections; and c - lithostratigraphic column.

a potential target for Fe-Ti-V mineralization. The Fe-Ti-V deposit at Fazenda Gulçari is associated with the Jacaré Sill. The deposit is divided into two zones: a Lower Zone and an Upper Zone. The Lower Zone (400 m) consists of gabbro, gabbronorite and anorthosite of generally coarse-grained and massive aspect without magnetite. The Upper Stratified Zone (600 m) consists of medium to coarse-grained gabbro with rhythmic layering in the Lower Member, manifest by alternations of magnetite and pyroxene at the base, grading gradually to melanogabbro with pyroxenitic bands in the Central Member; and by layered gabbro intercalated with zones of pyroxenite and magnetitite in the Upper Member.

The Fazenda Gulçari Fe-Ti-V deposit is hosted in the Lower Member of the layered part of the sill. It has an oval pipe-like shape (400 m x 150 m), displaying broadly concentric zonation, with an external aureole of hornblende grading to pyroxenite, magnetite-pyroxenite and magnetitite at the centre. Pegmatoid structures are often observed in the several aureoles. There occur two types of ore: massive and disseminated. The mineralization consists mainly of titanomagnetite, ilmenite and ulvospinel. The ilmenite forms discrete grains or ribbon-like exsolution structures composed of magnetite. Disseminated sulphide (>1%) is present. The gangue mineral consists of diopsidic augite. The reserves at Fazenda Gulçari are given as 6.1 Mt of ore at an average grade of 1.27% V_2O_5. Important PGE anomalies have been defined in association with magnetitite and are investigated.

More or less of the same age is the Campo Alegre de Lourdes Sill Fe-Ti-V deposit, situated in the Sobradinho Domain, N of the Central Compartment in the State of Bahia (Sampaio *et al.*, 1994).

The Serra das Éguas Magnesite Deposit

The Serra das Éguas magnesite deposit (Bodenlos, 1960) is associated with the Archean volcano-sedimentary sequence of the Brumado greenstone belt that overlies the basement rocks of the Gavião Block. The sequence consists of three units: the Lower Ultramafic Unit (200 m) consisting of ultramafic flows intercalated with siliceous-carbonate and carbonate rocks; an Intermediate Unit (500 m) consisting essentially of chemical sediments such as magnesitite and dolomite with intercalations of tuff and ultramafic flows; and an Upper Unit (*c.* 700 m) consisting of quartzite, ferruginous quartzite and itabirite with intercalated tuff and volcanic flows. The Serra das Éguas (Fig. 19) is situated near the town of Brumado, Bahia, and hosts the largest magnesite deposits in Brazil with reserves of about 150 Mt, and production of about 1.7 M tpa. The talc reserves are about 1 Mt, and the production is 30 000 tpa (Oliveira *et al.*, 1997). The main characteristic of the magnesite deposits is the sedimentary nature of the magnesitite, and the continuity and thickness of the beds, as well as the intimate association of these with dolomite. These factors favour an origin related to the chemical precipitation of magnesite, permitting a comparison of the Serra das Éguas Deposit to deposits of the Veistsch-type. However, the presence of submarine volcanism associated with sedimentation suggests the possibility that this volcanism may have contributed significantly to the supply of magnesium involved in the precipitation of magnesite.

The Boquira Pb-Zn Deposit

The Boquira Deposit (Fig. 20) is situated in the valley of the Paramirim River. The deposit was discovered in 1952,

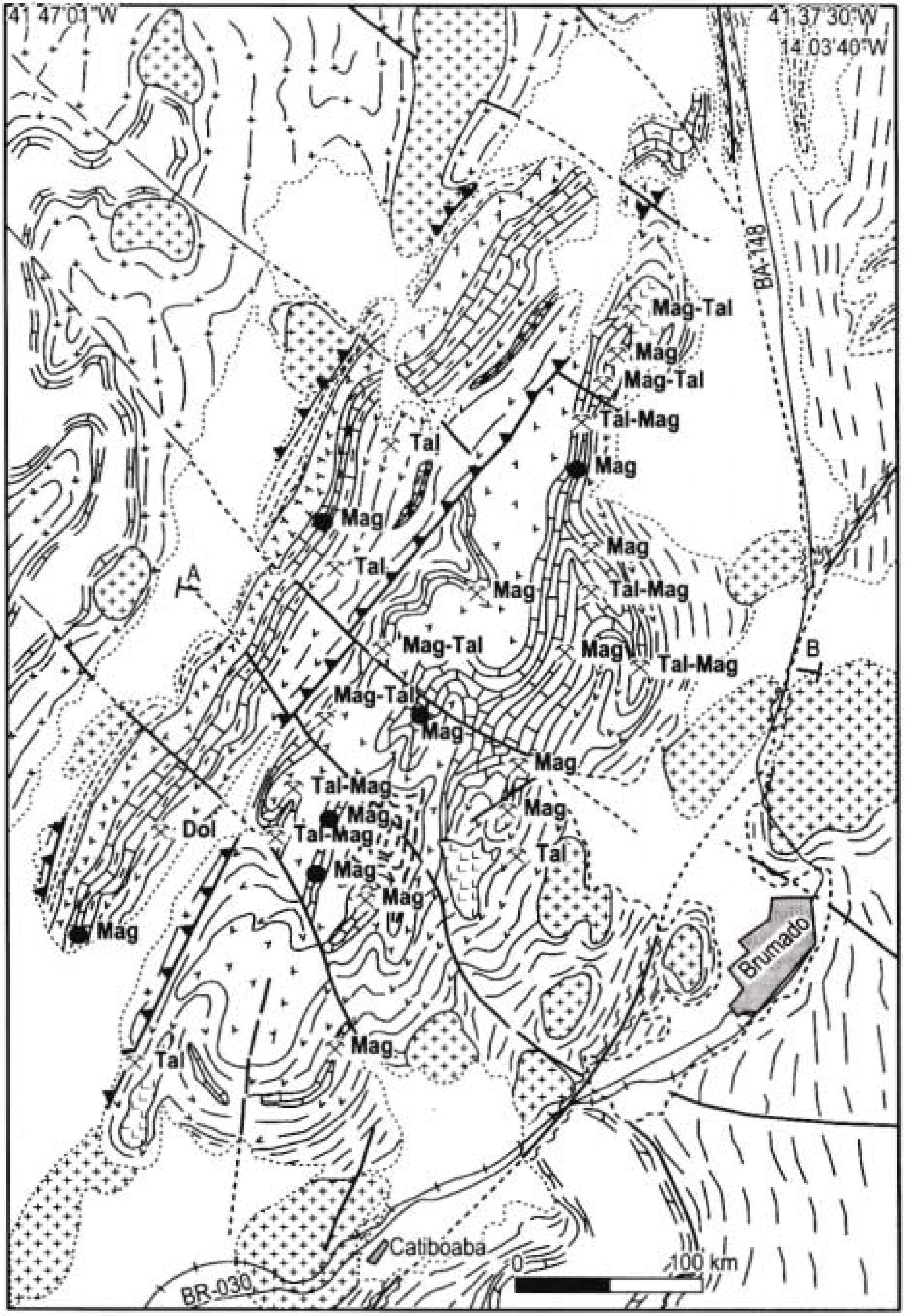


FIGURE 19 - Geological sketch map of the Serra das Éguas magnesite deposit: mag = magnesite; ta = talc (modified after Oliveira et al.,1997).

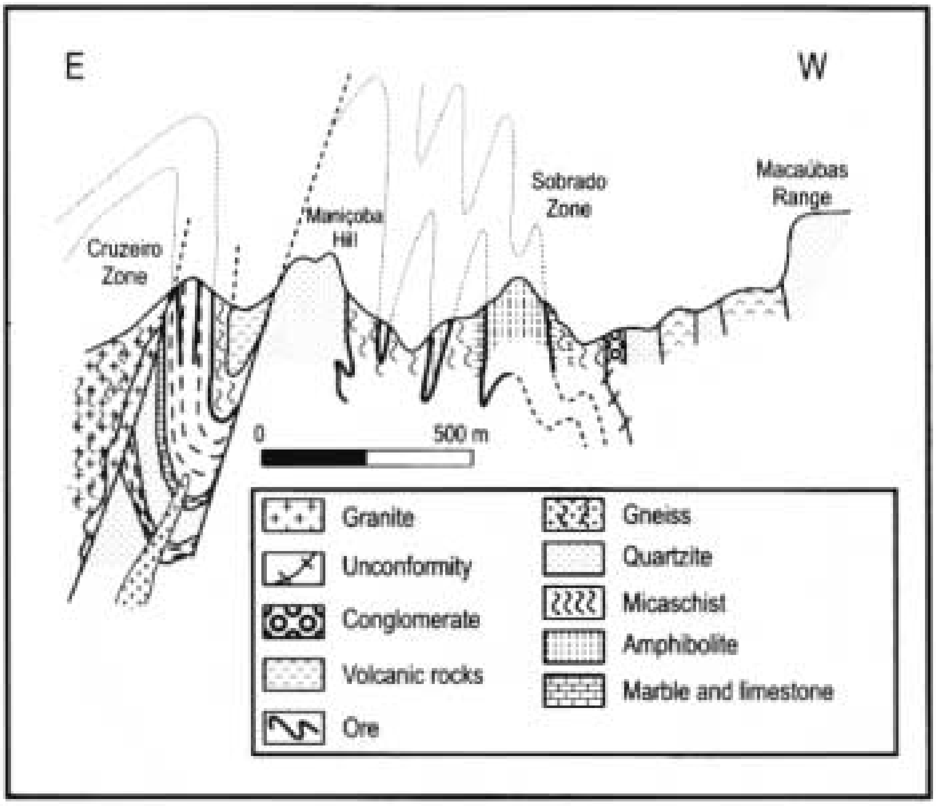


FIGURE 20 - Geological cross-section through the Boquira Mine (modified after Fleischer, 1976; Espourteille and Fleischer, 1988).

and between 1959 and 1992, mine production was about 650 000 t of Pb+Zn. The deposit is hosted in the Boquira Formation (Fleischer and Espourteille, 1999; Espourteille and Fleischer, 1988) consisting of quartzite, amphibolite, marble, BIF units and chlorite-garnet-biotite schist that pass transitionally to gneiss and migmatite of the Paramirim Block. The Boquira Formation, which is intruded by granite and pegmatite, disappears to the NW under the Mesoproterozoic cover of the northern Espinhaço range. The mineralized zones have been intensely folded and sheared, and display a characteristic banding that appears as quartz-magnetite, silicate-magnetite and carbonate-silicate amphibolite facies (Rocha, 1985). The mineralization has been dated at 2.7 Ga by Pb/Pb, and consists essentially of galena, rich in silver (up to 260 g/t Ag), and sphalerite associated with pyrite and subordinate chalcopyrite. Near the surface the mineralization is affected by weathering to a depth of 20 m with the formation of oxides such as cerussite, smithsonite, limonite and anglesite, along with pyromorphite, hemimorphite, hydrozincite, chrysocolla, bornite, covellite, malachite and smaller amounts of azurite.

The stratiform character of the mineralization, intimately associated with primary banding and the presence of banded iron formation units, favours a sedimentary-exhalative origin for the mineralization (Misi *et al.*, 1996, 1999; Carvalho *et al.*, 1997).

The Chapada Diamantina Diamond Deposits

The region around the towns of Lençóis, Andaraí, Mucugê, Xique-Xique, in the Chapada Diamantina (diamond tableland), in the State of Bahia, has been famous for its diamond production since the last century. Mesoproterozoic diamondiferous conglomerate occurs (a) in the Tombador and Morro do Chapéu formations of the Chapada Diamantina Group (*c.*1.2-1.0 Ga) and (b) in weathered alluvium and colluvium as the product of the erosion of the conglomerate beds by river action. The former has been worked mainly by *garimpeiros*.

The diamond fields have a large distribution throughout the Chapada Diamantina reaching about 300km from one extreme to another. Five different diamond fields are distinguished: Lençóis-Andaraí-Mucugê, Santo Inácio, Piatã-Serra do Bastião, Chapada Velha and Morro do Chapéu. With the exception of Morro do Chapéu, all the other fields are related to the Formação Tombador, the most important diamond-bearing unit of the Chapada Diamantina.

A characteristic feature of the Chapada Diamantina is the abundance of *carbonado* associated with gem diamond. This region has been mainly a producer of *carbonado*, which on average has larger dimensions than of the gem diamond. The color of the carbonado varies from dark grey to black. One *carbonado* weighing 3,167 ct, and believed to be the largest in the world, was found in 1895 near the town of Lençóis. Gem diamond is small, usually weighing less than one carat. The largest concentrations of diamonds occur in alluvial placers along the Paraguaçu, Santo Antonio and São José rivers with estimated reserves exceeding 1.5 M carats. The diamond reserves of the whole Chapada Diamantina are estimated at 3.8 M carats. The source of the diamonds remains unknown. Paleocurrents of the Tombador Formation, measured in the Lençóis-Andaraí-Mucugê field, indicate an extra-basinal origin for the diamonds coming from E-NE (Sá *et al.*, 1982; Sampaio *et al.*, 1994; Misi and Silva, 1996; Schobbenhaus, 1996).

The Lagoa Real Uranium Deposit

The Lagoa Real uranium deposit (Oliveira *et al.*, 1985; Forman and Waring, 1981) is situated near the town of Caetité (BA), to the E of the Serra do Espinhaço. The underlying rocks are Archean granite-gneiss and migmatite (Lagoa Real Complex) is intruded by several porphyritic granite bodies known as the São Timóteo Granite, dated at 1.74 Ga (Turpin *et al.*, 1988; Cordani *et al.*, 1992; Pimentel *et al.*, 1994). The gneiss of the Lagoa Real Complex and the São Timóteo Granite are cut by regional shear zones, along which occur a number of lenticular albitite bodies that host the uranium mineralization (Geisel Sobrinho *et al.*, 1980; Brito *et al.*, 1984; Lobato *et al.*, 1983; Raposo *et al.*, 1984). These bodies are distributed along two main lineaments that show that the shearing, sodium metasomatism and mineralization are contemporaneous (Lobato and Fyfe, 1990; Lobato *et al.*, 1998).

The metasomatic albitite forms lenticular bodies, the length of which varies from metres to kilometres, with thickness varying from a few centimetres up to a hundred metres. The bodies plunge along the lineation of cataclastic origin and form elongate ore shoots that may be 850 m long at depth, such as occur at the Rabicha Deposit. The mineralization consists mainly of uraninite in the form of microcrystalline and microgranular crystals (F » 0.023 mm). The age of the mineralization that has been dated at about 1.5 Ga (Turpin *et al.*, 1988; Cordani *et al.*, 1992) is related to a hypothetical Espinhaço event. The same mineralization was dated at 960 Ma by U/Pb in titanite (Pimentel *et al.*, 1994), undergoing recrystallization and remobilization at about 500 Ma, occurring during the Brasiliano tectono-thermal cycle.

The Lagoa Real District is the most important uranium district in Brazil with reserves given as 93 190 t U3O8.

The Western Compartment

In the Western Compartment are situated the Almas-Dianópolis, Guanambi-Correntina and Quadrilátero Ferrífero blocks, the granite greenstone terranes and volcano-sedimentary sequences of the Riacho de Santana, São Domingos and Rio das Velhas, the sedimentary-exhalative sequences of the Minas Supergroup and the Espinhaço sedimentary sequences.

The Occurrences of Gold and Base Metals of the Volcano-Sedimentary Sequence of Riacho de Santana

In the Guanambi-Correntina Block, the Riacho de Santana volcano-sedimentary sequence, considered to be a greenstone belt (Silva and Cunha, 1999; Lobato *et al.*, 1999), are found the most promising anomalies for gold and base metals in association with gossan (1.3% Cu and 2 to 5 g/t Au) overlying metatuff, chert and carbonate beds.

The Gold Deposits of the Almas-Dianópolis Volcano-Sedimentary Sequences

These sequences that occur on the São Francisco Craton to the N of the Brasilia Fold Belt are considered to be Paleoproterozoic greenstone belts (2.2 Ga). They contain numerous gold occurrences associated with volcanic rocks and intercalated banded iron formation units. The largest gold deposit (Córrego Paiol Mine) is situated near the town of Almas in the State of Tocantins where the gold is associated with a shear zone and intense hydrothermal alteration that affected the mafic rocks of the sequence (Cruz, 1998; 1993; Lobato *et al.*, 1999).

The Quadrilátero Ferrífero Au, Fe, Mn Province

The Quadrilátero Ferrífero Mineral Province (Fig. 21) is situated in the southern part of the São Francisco Craton, is well known for its deposits of gold, manganese and Cu-Ni-Co-Pt in the rocks of the Rio das Velhas Supergroup *(Archean), as well as for its deposits of iron and gold in the* Minas Supergroup (Paleoproterozoic).

The Mineral Deposits of the Rio das Velhas Supergroup

The Rio das Velhas Event (2.78-2.70 Ga) was coeval with the development of the Rio das Velhas greenstone belt at 2.772 Ga, and with the intrusion of tonalite, granodiorite and granite between 2.78 and 2.77 Ga (Noce, 1995; Noce *et al.*, 1998). The final phase of Archean cratonization is marked by granite intrusions at 2.612 Ga, and metamorphism at 2.61-2.59 Ga (Romano, 1989; Romano *et al.*, 1991; Machado and Carneiro, 1992). The Rio das Velhas Supergroup (Dorr, 1969) is divided into the Nova Lima and Maquiné groups. At its base, the Nova Lima Group consists of mafic and ultramafic volcanic rocks, including komatiite and tonalite associated with banded iron formation units of the Algoma-type, phyllite with chlorite and graphite, greywacke, felsic volcanic rocks and pyroclasts, all metamorphosed in the greenschist facies. At the top of the sequence the Maquiné Group consists mainly of metasediments consisting of conglomerate, quartzite, phyllite and greywacke, being subdivided into the Palmital and Casa Forte formations.

The Nova Lima Group gold deposits

The most famous of all the gold deposits in Brazil are associated with the rocks of the Nova Lima Group: Morro Velho (> 470 t Au), Raposos (> 40 t Au), São Bento (> 80t Au), Faria, Bicalho, Bela Fama, Brumal (> 30 t Au), Cuiabá (> 180t Au), Lamengo (> 10 t Au) (Ladeira, 1980, 1988, 1991; Ribeiro-Rodrigues, 1998; Ribeiro-Rodrigues *et al.*, 1996; Sales, 1998; Lobato *et al.*, 1998; Vieira and Oliveira, 1988; Abreu *et al.*, 1988).

The mineralized bodies have an elongate shape (Fig. 22), and they are controlled by the stretching lineation the strike of which coincides with the fold axes, and which is associated with ductile shear zones locally kilometres in

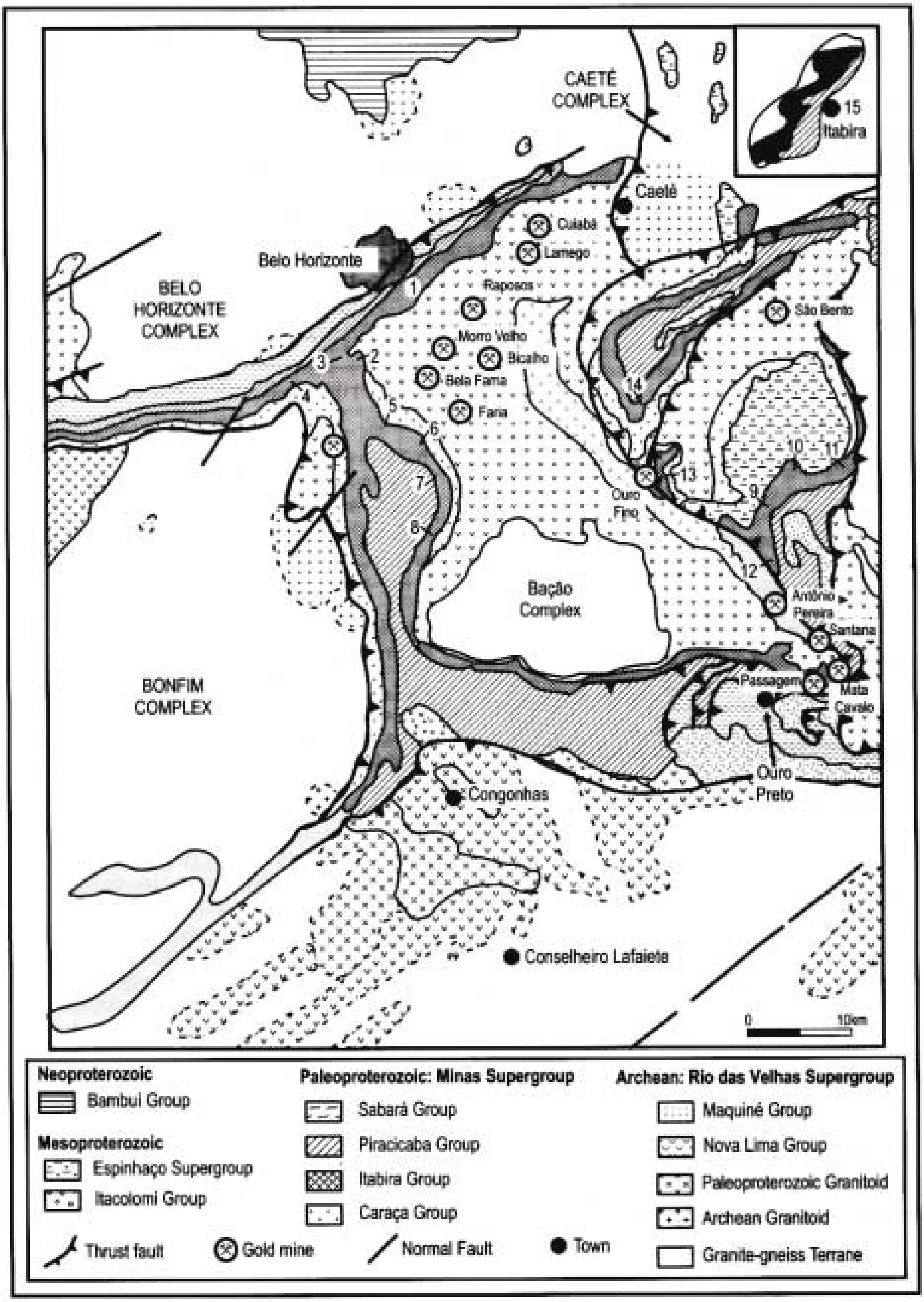


Fig. 21 - Geological map of the Quadrilátero Ferrífero (modified after Noce,1995; Pedrosa-Soares et al., 1994) showing main gold ore deposits and iron ore deposits. Gold deposits: ..Iron deposits: 1 - Águas Claras; 2 - Mutuca; 3 - Capão Xavier; 4 - Jangada/Samambaia; 5 - Tamanduá; 6 - Serra/Capitão do Mato; 7 - Abóboras; 8 - Pico; 9 - Miguel Congo; 10 - Alegria; 11 - Fazendão; 12 - Timbopeba;13 - Capanema; 14 - Gandarela, 15 - Itabira

length. The mineralization is concentrated in the hinges of the folds the axes of which are displayed parallel to the bedding. These shear zones are associated with intense hydrothermal alteration, attention to which was drawn by Vieira who also described these features in detail (Vieira, 1987, 1988, 1991; Lobato *et al.*, 1998). In the mafic and ultramafic volcanic rocks, the hydrothermal alteration is manifest in an external chloritization zone, an intermediate zone of carbonatization (ankerite), and an internal zone with sericitization, albitization, silicification, tourmalization and sulphidization. The sulphide mineralization occurs preferentially in the Algoma-type banded iron formation units that have as their principal feature magnetite-rich banding and/or siderite as may be seen at the Cuiabá, Lamengo, Raposos, São Bento deposits. Elsewhere, such as at Morro Velho, Bicalho, Bela Fama, the sulphide mineralization occurs in a generally massive carbonate zone (Lapa Sêca), locally banded and consists of siderite and ankerite together with quartz, albite, sericite and sulphide. However, some deposits and many mineralized zones in diverse deposits are associated with the development of shear zones in hydrothermally-altered schist, as may be seen at the Juca Vieira Deposit in which the sulphide mineralization occurs with sericitization and carbonatization, intimately related with quartz veining (Lobato *et al.*, 1998), but the main structural features are related to the Transamazonian Event.

The main point of discussion over the gold deposits of the Nova Lima Group is over the existence of syn-sedimentary stratiform mineralization associated with banded iron formation units prior to shearing; and the age of the shearing that gave origin to the hydrothermal mineralization: Archean (*c.* 2.6 Ga) or Transamazonian (2.0 Ga). Some consensus exists that the first and mineralizing tectonic event is of Archean age (DeWitt *et al.*, 1994; Thorpe *et al.*, 1984).

The Conselheiro Lafaiete Mn deposit.

In the region of Conselheiro Lafaiete-Ritápolis-Nazareno there are numerous occurrences associated with manganese found in the volcano-sedimentary sequence of the Barbacena Group, correlative with the Nova Lima Group of the Rio das Velhas Supergroup. The manganiferous ores are of two types (Pires, 1977, 1983): gondite, rich in silicate, and manganese with rodonite, spessartite, tefroite etc.; queluzite, rich in manganese carbonate such as rhodochrosite.

Taking for example the deposit of Morro da Mina, the mining operation initially started working the products of lateritic weathering, enriched in Mn (average grade 46% Mn), and consisting of cryptomelane and pyrolusite. After the oxide ore had been worked out, mining started in the carbonate-rich proto-ore (queluzite) having manganese grades between 30% and 37%. In 1997, the reserves at Morro da Mina were about 3 Mt, and the production was 150 000 tpa. The origin of the primary mineralization is attributed to the classical volcano-sedimentary model.

The Morro do Ferro greenstone belt Ni-Cu-Co-PGE + Au deposit

The Rio das Velhas Supergroup is also related to the greenstone belt sequences that occur to the W of the Quadrilátero Ferrífero. These sequences have been dated at about 3.0 Ga (Noce, 1995) and they are associated with the chromite deposit of the Pium-hi greenstone belt, the nickel laterite deposit at Morro de Niquel, and the O'Toole Ni-Cu-Co-PGE + Au deposit in the Morro do Ferro greenstone belt of the Fortaleza de Minas region.

The O'Toole Ni-Cu-Co-PGE + Au deposit of the Morro do Ferro greenstone belt (Brenner *et al.*, 1990; Cruz *et al.*, 1986; Teixeira *et al.*, 1987) is hosted in a unit of a komatiitic suite consisting of olivine peridotite, peridotite, pyroxenite and basalt, all metamorphosed in the greenschist facies. The basalt has a massive or layered aspect with olivine cumulate at the base and spinifex textures at the top, as well as pillow structures and breccia intercalated with tuff and banded iron formation units. Clinopyroxenite, amphibolite and BIF overlie the serpentinite body. The main ore-types are brecciated, disseminated, banded and stringer ore. The mineralization consists of pyrrhotite, pentlandite, chalcopyrite, cobaltite and PGM. The reserves are given as 6.6 Mt of ore at 2.2% Ni, 0.4% Cu, 0.05% Co, and 1.2 ppm PGM + Au. The O'Toole Deposit is similar to Ni sulphide deposits associated with Archean komatiite sequences. However, the mineralization occupies an unusual position in the ultramafic sequence, being situated in the upper part of the sequence, whereas it is more usual to find this type of deposit at the base.

The Deposits of the Minas Supergroup

The evolution of the Minas Supergroup (Dorr, 1969) (Fig. 21) probably began in Paleoproterozoic times with the deposition of the Caraça Group and the Cauê and Gandarela formations of the Itabira Group in basins that resulted from the rifting of the Archean Platform (Renger *et al.*, 1994). At the base of the Caraça Group, the Moeda Formation contains conglomerate beds with Au-U-Py Witwatersrand-type mineralization (Renger *et al.*, 1988; Minter *et al.*, 1990). The Gandarela Formation was dated at 2.42 Ga. The sedimentation of the Piracicaba Group defines a period of oceanic expansion and the subduction of the ocean crust manifest in the intrusion of the Maranhão Batholith at 2.124 Ga. The basin closed with crustal collision between 2.065 and 2.035 Ga during the Transamazonian Event (Marshak and Alkmin, 1989; Marshak *et al.*, 1992), and was succeeded by the deposition of the Itacolomi molasse. The Transamazonian Event brought about the individualization of the extensive Cinturão Mineiro (Teixeira, 1985) that lies along the southern margin of the São Francisco Craton, with prolongation to the NE, where its definition is complicated by tectonic events occurring in the Mesoproterozic and Neoproterozoic.

The iron ore deposits of the Minas Supergroup

The huge iron ore deposits of the Quadrilátero Ferrífero (Melo *et al.*, 1986; Gomes, 1986; Barcelos and Büchi, 1986) are associated with the Cauê Formation of the Itabira Group, and resulted from the lateritic weathering of the Cauê Itabirite, increasing the iron grade to 36% to 49%, and locally to 65% by the total or partial leaching of silica and the precipitation of iron oxides and hydroxides together with the residual hematite and the transformation of the compacted itabirite to a rich, friable iron ore.

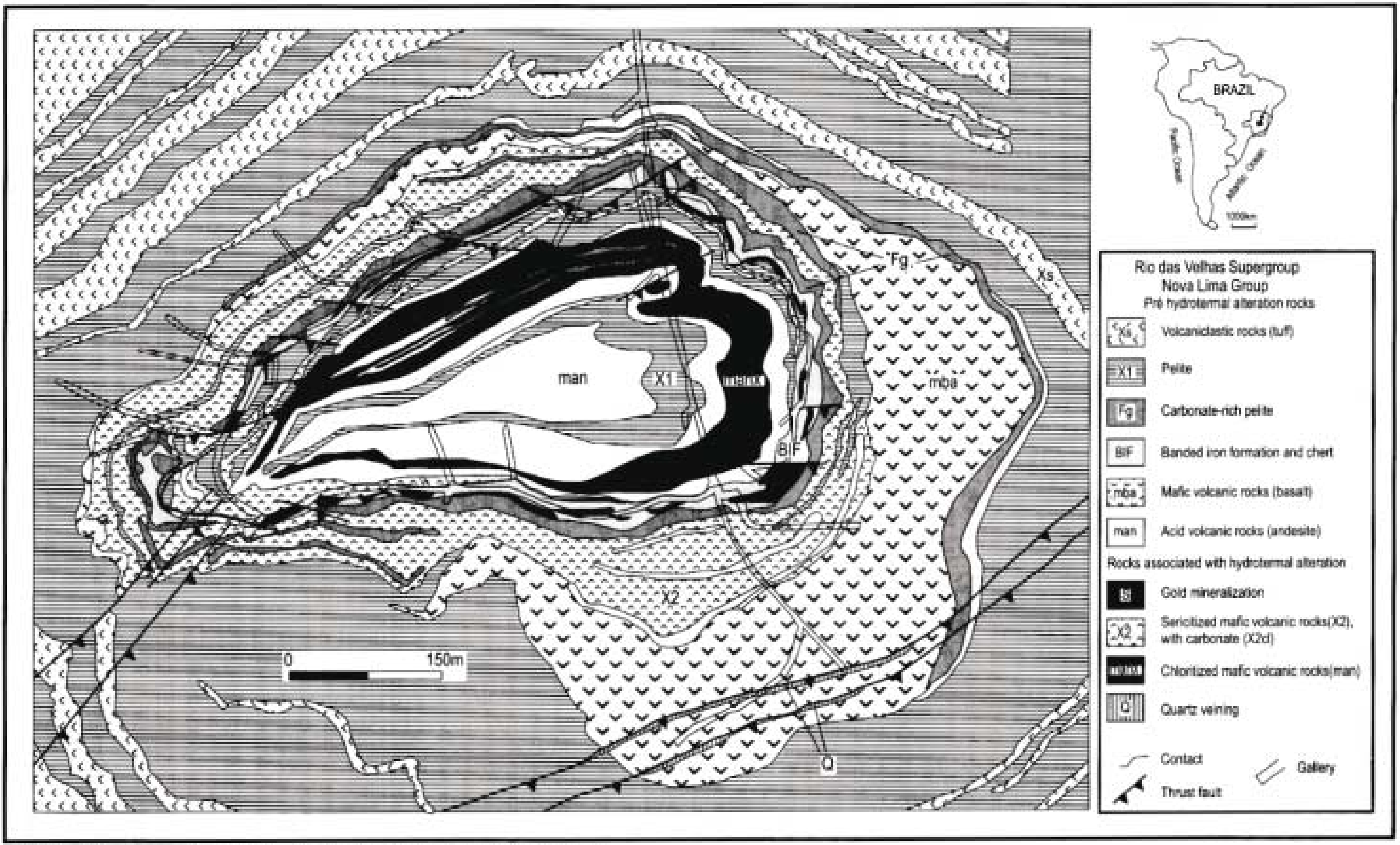


FIGURE 22 - Geological map of the Cuiabá Mine, level no. 3 (modified after Vial, 1988; Vieira, 1991).

The itabirite of the proto-ore is generally preserved in a synform, greatly affected by overthrusting and shear zones associated with the Transamazonian tectonic event at about 2.0 Ga (Noce, 1995).The itabirite displays a banding typical of banded iron formation units of the Superior Province-type, with an alternation of siliceous lamina in the form of quartz, and lamina rich in iron oxide, principally hematite and subordinately secondary magnetite in large martitized crystals. In many deposits, such as the Águas Claras Deposit, the itabirite shows banding consisting of dolomite and quartz/hematite at the base. Lateritic weathering is especially deep over the dolomitic itabirite in function of the higher solubility of the carbonate. The reserves of the Quadrilátero Ferrífero have been estimated at about 29 billion t of iron ore at grades between 50% and 65% Fe. In 1998, the production from all the mines of the Quadrilátero Ferrífero was about 200 Mt of iron ore. The genetic model advanced here proposes a sedimentary exhalative SEDEX-type for this iron deposit.

The gold deposits of the Mariana District

Near the towns of Ouro Preto and Mariana occur several gold deposits: Santana, Antônio Pereira, Passagem de Mariana etc., situated along the Mariana Anticline that constitute a gold district (Duarte and Pires, 1996; Chauvet and Menezes, 1992, Chauvet *et al.*, 1994; Ledru and Bouchot, 1993). These deposits show distinct characteristics, which permit their distinction from deposits associated with the Nova Lima Group. In the Mariana District the gold mineralization occurs in the tectonic contact between units assigned to the Nova Lima Group and the Itabira Group. The gold is hosted in quartz veins with ankerite, tourmaline and arsenopyrite (Vial, 1988), situated between the Paleoproterozoic itabirite and the Archean schist. The gold is found in association with bismuthinite and in the interstices and microfractures of arsenopyrite, quartz, carbonate and tourmaline. The mineralization was already considered to be syngenetic by Fleischer and Routhier (1973), and is related to an extensional phase following the development of a low-angled shear zone (20°-25°) of Transamazonian age (*c.* 2.0 Ga) (Ribeiro, 1998) or during the Brasiliano Tectonic Event as proposed by Chauvet *et al.* (1994).

The gold deposits associated with itabirite

At the Cauê and Conceição mines of the Itabira District, situated to the NE of the Quadrilátero Ferrífero, the gold deposits are hosted in the itabirite. The gold mineralization (*Jacutinga*) is very rich, with grades varying from 10 g/t Au to 1000 g/t Au. The mineralization is contained in at special type of itabirite distributed along the stretching lineations during the Transamazonian Event (2.0 Ga). However, according to Galbiatti *et al.* (1999), Galbiatti (1999), and Pereira *et al.* (1999), the formation of ore bodies is associated with dextral transcurrent shear zones having a transtensive component generating a fracture system that cuts the main foliation of the itabirite and hosts the mineralization. The transcurrent fault is related to the Brasiliano Event.

The Emerald Deposits of Itabira

In the region of Itabira, important emerald deposits are hosted in the hydrothermal alteration zone that occurs around the intrusions of Borrachudo-type granite (1.75 Ga) into the ultramafic rocks of the Nova Lima Group (Giuliani *et al.*, 1993) and Brasiliano pegmatite (570 Ma).

The Diamond Deposits of Diamantina

The Diamantina region is well known for its diamond production since the middle of the XVIII century. The diamonds occur in Mesoproterozoic conglomerate beds of the Sopa-Brumadinho Formation of the Espinhaço Supergroup (1.77-1.71 Ga). These deposits have been mined mainly by *garimpeiros* from weathered conglomerate as well as from alluvial deposits derived from conglomerate beds by fluvial erosion. The placers along the Jequitinhonha River are the source of the largest part of the diamond production of Brazil.

The source of the diamonds has been subject of controversy: intra-basin source versus extra-basin source (Chaves and Uhlein, 1991). The main diamond fields in the Diamantina District are: Campo Sampaio-São João da Chapada, Sopa-Guinda and Extração.

Abreu *et al.* (1997) recognized a quartzitic metabreccia of the top of the Sopa-Brumadinho Formation as a primary source of the diamonds. This breccia is interpretaded by the cited authors as vent-breccia deposited in craters of the *maar*-type.

The measured reserves of the Diamantina District are of about 15 M carats. The grade varies between 0.01 and 0.20 ct/m^3 (DNPM-Brazilian Mineral Yearbook, 1978).

THE UPPER PROTEROZOIC FOLD BELTS AND RELATED COVER DEPOSITS

At the end of the Mesoproterozoic the São Francisco and Amazonian cratons were surrounded by Neoproterozoic elongated sedimentary basins, the closure of which by orogenic collage at the end of the Brasiliano Cycle resulted in the development of extensive mobile belts known as the Brasília, Araçuaí, Ribeira, Dom Feliciano and Paraguay-Araguaia belts. In Northeastern Brazil, the Borborema Province represents a complex network of old basement nuclei and Neoproterozoic belts.

The Paraguay-Araguaia Belt

Barbosa *et al.* (1966) and Almeida (1967) first described this fold belt that lies around the margin the Amazonian Craton for over 2500 km. Although it constitutes a prominent tectonic feature of apparent continuity, the Paraguay and Araguaia belts probably represent two independent units with distinct sedimentary and tectonic histories.

The Araguaia Belt (Hasui and Costa, 1990; Hasui *et al.*, 1994; Abreu *et al.*, 1994) that can be traced along a N-S strike length for over 1000 km is about 150 km wide, and may be divided into two main domains: a) the internal zone occupied by the Estrondo Group, consisting of gneiss, mica schist and quartzite, with basement exposure at the centre of structural domes (e.g., the Colmeia, Xambioá and Lontra domes); b) the external zone is represented by rocks of the Tocantins Group consisting mainly of psammite and phyllite. The limit between the external zone and the Amazonian Craton is marked by the Tocantins-Araguaia

Lineament, over 700 km long, and which is expressed by a series of mafic-ultramafic bodies that represent ophiolite fragments (Gorayeb, 1989; Souza *et al.*, 1995). The Araguaia Belt was affected by two main tectonic events: the first displays regional compression with vergence to the NW; the second is characterized by ductil-ruptile shears striking N-S. In this belt the most important prospects are related to base metals associated with ophiolitic bodies (Teixeira, 1996; Kotschoubey *et al.*, 1996).

The Paraguay Belt developed during the Vendian (650-550 Ma) and displays sedimentary and tectonic zonation described by Almeida (1945, 1964), Alvarenga and Trompette (1993). From W to E three zones may be distinguished: a cratonic zone with subhorizontal beds; a pericratonic zone, the characteristic of which is the presence of long, large-amplitude holomorphic folds; and a deep basin zone containing metamorphites with vergence to the W. Regionally, the stratigraphy of the Paraguai Belt may be divided from base to top into four units: a) the Puga Formation, of glacial origin and lateral equivalents corresponding to the Jangada Group, a talus deposit, with the deposition of proximal glacio-marine turbidite beds; b) the Cuiabá Group represented by distal turbidite beds and basin pelite; c) the Corumbá Group, consisting essentially of carbonate rocks including limestone and dolomite; and d) the Alto Paraguai Group consisting mainly of sandstone and arkose.

The only known large deposits in the Paraguay-Araguaia Belt are those of the Fe-Mn Urucum-Mutún mines, near Corumbá, Mato Grosso do Sul.

Historically, the phyllite of the Cuiabá group have been noted for the presence of numerous small gold deposits associated with hydrothermal veining (Alvarenga *et al.*, 1990), and surficial concentrations of gold of lateritic origin (Cuiabá-Poconé Province and the Nova Xavantina District).

In the Cuiabá-Poconé or Baixada Cuiabana Province gold deposits occur as (a) quartz and quartz-pyrite veins cutting low-grade metasediments of the Cuiabá Group; (b) supergene enrichment in laterite; and (c) as placer deposits. The gold grade varies between 0.3 and 2 g/t Au. In 1984/85, the district produced 2.5 t/Au from *garimpeiro* workings (Souza, 1988). In the Nova Xavantina District, situated some 650 km NE of Cuiabá, gold occurs in like manner to the Cuiabá-Poconé Province. Highly brittle phyllite and felsic volcanic rocks represent the Cuiabá Group in this district. The average gold grade in quartz veins is 15 to 20 g/Au m^3. Monthly production from *garimpeiro* workings is between 500-600 kg (Souza, 1988).

The Urucum-Mutún Fe-Mn Deposit

The Corumbá Graben is situated in the junction of the Paraguay Belt with the Chiquitos-Tucavaca Aulacogen that separates the Amazonian Craton from the Apa Block (Litherland *et al.*, 1986), along the border between Bolivia and Brazil. In this extensional environment (Haralyi and Walde, 1986), the graben was filled with sediments of the Jacadigo Group (Fig. 23), which may be divided into three formations (Dorr, 1945, Walde *et al.*, 1981): Urucum Formation, green in colour at the base, and consisting of conglomerate and arkose; the Córrego das Pedras Formation, an intermediate unit, consisting of conglomerate and reddish arkose, enriched in hematite; and the Band'Alta or Santa Cruz Formation consisting of jaspilite with intercalated manganiferous beds. To the N and S, the Jacadigo Group is overlain by carbonate sediments of the Corumbá Group. The conglomerate and arkose of the Urucum Formation represent piedmont sediments along the base of the fault-scarps that delimit the graben. The beds of jaspilite and manganese are attributed to chemical precipitation of alternating bands of iron oxide and silica. However, the jaspilite sequence is intercalated with very many beds of diamictite and arkose with gradational structures that are intensely transformed and substituted, partially or totally, by iron oxide and silica. These observations support the view that the siliciclastic sedimentation persisted during the phase of chemical sedimentation in the form of turbidite beds and subaqueous gravity flows (Dardenne, 1998; Trompette *et al.*, 1998). However, according to a divergent view, the control over the siliciclastic deposits was tectonic rather than sedimentary. The pure jaspilite that formed only by chemical precipitation with alternation of hematite and silica lamina occurs in the upper part of the rhythmic sequence, showing from base to top: ferruginous diamictite and conglomerate, ferruginous arkose with gradational structures, ferruginous shale, and finally, pure finely-laminated jaspilite, with an ocellar texture due to the presence of numerous small pink siliceous nodules, coloured by a fine-grained hematite powder. During supergene alteration, these nodules were leached, preferentially, resulting in a vacuolar aspect, very specific to these jaspilites. The manganese beds consist mainly of cryptomelane, and locally, braunite, appear as zones as at the Morro do Urucum, or as nodules in a kaolinitic and sandy matrix as at Morro do Rabicho. These observations permit the interpretation of the iron and manganese mineralization as the result of chemical precipitation of these elements, and the silica from exhalative (SEDEX-type) hydrothermal fluids circulating in large convection cells. These cells were related to the development of the rift, and the hydrothermal fluids permitted the leaching of basalt associated with up-welling of the upper mantle below the Corumbá Graben (Dardenne, 1998). The continuation of the ferro-magnesian sequence to the W in Bolivia is found at the Serranía de Mutún.

The Brasília Belt and the Goiás Massif

The Brasília Fold Belt (Fig. 24) runs for over 1000 km N-S along the western margin of the São Francisco Craton (Almeida, 1977). In general, the several lithostratigraphic units of the Brasilia Fold Belt show more intense progressive deformation, accompanied by increasing metamorphism from E to W, reflecting in the polarity of the belt and an eastward vergence towards the São Francisco Craton. Three distinct tectonic zones are recognized: a Cratonic Zone, an External Zone and Internal Zone (Fuck *et al.*, 1993, 1994). The Pirineus Mega-inflection (Marini *et al.*, 1984a, b; Araújo Filho, 1999), with general strike E-W, permits the division of the Brasília Fold Belt into two distinct parts: northern

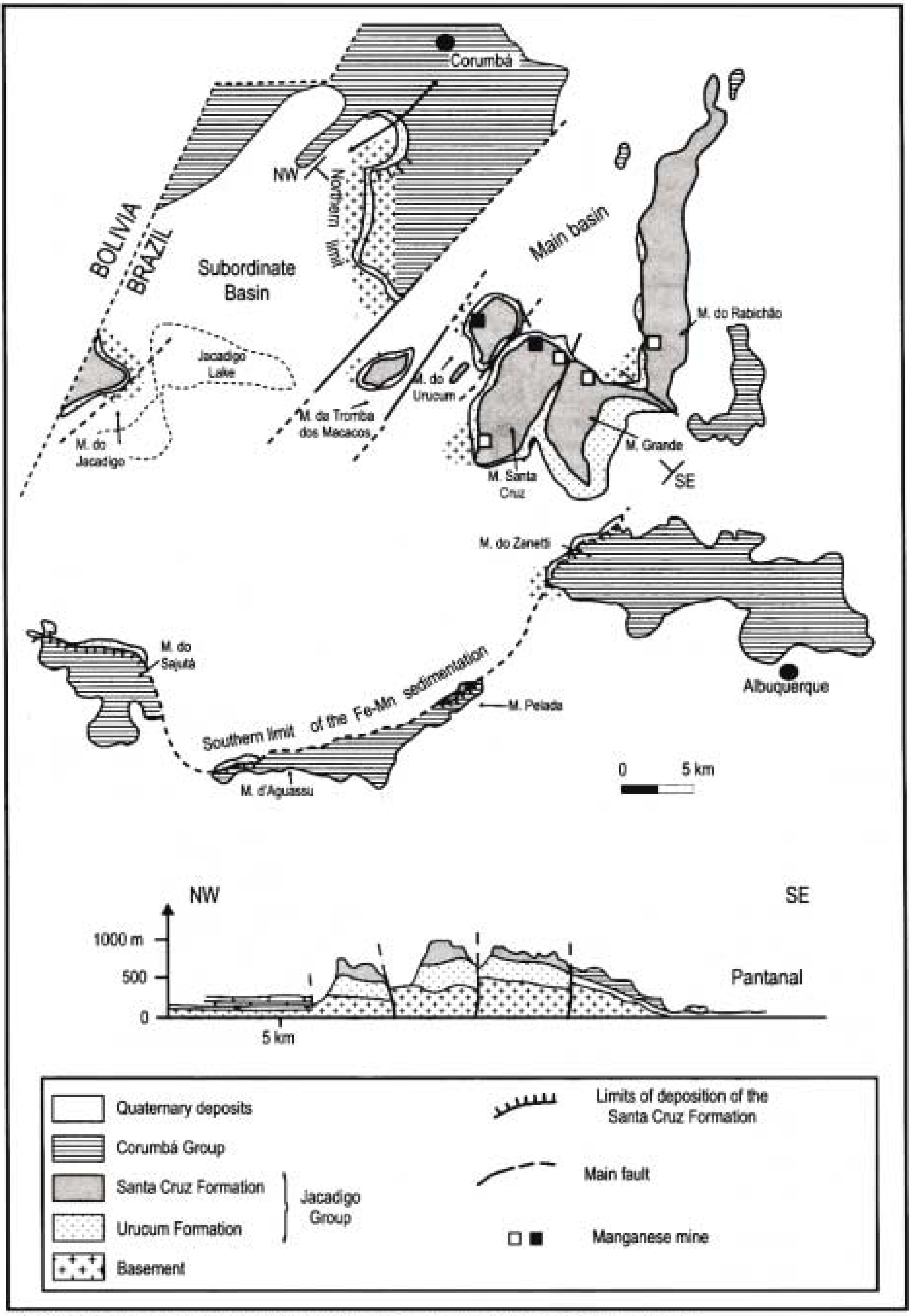


FIGURE 23 - Geological map and cross-section of the Corumbá graben system (modified after Walde et al., 1981).

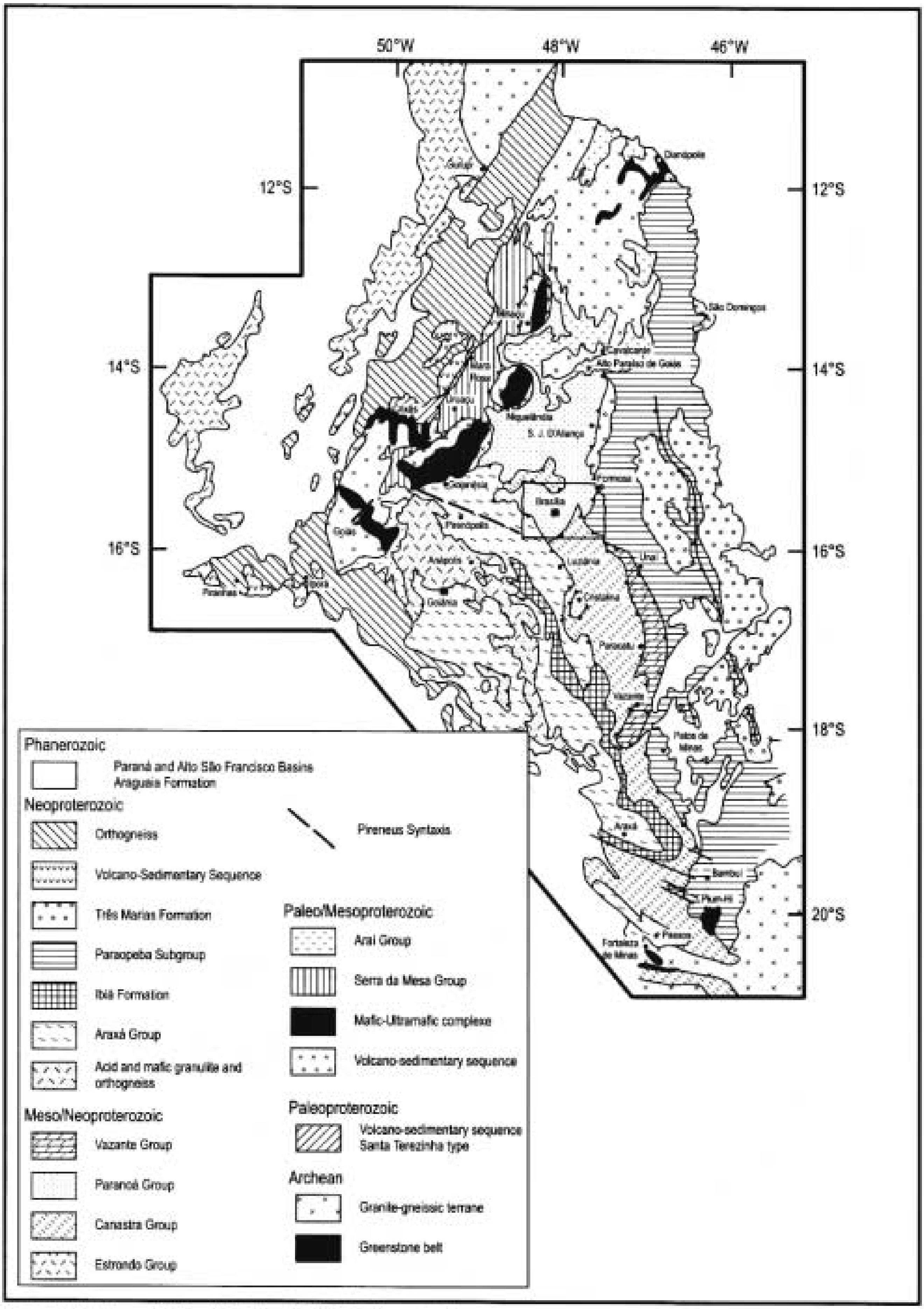


Fig. 24 - Geological map of the Brasília Belt (modified after Dardenne, 1999).

and southern, each undergoing a somewhat different tectonic evolution during the Brasiliano Cycle.

The internal zone of the Brasília Fold Belt and the oldest terranes were both very much affected by deformation and metamorphism during the Brasiliano Event. For this reason both are taken together in the discussion of the tectonic evolution of the Brasília Fold Belt.

The Goiás Massif

The Archean terranes showing ages between 3.0 and 2.5 Ga (Queiroz *et al.*, 1999) occupy an oval-shaped area in the northwestern part of Goiás, in which there occur greenstone belt sequences: Crixás, Pilar de Goiás, Guarinos e Goiás, preserved in elongate synforms in the older granite-gneiss complex: Anta, Caiamar, Hidrolina, Itaporanga and Uvá (Jost *et al.*, 2000). This older nucleus stabilized at about 2.5 Ga, and was accreted to the Santa Terezinha volcano-sedimentary sequence that was deformed and metamorphosed at about 2.0 Ga by the Transamazonian tectono-thermal event (Kuyumjian, 2000).

In the ambit of the Goiás Massif, the principal mineral resources are:

- Gold deposits associated with the Crixás, Guarinos, Pilar de Goiás and Goiás Velho greenstone belts (Carvalho, 1999); Mina III and Mina Nova in the Crixás greenstone belt (Fortes, 1996; Magalhães, 1991); Maria Lázaro and Caiamar in the Guarinos greenstone belt (Lacerda, 1991; Pulz, 1990, Pulz *et al.*, 1991); Cachoeira do Gogó in the Pilar de Goiás greenstone belt (Pulz, 1995).
- The occurrence of Ni sulphide at Boa Vista in the Crixás greenstone belt (Costa Jr. *et al.*, 1997).
- An emerald deposit in the Santa Terezinha Paleoproterozoic volcano-sedimentary sequence that has been affected by the Transamazonian Event at 2.0 Ga (Giuliani *et al.*, 1993).

The Crixás Gold Deposit

The Crixás Greenstone Belt (Fig. 25) is one of the most important from the economic point of view. Here mining is carried on a large scale by Mineração Serra Grande S.A. at Mina III and Mina Nova, in addition to which there are two occurrences known as Meia Pataca/Pompex and Mina Inglesa.

The Mina III deposit (Yamaoka and Araújo, 1988) is situated 2.5 km from the town of Crixás, and the mine has been worked since 1990. The gold mineralization occurs at the base of metasediments of the Ribeirão das Antas Formation near the contact with the mafic volcanic units of the Rio Vermelho Formation. There are three mineralized zones: the lower and upper zones show a homogeneous distribution of the gold, whereas the intermediate zone is somewhat discontinuous. In 1994, the reserves are given at about 4.792 Mt of ore at an average grade of 10.12 g/t Au (Carvalho, 1999).

The lower zone consists of quartz veins, concordant with the principal foliation and varying in thickness from 0.5 m to 5 m; carbonaceous schist with disseminated sulphide (arsenopyrite and/or pyrrhotite) near the veins (Fortes and Coelho, 1997). The mineralized bodies are discontinuous and about 500 m wide along the strike of the foliation, and length of about 1200 m along the dip of the stretching lineation. In this zone the gold occurs preferentially associated with quartz and in the carbonaceous schist. The average grade of the ore is 12 g/t Au (Carvalho, 1999). The upper zone consists of a zone of massive sulphide (pyrrhotite and/or arsenopyrite), between 0.5 m and 2 m thick, associated with Fe-dolomitic marble, quartz-chlorite-carbonate schist, pyrrhotite-magnetite-biotite schist and marble with biotite (Fortes and Coelho, 1997). The ore bodies are lenticular and 50 m to 200 m wide along the strike of the foliation, and 400 m long along the dip of the stretching lineation. In this zone there occur two ore-types: one rich in arsenopyrite, and the second rich in pyrrhotite. The mineralization is accompanied by hydrothermal alteration manifest by silicification, carbonatization and chloritization (Fortes, 1996).

The Mina Nova Mine is situated near Mina III, and has been worked by underground methods since 1996. The gold mineralization is associated with a zone of carbonaceous schist, locally at the contact with marble, chlorite-garnet schist and quartz veins. It is accompanied by a carbonate-rich alteration halo some 9 to 12 m thick. According to Portocarrero (1996) there are three ore-types: Type I consists of a zone 1.5 m to 2.8 m thick of carbonaceous schist with disseminated pyrrhotite, arsenopyrite and subordinate chalcopyrite; Type II occurs in a zone overlying the Type I ore, 0.3 m to 1.7 m thick and consisting of carbonaceous sericite schist with disseminated arsenopyrite; Type III ore occurs rarely in thin quartz veins with disseminated gold, arsenopyrite and pyrrhotite. In 1996, the reserves were given as 3 Mt of ore at 6 g/t Au (Carvalho, 1999). In 1998, the production of the Mineração Serra Grande Ltda. was about 4.5 t Au.

According to Thomson and Fyfe (1990), Fortes *et al.* (1997), the mineralization is associated with a low-angled shear zone, related to the Brasiliano Event.

The Paleo-Mesoproterozoic Intracontinental Rift

The development of the intracontinental rift during the Paleo-Mesoproterozoic (Nilson *et al.*, 1994) occurred through several stages: 1) the intrusion of the mafic-ultramafic complexes of Cana Brava, Niquelândia and Barro Alto at about 2.0 Ga (Correia *et al.*, 1996, 1997); 2) the intrusion of anorogenic tin granite at 1.77 Ga in the Rio Paranã sub-Province, and at 1.59 Ga in the Rio Tocantins sub-Province (Pimentel *et al.*, 1991; Marini and Botelho, 1986; Botelho and Moura, 1998); 3) the deposition of the Araí and Serra da Mesa sediments in the pre, syn and post-rift phases (Dardenne and Freitas Silva, 1999).

Several mineral deposits are associated with the evolution of the rift:

- Deposits of Ni laterite associated with mafic-ultramafic complexes of Niquelândia and Barro Alto;
- Promising occurrences of PGE in the transition zone between peridotite and pyroxenite in the mafic-ultramafic complexes of Niquelândia and Cana Brava (Ferreira Filho *et al.*, 1992; Ferreira Filho *et al.*, 1994; Medeiros and Ferreira Filho, 1999; Oliveira, 1993; Lima, 1997; Suita, 1996, 1998);
- Large asbestos deposit that originated as the results of Brasiliano tectonics in the mafic ultra-mafic Cana Brava

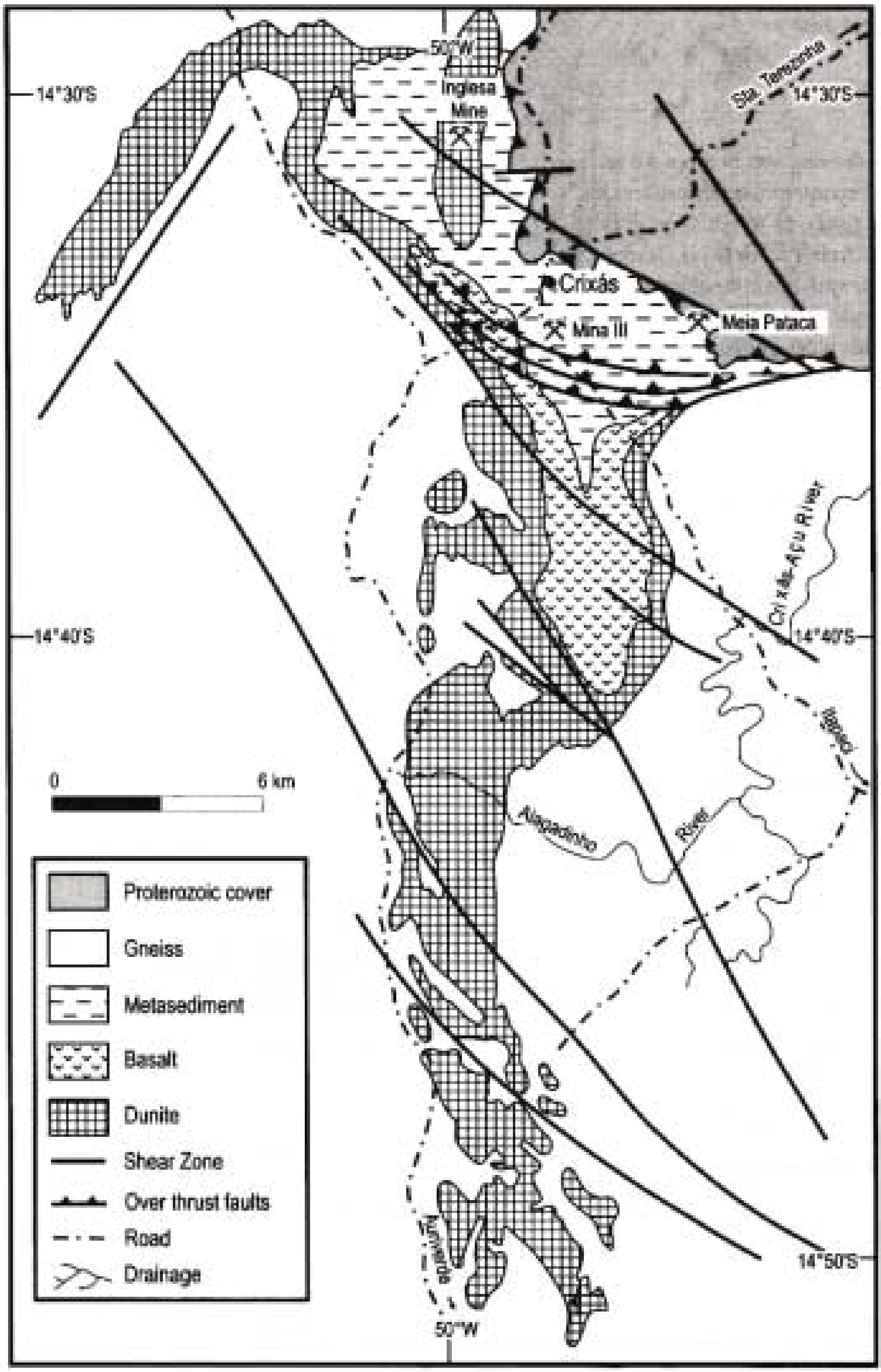


FIGURE 25 - Geological map of Crixás Greenstone Belt (modified after Magalhães, 1991).

complex (Pamplona and Nagao, 1981; Ianhez *et al.*, 1997).

Deposits of cassiterite and indium associated with greisenization and albitization related to the anorogenic granitic intrusions (Marini and Botelho, 1986; Botelho, 1992; Botelho and Moura, 1998).

The Cana Brava Asbestos Deposit

The mafic-ultramafic Cana Brava Complex is part of a high-grade terrane (Goiás Granulite Belt) that was placed over the metasediments of the Araí and Paranoá groups of the Brasília Fold Belt by Brasiliano collisional tectonics. The asbestos deposit, discovered in 1962, near the town of Minaçu, is associated with serpentinite at the base of the complex in its southeastern extremity. The mineralized belt (Ianhez *et al.*, 1997) is about 6300 m long (Pamplona and Nagao, 1981), and is essentially tabular in shape. It is about 4800 m N-S and 1500 m E-W, and it contains the A, B, C and F ore bodies, having an average thickness of between 100 m and 110 m. The dip varies between 10° and 70° to the NW and W. These bodies extent to a depth of 290 m, and they are separated by dextral transcurrent shear zones the strike of which is NE-SW. The principal foliation is mylonitic and is roughly parallel to the original banding. Metamorphism is in the greenschist to amphibolite facies, resulting in the development of type I brown serpentinite. The zones of transverse and transcurrent shearing were initially ductile (greenschist facies) and subsequently ruptile, and resulted in the development of type II green serpentinite. The most important mineral species is chrysotile. The mineralization occurs in stockworks, and is restricted to extension fractures distributed in the serpentinite mass. The long axis of the fibrous chrysotile permits the grouping of the fibers into two types: the slip fibers are oriented parallel to the walls of the fractures, whereas the cross fibers are transverse to the vein wall. The length of the fibers varies between 1 mm and 20 mm, for an average length of about 6 mm. The accessory minerals are magnetite and hematite, chlorite, carbonate and talc. In 1997, the measured reserves for the A and B bodies are given as 122.89 Mt of fibrous ore at 5.2%.

The Brasiliano Cycle

The reconstruction of the tectonic evolution permits the differentiation of some fundamental phases in the development of the Brasiliano Cycle.

The Development of the Mesoproterozoic/Neoproterozoic Passive Margin

The development of the passive margin is characterized by the deposition of metapelite, limestone and dolomite on a marine platform dominated by tides and/or storms. These sediments are assigned to the Paranoá and Canastra groups (Fuck *et al.*, 1988, 1993). The Vazante Group that occurs in the southern part of the Brasília Fold Belt may correspond to the upper carbonate and pelitic part of the Paranoá Group. To the W of the mafic-ultramafic complex, in the northern part of the Brasília Fold Belt, occurred the opening of an ocean at 1.2 Ga (Correia *et al.*, 1999) in which were deposited the volcano-sedimentary sequences of Palmeirópolis, Indaianópolis and Juscelândia. The principal mineral deposits related to the passive margin are:

- Small deposits of Pb-Zn-Ag (Cu) of the VMS-type, associated with the Palmeirópolis and Juscelândia sequences (Araújo and Nilson, 1988; Araújo, 1999).

The Goiás Magmatic Arc

The development of the Goiás Magmatic Arc, situated along the western margin of the Brasilia Fold Belt started at about 900 Ma (Pimentel and Fuck, 1991, 1992), and remained active until 600 Ma. The arc consists of gneiss, granitoid rocks and volcano-sedimentary sequences of the island arc-type. The Goiás Magmatic Arc is related to the formation of a back-arc basin in which were deposited the Ibiá and Araxá groups.

The mineral deposits are associated with the rocks of the volcano-sedimentary sequence, and are classified as being of the VMS-type: Cu-Pb-Zn-Au at Chapada (Kuyumjian, 1991, 1995, 1999; Richardson *et al.*, 1986); Au-Ag-Ba at Zacarias (Arantes *et al.*, 1981) and Cu-Au at Bom Jardim de Goiás.

The pre-Collisional Event at 790 Ma

This event was responsible for the granulitization observed at the base of the mafic-ultramafic unit, and for the generation of syn and late-tectonic granite, enriched in tin in the Ipameri region (Pimentel *et al.*, 1999). It is probable that the beginning of the evolution of the shear zones responsible for the gold mineralization date from this event.

The Foreland-type Bambuí Basin

With the uplift of the Brasília Fold Belt developed a depression in front of a mountainous chain in which began the deposition of pelite and carbonate of the Bambuí Group in a foreland-type basin. This sedimentation extended much further than the original depression, covering a large part of the São Francisco Craton to the E in the states of Bahia and Minas Gerais (Dardenne, 1978).

The saccharoidal pink dolomite belonging to the upper part of the first regressive carbonate cycle of the Bambuí Group is related to small deposits and occurrences of Pb-Zn-Ag-CaF_2 found along the valley of the São Francisco River in the vicinity of Januária, Itacarambi, Montalvânia and Serra do Ramalho. These deposits show clear indications of dissolution, substitution and secondary dolomitization by circulating connate hydrothermal fluids that permit the classification of these deposits as being of the MVT-type (Dardenne, 1978, 1979; Dardenne and Freitas-Silva, 1998, 1999).

Large deposits of phosphate, lead and zinc are found in the Vazante Group (Dardenne and Freitas Silva, 1998) that probably constitutes the transition between the Paranoá (Mesoproterozoic) and Bambuí (Neoproterozoic) groups.

The phosphate deposits of Rocinha-Lagamar

The phosphate deposits of Rocinha-Lagamar (Dardenne *et al.*, 1997; Chaves *et al.*, 1976) situated in the northwestern part of the State of Minas Gerais occur in the basal part of the Vazante Group in the external zone of the

Brasília Fold Belt. The phosphorite, associated with carbonaceous and carbonate-rich slate, dark grey in colour and intensely microfolded, occurs as phosphoarenite, phosphorudite and phospholutite. The phosphoarenite consists of intraclasts and phosphatic pellets, set in a cryptocrystalline phosphomicrite. Locally, the intraclasts are surrounded by fibrous cement of microcrystaline, limpid, prismatic apatite. The main mineral species is fluorapatite that resulted from the leaching of CO_2 of the regional carbonate-fluorapatite by fluids related to both metamorphism and weathering, culminating in the development of apatite, rich in aluminum and strontium of the wavelite-type.

The origin of the phosphate is related to the evolution of organic matter in physio-chemical conditions that were transitional between reducing and oxidizing environments in relatively deep water, probably representing a glacio-marine depositional system.

The reserves of the Lagamar Deposit are about 5 Mt at 30% to 35% P_2O_5, whereas the reserves of the Rocinha Deposit are estimated about 400 Mt ore at 10% to 12% P_2O_5.

The Morro Agudo Pb-Zn deposit

The Morro Agudo Pb-Zn deposit (Fig. 26) is associated with dolomite of the Vazante Group, situated in a back-reef facies that developed on the western flank of a stromatolitic bioherm of Morro do Calcário (Dardenne, 1978, 1979). The mineralization is essentially disseminated and consists mainly of sphalerite and galena with subordinate pyrite and barite. Breccia, dolarenitic breccia and dolarenite are the main host rocks of the main mineralized zones, denominated I, J, K and L. Zone M has a stratabound character, whereas zone N is stratiform with regular banding of chert lamina, galena, sphalerite and pyrite. Pyrite is exceptionally abundant in this zone (Romagna and Costa, 1988; Oliveira, 1998). The mineralized beds are limited by a syn-sedimentary normal fault with strike N10°W that acted as a preferential conduit for the mineralizing fluids. The disseminated mineralization shows evidence for the substitution of non-consolidated dolomitic material by sphalerite and galena that developed from the syn-diagenetic stage to the late-diagenetic stages (Dardenne, 1979; Dardenne and Freitas-Silva, 1999; Freitas-Silva and Dardenne, 1997). The data favour the comparison of the Morro Agudo Deposit with the Navan Deposit, Ireland (Hitzmann, 1995), that show the same characteristics as described by Dardenne (In: Pedrosa-Soares *et al.*, 1994), Freitas-Silva and Dardenne (1997), Dardenne and Freitas-Silva (1998, 1999), Hitzmann *et al.* (1995), and classified as the SEDEX-type by Misi *et al.* (1999). The reserves of Morro Agudo Pb-Zn deposit is about 17.5Mt ore at 5.1% Zn, 1.53% Pb and 300 ppm Cd.

The Vazante Zn deposit

The Vazante Zn deposit (Fig 27) is associated with a major tectonic structure, represented by a normal fault the attitude of which is N45°E/50° to 70°NW (Dardenne, 1979; Dardenne and Freitas-Silva, 1998, 1999). The fault zone is practically restricted to the pelitic interval occurring between dark grey dolomite at the base of the section and pink dolomite at the top, assigned to the Vazante Group (Dardenne 1979; Rigobello *et al.*, 1988; Oliveira, 1998). The mineralization contained in the fault zone is intensely sheared, and occurs in the form of lenticular and imbricate pockets of ore and dolomite (Pinho, 1990; Rigobello *et al.*, 1988; Dardenne, 1979; Dardenne and Freitas-Silva, 1998, 1999). The ore consists mainly of willemite along with hematite and zincite with subordinate franklinite, smithsonite, sphalerite and galena (Monteiro, 1997; Monteiro *et al.*, 1996). The willemite ore is extremely rich in Zn, containing 40% to 45% Zn. The mineralization is accompanied by intense silicification and sideritization of the wall rock that also display a network of fractures and veins filled with siderite/ankerite and red jasper. The data suggest that the hydrothermal mineralization originated by filling of a listric fault that had been reactivated during the Brasiliano Event. The partial reserves of the Vazante Deposit are about 8.5Mt ore at 23% Zn.

The Irecê phosphate deposit

The phosphate deposit discovered in 1985 by the CPRM (Bonfim, 1986) is situated at Fazenda Três Irmãs. It is associated with columnar stromatolites of the Jurussania Krylov-type intercalated with units of cross-bedded dolarenite assigned to the Salitre Formation of the Una Group (Neoproterozoic), equivalent to the Bambui Group in the Irecê Synclinorium. This dolomitic and phosphatic unit, approximately 18 m thick, is overlain by a sequence of silicified dolosiltstone, rich in sulphide (pyrite, sphalerite and galena with associated pyrite) and barite nodules, investigated by RioFinex in 1976 and by the CBPM. Reserves are estimated at 1.0 Mt at 8% Pb+Zn and 120 g/t Ag. Three types of primary phosphorite are present: columnar stromalitic phosphorite, laminar stromatolitic phosphorite, and intraclastic phosphorite. The highest grades are found in the columnar stromatolitic phosphorite where these may attain 20% P_2O_5. The phosphorite consists of micro and cryptocrystalline fluorapatite, associated with calcite and dolomite, in addition to detrital quartz and microcline, fluorite veins, microcrystalline quartz, pyrite, sphalerite and galena (Misi, 1992; Misi and Kyle, 1994; Kyle and Misi, 1997). The intraclastic phosphorite resulted from the erosion of the columnar and laminar stromatolitic phosphorite, forming the intercolumnar material and the beds intercalated with columnar and laminar stromatolites. The phosphatization is early, occurring in a syn-diagenetic phase prior to the dolomitization and is intimately associated with the development of cianobacteria colonies that formed the stromatolitic lamination. The time of the fluorapatite precipitation has not yet been defined. This may have occurred directly as the result of bacterial activity or, alternatively, as the early substitution of the carbonate lamina, rich in organic matter.

The secondary phosphorite resulted from the supergene alteration of primary phosphorite by the preferential leaching of carbonate, inducing a significant enrichment in phosphate. This type of ore attains grades exceeding 30% P_2O_5 (up to 38% P_2O_5). The estimated reserves of the Irecê Deposit are about 40 Mt of ore at 14% P_2O_5.

The Late Collisional Event at 630 Ma

This event is manifest in the overthrusted sheets of Araxá, Ibiá and Canastra sediments as nappes along low-angled faults over rocks of the Vazante and Bambui groups.

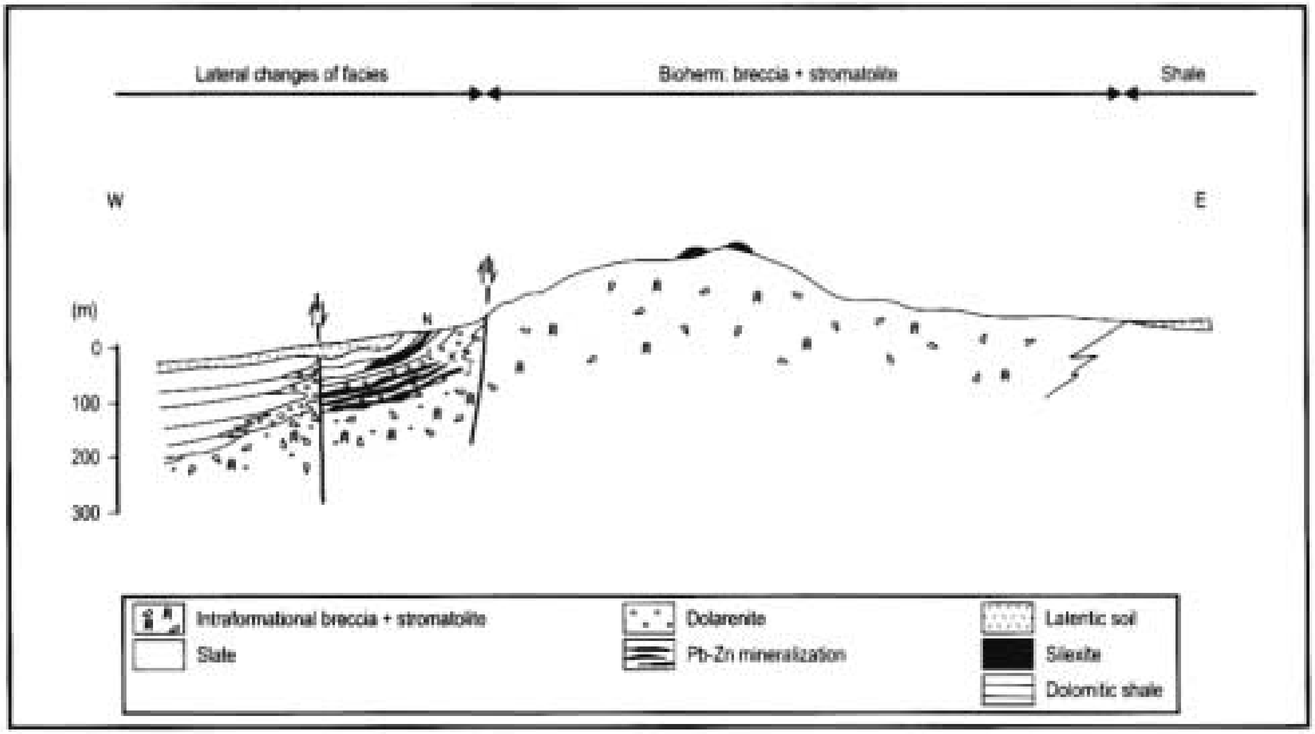


FIGURE 26 - Schematic geological section of Morro Agudo Pb-Zn Deposit (modified after Dardenne, 1978; Dardenne and Freitas Silva, 998).

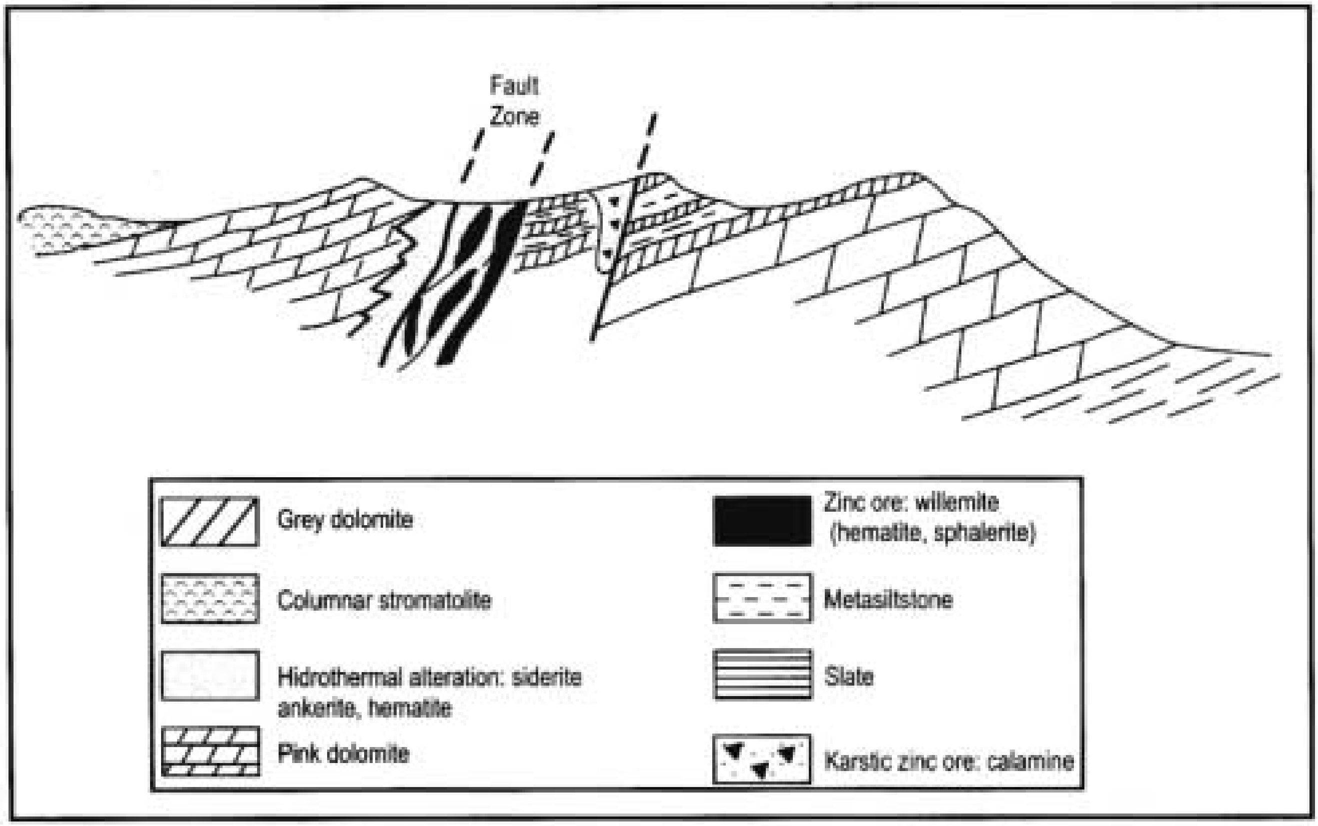


FIGURE 27 - Schematic cross-section of the Vazante Mine (modified after Dardenne, 1978; 1999).

Many gold deposits are associated with the development of high-angled shear zones: Buracão, Santa Rita, Rio do Carmo, Buraco do Ouro (D'El Rey Silva and Senna Filho, 1998; Lacerda, 1986; Giuliani *et al.*, 1993, Olivo, 1989; Olivo and Marini, 1988; Magalhães *et al.*, 1998; Magalhães and Nilson, 1996); and low-angled shear zones: Araxá, Luziânia, and Morro do Ouro in the external zone of the Brasilia Fold Belt (Hageman *et al.*, 1992; Freitas-Silva *et al.*, 1991; Freitas-Silva, 1996). In the region occupied by the Goiás Magmatic Arc, gold deposits are also associated with shear zones: a gold occurrence at Posse, for example (Arantes *et al.*, 1981; Oliveira *et al.*, 1997).

At the end of this second collisional event there occurred late and post-tectonic granitic and mafic-ultramafic intrusions. The mafic-ultramafic complex of Americano do Brasil and Mangabal I and II contain Cu-Ni-Co mineralization in the form of chalcopyrite, pentlandite and bornite (Nilson, 1981).

The Morro do Ouro deposit

The Morro do Ouro Deposit (Freitas-Silva *et al.*, 1991; Freitas-Silva, 1996) is hosted in carbonaceous phyllite (Morro do Ouro Member) of the Paracatu Formation (Canastra Group), which overthrusts the rocks of the Vazante Group in the external zone of the Brasilia Fold Belt. These rocks were deformed and metamorphosed in the greenschist facies (chlorite) and display intrafolial, isoclinal and recumbent folds related to a monocline, associated with a thrust fault (Fig. 28) of large amplitude, the attitude of which is N10°W/15°SW. This fault developed in a ductile-ruptile shear zone accompanied by mineral lineation and stretching (elongation) fabrics, mylonitic foliation and boudinage of the quartz veins. The stretching lineation is orientated S70°W/15 °. The gold is disseminated in segregations of metamorphic quartz (boudins), along with arsenopyrite, pyrite, sphalerite, galena, siderite and sericite. The gold particles are more concentrated at the margins of the boudins and in the proximity of sulphide and carbonate species. The hydrothermal alteration is restricted to the boudins, where the principal processes are pyritization, sideritization and sericitization. The gold is usually free in the quartz, although a small amount may be associated with sulphide. The average gold grade in the boudins is about 2.5 g/t Au. In the ore, the gold grade is very low, about 0.45 g/t Au. Nevertheless, the annual production is roughly 8.0 t Au, and the reserves exceed 250 t Au.

The Araçuaí Belt

The Araçuaí Fold Belt (Almeida, 1967, 1977; Almeida *et al.*, 1981) that lies along the southern and southeastern margin of the São Francisco Craton in the NE of Minas Gerais and along the divide with Bahia, is arc-shaped and concave to the SE. This belt resulted from the development of a rift that began about 800 Ma with the rupture of the continental crust, and continued opening until ocean crust began to form in the middle of the structure (Pedrosa-Soares *et al.*, 1992; 1998; Fuck *et al.*, 1993). The rift basin filled with sediments assigned to the Macaúbas Formation that were distributed in three domains: continental, transitional and internal, resulting in a sedimentary zonation of the belt (Uhlein, 1991; Pedrosa-Soares *et al.*, 1992, 1998; Uhlein *et al.*, 1999). The closure of the rift from 700 Ma that culminated in the principal orogenic phase at between 659 and 550 Ma, brought about deformation and metamorphism, resulting in a polarity varying from E-W to N-S and the development of a series of thrusts in the transitional/continental domains, anatexis and granitic intrusions in the internal domain (Pedrosa-Soares *et al.*, 1999).

Older terranes, related to the Espinhaço, Minas and Rio das Velhas supergroups, as well as younger units such as the Bambui Group at the edge of the São Francisco Craton were involved in the deformation and metamorphism of the Araçuai Belt. The main mineral resources of the Araçaui Belt are:

- The Riacho dos Machados gold deposit (Fonseca *et al.*, 1997) is hosted in a volcano-sedimentary sequence (Archean or Paleoproterozoic in age) developed in a Brasiliano shear zone that has affected the basement of the Araçuaí Belt.

- Iron deposits of the sedimentary-exhalative-type (SEDEX) present in the diamictite beds of the Macaúbas Group in the Porteirinha region (Vilela, 1986);

- Graphite deposits of the Minas Gerais-Bahia area. These deposits are very important. They occur near the towns of Pedra Azul, Salto da Divisa and Maiquinique, and they are associated with schist and gneiss cut by shear zones (Pedrosa-Soares *et al.*, 1994, 1999; Faria, 1997; Reis, 1999);

- The Western Pegmatite Province of Brazil, famous for its collector-quality mineral specimens, is associated with granitic magmatism of the internal zone of the Araçuaí Belt (Correia Neves, 1997; Pedrosa Soares *et al.*, 1994; Quéméneur and Lagache, 1999; Correia Neves *et al.*, 1986, 1987).

The Ribeira Belt

The Ribeira Fold Belt is a continuation of the Araçuaí and the Brasilia belts, along the southeastern-southern coast of Brazil. The characteristic of the Ribeira Belt is the presence of swarms of subvertical longitudinal faults representing dextral shear zones, locally with displacement of tens of kilometres. In the N of the belt, these subvertical shear faults give way to subhorizontal thrusts and overthrust. In the Cenozoic, these sequences underwent uplift of the central zone that resulted in the relief of the Serra do Mar. The dextral longitudinal faults that cut the basement as well as the metasedimentary sequences of the Ribeira Fold Belt define, in the internal part of the uplifted area, a corridor about 1000 km long and 100 km wide known as the Apiai-São Roque Fold Belt. This belt contains metasediments of the Açungui and São Roque groups with which are associated numerous Brasiliano granitic intrusions that have affected the older basement terranes and the metasediments of the Setuva Group.

In the Ribeira Belt, the principal mineral resources are found in the Vale do Ribeira (valley of the Ribeira River) (Fig. 29) that include:

- Deposits of Pb-Zn-Ag-Ba of the Perau-type in the Perau/Água Clara complexes of Mesoproterozoic age. These are generally concordant and stratiform, and are considered

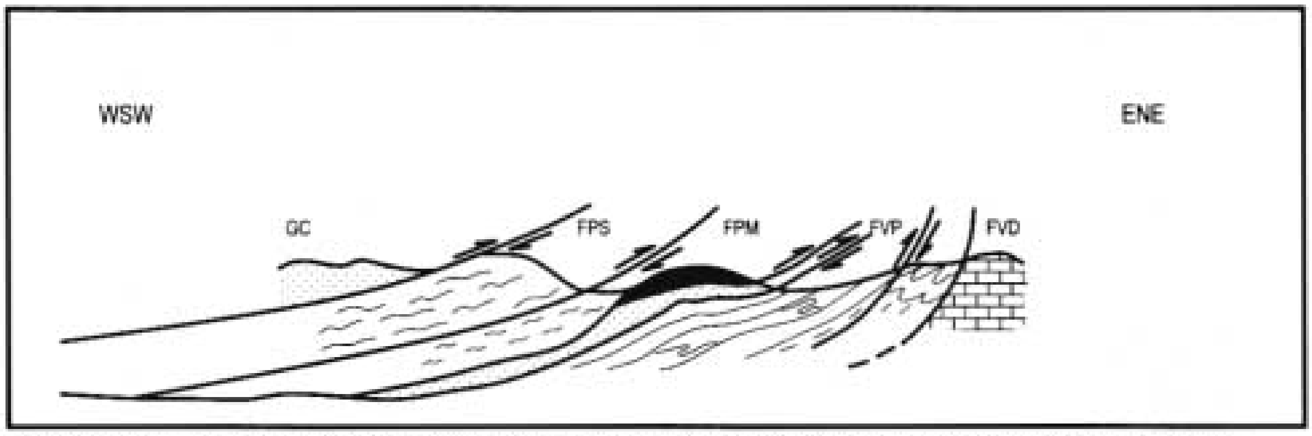


FIGURE 28a - Schematic representation of the structure in the Morro do Ouro gold mine. FP = Paracatu Formation; S = Serra da Anta Facies; FV = Vazante Formation; D = dolomite; P = psamopelite; GC = Canastra Group; black = Morro do Ouro gold deposit (modified after Freitas-Silva et al., 1991).

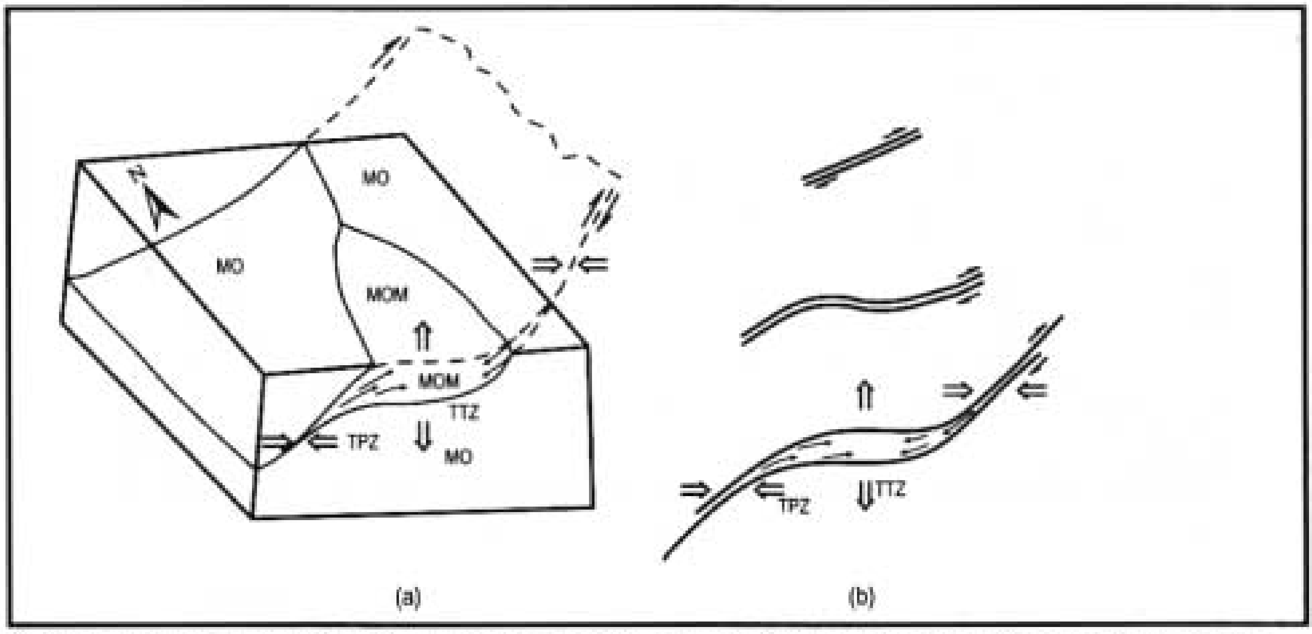


FIGURE 28b - Schematic representation of the formation of the Morro do Ouro gold deposit. (a) - MO = Morro do Ouro Facies, MOM = Morro do Ouro deposit; TPZ = transpressive zone; TTZ = transtensive zone; single tailed arrows = fluid migration direction. (b) - Evolution stages of gold concentration (modified after Freitas-Silva et al., 1991).

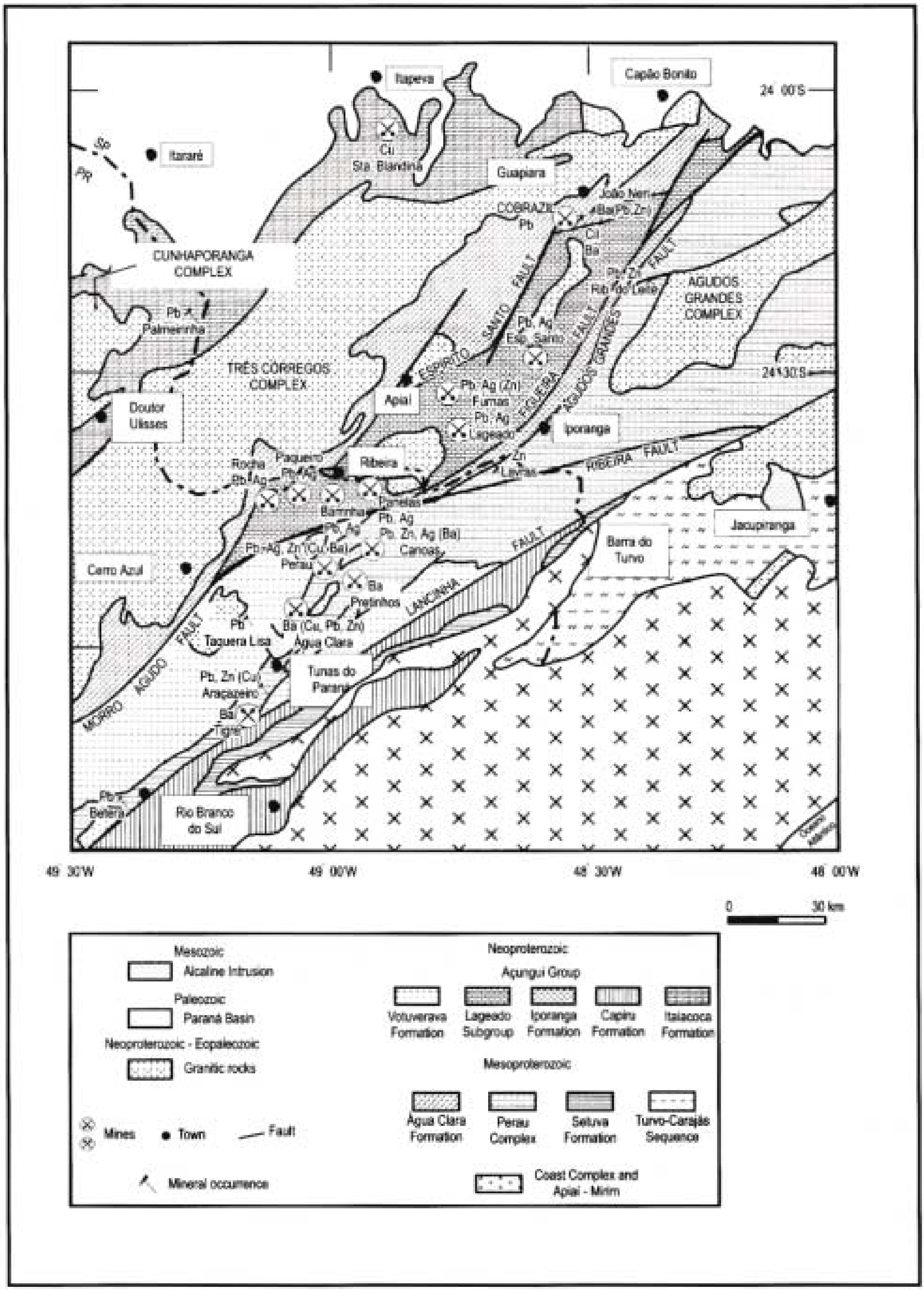


FIGURE 29 - Distribution of base metals deposits in the Vale do Ribeira region (modified after Daitx, 1998).

to be of sedimentary-exhalative origin of the SEDEX-type (Fleischer, 1976; Daitx, 1998);

- Deposits of Pb-Zn-Ag of the Panelas-type in the Lageado and Itaiacoca subgroups. These are generally stratabound in the form of vertical veins in carbonate rocks of Meso- to Neoproterozoic age (Fleischer, 1976; Daitx, 1998).
- Stratabound deposits of fluorite at Sete Barras, Volta Grande and Mato Dentro (Dardenne and Touray, 1988; Dardenne *et al.*, 1997; Ronchi *et al.*, 1993);
- Tungsten deposits associated with the Itaóca granite intrusion (Mello and Bettencourt, 1998);
- Talc deposits in the Itaiacoca Group at Abapã, controlled by vertical shear zones at the contact between quartzite and dolomite and their reworked products deposited in karst depressions (Lima, 1993; Lima and Dardenne, 1987).

The Dom Feliciano Belt and the Rio De La Plata Craton

According to Jost (1981) and Fernandes *et al.* (1995) the Dom Feliciano Fold Belt, situated in the southern extremity of Brazil developed between the Rio de La Plata Craton and the Kalahari Craton as a result of subduction to the NW of the oceanic crust and from the accretion of older magmatic arcs between 850 and 750 Ma at the margin of the Rio de La Plata Craton giving rise to the Pelotas Batholith. The opening of a back-arc basin followed by collision around 650 Ma led to the accretion of a second magmatic arc and the intrusion of calc-alkaline to alkaline granite into the Encruzilhada do Sul metasedimentary sequence with vergence to the NW. Marine and continental molasse deposits accompanied by alkaline volcanism (Bom Jardim Group) were deposited in intramontane basins formed by grabens and half-grabens.

The main mineral deposits observed in the Dom Feliciano Belt are:

- Occurrences of Pb-Zn of the VMS-type in the Vacacaí volcano-sedimentary sequence;
- Deposits of porphyry gold-type;
- Tin deposits associated with S-type granite (Franz, 1997; Franz *et al.*, 1998);
- Deposits of Cu-Pb-Zn in the Camaquã region.

Deposits of the porphyry-gold-type

Most of the gold mineralization of the porphyry-gold-type is found in the Lavras do Sul Granitic Complex, as well as in Neoproterozoic felsic volcanic rocks and fluvio-lacustrine sediments assigned to the Cerro dos Martins Formation in the State of Rio Grande do Sul. The mineralization occurs as the disseminated and vein types, and is associated with faults and intense shearing, brecciation and hydrothermalism. The mineralization is genetically related to late magmatism of the Brasiliano Event (610-580 Ma) having shoshonitic and alkaline affinities. The parageneis is of the Au-Cu-Pb-Zn-Ag type. The most important deposit is that of Volta Grande (7 t Au), and the Bloco Butiá (6.5 t Au) and Cerrito (3.5 t Au) prospects (Santos *et al.*, 1998; Andrade *et al.*, 1988; Reischel, 1980).

The San Gregorio Gold Mine of northern Uruguay (Fig. 2) may also be an example of mineralization of the porphyry-gold type. The gold mineralization followed the intrusion of the Corrales Granite, and consists of auriferous pyrite, chalcopyrite, pyrrhotite, galena, and Fe-rich sphalerite. This granite is probably of Brasiliano age and is intruded into a Paleoproterozoic granite-gneiss complex of the Rio de la Plata Craton. E-W and NW-SE shear zones cut this complex. The mineralized zones currently being mined at the San Gregorio Mine are the same as that of the wall rock. The mineralized zones are hydrothermally altered gneiss and metabasalt, in addition to a quartz vein system. (Ellis *et al.*, 1995). The gold reserves at the San Gregorio Mine are about 6.5 Mt at 2.8 g/t Au and 2.8 g/t Ag (0.65 Moz Au and 0.65 Moz Ag) (J. Spoturno, personal communication).

Camaquã District

The mineral deposits of the Camaquã District (Fig. 30), situated in the central-southern region of the State of Rio Grande do Sul, are associated with conglomerate and sandstone of the red bed-type. These red beds belong to the Vargas Member of the Arroio dos Nobres Formation of the Bom Jardim Group deposited in a system of alluvial fans at the end of the Dom Feliciano (630-600 Ma) collisional orogenesis in a molasse basin, delimited by faults striking NE-SW. This basin has been interpreted as being of the foreland-type or an intramontane basin of the strike-slip-type with rhyolitic, dacitic and andesitic volcanism of the Hilário Member at the base. The Bom Jardim Group is covered by an angular unconformity by sediments, also of the red bed-type assigned to the Guaritas Formation with which are associated the rocks of the Rodeio Velho Member, dated at 470 Ma by Hartman *et al.* (1998), implying that the basin developed between 600 and 470 Ma. To the NW of the basin occur a number of granite intrusives of calc-alkaline to shoshonitic composition, referred to as Lavras do Sul, Caçapava do Sul and São Sepé that have been dated at between 590 and 560 Ma (Remus *et al.*, 1999). In this district, three types of mineralization are recognized:

1) Vein mineralization, discovered in 1865, and intensely mined to 1996 at the Camaquã mines known as São Luiz (underground) and Uruguai (underground and open pit), which have produced about 398 Mt of ore at 1.06% Cu, 0.2 g/t Au and 8 g/t Ag (Teixeira and Gonzalez, 1988; Remus *et al.*, 1999). These deposits have been described successively by Bettencourt (1976), Ribeiro (1991), Remus *et al.* (1999) and Ronchi *et al.* (1999). The ore occurs as *amas*, veins, ribbons and stringers, locally forming stockworks with orientation parallel to the faults striking NW-SE, and is surrounded by hydrothermal alteration halos displaying chloritization, sericitization and silicification (Remus *et al.*, 1999; Ronchi *et al.*, 1999; Bettencourt, 1976). The paragenesis is pyrite-chalcopyrite and quartz, and bornite-chalcopyrite-hematite-barite-calcite.

2) Disseminated mineralization in the sandstone and conglomerate units of the Vargas Member:

- Copper mineralization around the Camaquã mines (São Luiz and Uruguai) with paragenesis of pyrite-chalcopyrite (Veigel and Dardenne, 1990).
- Lead and zinc mineralization with subordinate copper at

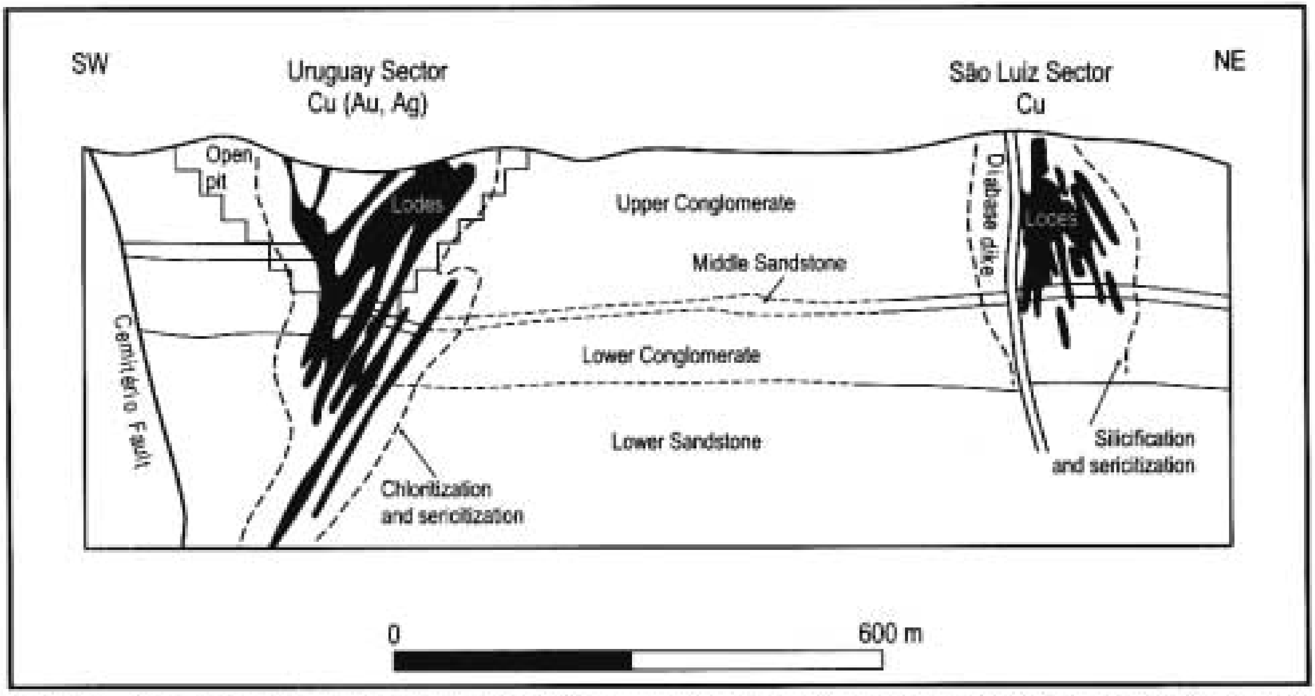


FIGURE 30 - Schematic cross-section of the Uruguay and São Luiz sectors of the Camaquã Cu (Au, Ag) Mine (modified after Teixeira and Gonzalez, 1988).

the Santa Maria Deposit with paragenesis of galena-sphalerite-chalcopyrite (Veigel and Dardenne, 1990). The reserves are given as about 33.4 Mt of ore at an average grade of 1.44% Pb, 1.08% Zn and 12 to 14 g/t Ag (Badi and Gonzalez, 1988).

3) The secondary mineralization occurs as oxide, and the cementation phases with the associated mineral species hematite-bornite-chacocite-covellite at the Camaquã mines, and hematite-bornite-chalcocite-stephanite at the Santa Maria Deposit (Veigel and Dardenne, 1990).

The origin of the Cu-Au and Pb-Zn-(Cu)-Ag mineralization of the Camaquã region has been the subject of discussion and several hypotheses for this have been proposed: a) epigenetic hydrothermal mineralization resulting from the canalization of connate waters, heated by volcanism along the NW-SE faults (Veigel and Dardenne, 1990); b) epigenetic hydrothermal mineralization without specifying the source of the mineralizing fluids (Ronchi *et al.*, 1999); c) epithermal mineralization associated with the intrusion of the Lavras do Sul and Caçapava do Sul granites (Bettencourt, 1976; Remus *et al.*,1999).

The Borborema Province

The Borborema Province or Northeastern fold region (Fig. 31), which resulted from the Brasiliano collage, is a complex mosaic of Neoproterozoic fold belts and a basement nucleus attributed to the Transamazonian collage (Van Schmus *et al.*, 1995). The main structures have a fan-shaped geometry permitting the division of the Province into five domains (Brito Neves *et al.*, 1999): Median Coreaú Domain; Northern Domain; Transversal Domain; and the Southern Domain.

The main mineral deposits found in the Borborema Province are:

- Magnesite deposits at José de Alencar in the Orós Belt, Ceará, associated with a Paleo-Mesoproterozoic volcano-sedimentary sequence (2.0-1.7 Ga), interpreted as evaporite deposits (Parente and Guillou, 1995; Parente and Arthaud, 1995; Parente, 1995);
- Copper deposits of the Martinópole volcano-sedimentary sequence (Pedra Verde) in the State of Ceará, interpreted here to be of the sedimentary-exhalative or SEDEX-type.
-Gold deposits in shear zones, associated with quartz veins and skarn with paragenesis W-Mo-Au in the Seridó Province of the states of Rio Grande do Norte and Paraíba, described by Melo and Legrand (1993); Legrand *et al.* (1993, 1996), Souza Neto *et al.* (1996), Melo *et al.* (1996). At the São Francisco Deposit, to the E of Currais Novos, the gold mineralization is associated with biotite-garnet schist and occurs as the result of successive hydrothermal phases that accompany the metamorphic evolution. This resulted in mineralization in auriferous veins, coeval with shearing. The deposits contain about 1.75 t Au (Silva and Legrand, 1996; Ferran, 1988)
- The Scheelite Province of the State of Rio Grande do Norte (Salim, 1993);
- The uranium deposit in the region of Itataia in the State of Ceará;
- The Pegmatite Province of Seridó, associated with Brasiliano Cycle granite intrusions, dated at 555 Ma (Legrand *et al.*, 1991; Legrand *et al.*, 1993). The pegmatite bodies are intruded along the foliation striking NNE-SSW in mica schist, and contain Ta, Nb, Li, Be and Sn (Silva and Dantas, 1997).

The Seridó Scheelite Province

The Seridó Scheelite Province in the states of Rio Grande do Norte and Paraíba contains a number of deposits including Brejuí, Barra Verde, Boca de Lage, Bodó, Parelhas and Bom Fim (Fig. 32). These deposits have been mined

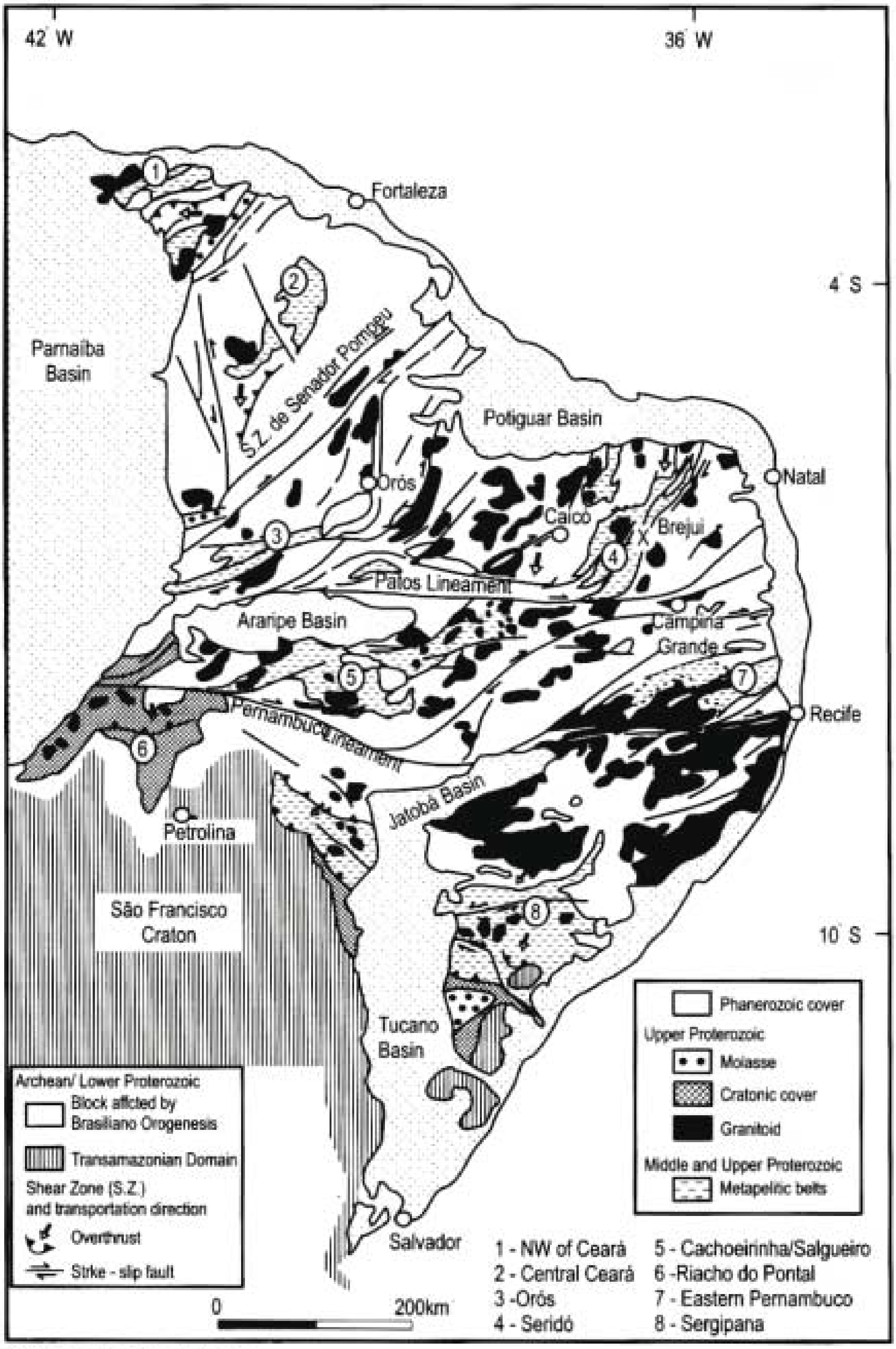


FIGURE 31 - The Borborema Province.

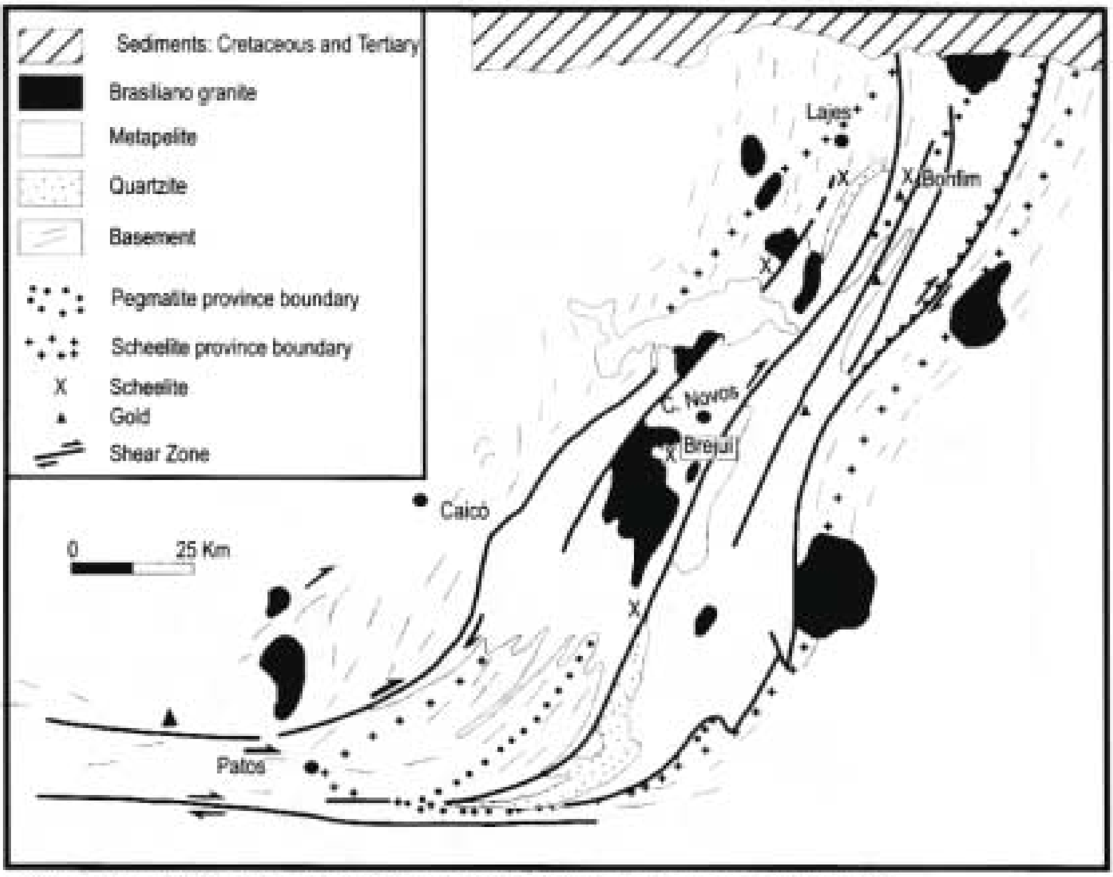


FIGURE 32 - Distribution of mineral deposits in the Seridó Belt, PB-RN (modified after Legrand et al., 1996).

intensely from the Second World War up to 1985. Production is estimated at 60 000 t of concentrate (70% WO3) from ore containing 0.7% to 1% WO3. In the region occurs a basement gneiss known as the Caicó Complex, which is generally considered to be of Archean age, reworked during the Transamazonian Cycle, and a metasedimentary sequence known as the Ceará Series and/or Seridó Series (Jardim de Sá and Salim, 1980; Archanjo and Salim, 1986). This metasedimentary sequence is divided into three formations or groups according to different authors: the Jucurutu Formation consisting mainly of finely-banded biotite gneiss, rich in epidote, intercataled with quartzite, mica schist, marble and amphibolite associated with banded iron formation units in which are found the principal scheelite deposits; the Equador Formation consisting of muscovite-rich quartzite with intercalated paragneiss, mica schist and marble; the Seridó Formation consisting of a thick sequence of aluminous mica schist with intercalated paragneiss, quartzite and marble with a unit known as the Parelhas Conglomerate at the base. The age of the metamorphism and the plutonism of the Seridó Series is dated at between 650 and 550 Ma. The intrusive rocks are related to an early, pre- to syn-tectonic dioritic suite dated at between 600 and 500 Ma (Jardim de Sá *et al.*, 1986; Legrand *et al.*, 1991; Leterrier *et al.*, 1990).

In the Seridó Province the principal scheelite mineralization is associate with skarn deposits of the Jucurutu Formation, and the most important mines (Brejuí, Barra Verde, Boca de Lages) are situated around the Acari Granite Massif (555 Ma) (Legrand *et al.*, 1991) at the contact marble/metasediment and marble/granite in the Jucurutu paragneiss. Two types of scheelite are described in the various mines in the region: fine-grained scheelite orientated along the foliation of the primary skarn deposits, generally considered of early genesis; coarse-grained scheelite, related to late hydrothermal alteration in retrograde skarnite, forming high-grade concentrations in the hinges of vertical folds, and in shear zones associated with these folds (Salim, 1993). Locally, the scheelite occurs in quartz veins and pegmatite that cut the mineralized skarnite. The scheelite is of variable colour from white to yellow. There also occurs a black variety related to the presence of thin laths of molybdenite, pyrite, chalcopyrite and bornite. The accessory minerals are magnetite, native bismuth and bismuthinite. The sulphide minerals have developed in zones of late hydrothermal alteration with minerals of zeolite paragenesis substituting the silicate minerals of the primary skarnite (plagioclase, amphibole, diopside, garnet) and secondary skarnite (scapolite, vesuvianite, epidote). Gold is often observed associated with molybdenum and tungsten (Au-Mo-W) in the skarnite of the Seridó Province (Legrand *et al.*, 1993, 1996; Melo and Legrand, 1993; Melo *et al.*, 1996; Souza *et al.*, 1996).

The Itataia Uranium Deposit

The Itataia Deposit (Forman and Waring, 1981) is situated in the Municipality of Santa Quitéria some 220 km from the city of Fortaleza in the State of Ceará. It occurs in a metamorphic sequence consisting of migmatite at the base, overlain by quartzite and gneiss and covered by crystalline carbonate known as the Itataia Group (Mendonça *et al.*, 1985), to which a Paleoproterozoic age has been assigned. Brasiliano pegmatite and granite intrude it.The uranium mineralization is associated with episyenite, the intrusion of which resulted in the sodic metasomatism of the gneiss; to massive collophanite; and to collophanite stockworks filling fractures in marble and carbonaceous breccia (Mendonça *et al.*,1985).The collophanite occurs as microcrystalline fluorapatite, limpid and in spherulites with a fibro-radial structure, intimately associated with masses of cryptocrystalline collophanite. The age of the mineralization is considered to be Brasiliano to Cambro-Ordovician. The measured reserves are 79.5 Mt of ore at 11% P_2O_5 and 1000 ppm U_3O_8. It is very similar to the deposits of Espinharas in the State of Paraíba. It may be related to ringed igneous granite intrusions of the Itaperuaba-type, dated at between 550 and 450 Ma, which show albitization accompanied by uranium mineralization (Haddad, 1981).

PHANEROZOIC PLATFORM COVER AND ASSOCIATED MAGMATISM

During the Phanerozoic (Fig.33) the evolution of the South American Platform was dominated in the Paleozoic by the development of huge intracratonic synedises represented by the Amazonas-Solimões, Parnaiba, Paraná and Chaco-Paraná basins in which the sedimentation began in the Silurio-Ordovician and ended at the close of the Permian (Milani and Zalán, 1999). In the Mesozoic there occurred the final in-filling of the Paleozoic basins. Rifting related to the opening of the North Atlantic Ocean in Triassic-Jurassic times, and the opening of the South Atlantic Ocean in the Cretaceous, led to the formation of basins on the Brazilian continental margin as well as in isolated Cretaceous basins in the northeastern region of Brazil. During the Cenozoic lateritic weathering profiles developed over the South American Platform from the beginning of the Tertiary. Finally, there occurred marine sedimentation in marginal basins along the Brazilian coast, and the deposition of fluvial continental sediments in the interior.

Paleozoic Deposits

The mineral resources of the Paleozoic basins (Fig.33) are very limited and restricted to the following: occurrences of Devonian oolitic ironstone formation units in the basal part of the Pimenteiras Formation in the Parnaiba Basin (Ribeiro and Dardenne, 1978; Ribeiro, 1984), in the Jatapu region of the Amazonas Basin (Façanha da Costa, 1966; Hennies, 1969), and in the Serra do Roncador region of the Paraná Basin, showing a Devonian metallogenetic phase for this type of deposit; potassium deposits associated with Permo-Carboniferous evaporites in the Amazonas Basin; coal and pyrobituminous schist deposits in the Permian sediments of the Paraná Basin (see Lopes and Ferreira, this volume); and the Figueira uranium deposit, likewise associated with the Permian sediments of the Paraná Basin.

The Potassium Deposits of Fazendinha and Arari of the Middle Amazonas Basin

From the Silurian to the end of the Devonian the Amazonas Basin underwent a marine transgression from E to W. Following a period of generalized flooding, there occurred a slight tilt of the basin to the W with concomitant uplift along part of the eastern margin, causing an inversion of the direction of the marine invasion, that now came from W to E with the deposition of a transgressive sequence (Monte Alegre and Itaituba formations), followed by a phase of very restricted circulation resulting in the deposition of the evaporite sequence of the Nova Olinda Formation, with which are associated the potassium deposits at Fazendinha and Arari, transitional to the continental sediments of the Indirá Formation (Upper Permian). At this time the Amazonas Basin (*sensu lato*) (including the Solimões Basin) was divided from E to W by the physical barriers of the Iquitos, Purus and Gurupá highs into the Juruá (Upper Amazonas) and Middle Amazonas sub-basins (Fig. 34). According to Sad *et al.*, 1982, 1997), the cyclic re-occurrence of high and low salinity, separated by clastic sedimentation or by less soluble chemical sediments such as limestone and anhydrite, has permitted the separation of the evaporitic sequence into 11 cycles. Cycle VII marked the period of greatest restriction of the evaporite basin with highly saline brines and the deposition of finely crystalline banded halite with high bromine content (>70 ppm Br), culminating with the precipitation of potassium and magnesium salts in the form of chloride and sulphate. Cycle VII terminated with fresh water incursion from continental sources bringing about the development of continental lacustrine conditions.

In the Fazendinha region, the mineralized beds are sub-horizontal and lie at a depth of 980 m to 1140 m below the surface. Their average thickness is 2.7 m and the KCl content varies between 14.31% and 38.69% (average 27%). The potassium-rich zone is divided into three intervals:

- A lower interval with milky white sylvinite, finely laminated that grades, transitionally, to an overlying sequence of finely banded halite beds, implying a primary origin for the chemical precipitation of the sylvinite. This interval is 1 to 1.8 m thick and contains 29.7% KCl.
- An intermediate interval denominated the sulfate zone, in function of the presence of minerals such as kainite, kieserite, leonite, langbeinite, polyhalite and anhydrite associated with halite and silvinite, implying a marine transgression bringing solutions rich in calcium and sulfate. This interval is between 0.5 m and 1.6 m thick and contains 20% KCl;
- An upper interval consisting of coarse-grained red sylvinite with irregular beds of anhydrite and discontinuous beds of halite. These features together with the absence of lamination lead to the interpretation that the original mineral was carnallite that underwent sylvinitization as the result of preferential leaching of magnesium, thus leading to the view that the silvinite is secondary. This interval is 0.80 m thick and contains 32% KCl, and is overlain by pink coarse-grained halite.

The measured *in situ* reserves of the Fazendinha Deposit exceed 520 Mt of ore at 28.8% KCl, permitting the recovery of 36 Mt of KCl, whereas, the reserves of the Arari Deposit are about 659 Mt with 17.7% KCl.

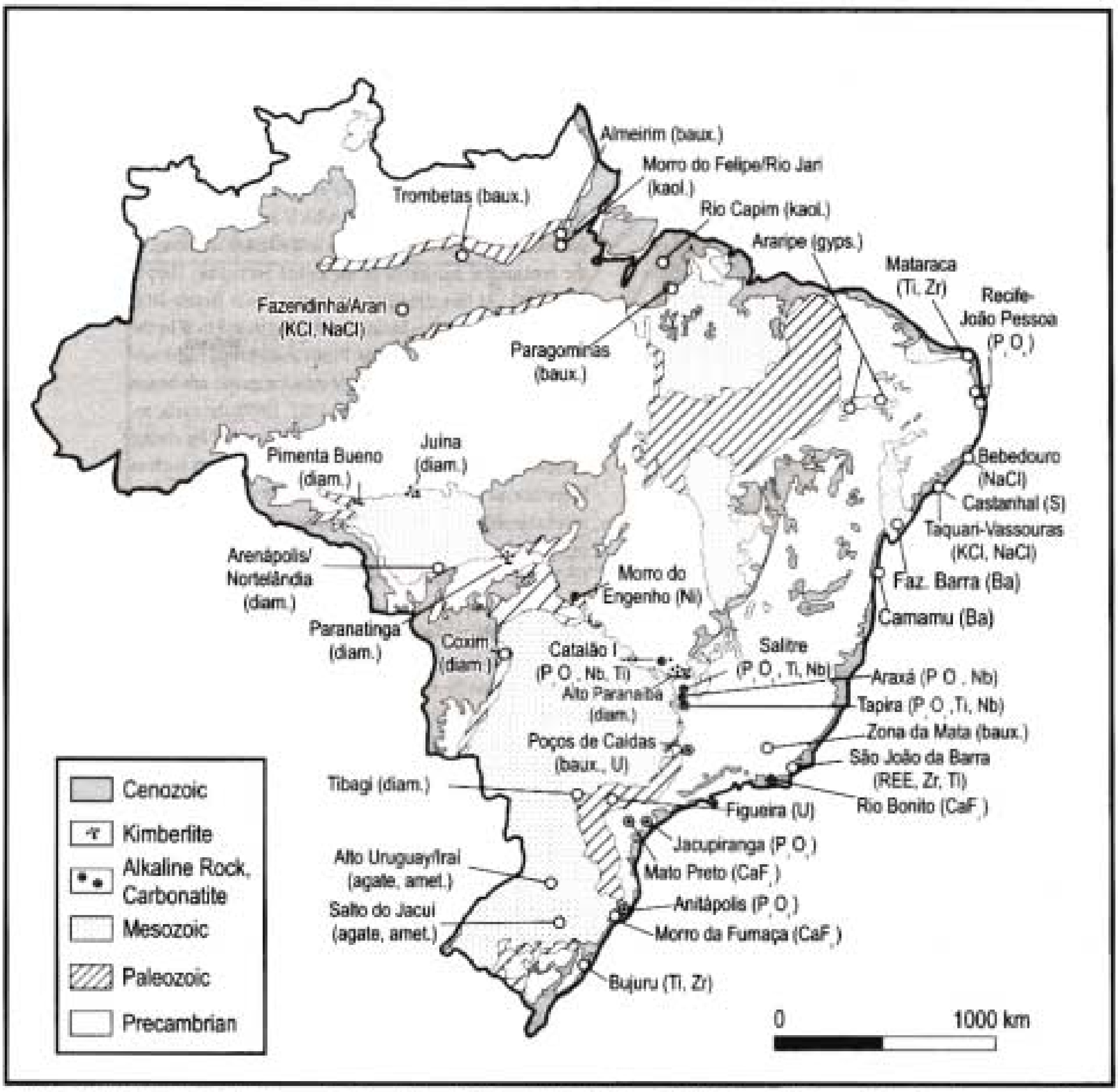


FIGURE 33 - Distribution of main Phanerozoic mineral deposits in Brazil (modified after Schobbenhaus and Campos, 1984, and other sources cited in text). Abbreviations: amet. - amethyst; baux. - bauxite; diam. - diamond; gyps. - gypsite; kaol. - kaolin; pyr.sh. - pyrobetuminous shale; REE - Rare Earths.

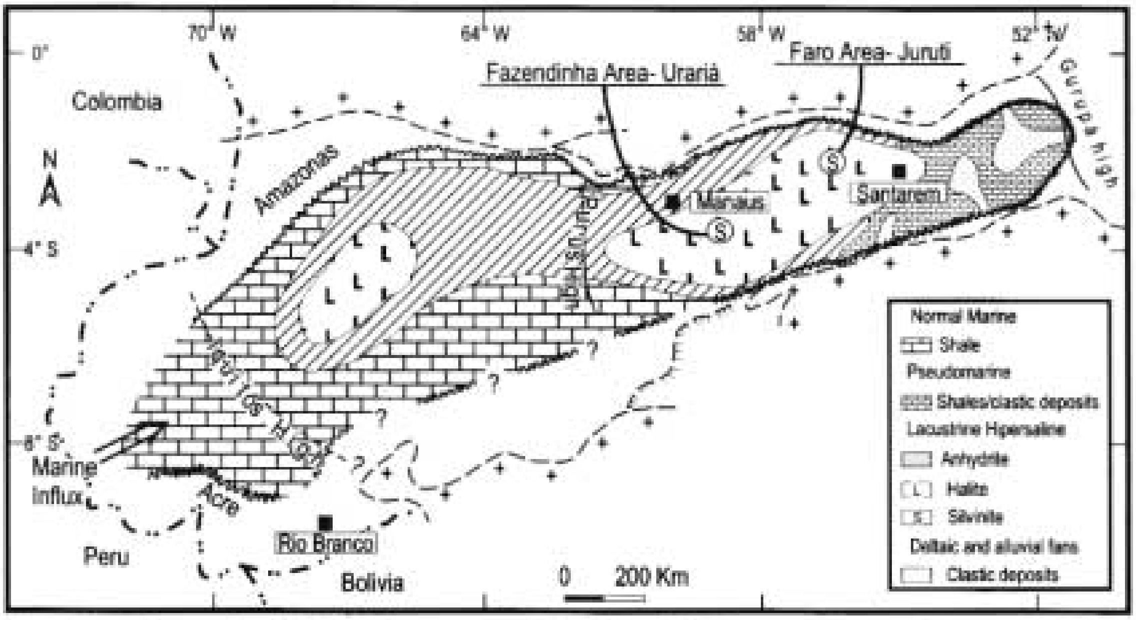


FIGURE 34 - Paleogeography of the Carboniferous Amazonas Basin showing the distribution of the evaporite facies (modified after Sad et al., 1997).

The Figueira Uranium Deposit (PR)

The uranium deposit is associated with the Triunfo Member at the base of the Rio Bonito Formation of the Paraná Basin. The deposit is confined between a coal bed at the base and a medium to coarse-grained sandstone at the top. The deposit is tabular in shape and is peneconcordant (Morrone and Daemon, 1985). In the sandstone unit the mineralization appears in the interstices of the quartz grains in the form of uraninite, intimately associated with pyrite and other sulphide species such as chalcopyrite and sphalerite. The molybdenum (average grade 0.2%) and the vanadium (200 to 500 ppm), together with selenium, nickel and germanium anomalies accompany the uranium mineralization. The reserves are estimated at about 8000 t of U_3O_8. From the paleogeographical point of view the sediments that host the Figueira Deposit and other occurrences known in the region (Telêmaco Borba and Sapopema) are associated with a system of island barrier lagoons with the development of peat deposits (Della Favera *et al.*, 1993). The evolution of the organic matter during burial led to the development of a reducing environment favourable to the fixation of uranium in its oxide form. The uraninite is associated with pyrite, and fills the secondary porosity and substitutes the wall rock sandstone. The anomalies for Mo, V, Se and Ge, associated with the uranium mineralization suggest an initial concentration of these elements together with organic matter.

Mesozoic Deposits

The mineral resources found in the Mesozoic basins and associated structures (Fig. 33) are related directly or indirectly to a global tectonic event that came about by rifting that lead to the break-up of Gondwana and the separation of the African and South American continents. The tectono-sedimentary evolution of the rifting process was divided into four stages (Ojeda, 1981, Cainelli and Mohriak, 1999): pre-rift stage; taphrogenic rift stage; transition stage of the proto-oceanic transgressive gulf during which time occurred the deposition of evaporite deposits; and the transgressive open ocean stage corresponding to a phase of thermal subsidence. These stages, which refer to the progressive opening of the South Atlantic Ocean, had important reflexes in the interior of the South American Platform as the result of successive reactivation along ancient lineaments, as well as by the appearance of new tectonic structures and the individualization of regional uplift.

The mineral deposits related to this tectono-sedimentary evolution have been classified in five categories (Dardenne, 1999): deposits related to volcanism; deposits associated with ultramafic-alkaline carbonatite complexes; deposits associated with kimberlite and lamproite intrusions; hydrothermal vein deposits; sedimentary deposits.

Deposits Associated with Volcanism

At the beginning of the Cretaceous, between 140 and 120 Ma, the pre-rift stage in the Paraná Basin is characterized by vast flows of tholeiitic basalt, basaltic andesite and minor dacite and rhyolite related to continental fissural volcanism of the Serra Geral Group. In Rio Grande do Sul, the Alto Uruguai/Araí and Salto do Jacuí amethyst and agate deposits are related to this volcanism (Fig.33). These deposits are of great economic importance, and have been intensely worked (Schmitt *et al.*, 1991; Szubert *et al.*, 1978; Cassedanne, 1991; Castro *et al.*, 1974). The origin of the silica required for geode formation is related to the dissolution of the silica in intertrap sandstone by supercritical water liberated by the crystallization of the basalt.

In the State of Piauí, the opal deposits at Pedro II are associated directly or indirectly to the circulation of hydrothermal waters originated by the intrusion of diabase sills (Orozimbo Formation) in the Paleozoic sediments of the Cabeças Formation (Devonian). These diabase sills are considered to be of Triassic-Jurassic age, corresponding to volcanic manifestations that accompanied the rifting that preceded the opening of the North Atlantic Ocean.

The mineralization occurs in fractures and siliceous breccia related to the shale and sandstone beds, and even the diabase at the base of the sill (Rosa, 1988; Samama *et al.*, 1983; Roberto and Souza, 1991; Cassedanne, 1991).

Deposits Associated with the Ultramafic-Alkaline-Carbonatite Complexes

According to Amaral *et al.* (1967), Hasui and Cordani (1968), Ulbrich and Gomes (1981), Cordani and Hasui (1968), these ultramafic-alkaline-carbonatite intrusive complexes show two groups of ages (Fig. 35) the first group occured between 130 and 120 Ma, and includes the complexes of Jacupiranga, Juquiá, Ipanema, Barra do Itapirapuã and Anitápolis, which are concentrated in the southeastern region of Brazil, and are contemporaneous with the basaltic volcanism of the Paraná Basin; and a second group, occurring between 90 and 65 Ma, including the complexes of Iporá, Santa Fé, Catalão, Serra Negra, Salitre, Tapira, Araxá, Poços de Caldas and Mato Preto, related to the re-activation along an Upper Cretaceous rift (Barbosa *et al.*, 1970). These complexes, which are distributed on the margin of the Paraná Basin along lineaments and regional uplift, occurred between the Lower and Upper Cretaceous, and are of great importance in the Brazilian mineral economy in function of the deposits associated with these. The mineral deposits are intimately related to the magmatic evolution of the complexes (Figs. 36, 37), and consist mainly of phosphate in the form of apatite, as well as magnetite, niobium, titanium, vermiculite, barite, fluorite, uranium and rare earths elements (CBMM, 1984).

In all the deposits associated with these complexes, the laterite weathering has played a fundamental role in the economics of the deposits, tending to increase the grades in the weathering profile by two mechanisms: a) relative concentration of the resistate minerals in the laterite cap, principally pyrochlore and apatite; b) neoformation of nickel minerals (silicate and oxide, enriched in Ni), alumina (gibbsite in the bauxite) and titanium (anatase).

The Diamond Deposits Associated with Kimberlite Intrusions

The principal occurrences of kimberlite in Brazil are distributed along the Transbrasiliano Lineament and a lineament with azimuth 125° (Gonzaga and Tompkins, 1991; Tompkins and Gonzaga, 1989). The Transbrasiliano Lineament is associated with the Gilbués/Picos kimberlite in the State of Piaui and the Poxoréu kimberlite in the State of Mato Grosso. To the 125° lineament is related the Cretaceous kimberlite provinces of the Paranatinga region (Batovi Kimberlite, dated at 121 Ma); of the Aripuanã region (Juína Kimberlite) in the State of Mato Grosso; of Pimenta Bueno in the State of Rondônia and of Alto Paranaiba (dated at 70 Ma) in the State of Minas Gerais (Bizzi, 1993). Only the Juína Kimberlite (Teixeira, 1998) has shown significant diamond mineralization (Fig. 38).

Hydrothermal Vein Fluorite Deposits

In southern Brazil the veined fluorite mineralization (Dardenne and Touray, 1988; Dardenne *et al.*, 1997) occurs in the State of Santa Catarina in a belt about 30 km wide mainly containing the Brasiliano granite intrusives of Pedras Grandes and Tabuleiro in addition to dykes and sub-volcanic acid rocks (Eopaleozoic) and mafic rocks (diabase of the Serra Geral Formation) and Paleozoic sediments of the Paraná Basin. The fluorite veins that cut all the rock-types mentioned above are related to ancient Brasiliano lineaments striking NNE-SSW that were reactivated during the Cretaceous as transcurrent and normal faults: the Canela Grande, Grão Pará and Armazém lineaments (Bastos Neto, 1990, Bastos Neto *et al.*, 1992). Four main phases of mineralization may be observed. The first three phases occurred between 140 and 100 Ma, whereas the last phase corresponds to a late phase and dates at about 70 Ma (Bastos Neto *et al.*, 1992). These four phases are well defined in function of the tectonic evolution of the veining and the rare earth content in the several generations of fluorite. Fluorite, associated with chalcedony, occurs in the form of coarse to fine-grained banded structures; as hydraulic breccia and as cockade ore, all very characteristic (Dardenne and Savi, 1984; Bastos Neto, 1990).

The genetic model that is generally accepted for the generation of these veins (Savi and Dardenne, 1980) involves the leaching of the fluor of the regional granitoid rocks by circulating hydrothermal waters related to the thermal anomaly associated with the rifting along the margins of the South Atlantic Ocean.

In the southeastern region some of the larger fluorite veins are associated with alkaline rocks of the Taguá Massif, dated at 65 Ma. The fluorite deposits have characteristics that are similar to those of the Santa Catarina District (Becker *et al.*, 1997).

In Uruguay, vein deposits of fluorite show the same controls as those observed in Santa Catarina.

Sedimentary Deposits

The Cretaceous sedimentary deposits may be divided into four categories (Dardenne, 1999): clastic diamondiferous deposits; evaporite deposits; phosphatic deposits; and deposits associated with the circulation of connate waters.

Clastic Diamond Deposits

During the rift stage of the Lower Cretaceous, thick sequences of fluvial clastic deposits were layed down in the marginal coastal basins and interior basins of Brazil. In the Alto São Francisco Basin, the basal conglomerate beds of the Abaeté Formation (Areado Group) contain numerous occurrences of detrital diamond (Campos *et al.* 1993), the origin of which is related to the successive reworking of older deposits, principally those of the Sopa-Brumadinho Formation of the Espinhaço Supergroup, and those alluvial deposits probably associated with diamictite of the Macaubas and Santa Fé de Minas groups (Campos, 1996). The diamond occurrences of the Abaeté Formation, which

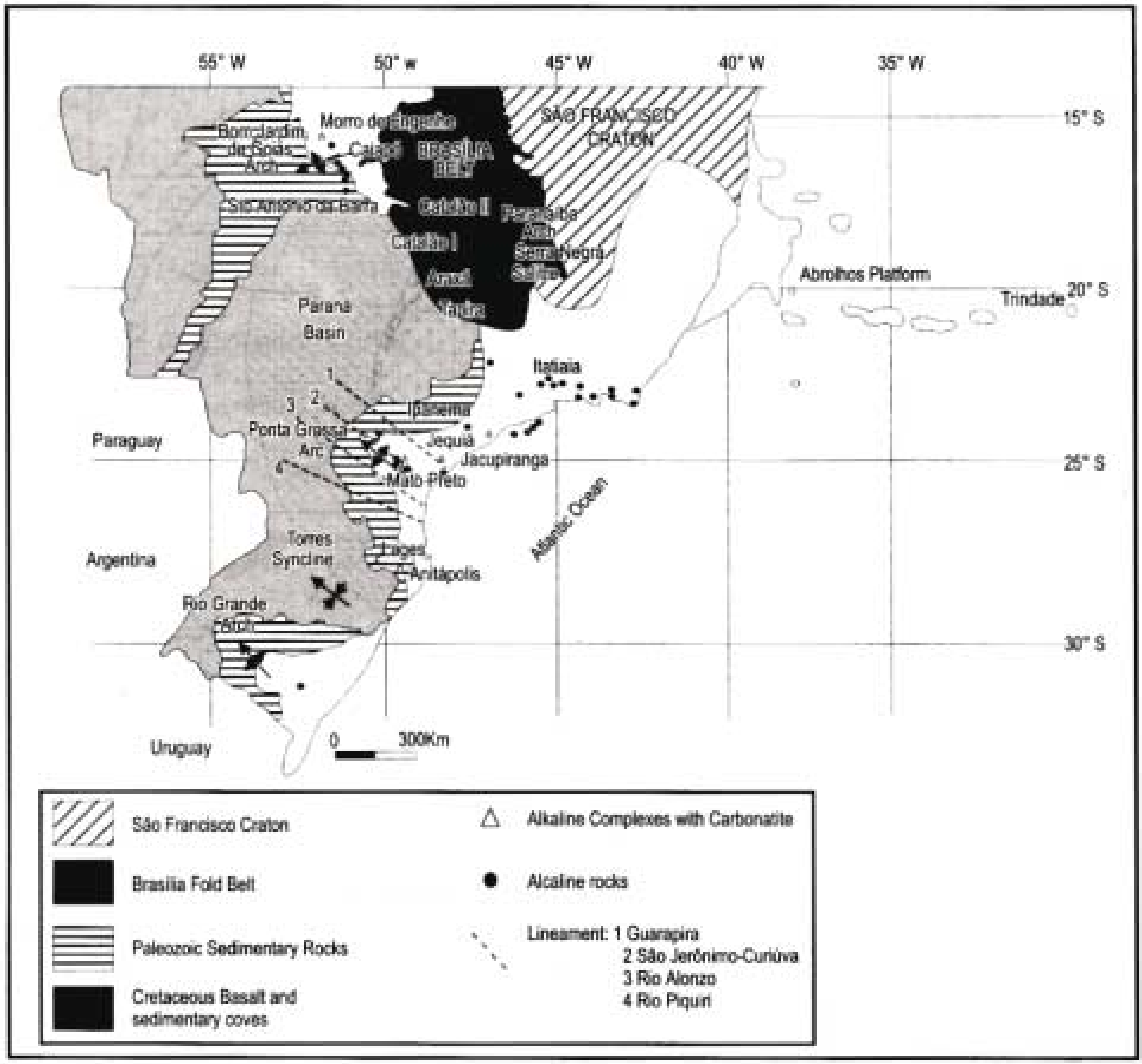


FIGURE 35 - Alkaline complexes in central - western and Southeastern Brazil.

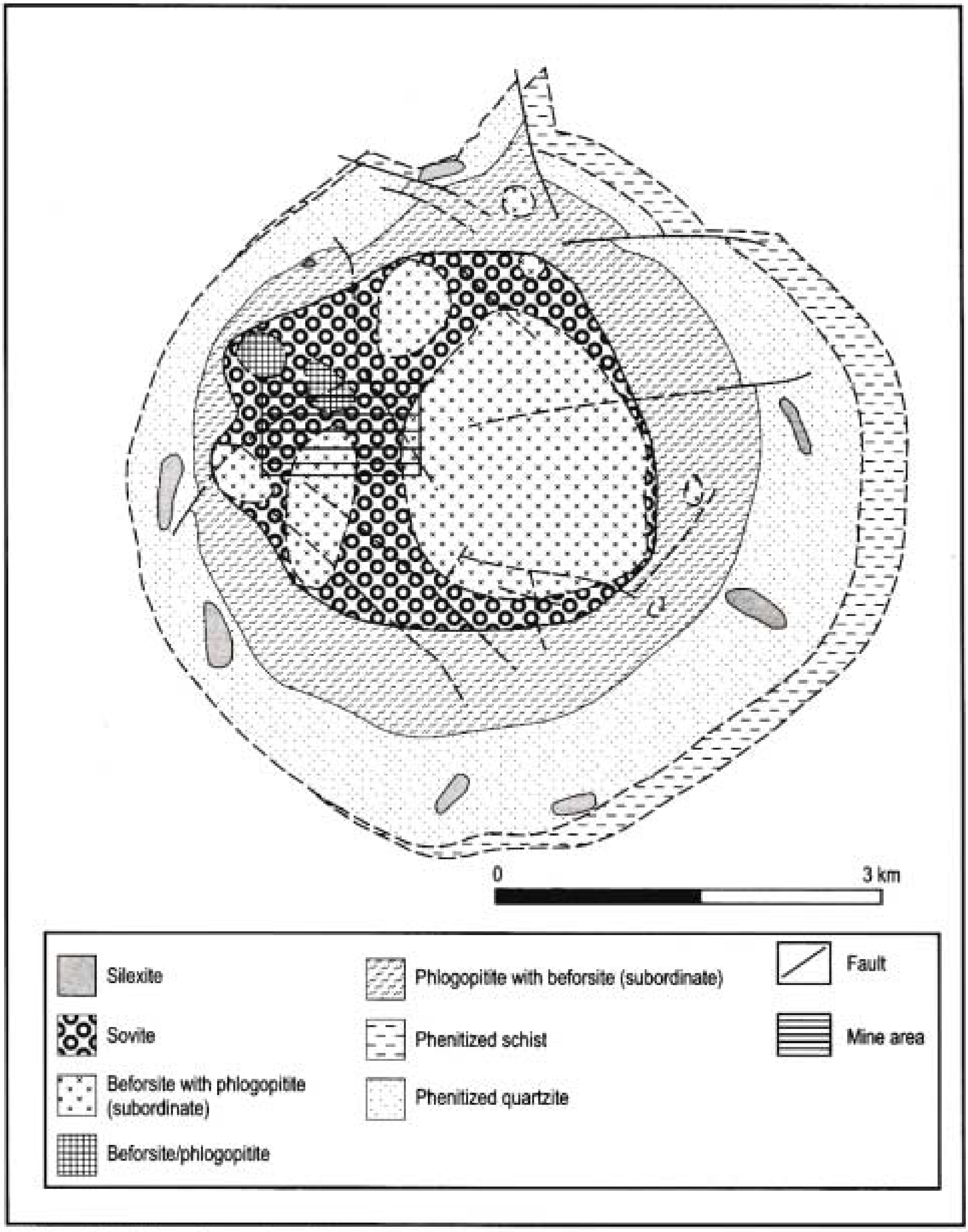


FIGURE 36 - Geological Map of the Barreiro Complex.

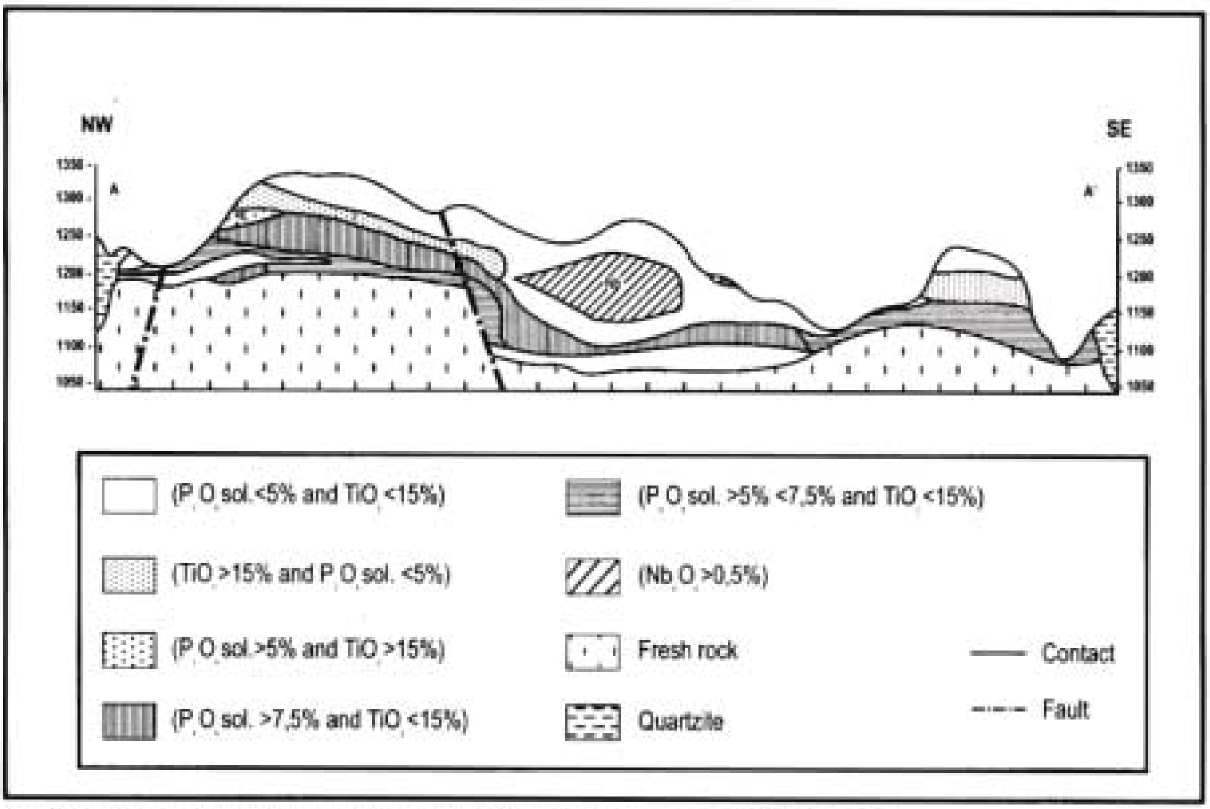


FIGURE 37 - Niobium, phosphate and titanium mineralizations of the Tapira Complex (CVRD - DOCEGEO).

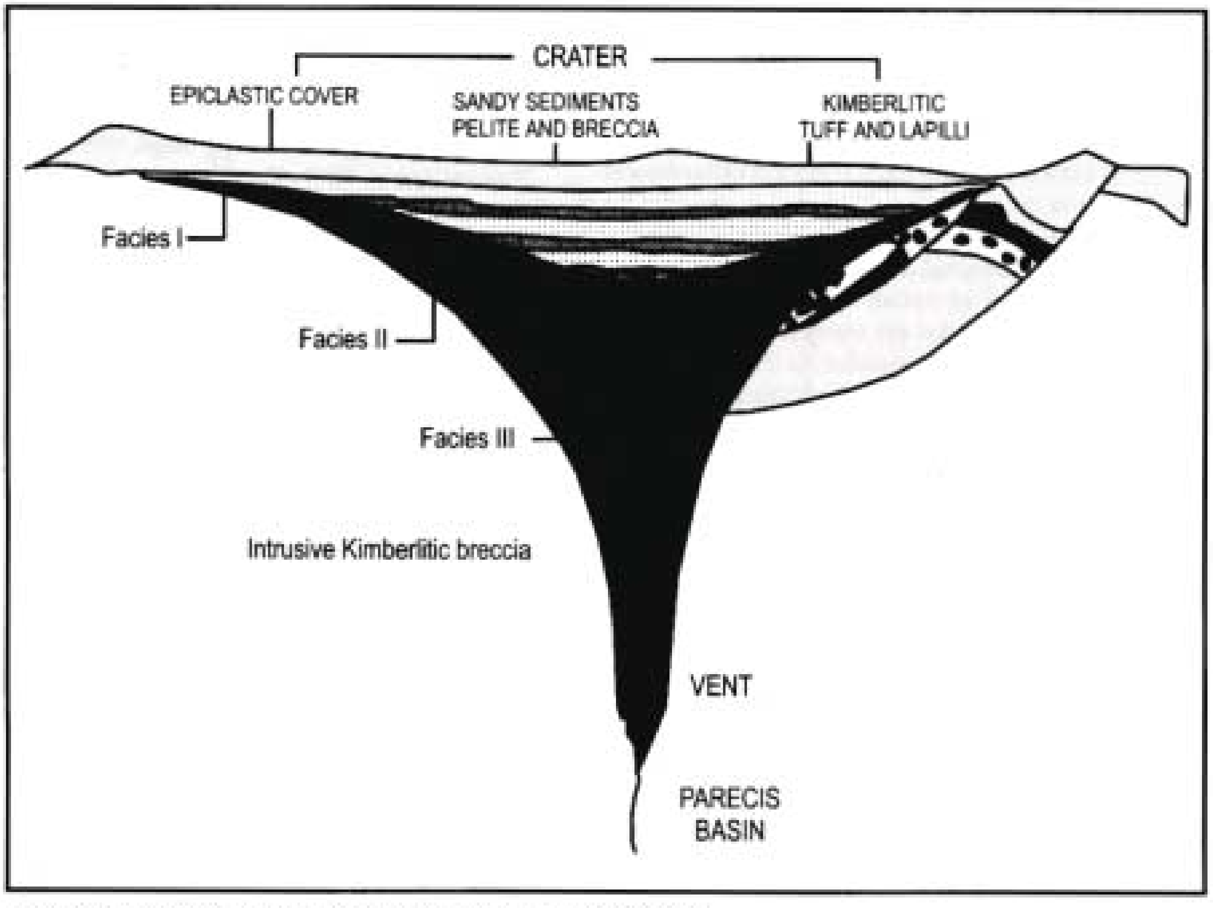


FIGURE 38 - Explosive kimberlite structure of Juína (modified after Teixeira, 1998).

have been amongst those most investigated and evaluated, are situated in the Cana Brava region of the State of Minas Gerais (Dardenne *et al.*, 1991; Campos, 1996) and the Serra do Cabral where the highest grades obtained reach a few points per m^3.

In the Brazilian Northeastern region, similar deposits are found in the Gilbués area of the State of Piaui where the diamonds are associated with the conglomeratic facies of the Pé do Morro Formation at the base of the Areado Group (Gonzaga and Tompkins, 1991).

During the re-activation of the Upper Cretaceous rift, there occurred an uplift of the Paranaiba High between the Paraná and São Francisco basins with which are related the alkaline intrusions, volcanic flows and kimberlite pipes of the Patos Formation. The erosion of these volcanic edifices resulted in the deposition of conglomerate and epiclastic sandstone units of the Uberaba Formation in the Bauru Basin, and the Capacete Formation in the Alto São Francisco Basin. To these rock-types are associated the diamonds of the Romaria Deposit (Gallo, 1991; Suguio *et al.*, 1979) and the provenance of inumerous occurrences found in Recent alluvium.

In the State of Mato Grosso the diamondiferous placers are related to the erosion of conglomerate beds of the Upper Cretaceous Parecis Formation (Arenápolis/Nortelândia diamond district; 400 000 carats at 0.02-0.04 ct/m^3) and the Bauru Group (Poxoréu diamond district; 0.04 ct/m^3) deposited, respectively, in the Parecis and Bauru basins; both separated by the Rondonópolis High (Schobbenhaus 1984; Souza, 1991; Fleischer, 1976; Weska *et al.* 1997; DNPM-Brazilian Mineral Yearbook, 1998).

Evaporite Deposits

In the northeastern region of Brazil, evaporite deposits occur in the marginal coastal basins as well as in the Cretaceous basins of the continental interior.

In the marginal coastal basins, the evaporite sedimentation of Aptian age developed during a transitional phase that also represented a proto-oceanic gulf phase, related to the evolution of a rift at the start of the opening phase of the South Atlantic Ocean. The marine transgression occurred from S to N when the oceanic waters flowed over the Walvis barrier at the latitude of Rio Grande do Sul. In this basin were deposited two evaporite sequences contained in the Muribeca Formation: the Paripueira Evaporites of Eo-aptian age, that are worked for halite by underground dissolution methods at Bebedouro near the city of Maceió in the State of Alagoas (Amaral and Melo, 1997); the Ibura Evaporites of Neoaptian age, which are associated with deposits of carnallite and sylvinite in the Santa Rosa de Lima and Taquari-Vassouras sub-basins of the Sergipe Basin (Fig. 39). Cycle VII consists of beds of halite and sylvinite with thin zones of carnallite, which are mined at the Taquari-Vassouras underground mine (Szatmari *et al.*, 1979; Cerqueira *et al.*, 1986, 1997). The lower sylvinite unit is yellow in colour and crystalline. It is 3.82 m thick, and contains 25.03% KCL. The upper sylvinite unit is reddish and whitish in colour and finely crystalline. The average thickness of this unit is 4.27 m and it contains 24.95% KCl. A halite zone having a maximum thickness of 14.62 m in the central part of the deposit separates these two sylvinite units, and locally the two units may merge to form a single sylvinite unit. The sylvinite reserves are given as about 42 Mt with 24.95% KCl. The annual production in 1991 was 275 000 t of KCl and 850 000 t of NaCl.

At the Siririzinho Anticline, which separates the two basins, there occurs the native sulphur deposit of Castanhal (Frota and Bandeira, 1997; Morelli *et al.*, 1982), situated in the lower part of the Ibura Member where it is intimately associated with the biogenic reduction of anhydrite beds in the presence of oil, water and sulphurous gas. In the interior basins of the Brazilian Northeast, the evaporite deposits consist mainly of gypsum and subordinate anhydrite, precipitated during an Aptian marine transgression. The main gypsum deposits, mined for the manufacture of Portland cement and plaster, occur in the Santana Formation on the Chapada do Araripe (Krauss and Amaral, 1997; Silva, 1988), and in the Codó Formation in the Maranhão Basin (Baquil, 1997).

The Phosphate Deposits of the Pernambuco-Paraiba Basin

In the Brazilian Northeastern Region, phosphate is associated with sedimentary sequences (Paraiba Group) of the Pernambuco-Paraiba Basin (Upper Cretaceous), extending as a narrow coastal belt some 15 to 20 km wide, N-S, for a distance of about 100 km between the cities of Recife and João Pessoa, and dipping gently towards the Atlantic Ocean. Along this coastal belt the phosphate beds indicate a marine transgression at the base of the Gramame Formation. These beds are essentially continuous and overlie the Beberibe Sandstone. The thickness of the phosphorite beds varies from a few centimetres to a maximum of 4 m, with grades between 20% and 35% P_2O_5 (Kegel, 1955; Moreira Neto and Amaral, 1997). The estimated reserves for the region are about 65 Mt of ore at 22% P_2O_5.

In the high-grade phosphorite the phosphatic material including moulds of mollusks, planktonic foraminifera, intraclasts, pellets, ooliths, cropolites, algal and coral fragments is abundant (Tinoco, 1971). The phosphorite consists essentially of fluorapatite with low CO_2 content (1.14% to 1.38%), high F/P_2O_5 ratios (0.195 to 0.146) (Boujo *et al.*, 1998; Menor *et al.*, 1977). The phosphorite has a certain amount of radioactivity, representing, according to White (1957) equivalent uranium grades of 0.018% to 0.25%.

Deposits of Barite associated with the Circulation of Connate Fluids

In the Cretaceous basins of Sergipe/Alagoas, Camamu, Recôncavo and Tucano, there are numerous occurrences of barite, galena and sphalerite related to circulation of connate fluids in rift environments (Dardenne, 1997, 1999). At the barite deposit of Fazenda Barra (Bandeira *et al.*, 1986) the barite originated by the replacement of an anhydrite cement in a sandy zone by barite carried in percolating waters rich in barium.

At the Camamu Deposit (Dardenne and Campos, 1984), genesis resulted from the replacement by leaching of an anhydrite zone of Eo-aptian age by barite derived from barium-rich solutions, in turn derived from the feldspar of acid granulite.

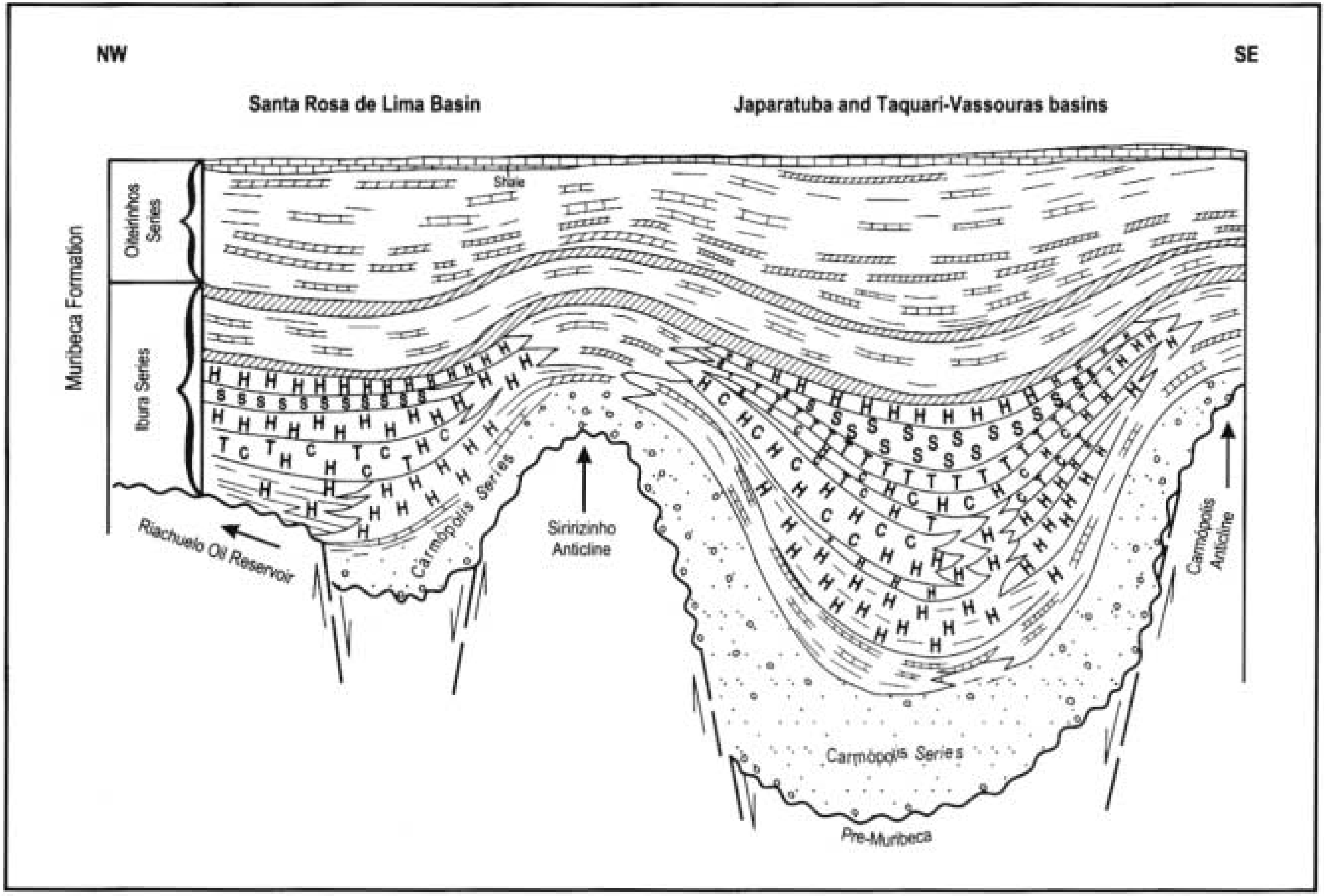


FIGURE 39 - Geological cross-section of Santa Rosa de Lima and Taquari-Vassouras basins, Sergipe-Brazil (modified after Cerqueira et al.,1997).

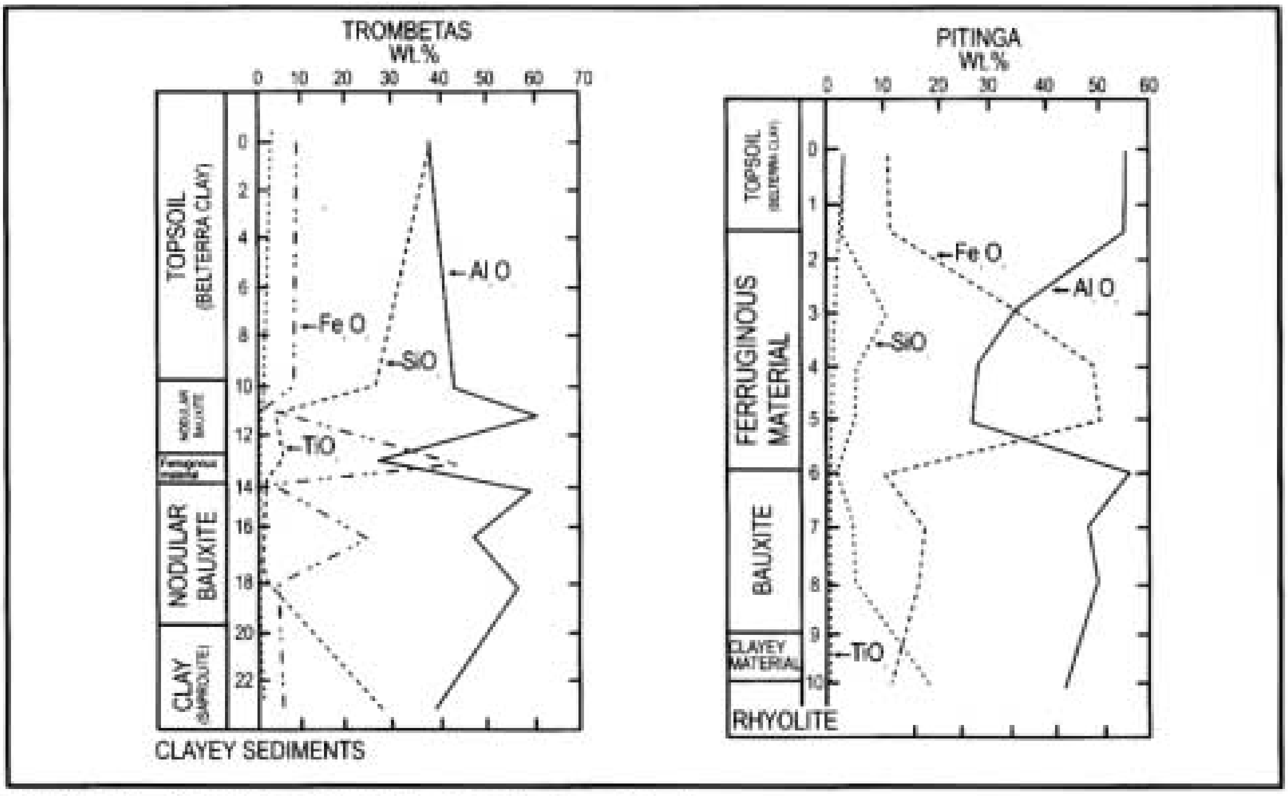


FIGURE 40 - Chemical variations in the lateritic bauxite profiles at Trombetas and Pitinga, modified after Boulange and Carvalho (1997).

Cenozoic

During the Cenozoic the principal mineral deposits have resulted from the weathering of laterite that developed on the South American Platform from the beginning of the Tertiary, and the accumulation of heavy mineral concentrates as placer deposits in alluvium, paleo-alluvium and in paleo-marine sediments along beaches at the continental margin.

Mineral Deposits of Lateritic Origin

A large part of the South American Platform is situated in the intertropical zone in which there predominate conditions favourable for the development of mechanisms of supergene alteration, leading to the development of thick lateritic cover. However, the main phase of lateritization, with which are associated the mineral deposits is related to the lower Tertiary (Eocene), and the second phase is generally attributed to the upper Tertiary (Miocene-Pliocene), which suggests a complex evolution and a fossil character for most of the mineral concentrations of lateritic origin. These minerals may be classified in two categories in function of the nature of their origin: a) lateritic deposits originating by relative concentration of their insoluble or slightly soluble chemical elements in the form of neoformed minerals. The most significant of these are aluminum, manganese, nickel, and very locally, titanium; b) lateritic deposits originating from residual accumulations of stable minerals, resistant to supergene alteration. These include hematite in itabirite, cassiterite in albitite; pyrochlore, apatite and barite in alkaline-carbonatite complexes and locally gold.

In this review, only those lateritic deposits belonging to the first category will be discussed, whereas the importance of the deposits included in the second category will be stressed before the genesis of the primary mineralization is discussed.

Bauxite Deposits

The bauxite deposits are widely dispersed in different regions of the South American Platform, and may be divided into three main provinces: a) Eastern Amazon Basin; Berbice Basin in Guyana and Suriname; c) Los Pijiguaos in Venezuela; d) Central-eastern region of Brazil; e) Southeastern region of Brazil.

The bauxite deposits of the Eastern Amazonas Basin

In the states of Amazonas and Pará, the main bauxite deposits: Trombetas, Nhamundá, Juruti, Almeirim, and Paragominas, display similar weathering profiles (Fig. 40) developed from argillaceous sediments and argillaceous-sandy sediments of the Ipixuna, Itapecuru and/or Alter do Chão formations, of Lower to Upper Cretaceous age. The distribution of the zones in the weathering profile may have a bearing on the origin of the bauxite of Amazonia, which is still somewhat controversial:

- the bauxite is overlain by a thick kaolinitic cap (up to 20 m) known as the Argila de Belterra. This deposit is considered to be allochthonous, having being deposited in a lacustrine environment (Grubb, 1979; Truckenbrodt and Kotschoubey, 1981; Kotschoubey *et al.*, 1981, 1997); or autochthonous, having developed *in situ* in the weathering profile (Lucas, 1997; Boulangé and Carvalho, 1997; Aleva, 1981).

- the presence of a nodular ferruginous zone intercalated between two bauxitic zones, suggesting polyphasic evolution, involving climatic diversity with alternating humid and dry periods (Kotschoubey *et al.*, 1997), or alternatively, the migration of iron through the weathering profile to form an intermediate ferruginous crust (Lucas, 1997; Boulangé and Carvalho, 1997; Aleva, 1981). These observations have led to two distinct models: the allochthonous model implying an evolution involving climatic diversity, and the autochthonous model implying polyphasic alteration *in situ*. proposed a similar model for the evolution of bauxite deposits on the Guiana Shield. The deposits of Eastern Amazonia contain huge reserves of bauxite.

The total reserves of the Eastern Amazonas region exceed 1.5 billion t of ore.

The bauxite deposits of the Berbice Basin

The coastal basin of Berbice in Guyana and Suriname contains the world's largest reserves of high-grade gibbsitic bauxite suitable for refractory liner requiring a very low iron content, as well as for usage in the chemical and metallurgical industries. It seems that these bauxite deposits developed in the Paleogene and some were covered by Oligocene sediments (Gibbs and Barron, 1993).

In Guyana, the deposits are situated in the Berbice and Demerara river regions, and in Suriname, at Moengo, Onvervacht and Paranam (Fig. 5).

The Los Pijiguaos bauxite deposits

The Los Pijiguaos bauxite deposits are the most important in Venezuela. These deposits are developed over the Parguaza rapakivi granite of Mesoproterozoic age. The high-grade ore occurs at an erosion level between 620 m and 690 m, and formed during an intense weathering cycle during the Upper Cretaceous and lower Tertiary. Measured and indicated bauxite reserves are 201.8 Mt of ore at 48.7 % Al_2O_3, and 10.9% SiO_2.

The Parguaza Granite is a batholith that covers an area of at least 10 000 km^2 in the State of Amazonas extending into Venezuela. The granite is intruded into the volcanic rocks of the Cuchivero Group (Uatumã Supergroup) (Sidder and Mendoza, 1995). The granite protolith contains 65% to 73% SiO_2, and 13.5% to 15% Al_2O_3. The average thickness of the Los Pijiguaos ore is about 7.5 m, and the overburden, when present, is <1 m. The main mineral is gibbsite with smaller amounts of kaolinite. Structural and physical features such as joints, fractures and the slope angle control the Al_2O_3 enrichment and the depletion of SiO_2 in the granitic rocks. The ore zones enriched in alumina and depleted in silica may be correlated with zones having the highest density of fractures. A slope with inclination between 2° and 10° is considered favourable for the formation of ore (Sidder, 1995).

The bauxite deposits in the Central-eastern region of Brazil (Zona da Mata)

The bauxite deposits in the Central-eastern region of Brazil, also known as the Zona da Mata, are found in the southern part of the State of Minas Gerais and on the elevated terrains of the Serra da Mantiqueira. The bauxite deposits have developed over different Precambrian rock-types. Of note, are the deposits associated with granulitic rocks in the region of Cataguazes in Minas Gerais, which constitute an extensive aluminous belt orientated NE-SW, between the towns of São João do Nepomuceno and Cataguazes. The total reserves exceeding 100 Mt are of great economic importance in function of their strategic situation near to the large markets of Rio de Janeiro, São Paulo and Belo Horizonte (Roeser *et al.*, 1984; Valeton and Melfi, 1988; Valeton *et al.*, 1991; Beissner *et al.*, 1997).

The bauxite deposits of the Alkaline Province of Southeastern Brazil

Bauxite deposits originated from the chemical weathering of alkaline rocks occur in the Poços de Caldas Province, the Coastal Province of Rio de Janeiro and São Paulo and the Province of Lages-Anitápolis in the State of Santa Catarina. The more important reserves are associated with the Poços de Caldas Alkaline Complex, and are estimated at about 50 Mt (Schulmann *et al.*, 1997).

The Kaolin Deposits of the Amazon Region

There are three main districts in the Amazon region known for their kaolin deposits: Rio Capim, Morro de Felipe and Manaus-Itacoatiara (Costa and Moraes, 1998). The more important deposits developed as the result of the *in situ* alteration of Cretaceous sediments of the Ipixuna-Itapecuru and Alter do Chão formations (Murray and Partridge, 1982). The thickness of the kaolinitic zone varies from 10 to 20 m (Fig. 41). The kaolin deposits are characterized by their whiteness in function of their low iron oxide and hydroxide content, and are used mainly in the paper industry. Production from several mines at Morro do Felipe and from the Rio Capim District is about 2 M tpa. According to Costa and Moraes (1998) and Kotschoubey *et al.* (1996), the kaolin deposits are related to the lower zones of the laterite profile that developed initially in the lower Tertiary and evolved progressively by desferrification and resilicification in reducing and acid environments, principally in the Oligocene-Miocene transition.

Nickel Laterite Deposits

The principal nickel laterite deposits are found in the Amazon region, and specifically in the Carajás Mineral Province. Here the deposits are associated with differentiated intrusive bodies, dated at 2.645 Ga, including Vermelho, Puma-Onça and Jacaré-Jacarezinho. In the southwestern region of Brazil there occur deposits related to the mafic-ultramafic complexes of the Niquelândia and Barro Alto, dated at between 2.0 and 1.7 Ga, and to the ultramafic-alkaline complexes of Upper Cretaceous age such as Santa Fé de Goiás, Morro do Engenho, Morro dos Macacos, Rio dos Bois and Montes Claros.

In the nickel laterite deposits of the Vermelho-type (Fig. 42) (Alves *et al.*, 1986) the weathering profiles are developed over peridotite and serpentinized dunite with pyroxenite intercalations where the nickel is concentrated in ferruginous zones with limonitic ore (1.2% Ni) as well as in coarse-grained saprolite (1.5% to 2.0% Ni) as silicate ore in the form of garnierite and smectite (1.5% to 2.0% Ni). The relative amounts of the two ore-types are approximately the same (Costa, 1997; Bernadelli *et al.*, 1983; Castro Filho and Matos, 1986). The reserves at the Vermelho deposit are estimated at 44 Mt of ore at 1.5% Ni.

At the nickel laterite deposits found at the Niquelândia

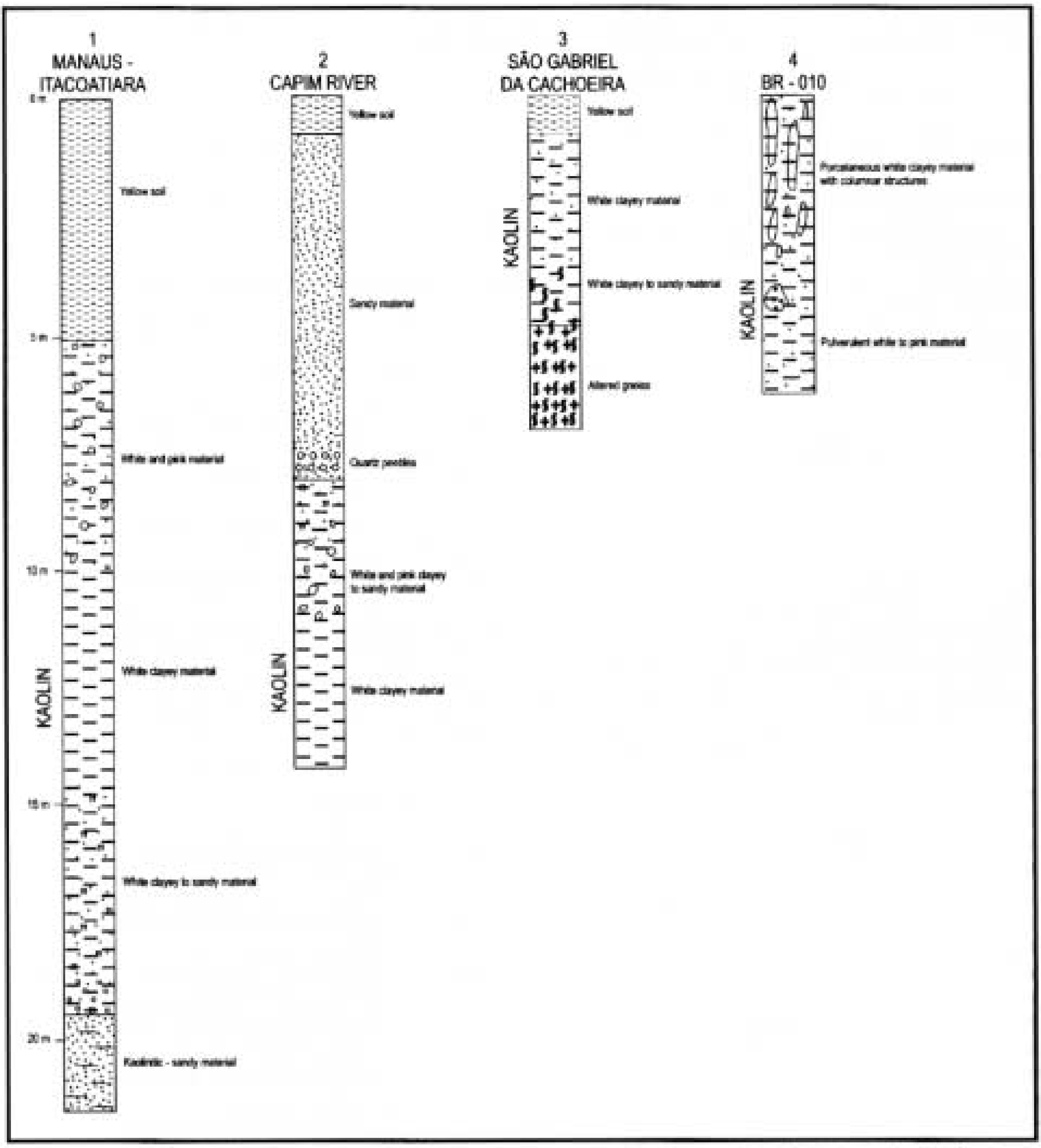


FIGURE 41 - Geological profiles of kaolin deposits (modified after Costa,1997): 1 - Manaus-Itacoatiara; 2 - Capim River; 3 - São Gabriel da Cachoeira; 4 - BR - 010 (Belém-Brasília).

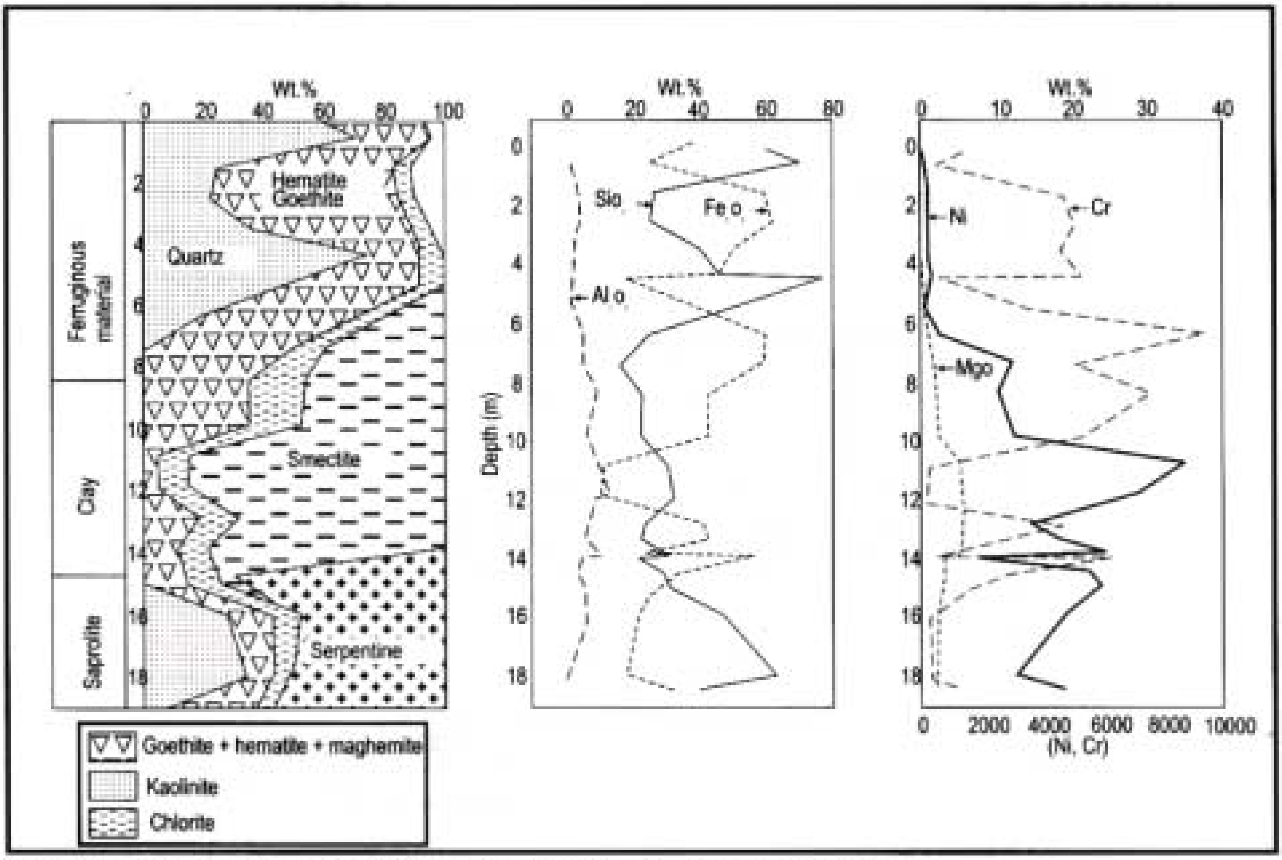


FIGURE 42 - Mineralogical and chemical variations through the nickel lateritic deposit of Vermelho/Carajás.

and Barro Alto complexes (Baeta *et al.*, 1986) the weathering profiles are developed over partially serpentinized peridotite and dunite and pyroxenite, with nickel concentration on the oxide ore, rich in goethite, and in the silicate ore, rich in smectite. The polyphasic evolution of these profiles (Fig. 43) may be observed in all the deposits of the Central-Western region of Brazil (Oliveira and Trescases, 1982; Melfi *et al.*, 1980, 1988). The reserves at the Niquelândia Complex are estimated at about 60 Mt of ore at 1.45% Ni, and have been intensely mined by Niquel Tocantins and CODEMIN, whereas the reserves at the Barro Alto Complex have been evaluated at about 72.39 Mt of ore at 1.67% Ni.

Finally, there is the Rincón Del Tigre igneous complex in Bolivia, near the frontier with Brazil. This is a differentiated mafic-ultramafic layered intrusion some 3000 to 4000 m thick, dated at 993±139 Ma. Tertiary weathering cycles produced a secondary nickel concentrate over the serpentinized dunite of the complex. Extensive resources of secondary nickel silicate ore have been proved (Litherland *et al.*, 1986).

Lateritic Gold Deposits

During lateritic weathering the gold was partially or totally remobilized in profiles developed over primary mineralization, resulting in very high gold concentrations, as can be seen at the Igarapé Bahia Deposit in the Carajás Mineral Province, and at the Cassiporé Deposit in Amapá (Fig. 44) (Costa, 1997; Costa *et al.*, 1993, 1996).

Placer Deposits

Placer deposits developed during the Cenozoic in drainage in the interior of the South American Platform as well as along the littoral regions led to the mechanical concentration of heavy minerals.

Gold and Cassiterite Placers in the Amazon Region

The economic importance of gold and cassiterite placer deposits is very great. Gold concentration along drainage occurs in alluvial and paleo-alluvial deposits in the proximity of primary deposits in the mineral provinces of Amapá, Tapajós, Rio Madeira and Alta Floresta. The cassiterite provinces are Pitinga and Rondônia. Whereas the heavy mineral concentrates in Recent alluvium are of limited economic importance, this is not the case with the terrace and buried paleo-alluvial deposits (Figs.45 and 46) that may be of economic value, locally (Bastos, 1988; Bettencourt *et al.*, 1997; Veiga *et al.*, 1988; Veiga, 1988).

Beach Placers along the Brazilian Coast

Along the Brazilian coastline from the NE to S, occur placer deposits in beach sands with monazite (REE oxide), ilmenite/rutile and zirconite. Ilmenite deposits are also found along the littoral of Argentina.

The more important Brazilian deposits of this type are found along the littoral of the states of Paraíba, Bahia, Espirito Santo and Rio de Janeiro. The largest deposit of monazitic sands occurs at São João da Barra in the State of

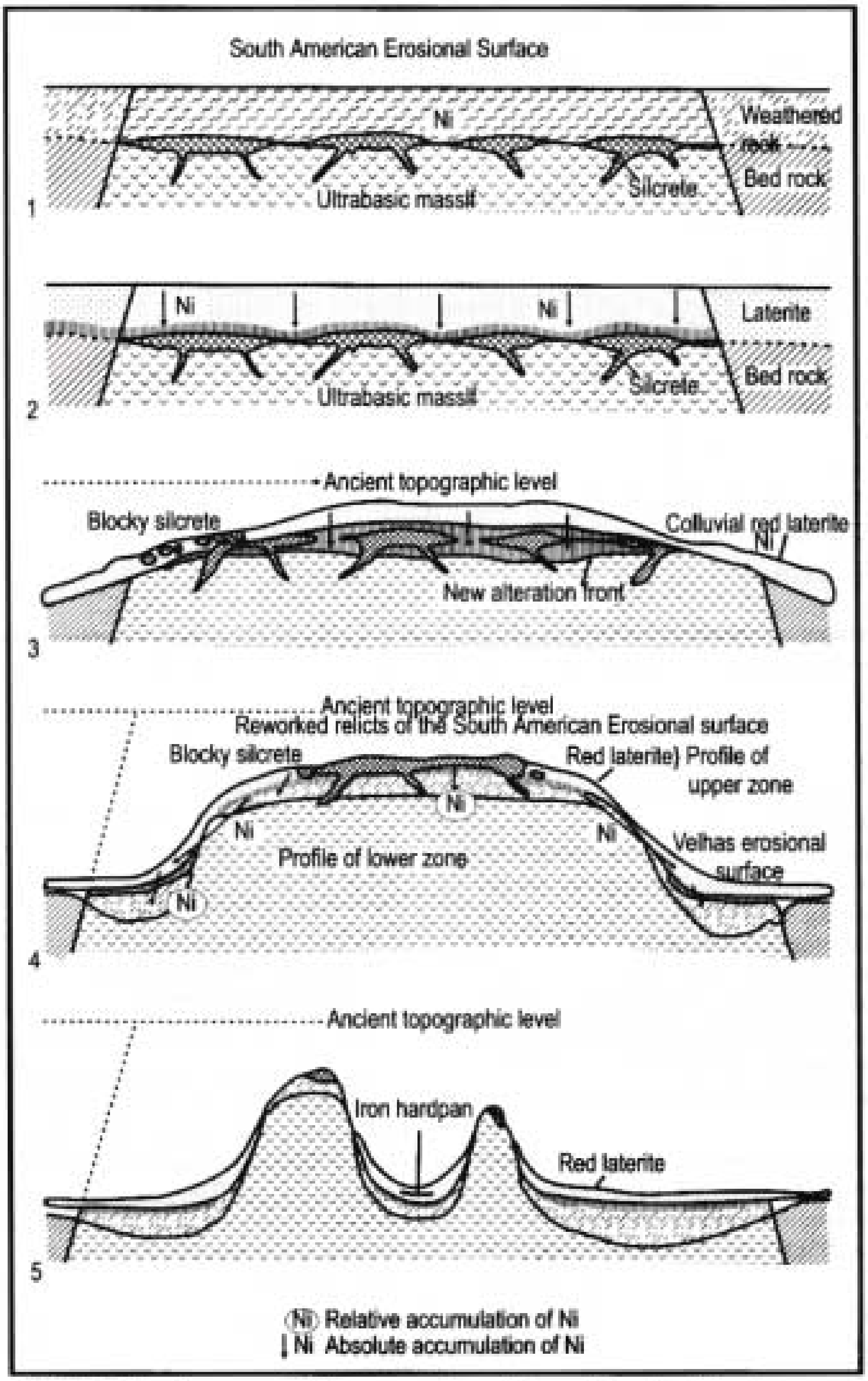


FIGURE 43 - Schematic sequence of the different morphotectonic phases during the evolution of the Ni lateritic deposits in Central Brazil (modified after Melfi et al.,1988).

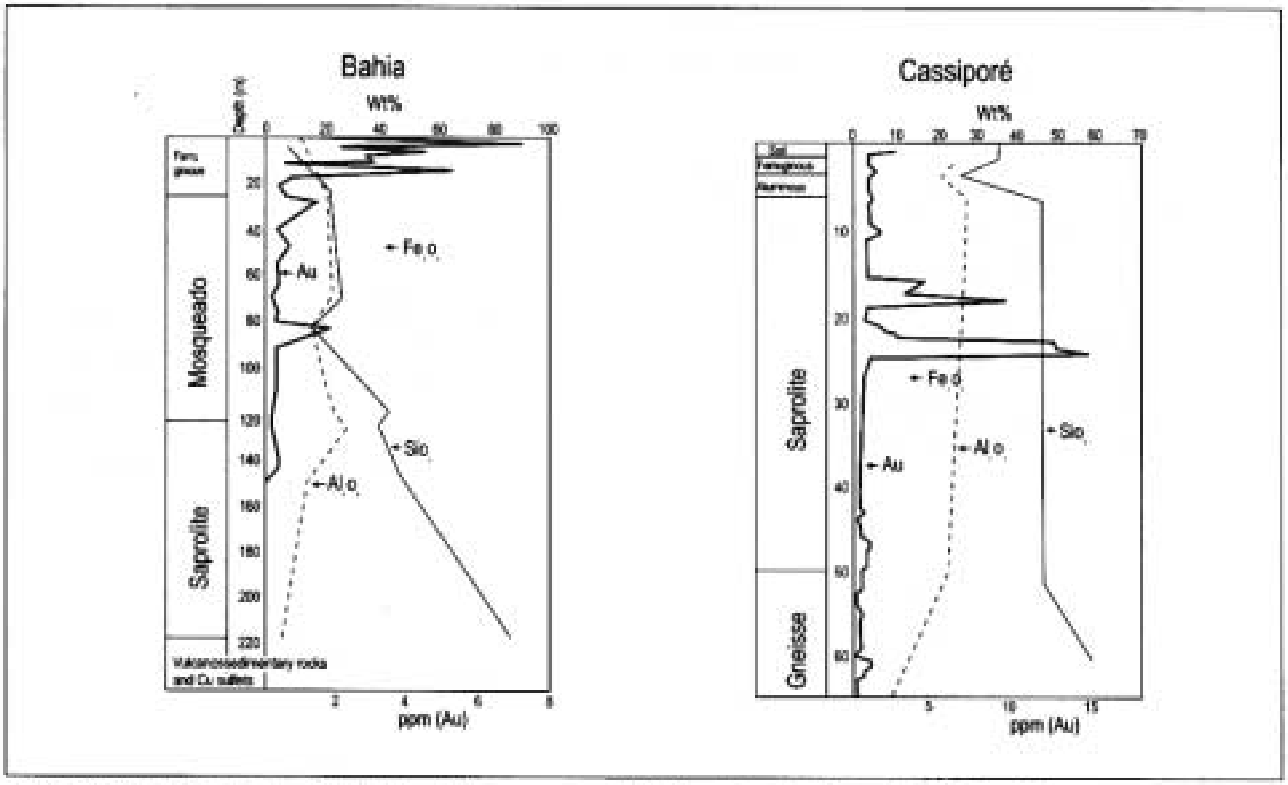


FIGURE 44 - Vertical distribution of principal chemical components and gold in lateritc deposits of Igarapé Bahia (Carajás) and gold mines of Cassiporé (modified after Zang and Fyfe 1993; Costa et al., 1993)

Rio de Janeiro. It contains about 40 000 t of monazite. Mataraca, in the State of Paraíba, has the largest deposits and is the largest Brazilian producer of ilmenite concentrate (c. 100 000 tpa) and zirconite (Source: DNPM). However, the largest recently evaluated total reserves of ilmenite occur at Bujuru in the State of Rio Grande do Sul with 10.8 Mt of ilmenite (Santos *et al.*, 1998).

At Mataraca, the average grade of the heavy minerals varies between 3% and 5%. The measured reserves at Mataraca are 2.7 Mt of ilmenite (81.54%), rutile (2.4%) and zirconite (16.06%).

THE DISTRIBUTION OF MINERAL DEPOSITS THROUGHOUT GEOLOGICAL TIME ON THE SOUTH AMERICAN PLATFORM – METALLOGENIC EPOCHS

During the development of the South American Platform from the Archean to the Proterozoic, as well as during its tectonic evolution during the Phanerozoic, a number of mineral deposits were formed. The synthesis shown in Figure 47 gives a general view of the chronostratigraphic position of the principal mineral deposits in relation to the major tectonic events, as well as an indication of the principal metallogenic epochs occurring on the platform.

The definition of the metallogenic epochs, this is to say, the geological time interval during which the formation of the mineral concentrations of a certain metal or substance

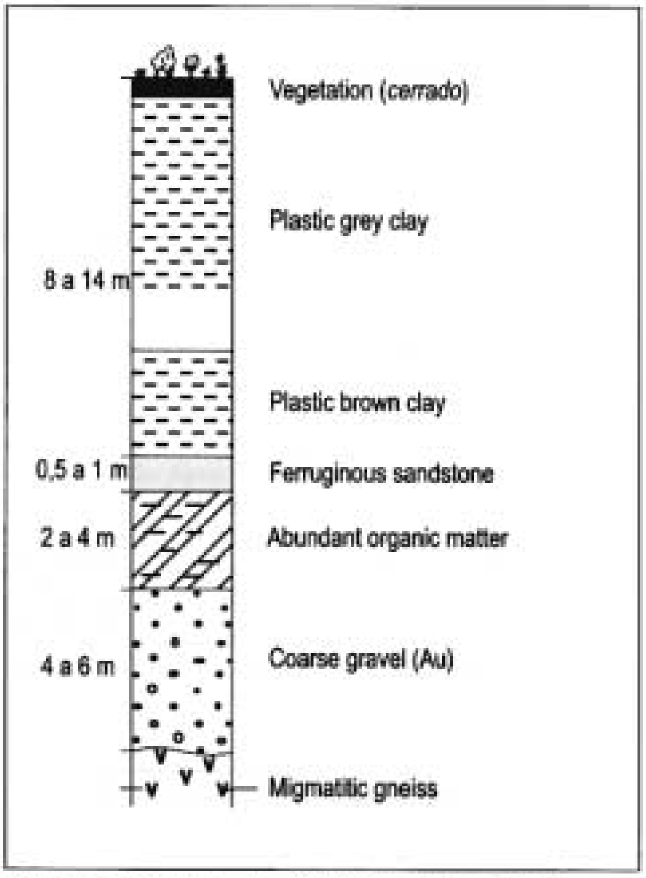


FIGURE 45 - Burried paleovalley of Rio Madeira: Periquito gold mine.

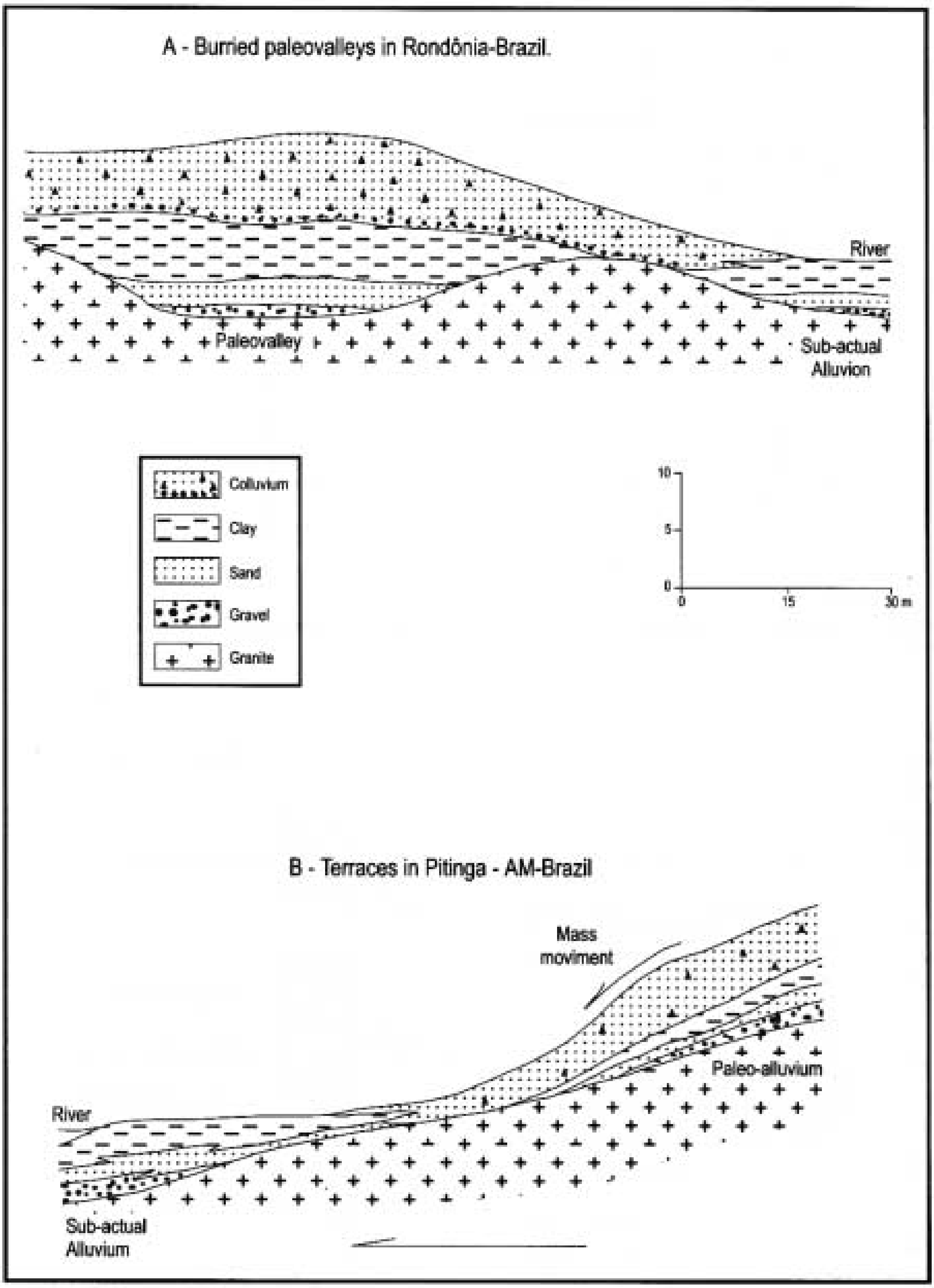


FIGURE 46 - Schematic model for Au and Sn placers (modified after Veiga et al., 1988).

was especially favourable or pronounced, remains relatively difficult for certain regions of the South American Platform, seeing that this implies the application of a time-bounded concept. The inherent difficulties lie in a more precise level of definition, not only of the mineralization, but also of the geochronological positioning of the host unit and/or generator of the mineralization. This view is especially valid for the oldest units that underwent a complex geological history.

In spite of these difficulties it is now possible to position the most important mineralizations in their geochronological context, and relate this to specific tectonic and/or magmatic events that were especially favourable for the generation of certain mineral deposits or groups of deposits. This may be attributed to the advances in recent years in metallogenic and geochronological studies in the more important mineral provinces/districts of the South American Platform.

In this setting, it can be noted that throughout time there occurred regional specialization of certain groups of mineral deposits reflecting crustal evolution and highlighting the limits between the chronostratigraphic units and emphasizing the heterogeneity of the primitive crust and mantle (Dardenne, 1982, Schobbenhaus, 1984; Schobbenhaus and Campos, 1984; Delgado *et al.*, 1994; Tassinari and Melito, 1994).

In the **ARCHEAN**, three major divisions may be defined: Paleo-Archean, Meso-Archean and Neo-Archean. In the Meso-Archean and Neo-Archean, the development of volcano-sedimentary sequences and associated plutonism was omnipresent, defining distinct metallogenic epochs in function of their age and metals content.

In the **Paleo-Archean** there occurred the individualization of the oldest continental block recognized on the South American Platform between 3.4 and 3.7 Ga that is represented by the Imataca Block in Venezuela. In the Imataca Block, rocks of this age include banded iron formation units of the Superior Province-type or more probably associated with volcanism (Algoma or Carajás type), and secondarily, of the Algoma-type, deformed and metamorphosed in the granulite and amphibolite facies between 2.8 and 2.7 Ga (Aroense Event), and between 2.15 and 2.0 Ga (Transamazonian Event). Supergene alteration of these rocks resulted in important concentrations of iron ore (e.g. Cerro Bolivar, San Isidro, El Pao). Manganese mineralization (gondite) is also found associated with the Imataca Complex.

In other areas of the South American Platform there are indications of primitive crustal continental nuclei older than 3.0 Ga. However, the related metallogenic epoch has not yet been defined.

In the **Meso-Archean**, between 3.0 and 2.8 Ga there occurred the development of the oldest granite-greenstone terranes, and the formation of continental blocks in the areas of Rio Maria (Central Brazil Shield), Crixás (Goiás Massif), and Pium-hi, Fortaleza de Minas and the Gavião Block (Atlantic Shield).

In the Rio Maria area there can be observed the importance of rifting mechanisms and the evolution of the volcanism, the composition of which varies from komatiitic to tholeiitic and calc-alkaline which presupposes the involvement of plate tectonics from the earliest Meso-Archean times. This led to the definition of a continental microplate at *c.* 3.0 to 2.9 Ga, which was affected by the deformation and metamorphism of the Aroense Event (2.8–2.7 Ga) that gave rise to large high-angled shear zones with which are associated the gold deposits of Babaçu, Lagoa Seca and Diadema.

Although gold is found in the Meso-Archean granite greenstone terranes, large deposits formed at this time are not known. With respect to the Crixás gold deposit, there exists a difference of opinion regarding the age of the mineralization. This age is defined by the Brasiliano tectonic overriding that is younger and therefore not related to the greenstone belt rocks. However, there occur mineral deposits having a more diversified content. For example, the magnesite deposits of the Serra das Éguas in the Brumado greenstone belt, the barite deposit at Itabura in the Mundo Novo greenstone belt, the Fe-Ti-V+PGE of the Jacaré and Campo Alegre de Lourdes sills, the chromite of the Pium-hi greenstone belt, and the O'Toole Deposit (Ni-Cu-Co+PGM) of the Morro de Ferro greenstone belt. In the Gavião Block the base metals anomalies are numerous.

In the **Neo-Archean**, between 2.80 and 2.50 Ga, there developed on the South American Platform two distinct nuclei showing distinct metalogenic features that are specific to each:

- *The Carajás Mineral Province*. This is a polymetallic mineral province with deposits of iron, copper, copper-gold, manganese, chrome and nickel, displaying a complex geotectonic evolution that is still not well understood. This geotectonic evolution involved specific metal deposits generated during distinct metallogenic epochs: a) About 2.76 Ga, an epoch during which iron was precipitated as jaspilite of the Carajás-type associated with the Grão-Pará volcano-sedimentary sequence can be distinguished. It also includes the Luanga mafic-ultramafic complex that hosts deposits of chrome + PGE associated. At the same time there occurs Fe oxide Cu-Au (-U-REE) mineralization related to the Igarapé Bahia-Alemão, Pojuca, and Salobo volcano-sedimentary sequences, and to the granitic intrusions of Sossego, Cristalino, and S-118 amongst others. Following a first phase of deformation, originating from the reactivation along large shear zones, there are recognized: b) An epoch of manganese deposition in the Águas Claras sedimentary sequences represented by the Azul Mn deposit; c) An epoch marked by the Serra Pelada-Serra Leste gold deposit, associated with fractures related to further reactivation of the shear zones, and mafic intrusions at 2.645 Ga. This epoch terminates with Ni and perhaps PGE mineralization related to the differentiated mafic-ultramafic complexes: Vermelho, Onça, Puma, Jacaré and Jacarezinho, indicating the stabilization of the Amazonian Craton at the end of the Archean.
- *The Quadrilátero Ferrífero Mineral Province*: The gold (Cuiabá, Morro Velho, Raposos, Lamengo, São Bento, Juca Vieira, etc.) and manganese (Lafaiete) deposits are directly related to the evolution of the Rio das Velhas greenstone belt (2.77 Ga) and to its association with BIF units of the Algoma-type. Whereas the volcano-sedimentary origin of the manganese in the form of queluzite is widely accepted, there exists a considerable doubt regarding the early volcanogenic sulphide-associated gold mineralization present in the banded iron formation units. The large gold

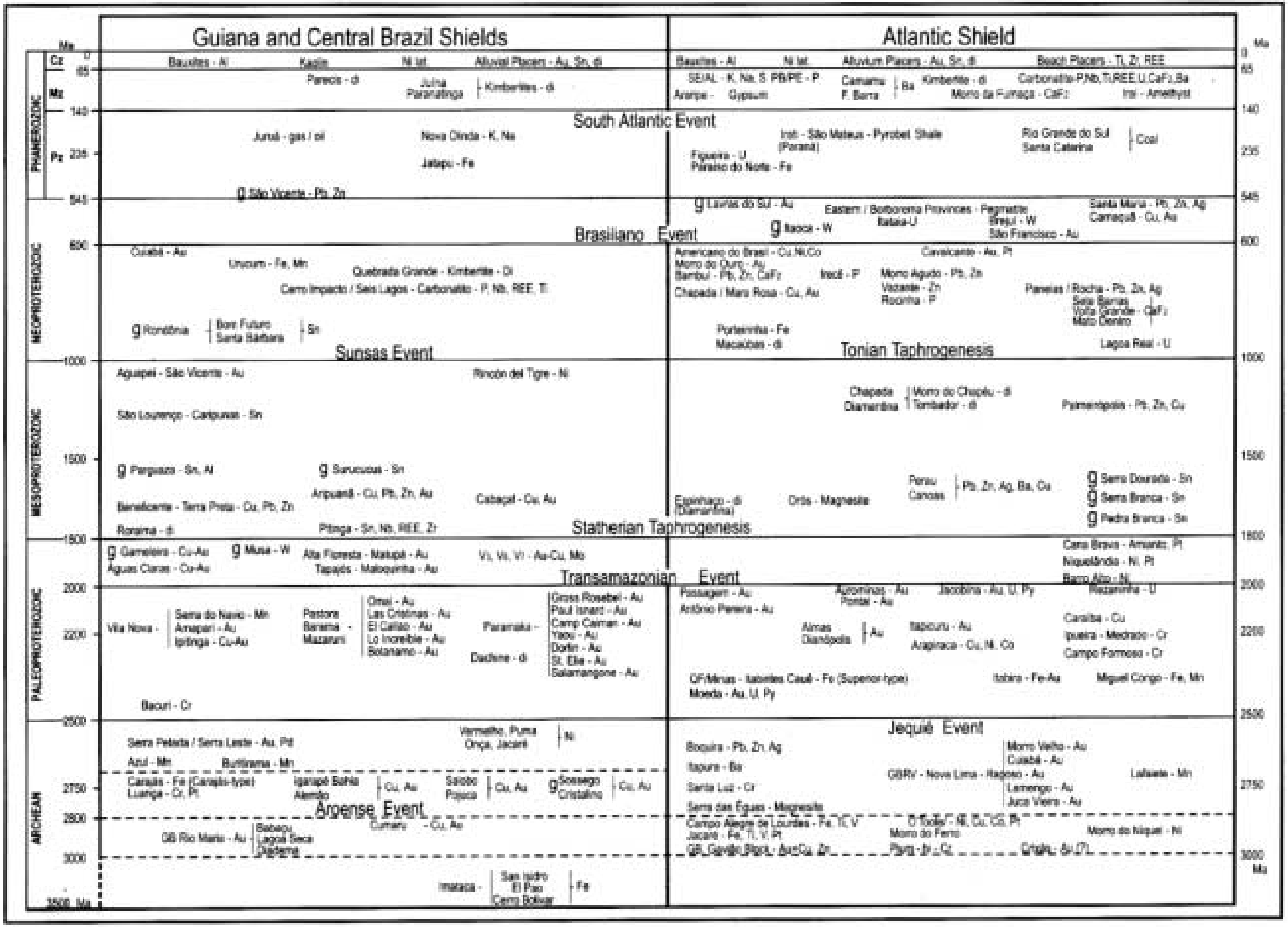


FIGURE 47 - Metallogenetic Epochs in the South American Platform.

deposits are related to low-angled shear zones that developed during Archean tectonic cycles at about 2.6 Ga, with important remobilization during the Transamazonian Event between 2.0 and 1.8 Ga. These observations lead to the definition of a gold province and an epoch of gold mineralization of fundamental importance to the evolution of the South American Platform.

In the **PALEOPROTEROZOIC** (2.5-1.8 Ga) the metallogenesis was well diversified with well-developed metallogenic epochs in the Amazonian and São Francisco cratons.

On the Guiana Shield, a gold epoch (2.2 to 2.0 Ga) is related to volcano-sedimentary sequences of the greenstone belt-type known as Pastora, Barama-Mazaruni, Paramaka and Vila Nova in which the gold mineralization is intimately associated with Transamazonian shearing (2.0 Ga). In the region of Dachine, new occurrences of diamond have been recently discovered in association with pyroclastic rocks showing a komatiitic nature. At the end of the Paleoproterozoic occured the anorogenic granite intrusions of Pitinga (1.8 Ga) with Sn-Ta-Nb-REE mineralization.

On the Central Brazil Shield a new epoch of gold mineralization between 1.9 and 1.8 Ga is developed with the definition of the Tapajós and Alta Floresta gold provinces, where the gold mineralization is associated with granitic calc-alkaline type I intrusions, and is classified as being of the porphyry-Au and epithermal Au types. At this time there can be correlated the first manifestations of anorogenic granite intrusion (1.88 Ga) with Sn-W mineralization (Musa) Granite and the Cu-Au deposits of Águas Claras (Carajás Granite) and Gameleira (Pojuca Granite).

On the Atlantic Shield the epoch of gold mineralization (2.1-2.0 Ga) is equivalent to that observed on the Guiana Shield. It is related to the volcano-sedimentary sequence of the Rio Itapicuru greenstone belt (2.2-2.1 Ga) with the gold deposits at Fazenda Brasileiro and Maria Preta, associated with shear zones formed during the Transamazonian Event. In this epoch are also included the Passagem de Mariana, Antônio Pereira gold deposits, amongst others, of the Quadrilátero Ferrífero. This period is also marked by the presence of paleoplacers of the Witwatersrand-type, assigned to the Moeda Formation of the Quadrilátero Ferrífero dated at 2.5 Ga, and the Jacobina Group in the State of Bahia dated at about 2.0 Ga; and above all the huge iron ore deposits of the Superior Province-type in the form of itabirite, occurring in the Quadrilátero Ferrífero in the State of Minas Gerais. At this time there also occurred the emplacement of the differentiated mafic-ultramafic sills with copper mineralization (Caraiba) and chrome (Rio Jacurici and Campo Formoso). Also included are the mafic-ultramafic complexes of Goiás, which mark a proto-rift system, striking approximately N-S and with which are associated the deposits of nickel (Niquelândia and Barro Alto), asbestos (Cana Brava) as well as the considerable possibility of PGE deposits (Niquelândia and Cana Brava).

In the **MESOPROTEROZOIC** (1.8-1.0 Ga) the development of intracontinental rifts has affected the stable cratonic nuclei. These rifts mark large areas of crustal weakness dominated by taphrogenesis that have as their main characteristic an association with extensive continental volcanism, anorogenic granite intrusion, and clastic sedimentary cover. The anorogenic granite intrusives are associated with tin mineralization and define a metallogenic epoch common to the Amazonian and São Francisco cratons dated at about 1.8-1.75 Ga. On the Amazonian Craton the intrusion of the anorogenic granite and associated tin mineralization migrated in time from NE to SW, together with the continental volcanism and the sedimentary cover. The principal phases of tin granite intrusion are:

- 1.88 Ga Carajás-Musa-type Granite
- 1.8 Ga Pitinga-type Granite
- 1.5 Ga Surucucus-type Granite
- 1.3 Ga São Lourenço-Caripunas Granite
- 950 Ma Rondônia-type Granite (YRG) such as the deposits at Bom Futuro and Santa Bárbara.

In the State of Goiás the tin anorogenic granites occur in the Paranã (1.75 Ga) and Tocantins (1.59) sub-provinces.

To the Mesoproterozoic are also related the diamondiferous conglomerate assigned to the Roraima Group and the Espinhaço Supergroup, between 1.7 and 1.8 Ga.

Rarely, these rifts evolve to the point where oceanic crust started to develop. Exceptions are the Alto Jauru volcano-sedimentary sequence (1.75 Ga) with the Cu-Au deposit at Cabaçal (Alto Jauru District), in Mato Grosso, and the Palmeirópolis-Juscelândia volcano-sedimentary sequence (1.3 Ga) in Goiás with its associated Pb-Zn deposits.

In the Ribeira Belt a metallogenic event at *c.* 1.7 Ga, is related to stratiform deposits of Cu-Pb-Zn-Ba-Ag of the Perau-type, of sedimentary-exhalative origin. Also at *c.* 1.7 Ga it is possible to define an epoch of magnesite precipitation, of probable evaporitic origin, in the Orós Belt of the Borborema Province (Northeastern Brazil).

At the end of the Mesoproterozoic the reactivation of the Aguapeí Rift is the result of the Sunsas orogenic event at 1.0 Ga that led to the formation of a number of small gold deposits related to high-angled shear zones. These deposits define the Alto Guaporé Gold Province. To the end of the Mesoproterozoic are also related the diamondiferous conglomerate beds of the Tombador Formation and Morro de Chapéu of the Chapada Diamantina, probably deposited between 1.2 and 1.1 Ga.

In the **NEOPROTEROZOIC** there occurred the evolution between 900 and 550 Ma of fold belts and sedimentary cover that lie around the margin of the São Francisco Craton, leading to the development of mineral deposits of very variable type, reflecting the characteristics of each of the different belts.

In the **Brasília Belt** the most important deposits include a) Au and Cu-Au deposits associated with the Goiás Magmatic Arc that developed between 950 and 600 Ma; b) the Morro do Ouro gold deposit, the origin of which is attributed to tectonic overriding resulting from the Brasiliano Event (600 Ma); c) deposits of Pb-Zn-CaF_2 of the MVT-type, and the phosphate deposits at Irecê, associated with the Bambuí cover. In the external zone of the Brasília Belt, the Morro Agudo and Vazante deposits define a Neoproterozoic Pb-Zn metallogenic epoch; d) the post-tectonic intrusions (610 Ma) of the differentiated mafic-ultramafic complexes of Americano do Brasil and Mangabal with Cu-Ni-Co mineralization.

In the **Araçuaí Belt** there occur: a) iron ore deposits of the Rapitan-type in the external zone in the region of Porteirinha, representing an epoch of iron precipitation at about 900 Ma. These deposits are probably of the sedimentary-exhalative (SEDEX) type; b) graphite deposits at Pedra Azul and Salto da Divisa in the internal belt. These deposits are associated with the amphibolite and granulite facies of the metasedimentary sequences; c) the Eastern Pegmatite Province (Li, Be and gemstones), related to granite intrusions dated at *c.* 550 Ma.

In the **Ribeira Belt** the principal epochs of Neoproterozoic metallogenesis are related to a) stratabound deposits of the Pb-Zn-Ag Panelas-type associated with limestone and dolomite beds of the Águas Claras Formation; b) granite intrusions with deposits of wolframite and gold.

In the **Dom Feliciano Belt**, the mineral deposits occur associated with a) gold-bearing porphyritic granite of the Lavras do Sul-type dated at about 570 Ma; b) the molasse sequence at Camaquã hosting deposits of Cu-Pb-Zn.

In the external zone of the **Paraguai Belt**, the graben in the Corumbá region, was filled by about 650 Ma by jaspilite intercalated with beds of manganese of sedimentary-exhalative origin. Thus the Urucum-Mutún deposits of the Rapitan-type define the last Fe-Mn epoch at the end of the Mesoproterozoic. In the internal zone of the Paraguai Belt, the gold deposits associated with phyllite of the Cuiabá Group permit the definition of a new gold province (Cuiabá-Poconé), which developed at the end of the Brasiliano Cycle.

In the **Borborema Province** the Seridó Belt contains: a) Tungsten in the form of scheelite in skarnite; b) gold associated with shear zones and; c) Pegmatite (Ta, Nb, Be, Sn) related to the Brasiliano magmatism.

On the Amazonas Craton a diamandiferous epoch at about 710 Ma can be defined with the discovery of the Quebrada Grande kimberlite, in Venezuela.

In the **PHANEROZOIC**, the South American Platform was completely stable, which permitted the development of the broad intracratonic Paleozoic syneclises of the Paraná, Parnaíba, Amazonas and other basins, at the beginning of Siluro-Ordovincian. There was an epoch of oolitic ironstone deposition in the Devonian that occurred in the three basins; and an epoch of evaporite precipitation in the Amazonas Basin (*sensu lato*) during the Permo-Carboniferous, with the formation of extensive potassium deposits. Of the diamond occurrences associated with Paleozoic sediments, the most significant are those associated with the Devonian Furnas Formation near the town of Tibagi in the State of Paraná, and the Permo-Carboniferous Aquidauana Formation near the town of Coxim on the divide between the states of Mato Grosso do Sul and Mato Grosso. Both these occurrences are within the ambit of the Paraná Basin.

The break-up of the Gondwana Supercontinent by rifting leading to the opening of the South Atlantic Ocean during the **Mesozoic** resulted in successive reactivation of the South American Platform. This in turn, led to the formation of important mineral deposits that define the South Atlantic Metallogenic Epoch. In the Lower Cretaceous a phase of extensive basaltic volcanism in the Paraná Basin is associated with important agate and amethyst deposits in southern Brazil and in Uruguay. To this epoch is related the vein fluorite deposits of Santa Catarina and the first alkaline-carbonatite complexes of Anitápolis and Jacupiranga, with apatite deposits in the southern and southeastern region of Brazil, as well as the diamondiferous kimberlite pipes of Paranatinga and Juína. On the Brazilian coast, the opening of the South Atlantic Ocean, led to the development of a gulf that provided the depositional conditions for the precipitation of Aptian evaporite beds and potassium deposits, defining thus, an evaporite epoch. Between 80 and 90 Ma, the reactivation of the rift gave rise to a second epoch of alkaline-carbonatite complex intrusion along with deposits of apatite, niobium, titanium, nickel, barite, uranium, fluorite and REE, in addition to the diamondiferous kimberlites of Alto Paranaiba. Barite was formed in coastal basins at Camamu and Fazenda Barra, and phosphorite was deposited in the Paraiba-Pernambuco Basin between the cities of Recife and João Pessoa.

Finally, the mineral deposits that originated during the **Cenozoic** are related to lateritic weathering on the South American Platform that resulted in the formation of important deposits of bauxite, kaolin, nickel, in addition to iron, gold, titanium, manganese and niobium from the lower Tertiary to Recent times. Concomitantly, placer deposits of cassiterite, gold and diamonds resulted from the mechanical concentration of heavy minerals in drainage. In like manner, placer deposits of ilmenite, rutile, zirconite and monazite have formed in beach deposits along the Brazilian coast.

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