Revista Brasileira de Geociências 12(1-3): 78-88, Mar.-Set., 1982 - São Paulo

THE GEOLOGIC EVOLUTION OF SOUTH AMERICA DURING THE ARCHAEAN AND EARLY PROTEROZOIC

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ABSTRACT In the South American continent, Archaean and Lower Proterozoic terranes can be found in all tectonic domains, but especially within the Amazonian and São Francisco cratons. They can also be found within the São Luís, Luís Alves and Rio de La Plata cratonic fragments, as well as within all mobile belts of the Brasiliano orogenic cycle, as reworked basement. The Arequipa massif is the only identified Lower Proterozoic unit in the Andean belt.

Within the Amazonian craton, the Central Amazonian province is made up of Archaean rocks, exhibiting cratonic conditions since at least the Lower Proterozoic. It is bounded to the north by the Maroni-Itacaiúnas mobile belt, in which the major tectonomagmatic episode occurred in the early Proterozoic, the Transamazônico orogenic cycle. It comprises large portions of supracrustal rocks, identified as greenstone belts, associated to gneisses and migmatites, as well as fragments of high-grade polymetamorphic terranes in which Archaean ages were obtained.

Within the São Francisco craton, three main types of ancient geologic terranes occur: 1) Archaean granite-greenstone terranes, such as the Brumado-Anajé area in Bahia, and the Quadrilátero Ferrífero area in Minas Gerais; 2) Lower Proterozoic supracrustal belts, such as the Jacobina, Serrinha and Contendas-Mirante sequences in Bahia, and the Minas Group in Minas Gerais; and 3) Medium to high-grade metamorphic terranes, subjected to extensive granitization during the Transamazônico orogeny (Salvador-Juazeiro mobile belt), and including Archaean "cratonic fragments", of granulitic composition, such as the Jequié-Mutuípe complex in Bahia.

Ancient terranes were also found within the mobile belts of the Brasiliano cycle, where they make up their ensialic basement. Lower Proterozoic type radiometric ages are predominant, especially within the Borborema province and the Ribeira belt. Taking into account the general distribution of the ancient terranes, it seems that a major part of the South American continental crust was already existent as such just after the Transamazônico cycle. Moreover, since the known Transamazônico belts are ensialic, it is clear that large portions of continental material were formed earlier, in Archaean times.

INTRODUCTION The geologic knowledge of South America is very irregular, and reconnaissance studies still predominate. Areas in which the geology is well known, and mapping has been accomplished in a detailed scale (1:50,000 or more) are scattered, and located mainly in the eastern part of Brazil.

Geochronological data are fundamental for any research dealing with geologic evolution, especially for the very ancient times of the Earth's history. The main objective of this work is to produce a synthesis of the crustal evolution of South America, during the Archaean and Early Proterozoic, with the aid of the existing radiometric data. Many of them are already available in the specialized literature, but several among these here presented are still unpublished. At present, something like 12 or 13 thousand age determinations were obtained in South American samples, more than half of which in Precambrian rocks. Of these, about 75% were produced by the geochronology laboratory of the University of São Paulo.

In this work, the radiometric data were always interpreted taking into account all pertinent geologic, petrologic and geochemical data, when existent and available. In addition, the related geologic literature was reviewed, and the different ideas, models, and schools of thought proposed for the geologic evolution of certain regions of the continent were all considered in our synthesis. The present authors are fully aware of the existing difficulties, and of the inescapable speculative nature of many of the proposed ideas on the early evolution of South America. The Archaean era, plus the Early Proterozoic, include more than half of geologic time. The geologic documents for the earlier events are fragmentary, scanty, and they diminish with time in such a way that no traces are known for events occurred in the first 700 Ma of the Earth's history. Moreover, repeated metamorphic episodes, recycling, overprinting and rejuvenation, in many cases, make very difficult the task of interpreting radiometric data.

In dealing with ancient geological events, the principle of uniformitarianism becomes questionable. On the other hand, the great majority of Archaean and Early Proterozoic rocks, as remnants of the ancient crust, were formed in deep-seated environments, by physical-chemical processes which should be similar to the modern ones (shall we doubt the invariability of the physical laws, in our Universe?). Thus, our approach in dealing with geochronologic interpretation will be uniformitanian, but accepting a more or less permanent and irreversible geochemical differentiation, in which continental crustal material is produced continuously, in time, from sources in the mantle.

Finally, in this paper, the reconstruction of paleo-environments will be based on the present geographical situation, for practical reasons, not implying in a "fixistic" way of thinking of the present authors. We are aware that any grouping of Archaean and Early Proterozoic areas and

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occurrences is the final result of several different geologic processes, many of them geologically young. Horizontal movements of continental fragments within orogenic belts, and of continental masses in plate tectonic processes, are common at present, and should have been similarly active in the past. However, even if we know (or suspect) that now adjacent fragments could be of different origin and different age, and probably were separated in ancient times, there is no way to indicate their probable relative position, at the time of their formation or at any moment of their evolution. Thus, making use of a selected reconstruction will have no more value than employing, as it is, the actual geographical situation.

PALEOGEOLOGIC FEATURES OF THE ARCHAEAN AND EARLY PROTEROZOIC As observed in the previous chapter, one of the major geotectonic problems is to understand clearly to what extent the existing geodynamic patterns could be extrapolated to the remote past. Discussions in this field remain very polemic, and it was considered advisable, by the present authors, to explain some of their fundamental ideas on the matter.

Archaean geology From arguments such as heat production by radioactivity, and by processes connected with the early differentiation of the Earth, it is admitted that heat dissipation by convection was much more active in the Archaean than in later times. As a corollary, the tectonic regimes should have been much more mobile, and geodynamic processes more intense. (Moorbath, 1980; Kröner, 1981; Allègre, 1982). Primary magmas, such as the Mg-rich komatiites, are typical of the Archaean regimes, and were formed by the fusion of a large fraction of mantle material. In addition, mantle derived calc-alkaline suites present high Na K ratios, differently from later magmatic processes.

Archaean regions can usually be classified into two general categories: low grade terranes (LGT), in which supracrustals of metavolcanic and metasedimentary origin, generally described as greenstone belts, are found in association with granitic and gneissic rocks, and high grade terranes (HGT), in which granulites are usually found, combined together with complexes of gneisses, migmatites and granitoid rocks (Windley, 1977). From the paragenesis of these HGT, which would represent lower crustal environments, it seems that crustal thicknesses in Archaean times were not substantially different from the present values of about 35-40 km. On the other hand, the horizontal dimensions of the Archaean continental masses should have been considerably smaller than in subsequent times. From the structural evidence obtained mainly in greenstone belt terranes, in which strong multilateral stresses are demonstrated by tight folding and re-folding, overthrusting, crustal shortening, etc., horizontal mobility seems to have been a major driving mechanism for the earlier lithospheric plates, which should have been much smaller and much faster than the modern ones.

The geochemical processes at the surface of the Earth should have been substantially different in the Archaean, in view of the lack of extensive continental margins, and the lack of a vegetal cover on the emerged lands. Greywackes and chemical sedimentary rocks predominated, and are found in association with extensive volcanogenic formations.

The evidence of the radiogenic isotopes of *Sr*, *Pb* and *Nd* indicates to irreversible accretion-differentiation processes, adding continental crustal material more or less continuously, from mantle-derived sources. Reworking of still older crustal material, although evident in some cases, would have been of subordinate importance, on the global scale (Moorbath and Taylor, 1981). The general picture is one of great mobility, in which numerous small continental fragments grow by magmatism, are destroyed by subduction and then recycling into the mantle, and collide among each other until large and tectonically stable continental masses appear, by the end of the Archaean. The first large fragment of calc-alkaline continental crust which is known, as part of Greenland, surviving to any later geologic process, was formed at about 3,800 Ma ago. The geologic phenomena which pre-date this landmark are not accessible, and their nature is completely open to any theory, conjecture, or speculation.

Early Proterozoic geology In terms of tectonic regimes and crustal evolution, the Archaean-Proterozoic transition seems to have been a major discontinuity (Kröner, 1981). For the Earth's geologic history, it assumes an importance similar to one other major one, the Proterozoic-Phanerozoic transition, the latter being considered in terms of biospheric evolution, and modifications in the superficial environments of the planet. Substantial changes can be detected from the Late Archaean to the Early Proterozoic, most of them related to the slowing down of the Earth's heat production (and as a consequence, the rate of continental accretion), as well as, on the other hand, the increase of recycling of previous crustal material, in the tectonomagmatic processes (Windley, 1977; Salop, 1977).

In the Late Archaean, large continental masses, with dimensions of the order of thousands of kilometers, can already be conceived. Thus, for the first time in the Earth's history, the accumulation of very extensive and thick sedimentary piles could occur either in the interiors of the continental lands, in aulacogenic type features, or in their margins, leading to the development of elongated folded belts, with linear structural trends.

During the Early Proterozoic, simply because of the existence of large continents, the terrains can be subdivided into tectonically stable land masses (cratonic areas, or platforms), and tectonic zones. These would be, since then, the preferred sites of the geodynamic processes which would conduct to the formation of new continental crust (geosynclines, folded belts, metamorphic belts, schist and gneiss belts, and so on) (Rutland, 1976; Kröner, 1980). These major units, which could be generally classified as "mobile belts", would include supracrustal rocks (many of them newly "accreted" to the continent), and "basement rocks", reworked and reactivated during the tectonomagmatic episodes.

Sedimentation during the Early Proterozoic was apparently very unique (banded iron formations, *Au* and *U* bearing conglomerates, carbonatic rocks with sulfides, etc.) and large basic and ultrabasic complexes seem to be typical for the magmatic regimes, related to the new lithospheric peculiarities of that period.

In relation with tectonic regimes, two main conditions would prevail, depending on the relative position of the deep-seated processes and the lithospheric plates. On one hand, the still quite intense internal heat of the Earth would produce large rifts and fracturing of the continental masses, allowing the formation of large structures such as aulacogens, and or intraplate (ensialic) mobile belts. On the other hand, especially at continental margins, large folded belts would develop, partly ensialic and partly ensimatic, in

which continental accretion would occur, possibly through the action of magmatic arcs related to ancient subduction zones. This tectonic regime, associated with the development and evolution of mobile belts, mainly at continental margins, would be the prevailing one in subsequent times. For instance, in the Phanerozoic, the internal heat production of the Earth decreased roughly by a factor of three, in relation to the Archaean.

DISTRIBUTION OF ARCHAEAN AND EARLY PROTEROZOIC TERRANES IN SOUTH AMERICA

Fig. 1 (adapted from Almeida *et al.*, 1976; and from Cordani, 1981) shows the major geotectonic features of the South American continent. Archaean and Early Proterozoic terranes can be found in several domains, but especially within the cratonic areas of late Precambrian times, the Amazonian and São Francisco cratons, as well as within the Rio de La Plata, São Luís and Luís Alves cratonic fragments. They can also be found, as reworked basement, within all mobile belts of the Brasiliano orogenic cycle, and at least in one area within the Andean belt.

Precambrian terranes are known within the Andes, but the geochronological control existent, at present, indicates mainly Middle to Late Proterozoic rocks. The only demonstrated Early Proterozoic is found within the Arequipa massif (Dalmayrac *et al.*, 1977), where the tectonic evolution in relation to the nearby Andean structures is not completely known, and the possibility of being an allochthonous terrain must be seriously considered.

At any rate, it is not known to what extent the Andean belt is ensimatic, and formed during the Meso-Cenozoic tectonomagmatic episode related to the subduction of the Nazca plate, and to what extent it is ensialic, developed over previous continental crust, attached to the Brazilian Platform. Moreover, it is known that many of the schistose-gneissic-granitic terranes largely considered "pre-Mesozoic", or "pre-Devonian" are in fact Paleozoic, or Late Precambrian, but it is not known if such material has a still older "basement", part of which could even be Archaean or Early Proterozoic.

The sub-Andean basins are pericratonic, and conceal the western boundaries of the Brazilian Platform, parts of which, especially along the Guiana Shield, could be formed by ancient terranes. The intercratonic and the marginal basins also conceal areas of Archaean and Early Proterozoic rocks, as was demonstrated by some isolated age measurements in drill core samples (Kovach *et al.*, 1976). However, the nature and dimensions of those ancient areas are virtually impossible to disentangle.

In the Patagonian Platform, which was attached to the main part of the Brazilian Platform (Almeida, 1978) at the

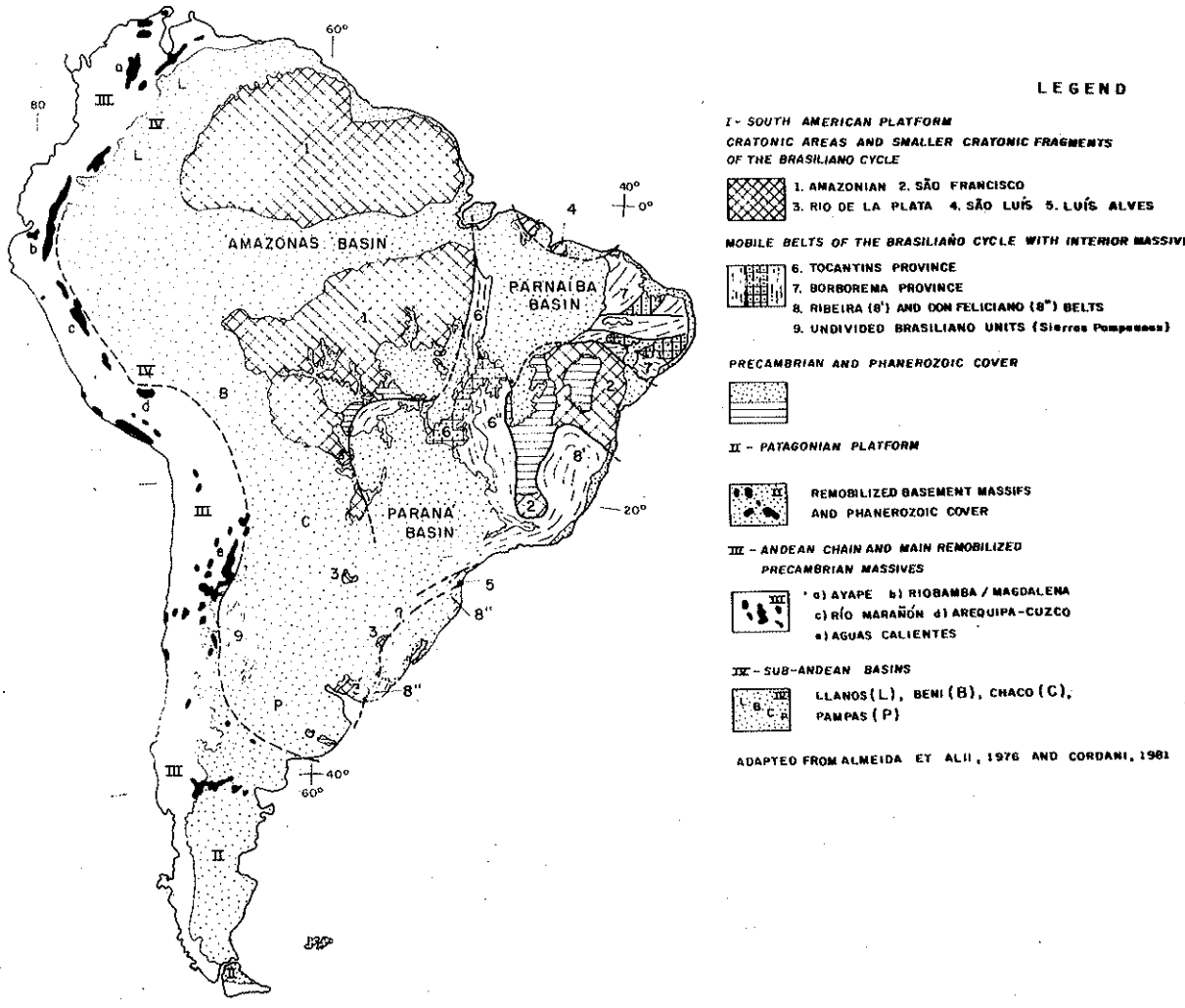

Figure 1 — The major geotectonic features of South American continent

end of the Paleozoic, volcano-sedimentary sequences of Meso-Cenozoic age predominate, covering a basement in which the oldest dated rocks are referred to the latest Precambrian. Archaean and Early Proterozoic terranes are not known, at present.

Things being so, the only important occurrences of ancient terranes to deal with, in this paper, are confined to the so-called Brazilian Platform, and especially within all the stable cratons, as defined for the Brasiliano orogenic cycle. Archaean and Early Proterozoic areas, reworked by this late Precambrian orogeny, are also found in all the mobile belts developed in this time. Their description, and tentative tectonic interpretation, are attempted in the subsequent chapters.

ANCIENT TERRANES IN THE CRATONIC DOMAINS The Amazonian Craton This very large unit, which acted as a stable foreland, in Late Precambrian times, for the Paraguay-Araguaia folded belt, is a complex and well differentiated geotectonic unit. From recent work (Cordani *et al.*, 1979; Cordani, 1981) it can be described as an ancient core (Central Amazonian province) surrounded by mobile belts of Early to Middle Proterozoic ages (Maroni-Itacaiúnas, Rio Negro-Juruena and Rondonian) (Fig. 2).

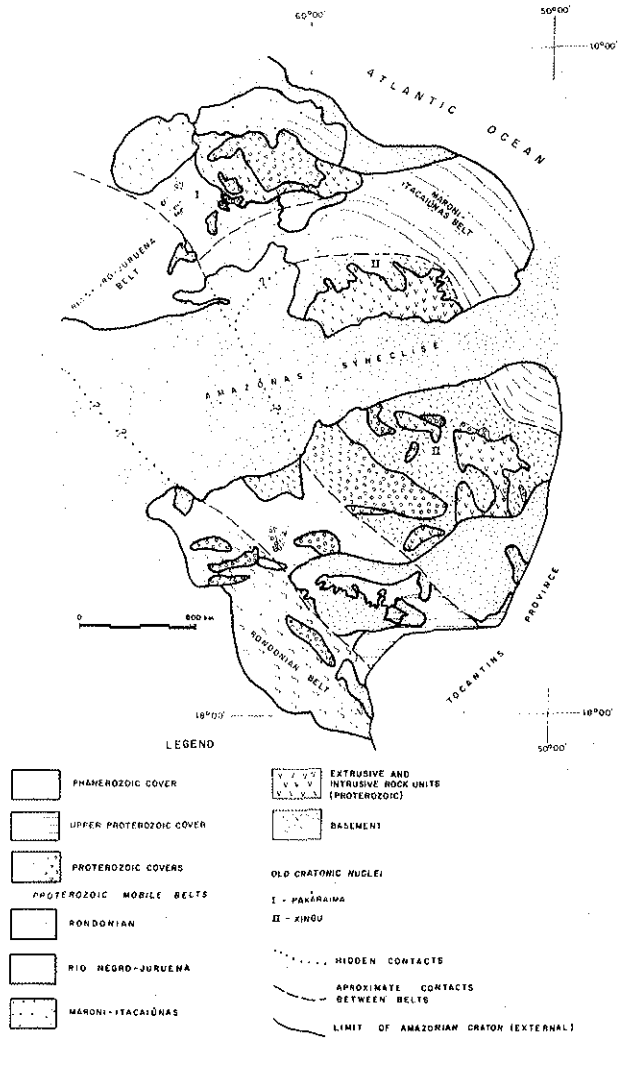

Figure 2 — The Amazonian craton

The Central Amazonian province is in fact composed of two quasicratonic nuclei (Pakaraima and Xingu) separated by a mobile zone which is a prolongation of the Maroni-Itacaiúnas mobile belt. Both cratonic nuclei were submitted to paraplatformal conditions for long time. Unfolded and unmetamorphosed volcanic-sedimentary sequences demonstrate the long duration of the cratonic conditions, starting at least in the Early Proterozoic (Surumu and Caicara volcanics, about 1,900 Ma), and continuing with the Iricoumé and Dalbana volcanics (about 1,800 Ma), and with the Iriri and Uatumã (*s.s.*) volcanics (about 1,700 Ma), in the Middle Proterozoic (Basei, 1974). In addition, anorogenic granites are found spread out in the entire cratonic domains, covering an age span between 1,800 Ma and 1,300 Ma (Parguaza, Surucucu, Velho Guilherme, etc.). These tectonic episodes, which typify successive reactivations, indicate the permanent cratonic conditions of the area, at least since the Early Proterozoic (Montalvão and Bezerra, 1980).

The basement to these volcanic-sedimentary sequences is in part gneissic-granitic, of still unknown age, and in part of granite-greenstone terrains, in which sparse age determinations indicate ages of about 2,500 Ma (Tapirapé, Inajá, etc.). Truly Archaean radiometric ages are very scanty, at present, possibly due to the already mentioned pervasive cratogenic magmatic activity, which produced in later times a great variety of plutonic and volcanic rocks, now exposed at the surface of the entire area.

The Pakaraima and Xingu cratonic nuclei are bounded to the north by the Maroni-Itacaiúnas mobile belt, a geotectonic unit in which the major tectonomagmatic episode occurred in the Early Proterozoic. This mobile belt has a large extension, of at least 2,000 km, starting in the southeast, along the Itacaiúnas River, and surrounding the eastern and northern borders of the Xingu cratonic nucleus, along the territories of Amapá, French Guiana, Surinam, the Republic of Guyana and Roraima, in Brazil. It is truncated by the younger structural trends of the Juruena-Rio Negro mobile belt, of Middle Proterozoic age, along the Venezuelan-Brazilian border. A second arm of the same Maroni-Itacaiúnas belt surrounds the Pakaraima cratonic nucleus, from Surinam to Venezuela, being concealed in its northwestern part by the sub-Andean sedimentary cover.

The Maroni-Itacaiúnas mobile belt exhibits a strong petrological, structural and geochronological coherence, and its Guyanan part was recognized as a folded and metamorphic belt by Choubert (1969), who called it the "Guyano-Ebournéides geosyncline". It comprises a large portion of supracrustal rocks identified as metavolcanic and metasedimentary sequences, metamorphosed at the greenschist to amphibolite facies and intensely deformed (Carichapo-Pastora, Barama-Mazaruni, Orapu, Bonidoro, Vila Nova, Grão-Pará, and others). The nature, composition and evolution of these rocks have lead some authors to consider them as Early Proterozoic greenstone belts, such as Gibbs (1980), after examining the Barama sequences in Guyana. Associated to the supracrustal rocks, gneissic, migmatitic and granitic terranes occur, most of them formed during the same tectonomagmatic episode of the entire province.

The geochronological pattern indicates U-Pb zircon ages in the metavolcanic sequences (and in some gneissic rocks) in the 2,100-2,250 Ma age range. Rb-Sr total rock isochrons are in the 1,900-2,100 age range, and the K-Ar cooling ages are slightly younger, at about 1,800-1,900 Ma. This geochronological pattern indicates a complete evolution of a geotectonic unit, during a major event, the importance of which

in the continental scale was first recognized by Hurley *et al.* (1967), who named it the "Transamazônico orogenic cycle".

In several places, along the Maroni-Itacaiúnas mobile belt, a pre-existing basement is identified, consisting of high grade polymetamorphic terrains in which Archaean ages were obtained, such as the Imataca, Kanuku, Adampa-da-Fallawatra, Mucujaí complexes, most of them made up of granulite facies metamorphic rocks, reworked during the Transamazônico orogeny. These ancient cratonic fragments, which seem to exist also in the less studied areas of Amapá and Pará in the Brazilian territory, demonstrate the ensialic character of the mobile belt, which was formed, probably in its major part, over pre-existing continental crust.

The Rio Negro-Juruena belt occurs in the south-western border of the Central Amazonian province, and its predominant rocks are granitic to granodioritic, many of which exhibiting gneissic structure. The age span for the tectono-magmatic events in this unit is 1,750-1,500 Ma, and to the present no indication of an older basement was found. This fact induced Tassinari (1981) to propose a possible origin for the Rio Negro-Juruena belt by the evolution of a mantle-derived Middle Proterozoic magmatic arc.

The Rondonian mobile belt, the youngest of the Amazonian Craton, is covered in part by the sub-Andean basins. Its history belongs to the Middle Proterozoic, since the main known tectonic/magmatic events occurred around 1,400-1,100 Ma. However, it is clearly ensialic, and exhibits several regions of exposed basement of at least Lower Proterozoic ages. For example, some granulitic rocks (Lomas Maneches Group) that outcrop along the courses of Paraguai and Guaporé rivers yielded Rb/Sr ages of about 1,960 Ma (Litherland and Bloomfield, 1981).

The São Francisco Craton This cratonic unit, defined by Almeida (1967), and recently redefined with improvements by the same author (Almeida, 1977) occupies large portions of the states of Bahia and Minas Gerais. According to its primary conception, it is completely surrounded by Late Proterozoic mobile belts of the Brasiliano orogenic cycle. (Fig. 3). The general degree of knowledge about it is generally good, geological maps being available from reconnaissance up to semidetailed and detailed scales. The bibliography about the São Francisco is one of the richest and most extensive among all the Brazilian structural provinces, this being due to the uncommonly good exposition of all geologic elements throughout the province.

Most of the São Francisco craton is covered by the Late Proterozoic chemical and chemical-clastic sedimentary rocks of the Bambuí and Una Groups, slightly folded and metamorphosed, especially at the borders of the cratonic unit. In turn, the sedimentary sequences overlie the Middle Proterozoic sediments of the Espinhaço Supergroup, which are moderately to tightly folded and faulted along the Espinhaço folded system. As a matter of fact, this folded system practically divides the São Francisco craton, in Central Bahia (see Fig. 3). In this intracratonic unit, the Espinhaço Supergroup comprises clastic sediments and volcanics, submitted to low metamorphic grade, and exhibits linear structural trends (N-S, NNW-SSE) produced by idiomorphic movements which followed deep faults of its rigid basement. Part of these clastic sequences transgresses eastward over the high grade terranes of the craton, as a moderately folded cratonic cover (Chapada Diamantina Group). As pointed out by Brito Neves *et al.* (1980), this cover seems to have been preserved mainly when it overlies old Archaean portions of the craton.

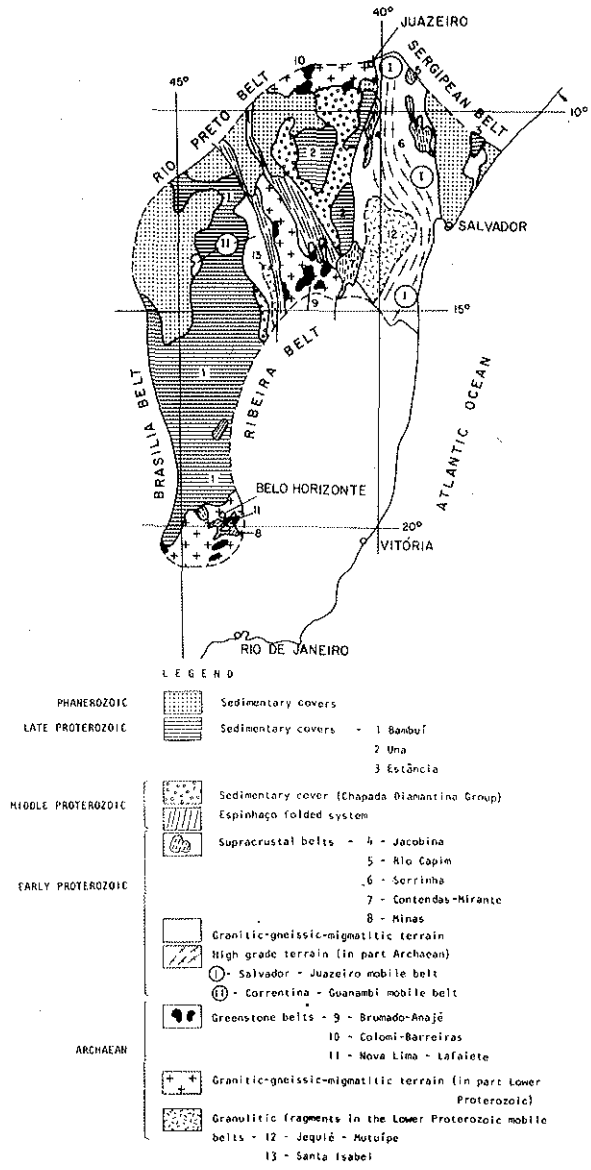

Figure 3 – The São Francisco craton

The Archaean and Lower Proterozoic "basement" to the Espinhaço, Bambuí and Una sedimentary and metasedimentary sequences is well exposed in two main regions of the São Francisco craton: a very large terrain in Central and Eastern Bahia State, and an area at the southernmost portion of the cratonic unit, to the SW of Belo Horizonte, in Minas Gerais State. In these ancient areas three main types of geologic terranes occur:

1. Archaean greenstone-granite terranes, such as the Brumado-Anajé area in Bahia, and the Quadrilátero Ferrífero area in Minas Gerais.
2. Lower Proterozoic supracrustal belts, such as the Jacobina, Serrinha and Contendas-Mirante sequences in Bahia, and the Minas Group in Minas Gerais.
3. Medium to high-grade metamorphic terranes, subjected to Lower Proterozoic extensive granitization, and includ-

ing Archaean "cratonic fragments", of granulitic composition, such as the Jequié-Mutuípe and Santa Isabel complexes in Bahia.

The general behavior and organization of the Lower Proterozoic structures (Transamazônico cycle) and its physical processes have enabled Brito Neves *et al.* (1980), to suggest the existence of two mobile belts: in the west – the Correntina-Guanambi belt in the São Francisco tectonic domain – and in the east – the Salvador-Juazeiro belt in the Eastern Bahia shield – separated by a central stable cratonic area, syn-Transamazônico, in which the Archaean rocks are covered by the Chapada Diamantina Group.

Along these two Lower Proterozoic mobile belts it was possible to identify some Archaean granulitic portions that kept their isotopic Rb/Sr system unchanged during the accretion phenomena of the Transamazônico cycle; for instance, the already mentioned Jequié-Mutuípe and Santa Isabel complexes (Fig. 3), which have played a role of cratonic remnants within the younger mobile belts. The geochronological control indicates that the high-grade metamorphism in these units is Late Archaean (Jequié orogenic cycle, about 2,700 Ma), but some nuclei within the Jequié Complex yielded older results, up to 3,200 Ma, by Rb/Sr whole rock isochrones (Cordani and Iyer, 1979). However, the granulitic terranes of Bahia may not be all Archaean: there are some strong geochronological indications for those occurring along the Atlantic coast (Itabuna block) being Lower Proterozoic, perhaps slightly older than the Transamazônico cycle (Brito Neves *et al.*, 1980).

Several greenstone belts have been described within the São Francisco craton (Mascarenhas, 1979). Those occurring in Central-Southern Bahia, in the Brumado area, are associated with granitic-gneissic complexes which yielded Archaean ages (up to 3,200 Ma, see Marinho and Sabaté, 1982) and seem to characterize a typical Archaean granite-greenstone terrain. This ancient area includes the greenstone belts of Ibitira, Brumado, Umburanas, Guajeru, and other smaller ones, and if an extrapolation following Brito Neves *et al.* (1980) could be made as to include the Boquira, Barreiros, Salitre and Colomi complexes, as well as the basement for the Chapada Diamantina Group, a large Syn-Transamazônico cratonic nucleus with more than 100,000 km^2 can be envisaged, in Central Bahia.

The Southernmost portion of the São Francisco craton (southwest of Belo Horizonte) presents a granite-greenstone pattern and Archaean ages resembling the Central Bahia conditions. It is a kind of basement window, surrounded by Late Proterozoic fold systems and cratonic covers. It includes the Nova Lima greenstone belt, and some granitic--gneissic rocks for which Late Archaean ages (about 2,700 Ma) were referred. However, the geochronological interpretation is made very difficult, in this area, by the overprinting of at least two main deformational episodes, one in the Lower Proterozoic and associated to the Minas orogeny, and the other in the Upper Proterozoic (Brasiliano cycle) (see Cordani *et al.*, 1980).

Other supracrustal belts, which include metavolcanic and metasedimentary sequences, such as the Jacobina, Contendas-Mirante, Rio Capim and Araci-Serrinha, exhibit structures that can be followed along the trends of the already mentioned Salvador-Juazeiro Transamazônico mobile belt. Until now, all the efforts in geological and radiometric research are leading to this interpretation, since most of these supracrustal rocks (as well as their associated granitic intrusions) exhibit Early Proterozoic ages. Therefore, they have been regarded as structures that belong to the development of the Transamazônico mobile belts, by Brito Neves *et al.* (1980), and they are regarded as Lower Proterozoic folded belts, possible lower grade equivalents of the gneissic rocks which make up the bulk of the Transamazônico mobile belts described hereafter. From the basement of the Contendas-Mirante supracrustal belt the oldest geochronological result for the São Francisco craton was obtained by Rb-Sr whole rock isochron method (the 3,400 Ma of the Boa Vista and Sete Voltas granitoid rocks, see Marinho and Sabaté, 1982), indicating that very probably this basement is a prolongation of the Brumado-Anajé granite-greenstone terrain described earlier, in this paper.

The present authors would like to emphasize that several rock complexes identified as greenstone belts in Bahia State seem to be in fact Lower Proterozoic, as does the Barama--Mazaruni greenstone belt described earlier, within the Amazonian craton. The unescapable evidence is that the tectonic regime responsible for the origin and evolution of such sequences remained active until at least 2,000 Ma ago.

In the southern part of the São Francisco craton, in view of its very large iron formations (the itabirites and related rocks of the Cauê Formation), the Minas Supergroup was always regarded as Lower Proterozoic. Recent geochronological work on granitoid rocks associated to the Minas orogeny confirmed their association to the Transamazônico cycle (Cordani *et al.*, 1980). To the same tectonic episode also belong the forced "intrusion" of basement rocks in the mantled gneissic dome of the Bação complex, and related structures. There, the material is Archaean (about 2,700 Ma), but was remobilized into the Minas Supergroup at about 2,000 Ma.

The Transamazônico cycle is the most important, and the one with best geochronological support, of the São Francisco craton geotectonic events. Its extensiveness is certainly responsible for the concealing effects of previous tectonomagmatic events, the Jequié or older cycles. First of all, special mention should be given to the gneissic migmatitic-granitic complexes that make up large parts in Bahia, within the Transamazônico mobile belts, and in the southernmost part of Minas Gerais. These complexes are associated to remnants of metavolcanic-metasedimentary sequences (supracrustals) that exhibit usually tight folding, complex structure, and medium grade metamorphism.

A large part of the granitic rocks, within the São Francisco craton, present Early Proterozoic ages. Granitization, migmatization, feldspathization, anatexis, fissural intrusions, and so on, have been described throughout the unit, in relation to the granitic rocks of the Transamazônico cycle. Both the granulitic terranes, and most metavolcanic and metasedimentary sequences, have been affected by such mesozonal processes. The cratonization process which followed the Transamazônico cycle was marked by epeirogenetic and denudation phenomena, and by reactivation of old fault lines of the basement. Therefore, K-Ar cooling ages around 1,800-1,700 Ma are quite common all over the cratonic area.

From the above description, the ideas of the present authors on the ancient geologic evolution of the São Francisco craton can be readily envisaged. From the agglutination of fragments of continental crust of different ages, by the late Archaean, an extensive crustal mass was already in existence. Such continental land was already stratified, with a granulitic lower crust, and its erosional surface should have been at a crustal level compatible with the granite-

-greenstone terrains observed today, for example, in the Brumado region of Bahia.

During the Lower Proterozoic, ensialic belts were superimposed on the Archaean continents, and they evolved during orogenic cycles of which the most important was the Transamazônico. Important accretion from mantle sources occurred, as well as reworking of previous continental material. After the Transamazônico orogeny, the infra-structure of the Lower Proterozoic mobile belts was exposed at the surface, including large portions of Archaean granulites, mainly retrograded to amphibolite facies conditions.

After the Lower Proterozoic, for most of the area of the São Francisco craton, the erosion rate became very low, and the crustal level exposed at the surface remained more or less unchanged. Moreover, the subsequent geotectonic units (the Espinhaço and Brasiliano folded systems) were ensialic, and did not allow important additions of material to the continental crust.

SMALLER CRATONIC FRAGMENTS OF SOUTH AMERICA

a) Rio de La Plata Craton Based in the geochronological control, Almeida *et al.* (1973) defined the Rio de La Plata cratonic area, in Uruguay and Argentina. Working in northern Uruguay, Ferrando and Fernández (1971), had described gneissic-migmatitic terranes, along E-W structural trends, covered by low grade volcano-sedimentary belts. Similar occurrences of such types of terranes had been also described in Tandilia and Sierras Australes, in Argentina. The largest part of this cratonic unit is covered by sediments of the Paraná syneclise and/or Cenozoic deposits. Recently, Fragoso César (1980) accomplished a review of this area, and interpreted the mentioned lithological associations as a typical granite-greenstone terrain (Fig. 4).

In the Uruguayan shield, the geochronological studies have obtained a consistent group of ages, around 2,000 Ma, by K/Ar and Rb/Sr methods, in both basement and meta-volcano-sedimentary sequences. In the northern basement windows of Canãpirú-Vichadero and Aceguá, litho-structural features are similar to those of the Rio de La Plata area, and they have always been assumed as part of it. To the north, in the western portion of the Rio Grande do Sul shield, litho-structural types of the same nature seem to outcrop again: gneisses, migmatites, granulites, mafic-ultramafic associations, etc. The radiometric Rb/Sr and K/Ar ages obtained in this area (until now) are confirming the importance of the Transamazônico activity.

b) Luís Alves The Luís Alves cratonic area was defined by Kaul (1980) in the northeastern part of Santa Catarina State. It is a typical domain of high-grade terranes, composed of quartz-feldspathic gneisses, migmatites, meta-ultramafics, with intercalations of quartzites, banded iron formations, calc-silicatic rocks, etc., with a NNE structural trend. The metamorphic grade is usually amphibolite to granulite facies.

The geochronological pattern of this area is quite coherent: U/Pb measurements on zircons, and Rb/Sr whole rock ages, confirm events of the Jequié cycle, for the granulites. Other Rb/Sr results, and most K-Ar apparent ages indicate activities of the Transamazônico cycle, responsible for the cratonization.

The extension of this cratonic nucleus, below the sediments of the Paraná syneclise is still obscure. In Fig. 4, its possible connection with the Rio de La Plata cratonic area is shown, following the ideas of Fragoso Cesar (1980).

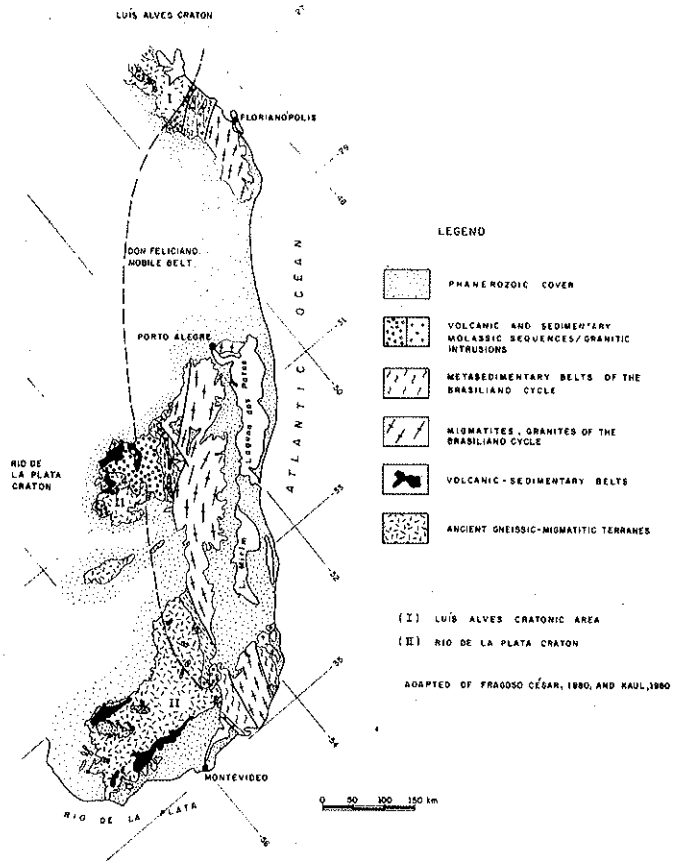

Figure 4 – Río de la Plata craton and Luís Alves cratonic area

c) São Luís The São Luís craton was suggested by Hurley *et al.* (1967) when they identified a basement fragment along the coastal areas of Pará and Maranhão states, where some Transamazônico ages were obtained. The sparse basement outcrops of the region are part of a Mesozoic structural arch that limits the Parnaíba syneclise to the north.

The expositions of gneisses, migmatites and schists had yielded some isotopic results around 2,200-1,700 Ma, with Rb/Sr and K/Ar methods (Abreu *et al.*, 1980). Also, a group of intrusives and extrusives of calc-alkaline character (Tromai Association) indicated the same coherent range of ages. To the south of these uplifted areas there are belts of metasedimentary and metavolcanic rocks that were formed or reworked during the Brasiliano cycle. The São Luís cratonic fragment acted as a foreland for these low grade belts, in Late Precambrian times.

ANCIENT TERRANES WITHIN THE MOBILE BELTS OF THE BRASILIANO CYCLE

In dealing with such regions, it is necessary to emphasize that the final architecture of all of them was obtained only in the Brasiliano cycle. Rock-making processes, deformation of previous formed rocks, horizontal and vertical tectonic mobility, heating, and so on, are common components of this cycle, as a whole.

The identification of some Archaean and Early Proterozoic rock units is possible in tectonic highs (median massifs, geanticlinal zones), or in some fortunate cases in the basement of the vestigial systems. All attempts to review the paleogeographic and paleotectonic conditions of the Brasiliano regions are rather difficult and subordinated to various risks, since it is necessary to keep in mind probable occurrences of large horizontal displacements of crustal masses during the Late Proterozoic cycles, and on account of the lack of geophysical data. For similar reasons, the discrimination between Archaean and Early Proterozoic domains is not yet possible, or can only be outlined in some cases. The discussion which will follow is based, with the pertinent modifications and adaptations, on the framework provided by the structural provinces of Brazil, as defined by Almeida *et al.*, 1981.

1 – The Tocantins structural province of central-western Brasil During the Late Proterozoic this central region of Brazil was conditioned by the tectonic evolution of two mobile belts: Paraguay-Araguaia (W) and Brasília (E). The tectonothermal influence of these major structures extrapolated very much their present outcropping outline. However, their influence was not strong enough in order to conceal completely the geological pattern of its Archaean and Lower Proterozoic infrastructure (Fig. 5).

In fact, in the central massif of Goiás it is still possible to observe, with good conditions of preservation, some of the most complete profiles of Archaean terranes of the South American Platform (Danni, *et al.*, 1982). Some granitic-gneissic terranes were also formed during the Brasiliano cycle, in the western part of Goiás (see Tassinari *et al.*, 1981), however, their distribution is quite restricted. On the other hand, the thermal overprint in Late Precambrian times was intense (temperatures over 250°C-300°C), and extensive, all over the Tocantins province, as revealed by K-Ar determinations on micas (Hasui and Almeida, 1970).

Several very important tectonic lineaments, such as the Transbrasiliano, Pirenópolis and Araguaia-Tocantins, with their polycyclical deep fault characteristics, could be accountable for important translations of continental masses. They can be regarded as boundaries of tectonic blocks, and may separate crustal fragments of different lithologies and different geologic evolution. In this case, the central massif of Goiás would be a mosaic of old "cratonic fragments", of different origin, juxtaposed and overprinted by orogenic cycles during Middle and Late Proterozoic. For detailed information, recent review papers are recommended, such as those of Tassinari *et al.* (*op. cit.*) and Danni *et al.* (*op. cit*).

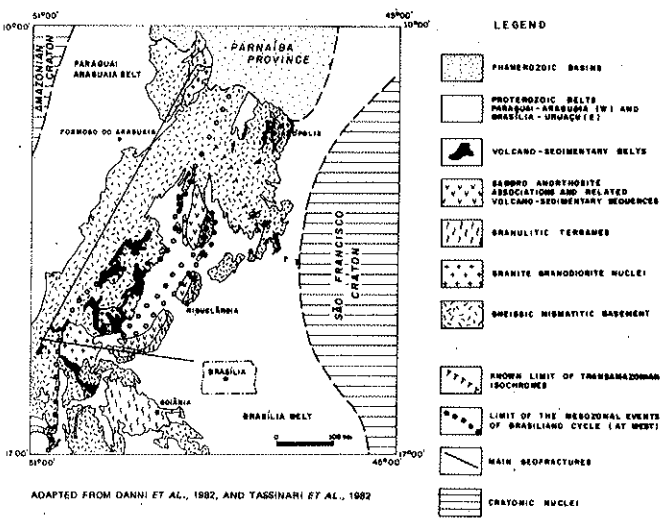

Figure 5 – Tocantins Province

The ancient terranes of central Goiás, which were thermally affected by the Brasiliano orogeny, but kept virtually unchanged the original rock structures, can be classified into four cathegories, based on the lithology and/or crustal level exposed at the surface (Fig. 5): low to medium grade granite-greenstone terrain, such as in the Crixás-Rubiataba region, basic-ultrabasic terrain, such as within the Barro Alto, Niquelândia and Cana Brava complexes, high-grade granulitic terrain, such as the Goiânia region, and medium grade gneissic-migmatitic terrain, which covers the largest portion of the area.

For the metavolcanic and metasedimentary sequences of the granite-greenstone terrains, the geochronological data are scarce. Tassinari and Montalvão (1980) obtained a Rb/Sr whole rock isochron for gneissic rocks associated to the Crixás greenstone belt, with a Late Archaean age, and there are reasons to believe that the similar structures of Goiás Velho, Mara Rosa and Pilar de Goiás belong to the same ancient terrain. An Archaean age was also obtained from the Rubiataba granite (Tassinari *et al.*, 1981).

Three large gabbro-anorthositic complexes occur at the axial zone of the Tocantins province, with a rough north-south trend. Up to the present moment, only K-Ar ages are available from their rocks, with apparent results between 3,900 and 500 Ma. The oldest results have been taken as evidence for a primitive emplacement of the complexes, but the possibility of excess argon making these results too old is also possible. A Lower Proterozoic age for the primary formation of these rocks seems to be the most probable, to the present authors.

Some granitic rocks with Rb-Sr whole rocks isochrones typical of the Transamazônico cycle were identified by Tassinari *et al.* (1981), in the northeastern part of the Central Goiás massif (Nova Roma and Natividade granites). Nevertheless, the gneissic-migmatitic terrain has yielded different age values, most of them older than the Transamazônico cycle. The oldest result, to the moment, is the ca. 3,100 Ma age obtained in some gneisses of the Rio Preto region.

Several occurrences of granulitic rocks have been observed, some of them in close relationships with the gneissic-migmatitic terrain, while others are associated to the gabbro-anorthositic complexes, occurring at their eastern margins. The geochronological data (K-Ar and Rb/Sr) are scattered, and non conclusive, because of the generally low K and Rb contents of the rocks, and overprinting by Middle and Late Proterozoic events.

2 – The Borborema province of northeast Brazil The northeast region of Brazil is a typical structural province of the Brasiliano orogenic cycle. It is geotectonically located between the São Francisco and São Luís cratonic areas (Fig. 6), and is part of a much larger unit, which includes the territories of Dahomey, Nigeria and Cameroon, in West Africa. Two fundamental types of terranes can be found in the Borborema province: gneissic-migmatitic-granitic massifs and metavolcanic-metasedimentary folded belts (Brito Neves, 1975).

The folded systems exhibit linear structures, the final development of which was attained in the Brasiliano cycle.

Some of them keep, well preserved, most of its suprastructure (Seridó and Sergipe folded belts), but in some others (Jaguaribe, Riacho do Pontal) the infrastructure was exposed at the surface. The massifs are located in between the different folded belts, have polygonal shapes, and exhibit lithological and structural association similar to the basement rocks of the neighboring fold systems. In all these areas K-Ar ages on micas are close to 500 Ma, indicating the regional cooling after the Brasiliano orogenic cycle.

In contrast with central Goiás, within the Borborema province the effects of the Late Precambrian orogeny were very strong. Regional metamorphism, granitization, formation of new tectogenic structure, horizontal movements associated to large geofractures, and other tectonothermal activities, affected the basement rocks throughout the area (Brito Neves, 1975). In addition, a large variety of granitic rock types, intrusive bodies of all sizes and shapes, was formed during the Brasiliano orogeny in the entire area of the Borborema province.

Nevertheless, a few tenths of Rb-Sr whole rock isochrones are already available, from basement rocks, indicating the presence of Archaean or Early Proterozoic terranes, and demonstrating, beyond any doubt, that the entire Borborema province is ensialic. Fig. 6 shows the approximate locations of the dated samples.

The identification of Late Archaean terranes (about 2,700 Ma) is conspicuous at both margins of the Seridó belt, in the Rio Piranhas and Caldas Brandão massifs. Also in the southern border of the Pernambuco-Alagoas massif, some Archaean ages seem to indicate a crustal continuity with the São Francisco craton, through the basement of the Sergipe geosyncline.

Early Proterozoic isochrones, related to the Transamazônico orogenic cycle, predominate in the basement rocks of the Borborema province (Fig. 6). These data were obtained mainly in gneissic-migmatitic rocks of the massifs, or on the basement of the folded systems, in geanticlinal zones.

As already stated earlier in this paper, the present authors are aware of the difficulties in delineating a paleotectonic reconstruction, because of the intense tectonic mobility which occurred at least in the Late Proterozoic. Nevertheless, it should be indicated that the several occurrences of Transamazônico ages in the western part of the province (along the Jaguaribean belt, the Riacho do Pontal belt, and the Tróia massif) suggest a northward continuation of the Salvador-Juazeiro mobile belt, already defined within the São Francisco craton, where structural trends are roughly north-south.

3 – The Ribeira and Don Feliciano mobile belts

With the recent identification of the Luís Alves cratonic area, a subdivision of the former Ribeira belt (Almeida *et al.*, 1973) into two units has become necessary. According to Fragoso César (1980), the northern unit would keep the original denomination of Ribeira belt, and the southern unit would be named Don Feliciano belt. Both are orogenic units which belong to the Brasiliano cycle (Fig. 1 and 4).

The special incidence of vertical movements in the Meso-Cenozoic, associated to the onset of the South Atlantic rift, induced unusual erosion, and the exposure of deep crustal levels, in both the Ribeira and Don Feliciano mobile belts. Gneisses and migmatites of the infrastructure of the units predominate, together with frequent nuclei of reworked basement, especially within the Ribeira belt. Moreover, in this unit, there are geochronological indications that high-grade kinzigitic gneisses and granulites of Late Precambrian age were exposed along the eastern coast of Brazil (Siga Jr. *et al.*, 1982). Supracrustal rocks of the Brasiliano cycle also occur, like the Araçuaí and Apiaí folded systems within the Ribeira belt, and the Tijucas and Eastern Uruguay folded systems in the Don Feliciano belt.

In relation to basement, there is a big difference between the Don Feliciano and Ribeira mobile belts. The latter is undoubtedly ensialic, but the former seems to be originated by a magmatic arc, in the Late Precambrian. The only evidence of a Lower Proterozoic terrain is restricted to a small outcrop of the Encantadas Formation, a basement window within supracrustal rocks, which yielded an isochron age of about 2,300 Ma (Fragoso César, 1980).

In the Ribeira belt, like in the Borborema province, the Brasiliano overprinting on previous rocks was very strong,

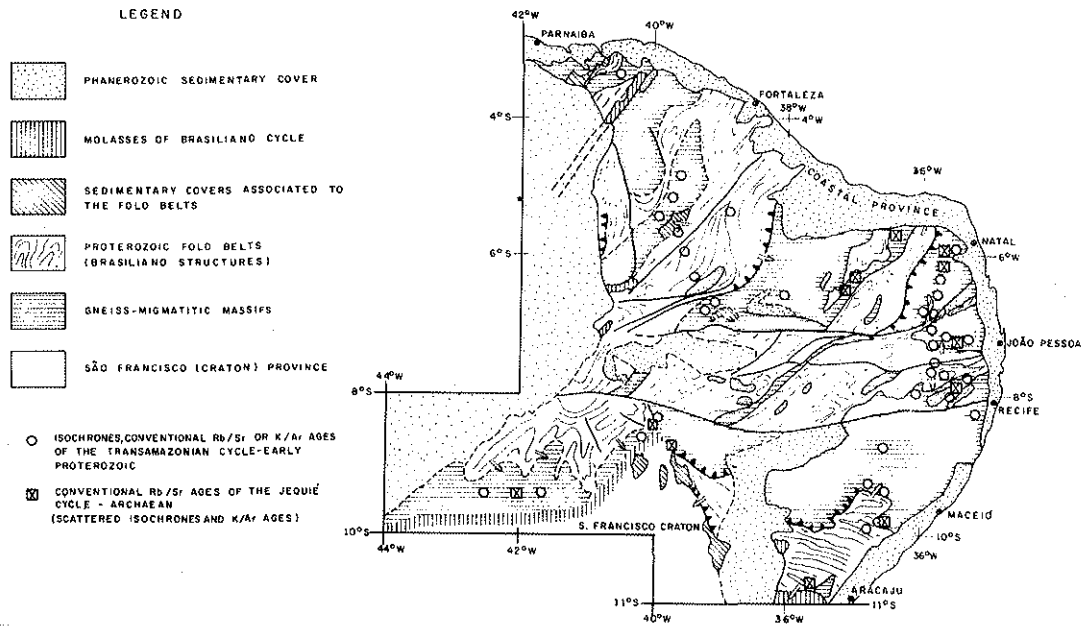

Figure 6 – Borborema Province. Geochronological control of the ancient terranes

affecting the structural and petrological features. The K-Ar results of micas and amphiboles, in the entire area, yielded cooling ages around 500 Ma. Nevertheless, Archaean and Lower Proterozoic basement was largely indicated by Rb-Sr whole rock isochrones, and U-Pb measurements in zircons.

Late Archaean ages (around 2,700 Ma) were obtained in the coastal region of Paraná and São Paulo states, in the granulitic nuclei of Serra Negra and Itatins, which occur associated to a gneissic-migmatitic terrain adjacent to the Apiaí folded belt. In this area, some gneissic rocks yielded Transamazônico results, and the Brasiliano orogenic cycle overprinted the entire terrain with a regional metamorphism at amphibolite facies.

In the northern part of the Ribeira belt, a clear metamorphic zoning is indicated with grade increasing toward the east, away from the São Francisco craton (Siga Jr. *et al.*, 1982). Some Late Archaean ages were determined for gneissic rocks within the epizonal domain (Gouveia, Guanhães), and for granulitic rocks within the mesozonal domain (Juiz de Fora). However, in these regions most radiometric results obtained in the basement rocks indicated Transamazônico ages.

The best geochronological control is found in the Rio de Janeiro-Minas Gerais boundary area, in which the granulitic rocks of the Paraíba do Sul Formation yielded Lower Proterozoic results by Rb-Sr whole rock isochrones and U-Pb ages on zircons (Cordani *et al.*, 1973). This high-grade belt of Transamazônico age can be extended to the north, at least to the Caratinga and Governador Valadares region, and perhaps to the southwest, so as to include the Varginha-Guaxupé, Silvianópolis and Amparo complexes. Isolated results of Archaean age, such as the already mentioned granulites of Juiz de Fora, can also be found in the area.

Gneissic rocks of Transamazônico age occur to the east of the São Francisco craton, within the epizonal domain of the Ribeira belt. In this region, a metamorphic recrystallization, at amphibolite facies, was determined by Cordani *et al.* (1980), affecting previous Archaean rocks, and associated to the Minas orogeny. From the nature and location of the Transamazônico rocks found within the basement of the Ribeira belt, it can be seen that this Late Precambrian unit is superimposed over a Lower Proterozoic mobile belt, (the Paraíba do Sul belt, Cordani *et al.*, 1973), with similar structural trends and metamorphic zoning. Thus, the Minas Group, located at the boundary of the São Francisco craton and the Ribeira belt, is the supracrustal equivalent of the Transamazônico gneisses which occur to the east, and also of the granulites of the Paraíba do Sul Formation. Such paleotectonic situation is similar to the one already described for the northeastern part of the São Francisco craton, in Bahia, within the Salvador-Juazeiro mobile belt, to which the southern Transamazônico terrain can be correlated.

It seems to be clear that the Transamazônico belt here envisaged is ensialic, due to the various indications of Archaean ages obtained in what is supposed to be its basement. Moveover, if the correlations here attempted are valid, and if the Transamazônico outcrops found within the Borborema province can also be attributed to an extension of the same mobile belt, this geotectonic unit can be traced along a very large distance (about 2000 km, from São Paulo to Ceará), a longitudinal extension which makes this Lower Proterozoic belt equivalent, in importance, to the Maroni-Itacaiúnas mobile belt of the Amazonian craton.

CONCLUSIONS · From the descriptive framework of the Archaean and Lower Proterozoic terranes of South America, together with the ideas of the present authors about ancient tectonic regimes exposed in the earlier chapters, the geologic evolution of the continent during the first half of the Earth's history can be envisaged as follows.

During the entire Archaean, in successive differentiation-accretion processes, continental crust was formed in different fragments, relatively small (dimensions of 5-10,000 km^2) and geochemically stratified, with a low to medium grade upper part (the granite-greenstone terranes) and a high-grade lower part (the granulites and related rocks). In the Late Archaean (about 2,700 Ma) an extensive process of accretion and agglutination of pre-existing continental fragments occurred, characterizing the Jequié cycle, and the cratonization which followed the Jequié cycle formed extensive continental masses with dimensions of thousands of kilometers. Remnants of the ancient cratonic areas formed in this way are the Brumado region in Bahia, the Crixás terrain in Goiás and the eastern part of the Central Amazonian province, in Southern Pará. These granite-greenstone terranes were not structurally disturbed thereafter, not taking into account the thermal overprint of the Brasiliano orogeny in Southern Bahia and Goiás.

Very large and tectonically stable continental masses were in existence during the Lower Proterozoic. Part of them survived as such to the present day, like the Pakaraima nucleus, over which the non folded and non metamorphic Surumu-Roraimã volcanic-sedimentary sequence occurs, with about 1,900 Ma.

During the Transamazônico orogenic cycle (about 1,800-2,100 Ma) elongated belts were formed on the Archaean basement. The major ones seem to be the Maroni-Itacaiúnas mobile belt in the Amazonian craton, and the Salvador-Juazeiro mobile belt in the São Francisco craton. This latter can probably be extended further north and further south, within the basement of the Late Precambrian Borborema province and Ribeira belt, respectively. The Transamazônico mobile belts are ensialic in character and produced important reworking of preexisting continental material. However, they were also sites of important differentiation – accretion processes, as indicated by low initial Sr^{87}/Sr^{86} ratios of many isochrones of granitic rocks. Associated to both major belts, Maroni-Itacaiúnas and Salvador-Juazeiro, supracrustal rocks described as greenstone belts occur, a fact which seems to extend the tectonic regime reponsible for their appearance at least to the Lower Proterozoic, a situation similar to the West African craton, and to the Churchill Province of the Canadian Shield.

Transamazônico ages are also found within the small cratonic fragments of São Luís, Luís Alves and Rio de La Plata, as well as in the basement of most of the Middle and Late Proterozoic mobile belts of South America. This seems to indicate that a major part of the South American continental crust was already existent as such just after the Transamazônico cycle. Since the Transamazônico belts are ensialic, it is clear that a great portion of this material was already there, as continental crust, since at least the Late Archaean, but the relative proportions of material accreted to the crust in both time intervals can not yet be estimated.

In a general balance, for the making up of the continental crust of South America, and not taking into account the important contributions of the Andean belt during Phanerozoic times, Middle and Late Proterozoic orogenic pro-

cesses were much less important than the ancient ones. Newly accreted material seems to have been negligeable in the Espinhaço belt, in the Brasília belt, and very subordinate in the Rondonian belt, and in the Paraguay-Araguaia belt. Nervertheless, some important mantle-derived contributions can be pointed out, for the Middle Proterozoic, if the magmatic arc hypothesis for the Rio Negro-Juruena belt could be confirmed, and for the Late Proterozoic, extensively within the Don Feliciano mobile belt, and moderately within the Borborema province and the Ribeira belt.

Acknowledgements The authors would like to acknowledge sincerely their colleagues Miguel Basei, Wilson Teixeira, Colombo Tassinari Oswaldo Siga Jr., Koji Kawashita and Reinhardt Fuck for the helpful and profitable discussions, and for the cession of some unpublished data. Special mention to M. H. Figueiredo and T. Fairchild for assistance in the final revision of the manuscript. To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) the authors are grateful for different kinds of financial support in several opportunities.

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Recebido em 15 de agosto de 1982