JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol. 29, Mar. 1987, pp. 309 to 326

Granulite facies rocks of Brazil: a review of their geologic setting, Geochronological evolution, Petrographic and Geochemical Characteristics*

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Abstract

An attempt to assemble the available data on the granulite facies rocks spread around Brazil is made with a view to discuss their geological setting, geochronological evolution, petrographic and geochemical evolution. The isotopic ages of the granulites fall into different groups ranging from Archaean to Late Proterozoic. The geotectonic evolution of these rock types is discussed in terms of their being either fragments of geochemically differentiated lower crustal layers or eroded segments of modern Cordilleran (Himalayan) type collision belts. The geochemical feature of the rock types demonstrates the non-systematic fractionation of trace elements.

INTRODUCTION

A study of the geological evolution of the granulite facies terrane adds to our knowledge of the nature and evolution of the earth's lower crust. Brazil with its extensive area of high-grade metamorphic terranes ranging in age (mainly Rb-Sr whole-rock isochron) from Archaean (~3200 Ma) to upper Proterozoic (~600 Ma) offers a good opportunity to evaluate the role of these rock types in crustal evolution. An attempt is made here to assemble the available data on the granulite facies rocks from Brazil and discuss them in the light of modern theories on the origin of these rock types. The review is not meant to be an exhaustive coverage of literature but is intended to lay emphasis on the geochronological and geochemical nature of the terrane. The review is attempted keeping in view the geologist not familiar with Brazilian geology.

The Brazilian territory forms a part of the South American platform, whose basement is composed mainly of igneous and metamorphic rocks of mostly Precambrian age. In the tectonic evolution of the basement, two large older areas (cratons) namely, Amazonian and Sao Francisco cratons, tectonically stable in the late Precambrian are distinguished (Almeida *et al*, 1981). They are surrounded by mobile belts belonging to the Late Precambrian orogenic cycle (1100 - 570 Ma). Small cratonic fragments, viz., Rio del Plata, Sao Luis and Luiz Alves have also been observed in close relation with the Proterozoic mobile belts (Fig. 1).

The geotectonic environments of early Precambrian granulites in Brazil have been discussed by Wernick and Almeida (1979). In their work, granulite facies rocks are considered to be generally reworked Archaean material and are shown to occur in

* Dedicated to the memory of Prof. V. S. Venkatasubramanian.

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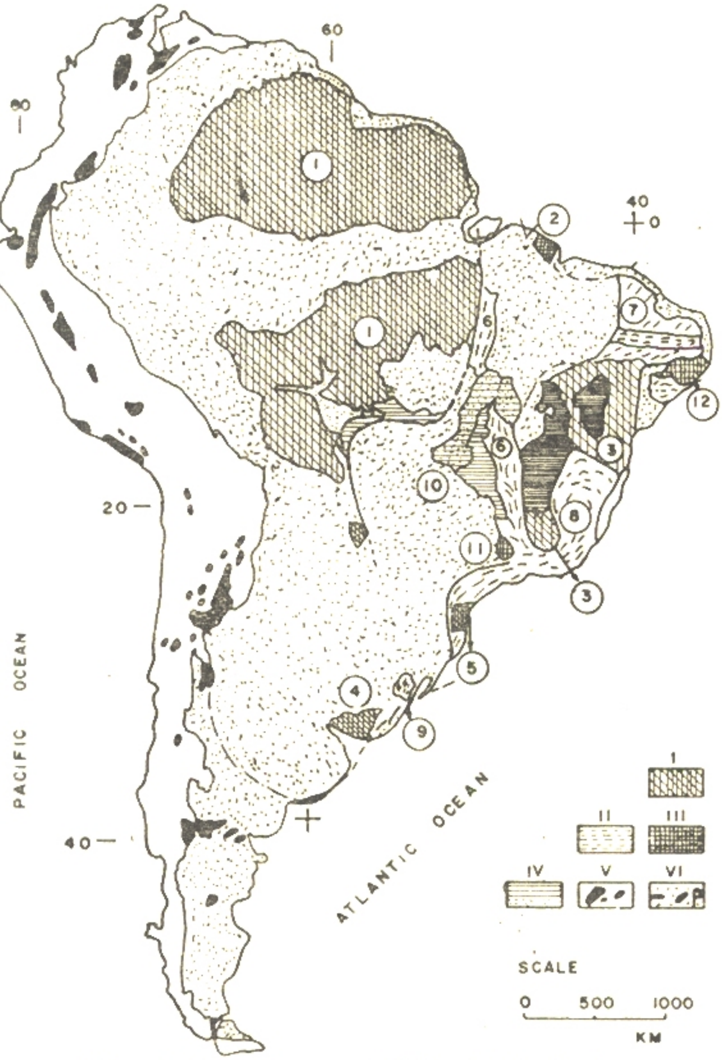

Figure 1. Major Geotectonic Units of South America.

I. Cratonic areas and cratonic fragments: (1) Amazonian, (2) Sao Luis, (3) San Francisco (4) Rio de La Plata, (5) Luis Alves. II. Upper Precambrian mobile belts: (6) Tocantins Province, (7) Borborema Province, (8) Ribeira belt, (9) Don Feliciano belt. III. Median Massifs: (10) Goias, (11) Guaxupe, (12) Pernambuco-Alagoas. IV. Precambrian and Phanerozoic Cover. V. Andean Chain, including Precambrian Nucleii. VI. Patagonian platform, including Precambrian Basement.

(Adapted from Cordani and Brito Neves, 1982).

cratonic regions, within major metamorphic complexes and as basement inliers within the mobile belts of Brazilian orogenic cycle. The granulite facies rocks in each of the geotectonic environment is discussed below in relation to their geological occurrence, geochronological data and geochemical characteristics.

GRANULITE FACIES ROCKS IN CRATONIC DOMAINS

Amazonian Craton

In the northern portion of the Amazonian craton, granulite facies rocks occur in the form of belts and remnant nucleii. In the Brazilian part of the craton, exposures of the granulite facies rocks are in the Federal territories of Amapa and

Roraima (Scarpelli. 1969; Amaral, 1974). A general review of the lithological, structural and geochronological characteristics of the granulite facies rocks of the northern Amazonian craton has been given by Lima *et al* (1982), who correlated the granulite facies rocks from the Brazilian territory with those from neighbouring countries like Venezuela, Guyana and Surinam,

Among the granulite facies rocks in the Federal territory of Roraima, charnockites, mafic granulites and kinzigites have been recorded. The geochronological study of the granulites yielded an isochron age close to 1900 Ma with an initial ($^{87}Sr/^{86}Sr$) ratio of 0.701 (Basei and Teixeira, 1975). This age value has been interpreted by the authors as the age of granulite facies metamorphism. Lima *et al* (1982) have tried to correlate the granulite facies rocks of Roraima with similar rock types in Bakhuis mountain complex of Surinam, Kanuku complex of Republic of Guyana, where age values in the range of 2000-2100 have been obtained. The granulite facies rocks in the Federal territory of Amapa, referred to as the metamorphic complex of Tartarugal grande (Jorge Joao *et al.*, 1979) are made up of charnockites, enderbites and kinzigites. The geochronological data (Lima *et al*, 1982) show an age of 2450 ± 80 Ma ($^{87}Sr/^{86}Sr$) initial $= 0.7063$, which was interpreted as the age of the granulite facies metamorphism. The granulite complex is correlated by the above mentioned authors with similar rock formations of Rio Coeroeni (S.E. Surinam) and Serie Ile de Cayene (French Guyana).

The Imataca Complex of Venezuela which lies outside the Brazilian territory, but within the northern Amazonian craton, is made up of quartzo-feldspathic gneisses, pyroxene-amphibole gneisses and metamorphosed iron formation, all folded, faulted and metamorphosed to granulite facies. The geochronological data indicate an early Archaean age for the basement rocks with the granulite facies metamorphism at 2000 Ma ago, resulting in extensive depletion of uranium relative to lead (Montgomery, 1979). Another granulite facies complex outside Brazil namely, El Garzon is found in the western part of Colombia in the Andean mobile belt and is composed of charnockites, enderbites and kinzigites. The age values obtained are of the order of 1180 Ma (Kroonberg, 1981). Even though situated in Andean mobile belt, the complex probably is related to the margin of the Amazonian craton.

The granulite facies rocks of Roraima Federal territory were analysed by Basei and Teixeira (1975), which yielded an age close to 1900 Ma with an initial Sr isotope ratio of about 0.701. This was interpreted by the authors as the age of metamorphism occurring during the Transamazonian orogenic event. The age values of 1900 Ma to 2000 Ma have been obtained for a large area of granulite facies rocks from the north of Rio Negro (Brazil) to Paramaribo (Surinam), including regions of Serra de Mucajai (Brazil), Kanuku Mountains (Republic of Guyana) and Bakhuis mountain (Surinam) (Lima *et al*, 1982).

In the southern portion of the Amazonian craton, the metamorphic grade varies and it reaches up to granulite facies. In many areas, the rocks are affected by migmatisation. In the western limit of the craton bordering Bolivia, the complex is mainly biotite gneiss, biotite hornblende gneiss, migmatite, anatectic granite, amphibolite, granulite and charnockite.

In Eastern Bolivia, a variably defined zone of rocks containing granulite facies assemblages is referred to as the Lomas Manaeches granulite group, which is made up of a basal unit of K-feldspar leptites (quartz-feldspathic granulites) and charnockitic hypersthene gneisses. Higher structural levels are formed of garnet-biotite paragneisses with well defined layers of enderbetic hypersthene granulites, basic granulites, calc-silicate, granulites, amphibolites, etc. The Rb-Sr isotope data yield an age of 1960 Ma (Litherland and Bloomfield, 1981). According to these authors a later tectono-orogenic event, San Ignacio cycle (1400-1700 Ma), reworked the granulite basement (Litherland *et al*, 1985).

On the Brazilian part of the Amazonian Craton bordering Bolivia granulite facies rocks are described from Rio Ituxi terrain in the Federal territories of Rondonia and Acre (De Silva *et al*, 1976). Macroscopically, the rocks are medium to fine-grained and microscopically exhibit a granoblastic texture. The rocks are mainly of felsic type with microperthitic orthoclase, oligoclase and xenoblastic fine grained quartz. The mafic minerals present in lesser abundance are hypersthene and biotite and occasional hornblende. Geochronological studies carried out in the region show that the granulites and associated gneisses plot on a Rb-Sr isochron diagram and yield an age of 1417 ± 13 Ma with initial $^{87}Sr/^{86}Sr$ ratio of 0.700 ± 0.001. The age is much younger than that of Lomas Manaeches granulites, which are about 700 km SE of the dated granulites of Ituxi. The low initial ratio and the Post Transamazonian age seem to indicate that the age of metamorphism may be later in the Ituxi area. The geotectonic evolution model of the Amazonian platform, as presented by Cordani and Brito Neves (1982), envisages an Archaean Cratonic Nucleus (Central Amazonian province) surrounded by Early and Mid Proterozoic belts. The granulite facies rocks of the Imataca, Kanuku, Adamapada-Follawatra, Mucajai Complexes, which form part of the Transamazonian Maroni-Itacaiunas mobile belt, are considered to be different nucleii reworked during Transamazonian orogeny. The geochronological data indicate that the age of the granulite facies metamorphism may be Transamazonian, while that of the original rocks may be, at least in part, Archaean.

The Lomas Maneches granulite facies rocks of Bolivia and granulites of Ituxi, which occur in the SW part of the craton belong to the Rondonian mobile belt, where the granulite facies rocks are older up to Transamazonian age. The major tectono thermal event that occurred during the Middle Proterozoic (1400-100 Ma) reworked the basement. In this region there is no evidence of Archaean ages.

Sao Francisco Craton (Fig. 2)

The granulite facies rocks of Sao Francisco craton extend mainly along the coast of the state of Bahia. There are other occurrences in the granitic-gneissic terranes NW of Salvador (Caraiba Complex) in the Santa Isabel Complex of Guanambe region Central Bahia, in SW Belo Horizonte-Minas Gerais. The granulite facies rocks, associated with the Sao Francisco craton, have been broadly classified into two major groups based on tectonic style and geochronology. They are Jequie granulite Complex, an oval shaped irregular area with predominantly granulite facies rocks folded and foliated in variable patterns in SW-NE direction and the Itabuna Complex, whose structural trends are mainly in the NS or NNE-SSW direction (Cordani, 1973; Brito Neves *et al* 1980).

In the field, rocks from Jequie granulite complex are predominantly banded granulites, migmatised granulites and augen gneisses. Perographically the rocks comprise, mainly, felsic granulites with a few intermediate to mafic types varying in composition from charnockite to enderbite. With decreasing alkali feldspar and

Figure 2. Granulite Facies Terranes of Brazil and Adjoining Countries. (1) Rio Ituxi (Rondonia-Acre). (2) Mucujai-Kanuku-Bakhurs, (3) Imataca, (4) Coeroeni-Fallawatra, (5) I le de Cayene, (6) Tartarugal Grande, (7) Garzon, (8) Lomas Maneches, (9) Jequie, (10) Itabuna, (11) Caraiba, (12) Santa Isabel, (13) Paraiba do Sul-Juiz de Fora, (14) Ubatuba, (15) Itatins, (16) Serra Negra, (17) Luis Alves, (18) Santa Maria Chico, (19) Goias, (20) Porto Nacional, (21) Guaxupe, (22) Pernambuco-Alagoas, (23) Granja.

quartz from the former to the latter, there is a clear variation from medium to fine-grained rocks with a concomitant increase in gneissic character marked by the orientation of the mafic minerals. In thin section, textures are seen to vary from equigranular interlobate in the charnockites to inequigranular polygonal in the enderbites. A characteristic feature of the charnockites is the predominance of mesoperthite with lesser amounts of quartz, plagioclase and myrmekite. Common mafic minerals occurring sporadically are orthopyroxene relicts, brown hornblende minor red brown biotite and green chlorite as an alteration product ; accessory minerals are zircon and apatite both occurring as large euhedral grains and some opaques. The mafic granulites consist of plagioclase, sometimes antiperthitic, pleochroic pink orthopyroxene, brown hornblende, quartz with apatite and zircon as common accessory minerals ; the mafic minerals sometimes occur as aggregates in certain portions but, on the whole, well oriented. Occasionaly both pyroxenes show (100) exsolution lamellae attesting to their slow cooling from high temperature.

In the Itabuna region, felsic and mafic granulites occur with regional structural trends mainly in NS direction. The characteristic mineralogical association of the Itabuna granulites is orthopyroxene-plagioclase but, garnet, clinopyroxene and quartz are found occasionally (Sighinolfi, 1970, 1971). In the Salvador area felsic and mafic granulites occur interbedded. The felsic rocks contain aluminous minerals such as sillimanite-garnet-corundum-sapphirine and cordierite, whereas mafic granulites are predominantly orthopyroxene-plagioclase-bearing. Using the presence of sapphirine and cordierite, Braun (1983) estimated TP conditions prevailing during metamorphism for the sapphirine-bearing gneisses to be 750-830° and 7-8.5 K bars. The above-mentioned author invokes an anatectic origin for the rock types based on textural and microchemical data. Further detailed work, with petrographic and geochemical comparison on the nearby hornblende granitic complexes, may elucidate the origin of the rock types.

In the northern region of Bahia, detailed studies have been carried in the Caraiba Complex (Figueiredo, 1980). The region is composed essentially of banded felsic to intermediate gneisses and granulites, with subordinate layers and lenses of carbonate, calc-silicate rocks, banded iron formation, graphite-rich rocks and concordant mafic-ultramafic bodies. There is a broad metamorphic zonation with the greenschist facies rocks of the associated Rio Itapicuru Greenstone belt (Kishida and Riccio, 1980 ; Figueiredo, 1982) and the granulite facies rocks of Curucu valley region, amphibolite facies rocks occurring in the intervening zone,

From the geochronological point of view, Sao Francisco Craton is the most extensively dated region in South America with more than thousand samples analysed by K-Ar, Rb-Sr and U-Pb zircon methods (Cordani, 1973 ; Cordani and Iyer, 1979 ; Brito Neves *et al*, 1980 ; Mascarenhas *et al*, 1984 ; Cordani *et al*, 1985 ; Delhal and Demaiffe, 1985).

The general picture which has emerged is fairly complex, pointing to the polymetamorphic nature of the high-grade terranes and the consequent scale of Sr isotope homogenization. The Rb-Sr isotope data from the Jequie Complex yield isochron ages in the range of 3200-2400 Ma with initial $^{87}Sr/^{86}Sr$ ratios higher than 0.702. Rb-Sr isochron ages can be grouped into three major groups : 3200 Ma, 2700 Ma and 2400 Ma (Cordani and Iyer, 1979 ; Mascarenhas *et al*, 1984).

Recent U-Pb zircon studies, on the granulite facies rocks from the Jequie region by Delhal and Demaiffe (1985), show that the data points are aligned on a chord with computed upper intercept on the concordia cord at 2400 Ma. This age has been considered a geologically meaningful event by the authors. It is interesting to note that the geochronological studies using Rb-Sr and Pb-Pb isotopic methods on the granite-greenstone terranes on Central-Southern Bahia, which is to the west of Jequie (Cordani *et al*, 1985) showed ages older than 3000 Ma for Archaean granitic rocks with associated medium grade metamorphism occurring in most of the area at 2700 Ma ago.

The geochronological data show that the area has undergone a complex geological history with the Sr and Pb isotope system remaining isotopically closed since 2400 Ma and that Transamazonian orogeny does not seem to have a serious effect excepting a slight reheating of the minerals, some of which yield K-Ar dates of 1800 Ma. According to Delhal and Demaiffe (1985) the 2400 Ma event may represent one of the following:

a) Time of uplift at the beginning of Transamazonian cycle.
b) Granulite facies event with incomplete homogenization of Sr isotopes.
c) A discrete thermal event without tectonometamorphic and magmatic manifestations.

The age for the granulite metamorphism cannot be precisely defined. However, all the isochrons of Archaean granulites, yielding ages between 3200 and 2700 Ma have Sr isotopic initial ratios higher than the extrapolated mantle value at that time, indicating that these rocks are formed from the reworking of rocks older than 3000 Ma.

The data of Mascarenhas and Sa (1982), showing ages of 3500 Ma for the granitic tonalitic gneisses, without granulite mineralogy, occurring in the vicinity of the granulitic complex, seem to make this explanation more plausible. To define whether 2700 Ma or 2400 Ma represent the age of granulite metamorphism, further work on selected samples by different isotopic dating methods like Pb-Pb and Sm-Nd need to be carried out.

The Archaean Rb-Sr ages obtained for the granulite facies rocks imply that the isotopic system has remained closed since 2400 Ma for Sr.

In the Itabuna granulite belt, geochronological investigations carried out by the Rb-Sr method yield ages in the range of 2000 to 2300 Ma for the Itabuna block and ~2000 Ma for the Salvador with initial $^{87}Sr/^{86}Sr$ ratio of 0.703 (Cordani and Iyer, 1979; Brito Neves *et al*, 1980). The U-Pb isotope ages on zircons from the Itabuna area define ages of 2100-2150 Ma. These concordant Transamazonian data (unlike the case of Jequie) indicate that this orogeny had a greater influence in the granulite terrane of Itabuna. In this region, the age of the granulite being Lower Proterozoic or slightly older than Transamazonian, led Brito Neves *et al*, (1980) to conclude that these granulite terranes in Bahia may not be Archaean. It is interesting to note that there are at least two ages of granulite facies metamorphism (Jequie and Itabuna) in the Sao Francisco Craton.

The geochemical nature of the granulite facies rocks of Jequie has been investigated by Sighinolfi *et al*, (1981 a, b); Oliveira *et al*, (1982); Iyer *et al*, (1984). The granulites, in general, are enriched in large ion lithophile elements (LILE), whereas the LILE values in charnockites show a scatter. The rare earth element distribution of the granulites and charnockites shows that they, in general, have a higher total REE concentration and display strong negative europium anomaly. Various explanations for the geochemical behaviour have been advanced: according to Iyer *et al*, (1984) the relative high concentration of the radioactive and other elements may be related to the nature of the fluid as well as its relative volume through the rock. Recent investigations by Valley *et al*, (1983), Valley and O'neil (1984) have shown that during granulite facies metamorphism the fluid rock ratios, were in many cases between 0.00 and 0.1 and that externally derived fluid as well as fluid derived by volatilization rose along localized channels and were not pervasive. Such a phenomenon can probably account for lack of isotopic homogenization of Sr on a regional scale and may explain geochemical nature of the granulites and charnockites.

The Itabuna and Caraiba Complexes have geochemical compositions considerably more heterogeneous with a bimodal distribution (granodioritic, tonalitic and basic rocks) and probably dominated by supracrustal rocks (Figueiredo, 1982). The chemistry of the granodioritic-tonalitic rocks of Caraiba Complex is interpreted as metadacite andesite (or elese, metagranodiorite tonalite) and/or meta-arkose and greywacke.

Remobilization of LIL elements (including REE) seems to have taken place during the K-metasomatism of amphibolite facies rocks. In the Itabuna Complex, granulites have a more mafic composition than the Jequie and Caraiba granulites and based on the heterogeneous geochemical characteristics, the granulites of Itabuna and Salvador have been interpreted by Sighinolfi (1970) and Fujimori (1968) as metasedimentary. The geochemical data for the Itabuna granulites show that they have higher K/Rb and Th/U ratios compared to Jequie granulites.

The geotectonic evolution of the Sao Francisco craton has been discussed by Cordani and Brito Neves (1982). In their opinion, throughout the Archaean, several fragments of the continental crust were formed during various episodes and these fragments probably coalesced at ~ 2700 Ma at the end of the Archaean. Such a continental crust was stratified with a lower granulite crust. During the Lower Proterozoic, ensialic belts were imposed on the Archaean continents and they evolved during orogenic cycles, of which the most important was Transamazonian. During the Transamazonian orogeny important accretions from mantle source occurred in addition to reworking of the previous continental material.

Based on the Lower Proterozoic structures and physical processes, Brito Neves *et al* (1980) suggested the existence of two mobile belts in the Sao Francisco Craton, which are separated by a Central Stable Cratonic Area. The Jequie Complex occurs in the mobile belt and appears to be an Archaean cratonic remnant within the younger mobile belt. The Itabuna granulite belt may belong to a different tectonothermal event probably associated with Transamazonian orogeny.

The radiogenic heat production data for the granulites from the Jequie area yielded 2.7 po W/m^3 and this value is higher than that of many granulite terranes. The heat flow data from the region is not available. However, using the heat flow data from nearby region an estimate of the relative thickness of the continental lithosphere shows it to be 150 km thicker than old oceanic crust (Iyer *et al*, 1984). Such a thick lithosphere may work as an ideal mechanism against further tectonic thermal mobilization of the late Archaean nucleii and it is interesting to note that the Jequie system has remained isotopically closed for Sr and Pb since 2400 Ma.

Rio de La Plata Craton

Two important occurrences of granulite facies rocks in the Rio de La Plata craton are the Santa Maria Chico Complex, near Bage in the state of Rio Grande do Sul (Nardi and Hartman, 1979) and the granulitic complex of Luis Alves, Santa Catarina State (Hartman, 1981). The granulitic rocks of Santa Maria Chico is essentially made up of basic gneisses and intermediate type, also contain ultramafics, anorthosites and marble in subordinate amounts. Based on the occurrence of the paragenesis hypersthene + plagioclase + clinopyroxene + garnet, Nardi and Hartman

(1979) consider the granulite facies metamorphism to be of intermediate to high pressure. In the Luis Alves Complex the rock types observed are norites, enderbites, ultramafics etc. (Kaul and Teixeira, 1982).

The geochronological studies from the Santa Maria Chico Complex and the granulite complex of Luis Alves (Kaul and Teixeira, 1982; Cordani and Brito Neves, 1982) indicate that the granulites of Luis Alves are of Archaean age (~2700 Ma) whereas the Santa Maria Chico is probably of Early Proterozoic age (~2100 Ma). The geochronological data show that the isotopic systems of Sr and Pb have remained closed since Early Proterozoic and that they have not been affected by Brazilian orogenic cycle.

Geochemical studies have been carried out on these areas by Nardi and Hartman (1979), Moreira and Marimon (1980). Nardi and Hartman (1979) interpreted the low content of P_2O_5 and TiO_2 as an indication of the dominantly sedimentary character for the precursors of the rock types in the Santa Maria Chico area. Trace element distribution shows that the K/Rb ratios are in the normal range observed for igneous rocks (Shaw, 1968).

Based on the geochemical analysis of major and trace elements Moreira and Marimon (1980) concluded that the granulites of Luis Alves area are of igneous origin and chemically similar to calc-alkaline igneous suites. The trace element data seem to show that the K/Rb ratios are in the normal range observed for igneous rocks. Thus, it appears that the granulites from Rio de La Plata craton, like the granulites of Jequie Complex, do not show high K/Rb ratios observed in Itabuna region and many other parts of the world.

GRANULITES IN THE LATE PRECAMBRIAN OROGENIC BELTS

Ribeira Belt

The Ribeira belt extends along the coastal region in the south and southeast of Brazil and is limited on the north by the Sao Francisco craton and on the west by the Phanerozoic cover of the Parana basin and in the south by Luis Alves Cratonic Area. (Fragaso Cesar, 1980). The belt is made up of diverse units and groups of amphibolites and granulite facies rocks which were migmatised and granitised to various degrees during Brazilian orogenic cycles. The granulites are generally present as small bodies and isolated nucleii composed of charnockites, kinzigites and leptinites.

The geochronological studies of the granulite facies rocks from the region may be interpreted in terms of at least two generations of high-grade metamorphic rocks.

1) Those related to Late Precambrian Brazilian orogenic cycle eg. Sao Fidelis (Batista, 1983), Ubatuba (Gasparini and Mantovani, 1979), Kinzigitic rocks of Rio de Janeiro/Espirito Santo (Siga Jr. *et al*, 1b82).

2) Older granulites of different ages: They are basement inliers rejuvenated in the Brazilian orogenic cycle. The granulite complexes and their ages are:

   Paraiba do Sul .... ~2.100 Ma (Cordani *et al*, 1973)
   Juiz de Fora....... .... ~2.700 Ma (Cordani *et al*, 1973)
   Serra Negra and Itatins ... 2.700 Ma (Kaul and Teixeira, 1982)

The diversity of the age values for the granulite facies rocks in the Ribeira belt indicate that, contrary to the belief of many geologists, all granulite facies complexes need not be related and they need not be of Archaean age.

Geochemical studies were carried out in this region by Oliveira (1982), Wernick and Oliveira (1982) and Gasparini and Mantovani (1979). The general geochemical trend for rocks of the Paraiba do Sul granulite belt (Oliveira, 1982), shows it to be calc-alkaline for a greater part of the rock types including granulites. The K/Rb ratios for the granulites are little higher than the associated granitic rocks, but are lower than the values obtained for the pyroxene granulites of Itabuna region. The geochemical data on the charnockites of Ubatuba in the coastal region of Sao Paulo State by Gasparini and Mantovani (1979) was interpreted by the authors as signifying that REE, Sc, Rb, Sr, Ba, Ta and Th are in concentration range of granites; whereas Cs, Au and U contents (and Th/U; K/Cs and Rb/Cs ratios) are in the range of granulite facies rocks.

Granulite Facies Rocks of Goias

The granulite terrane occurs in the eastern margin of the Goiana Complex or Central Goiana Massif, which is considered a mosaic of crustal blocks of different ages and origin juxtaposed together (Cordani and Brito Neves, 1982).

The granulite facies rocks occur in isolated segments, some of them in close relationship with the gneissic-migmatitic terrain, while others are associated with the gabbro-anorthositic complexes. Occurring in the eastern margin, near Goiana, the Anapolis-Itaucu Complex has a large exposure of granulite facies rocks which represents great lithological diversity: hornblende pyroxene-gneiss, and granodiorite gneisses, banded basic granulites, enderbites and leptinites. Quartzites, impure marble and calc-silicate rocks are also present in the region (Marini *et al*, 1984).

The geochronological data (Tassinari *et al*, 1982; and unpublished data) for the granulites indicate Mid Proterozoic ages: some isochron diagrams yielding ages around 1100-1200 Ma, while others in the range of 1600-1700 Ma. No age value older than 1700 Ma has been recorded indicating evidence either of Archaean or Transamazonian orogenic cycle leaving its imprint on the isotopic systems.

Granulites of Guaxupe Massif

Granulite facies rocks in South Minas Gerais State occupy broad belts of several hundred kilometers in length and are separated from granite-greenstone terranes to the north by conspicuous crustal lineaments. Apart from a few scattered examples, the main occurrences of granulites in these belts extend northwestwards from Varginha to Guaxupe along the Guaxupe Massif (Almeida, *et al*, 1981). It is nct clear whether this belt and the NE trending belt in the Juiz de Fora region merge at their respective SE and SW ends. There is evidence that, where the belts appear to converge, there are also several strips of high-grade rocks that are grouped in the Paraiba do Sul granulite belt (Oliveira, 1984). The current Brazilian maps do not take this into account and it is expected that detailed geological mapping in future will depict the occurrences in both belts more faithfully.

For the most part, the rocks are made up of charnockitic and enderbitic gneisses with intercalations of mafic two pyroxene granulites and minor pelitic gneisses (Chowdhuri and Szabo, 1982). Geochronological data from this region are not available. The granulites of Guaxupe-Varginha belt form a sequence consisting of basic to intermediate rocks at the base and acid granulites and migmatites at the top. The whole region has been affected by the Brazilian orogenic cycle as is evidenced by preliminary geochronological data (Rb/Sr, U/Pb). Petrologic and structural considerations by Oliveira (1984) suggest an evolution for this belt prior to this cycle, however, and regional study by the same author appears to indicate large scale thrusting of the granulite belt over the granite greenstone terrane to the north. In this context the possible emplacement of eclogite in the gneissic complex might also be indicative of strong tectonic activity (Hoppe *et al*, 1985).

In the Guaxupe Massif, some preliminary geochronological data seem to indicate two types of granulite facies rocks. At S. Jose do Rio Par do, Rb-Sr and U-Pb zircon data indicate 600 Ma age, where the granulites are associated with Pinhal migmatites. To the east, the granulites seem to be older and related to the rejuvenated basement, but their ages are unknown, may be as young as $\sim$1200 Ma.

Some trace element studies on the granulites and the associated gneisses from the Guaxupe massif by Fernandes (1982) showed that the K/Rb ratios in the granulites are higher than the gneisses and that the U, Th values are low in both the rock types.

Granulite Facies Rocks in Borborema Province

The basement of this region is built of two fundamental kinds of terranes namely, gneissic migmatitic terrane (massifs), metasedimentary and volcanic-sedimentary terrane (fold belts or fold-system). Granulitic facies rocks are found in almost all massifs (Pernambuco – Alagoas, Rio Piranhas, etc.) in modest amounts. Some of them display relict character within. The rock types are leptinites, hypersthene-migmatitic domain gneisses, silliminate-cordierite-garnet gneisses.

Geochronological data from the region show the predominance of Early Proterozoic ages in the basement rocks. The effect of late Precambrian orogeny within the Borborema Province is also strong. The age of granulite facies metamorphism has not been defined clearly.

DISCUSSION AND CONCLUSION

An important criterion needed in the modelling of the crustal evolution during Archaean and Proterozoic times is the temporal and spacial relationship between the greenstone belts and high-grade metamorphic terranes. In this publication, the complex nature of the temporal and spacial relationship of granulite terranes in Brazil is attempted.

The geotectonic evolution model of Cordani and Brito Neves (1982) envisages the formation of small geochemically stratified crustal fragments during the entire Archaean, extensive cratonisation by accretion and agglutination in Late Archaean (2700-2400 Ma) and formation of elongated mobile belts during Transamazonian. Since Transamazonian belts are ensialic, it appears that a substantial part of the South American Continental Crust has been in existence since Late Archaean. It is widely considered that the most important phase of continental growth in earth's history is in Late Archaean and the estimate of present crustal mass generated by Archaean-Proterozoic boundary ranges from over 50% (Condie, 1981) to about 85% (Dewey and Windley, 1981).

The geochronological data in Brazil show that important tectono-thermal events occurred during the Late Archaean and also throughout the entire Proterozoic. According to Windley (1984), though greenstone belts and granulite-gneiss belts are two characteristic forms in the Archaean, they continue to form in the Proterozoic, though in lesser abundance. A look at the geochronological data of the granulite facies rocks from different parts of Brazil (Table I) shows that there

GEOLOGICAL UNIT	SIZE	ROCK TYPE	GEOLOCHRONOLOGICAL EVOLUTION	GEOTECTONIC SIGNIFICANCE	GEOCHEMICAL FEATURES
Santa Isabel	Medium	Basic to intermediate gneisses and granulites migmatised	Archaean with rejuvenation at 2100 Ma	Internal zone of metamorphic belt	
Ribeira	Very Large	Charnockites Kinzigites, leptinites cord-sill gneiss	Late Proterozoic ages (600 - 700 Ma)	Internal zone of metamorphic belt	Metasedimentary, aluminium, rich, non depleted LILE
Paraiba do Sul and Juiz de Fora	Very Large	Banded granulites, enderbites, charnockites partially migmatized	2700 Ma, 2100 Ma metamorphic ages with rejuvenation at 700 Ma	Basement inliers	calc-alcaline trend "non depleted" LILE
Itatins	Small to Medium	Enderbites, charno-enderbites	2700 Ma high grade event with rejuvenation at 600 Ma	Basement inliers	calc-alcaline igneous trend, with "non depleted" LILE
Serra Negra	Small	enderbites, kinzigites	Same as above	Same as above	Same as above
Ubatuba, Parati	Small	Charnockites	Late Proterozoic ages (600 - 700 Ma)	Internal zone of metamorphic belt	Low Ca granite chemistry
Santa Maria Chico Rio grande do Sul	Medium	Mafic to intermediate type	2500 - 2100 Ma high grade event	High grade cratonic area (exposed lower crust)	Dominantly sedimentary character non depleted LILE
Luis Alves Santa Catarina	Medium	Norites Enderbites Ultramafics	2700 Ma high grade event	Same as above	calc-alkaline igneous chemistry, partially depleted LILE
Goiano Complex	Large	Mafic, Ultramafic Granulites Enderbites	Proterozoic ages of high grade metamorphism and rejuvenation at 700 Ma	Crustal blocks of different ages and origin and tectonically justaposed	
Porto Nacional Goias	Small	Mafic, Ultramafic granulites	Same as above	Same as above	
Guaxupe Massif	Large	Charnockites, Enderbites Mafic granulites, minor petitic gneisses	Proterozoic ages with rejuvenation at 700 Ma	Crustal blocks in Collision belts	
Pernambuco Alagoas Massif	Medium	Felsic granulites	Proterozoic ages of high grade rejuvenation at 600 Ma	Internal zone of metamorphic belt rejuvenated in Late Proterozoic	
Granja	Small	Leptinites, Kinzigites	Proterozoic age with rejuvenation at 600 Ma	Same as above	

Small < 200 Km² Medium = (200 - 1000) Km² Large = (1000 - 10 000) Km² Very Large > 10 000 Km²

TABLE 1 GENERAL CHARECTERISTICS OF GRANULITE FACIES TERRANES OF BRAZIL AND NEIGHBOURING COUNTRIES

GEOLOGICAL UNIT	SIZE	ROCK TYPE	GEOLOCHRONOLOGICAL EVOLUTION	GEOTECTONIC SIGNIFICANCE	GEOCHEMICAL FEATURES
Rio Ituxi (Rondonia - Acre)	Medium	Felsic granulites charnockites	Mid Proterozoic age (1400 Ma)	Basement inlier rejuvenated in Mid or Late Proterozoic	
Mucujai - Kanuku - Bakhuis	Very large	Banded charnockites Felsic granulites Sillimanite - gneisses	2100 Ma (probable high grade event)	Basement Inliers	
Imataca, Venezuela	Very large	Felsic granulites charnockites	Early Archaean metamorphosed to high grade at 2100 Ma	Exposed lower crust	U depletion
Coeroeni Ile de Cayene Tartarugal Grande	Small or Medium	Cordierite Gneiss charnockites	Late Archaean age 2400 Ma	Basement inlier	
Garzon, Colombia	Very large	Charnockites Enderbites Basic granulites Sillimanite Gneiss Calc - Silicates	Mid to lower Proterozoic age (1180 Ma)	Cratonic border basement inlier rejuvenated in Phanerozoic times	
Lomas Maneches Bolivia	Very large	Banded Felsic granulites charnockites	Age of formation 2000 Ma and rejuvenation at 1100 Ma	Basement inlier rejuvenated	
Jequié, Bahia	Very large	Banded granulites (partially migmatised) acid types predominate	Early Archaean photoliths. 2400 or 2700 Ma high grade event rejuvenation at about 2000 Ma.	Cratonic region (exposed lower crust)	Granitic Chemistry with "non depleted" LILE concentration
Itabuna, Bahia	Very large	Felsic to mafic granulites Calc. Silicate and banded iron formations intercalations	Early Proterozoic high grade metamorphic event (2100 Ma)	Internal zone of metamorphic belt.	Heterogeneous with "depleted" LILE concentration
Caraiba, Bahia	Large	Banded, Felsic to intermediate gneisses and granulites highly migmatised	Late Archaean rejuvenated al 2100 Ma	Internal zone of metamorphic belt	Grano dioritic-tonalitic composition Remobilization of LILE

are different isotopic ages for the high-grade terranes. The ages range from Archaean (2700 Ma), through Early and Middle Proterozoic (2400 Ma ; 2100 Ma ; 1700 Ma ; 1500 Ma ; 1200 Ma) and also Late Proterozoic (600 Ma). Thus, the widely held belief that most (or all) granulites are of Archaean age does not find support in South America.

Using the Sm-Nd model age formalism, Othman *et al* (1984) have shown that the time interval between the age of the protolith and the high-grade metamorphic event is fairly large ; whereas studies by Bernard Griffith *et al* (1984) and Black and Mcculloch (1984) show that the interval could be short. Most of the granulite terranes of Brazil seem to show a large interval between the age of the protolith and the high-grade event.

The Archaean granulite terranes, probably represent geochemically stratified lower crustal segments, whereas the Proterozoic granulite gneiss belts represent uplifted or upturned segments of orogenic belts. According to Windley (1984) most of the granulite-gneiss terranes may be compared with their Archaean counterpart on the one hand and, on the other, with deeply eroded segments of modern Cordilleran (or Himalayan) type collisional belts.

However, as pointed out by Ashwal *et al* (1983), three stages in granulite facies metamorphism of suprarcrustal rocks must be accounted for, namely, transport from the surface to depths of 15–30 km, heating to 700°C or more and reexposure at the surface. The authors discuss the various possible mechanisms for the heating step, pointing out that the simple continental collision alone cannot generate granulite facies rocks. In Brazil, all granulites with the exception of some charnockite massifs of igneous character, exhibit signs of strong deformation, thereby strengthening the assumption of their being deeply eroded segments of collision belts. This may imply that the collision regimes were active during the entire Proterozoic at least in parts of South American continent. A word of caution must, however, be applied in this context, as the collisions have to be proved unequivocally by careful tectonic studies.

In some cases, it is clear that the granulite facies rocks are polycyclic (or polyphasic or at least polymetamorphic) and in such cases, the chemical system may have a long previous crustal history predating the high-grade event. There are several examples where the granulite facies rocks are basement inliers in younger belts. In these cases, studies indicate that the younger and superimposed belts are ensialic and that granulites were brought tectonically (from deeper levels within the orogen) to near surface position by large overthrusts associated with the compression that occurred during the evolution of the younger belt. In such situations, the tectonic evolution of the granulites may be considered to have undergone at least a two-stage history. In the first stage, they were formed and brought isostatically to some higher level, but not exhumed ; in the second stage, they were brought tectonically into higher levels. Commonly they are associated, in the second stage, with the mesozonal rocks of the younger belt (migmatites etc) and they show evidences of retrogression at the amphibolite facies conditions. The exhumation of the granulites occurs at the final episode of cooling, uplift and erosion, associated with the younger cycle.

The interesting feature of the geochemical data from the granulite facies rocks of Brazil is that many of the Brazilian granulites have large ion lithophile elements in concentration which are ' normal ' or ' undepleted '. In several cases, we do not have complete chemical data available, but from geochronological work (Rb/Sr value) we can suggest that the 'undepleted' granulites are indeed more frequent. On an average, the Rb contents are of the order of 100 ppm and Sr contents of the order of 30–50 ppm for granulites of Jequie, Santa Isabel (Bahia), the high grade kinzigitic gneisses of the Ribeira belt, the Paraiba do Sul granulites and many others. Some of the granulites like those from Itabuna, Barro Alto and may be Juiz de Fora, part of Luis Alves, Guaxupe etc many be termed 'depleted' based on the relatively lower Rb/Sr ratios.

From this data it is clear that in South America geochemical differentiation associated with depletion of LIL elements in granulites is not universal and the data seem to be in agreement with the observation of Barby and Cuney (1982) who pointed out fractionation of LIL elements is not systematic in granulites and it depends on original lithology, mineralogy, mineral-fluid equilibria during progressive (retrogressive) metamorphism and mineral-fluid equilibria during anatexis.

Like Brazil, the Precambrian Shield of South India has an extensive area of granulite facies rocks, where geochronological and geochemical studies have been carried out. Majority of the data, however, are from the northern portion of the belt, where a late Archaean age for the granulite facies metamorphism is obtained. In Brazil such an age value has been observed in many areas and many geologists even call it 'Jequie event'. In India reliable geochronological data for granulites from other parts of the shield are few and, may be, future studies could reveal other periods of granulite facies metamorphism. According to Drury *et al* (1984) most of the Eastern Ghat granulites are Archaean and some may be related to Proterozoic crustal thickening.

In Brazil the granulite facies rocks border the granite-greenstone terranes all along the southern part of the Sao Francisco Craton. But unlike in India, the transition from granite-greenstone to granulite has not been observed. Further, there is no evidence for large scale charnockitization in Brazil. This may be attributed probably to the different tectonic regimes that operated in the two regions.

The geochemical studies of the granulites of India have shown that, similar to Brazil, there are terranes where LIL elements are in 'normal' or 'undepleted' concentrations (Weaver and Tarney, 1983), probably indicating the important role of fluids in the elemental fractionation during metamorphism. The geotectonic evolution of the granulites of South India has been discussed by Drury *et al* (1984), who attributed it to the crustal thickening and migration of CO_2-rich fluids.

The review presented here shows the complex nature of the age, chemistry, tectonics and conditions of formation of various granulite facies terranes in Brazil and should serve to caution many geologists, especially in South America, who try to use granulites as general guides for regional correlations.

ACKNOWLEDGEMENT

We are grateful to the authorities of IPEN/CNEN/SP for extending facilities. Miss Suely da Cunha Santos typed the manuscript.

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(Received: March 29, 1986; Revised form accepted: Aug. 12, 1986)