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GEOCHEMICAL STUDIES IN THE PROTEROZOIC METAMORPHIC TERRANE OF THE GUAXUPÉ MASSIF, MINAS GERAIS, BRAZIL. A DISCUSSION ON LARGE ION LITHOPHILE ELEMENT FRACTIONATION DURING HIGH-GRADE METAMORPHISM

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Abstract

Fernandes, J.F., Iyer, S.S., Imakuma, K. and Choudhuri, A., 1987. Geochemical studies in the Proterozoic metamorphic terrane of the Guaxupé Massif, Minas Gerais, Brazil. A discussion on large ion lithophile element fractionation during high-grade metamorphism. Precambrian Res., 36: 65-79.

The trace element composition of high-grade metamorphic rocks in the Guaxupé Massif is investigated. The large ion lithophile element composition is compared in both the granulite facies rocks and the associated amphibolite facies gneisses. The K, Rb, Th contents in the granulite facies rocks from other parts of Brazil show that the depletion of these elements is variable. The covariance of K-Rb ratios with K suggest the importance of mineralogical control, protolith composition, nature of fluid etc. The distribution of U and Th appears to indicate the protolith composition of the rock types.

Introduction

Intermediate and high-pressure granulite facies rocks represent the surface exposure of the lower crustal material (Smithson and Brown, 1977; Haack, 1983) and the geochemical data from many granulite terranes around the world are well documented. The assembled data, especially those relating to large ion lithophile elements (LILE), have provided conflicting views on the nature and the extent of LILE fractionation (Drury, 1973; Collerson, 1975; Gray, 1977; Dostal and Capedri 1978; Dupuy et al., 1979; Sighinolfi et al., 1981).

The explanations offered for the presence or lack of fractionation are subjects of much conjucture and debate. A perusal of the literature shows that to many investigators fractionation (depletion) is a 'fait accompli' and granulites with normal LILE concentration are assumed to have two stages of development; an initial metamorphic LILE depletion followed by addition of LILE elements in sufficient quantities during a later metasomatic event. In many cases

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isotopic data (Sr and Pb) do not support such a model (Iyer et al., 1984).

Barbey and Cuney (1982) summarized the available data on LILE in the high-grade metamorphic terranes and pointed out that their fractionation is not systematic but depends on original lithology–mineralogy, mineral–fluid equilibria during progressive or retrogressive metamorphism, and mineral–fluid equilibria during anatexis. It has been suggested by some investigators that fractionation may occur even before the onset of the granulite facies metamorphism, i.e., during the amphibolite facies metamorphism (Lambert et al., 1976). Thus a comparative geochemical study of granulites and associated amphibolite facies rocks is of great value in understanding the nature and extent of element mobility during high-grade metamorphism provided the amphibolites are not retrogressed from the granulites and that the original compositions are the same.

Brazil has an extensive area of high-grade metamorphic rocks of Archaean and Proterozoic ages in the São Francisco Craton (Sighinolfi, 1971; Cordani and Iyer, 1979; Figueiredo, 1982). Paraíba do Sul (de Oliveira, 1982), southern Brazil (Wernick and de Oliveira, 1982). However, published geochemical data, especially those of radioactive elements, are largely confined to the Archaean granulite belts of Bahia (Sighinolfi and Sakai, 1977; Sighinolfi et al., 1981; Iyer et al., 1984).

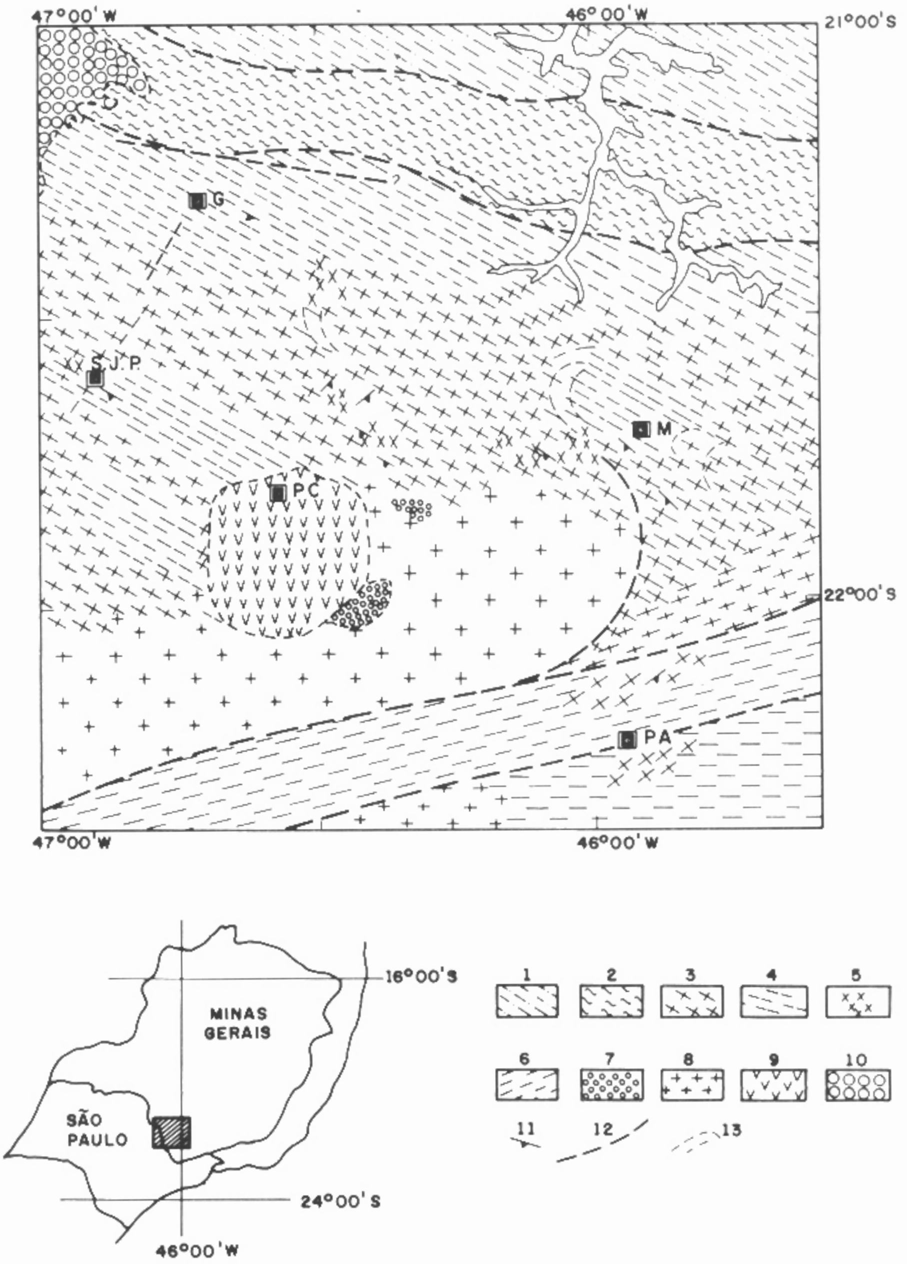
In this study we present trace element distribution data for high-grade metamorphic rocks in the Guaxupé Massif, which forms part of the Paraíba do Sul belt (Fig. 1). A comparative study of the trace element distribution in the amphibolite and the granulitic facies rocks was carried out in small areas near Guaxupé, Machado, Pouso Alegre, the total area, which underwent sampling, about 100 km^2.

Geological setting

Much of the detailed work being carried out today in Minas Gerais State is based on the reconnaissance mapping by Ebert (1956, 1962) including the first serious attempt to establish a coherent Precambrian stratigraphy in the area. It is in this part of southern Minas Gerais that de Almeida et al. (1976) first defined the Guaxupé massif; according to de Almeida et al. (1981), the massif is a gneiss–migmatite complex consisting of granulites, gneisses and amphibolites, and constitutes the basement of the largely metasedimentary Uruaçu fold belt to the north. According to de Oliveira (1984) the granulite belt is thrust at a low angle over the granite–greenstone terrain north of Guaxupé which forms the southern margin of the São Francisco Craton. Field observation in the study shows a predominance of granulite facies gneisses to the north, grey tonalitic and granodioritic and migmatites in the central region and to the southeast, and pink potassic granites and migmatites to the west and northwest (Fig. 1).

Based on gravimetric and magnetometric data, Haralyi et al. (1985) have interpreted the crustal structure in eastern and southern Minas Gerais, which includes the area of the present investigation, as late Archaean blocks of granite–greenstone terrain separated by belts of high-grade rocks. According to them, these belts represent lower parts of southern blocks upthrust over the Brasilia block to the north along low-angle ductile shear zones. This regional structure is affected by several sets of faults of the Trans-Amazonic event and find expression as high-angle ductile shear zones. It is suggested by these authors that the late Proterozoic Brasilian thermal event (remobilization or migmatization) affected the high-grade terrain preferentially along lines of pre-existing weakness. Such an interpretation would be in keeping with the more local tectonic relations as deduced by de Oliveira (1984) for the high-grade terranes mentioned above.

In contrast, the pink migmatites, which engulf the granulites to the northwest in many places, yield much younger ages corresponding to the 600–900 Ma Brazilian Cycle (DNPM, 1979). These migmatites have caused



GEOLOGICAL SKETCH MAP OF GUAXUPÉ MASSIF, MINAS GERAIS

Fig. 1. Geological sketch map of the Guaxupé Massif compiled and modified after Ebert (1976), and Departamento Nacional de Produção Mineral (1979). Lithological patterns generally represent predominance of the indicated rock type.
M-Machado, PA-Pouso Alegre, PC-Poços de Caldas, G-Guaxupé, SJP-São José do Rio Pardo, MG-Minas Gerais. (1) Archaean basement gneiss, (2) migmatites and gneisses of the Campos Gerais Complex, (3) migmatites-gneisses complex of the Guaxupé Massif, (4) granulite concentration, (5) amphibolite concentration, (6) banded biotite, hornblende gneisses and metasediments, (7) syenites, (8) pink potassic granites and migmatites, (9) Tertiary alkaline complex, (10) Palaeozoic formations, (11) general trend of gneissic foliation, (12) major faults, (13) possible faulted contacts and lithological boundaries.

retrogression of granulite facies rocks to amphibolite facies gneisses where the effects are intense, but are not encountered in the gneissic terrain. In spite of this, however, many outcrops preserve original granulite facies parageneses. The latter lithologies are frequently intercalations of quartzo-feldspathic and mafic granulites with intense isoclinal folding and transposition, similar in structure and attitude to folds in the grey tonalite–migmatite complex. Owing to breaks in continuity of exposures and lack of outcrops, however, these units cannot be strictly separated on large-scale maps as has been done recently by Schobbenhaus et al. (1984).

From field relations, we assume that the granulite facies gneisses belong to the older grey migmatite complex as they are not only conformable but also show the same folding styles, trends and transposition, whereas the pink migmatite units show clear discordant relation to the gneiss on an outcrop and regional scale. Though no gradual transition zones have so far been observed between the amphibolite facies grey tonalitic gneisses and the granulites facies gneisses, a case can be made for their equivalence since there in no structural break between them, and since they have similar modal (Fig. 2) and major-element compositions together with rare evidence for pro-grade metamorphism seen in the transformation of amphibole to pyroxene (Choudhuri et al., 1978). Theoretical considerations for such reactions are discussed by Choudhuri (1984), and we advocate the model adopted by Janardhan et al. (1979) for the granulite facies metamorphism which implies low mole fraction of H_2O in the fluid phase diluted by CO_2. The granulite facies rocks are thought to represent lower crustal units while the amphibolite facies occupying intermediate crustal levels are considered to have formed from calc-alkaline gneiss sequences similar to those analysed by de Oliveira (1973). Field and petrographic study clearly shows that the amphibolite facies grey gneisses are not products of retrogression of the granulites. On the other hand, outside the grey gneisses domain, where retrogression of granulites has occurred due to the late pink migmatites, the relationship is evident in the outcrops as diffuse remnants of the former surrounded by granitic material. Evidence of such effects is seen in thin-sections of granulites facies rocks.

Structural relations among the rocks provide evidence for a succession of deformation and intrusive events (Fiori and Choudhuri, 1981). The grey tonalites and migmatites as well as the granulite facies gneisses were subjected to at least three phases of deformation before the latter were affected by the pink potassic granitic injections which do not occur in the tonalite gneiss area. In the tonalites strong deformation along broad shear zones along major faults (Fig. 1) post-date other folding events and accentuate the banding of these banded grey gneisses. These grey gneisses are veined by granitic material and their migmatitic structures abut abruptly, although concordantly, against migmatic augen gneisses, which have yielded a Rb–Sr age of 1900 Ma from a quarry near the town of Pouso Alegre (DNPM, 1979). The tonalitic gneiss and compositionally similar granulite facies gneisses have been interpreted by de Oliveira (1982) as having been derived from calc-alkaline suites; preliminary U–Pb dating of zircons from the tonalitic migmatite gave ages around 2700 Ma (M.A.F. de Oliveira, personal communication, 1985). The augen gneisses in turn are at places discordantly cut by leucotrondhjemitic gneiss, so that a sequence of events can be established for the migmatite complex. We assume therefore that the 1900 Ma Trans-Amazonic age represents the remobilization and migmatization of the grey gneisses during which the augen gneisses were emplaced as syntectonic concordant bodies in the basement gneiss.

Amphibolite facies gneisses

The main rock types of the amphibolite facies grey gneisses are hornblende tonalite and biotite — hornblende tonalite grading into trondhjemite and granodioritic types which occur in

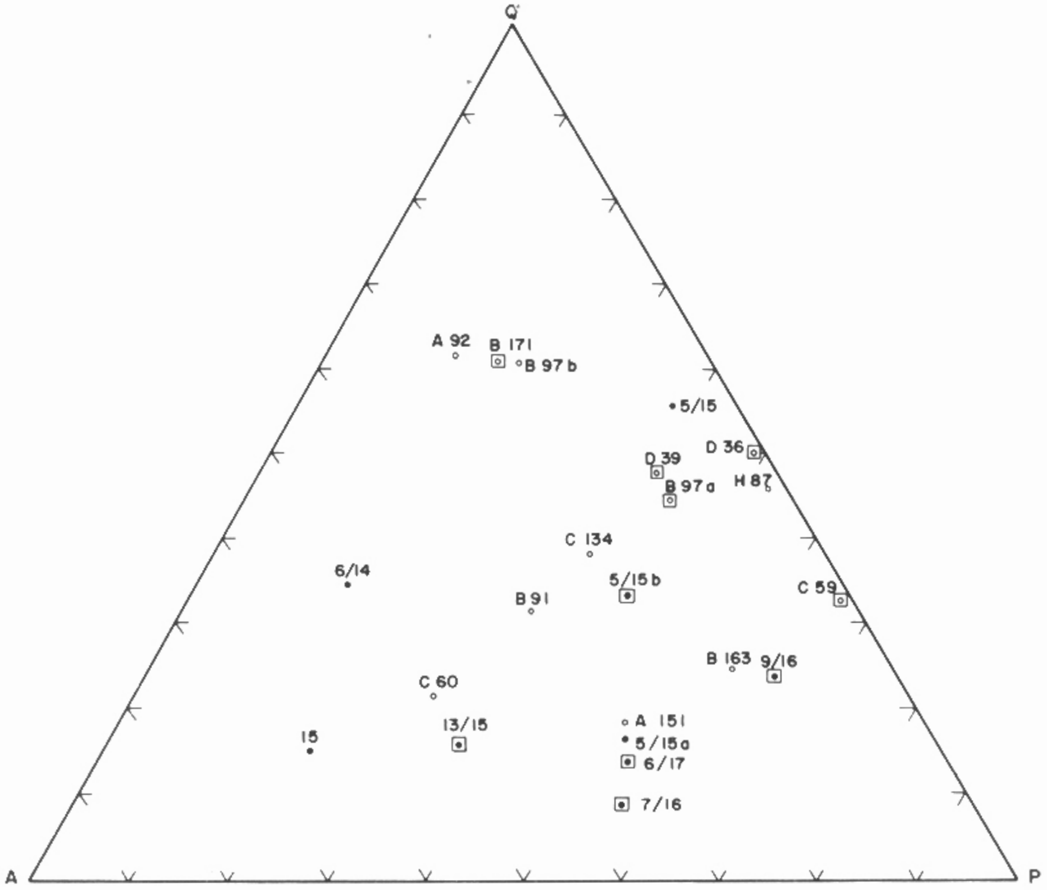


Fig. 2. Modal proportions of quartz and feldspars in amphibolite (○) and granulite facies gneisses (●). Samples analysed chemically are marked in squares.

minor amounts. Banded migmatitic structures, often with complex folding, are common in these gneisses, and the banding consists of mafic and quartz–feldspar-rich portions. At places, lenses of amphibolite and/or hornblende-rich bands are common, of the order of some metres or tens of metres, while in the more leucocratic rocks smaller mafic schlieren can be seen imparting a conspicuous foliation to these gneisses. Rare autoliths of hornblende tonalite also occur in a migmatite matrix. Large massive metabasic bodies several hundred metres wide occur in some of the outcrops and have been interpreted as differentiated sills that were metamorphosed and folded with the country-rock gneiss (Choudhuri and Szabo, 1982); in some of these, compositional banding probably represents relict igneous layering.

A second rock type in the gneiss complex is a grey augen gneiss which is typically coarse grained with megacrysts of microcline drawn out into augens and sometimes smeared out, the latter feature being common in the migmatitic types. Here also occasional mafic schlieren are enclosed in the main gneiss. These augen gneisses are porphyritic hornblende–biotite granodiorites emplaced in the basement grey gneisses during the Trans-Amazonic event, as mentioned above. In the gneissic complex as a whole, relatively homogeneous leucocratic non-porphyritic granitic gneisses are much less common.

Petrography

The tonalitic gneisses consist of mainly pale green to pale olive-green hornblende, calcic oligoclase and quartz; where migmatization is prominent with separation of quartz-feldspathic neosome, biotite comes in as a potassic phase, often replacing hornblendes along margins and cleavages. Potash feldspar is rare or totally absent in most rocks and occurs subordinately in the more granodioritic types. Where microcline occurs, it is neoformation and interstitial to the main mineralogy and is accompanied by the appearance of cross-cutting late biotite. Except for extremely rare xenoliths of scapolite–diopside–silicate gneiss, nowhere in the field or in the more than 100 thin-sections examined is there evidence that the gneisses retrogressed from granulite facies. Rather, the neoformation of microcline and biotite is taken to be coincident with the Trans-Amazonic event with which the emplacement of the augen gneisses was apparently synchronous. Common accessory minerals are zircon, allanite, sphene, apatite and ore minerals. In general, the majority of these rocks are granoblastic with marked orientation of mafic minerals, either individually or in aggregates and clots.

The augen gneisses contain megacrysts of microclines set in a matrix of oligoclase, quartz, hornblende and biotite with accessory epidote, zircon and apatite. It is interesting to note that these rocks are apparently iron-rich as can be deduced from the much darker green hornblendes and dark brown biotites compared with those in the tonalites. Thin sections of rocks from the main fault zone show strong cataclastic texture which was later annealed and recrystallized. These augen gneisses show no signs of having retrogressed from granulite facies; rather, massive charnockitic augen gneisses occur among the granulite facies gneisses, and may have been similarly emplaced during or before granulite facies metamorphism, although no gradation between the respective augen gneisses has yet been observed.

Granulite facies gneisses

Rocks of the granulite facies are mainly charnockitic gneisses, enderbitic gneisses and mafic granulites, the latter types being more common. Besides the relatively homogeneous and granular variety, there are also charnockitic augen gneisses, but their relation to the others is not yet clear. Minor amounts of sillimanite–garnet quartzites and gneisses occur locally.

A conspicuous feature of these rocks in the field is their banded character with alternation of light and dark bands discernable in spite of their overall dark colour. This gneissic banding is also marked by the orientation of mafic minerals and shows complex folding styles and transposition similar to those observed in the amphibolite facies gneisses. As a result, except for their darker colours and diagnostic mineralogy, there is hardly any difference. Sometimes the dark and light banding has a diffuse anatectic aspect with schlieren of mafic portions, and rarely there are leucocratic, but still dark-coloured, charnockitic veins cross-cutting mafic granulite. Such migmatitic features are infrequent compared with the amphibolite facies gneisses; or if they had been more common, they were probably obliterated or masked by strong deformation and transposition. Thin sections often show effects of cataclastic deformation and flattening of quartz in the more felsic varieties, and it is evident that this kind of deformation took place after the formation of the granulite facies paragenesis. In general, in fresh road-cuts three folding phases can be separated, and these structures are discordantly enclosed by pink granitic material of the potassic migmatites which itself may or may not be transposed.

Petrography

The granulites are essentially made up of hypersthene, diopsidic clinopyroxene, hornblende, plagioclase, alkali feldspar and quartz in varying proportions depending on the rock type. Modal compositions vary from quartz diorite to granitic types with the exception of the mafic granulites. Biotite is rare or absent in these assemblages, but becomes a common late mineral replacing hornblende and pyroxene where retrograde effects caused by the pink migmatite are intense. In such cases only relics of granulite mineralogy are observed in thin-sections.

Granoblastic textures typical of high-grade rocks are a common feature of these granulites. In the quartz-rich felsic granulites quartz occurs as flattened elongated grains, whereas it is an interstitial mineral in the intermediate and mafic varieties. Plagioclase is generally granoblastic and varies from oligoclase to labradorite from felsic to mafic rocks. Grey alkali feldspar in the charnockitic gneisses is orthoclase perthite or mesoperthite and occurs as megacrysts as well as in the matrix of the augen gneiss.

Pink pleochroic hypersthene and pale green clinopyroxene occur as anhedral grains frequently intimately intergrown, accompanied by olive-green hornblende in stable association in mafic granulite. In some of the charnockitic gneisses garnet occurs as a reaction between plagioclase and hypersthene and nucleates as small anhedral grains.

Analytical techniques

The analytical techniques used were X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA). Trace elements other than U and Th were determined by XRF on pressed pellets of rock powders; the method used is that of Reynolds (1963, 1967). Iron and potassium were determined using the calibration curves developed for USGS rock standards. The precision and accuracy of the methods are of the order of ~5%. Concentrations of U and Th were determined by INAA the details which are described in Iyer et al. (1984). The precision and accuracy of the method are of the order of 1–2%.

Geochemical composition

Statistical comparison

Table I presents the geochemical data for the granulites and the amphibolite facies rocks from the region. The table shows the range of values and the standard deviation for each element. The individual values of the rock samples are given in Fernandes (1982) and can be obtained from the author on request.

Table I shows that the K–Rb ratios in the granulites are in the range of 300–600, whereas the amphibolite facies rocks display a wide range of ratio values (90–518) and many of the ratios are lower (Fig. 3). This behaviour of K–Rb is due to the lower abundance of Rb in the granulites. In the Proterozoic amphibolite–granulite transition zone in Norway, Field and Clough (1976) observed a similar behaviour which was interpreted by them as depletion of Rb during highest grade metamorphism. The average K–Rb ratios of the Guaxupé Massif are compared with the values from granulites (meta-igneous) from other parts of Brazil (Table II).

From the table it can be seen that the average K–Rb value for the Guaxupé granulites is, in general, high compared with other granulite facies rocks, except that of Itabuna Complex in Bahia. Rudnick et al. (1985) argued that, although K–Rb ratios for granulites with $K > 1\%$ appear to require no metamorphic effect to explain their ratios, a study of individual terrains and the fact that the majority of granulites have K–Rb ratios above the Main Trend reveal an average increase of K–Rb ratio by a factor of 1.3 attributable to granulite facies metamorphism. They observed that Archaean granulites form greatest proportions of rocks with high K–Rb ratios. In Brazil, the average Archaean granulites of Bahia show higher K–Rb ratios compared with other Proterozoic granulites.

The Rb–Sr distribution plot (Fig. 4) shows that the Rb–Sr values for the amphibolite and

TABLE I

Chemical composition, elemental ratio of granulites and amphibolite facies rocks from Maciço de Guaxupé

	Gneisses (amphibolite facies)					Granulites				
	$\bar{X}$	Max	Min	S	N	$\bar{X}$	Max	Min	S	N
K_2O	4.01	5.88	1.29	1.26	16	2.90	5.60	0.67	1.71	12
Fe_t	5.55	10.23	2.81	2.13	16	6.33	12.40	4.14	2.46	12
Rb	155	248	17	53	16	70	124	24.5	35	10
Sr	271	505	117	105	16	337	826	119	200	12
Nb	53	97	19	23	16	52	139	< 8	38	11
Zr	521	1072	89	304	16	525	1355	45	435	12
Cu	47	62	40	6	16	36	55	26	8	12
Ni	25	36	13	7	16	19	29	7	7	11
Zn	123	204	53	44	16	119	236	25	53	12
U	1.4	3.2	< 0.5	0.8	16	1.5	4.9	< 0.5	1.5	12
Th	5.5	20.0	< 0.2	5.9	16	2.0	7.3	< 0.2	2.3	12
K-Rb	385	1518	90	327	16	421	615	302	105	10
Rb-Sr	0.55	2.12	0.10	0.51	16	0.30	0.63	0.06	0.23	10
Th-U	4.24	12.15	0.27	4.21	14	1.68	3.00	< 0.29	1.19	12
Cu-Ni	1.99	3.69	1.26	0.58	16	2.07	4.29	1.12	0.90	11

K_2O and Fe_t in %, Rb, Sr, etc in ppm.
$\bar{X}$ = mean; max = maximum; min = minimum; S = standard deviation; N = number of samples.

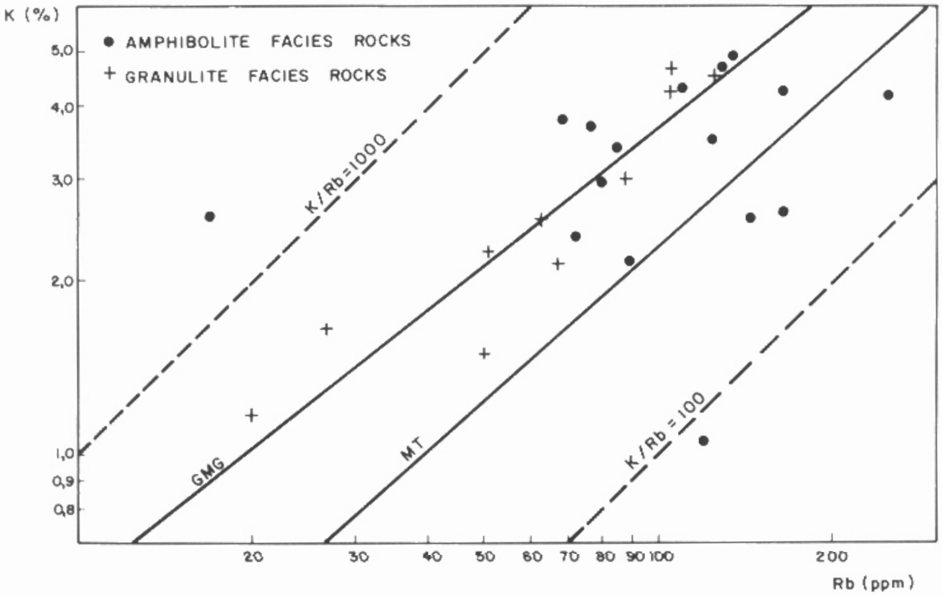


Fig. 3. K-Rb distribution plot for the granulite and the amphibolite facies gneisses of Guaxupé Massif. MT-Main Trend, GMG-Guaxupé Massif Granulites.

the granulite facies rocks of Guaxupé Massif overlap unlike those of the Lewisian Complex, where the Rb–Sr values for most granulites are below 0.02 and the amphibolites show an average ratio of 0.2 (Tarney and Windley, 1977).

The Rb–Sr values for granulite facies rocks from other parts of Brazil show that they are variable from 0.04 to 2.9. The highest values are

TABLE II

Trace element concentration of some granulite facies rocks of Brazil

	1	2	3	4	5	6	7	8
K_2O	2.90	2.28	2.78	5.07	2.42	0.40	0.5	5.9
Fe tot	6.33	7.82	3.53	15.0			8.32	
Rb	70	46	57	161	81	24	21	147
Sr	337	543	481	160	373	480	5	99
Nb	52	–	–	13	–	26	–	–
Zr	525	222	255	430	234	159	47	–
Cu	36	39	–	21	–	64	39	–
Ni	19	–	7	3.7	–	80	101	–
Zn	119	94	–	32	–	–	–	–
U	1.5	1.02	–	42	–	–	< 1	1.8
Th	20	18.54	–	26	–	–	–	14
K/Rb	421	626	405	307	324	253	194	330
Rb/Sr	0.3	0.094	0.12	2.4	0.3	0.05	0.04	2.9
Th/U	1.68	16.2	–	8.3	–	–	–	–
radiogenic W m^{-3} heat production	0.81	1.89	0.78	2.7	–	–	–	–

1. Granulites of Maciço Guaxupé (this work).
2. Granulites of Itaberaba, Bahia (Sighinolfi, 1971; Sighinolfi and Sakai, 1977).
3. Granulites of Caraiba complex Bahia (Figueiredo, 1980).
4. Granulites of Jequié (Cordani and Iyer, 1979; Sighinolfi et al., 1981; Iyer et al., 1984).
5. Granulites of Paraiba do Sul belt (de Oliveira, 1982).
6. Granulites of Luis Alves Craton (Kaul and Teixeira, 1982).
7. Granulites of Rio Grande do Sul (Nardi and Hartman, 1980).
8. Charnockites of São Paulo State (Gasparini and Mantovani, 1979).

associated with the lower Sr content in charnockitic rocks having relatively greater amounts of microcline than plagioclase.

The U and Th values in the granulites and the amphibolite facies rocks are low probably due to the very low abundances of the radioactive accessory minerals like zircon, apatite etc. The spread in the Th–U values in the granulites (0.3–3.0) and the granitic gneisses (0.3–12.15) can be attributed to the larger variation in Th values. A comparison of U and Th values of the granulites of the Guaxupé Massif with similar granulites from other parts (Table II) show that, in general, basic meta-igneous rocks present low U and Th contents similar to non-metamorphic low K tholeiites (Barbey and Cuney, 1982, fig. 3).

Dostal and Capedri (1978) studied the distribution of uranium in metamorphic rocks by the fission track method and concluded that in amphibolite facies rocks, in general, U is mainly concentrated along the fractures, margins and cleavage planes of mainly ferromagnesian minerals and in accessory minerals (apatite, zircon, sphene, rutile), while in granulites U is concentrated mainly in accessory minerals. Their study showed that in amphibolite the bulk of the U (50–60%) is concentrated along cleavage planes, fractures and margins mainly of amphibole. In the area we studied the bulk U concentration in the granulites and the amphibolite facies rocks are of the same order.

A comparison of the Cu, Ni and Zn values in the two rock types show that the Cu and Ni values are slightly higher in the amphibolite facies rocks compared with the granulites. A comparison of the average Cu, Zn, Ni values with the

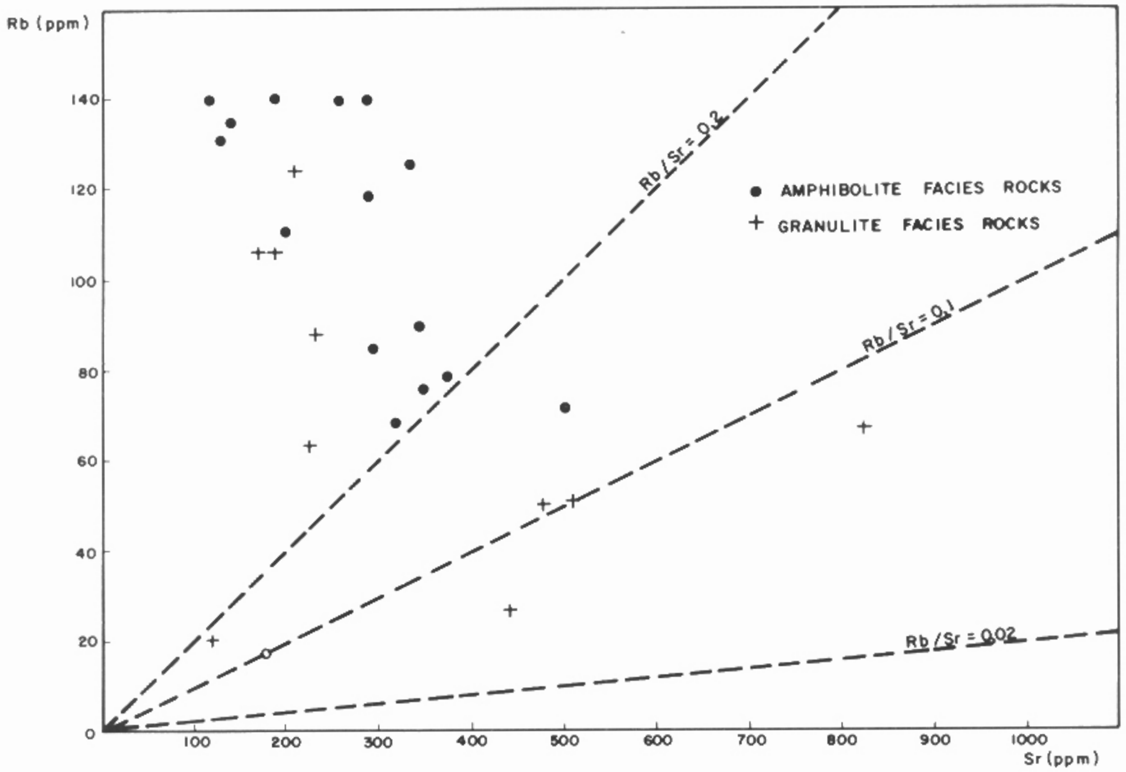


Fig. 4. Rb–Sr distribution plot for the granulite and amphibolite facies rocks of Guaxupé Massif.

granulites of other regions shows that the values are of the same order.

Lile fractionation

The nature and the extent of the LILE fractionation during high grade metamorphism are investigated by comparing the K–Rb and Th–U ratios in the two types of the Guaxupé Massif.

The K–Rb data of the rock types are shown in Fig. 3 from which the following observations can be made.

(1) For the granulites, the plot of K (%) vs. Rb (ppm) is approximately linear, but the data points for the amphibolite facies rocks show a scatter as a consequence of their migmatitic nature and variable amounts of granitic neosome.

(2) There is a considerable overlap of data points.

Generally K–Rb distribution in the igneous and metamorphic rocks are analysed following the method of Shaw (1968), who defined K–Rb fractionation trend for igneous rocks (Main Trend). Various authors have proposed different trends supposed to characterize high grade metamorphic terranes (Sighinolfi, 1971; Lewis and Spooner, 1973; Collerson, 1975; Field and Clough, 1976). According to Barbey and Cuney (1982) such trend lines can be interpreted as mixing lines based on the weighted average of the different K–Rb ratios of mineral constituents of the rock rather than on the nature of the metamorphism.

Table III (Fig. 3) shows the results of the analyses of the K–Rb data for the granulites and the amphibolite facies rocks of the Guaxupé Massif. The correlation coefficient for the linear regression equation for the amphibolite facies rocks is low, while the data for the granulites are well correlated. The spread in the K–Rb ratios in the amphibolite facies rocks may

TABLE III

Summary of statistical analysis of K-Rb (covariance)

	n	*r*	*a*	*b*
Main Trend (Shaw, 1968)	–	–	1.115	1.597
Granulite and amphibolite facies metabasites Norway (Field and Clough, 1976)	181	0.884	1.770	1.446
Charnockite Suite-Brazilian Shield (Sighinolfi, 1977)	62	0.930	1.433	1.196
Granulites of Luis Alves (Kaul and Teixeira, 1982)	10	0.939	0.491	1.06
Granulites facies rocks from Escudo Sulriograndense - Brazil (Nardi and Hartman, 1980)	12	0.898	0.791	1.631
Gneisses granulite facies rocks from Caraíba Complex - Brazil (Figueiredo, 1980)	21	0.851	1.775	1.045
Granulite facies rocks from Paraíba do Sul Brazil (de Oliveira, 1982)	26	0.620	1.039	1.580
Granulite facies rocks from Jequié - Brazil (Iyer et al., 1984; Sighinolfi et al., 1981)	51	0.835	2.152	0.140
Granulite facies rocks from Maciço de Guaxupé - Brazil (This work)	16	0.928	1.252	1.287
Amphibolite facies rocks from Maciço de Guaxupé - Brazil (This work)	16	0.217	3.725	0.153

n = number of samples.
r = correlation coefficient.
a = slope.
c = intercept.

be due to the varying modal proportions of the potassium-bearing minerals, namely K-feldspar and biotite. K-feldspar in general has high K–Rb ratios, whereas K–Rb ratios in biotite are lower. In granulites the potassic phase in general is K-feldspar. Small amounts of biotite may be present due to retrograde effects subsequent to later migmatization.

Recently Rudnick et al. (1985) have suggested that the high K–Rb ratios on granulites with $K > 1\%$ are mainly due to the presence of K-feldspar which has a $K_D{}^{Rb}$ value close to, but below one (~ 0.8). Thus, if an originally Rb-poor aqueous fluid equilibrates with K-feldspar, it lowers the Rb content of the rock and increases K–Rb ratio slightly.

Table III shows a summary of the statistical analysis of K–Rb data on granulites from various parts of Brazil. A similar table for rock types for other parts of the world was compiled by Barbey and Cuney (1982). The table seems to confirm the interpretation of Barbey and Cuney that the various trend lines are nothing but mixing lines based on the weighted average of the different K–Rb ratios corresponding to each mineral species. Table III also shows that basic and meta-igneous granulites in general show types of K–Rb distribution pattern, one group having lower ratios, where the slope of the regression line is nearer unity and the other group having higher ratios. These distribution patterns may be explained as due to the result of the complete or partial rehomogenization of the K–Rb ratios among different rock types (sediments, volcanics, plutonics, etc) of the area which underwent prograde metamorphism. The major factor controlling the frationation is the composition and nature of the fluid that participated in the reaction prohibiting or promoting the growth of the OH bearing minerals in the rocks (Glassley, 1983).

The U, Th concentrations and the Th–U

ratios in the granulite and amphibolite facies rocks have been analysed by various investigators. The regional depletion of uranium during high-grade metamorphism was first pointed out by Heier and Adams (1965) and many investigators seem to have observed the process in Canada (Fahrig et al., 1967), Norway (Heier and Thorensen, 1971), Brazil (Sighinolfi and Sakai, 1977) and India (Iyer and Kutty, 1978). Possibly the process is better understood by lead isotopic studies (Moorbath and Welke, 1969; Gray and Oversby, 1972). However, some granulite facies rocks do not seem to have suffered depletion of uranium (Wilson, 1978; Iyer et al., 1984) and in many Archaean gneisses the depletion of uranium has been observed in both amphibolite and granulite facies rocks (Moorbath and Welke, 1969; Moorbath, 1976; Lambert et al., 1976).

The mobility of uranium is controlled by the nature of the site of the uranium and its solubility in metamorphic fluid, which in turn depends on $f0_2$, aH^+, nature and concentration of the complexing agent, temperature and the relative volume of fluid that passed through the rocks. Barbey and Cuney (1982)pointed out that high Th–U ratios are typical of metasedimentary granulites because of the selective but nonsystematic loss of uranium.

According to Rudnick et al. (1985) the degree of the U and Th depletion will depend on the position of U and Th in the protolith, the presence of fluid phase and the stability of various accessory phases during granulite facies metamorphism.

The U, Th contents of the granitic gneisses and the granulites of the Guaxupé Massif are similar to the meta-igneous granulites and their Th–U values are low and closer to mean crustal values of Shaw (1967). The U, Th distribution appears to be a characteristic primary feature of the rock types.

The distribution of radioactive elements in the high-grade metamorphic rocks has important implications for the geophysical modelling of the continental crust (Smithson and Brown, 1977: Allis, 1979; Haack, 1983) because the thermal modelling of the lower crust uses radiogenic heat production values in the amphibolite and granulite facies rocks. In these models the radioelement distribution and its attendant heat production values that are used assume the depleted nature of the radioactive elements during high-grade metamorphism. For example, Haack (1983) assumed an average value of 0.721 μW m^{-3} for granulites in general, based on an average of 0.815 μW m^{-3} for acid granulites and 0.336 μW m^{-3} for basic granulites.

The radiogenic heat production values from various granulite terranes show a large spread in the value of 0.81–2.3 μW m^{-3} (in Guaxupé the calculated value is 0.8 μW m^{-3}). A large spread may be the result of the complex nature of the fractionation of radioactive elements, especially U, during high-grade metamorphism. Further, based on geological, geophysical and geochemical considerations Smithson and Brown (1977) showed that the lower crust is heterogeneous on all scales; probably similar to many granulite terranes. Hence the term mean composition should be used for specific areas.

Discussion and conclusion

The type of elemental fractionation occurring during high grade metamorphism is complex and not all granulite facies rocks suffer total fractionation of LILE. Earliest work in this regard was that of Moine et al. (1972) who observed no significant major chemical changes at the amphibolite–granulite at the Bamble sector, Norway. Their study indicated that the chemical pattern is to a large extent inherited. Recently many granulite terranes from different continents have been reported which show the non-fractionated character of LILE. They include granulites from Strangways Range and Fraser Range of Australia (Iyer, 1974; Woodford, 1974; Wilson, 1978; Allen, 1979), Poland, Central Europe (Tarney and Windley, 1977), Saxonia, Tovqussap West Greenland (Rollinson and Windley, 1980), Tanzania (Coolen, 1980), Jequié, Brazil (Iyer et al., 1984).

The interesting feature of the geochemical data from the granulite facies rocks of Brazil is that many of them have LILE concentration which may be considered 'normal' or 'undepleted'. From many other areas complete chemical data are not available, but from geochronological (Rb–Sr) data it appears that 'undepleted' granulites are more frequent (U.G. Cordani, personal communication, 1986). It has to be pointed out that data on U and Th from granulites of Brazil are few and hopefully future lead isotope studies in these areas may shed more light on the depletion of U and Th.

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