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INVESTIGATIONS INTO THE DEEP LEVELS OF THE CONTINENTAL CRUST: PETROLOGY AND CHEMISTRY OF THE GRANULITE FACIES TERRAINS OF BAHIA (BRAZIL)

Summary — Petrographic and chemical data on the Brazilian Precambrian crystalline basement in the southern part of Bahia are given. Major elements, the trace elements Li, Rb, Sr, Ba, Cr, Cu, Zn, Y, Zr, Nb and some element ratios relative to 62 rock samples were determined; averages and relative standard deviation data are also reported. The basement area studied consists of granulite terranes. Their more widespread mineralogical associations and their chemically « intermediate » character indicate that these terranes are typical of medium- to high-pressure granulite facies. These granulitic rocks are relatively uncommon at the earth's surface and are probably formed at considerable depth in the continental crust. Thus this material is of great value in any investigation of the evolution of the earth's crust. Comparative data relative to granulite terranes of different shields (Australian and Canadian) are also reported.

INTRODUCTION

The study of the composition of the material from the deepest crustal levels is at present of great relevance in the investigation of the thermal hystory and the evolutive processes of the earth's crust. It is generally held that the metamorphic regional event, intimately associated with orogenies and accompanied by partial melting of geosynclinal and basement rocks, may affect the composition of the continental crust: at least a vertical chemical zoning of it could result (see the review by WEDEPHOL [1969], on the earth's crust).

As indicated by geophysical measurements (GREEN, LAMBERT

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[1965]; RINGWOOD, GREEN [1966]) and by experimental data (GREEN, RINGWOOD [1967]), a dominance of essemblages of anhydrous granulite facies exhibiting appropriate mineralogical and chemical features must result in the deep crust.

The view currently held by many authors (e.g. HEIER, ADAMS [1965]; HEIER [1965]; LAMBERT, HEIER [1968]) is that granulite facies terranes containing medium- to high-pressure mineral assemblages may be regarded as a material representative of the deeper crustal levels available to any area extent on the earth's surface.

The present work reports the results of petrographic and chemical investigations into high-grade metamorphic terranes belonging to the Brazilian shield and situated in Bahia State. The objects of this study are:

1) to arrive at a deeper understanding (based on petrographic and chemical data) of the Brazilian crystalline basament, hitherto relatively unknown;

2) to estimate the average chemical composition of a number of granulite facies terranes and subsequently of a part of the Precambrian shield in the Bahia area, thereby contributing towards an understanding of the composition of the lower continental crust;

3) to define the rate of fractioning of elements and element ratios due to regional metamorphic processes;

4) to confirm at least the proposed chemical crustal zoning and hence to strengthen the hypothesis of a continual crustal evolution.

This paper deals only with petrographic descriptions and chemical data (comprising averages and relative standard deviation data); a discussion of the results will be conducted in a following paper.

GENERAL FEATURES OF THE CRYSTALLINE BASEMENT IN THE BAHIA AREA

It is known that the Brazilian Precambrian complex is characterized by a great variety of crystalline rocks among which gneisses and migmatites are predominant. It is also well known

that metamorphic rocks typical of the granulite facies are extensively associated with these lithotypes. These granulitic terrains outcrop in a wide area ranging right from the Amazon region to the extreme southern part of the Brazilian shield (Rio Grande do Sul); they are particularly well represented in Bahia State.

A short petrographic description of crystalline basement rocks outcropping in the southern part of Bahia is given by ALLARD [1963] and by DE CARVALHO [1965]. They observe that the Precambrian undifferentiated crystalline complex in this area consists predominantly of metamorphic rocks (gneiss and granulites) with which basic rocks (amphibolites and gabbros) and partially metamorphosed diabasic dikes are associated. A similar lithologic association has recently been observed by FUJIMORI [1968] in the Salvador range, about 300 km N of the area considered in this paper. In one very limited area the author recognized some distinct granulitic assemblages belonging to a typical charnockite series which consisted of strictly alternating rocks ranging in composition from acid to basic.

FUJIMORI [1968] proposes a sedimentary sequence in which arenitic-arkosic types predominate as a possible starting material for these rocks.

Observations on the crystalline basament reveal, furthermore, the widespread occurrence of alkali rocks forming intrusion-like bodies in the metamorphic terranes. Recently FUJIMORI [1969] described some alkalic bodies of different composition from the south of Bahia State, near the area investigated here. As a possible genesis for these rocks he proposes a partial melting of a sedimentary sequence characterized by alternating evaporitic deposits and pelitic rocks, which underwent conditions of ultrametamorphism.

Age determinations on rocks of the crystalline basement in the western part of the Bahia area (S. Francisco craton), carried out by CORDANI et al. [1967] and also cited by TUGARINOV [1967], give 1900-2100 m.y.. More recently CORDANI et al. [1969] gave new age data on metamorphic rocks from the extreme eastern part of Bahia and on samples belonging to the same area investigated in this study; the results confirm an absolute age of 1900-2100 m.y.. For this reason it seems very likely that the cratonic area of Western Bahia spans eastward as far as the Atlantic seacoast.

Age determinations on some alkaline intrusion of Southern Bahia indicate that these rocks are about 770 m.y. old.

GEOLOGICAL SETTING AND CHARACTERISTICS OF THE AREA INVESTIGATED

The rock samples were collected from an area of some 13.000 square kilometres situated about 300 km south of Salvador (see Fig. 1). To the east this area includes about 130 km of the Atlantic seacoast (including the towns of Itacaré, Ilheus and Una); to the west it stretches for about 100 km as far as S. Cruz da Vitoria. Soil cover due to weathering or sedimentary deposits of limited thickness are locally abundant. Nevertheless well-exposed Precambrian basement terrains occur everywhere and they permit good petrographic observations.

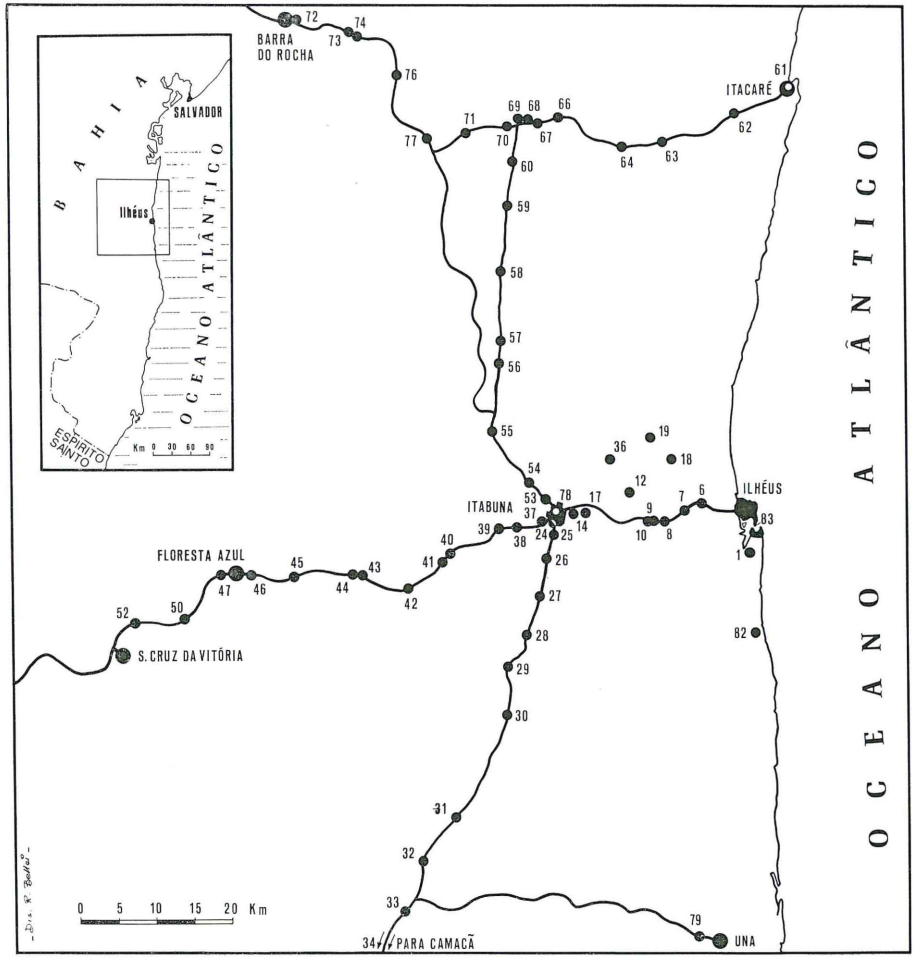

Fig. 1 - Sample collection points in the area investigated.

There is no detailed geological mapping of this region or of the surrounding areas available, but only some unpublished partial reconnaissance mapping, carried out by workers of the Federal University of Bahia. The geological and petrographic features of this area are therefore largely unfamiliar; sufficient is known, however, to enable certain purposes to be pursued in the collecting of samples.

Generally, the well-exposed rocks are remarkably fresh, particularly in the outcrops near the Atlantic seacoast. The Precambrian crystalline complex appears to consist of a high- grade metamorphic sequence formed by banded granulites, fine- to medium-grained, which sometimes exhibit a faint irregular gneissosity. The granulites have the almost greasy lustre and dark bluish-grey or olive-brown colour typical of this group of rocks. Macroscopically the quartz usually appears light greyish-blue or olive-brown in colour and the felspar greenish-yellow. Basic rocks of amphibolitic and gabbroic types, normally medium- to coarse-grained, appear to be interlayered between the banded granulite complex. In an area situated between Itabuna and Ilheus they form a intrusive-like body, extending NE-SW and showing at the borders some anorthositic well-interlayered rocks which may grade along the strike into amphibolites. Little outcrops of very coarse-grained alkali rocks (normally nepheline syenites) are widespread in the basic body. Diabasic dikes, discordant or not with banding or the gneissosity of the granulites, are everywhere present; their mutual intersections act as supports for different, successive generations.

A calcareous-silicate rock outcrops in the north of the area, near the locality of Barra do Rocha; its mineralogical assemblage consists of calcite, quartz, diopside, scapolite and epidote. Its contact with the surrounding granulites is unexposed, therefore it is impossible to know wheter the rock constitutes a marble layer, a lens or a band. Ultramafic rocks were not discovered over the whole area investigated.

According to field estimate the metamorphic terranes of granulite facies definitely account for more than 80% of the total area of exposed rocks. The present work deals only with these granulitic rocks, and not with basic and alkali bodies, relations of which to the metamorphic sequence are not yet well understood. The present data, therefore, do not provide a direct estimate of the bulk crystalline basement composition, although they do refer to more than 80% of it.

The bedrock samples derive from a semi-systematic array of collection points on the basis on field observations. A special effort was made to collect the rock samples as far as possible in the proportions in which they occur on the surface; the average composition thus obtained may well be considered representative for the exposed granulitic rocks. 62 rocks considered to be the most representative on the basis of petrographic and field observations were selected from a large number of collected samples and analyzed for the major and some trace elements. The collection points are shown on the sketch map of Figure. 1.

Petrographic description of the metamorphic terranes

The metamorphic rocks in this part of the basement show various and complex mineralogical associations: taking into account the most representative and critical paragenesis they are grouped as follows.

A) Plagioclase-orthopyroxene-clinopyroxene-quartz-perthites (anti-meso-cryptoperthites)-(biotite and hornblende).
This paragenesis is presented by the most of the samples (31). They are: Il 1, Il 8, Il 9, Il 18, Il 24, Il 25, Il 26, Il 27, Il 29, Il 31, Il 42, Il 44, Il 50, Il 53, Il 55, Il 56, Il 57, Il 58, Il 59, Il 62, Il 66, Il 67, Il 68, Il 70, Il 71, Il 72, Il 73, Il 76, Il 77, Il 78, Il 83.

B) Plagioclase-clinopyroxene-quartz-perthites.
This is shown only by two samples: Il 61 and Il 69.

C) Plagioclase-orthopyroxene-clinopyroxene-quartz-perthitic orthoclase-garnet-(biotite and hornblende).
Here are grouped samples exhibiting variable and complex mineral assemblages. The common feature is the presence of garnet. The samples (6) are: Il 6, Il 28, Il 43, Il 60, Il 63, Il 74.

D) Plagioclase-orthopyroxene-clinopyroxene-quartz-biotite-hornblende.
The main feature is the presence of noticeable amounts of biotite and/or hornblende. The samples (17) are: Il 7, Il 10, Il 12, Il 19, Il 30, Il 32, Il 33, Il 36, Il 39, Il 40, Il 41, Il 45, Il 46, Il 47, Il 54, Il 64, Il 82.

E) Plagioclase-clinopyroxene-hornblende-orthoclase-quartz-(biotite).
Orthoclase is present in great amounts. Samples: Il 34 and Il 52.

F) Plagioclase-biotite-amphibole-quartz.
Two samples belong to this group: Il 79 shows hornblende and Il 38 tremolitic amphibole and scapolite.

G) Plagioclase (largely predominant)-clinopyroxene-hornblende-(epidote).
The great abundance of a calcic plagioclase accounts for the typical anorthosite composition of samples Il 14 and Il 17.

A constant textural feature of the granulites is the even grain of the constituents. In thin section the quartz shows evidence of strain and frequently appears in myrmekitic association with plagioclase. The plagioclase frequently is meso- or anti-perthitic with the irregular blebs of potash felspar regularly orientated in the crystals. Its composition is extremely variable, depending on the rock composition, and ranges from An_{25} to $An_{65, 70}$. An augitic pyroxene is the most prominent mafic constituent accompanied by subordinate amounts of strongly pleochroic orthopyroxene. Textural relations between ortho- and clinopyroxene show that they seem to be syngenetic.

Both the pyroxenes frequently have frayed rims and are surrounded by reaction rims, normally consisting of hornblende and biotite (and in two samples of garnet too). The potash felspar is strongly perthitic. Reddish-brown biotite and olive-brown hornblende are normally present in small amounts, but sometimes they may be the prevalent mafic mineral, as in the case of the samples belonging to paragenesis D. Generally biotite and hornblende clearly seem to form from the transformation of pyroxenes.

The above-described reaction rims and the occurrence of some evident structural relicts clearly indicate that the basement complex has undergone a number of metamorphic cycles.

The general features of the granulite sequence allow it to be classified as a typical charnockite series, whose characteristics and compositional complexities were recently pointed out by DE LA ROCHE [1967].

As is well known, granulite facies terranes can be classified as low-, medium- and high-pressure terranes on the basis of certain critical associations. Following the current interpretations (e.g. LAMBERT, HEIER [1967] and GREEN, RINGWOOD [1967]) the anhydrous plagioclase-orthopyroxene-clinopyroxene-quartz association, accompanied by an « intermediate » chemical composition of the rock, characterizes the medium-pressure granulite facies. At increasing

pressure the garnet-orthopyroxene-clinopyroxene-plagioclase association would develop, albeit at a rate depending on the rock composition (RINGWOOD, GREEN [1964]; GREEN, LAMBERT [1965]; etc.). The anhydrous mineralogical association, largely predominant in the studied area, indicates therefore that these granulites were formed under conditions of medium to high pressure and, of course, of low water pressure. The sporadic occurrence of garnet in this context does not seem to be easy to interpret; sometimes its development in the anhydrous association seems to indicate an effective local increase in the pressure gradient, at other times it appears to be syngenetic with the hydrous phases.

Biotite and hornblende, which are mere accessories in typical anhydrous association, are present in remarkable amounts in one group of samples. Hydrous minerals in granulite facies are normally indicative of low pressure conditions, but the development of biotite or hornblende can also be caused by other factors. Where metamorphism, for instance, takes place at slightly higher water pressure the assemblages are affected by the development of such minerals. Regression reactions can also cause development of hydrous phases in high metamorphic rocks. In our case biotite and hornblende reaction rims surrounding pyroxenes clearly indicate that they, for the most part least, are due to a retrometamorphic episode, probably accompanied by metasomatic phenomena. The retrogression of granulite facies regions is fairly common (HEPWORTH [1964]).

Systematic observations of the mineral associations at different points throughout the area do not reveal regular variations in the intensity of the retrometamorphic episode. However many samples from the western part of the area show evidence of a major rate of formation of hydrous minerals from pyroxenes, which remain sometimes only as relicts.

CHEMICAL DATA

Data relative to the major elements and to the trace elements Li, Rb, Sr, Ba, Cr, Cu, Zn, Y, Zr and Nb are reported in Table 1. In the same Table the average contents, the relative standard deviation for each element and some important element ratios are re-

ported. On the basis of the chemical composition, which of course reflects the relative proportions of ferromagnesian minerals, we can divide the granulitic rocks into acid, sub-acid, intermediate and basic groups. Subdividing them as suggested by LAMBERT, HEIER [1968], these groups are seen to correspond roughly to the following SiO_2 ranges: acid $> 70\%$, sub-acid 65 to 70%, intermediate 55 to 65% and basic $< 55\%$.

Accepting this subdivision, the relative proportions of the major rock types in the investigated area are: acid granulites 14.5%, sub-acid granulites 17.7%, intermediate granulites 40.3% and basic granulites (comprising two gabbroic anorthosites) 27.5%. Intermediate and basic granulites largely predominate, therefore, over the acid granulites. This is to be expected from the observation of the mineralogical associations and conforms with current opinions on the deep crustal levels. Granulite facies terranes containing medium- to high-pressure mineral assemblages must in effect have an average « intermediate » composition, as is clear from direct observations and experimental studies. Moreover the seismic velocities observed in the deep crust fit the intermediate rocks of high-pressure granulite facies and those of eclogite facies (GREEN, LAMBERT [1965]; RINGWOOD, GREEN [1966]).

It is instructive to compare the averages for our granulite types with the composition data proposed for the deep earth's crust. DEN TEX [1965], for example, on the basis of relative amounts of high-grade metamorphic rocks exposed at the earth's surface, gives the following proportions: acid granulites to intermediate charnockites 50%, basic granulites 22.5%, eclogites 22.5% and garnet peridotites 5%. The differences between the two averages are due essentially to the total lack of eclogites and of other ultramafic rocks in the area studied, while the relative proportions of the granulitic rocks are more or less concordant.

Some samples exhibit a particularly distinctive chemical composition, as was to be expected considering their mineralogical assemblages. For instance, samples Il 14 and Il 17 have a very high alumina (and Ca) content and a general chemistry typical of gabbroic anorthosites. As is well known, anorthosites are commonly associated with banded basement rocks in medium- to high-pressure granulite terranes. Normally they form homogeneous massifs or well-layered complexes (as in the present case); the genesis of these

different types of anorthosites has been recently discussed by ROMEY [1968]. In this context the experimental data of GREEN [1966] indicate that anorthosites could represent the residuals from partial melting of intermediate rocks in the lower crust.

Some samples are characterized by a marked alkalic composition: for example, samples Il 38 and Il 52 have a marked potassic character owing to an abnormally high occurrence of strongly perthitic orthoclase. It is likely that this alkalic character is due to a metasomatic enrichment which may have predated or may be syngenetic with the metamorphic event of granulite facies. The granulites with even a marked alkalic character (whether sodic or potassic) must not be confused, however, with the alkali bodies which appear as intrusion in the basement rocks and which are characterized by different mineralogical assemblages, structural features and a much lesser age.

As for the original material of the granulite terranes, its great heterogeneity is confirmed by mineralogical and chemical data (see the relative standard deviation values for the various elements given on Table 1). Nevertheless, general settings and some compositional characteristics seem to indicate, according to current interpretations, that most of the granulites have a metasedimentary origin.

The chemical data presented here may contribute in some measure towards a better understanding of the composition of the bulk continental crust. Several authors have estimated the average composition of crystalline shield region (SEDERHOLM [1925]; GROUT [1938]; POLDERVAART [1955]; EADE et al. [1966], SHAW et al. [1967]). Chemical data regarding only the deep crust are, on the other hand, relatively scanty and average estimates are based essentially on petrographic observations. In Table 2, for purposes of comparison, we report our average data together with some partial average estimates of other crystalline shield regions and average values accepted for the bulk continental crust. From these comparative data the average composition of the Brazilian granulite terranes in question is seen to have a slightly more basic character than similar terranes of the Canadian shield and parts of the Australian shield. It has, however, a surprisingly similar average composition to the medium- to high-pressure granulite terranes of the Musgrave Range block of the Australian shield. In comparison with the chemical average estimates of the whole Canadian shield (SHAW [1967]; FAHRIG, EADE

TABLE 2 - *Comparative data of average shield compositions*

	Brasilian shield	Canadian shield					Australian shield					
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	60.70	64.7	63.4	64.5	65.3	64.93	60.6	54.8	66.9	67.6	67.0	66.4
TiO_2	0.95	0.47	0.53	0.48	0.53	0.52	0.9	1.3	0.9	0.7	0.5	0.6
Al_2O_3	15.83	16.0	16.7	16.1	15.9	14.63	15.4	15.5	13.8	13.6	14.5	15.5
Fe_2O_3	1.71	1.5	1.5	1.5	1.4	1.36	7.2*	11.3*	5.4*	4.5*	1.5	1.8
FeO	5.50	2.9	3.4	2.9	3.1	2.75	—	—	—	—	3.0	2.8
MnO	0.114	0.08	0.07	0.08	0.08	0.068	0.2	0.2	0.1	0.1	0.2	0.1
MgO	3.02	2.3	2.2	2.3	2.2	2.24	3.9	4.4	1.0	1.3	2.5	2.0
CaO	5.28	3.3	3.6	3.3	3.4	4.12	5.7	7.4	3.1	2.9	4.0	3.8
Na_2O	3.55	4.0	4.0	4.0	3.9	3.46	2.8	2.1	2.7	3.0	2.5	3.5
K_2O	2.28	2.81	2.58	2.78	2.87	3.10	2.6	1.7	4.6	4.5	3.0	3.3
H_2O+	0.77	0.9	0.7	0.8	0.8	0.92	—	—	—	—	—	—
Rb	45.8						70	45	180	190	115	
Ba	1217				730	1070	1090	420	780	625	610	
Sr	543				380	340	340	170	190	160	135	
Zr	222						310	115	400	525	220	

1) Average composition of the granulite terranes from Southern Bahia.
2) Amphibolite facies rocks of the New Quebec area (Eade et al., 1966).
3) Granulite facies rocks of the New Quebec area (id.).
4) Average composition of the entire New Quebec area (id.).
5) Weighted shield average (Fahrig & Eade, 1968).
6) Shield average (Shaw et al., 1967).
7) Granulite facies rocks of the Musgrave Range (Lambert & Heier, 1968).
8) Amphibolite facies rocks of the Fraser Range (id.).
9) Amphibolite facies rocks of the Cape Naturaliste (id.).
10) Granulite facies rocks of the Cape Naturaliste (id.).
11) SW Shield average (id.).
12) Average composition of shield crystalline surface rocks (Poldervaart, 1955).
(*) = Total Fe as Fe_2O_3.

[1968]) and of all the shield crystalline surface rocks (POLDERVAART [1955]) we note that our Brazilian granulite averages are sensibly more basic. This is obvious, because granitic or sub-acid rocks predominate between the shield surface rocks, while again a general lack of acid rocks in medium- to high-pressure granulite terranes occurs in different crystalline shields (GROVES [1935]; RAMBERG [1951]; PICHAMUTHU [1953]; WILSON [1954, 1960].

CONCLUSIONS

Petrographic evidence and chemical characteristics demonstrate that the Brazilian Precambrian crystalline basement in the southern part of the Bahia State consists predominantly of medium- (and high-) pressure granulite terranes. They present petrographic characteristics of a typical charnockite series; alkalic granulites and anorthosites are present too.

Chemical analyses reveal a high grade of heterogeneity in the original material which appears to consist largely of a sedimentary sequence. Intermediate and basic granulites predominate over acid types.

A discussion concerning major and trace elements, relative behaviour and some indicative element ratios will be conducted in a subsequent paper. These data will be examined from the point of view of their relevance to the interpretation of the geochemical processes underlying crust development, and to the hypothesis of continual crustal evolution in particular.

ANALYTICAL METHODS

Si and *Al* were determined by atomic absorption spectroscopy using the decomposition procedure described by BERNAS [1968] and modified by the author in certain details. Each sample was determined in duplicate. *Mn, total Fe, Mg, Ca, Na, K, Li, Cu* and *Zn* were determined by atomic absorption spectroscopy using the methods given by SIGHINOLFI [1969]. *Ti, Ba, Rb, Sr, Cr, Y, Zr,* and *Nb* were determined by X-ray fluorescence analysis using the techniques of HAHN-WEINHEIMER and ACKERMANN [1963]. Rb contents lesser than 10 ppm were determined by atomic absorption spectroscopy using

a highly sensitive procedure developed by the author. Precision and accuracy checks for the major elements were carried out on the standard rocks W-1, G-2, AGV-1, GSP-1, BCR-1, Syenite-1, T-1, GR, GA and BR. The same standard rocks were used to construct calibration curves for the trace element determinations with both the techniques described above. The analytical error for most trace elements is estimated to be 3%.

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