

Geochemistry and Petrology of the Jequié Granulitic Complex (Brazil): An Archean Basement Complex

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Abstract. The Jequié granulitic complex is part of the extensive high-grade metamorphic terrain located within the Sao Francisco craton of northeastern Brazil. Some Jequié rocks appear to have been formed in the middle Archean (~3.1 Ga) from preexisting sialic crust. The dominant mineral composition of these rocks is quartz-microcline-plagioclase-hyperstene and occurs over an extensive area (~2,000 km²).

Scattered enrichment of normal granites with many minor elements (e.g. Rb, Y, Zr, Nb, Ba, REE), and the non-depletion of other elements (e.g. Cs, U), normally considered mobile during granulite facies metamorphism, must lead either to the reconsideration of regional metasomatism subsequent to granu-

lite facies metamorphism, or at least raise some doubts about common wisdom concerning the distribution of heat-producing elements at depth. The region includes large-scale thrust structures, which could play a part in influencing high-level emplacement of the rocks and their regional metasomatism and structures.

Introduction

The major rock formations of the Bahia State, located within the Sao Francisco craton of northeastern Brazil (Almeida 1977),

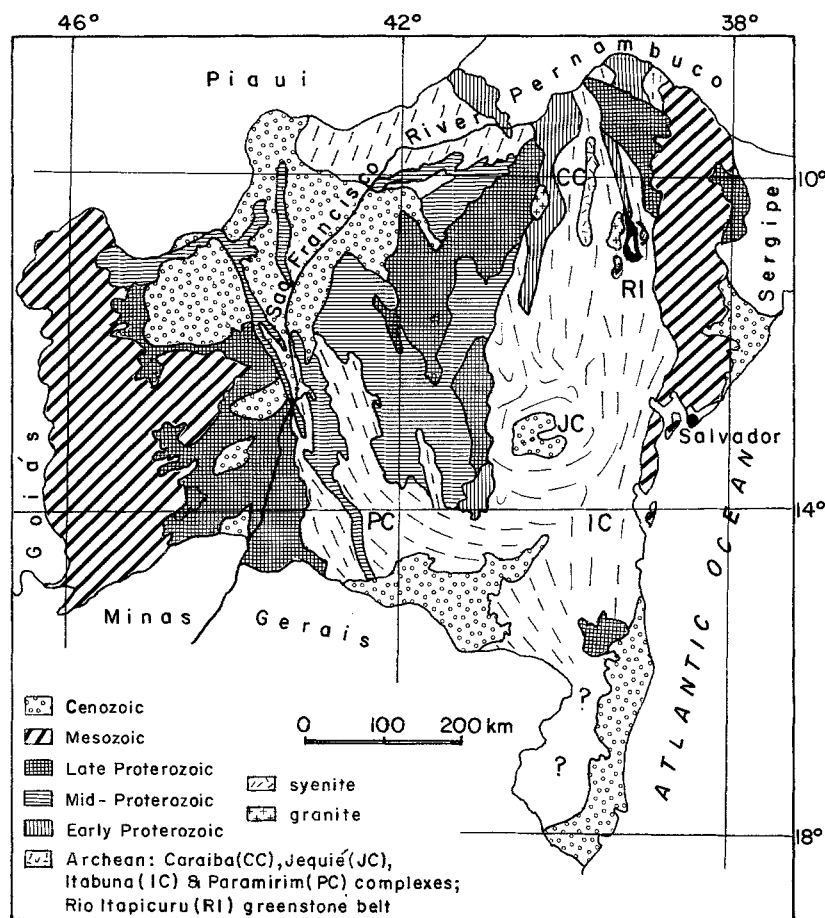


Fig. 1. Geological sketch map of the state of Bahia (after Figueredo 1980)

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consist mainly of high-grade metamorphic basement rocks covered by a succession of younger sedimentary sequences (Fig. 1). The basement rocks have a middle Archean (~3.1 Ga) nucleus (the granulitic Jequie complex) surrounded by late Archean (~2.7 Ga) mobile belts (the granulitic-gneissic-migmatitic Caraiba, the granulitic Itabuna, and the gneissic-migmatitic Paramirim complexes). These high-grade terrains of the Bahia State are particularly interesting because they constitute a major remnant of the Archean – Proterozoic crust. This first study of rocks from the Jequie complex deals with their chemical and petrological characteristics.

Regional Geology

The Jequie orogenic cycle (2.7 ± 0.2 Ga, Table 1) is associated with the formation and stabilization of almost all the high-grade terrains of the Bahia State. During the Jequie cycle pre-existing rocks were reworked, and it is probable that new material was also added to the crust. This is corroborated by studies showing that parts of the Caraiba and Paramirim complexes have relatively low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($R_o=0.704$ and 0.703 respectively) in contrast to those from other parts of the Caraiba, Itabuna, and Paramirim complexes ($0.707\text{--}0.715$), which indicates the re-

Table 1. Subdivision of the Precambrian of the Sao Francisco Craton in the state of Bahia

	Brazilian Cycle (0.7 ± 0.2 Ga*)			
Late Proterozoic				
	Espinhaço Cycle (1.5 ± 0.2 Ga)			
Middle Proterozoic				
	Transamazonian Cycle (2.0 ± 0.2 Ga)			
Early Proterozoic				
	Jequie Cycle (2.7 ± 0.2 Ga)			
Archean				
Archean and Early Proterozoic geochronological data from whole-rock isochrons in the state of Bahia				
	Northeastern Bahia	Central Bahia	Southeastern Bahia	Southwestern Bahia
	Santa Luz granite ⁵ $R_o=0.7031^{**}$ 2.064 ± 0.025 Ga*			Paramirim intrusives ² $R_o=0.705$ 2.080 ± 0.070 Ga
Transamazonian Cycle (2.0 ± 0.2 Ga)	C. Formoso granite ⁴ $R_o=0.708$ 1.911 ± 0.013 Ga Jacobina quartzite ² $R_o=0.712$ 2.100 ± 0.060 Ga			
($2.5\text{--}2.2$ Ga)		Itaberaba gneisses ^{2,3} $R_o=0.7109$ 2.362 ± 0.035 Ga $R_o=0.715$ 2.30 ± 0.10 Ga Salvador granulites ⁶ $R_o=0.703 \pm 0.001$ 2.27 ± 0.04 Ga	Jequie granulites ¹ $R_o=0.7069$ 2.345 Ga Ilheus granulites ³ $R_o=0.7036$ 2.248 ± 0.072 Ga Mutuipe granulites ⁶ $R_o=0.7066 \pm 0.001$ 2.44 ± 0.04 Ga	
Jequie Cycle (2.7 ± 0.2 Ga)	Caraiba granulites ⁵ $R_o=0.704$ 2.85 ± 0.20 Ga	M. Novo migmatites ² $R_o=0.707$ 2.69 ± 0.10 Ga	Jequie granulites ^{1,6} $R_o=0.715$ 2.61 ± 0.06 Ga $R_o=0.72 \pm 0.015$ 2.52 ± 0.2 Ga Mutuipe granulites ⁶ $R_o=0.7065 \pm 0.002$ 2.73 ± 0.05 Ga	Paramirim migmatites ² $R_o=0.703$ 2.60 ± 0.08 Ga $R_o=0.707$ 2.57 ± 0.22 Ga
Pre-Jequie (> 2.7 Ga)			Mutuipe granulites ⁶ $R_o=0.711 \pm 0.004$ 3.16 ± 0.06 Ga	

*Ga = 10^9 years; ** R_o = Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio; ¹ Cordani 1973; ² Jardim de Sa et al. 1976; ³ Cordani and Iyer 1976; ⁴ Torquato et al. 1978; ⁵ cited by Inda and Barbosa 1978; ⁶ Cordani and Iyer 1979

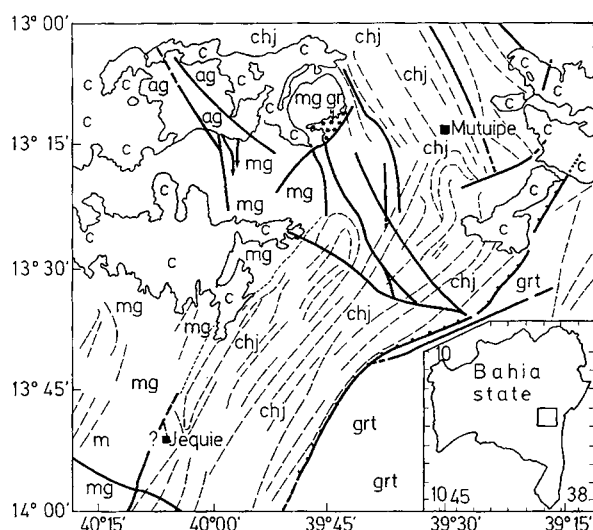


Fig. 2. Sketch map of Jequie Complex. *ag*: augen gneiss; *c*: tertiary and quaternary cover; *chj*: charnockitic suite (middle Archean); *gr*: granite; *grt*: Itabuna granulites (late Archean); *mg*: migmatized granulites

working of older rocks. Some age dates for the high-grade terrains of Bahia State are between 2.5 and 2.2 Ga, and these may represent late tectonic-magmatic events of the Jequie cycle or the overprinting of events associated with the Transamazon cycle (2.0 ± 0.2 Ga). In other regions of Bahia there is evidence of the metamorphic effects of the later Brazilian cycle.

The late Archean Caraiba and Itabuna complexes contain predominantly felsic to intermediate gneisses and migmatites, with subordinant layers and lenses of carbonate-calc-silicate rocks, iron formations, and graphite-rich rocks. In these areas subconcordant mafic-ultramafic bodies are more heterogeneous than the granulites of the Jequie complex and probably have a substantial supracrustal component (Sighinolfi 1971; Figueredo 1980). Along with the high-grade rocks of the Caraiba complex, low-grade meta-volcanic and meta-sedimentary units also occur (Rio Itapicuru greenstone belt, Kishida and Riccio 1980).

The high-grade metamorphic rocks of the Jequie complex (Fig. 2) are folded and foliated in a regional configuration, NE-SW. Recent geochronology and strontium isotope studies (Cordani and Iyer 1979) show that the Jequie complex contains an ancient crustal fragment centred around Mutuipe, dated at 3.16 ± 0.06 Ga. The high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ($R_0 = 0.711 \pm 0.004$) suggests that these rocks were formed from the reworking of even older crustal material of a sialic nature. It has been established that the Jequie rocks differ in origin from the granulitic Itabuna complex (Sighinolfi 1970, 1971), which is primarily composed of felsic to mafic granulite facies rocks resembling those of the Caraiba complex in composition, texture, and structure (Figueredo 1980).

The predominant rock types in the Jequie complex are felsic granulites, migmatized granulites, and augen gneisses, at times interleaved with contrasting rock types, such as pegmatites, amphibolites and metabasalts. Augen gneisses and migmatized granulites are dominant to the west, and rather homogeneous granulites (hypersthene-bearing gneisses) are more common towards the centre. These are minor occurrences of metasediments (meta-quartzites, calc-silicate rocks) throughout the area, but are less evident in the eastern part of the complex.

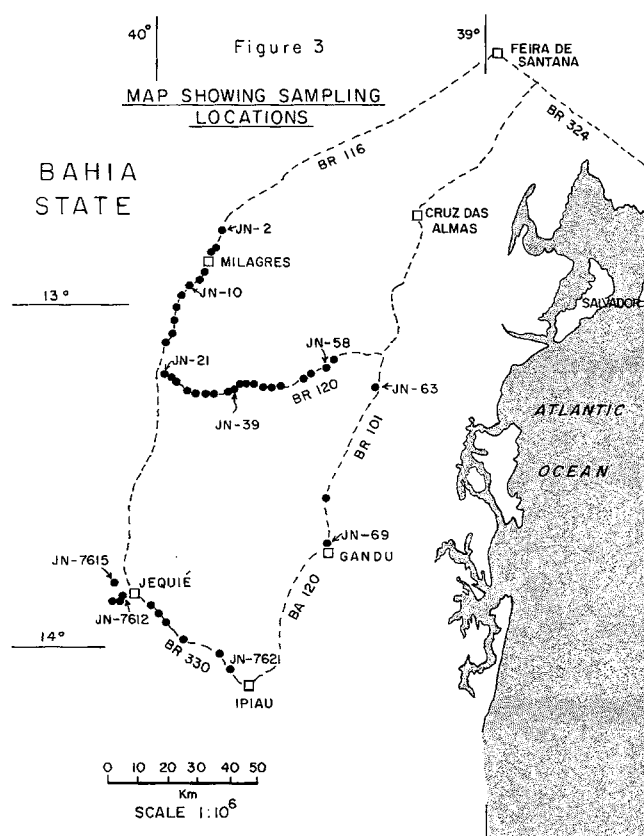


Fig. 3. Map showing sampling locations

Petrography

In the field, rocks were classified as granulites, foliated granites and charnockites. As shown below, the mineralogy of the first two types is basically similar, and any differences are mainly in texture. Charnockitic rocks can be recognised by their darker colours and typical xenoblastic textures.

All granulite facies rocks are dominated by the presence of quartz, antiperthite-perthite feldspars, hypersthene, and diopside. In the 'granitic' types (i.e. foliated granites), hornblende and biotite are the dominant dark minerals, hypersthene being either absent or present in very small amounts. Most granulitic rocks contain minor amounts of retrograde chlorite and biotite. Accessory minerals include zircon, apatite, and magnetite.

The charnockitic rocks are typically dominated by perthitic and antiperthitic feldspars, quartz and hypersthene with minor amounts of magnetite and zircon. Microfracturing of grains and other deformation structures are common. Retrograde minerals include biotite, muscovite, chlorite and epidote.

Analytical Notes

Concentrations of major and minor elements were determined using standard X-ray fluorescence techniques (Norrish and Hutton 1969). Errors are considered to be in the 1% range for elements whose concentrations exceed 1%. For minor elements, errors are 5–25% depending on the element.

Rare earth element concentrations were determined by spark-source mass spectroscopy using the methods of Taylor (1965).

Chemistry

Chemical data of selected samples (Fig. 3) are shown in Tables 2 and 3, with averages given in Table 4. The data in Table 2 refer

Table 2. Major and minor element data for the Archean granulitic rocks of the Jequie complex

	(wt.%)												
	JN 2	JN 3	JN 4	JN 7	JN 8	JN 10	JN 12	JN 14	JN 16	JN 17	JN 21	JN 22	JN 23
SiO ₂	72.73	69.28	70.02	69.68	67.48	68.51	70.54	68.03	70.53	71.21	67.64	68.96	68.02
TiO ₂	0.19	0.17	0.18	0.59	0.81	0.59	0.13	0.40	0.38	0.22	0.70	0.64	0.80
Al ₂ O ₃	14.24	15.68	16.18	13.71	13.12	13.64	15.71	15.31	13.24	12.94	13.54	13.47	12.91
FeO	0.39	1.06	0.27	2.52	2.60	2.76	0.05	1.47	2.26	1.37	2.77	2.46	3.09
Fe ₂ O ₃	1.20	0.46	1.16	1.12	1.97	2.51	1.41	1.07	1.39	1.43	2.34	1.42	1.99
MnO	0.01	0.03	0.01	0.05	0.07	0.10	0.03	0.02	0.07	0.08	0.07	0.06	0.08
MgO	0.21	0.45	0.46	0.58	0.57	0.29	0.35	0.44	0.20	0.05	0.57	0.49	0.62
CaO	1.15	2.34	1.72	2.19	2.51	2.08	1.65	1.82	1.42	1.24	2.26	1.97	2.24
Na ₂ O	3.20	4.16	4.54	2.94	2.63	3.02	3.41	3.24	3.16	3.28	2.78	2.80	2.70
K ₂ O	5.44	3.49	4.10	4.93	5.03	5.34	5.50	5.78	5.45	5.24	5.35	5.45	4.96
P ₂ O ₅	0.05	0.06	0.12	0.25	0.35	0.20	0.06	0.16	0.08	0.04	0.23	0.25	0.27
H ₂ O ⁺	0.44	0.60	0.36	0.26	0.23	0.12	0.44	0.59	0.37	0.51	0.31	0.30	0.37
	(µg g ⁻¹)												
Sc	4.3	4.8	3.7	9.3	12.8	6.3	3.7	4.3	3.0	3.2	7.6	7.2	9.3
V	5.2	7.2	15.7	17.1	14.2		6.0	15.7					3.3
Cr	0.5	2.7	8.8		0.3		1.5	6.4				8.9	0.2
Co		2.2		3.9	5.7	4.1	1.4	1.8	3.1		5.9	7.1	6.6
Ni	10.4	21.8	14.8	20.3	22.2	28.3	13.1	13.1	21.5	17.4	17.9	22.6	17.7
Cu	15.0	2.3	1.0	1.9		4.4	3.0	0.6		23.1			3.5
Zn	18.4	16.4	19.5	27.2	34.5	70.9	13.8	20.7	40.1	56.4	41.0	24.5	39.7
Rb	250	76	94	149	167	127	190	191	197	216	181	199	184
Sr	107	404	266	176	156	87	135	176	60.6	32.6	78.6	121	112
Y	8.5	6.6	10.4	57.6	98.3	151.1	10.1	15.8	133.4	186.7	154.1	96.1	115.2
Zr	289	217	250	276	840	916	199	631	574	686	463	392	478
Nb	12.5	10.1	5.2	11.7	20.0	21.2	0.9	6.8	25.9	21.8	33.3	17.9	19.3
Cs		<0.2		0.2		0.6	<0.2				0.3		0.6
Ba	641	1,035	647	838	733	1,208	853	918	865	575	551	805	744
Th		8		9		28	12				100		16
U		1		2		3	4				5		3
K/Rb	181	382	362	275	249	350	240	252	230	201	245	226	224
Rb/Sr	2.322	0.188	0.353	0.846	1.070	1.451	1.407	1.085	3.250	6.626	2.304	1.642	1.641
Th/U		8.0		4.5		9.3	3.0				20		5.3
	(wt.%)												
	JN 27	JN 28	JN 33	JN 37	JN 41	JN 42	JN 45	JN 47	JN 49	JN 51	JN 53	JN 54	JN 58
SiO ₂	67.77	66.89	66.69	70.11	69.52	63.11	68.43	67.82	69.68	65.76	70.67	65.20	62.25
TiO ₂	0.54	0.65	0.27	0.16	0.49	1.36	0.38	0.61	0.61	0.31	0.25	1.0	1.22
Al ₂ O ₃	13.52	13.97	14.97	15.11	14.31	14.54	16.07	13.67	13.11	17.59	14.61	14.84	14.86
FeO	2.66	2.96	1.13	<0.01	1.63	4.22	2.55	3.96	2.83	1.80	0.78	3.42	4.69
Fe ₂ O ₃	1.71	1.95	1.91	1.69	1.43	2.54	0.89	1.40	1.48	0.74	1.13	1.72	2.29
MnO	0.07	0.07	0.06	0.02	0.03	0.11	0.09	0.10	0.06	0.04	0.03	0.08	0.10
MgO	0.39	0.58	0.30	0.32	0.68	1.09	1.37	0.70	0.46	1.43	0.28	0.65	1.42
CaO	1.94	2.50	1.77	1.47	1.82	4.23	2.75	2.02	1.78	3.55	1.42	3.47	4.63
Na ₂ O	3.22	2.86	3.50	3.99	3.05	2.87	4.00	2.57	2.80	5.12	2.88	3.74	2.78
K ₂ O	5.22	5.11	6.51	4.75	4.87	4.16	2.02	5.93	5.72	2.27	6.14	3.80	4.00
P ₂ O ₅	0.20	0.27	0.12	0.06	0.25	0.65	<0.01	0.12	0.10	0.21	0.08	0.45	0.25
H ₂ O ⁺	0.27	0.53	0.63	0.46	0.44	0.06	0.47	0.52	0.55	0.51	0.53	0.25	0.26
	(µg g ⁻¹)												
Sc	6.5	9.9	3.8	5.2	6.7	16.4	11.1	9.4	8.3	7.7	4.1	10.4	16.0
V			14.4	9.0	11.2	6.4	5.1			39.6	58		40.5
Cr			1.9	5.8	9.6	9.8	0.8	0.7	1.4	34.4		0.9	4.6
Co	5.1	6.7	1.7		2.4	6.5	7.5	7.0	2.6	7.7	1.4	6.5	13.9
Ni	20.4	17.9	29.9	39.4	15.9	21.9	34.0	19.6	19.1	44.6	20.5	19.3	21.7
Cu	2.9	6.6		4.7	1.3	8.4		5.8	3.8	3.0	1.3	9.2	7.8
Zn	48.1	53.4	54.1	16.4	15.2	38.7	10.0	41.7	23.5	21.3	11.7	35.3	47.9
Rb	189	170	189	99.0	173	82.0	34.4	331	364	50.7	191	67.7	80.7
Sr	88.9	160	95.0	349	196	292	101	61.2	63.3	541	113	278	367
Y	135	80.5	215	7.2	24.5	88.0	225	104	70.5	14.4	23.0	55.0	61.2
Zr	390	363	464	104	273	569	441	490	432	235	446	459	331
Nb	26.4	12.3	20.7		6.6	23.3	1.7	39.5	38.1	0.2	5.3	12.4	8.2

Table 2. (continued)

	(wt.%)												
	JN 27	JN 28	JN 33	JN 37	JN 41	JN 42	JN 45	JN 47	JN 49	JN 51	JN 53	JN 54	JN 58
Cs		<0.2				0.2	0.2	0.6			<0.2	<0.2	<0.2
Ba	764	1,061	782	517	851	1,601	437	638	630	779	786	1,574	1,579
Th		25				2	6	80			50	2	
U		1				<1	1	2			<1	<1	<1
K/Rb	228	249	285	396	233	422	488	149	131	371	266	465	411
Rb/Sr	2.126	1.064	1.992	0.285	0.885	0.280	0.341	5.402	5.747	0.094	1.690	0.244	0.220
Th/U		25				>2	6	40			>50	>2	

	(wt.%)											
	JN 59	JN 63	JN 7612	JN 7613	JN 7614	JN 7615	JN 7616	JN 7617	JN 7618	JN 7620	JN 7621	AP 7604
SiO ₂	61.74	71.85	71.78	71.37	73.63	70.36	72.47	63.36	69.57	72.71	68.28	69.81
TiO ₂	1.41	0.31	0.28	0.23	0.22	0.25	0.02	1.13	0.57	0.02	0.54	0.46
Al ₂ O ₃	14.35	12.41	15.15	14.06	12.89	14.80	15.75	13.35	13.60	15.14	15.66	13.75
FeO	2.98	1.87	0.97	2.37	0.22	1.07	0.27	0.70	2.56	<0.01	2.36	2.56
Fe ₂ O ₃	4.44	2.39	0.92	0.46	2.44	1.14	0.32	1.51	1.39	0.21	1.09	1.07
MnO	0.10	0.07	0.03	0.06	0.04	0.02	0.05	0.22	0.04	<0.01	0.02	0.04
MgO	1.33	0.20	0.48	0.53	0.12	0.31	0.11	0.88	0.37	<0.01	0.99	0.33
CaO	4.62	1.18	2.11	2.28	0.87	1.75	0.84	3.11	1.67	0.57	3.19	1.80
Na ₂ O	2.88	3.52	4.18	3.18	2.95	3.30	4.06	2.82	2.74	2.70	4.39	2.70
K ₂ O	3.78	5.52	3.54	3.73	5.84	4.93	5.60	5.10	6.02	7.60	1.81	6.13
P ₂ O ₅	0.62	0.02	0.04	<0.01	0.01	0.09	0.04	0.49	0.11	0.02	0.08	0.13
H ₂ O ⁺	0.42	0.18	0.21	0.47	0.42	0.30	0.32	0.54	0.05	0.48	0.18	0.21

	(µg g ⁻¹)											
	JN 59	JN 63	JN 7612	JN 7613	JN 7614	JN 7615	JN 7616	JN 7617	JN 7618	JN 7620	JN 7621	AP 7604
Sc	15.1	0.3	4.5	6.9	5.0	4.1	2.7	13.9	6.8			6.9
V	26.7					8.5	6.3					
Cr	7.9					5.4	2.1					
Co	15.0		3.2	4.6	1.1	4.0		10.3	4.6	8.4	4.3	
Ni	23.6	18.6	19.1	20.1	22.1	20.9	18.6	21.5	7.3	17.2	21.7	10.2
Cu	6.7		2.0	6.0	1.2	4.9	7.4	1.7	0.7			0.5
Zn	48.0	77.4	16.5	20.1	42.8	17.6	3.4	68.4	20.5			18.2
Rb	90.6	211	69.7	78.0	191	114	106	250	420	158	34.4	436
Sr	245	29.0	254	165	48.2	207	133	141	114	267	429	70.9
Y	80.9	114	12.0	11.2	98.3	13.3	8.0	168	21.7	2.0	6.5	48.3
Zr	460	1,016	257	372	539	359	31.7	710	499	24.7	323	550
Nb	13.8	18.2	2.4	4.7	14.7	2.2		54.1	0.1		2.7	7.3
Cs	<0.2	0.2							0.6	1		<0.2
Ba	1,231	544	760	812	947	810	326	984	628	1,446	462	482
Th	2	6					<1	25	2		2	
U	<1	2					<1	4	1		<1	
K/Rb	346	217	422	396	254	358	438	169	119	456	436	117
Rb/Sr	0.370	7.262	0.274	0.471	3.965	0.552	0.795	1.769	4.055	0.593	0.080	6.151
Th/U	>2	3.0						6.3	2.0		>2	

to granulite facies rocks in general, including the 'granitic' types. Main chemistry of these rocks reveals that they are mostly granite in composition with a rather potassic character and moderate ($\approx 3\%$) iron content. The most striking feature of these rocks is their high content of trace elements (e.g. Rb, Cs, U, Sc, Y), which are normally highly depleted in high-grade metamorphic rocks.

The rocks, classified in mineralogical terms as charnockites, contain 52–66% silica (Table 3), and their composition closely resembles average andesites. In some samples Rb is highly depleted along with other incompatible elements, but in general, there is a great scatter of values for trace elements and some main elements (e.g. K, Ca).

This enrichment by incompatible elements seen in most granulite facies rocks of the Jequie complex also includes the rare

earth elements (Table 5, Figs. 4, 5). The Jequie rocks display REE patterns (Fig. 4) similar to those of other charnockites (e.g. Norwegian charnockites), but at much higher concentrations. The REE patterns in the more mafic charnockitic types are similar to those of other granulites and gneissic rocks of Archean complexes. In all samples europium shows a strong negative anomaly, suggesting that parent material of the Jequie rocks underwent some sort of feldspar fractionation. This is consistent with the crustal source material hypothesis, and is also corroborated by the high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Discussion

The most striking geochemical discovery of this study of the Jequie complex is that high-grade metamorphic rocks, typical

Table 3. Major and minor element data for charnockitic rocks of the Jequie complex

	(wt.%)										
	JE 1	JE 2	JE 3	JE 5	JE 10	JE 22	JE 23	JE 25	JN 11	JN 35	JN 66
SiO ₂	64.28	52.62	52.81	60.28	60.31	64.82	57.74	70.58	51.75	69.22	66.11
TiO ₂	0.60	2.00	0.76	0.81	0.68	0.61	0.90	0.32	1.16	0.30	0.55
Al ₂ O ₃	16.45	19.07	17.39	18.20	16.28	16.06	20.67	14.80	21.71	15.19	15.21
FeO	2.96	5.96	6.60	3.24	4.65	3.56	6.06	1.22	6.82	1.99	1.87
Fe ₂ O ₃	1.69	0.95	1.30	1.72	1.71	1.60	3.49	1.14	6.22	1.48	1.80
MnO	0.07	0.09	0.14	0.07	0.07	0.08	0.16	0.04	0.21	0.07	0.04
MgO	1.68	2.40	6.43	1.89	4.46	1.99	3.32	1.34	4.64	1.17	0.98
CaO	4.97	7.60	9.99	7.28	4.64	5.68	1.42	1.92	1.60	3.10	3.20
Na ₂ O	3.76	4.92	3.43	3.54	3.83	3.58	1.55	3.00	1.62	4.69	3.95
K ₂ O	1.11	1.10	0.53	1.10	0.86	1.07	3.10	4.11	2.48	1.19	3.67
P ₂ O ₅	0.22	1.32	0.13	0.23	0.28	0.28	0.04	0.10	0.05	0.11	0.39
H ₂ O ⁺	1.48	0.32	0.41	0.93	1.01	0.42	1.09	1.19	0.48	0.17	0.65

	(µg g ⁻¹)										
Sc		17.4	30.6	14.5		12.1	24.7			6.0	6.0
V		23.0	165	97.6		79.8	160			47.3	32.0
Cr		18.0	263	112		68.2	334		323	30.8	29.0
Co		43.1	67.7	65.2		76.2	119			11.0	5.6
Ni		74.8	128	89		67.9	152		186	22.1	27.3
Cu		46.7	77.7	35.9		36.0	28.3			21.7	3.3
Zn		43.2	38.6	32.0		23.0	84.1			26.7	25.2
Rb		8.3	6.1	8.1		9.8	107		69.5	6.9	80.6
Sr		797	195	384		187	167		182	214	580
Y		41.1	14.8	13.9		25.4	23.0		10.7	6.3	19.7
Zr		995	90.5	103		471	268		210	41.1	546
Nb		1.0									
Cs	<0.2	<0.2			<0.2		0.2				
Ba		1,190	177	515		493	974		1,000	227	1,225
Th	<1	5			2		25				80
U	<1	<1			<1		1				
K/Rb		1,096	721	1,123		908	239		296	1,435	377
Rb/Sr		0.010	0.031	0.021		0.052	0.641		0.382	0.032	0.139
Th/U		2.5			>2		25				80

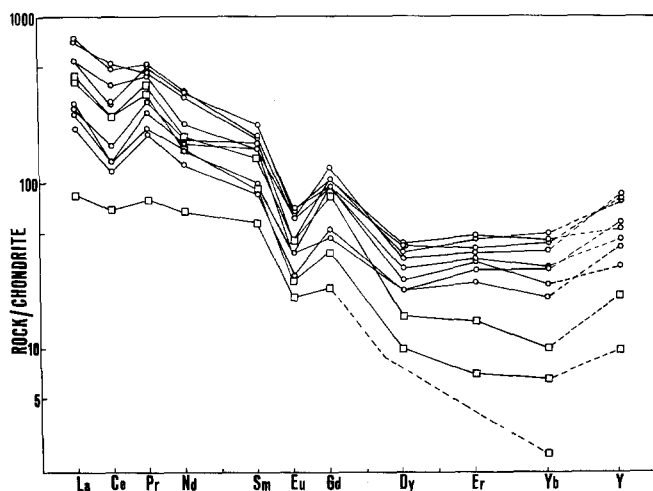


Fig. 4. Chondrite-normalized rare earths patterns in some granulites (circles) and charnockites (squares) of the Jequie complex

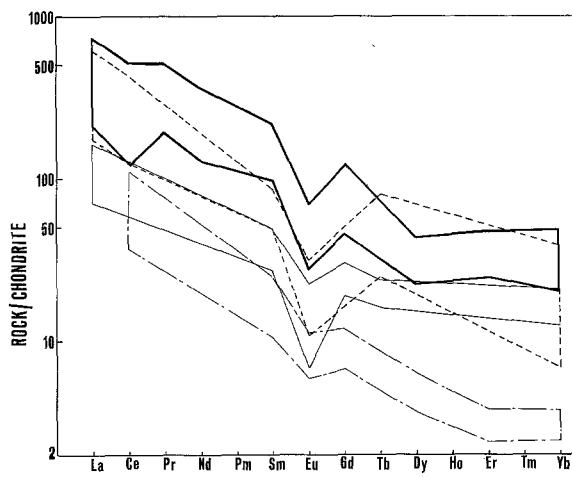


Fig. 5. Chondrite-normalized REE distribution in the Jequie granulites (heavy continuous line) compared with that in Norway charnockites (light continuous line), in Precambrian quartz monzonites from Barberton, South Africa (broken line, one hatching) and from Minnesota (broken line, two hatching). Data respectively from Ormaasen (1977), Condie and Hunter (1976) and Arth and Hanson (1975)

of what is commonly considered to be continental basement, contain mobile and heat-producing elements in normal or even larger concentrations than in other common rock types. The general depletion of these elements in granulite facies rocks has been widely observed (see Heier 1973, 1978; Sighinolfi 1971; Turner 1980). On the other hand, some authors (e.g. Moine

et al. 1972; Gray 1977) have observed, in various basement areas, typical granulite facies rocks with undepleted mobile and heat-producing elements. The problem to be resolved is why this depletion process is not general. This requires discussion of the possible depletion mechanisms of elements in deep-seated rocks. According to current opinion, these mechanisms are basically dehydration reactions and melting processes. Some authors (e.g. Fyfe 1973) suggest that during the genesis of granulite facies rocks, only the latter process is involved. However, an increasing number of researchers (e.g. Touret 1974; Clough and Field 1980; Rollison and Windley 1980) attribute a major role to the fluid phase in determining granulitic parageneses. On the basis of the dominant depletion mechanism, Nesbitt (1980) categorises granulites according to genetic type, i.e. dehydration granulites and fusion granulites.

To explain the peculiar undepleted character of the Jequié granulites a number of processes or possibilities must be considered:

a. The rocks underwent dehydration to become granulite facies without partial melting and substantial loss of minor elements.

b. The rocks were always dry and fluid loss during metamorphism was slight, preventing partial melting.

c. Retrograde metamorphism over wide areas was accompanied by the reintroduction of mobile elements. The rocks were once 'normal', but were recharged with elements such as U-Rb.

As shown by Brown and Fyfe (1970), rocks containing muscovite-biotite-hornblende produce granitic melts during prograde metamorphism at virtually every possible thermal gradient in the crust. The mass of melt produced is dependent upon how much water reaches the minerals of the amphibolite facies, mainly biotite and hornblende. Most of the Jequié rocks have very low Fe-Mg concentrations, and the water content of the pre-granulite facies might be correspondingly low, perhaps 0.2–0.4% H₂O. This quantity of water produces 6–12% water-undersaturated melt with about 3% water. It is unlikely that this melt remains in the rocks and trace elements such as U are scavenged by even a small quantity of melt. Rock textures do not provide evidence of the retention of this melt.

It has been frequently observed (e.g. Touret 1971, 1974, 1977; Touret and Bottinga 1979; De Negri and Touret 1979) that residual fluids in granulite facies rocks are rich in carbon dioxide. According to Clough and Field (1980), it is possible that the

Table 4. Average composition of the Jequié charnockitic-granulitic rocks, of Bahia Transamazonic granulites and of mangerite-charnockite intrusives

	1		2	3	4	5
	Jequié granul.		Jequié char.	Trans. gran.	mangerite	charnockite
	range	ave. (38)	ave. (11)	ave. (64)	ave. (4)	ave. (7)
SiO ₂	61.74–73.68	68.77	60.95	60.70	64.9	71.7
TiO ₂	0.02–1.41	0.50	0.79	0.95	0.54	0.4
Al ₂ O ₃	12.41–16.18	14.36	17.37	15.83	16.3	12.8
Fe ₂ O ₃	0.21–7.84	3.84	6.61	7.82	4.7	4.4
MnO	0.01–0.22	0.06	0.09	0.11	0.1	0.1
MgO	0.01–1.43	0.54	2.75	3.02	0.4	0.1
CaO	0.33–4.63	2.10	4.67	5.28	1.9	1.
Na ₂ O	2.57–5.12	3.28	3.53	2.28	4.9	4.2
K ₂ O	1.81–7.60	4.90	1.85	3.55	5.6	5.
P ₂ O ₅	0.0 –0.64	0.18	0.29		0.1	
Sc ppm	0.3 –16.	7.1	17.2			
V ppm	1.0 –40.5	8.8	97.4			
Cr ppm	0.2 –9.8	3.4	147			
Co ppm	0.8 –15.	4.5	54.			
Ni ppm	7.3 –54.1	20.7	93.4			
Cu ppm	0.6 –23.1	3.7	33.4	39		
Zn ppm	1.6 –77.4	31.6	42.3	94		
Rb ppm	34.4 –436.1	168	37.1	45.8	58	88
Sr ppm	29.0 –540.8	177	338	543	255	27
Y ppm	2.0 –224.8	71.9	19.4			
Zr ppm	24.7 –1016	430	340	222		
Nb ppm	0.2 –54.1	12.5				
Ba ppm	326 –1,601	839	725	1,227		
K/Rb	117 –465	296	774	626		
Rb/Sr	0.08–7.262	1.866	0.327	0.094	0.66	3.87

1, 2: this work; 3: Sighinolfi 1971; 4, 5: Ormaasen 1977

Table 5. Yttrium and rare earth element contents in rocks of the Jequié complex

Sample	(µg g ⁻¹)										
	JN 10	JN 21	JN 28	JN 42	JN 47	JN 58	JN 63	JN 7617	JE 2	JE 10	JN 66
La	174	100	86	92	234	178	70	246	135	28	146
Ce	265	120	116	148	457	336	103	422	226	62	220
Pr	56	30	24	35	51	49	22	58	43	9	38
Nd	210	105	92	109	198	135	78	216	114	40	96
Sm	40	29	18	31	33	29	15	35	25	10.5	17
Eu	4.6	2.6	2.6	4.7	3.1	4.2	1.9	4.2	3.1	1.4	1.7
Gd	26.4	24.0	11.6	23.8	26.4	24.2	13.0	30	18.6	5.8	9.6
Dy	11.8	13.0	7.0	9.4	13.4	7.9	6.9	10.8	4.8	3.0	3.1
Er	9.0	8.0	5.0	6.9	9.6	6.6	5.9	7.5	2.9	0.6	1.4
Yb	9.8	8.6	4.1	6.2	9.0	4.9	5.9	7.8	2.2	0.4	1.3
Y	151.1	154.1	80.5	88.0	104.4	61.2	113.7	168.1	41.1		19.7
Eu/Eu ⁺	0.44	0.32	0.56	0.54	0.32	0.49	0.41	0.40	0.41	0.56	0.44
Ce _N /Yb _N	6.14	3.16	6.44	5.42	11.50	15.59	3.97	12.28	23.36	31.29	38.46

Eu/Eu⁺ = chondrite-normalized Eu value divided by the value obtained by drawing a straight line between Sm and Gd; Ce_N/Yb_N = ratio Ce (chondrite normalized) / Yb (chondrite-normalized). Chondrite values from Haskin et al. 1968

CO₂-rich fluids inhibit melting and promote simple dehydration of hydrous phases. The origin of the carbon dioxide is unclear. Calc-silicate rocks are present in the region, but this is a small volume anomaly when compared to the regional granitic-andesitic compositions as a whole. Thus, according to current opinions (e.g. Newton and Sharp 1975) a deep origin for the CO₂-rich fluids should be investigated. Recently Newton et al. (1980) discussed the problem of carbon dioxide delivery to continental roots.

The second alternative, that these rocks are granitic-andesitic and contained no water during metamorphic events, is difficult to justify. In all these successions, rocks of supracrustal origin are present and as with any rocks originally formed near the surface, access to water is certain.

The third possibility, that granulitic basement rocks underwent pervasive metasomatism during the tectonic processes which returned them to the surface, must also be considered. In most continental terrains where basement rock is exposed, the crustal thickness is more or less constant. This implies that either the depth of the granulites was 30 km in many regions of the ancient crust, or that their movement to the surface was accompanied by substantial crustal shortening or thrusting. To answer such questions we need detailed studies of the nature of continental crust under high-grade terrains (Oliver 1978).

Here a spectacular start has been made. The recent studies of structures in the Appalachian belt by the Cornell group (Cook et al. 1979, 1980) clearly show that thrust mechanisms can move large masses of crystalline metamorphic rocks over much lower grade, younger rocks. These authors propose that this may be a fundamental mechanism in recent plate tectonics.

If such emplacement mechanisms are common, they may drastically change our views on the processes that affect basement rocks. If hot basement rocks are rapidly thrust over cooler low-grade rocks, prograde metamorphism of the underthrust rocks will occur, releasing fluids, and retrograde metamorphism of the overthrust rocks may occur when they are penetrated by such fluids. The wide literature on granulitic belts shows that retrograde metamorphic reactions extensively affect granulite facies rocks. One of the authors (WSF) investigated, in the SW corner of Bahia State (Lagoa Real), retrograde metamorphism of upper amphibolite-granulite facies basement, which had been locally converted into greenschist facies associations over a wide belt of rocks. Here a typical thrust structure was recognized, with thrusting of Archean basement rocks over upper Proterozoic metasediments. As shown by Cook et al. (1979), the overthrust belts have a width of 200–300 km, adequate to explain regional occurrences of retrograde metamorphism.

While no definite conclusions can be drawn at this time, we consider that regional metasomatism, accompanying emplacement of deep basement rocks by overthrusting, provides a most attractive concept for explaining the state of regional granulites on the surface. It would explain the scatter in chemistry and the fluid source for retrograde reactions and also how the rocks rise to the surface while maintaining a crust of normal thickness. Furthermore, this does not conflict with the current view that basement rocks have low radioactivity because the rocks may become recharged near the surface. Hopefully, future studies of the oxygen isotope systematics of altered rocks may assist as in resolving some of these problems. But we would stress that their chemical composition may have arisen from a complex interplay of various degrees of partial melting, CO₂-addition from underplated mantle magmas, and retrograde metasomatism during uplift.

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