PRELIMINARY SPECTROCHEMICAL AND AGE DETERMINATION RESULTS ON SOME GRANITIC ROCKS OF THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL (*)

by

NORMAN HERZ

United States Geological Survey

and

C. V. DUTRA

Instituto de Tecnologia Industrial, Estado de Minas Gerais, Brasil

RESUMO

A presente comunicação prévia descreve o trabalho atualmente em execução sôbre a espectroquímica e sôbre a determinação de idades absolutas das rochas graníticas do Quadrilátero Ferrífero. São apresentados os resultados das determinações espectroquímicas preliminares de 25 rochas graníticas da referida área e uma de Gouvêa, juntamente com a tentativa de determinação da idade geológica de 9 destas rochas.

A técnica das análises espectroquímicas é descrita em detalhe. A validade das curvas analíticas foi verificada usando-se as amostras W-1 e G-1 (Fairbairn, 1) com os valores recomendados por Ahrens (2), Smales (3) e Herzog e Pinson (4). Os resultados das análises espectroquímicas são apresentados na tabela 1 e da análise estatística na tabela 2. No capítulo "Resultados Preliminares" faz-se uma descrição petrográfica e dos elementos traços de cada amostra e na base dêstes elementos traços foram estabelecidos certos grupos de rochas. O grupo I tem, geralmente acima da média, Co, Cu, Ni e Sc; Ba, Nb, V, Y e Zr permanecem acima ou iguais a média; o Cr, em tôdas as amostras, exceto uma, está acima da média; e La, Sn e Sr variam de baixos a altos teores. Uma tentativa de determinação da idade dá para êste grupo, 1.260 milhões de anos.

O grupo II possui Co, Cr, Cu, Ni, Pb e Sc abaixo da média; Nb, V e Zr estão abaixo ou iguais à média; Ba, La, Sn, Sr e Y variam de altos a baixos teores. Uma tentativa de determinação da idade dêste grupo indicou uma idade de 475-560 milhões de anos.

O grupo III parece ser comagmático com II e tem uma correlação geral com os elementos traços de II. Uma tentativa de determinação da idade do grupo III revelou variar entre 475-555 m.a.

(*) Published by permission of the Directors of the Departamento Nacional da Produção Mineral and United States Geological Survey.

O grupo IV é encontrado na região Itabirito-Bacão-Cachoeira do Campo e possui La, Nb, Sn, V, Y e Zr abaixo da média; Co e Ni iguais ou abaixo da média; Cr e Sc iguais à média; Ba, Pb e Sr iguais ou acima da média; Cu var'a de baixos a altos teores. As determinações de idades dêste grupo variam de 2.520 a 720 milhões de anos. O grupo pode assim representar um granito mais antigo (2520-2440 milhões de anos) que foi remobilizado e sofreu reintrusão pelo menos em duas épocas mais recentes (1330 e 720-760 milhões de anos) com nenhuma mudança essencial em sua composição química.

O grupo V representa um conjunto de tipos petrográficos distintos encontrados a leste de Moeda. Todos possuem V e Y acima da média; Nb, Pb, e Zr iguais ou acima da média; Co, Cu, La, Ni, Sc, e Sn iguais à média; Ba e Sr iguais ou abaixo da média; Cr apresenta altos e baixos teores.

Não se tem ainda as determinações de idades para êste grupo.

Uma amostra do Morro das Pedras, Belo Horizonte, não apresenta nenhuma correlação evidente dos seus elementos traços com os dos outros grupos. Ela pode representar uma intrusiva relativamente recente, julgando-se pelas suas relações de campo.

A amostra de Gouvêa não parece correlacionar-se com nenhuma das do Quadrilátero Ferrífero, tanto na base dos elementos traços como na determinação da idade (880 milhões de anos).

INTRODUCTION

Quadrangle mapping in the Quadrilátero Ferrífero of central Minas Gerais has been going on since 1946 as part of a joint program of the United States Geological Survey and the Departamento Nacional da Produção Mineral of Brazil. Emphasis in this mapping has been on a declination of the iron formation and hematite ore; other rocks and formations have been studied on a semi-reconnaissance basis. In an effort to provide more data on other aspects of the geology of the region, especially regarding the igneous and metamorphic history, special petrologic and geochemical studies were initiated in 1957.

Within the area being mapped by the U.S.G.S. — D.N.P.M. there are large granitic complexes west of the Serra da Moeda, in the regions of Itabirito — Cachoeira do Campo and Jeceaba — Congonhas, east of Caeté, north of Belo Horizonte and the Serra da Piedade, east of Santa Bárbara, and north of Cocais, and in the general areas of Itabira and Monlevade (see map). Some of these granitic rocks are an apparent result of mixing of sedimentary or igneous country rock with "granitizing solution" and so have distinctively different appearances from one area to the next, depending on the rocks involved. Studies of the trace elements in selected rocks were begun to determine suites characteristic of the different granites in the hope that the trace elements of the rocks might suggest which had been affected by the same "granitizing solutions" and so could be correlatable. This paper is the first of a projected series devoted primarily to the results of these trace element studies. Preliminary results of a study of 25 granitic rocks of the Quadrilátero Ferrífero and one from Gouvêa, near Diamantina are presented. Preliminary results of absolute age determinations in progress are also reported in this paper.

Acknowledgments

The spectrographic analyses were made possible by the help of the Conselho Nacional de Pesquisas of Brazil which made available the laboratory instruments used in this study.

The age determinations were done in the laboratories of the Department of Geology and Geophysics of the Massachusetts Institute of Technology under the supervision of Professor P. M. Hurley.

The authors are deeply indebted to the assistance given by these organizations.

METHODS USED

Samples of different "granitic types" were collected throughout the region. The samples were selected from the freshest rock available in a district and from those that appeared to be typical of larger masses. The phrase "granitic types" refers to silicic rocks in general and includes in addition to granites, granodiorites, biotite gneisses and other related petrographic types.

Large samples were collected from each outcrop; an average of 10-20 kilos. Thin sections were made for modal analyses, then the samples were crushed and separate splits were taken for spectrochemical and chemical analyses. The bulk of most of the samples were then sent to Massachusetts Institute of Technology for age determination using mass spectrographic determination techniques on the isotopes potassium-40 and argon-40 found in the biotite. The results reported here are to be regarded tentative, subject to corrections of 5% more or less (P. M. Hurley, 1958, written communication).

The trace elements of the granites were determined by spectrographic methods without using internal standards and with the following apparatus and working conditions.

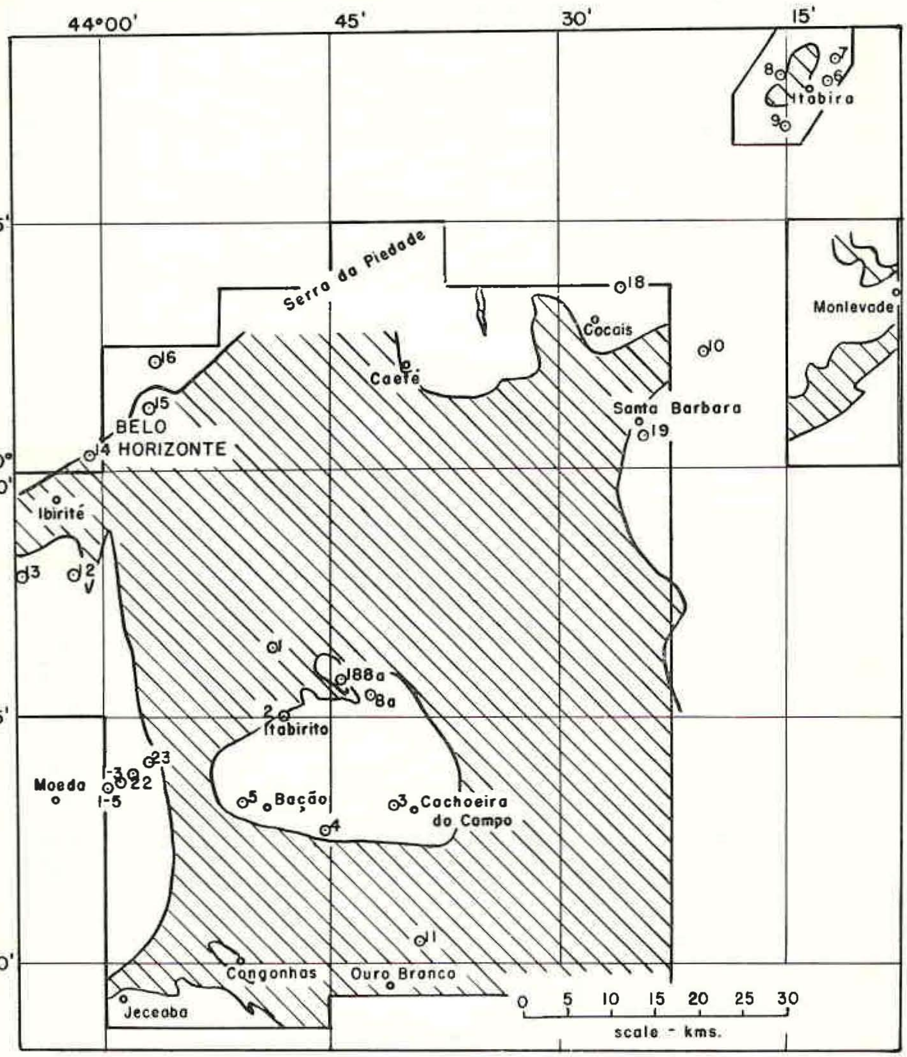
Spectrograph — Grating spectrograph with a 3-meter focal length, Eagle mount, and dispersion of 5A/mm. Slit 0.025 mm.

Cathode — Graphite electrode, 3 mm. diameter.

Anode — Graphite electrode of high purity (United Spectrographic Graphite) 6 mm diameter, with a cavity 3 mm wide by 7 mm deep and with a wall of 0.5 mm thickness. The external cut extended 9 mm below the lip of the cavity.

Analytical Gap — 4 mm maintained throughout the excitation period.

Excitation Source — Manufactured by Baird Associates, adjusted to furnish a direct current of 250 volts and 15 amperes.



Generalized map of the Quadrilátero Ferrífero

Granitic and gneissic bodies unhatched

Prefixed letters omitted from specimen locations

Length of Exposure — Total consumption of the sample in arc (± 110 seconds).

Wavelength Range and Photographic Emulsion — Region a) 2,460 to 3,870 A — Kodak plate SA-1. Region b) 3,980 to 5,400 A — Kodak plate III-F.

(The exposures in region b were made with a rotating two-step sector, on the secondary focus of the spectrograph).

Lines Used —

Ba	—	4,934.09 A
Co	—	3,453.50
Cr	—	4,254.35
Cu	—	3,273.96
La	—	4,333.73
Nb	—	3,163.40
Ni	—	3,050.83
Pb	—	2,833.07
Sc	—	4,246.33
Sn	—	3,262.33
Sr	—	4,607.33
V	—	4,384.72
Y	—	4,374.93(*)
Zr	—	3,391.97

Microphotometer — Jarrell-Ash comparator-projector (model 200).

Sample Preparation — The samples were thoroughly homogenized then mixed with half of their weight of powdered graphite of high purity. 25 milligrams of each mixture was transferred to the anode crater and volatilized in the arc to total consumption. All the exposures were made in duplicate.

Standards — A series of six standards containing all the trace elements was made using a base called "synthetic granite" (SiO_2 72.3%, Al_2O_3 15.5%, Fe_2O_3 1.5%, $CaCO_3$ 1.2%, $MgCO_3$ 0.5%, Na_2CO_3 3.5%, and K_2CO_3 5.5%, sintered at 900° C.) All the components of the standards are spectrographically pure products, except SiO_2 which was added in the form of finely ground clear quartz crystal. The trace elements added range from 1 to 333 ppm, except Ba and Sr which range from 10 to 3,330 ppm.

(*) Mn 4374.497 can interfere with this yttrium line. However, no granite sample that was analyzed showed an amount of manganese higher than the limits of interference.

The validity of the analytical curves constructed with these standards was tested on all the plates using samples G-1 and W-1 (1,2) obtained directly from the U.S. Geological Survey. Taking the values obtained for the granite G-1 in two plates as an example, the accuracy of the method used can be figured as:

Zr, Y, Pb, and V, always showed a deviation of less than ± 10% of the values recommended by Ahrens (2).

Ba and La, a deviation of less than ± 20%.

Cu and Cr, a deviation of less than ± 40%.

Deviation greater than — 50% were obtained in the cases of Ni (1.33 ppm) and Co (2.0 ppm). However, these values are very close to the results recently obtained by Smales (3) who used a technique of neutron activation and obtained 1.0 and 2.1 ppm, respectively.

The curves for the determination of Sr were corrected by taking into account the value (233 ppm) recommended by Herzog and Pinson (4) for G-1.

The results of the spectrographic study appear in table 1.

PRELIMINARY RESULTS

The trace element analyses, shown in table 1, were used as a basis for the calculations of the standard deviations for each element, shown in table 2. The variation from the arthmetic mean of each sample was then figured as a fraction of the standard deviation. This fraction, carried to two decimal places (Table 2) can used as a measure of correlation between different samples. For example, sample Ha-1 has 1000 ppm (Table 1) of BaO. The arithmetic mean for BaO is 882.4 and the standard deviation is 435.0 (Table 2) then 1000 — 882.4 = 117.6; 117.6/435.0 = 0.27. This is shown as + .27 since the value of 1000 lies above the arithmetic mean.

Certain samples calculated out more than 3 standard deviations from the arithmetic mean. These were considered aberrant for the purposes of correlation and are shown as *n* standard deviations from the arithmetic mean. For elements with such samples, the arithmetic mean and standard deviation were recalculated excluding the *ns* values. Ha-17 from Gouvêa, was also not included in the computations of standard deviation and arithmetic mean since these values are meant to be representative of the Quadrilátero Ferrífero alone.

Ha:1 Benga dam, north of Itabirito

Consists of 34% quartz, 9% microcline, 12% orthoclase, 11% plagioclase, 26% white mica, 6% carbonate, 1% opaque minerals, 0.3% biotite, and minor amounts of chlorite, tourmaline, and zircon.

TABLE 1 — Quantitative Results of Trace Element Analyses (in parts per million).

	Specimen	BaO	CoO	Cr_2O_3	CuO	La_2O_3	Nb_2O_5	NiO	PbO	SnO	SrO	Sc_2O_3	V_2O_3	Y_2O_3	ZrO_2	
I	Ha-1	1000	6.5	40	21	120	800	26	27	22	130	16	42	100	400	Bonga Dam
	Ha-5b	650	8.5	17	15	n.d.	26	25	20	13	330	17	48	50	250	Saboeira
	Ha-9	900	13.5	n.d.	40	120	50	11	n.d.	22	72	22	80	170	500 ±	Itabira
	Ha-16	1800	10	26	14	250	38	23	16	57	450	11	31	84	420 ±	Belo Horizonte
	Z-8a	1000	8.0	14	8.0	120	50	18	23	78	170	14	80	110	300	Rio das Pedras
	Z-188a	1300	8.8	48	45	85	70	29	25	78	240	23	100	110	410 ±	Rio das Pedras
II	Ha-6	1150	n.d.	2.3	0.6	35	33	2.5	19	4.5	150	7.0	10	47	130	Itabira
	Ha-7	850	n.d.	2.2	0.7	n.d.	30	2.7	17	4.8	140	5.8	2.0	35	145	Itabira
	Ha-11	500	3.2	1.5	0.7	130	15	5.0	12	86	62	3.8	10	30	290	Ouro Branco
	Ha-12	550	2.3	1.3	2.0	98	33	5.8	13	29	100	4.0	15	310	205	Casa Branca
	Ha-14	1500	n.d.	n.d.	2.4	n.d.	36	2.8	14	10	330	n.d.	5.5	12	155	Barreiro
	Ha-18	1000	2.5	0.5	2.4	n.d.	n.d.	n.d.	6.0	6.2	330	3.2	38	8.0	165	Cocais
III	Ha-8	500	n.d.	1.2	5.5	270	82	3.5	35	21	50	n.d.	12	400	550 ±	Borrachudos Dam
	Ha-10	tr.	n.d.	n.d.	2.5	140	160	5.0	25	98	17	n.d.	n.d.	250	370	Peti Reservoir
	Ha-13	900	5.6	4.2	2.5	110	16	8.0	11	43	150	12	42	92	390	Ibirité
	Ha-19	400	3.5	2.8	7.5	n.d.	47	10.5	7.5	19	130	4.5	56	80	145	Santa Bárbara
IV	Ha-2	1600	n.d.	2.0	1.5	60	22	3.0	30	13	170	5.5	12	28	150	Itabirito
	Ha-3	1100	n.d.	4.6	2.3	n.d.	13	5.0	23	6.0	280	5.5	20	14	150	Cachoeira do Campo
	Ha-4	1000	4.0	5.6	5.0	n.d.	10	8.5	20	8.0	340	6.6	20	12	155	Eng. Corrêa
	Ha-5a	780	n.d.	2.8	9.0	n.d.	10	3.0	27	2.5	230	6.4	11	29	80	Saboeira
V	Ha-22	800	4.4	65	6.0	90	32	10.0	20	32	160	7.0	60	210	200	Moeda Road
	Ha-23	370	4.0	1.0	7.5	90	280	6.0	37	24	86	4.8	54	90	390	Moeda Road
	WMST1-3	480	3.8	11	4.5	100	38	11	24	35	125	5.5	60	115	320	Moeda Road
	WMST1-5	430	3.8	10	3.3	80	41	13	120 ±	46	130	5.0	40	98	280	Moeda Road
	Ha-15	1500	3.6	2.4	1.5	200	35	11	40	n.d.	200	55	11	n.d.	300	Belo Horizonte
	Ha-17	520	5.0	10	22	40	51	13	24	29	115	7.7	38	33	260	Gouvêa

n.d. = not detected, below the limits of sensitivity
± = value determined by extrapolation, at some distance above the working curve set up by the standards.
tr. = trace, at same distance below the working curve set up by the standards.

TABLE 2 — Calculated Standard Deviations of Samples (see explanation in text)

	Specimen	BaO	CoO	*Cr_2O_3	*CuO	La_2O_3	*Nb_2O_5	NiO	*PbO	SnO	SrO	*Sc_2O_3	V_2O_5	*Y_2O_3	ZrO_2
I	Ha-1	+ .27	+ .76	+ ns	+ ns	+ .49	+ ns	+ 2.00	+ .69	− .29	− .52	+ 1.26	+ .28	+ .34	+ 1.01
	Ha-5b	− .53	+ 1.34	+ 3.00	+ 2.63	− 1.12	− .37	+ 1.88	− .05	− .60	+ 1.43	+ 1.42	+ .51	− .41	− .19
	Ha-9	+ .04	+ 2.77	− .96	+ ns	+ .49	+ .90	+ .13	− 2.17	− .29	− 1.08	+ 2.23	+ 1.70	+ 1.39	+ 1.81
	Ha-16	+ 2.11	+ 1.77	+ ns	+ 2.36	+ 2.24	+ .26	+ 1.63	− .47	+ .92	+ 2.61	+ .45	− .13	+ .10	+ 1.16
	Z-8a	+ .27	+ 1.19	+ 2.30	+ .79	+ .49	+ .90	+ 1.01	+ .27	+ 1.65	− .13	+ .94	+ 1.70	+ .49	+ .20
	Z-188a	+ .96	+ 1.42	+ ns	+ ns	+ .02	+ 1.97	+ 2.38	+ .48	+ 1.65	+ .56	+ 2.39	+ 2.44	+ .49	+ 1.08
II	Ha-6	+ .62	− 1.10	− .43	− 1.14	− .65	0	− .92	− .16	− .89	− .32	− .20	− .91	− .45	− 1.15
	Ha-7	− .07	− 1.10	− .45	− 1.12	− 1.12	− .16	− .90	− .37	− .88	− .42	− .39	− 1.21	− .63	− 1.03
	Ha-11	− .88	− .18	− .61	− 1.12	+ .62	− .96	− .55	− .90	+ 1.92	− 1.18	− .71	− .91	− .70	+ .13
	Ha-12	− .76	− .44	− .66	− .77	+ .19	0	− .51	− .79	− .05	− .81	− .68	− .72	+ ns	− .55
	Ha-14	+ 1.42	− 1.10	− .96	− .67	− 1.12	+ .16	− .87	− .68	− .70	+ 1.43	− 1.33	− 1.07	− .98	− .95
	Ha-18	+ .27	− .38	− .85	− .67	− 1.12	− 1.76	− 1.24	− 1.53	− .83	+ 1.43	− .81	+ .13	− 1.04	− .87
III	Ha-8	− .88	− 1.10	− .68	+ .14	+ 2.51	+ 2.61	− .80	+ 1.54	− .32	− 1.30	− 1.33	− .83	+ ns	+ 2.20
	Ha-10	− 2.03	− 1.10	− .96	− .65	+ .76	+ ns	− .55	+ .48	+ 2.34	− 1.62	− 1.33	− 1.28	+ 2.60	+ .76
	Ha-13	+ .04	+ .50	+ .02	− .65	+ .36	− .91	− .24	− 1.00	+ .44	− .32	+ .61	+ .28	+ .22	+ .92
	Ha-19	− 1.11	− .10	− .31	+ .66	− 1.12	+ .74	+ .07	− 1.37	− .39	− .52	− .60	+ .71	+ .04	− 1.03
IV	Ha-2	+ 1.65	− 1.10	− .50	− .91	− .32	− .59	− .86	+ 1.01	− .60	− .13	− .44	− .83	− .73	− .99
	Ha-3	+ .50	− 1.10	+ .11	− .70	− 1.12	− 1.07	− .55	+ .27	− .84	+ .95	− .44	− .53	− .95	− .99
	Ha-4	+ .27	+ .05	+ .34	+ .01	− 1.12	− 1.23	− .17	− .05	− .77	+ 1.54	− .26	− .53	− .98	− .95
	Ha-5a	− .24	− 1.10	− .31	+ 1.05	− 1.12	− 1.23	− .86	+ .69	− .96	+ .46	− .29	− .77	− .72	− 1.55
V	Ha-22	− .19	+ .16	+ ns	+ .27	+ .08	− .06	+ .01	− .05	+ .06	− .22	− .20	+ .95	+ 1.99	− .59
	Ha-23	− 1.18	+ .05	− .73	+ .66	+ .08	+ ns	− .49	+ 1.75	− .22	− .95	− .55	+ .73	+ .19	+ .92
	WMST1-3	− .93	0	+ 1.72	− .12	+ .22	+ .26	+ .13	+ .37	+ .16	− .57	− .44	+ .95	+ .57	+ .37
	WMST1-5	− 1.04	0	+ 1.37	− .44	− .05	+ .42	+ .38	+ ns	+ .54	− .52	− .52	+ .21	+ .31	+ .05
	Ha-15	+ 1.42	− .07	− .40	− .91	+ 1.56	+ .10	+ .13	+ 2.07	− 1.05	+ .16	+ ns	− .77	− 1.16	+ .20
	Ha-17	− .83	+ .33	+ 1.37	+ ns	− .58	+ .96	+ .38	+ .37	− .05	− .66	− .08	+ .13	− .66	− .11
	Arithmetic Mean	882.4	3.84	4.13	4.97	83.5	33.04	9.93	20.48	30.32	182.88	8.22	34.38	77.13	274.00
	Standard Deviation	435.0	3.49	4.29	3.82	74.4	18.78	8.02	8.02	28.91	102.21	6.16	26.82	66.44	125.04

(*) Calculation of the arithmetic mean and standard deviation (s) for these elements does not included those samples that lie more than 3s from the arithmetic mean. Such samples are called **ns** in the table and are considered aberrant for the purposes of comparison.

Trace elements in average concentrations are Ba, La, Sn, Sr, V, and Y; above average Co, Pb, and Zr; much above average Ni and Sc; and superabundant Cr, Cu, and Nb.

Ha-2: Itabirito, tentative A^{40}/K^{40} age 1330 m.y.*

Consists of 35% quartz, 17% microcline, 11% orthoclase, 26% plagioclase, 5.5% biotite, 3% white mica, 3% epidote, and minor amounts of chlorite.

Trace elements in average concentrations are Cr, La, Sr, and Sc; below average Cu, Nb, Ni, Sn, V, Y, and Zr; much below average Co; above average Pb; and much above average Ba.

Ha-3: Cachoeira do Campo, tentative A^{40}/K^{40} age 720-760 m.y.

Consists of 34% quartz, 9% microcline, 50% plagioclase, 6% biotite, and minor amounts of white mica, tourmaline, zircon, and epidote.

Trace elements in average concentrations are Ba, Cr, Pb, Sc, and V; below average Cu, Ni, Sn, Y, and Zr; much below average Co, La, and Nb; and above average Sr.

Ha-4: Engenheiro Corrêa, tentative A^{40}/K^{40} age 2440-2520 m.y.

Consists of 36% quartz, 5% microcline, 5% orthoclase, 45% plagioclase, 6% biotite, 1% opaque minerals, and minor amounts of white mica, epidote, and apatite.

Trace elements in average concentrations are Ba, Co, Cr, Cu, Ni, Pb, Sc, and V; below average Sn, Y, and Zr; much below average La and Nb; and much above average Sr.

Ha-5: Saboeira, felsic part of rock.

Consists of 29% quartz, 17% microcline, 8% orthoclase, 36% plagioclase, 5% biotite, 2.5% white mica, 3% epidote, and minor amounts of chlorite.

Trace elements in average concentrations are Ba, Cr, Sr, and Sc; below average Ni, Sn, V, and Y; much below average Co, La, Nb, and Zr; and above average Pb and Cu.

Ha-5b: Saboeira, mafic part of rock.

Consists of approximately 30% quartz, 8% microcline, 6% orthoclase, 40% plagioclase, 10% biotite, 1% white mica, 4% epidote, and minor amounts of zircon and apatite.

Trace elements in average concentrations are Cr, Nb, Pb, Sr, Sc, and Y; below average Sn; much below average La; and much above average Co, Cr, Cu, Ni, Sr, and Sc.

(*) m.y. = million years.

Ha-6: Itabira, tentative A^{40}/K^{40} age 475-560 m.y.

Consists of aproximately 55% quartz, 35% plagioclase, 9% biotite, and minor amounts of white mica, epidote, and garnet.

Trace elements in average concentrations are Cr, Nb, Pb, Sr, Sc, and Y; below average La, Ni, Sn, and V; much below average Co, Cu, and Zr; and above average Ba.

Ha-7: Itabira, tentative A^{40}/K^{40} age 490 m.y.

Consists of approximately 35% quartz, 6% orthoclase, 9% microcline, 37% plagioclase, 10% biotite, 3% white mica, and minor amounts of chlorite, apatite, and epidote.

Trace elements in average concentrations are Cr, Nb, Pb, Sr, Sc, and Y; Sc; below average Ni, Sn, and Y; and much below average Co, Cu, La, V, and Zr.

Ha-8: Borrachudos Dam, Itabira.

Consists of approximately 35% quartz, 40% potash feldspar, 15% plagioclase, 8% biotite, and minor amounts of white mica, opaque minerals, carbonate, epidote, zircon, fluorite, and leucoxene.

Trace elements in average concentrations are Cu and Sn; below average Ba, Cr, Ni, and V; much below average Co, Sr and Sc; much above average La, Nb, Pb, and Zr; and superabundant Y.

Ha-9: Itabira

Consists of approximately 50% quartz, 20% potash feldspar, 10% plagioclase, 15% biotite, 5% white mica, and minor amounts of chlorite, opaque minerals, carbonate, and epidote.

Trace elements in average concentrations are Ba, La, Ni, and Sn; below average Cr; much below average Pb and Sr; above average Nb; much above average Co, Sc, V, Y, and Zr; and superabundant Cu.

Ha-10: Peti Dam, northeast of Santa Bárbara, tentative A^{40}/K^{40} age 475-500 m.y.

Consists of approximately 30% quartz, 55% potash feldspar, 9% plagioclase, 3% biotite, 1% white mica, 1% chlorite, and 1% fluorite.

Trace element in average concentration is Pb; below average Cr, Cu, and Ni; much below average Ba, Co, Sr, Sc, and V; above average La and Zr; much above average Sn and Y; and superabundant Nb.

Ha-11: North of Ouro Branco.

Consists of approximately 30% quartz, 40% potash feldspar, 15% plagioclase, 6% biotite, 8% white mica, 1% chlorite, and minor amounts of epidote.

Trace elements in average concentrations are Co and Zr; below average Ba, Cr, Nb, Ni, Pb, Sc, V, and Y; much below average Cu and Sr; above average La; and much above average Sn.

Ha-12: Casa Branca

Consists of 37% quartz, 10.5% microcline, 14% orthoclase, 21.5% plagioclase, 6% biotite, 7% white mica, 2% chlorite, 2% epidote, 1% xenotime. zircon, and apatite.

Trace elements in average concentrations are Co, La, Nb, and Sn; below average Ba, Cr, Cu, Ni, Pb, Sr, Sc, V, and Zr; and superabundant Y.

Ha-13: Ibirité, tentative A^{40}/K^{40} age 555 m.y.

Consists of 25.5% quartz, 14% microcline, 16% orthoclase, 19.5% plagioclase, 7% biotite, 16% white mica, 1% chlorite, 0.5% epidote. and minor amounts of zircon and allanite.

Trace elements in average concentrations are Ba, Co, Cr, La, Ni, Sn, Sr, V, and Y; below average Cu, Nb, and Pb; and above average Sc and Zr.

Ha-14: Barreiro

Consists of 30% quartz, 8,5% microcline, 20% orthoclase, 32% plagioclase, 2% biotite, 3% white mica, 4.5% chlorite, and 1% epidote.

Trace element in average concentration is Nb; below average Cr, Cu, Ni, Pb, Sn, Y and Zr; and much average Ba and Zr.

Ha-15: Morro da Pedra, Belo Horizonte.

Consists of 30% quartz, 8,5% microcline, 20% orthoclase, 32% placlase, 7.5% biotite, 4.5% white mica, 2% epidote, 0.3% chlorite, and minor amounts of opaque minerals, zircon, and apatite.

Trace elements in average concentrations are Co, Cr, Nb, Ni, Sr, and Zr; below average Cu and V; much below average Sn and Y; much above average Ba, La and Pb; and superabundant Sc.

Ha-16: Prado Lopes quarry, Belo Horizonte, tentative A^{40}/K^{40} age 1260 m.y.

Consists of 20% quartz, 38% microcline, 4% orthoclase, 25% plagioclase, 10% biotite, 1% white mica, 1% hornblende, and minor amounts of chlorite, opaque minerals, apatite, and xenotime.

Trace elements in average concentrations are Nb, Pb, Sc, V, and Y; above average Sn; much above average Ba, Co, Cu, La, Ni, Sr, and Zr; and superabundant Cr.

Ha-17: Gouvêa, near Diamantina, tentative A^{40}/K^{40} age 880 m.y.

Consists of approximately 30% quartz, 15% potash feldspar, 35% plagioclase, 6% biotite, 7% white mica, 2% chlorite, 3% carbonate, and 2% epidote.

Trace elements in average concentrations are Co, Ni, Pb, Sn, Sc, V, and Zr; below average Ba, La, Sr, and Y; above average Nb; much above average Cr; and superabundant Cu.

Ha-18: Cocais

Consists of approximately 35% quartz, 30% potash feldspar, 20% plagioclase, 10% biotite, 4% white mica, and 1% epidote.

Trace elements in average concentrations are Ba, Co, and V; below average Cr, Cu, Sn, Sc, and Zr; much below average La, Nb, Ni, Sc, and Zr; and much above average Sr.

Ha-19: Santa Bárbara.

Consists of approximately 40% quartz, 25% potash feldspar, 20% plagioclase, 7% biotite, 2% white mica, 1% carbonate, 5% epidote and minor amounts of opaque minerals, zircon, and allanite.

Trace elements in average concentrations are Co, Cr, Ni, Sn, and Y; below average Sr and Sc; much below average Ba, La, Pb, and Zr; and above average Cu, Nb, and V.

Ha-22: BR-3 — Moeda Road.

Consists of approximately 20% quartz, 35% potash feldspar, 30% plagioclase, 7% biotite, 3% white mica, 3% epidote, 2% xenotime, and minor amounts of chlorite and zircon.

Trace elements in average concentrations are Ba, Co, Cu, La, Nb, Ni, Pb, Sn, Sr, and Sc; below average Zr; above average V; much above average Y; and superabundant Cr.

Ha-23: BR-3 — Moeda Road.

Consists of approximately 30% quartz, 35% potash feldspar, 15% plagioclase, 7% biotite, 10% white mica, 1% chlorite, 1% carbonate, and 1% epidote.

Trace elements in average concentrations are Co, La, Ni, Sn, and Y; below average Cr, Sr, and Sc; much below average Ba; above average Cu, V, and Zr, much above average Pb; and superabundant Nb.

WMSTI-3 — BR-3 — Moeda Road.

Consists of approximately 25% quartz, 30% potash feldspar, 30% plagioclase, 7% biotite, 2% white mica, 5% epidote, 1% xenotime, and minor amounts of apatite and allanite.

Trace elements in average concentrations are Co, Cu, La, Nb, Ni, Pb, Sn, Sc, and Zr; below average Ba and Sr; above average V and Y; and much above average Cr.

WMSTI-5 — BR-3 — Moeda Road.

Consists of approximately 30% quartz, 30% potash feldspar, 25% plagioclase, 6% biotite, 2% white mica, 3% chlorite, 3% epidote, and minor amounts of carbonate, apatite, xenotime, and fluorite.

Trace elements in average concentrations are Co, Cu, La, Nb, V, Y, and Zr; below average Sr and Sc; much below average Ba; above average Sn; much above average Cr; and superabundant Pb.

Z-8a: Rio de Pedras.

Consists of approximately 20% quartz, 40% potash feldspar, 20% plagioclase, 15% biotite, 3% epidote, 2% titanite, and minor amounts of white mica.

Trace elements in average concentrations are Ba, La, Pb, Sr, Y, and Zr; above average Cu, Nb, and Sc; and much above average Co, Cr, Ni, Sn and V.

Z-188a: Rio de Pedras.

Consists of approximately 20% quartz, 25% potash feldspar, 30% plagioclase, 20% biotite, 2% epidote, 4% titanite, and minor amounts of white mica.

Trace elements in average concentrations are La, Pb, and Y; above average Ba and Sr; much above average Co, Nb, Ni, Sn, Sc, V, and Zr; and superabundant Cr and Cu.

INTERPRETATION OF PRELIMINARY RESULTS

In order to interpret correctly the data obtained by spectrochemical analysis, supplementary evidence must be obtained from chemical analysis of the major constituents, absolute age determination, field mapping, and petrographic study. From studies of the trace elements alone, howewer, valuable suggestions can be obtained on the course of future work, on hypotheses of origin to check by other means, on suggested correlations between rocks that crop out at great distances apart. It is in this light that the interpretions that follow have been made.

Group I:

Specimen Ha-1, 5b, 9, 16, Z8a, and Z188a all have generally above average Co, Cu, Ni, and Sc; average or above of Ba, Nb, V, Y, and Zr; average or below of Pb. Cr is much above average in all but one and La, Sn, and Sr, range from low to high.

Ha-1 is found in a contact zone of granite and low metamorphic grade pelitic and carbonaceous rocks; Z8a and Z188a are found in a similar environment but with a higher metamorphic grade, i.e. the carbonaceous rocks have gone over to amphibolites. Ha-5b, 9, and 16 are all within bodies presently mapped as granite or gneiss. These bodies show relict sedimentary features such as a fine and coarse layering of mafic and felsic-rich bands and larger mafic-rich xenoliths that may represent a pelitic sediment.

The high Co, Cu, Ni, Sc, and Cr, and the above average V, are probably carried by the micas of these rocks (Rankama and Sahama, 5) since all these elements replace Mg or Fe. Ba replaces K in the micas and feldspars and Y and Zr may be present in mineral inclusions in biotite.

The only absolute age determination to date of this group, that is Ha-16, indicates 1260 m.y.

GROUP II:

Specimens Ha-6, 7, 11, 12, 14, and 18 all have generally below average Co, Cr, Cu, Ni, Pb, and Sc; average or below of Nb, V, and Zr. Ba, La, Sn, Sr, and Y range from low to high.

Ha-6 is considered to be a tonalite gneiss and 7 a quartz-muscovite gneiss both of mixed igneous-sedimentary origin and parts of larger igneous-looking bodies. Ha-12, 14, and 18 occur in similar environments to 6 and 7. Ha-11 is a small granitic body that has apparently granitized arkosic beds within the Piracicaba group.

This group has, in general, a very low concentration of rare elements. This may be a reflection of the country rock affected, since quartz-rich rocks and arkoses are known to carry less of trace elements here determined as below average than do pelitic rocks. Also, the granites or granitizing solutions involved may have separated just prior to the pegmatite stage, when the residual liquids are generally impoverished in most trace elements (Nockolds and Mitchell, 6).

Tentative age determinations on Ha-6 indicate 475-560 m.y; Ha-7,490 m.y.

Group III:

This group is a heterogeneous one but shows much similarity to Group II with some significant differences. It includes Ha-8, 10, 13 and 19.

Ha-8 is considered an "igneous" granite but has been mapped grading into types Ha-6 and 7. Co, Cr, Ni, Sc, V, all meet the requirements for

Group II whereas Cu, La, Nb, Pb, Y, and Zr are all higher. All these latter elements are known to concentrate late, that is in the pegmatite or hydrothermal stage. Sr and Ba are known to concentrate early in granitic rocks (5, p. 472). It is significant that Sr is lower than any sample of the group and that Ba is as low as the lowest. Thus, this rock may represent a later differentiate but a comagmatic facies of Group II.

Ha-10 is similar in appearance and in apparent field relations to Ha-8. In it, Co, Cr, Cu, Ni, Sc, and V fit the requirements of Group II. La, Nb, Pb, Sn, Y and Zr are all higher; Ba and Sr lower. This trace element behaviour also indicates a late stage crystallate. Tentative age determinations on this rock show 475-500 m.y.

Ha-13 is a granitic rock from Ibirité and is apparently typical of a much larger granitic mass. Cu, Nb, Ni, Pb, and V, fit group II; Co, Cr, Sc, and Zr, are all higher. Zr is concentrated in zircon, visible in thin section; Co, Cr, and Sc are probably concentrated in the biotite. The rock is apparent ly also comagmatic with Group II but may be either an early differentiate or may have admixed pelitic rocks to give it its more basic trace element nature. Tentative age determinations show 555 m.y. for this rock.

Ha-19 is a granitic rock from Santa Bárbara and represents a large homogeneous rock mass. Co, Cr, Pb, Sc, and Zr, fit group II, while Cu, Nb, Ni, and V are all higher. Cu and Ni may be present in the opaque minerals visible in thin section or they may be, together with Nb and V, in biotite.

Group IV:

Specimens Ha-2, 3, 4, and 5a, all have below average La, Nb, Sn, V, Y, and Zr; average or below average Co and Ni; average Cr and Sc; average or above average of Ba, Pb, and Sr; and low to high Cu.

This is actually a very heterogeneous group as far as absolute ages show. According to Hurley (written communication, 1958) the tentative age, subject to a correction of 5% or so, of Ha-2 is 1330 m.y., Ha-3 is 720-760 m.y., and Ha-4 is 2440-2520 m.y. The trace elements of these rocks show very good correlation despite this discrepancy of age.

The tentative conclusion drawn from these apparently conflicting data is that the later granites in the region of Itabirito-Bação-Cachoeira do Campo represent a remobilization, with no essential change of chemical composition, of the 2440-2520 m.y. old rock 1330 m.y. and 720-760 m.y. ago. In the lending credence to this idea.
field, the younger rocks are extremely difficult to separate among themselves,

Group V:

Specimens Ha-22, 23, WMSTI-3, and 1-5 have above average V and Y; average or above average Nb, Pb, and Zr; average Co, Cu, La, Ni, Sc, and Sn; average or below average Ba and Sr; and from low to high Cr.

The group represents a series of rocks collected west of the Serra da Moeda and each is typical of a mappable unit. The close similarity of the trace element analyses suggests that either all these units are comagmatic, or that, at least, they represent a remobilized ancient rock, as in the case of Group IV.

No absolute age determinations are available as yet on this suite of rocks.

Morro da Pedra granite:

Ha-15, from the Morro da Pedra, in Belo Horizonte, shows no obvious correlation using trace elements to any of the above groups. Its field relations show it to be a fairly late intrusive. Thus, it has contact metamorphosed country rock to a biotite isograde whereas other metasediments in the same general area, but away from this intrusion, all show a retrogression of biotite to chlorite.

The alternatives are that this rock represents a thorough mixing of a "granitizing solution" derived from Group II-III, and country rock, or that it is actually a facies of another magma. Neither choice can be proven or disproven at this point. The determination of the absolute age of this rock, which is still forthcoming, will be needed to settle its origin.

Gouvêa granite:

This sample, Ha-17, collected from Gouvêa, near Diamantina, shows no obvious correlation using trace elements to the granitic suites of the Quadrilátero Ferrífero. Its tentative age, 880 m.y. is also quite different from the ages determined to date of those suites.

CONCLUSION

Trace elements have been used to classify the granitic rocks of the Quadrilátero Ferrífero into certain distinctive groups. In the cases of Groups I and II-III, the trace elements have allowed a correlation of rocks separated by great distances and other intervening formations. In the cases of Groups IV and V, the trace elements have suggested a single mode of origin for rocks of either differing ages or appearances or both.

Tentative age determinations obtained to date appear to support the conclusions drawn from the spectrochemical work. Further work on these phases in conjunction with field mapping and petrographic and chemical analyses will prove or disprove the final validity of these hypotheses.

REFERENCES CITED

1. FAIRBAIRN, H. W., and OTHERS (1950-51 - *A cooperative investigation of Precision and Accuracy in Chemical, Spectrochemical and Modal Analysis of Silicate Rocks*. U. S. Geological Survey Bull. 980.

2. AHRENS, L. H. (1954) - *Quantitative Spectrochemical Analysis of Silicates. pp.* 20-38. Pergamon Press, London.

3. SMALES, A. A. (1955) - *Some Trace-element determinations in G-1 and W-1 by neutron activation.* Geochim. et Cosmochim. Acta vol. 8, p. 300.

4. HERZOG, L. F. and PINSON, Jr., W. H. (1955) - *The Sr and Rb contents of the granite G-1 and diabase W-1* Geochim. et Cosmochim. Acta vol. 8 pp. 295-298.

5. RANKAMA, KALERVO and SAHAMA, T. G. (1949) - *Geochemistry*. 912 p. Chicago.

6. NOCKOLDS, S. R. and MITCHEL, R. C. (1948) - *The Geochemistry of some Caledonian Plutonic Rocks: A study in the Relationship between the major and the trace elements of igneous rocks and their minerals.* Trans, Royal Soc. Edinburgh, volume LXI, part 2, pp. 533-576.