

COBALT, NICKEL, CHROMIUM, SCANDIUM AND NIOBIUM IN BIOTITE AND THE SCANDIUM GEOLOGICAL THERMOMETER*

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RESUMO

Determinações espectroquímicas de Co, Ni, Cr, Sc e Nb, foram realizadas em biotita e na rocha hospedeira correspondente, tomando-se 6 amostras de granito-granodiorito e 1 amostra de quartzo-biotita gnaisse do Quadrilátero Ferrífero de Minas Gerais. As determinações foram realizadas com o objetivo de verificar o comportamento do Sc na biotita como termômetro geológico, bem como para estudar a variação dos outros elementos nas citadas amostras.

Co e Ni se mostram mais abundantes na biotita do que na rocha correspondente, e ambos elementos diminuem em cada produto diferenciado sucessivo. A quantidade absoluta de Ni em ambas (biotita, 82 a 6 ppm, e rocha, 20 a 4 ppm) diminui mais rapidamente do que o Co (respectivamente 60 ppm a n. d. e 6,7 ppm a n. d.), exceto no último produto diferenciado, um granito pneumatólitico, onde Co não foi detectado (n. d.), mas onde foi encontrado Ni.

Cr geralmente diminui em cada amostra sucessiva de biotita (77 a 9.5 ppm) mas sempre se mostra mais abundante na biotita do que na rocha correspondente (12 ppm a n. d.). O fato de Cr formar complexos de CrO_4^{-5} nas últimas fases da diferenciação é provavelmente a causa desse elemento não ter sido completamente utilizado, como aconteceu com o Co.

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Geralmente o Sc diminui em cada amostra de rocha sucessiva (11 ppm a n. d.), mas aumenta na biotita de 8,2 ppm até o granito pré-pneumatolítico, onde atinge um máximo de 130 ppm. A biotita deveria ter causado uma utilização total de complexos de ScO_4^{-5} dentro da fase líquida. A biotita formada na fase pneumatolítica somente apresenta 4,6 ppm de Sc, mas na própria rocha correspondente o Sc já não é detectável, evidenciando a eficiência da biotita como "scavenger" de Sc.

Nb mostra pequeno teor na rocha (~ 15 ppm) até o início da fase pneumatolítica, quando atinge 112 ppm. Nas biotitas formadas em primeiro lugar, Nb não é detectável e quando começa a aparecer ele é relativamente abundante, chegando ao máximo na fase pneumatolítica (670 ppm).

Sc deve ser considerado com máxima cautela como um indicador de temperatura. Nessas rochas o Sc foi utilizado totalmente na fase pré-pneumatolítica e com a queda da temperatura nas fases finais, a quantidade de Sc também diminui.

ABSTRACT

Co, Ni, Cr, Sc, and Nb were determined spectrochemically in 6 samples of granite-granodiorite rock and their biotites and also in 1 quartz biotite gneiss and its biotite from the Quadrilátero Ferrífero of Minas Gerais. The analysis were made to check the variation of these elements and also to verify the use of Sc content in biotite as a geological thermometer.

Co and Ni were always more abundant in biotite than in the rock and both decreased in succeeding differentiates. The absolute amount of Ni in both biotite (82 to 6 ppm) and rock (20 to 4 ppm) decreased more rapidly than Co (60 ppm to n. d., 6.7 ppm to n. d.) except in the last differentiate, a pneumatolytic granite where Co was not detected (n. d.) but Ni was still present.

Cr decreased in succeeding samples of biotite (77 to 9.5 ppm) but was always higher in biotite than in the rock (12 ppm to n. d.). Because it forms CrO_4^{-5} complexes in the later stages of differentiation, Cr is not completely depleted as is Co.

Sc generally decreased in each succeeding rock sample (11 ppm to n. d.), but increased in the biotite from 8.2 ppm to a pre-pneumatolytic granite where it reached a maximum (130 ppm). This biotite must have caused depletion of the ScO_4^{-5} complexes in the liquid phase. The biotite formed in the pneumatolytic stage has only 4.6 ppm Sc, but in the rock Sc is not detectable, showing the efficiency of biotite as a scavenger for Sc.

Nb shows a low abundance in the rock (15 ppm) until the pneumatolytic stage, when it reaches 112 ppm. In the first biotite to appear, Nb is not detectable; in later biotite it is relatively abundant, reaching a maximum in the pneumatolytic stage (670 ppm).

Sc must be used with extreme caution as an indicator of temperature. Sc was impoverished in these rocks in a pre-pneumatolytic stage, and so with decreasing temperature in the final stages, the absolute amount of Sc also went down.

INTRODUCTION

In 1943, Oftedahl wrote on the abundance of Sc in mafic minerals, noting that Sc was high in pyroxenes of mafic rocks, about 100 ppm, and that it replaced Mg and Fe²⁺. Olivine, and possibly also amphiboles, were impoverished in Sc. Biotite varied from 10 to 30 ppm Sc in most rocks, but to about 500 to 1,000 ppm in late differentiates of granitic magmas. This variation was related to the rock type as follows:

- a) biotite in mafic and intermediate rocks contained about 10 ppm Sc
- b) biotite in high-silica rocks contained about 22 ppm Sc
- c) biotite in regionally metamorphosed rocks about 30 ppm Sc
- d) biotite in pegmatites contained about 100 ppm Sc, going up to about 1,000 ppm in thortveitite-bearing pegmatites.

Sc was practically absent in felsic minerals, and in muscovite appeared to depend on the tenor of Fe. Sc abundance in biotite, from these data, appeared to be temperature dependent, increasing with decreasing temperature.

Ingerson, in a comprehensive review of the methods of geologic thermometry (1955), drew up a curve relating Sc abundance in biotite to temperature of formation of the rock, based on Oftedahl's data. Ingerson also pointed out that this was only an initial attempt to use Oftedahl's data in a rigorous, quantitative way, and suggested other future tests, in other areas, and with other rock systems. Possible objections to Ingerson's curve were first, the lack of supporting experimental data, the usual basis for geologic thermometry, and second, that Sc might vary widely between petrographic provinces or magma series.

Engel and Engel (1960) determined the Sc content of metamorphic biotites in the northwest Adirondack mountains of New York State. Based on their previous work in the area, they had an absolute temperature control and so could relate temperature of formation of biotite to its Sc content. They found that in samples collected about 2.4 kilometers from a granite contact, where metamorphic temperatures had been the highest, that is about 600-625 °C, the biotite averaged 20 ppm of Sc. At a distance of 15.5 kilometers, where metamorphic temperatures only reached 500 °C, biotite had an average of 68 ppm of Sc. These data agreed with Oftedhal's and showed that Sc increased in biotite with decreasing temperature of formation.

DeVore (1955) also found an increase in average Sc content of biotite with decreasing temperature in different metamorphic environments. In hornblende, the reverse was true:

	average Sc in biotite	hornblende
epidote amphibolite facies	34	44
amphibolite facies	28	44
granulite facies	14	65

Kalenov (1961) described occurrences of granitic magma, such as cutting ultramafic rocks, where the amount of Sc was unusually high, and not necessarily temperature dependent. He also described certain rock types, which he called plumasite-pegmatites (largely oligoclase and corundum), that had an unusually high concentration of Sc.

The area of the Quadrilátero Ferrífero lacks the Sc-rich rock types described by Kalenov and appears to be a normal one in Sc abundance. It thus should be a good area to check the validity of Ingerson's Sc in biotite curve. In the spectro-chemical analyses, Sc as well as Co, Ni, Cr, and Nb were determined in the biotite samples and in the rock as a whole.

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GEOCHEMICAL BACKGROUND

Substitution (diadochy) of one element for another in any mineral is largely dependent upon their relative ionic radii (r), electronegativity (E), and ionic potential (IP) (table 1). Of the three, relative ionic radius seems to be the most important physical factor. Goldschmidt (1954) stated that one element could substitute diadochically for another only if its ionic radius is within 15% of the other. Of the trace elements shown in table 1, any could theoretically replace Fe^{2+} and any but Sc could substitute for Mg.

The next most important property is electronegativity, E , of the ion, defined by Pauling (1948) as the power of an atom in a molecule to attract electrons to itself. Ions with lower E have a tendency to form ionic bonds and are incorporated into silicates; ions with higher E tend to form covalent bonds and substitute with greater ease into sulfides.

Ringwood's rule (1955) states that whenever diadochy is possible in a crystal between two elements possessing similar r but appreciably different E , the element with the lower E will be preferentially incorporated. Of the trace elements shown in table 1, Mg and Sc have the lowest E and Nb the highest. The other elements, with similar r to both Mg and Fe, would have more trouble substituting for Mg because of its low E than they would substituting for Fe. Sc and Mg could, of course, substitute for Fe because of their lower E with greater ease than any of the other elements of table 1. Nb, with the highest E , would not generally substitute for any of the other elements in the table.

Ionic potential, IP , was defined by Goldschmidt (1954) as the cation charge, Z , divided by the ionic radius or Z/r . The ratio is significant as an indicator of the relative ability of cations to attract and become bonded to anions. Theoretically the effective charge of the nucleus is distributed around its periphery. If the ionic radius is small and the charge high, then Z/r will be high, and the cation will become quickly bonded to anions in a solution.

It will be noted that the trace elements in table 1 have a small range in values of r and E , but differ substantially in IP . Considering silicate structures, cations with $IP > 4.80$ are network formers, i. e., form polyhedra with 0, and those < 2.60 are network modifiers, i. e., substitute between the 0-polyhedra (Ringwood 1955). Cations between these values can act either as network modifiers or formers depending on the availability of oxygen.

In a silicate magma, as Ringwood (1955) pointed out, cations are competing for O and OH in what should be considered an ionic melt. Si, with $IP = 9.52$, and Al, with 5.88, will quickly bonded with polyhedra of O anions. Of the trace elements in table 1, Nb with $IP = 7.25$ would have the greatest tendency to form O polyhedra and form NbO_4^{-3} complexes in the melt.

Cations with lowest IP , < 2.60 , will only be network modifiers. No elements of table 1 fall into this group.

Cations with IP between 2.60 and 4.80 tend to become distributed as either network formers or modifiers throughout the course of crystallization of a melt. In the early stages of differentiation, this group cannot compete with Si or Al for the available O and exists only as free ions in the melt. During this early stage, any substitution of these elements within the silicate lattices will depend almost exclusively upon their relative ionic radii, r , and electronegativity, E .

With further differentiation, O and volatiles become relatively more abundant and many intermediate cations can behave as network formers. In these later stages of differentiation, cations with $IP > 3.5$ tend to become network formers, whereas those with $IP < 3.5$ tend to continue as network modifiers. In this stage, Cr and Sc may form CrO_4^{-5} and ScO_4^{-5} complexes and could possibly substitute for SiO_4^{-4} because of their higher net charge. Net charge is a good measure of the ionic bonding energy. Complexes with a higher ionic bonding energy are preferentially incorporated in the lattices of crystallizing minerals.

At the end stage of differentiation, during a pegmatitic-pneumato-lytic phase, the ratio of Si + Al to O + volatiles is very low, and volatiles are high compared to O. In this stage, cations in the entire intermediate range might behave as network formers, including those

with $IP < 3.5$. Co and Ni might form CoO_4^{-6} and NiO_4^{-6} and substitute for SiO_4^{-4} .

The NbO_4^{-3} complexes with a lower net charge than SiO_4^{-4} will tend to concentrate in the residual magma and may eventually form niobate minerals.

In the light of the concepts of ionic radius, r , electronegativity, E , and ionic potential, IP the elements studied would be expected to behave as follows:

- 1) In the early stages of differentiation Co and Ni would act as free ions and substitute readily for Fe in excess of their concentration in the magma, as all have similar r and E . They have low IP , close to 2.8, and so would have little tendency to form O-polyhedra. They will enter all mafic minerals and should become impoverished in the succeeding differentiates of a normal magma. In later differentiates, they may form complexes, depending upon the availability of O + volatiles. In such rocks, they are most commonly present only in biotite since it is the unique ferromagnesian mineral.
- 2) Cr, with an r and E close to Fe, behaves similarly to Co and Ni in the earlier stages of crystallization. However, with $IP = 4.76$, it might form complexes with O and OH in the succeeding differentiates and not be completely depleted from the liquid phase of the magma. In the latest stages, it could possibly become a network former in both biotite and Cr-muscovites.
- 3) Sc will have the greatest tendency of all to substitute for Fe in ferromagnesian minerals in the early stages of crystallization because of its low E . In the latest stages, with $IP = 3.70$, it might form complexes and become concentrated in biotite.
- 4) In the early stages of differentiation, Nb with a high E and very high IP would accumulate in the liquid phases of the magma and not substitute for Fe. In intermediate stages, it will enter mafic minerals as a network former. In the

final crystallates, it comes out in great abundance as a network former in niobates and in mafic minerals.

SAMPLE DESCRIPTION

The samples are described in table 2. Most of them have been described in greater detail elsewhere (Herz and Dutra, 1958, Herz and others, 1961). In this report, sample 5b is considered to represent an early stage of differentiation from a granitic magma; 4a, 13 and 38b intermediate stages; 34 late stage; and 10 latest or pneumatolytic-pegmatitic stage.

Sample 5b formed from a probable palingenic magma, represented by 4a. Samples 13, 38b, and 34 may have formed, in part, by palingenesi of the older granitic rocks and, in part by a younger magma. Sample 10 with its abundant fluorite and generally coarse grain size, represents a very late stage differentiate of the younger magma that retained many volatiles.

Biotite was separated from the six samples of granitic-rock and one quartz biotite gneiss (sample 39). The absolute abundance of Co, Ni, Cr, Sc, and Nb was determined in each sample of biotite and rock (tables 3-5). These abundances are shown in figures 1-5 where the abscissa is the differentiation index (DI) of the rock (Thornton and Tuttle, 1960), and the ordinate, a logarithmic scale of abundance. DI is defined as the sum of normative quartz + orthoclase + albite + feldspathoids, or, in other words, the salic constituents without anorthite. In these rocks, the $DI = \text{quartz} + \text{orthoclase} + \text{albite}$. With a higher DI, the sample presumably crystallized toward the lower temperature, final stages of differentiation. The validity of the DI is suggested by the total SiO_2 content of the rock, as determined chemically, which is also generally taken as an index of stage of differentiation (compare columns 2 and 3 of table 2).

Sample 39, a high-grade metamorphic rock, has also been included for comparison to Oftedahl's data (1943) which were for both igneous and metamorphic rocks.

SPECTROGRAPHIC ANALYSIS TECHNIQUE

The determination of Sc, Ni, Co, Cr, and Nb was made by spectrochemical techniques without using internal standards. The samples were volatilized in an electric arc during exposure to complete consumption.

An Eagle mount, grating spectrograph, with a 3 meter focal length, and a dispersion of 5.5 Angstrom in the first order was used.

The standards were sintered using a base containing 40% SiO₂, 18% Al₂O₃, 10% Fe₂O₃, 25% MgO, and 7% K₂O and with the trace elements varying between 1 and 500 ppm.

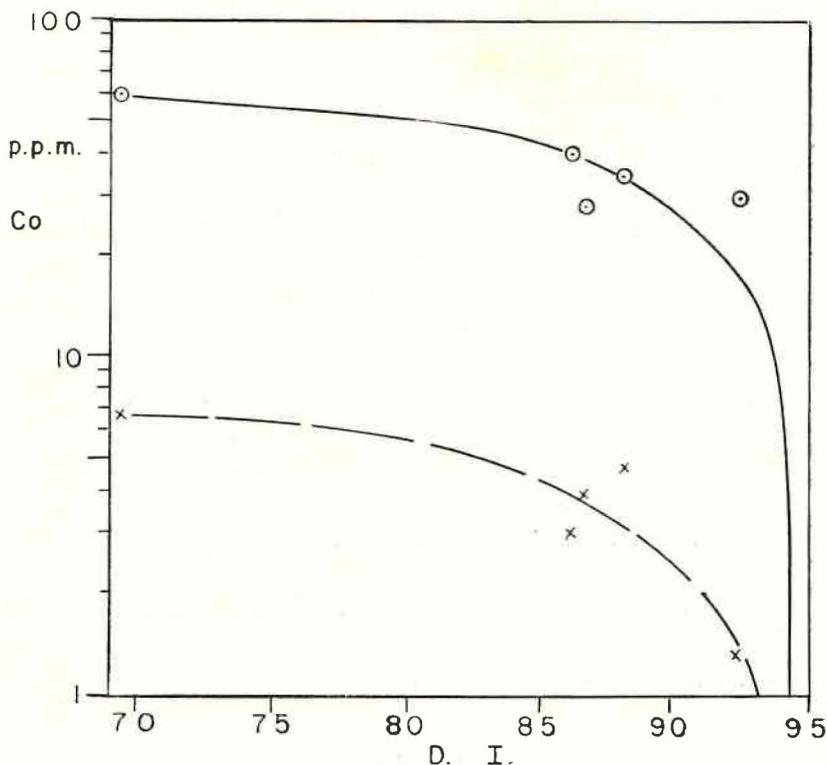


Fig. 1 — Abundance curves for Co in biotite (solid line) and in host rock (broken line).

To improve the burning conditions, the samples and standards were mixed with a base called "Soda-quartz" (10% Na₂CO₃ + 90%

SiO₂) and with powdered graphite in the ratio 1:1:1.

The lines used were:

Sc	4246.33	Angstrom
Cr	4254.35	
Ni	3050.83	
Co	3453.50	
Nb	3163.40	

A Jarrell-Ash comparator-projector (model 200) was used for the photometry of the lines.

RESULTS OF SPECTROGRAPHIC ANALYSIS

Cobalt and Nickel

Co and Ni have similar geochemical properties and will be discussed together. As Goldschmidt (1954) pointed out, although both are impoverished in succeeding differentiates, Ni decreases at a greater rate than Co (figs. 1, 2, table 3).

In the curves, it can be seen that the abundance of these elements is much greater in biotite than in the rock, indicating a tendency to enter biotite in excess of their concentration in the magma. In the earlier differentiates, Co and Ni entered biotite, substituting for Fe and also Mg as lattice modifiers. Co apparently did not form complexes in the later stages of differentiation, probably due to the lack of abundant volatiles, and was completely depleted before the pneumatolytic stage was reached. Ni, with a slightly higher *E* than Co was still present in the final stages, however, and may have entered biotite in O-polyhedra.

Chromium

The abundance of Cr decreases in succeeding differentiates but is always greater in biotite than in the rock (figure 3, table 4). Cr enters biotite in excess of its concentration in the magma, substituting

for Fe and Mg in the early crystallates and acting as a lattice modifier. Cr later may have formed O-polyhedra and was not entirely depleted in the last magmatic phases. Cr is always far more abundant in biotite than in the rock, showing the effectiveness of biotite as a scavenger for Cr. In sample 10, for example, Cr was actually not detected in the rock, but was found in biotite (9.5 ppb).

Scandium

Except in the earlier stages of differentiation, Sc is more abundant in biotite than in the rock (figure 4, table 4). In the early

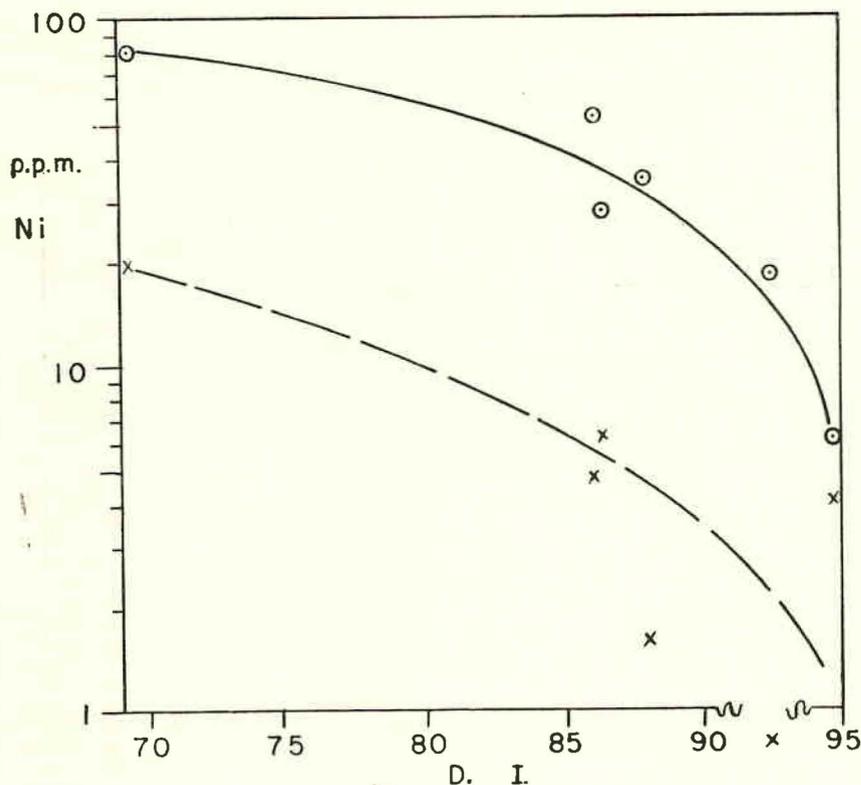


Fig. 2 — Abundance curves for Ni in biotite (solid line) and in host rock (broken line).

differentiates, Sc substitutes for Fe; in the later stages with an IP 3.70 it probably forms ScO_4^{-5} polyhedra. This tendency in Sc is less than in Cr, but higher than in either Co or Ni.

In late stages of differentiation, biotite apparently greatly impoverished the liquid in Sc. Sample 34, for instance has 130 ppm Sc as compared to only 1.3 in the rock as a whole. Sample 10, presumably formed during a later pegmatitic-pneumatolytic stage, contains 4.6 ppm Sc in biotite whereas Sc was not detected in the rock. This low abundance must be due to the effective scavenging by biotite in the pre-pneumatolytic stage. A curve relating Sc biotite/Sc rock would go up steeply throughout the entire course of crystallization (See table 4, column 4).

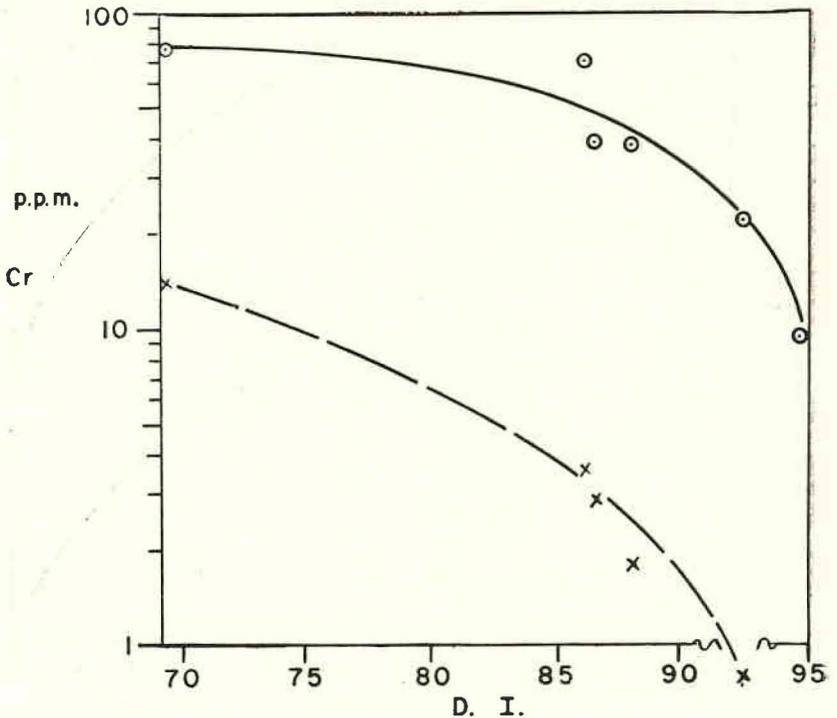


Fig. 3 — Abundance curves for Cr in biotite (solid line) and in host rock (broken line).

Ingerson's (1955, p. 364) curve relating Oftedahl's (1943) data on Sc abundance in biotite to temperature of formation shows about 5 ppm Sc for mafic and intermediate igneous rocks formed at 900 °C, 12 ppm Sc for high silica igneous rocks at 700° C, 22 ppm Sc for regionally metamorphosed rocks at 600° C, 30 ppm Sc for alkalic granite at 575 °C, and 100 ppm Sc for pegmatites at 525 °C.

In general, the same orders of magnitude for Sc abundance were found in the Quadrilátero Ferrífero rocks (figure 4, table 4). The most important difference is that Sc was depleted in the Quadrilátero Ferrífero "alkalic granite" stage where it shows an abundance equal to the pegmatitic stage of Oftedahl and Ingerson. In the later

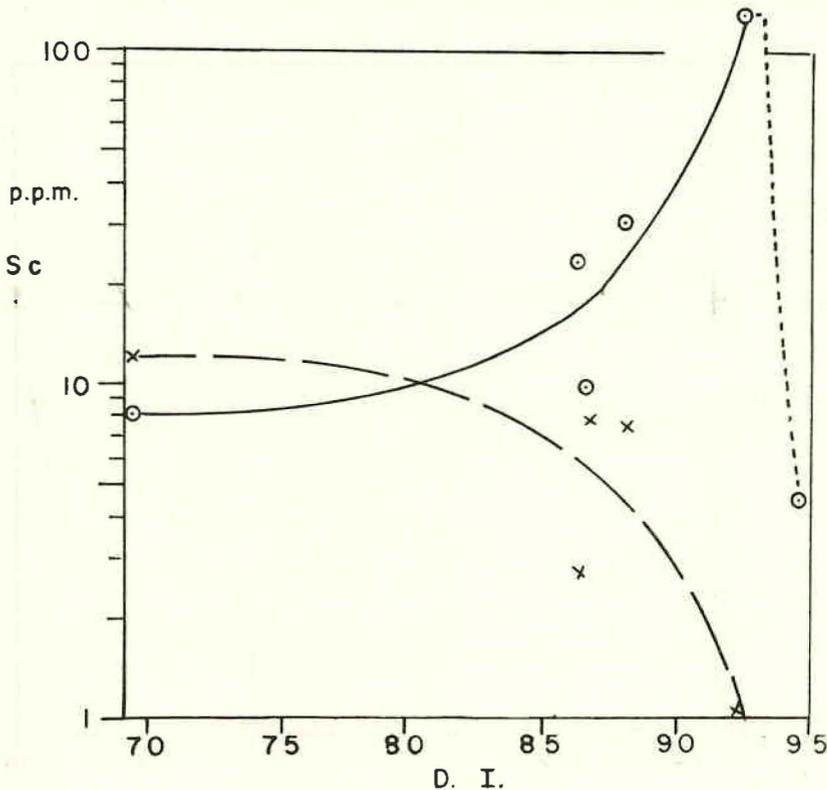


Fig. 4 — Abundance curves for Sc in biotite (solid line, short dashed line after Sc-depletion) and in host rock (long dashed line).

pneumatolytic stage, biotite only contains 4.6 ppm Sc because of this depletion.

The regionally metamorphosed rock, sample 39, probably formed at a lower temperature than the 600 °C attributed to the Norwegian rocks but has about the same abundance, 26 ppm vs. 22 ppm Sc for the Norwegian rocks.

Niobium

The abundance curves for Nb (figure 5 taken from table 5) differ from those of the other elements. Throughout most of the course of differentiation, Nb shows a low but more or less constant abundance in the rock, ranging from 11 to 24 ppm. In the earliest

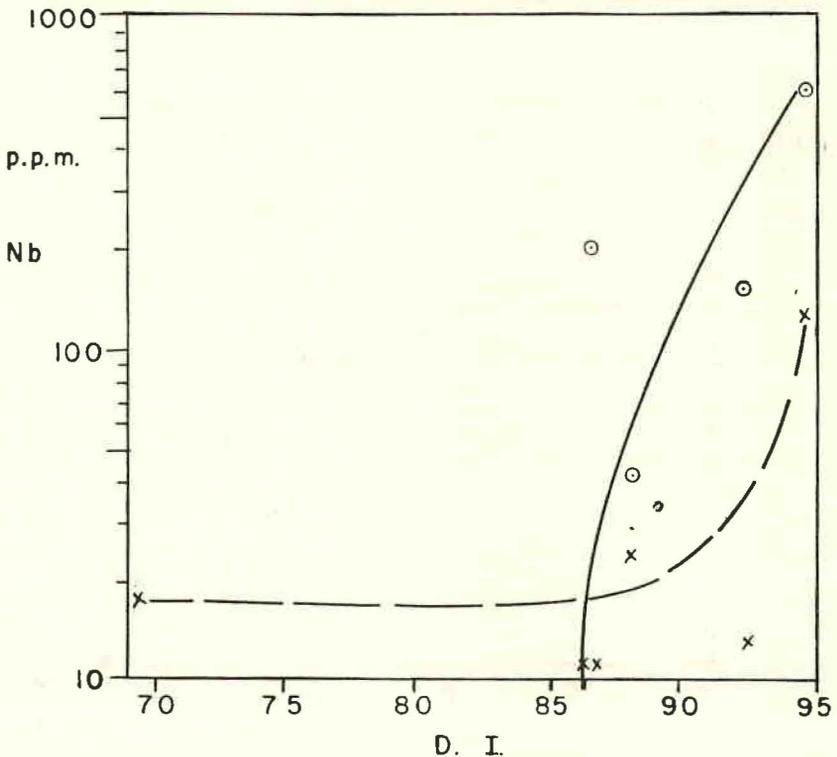


Fig. 5 — Abundance curves for Nb in biotite (solid line) and in host rock (broken line).

biotite, Nb is not detectable (detection limit of method used in biotite, about 20 ppm), but in the intermediate and late biotite, Nb becomes abundant ranging from 41 to 200 ppm. In the final stages, however, Nb is abundant in both biotite, 670 ppm, and the rock 112 ppm.

NbO_4^{-3} complexes were being concentrated in the liquid phase and only entered the crystallizing minerals in the final stages of differentiation when their concentration reached a sufficiently high level. In that final stage, Nb apparently came out in a "flood".

Applications to Geologic Thermometry

The results of analysis of these samples suggest that Sc in biotite is not an absolute geological thermometer. The actual amount of Sc in biotite depends not only on the stage of differentiation, but also on its geochemical behaviour and total availability in the liquid phase. The Sc ratio in biotite/whole rock generally increases in the later products of differentiation. This was also shown by Ingerson (1955) and Oftedahl (1943) for Sc in biotite alone. However, in the Quadrilátero Ferrífero rocks, nearly all the Sc was effectively "scavenged" before the pneumatolytic stage of crystallization was reached and so the absolute amount of Sc in biotite goes down in the final differentiation products.

Cr as well as Co and Ni also indicate temperature, for the amount in biotite of succeeding differentiates decreases. The ratio of Sc to Cr in biotite (table 4) increases gradually from 0.11 to 0.84 until the pre-pneumatolytic granite in which it reaches 5.91. In the pneumatolytic-phase granite, Cr is once again greater than Sc and the ratio is 0.47.

Sc/Cr ratios are similar in the rock except that Sc depletion takes place at an earlier stage than it does in biotite.

Co and Ni, as can be predicted by their known geochemical behavior (Goldschmidt, 1954), decrease in both rock and biotite. Except for the last differentiate, the Ni/Co ratios in both the biotite and the rock decrease, but show a greater depletion of Co than Ni from the liquid phase in succeeding differentiates.

Nb shows no particular trend in the early differentiates. To judge by its low abundance, there was little loss of Nb in the earlier stages of crystallization. In the last stages, it comes out in a flood in both biotite and the rock as a whole. Perhaps such Nb abundance in biotite might indicate a granite that formed during the onset of a pneumatolytic phase when volatiles were at a maximum.

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TABLE 1

PHYSICAL PROPERTIES OF SOME ELEMENTS. ARRANGED IN ORDER OF INCREASING IONIC RADIUS

<i>Element</i>	<i>radius Angstrom</i>	<i>Electronegativity</i>	<i>Ionic Potential</i>
Cr ³	0.63	1.6	4.76
Mg ²	0.66	1.2	3.03
Ni ²	0.69	1.7	2.90
Nb ⁵	0.69	1.9	7.25
Co ²	0.72	1.7	2.78
Fe ²	0.74	1.65	2.70
Sc ³	0.81	1.3	3.70
Si ⁴	0.40	1.8	9.52
Al ³	0.50	1.5	5.88

TABLE 3

RESULTS OF ANALYSIS OF Co AND Ni AND RATIOS OF Co AND Ni IN ROCK AND BIOTITE, PARTS PER MILLION (ppm)

<i>Sample</i>	<i>Co</i>			<i>Ni</i>			<i>Ni/Co</i>	
	<i>biot</i>	<i>rock</i>	<i>bi/rk</i>	<i>biot</i>	<i>rock</i>	<i>bi/rk</i>	<i>biot</i>	<i>rock</i>
5b	60	6.7	8.69	82	20	4.10	1.37	2.99
4a	40	3.0	13.33	53	4.7	12.13	1.33	1.57
13	28	4.4	6.36	28	6.3	4.44	1.00	1.43
38b	35	4.7	7.45	34	1.6	21.25	0.97	0.34
34	30	1.3	23.08	19	0.8	23.75	0.63	0.62
10	nd	nd	—	6.0	4.0	1.50	00	00
39	59	19	3.11	220	68	3.24	3.73	3.58

TABLE 4

RESULTS OF ANALYSIS OF Sc AND Cr AND RATIOS OF Sc AND Cr IN ROCK AND BIOTITE, IN ppm

<i>Sample</i>	<i>Sc</i>			<i>Cr</i>			<i>Sc/Cr</i>	
	<i>biot</i>	<i>rock</i>	<i>bi/rk</i>	<i>biot</i>	<i>rock</i>	<i>bi/rk</i>	<i>biot</i>	<i>rock</i>
5b	8.2	11	0.75	77	12	6.42	0.11	0.91
4a	24	2.8	8.57	70	3.6	19.44	0.34	0.78
13	10	8.0	1.25	39	2.9	13.45	0.26	2.76
38b	32	7.5	4.27	38	1.8	21.11	0.84	4.17
34	130	1.3	100.0	22	0.8	27.50	5.91	1.63
10	4.6	nd	00	9.5	nd	00	0.47	—
39	26	11.6	1.73	250	103	2.43	0.10	0.11

TABLE 2 SAMPLE DESCRIPTIONS

sample n. ^o	Rock SiO ₂	Rock DI ¹	Mineralogy ²	Petrography of rock Other characteristics	biotite n _y	biotite pleochroism ⁻³	K/Ar Age ⁻⁴	Location ⁻⁵
5b	63.8%	69.2	Ab ₈₃ (57%), microcline (13%), qz (17%); epid, apat, zir	granodiorite, layered 2-10 mm, plag av 1 mm microcline interstitial	1.633	mod. olive brown-yellowish gray (8%)	(1350)	Saboeira, Bação Quadrangle, N 5400, E 1900
4a	72.1%	86.2	Ab ₇₉ (51%), microcline (16%), qz (28%); apat, epid, opaques, sericite	granodiorite, granitic texture, plag .3--.7 mm, microcline interstitial	1.631	grayish olive-pale olive (6.2%)	2.400	Engenheiro Corrêa, Bação Quadrangle, N 700, E 11,700
13	72.0%	86.4	Ab ₈₈ (32%), microcline (29%), qz (30%), musc; chlor, epid, zir	granite, weakly foliated, plag full of inclusions .3-.5 mm, microcline fresher 2 mm	1.632	olive grayish yellow (6.9%)	550	Ibirité, Ibirité Quadrangle, NE 2700, E 3200
38b	71.9%	87.9	Ab ₈₂ (36%), qz (30%), microcline (29%); apat, opaques, zir	banded porphyritic flaser gneiss, plag with inclusions .3 to .5, micro to <2 mm	1.642	olive black-mod. greenish yellow (9.4%)	(550)	São Gonçalo, Quadrangle, N 2200, E 12,000
34	74.0%	92.3	Ab ₈₈ (37%), qz (30%), microcline (29%), musc; apat, epid, carbonate	granite, porphyritic microcline 1-1.5 mm, mortared gmass ~.07 mm	1.633	mod. olive brown-mod. greenish-yellow (2.1%)	(550)	Brumadinho Quadrangle, N 2000, E 8000
10	77.8%	94.6	Ab ₉₇ (37%), qz (37%), microcline (25%); musc, fluorite	foliated tonalite, feldspar perthitic to 10 mm, gmass .1-.5 mm	1.667	olive gray-mod. yellow greenish (2.4)	470	Petí dam, Florália quadrangle, N 13,500, E 1400
39			qz biotite gneiss with some Ab ₇₃ , musc, apat, magnetite		1.630	grayish olive green-grayish yellow green		Rio Piracicaba quadrangle, N 7550, E 4800

1. DI = differentiation index (Thornton and Tuttle, 1960)

2. Normative percent shown in (), plagioclase as percent albite g. Ab₈₈

3. Modal percent of biotite in rock shown in ().

4. From Herz and others 1961. Ages in () surmised.

5. From Dep. Nac. Prod. Min. (1959). Coordinates are meters north and east of southwest quadrangle corner.

TABLE 5

RESULTS OF ANALYSIS OF Nb IN ROCK AND BIOTITE. IN ppm

<i>Sample</i>	<i>Nb biot</i>	<i>Nb rock</i>	<i>Nb bi/rk</i>
5b	nd	18	0
4a	nd	11	0
13	200	11	18.2
38b	41	24	1.7
34	150	13	11.5
10	670*	112	6.0
39	36	26	1.4

* Determination made by U. S. Geological Survey, Washington, D. C. and then used as a standard together with granite G-1 (Nb = 19 ppm)