

Geochemistry of coexisting hornblende and biotite from the Ambalavayal granite, Kerala

M SANTOSH

Centre for Earth Science Studies, P.B. 2235, Sasthamangalam, Trivandrum 695 010, India

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Abstract. Major and trace element geochemistry of coexisting hornblendes and biotites from the Ambalavayal granite, northern Kerala, are presented. The hornblendes correspond to edenitic composition, whereas the biotites correspond to annite. The hornblendes typically show high Al_2O_3 contents (9.69–11.89%) comparable with those from anorogenic granites. The biotites are characteristically low Mg-type, similar to those reported from alkaline rocks. The distribution coefficients calculated for all the major and trace elements are presented and an evaluation of the nature of variation indicate near-chemical equilibrium conditions during the crystallization of the two minerals. The hornblende-biotite tie lines in the Fe^{3+} - Fe^{2+} -Mg compositional triangle, lie parallel to those of buffered biotites, indicating crystallization in an environment closed to oxygen and well above the Ni-NiO buffer. It is inferred that the f/H_2O increased towards the residual stage and fO_2 values were high, in the range of 10^{-15} bars.

Keywords. Granite; hornblende; biotite; geochemistry; distribution coefficients; fH_2O ; fO_2 ; Ambalavayal.

1. Introduction

The 595 million year (m.y.) old granite pluton of Ambalavayal in Wynad district of northern Kerala, emplaced within Precambrian biotite gneisses, is a typical member of the Late Precambrian Early Paleozoic granitic intrusives in the south-western Indian shield (Nair *et al* 1982; Santosh *et al* 1985). The granite is spatially related to the Moyar fault zone and the associated pegmatites and quartz veins show disseminated molybdenite mineralization, marking an event of taphrogenic metallogeny (Santosh and Nair 1983). Geochemical characters denote an alkaline nature and tectonic aspects suggest a probable anorogenic affiliation, like the other plutons in the region. This paper presents the major and trace element geochemistry of hornblende and biotite, the principal mafic minerals in the granite, based on which the conditions of crystallization are deciphered.

The granite is pink, medium grained and composed of interlocking quartz and alkali feldspar. Plagioclase of albitic composition occurs in subordinate amounts. The hornblende (constituting 3.74–5.63 volume %) and biotite (3.88–5.23 volume %) occur as subhedral laths with textural relations generally suggesting their formation towards the later stages of crystallization history as they commonly form interstitial laths between grains of plagioclase and perthite. Biotite shows a pleochroic scheme of $X < Y = Z$, where X = straw yellow and $Y = Z$ = dark greyish brown, whereas the pleochroism of hornblende is $X < Y \leq Z$ with X = yellowish green, Y = green and Z = deep bluish green. The accessories include zircon, apatite, epidote, monazite and sphene. Minor rebeckite is also noted, showing deep blue colour, anomalous extinction and $Z \wedge c$ varying between 3–9°. The opaque is mainly magnetite.

Hornblende and biotite fractions for the present study were obtained by mineral separation involving a combination of repeated heavy liquid and electromagnetic techniques. The final purity of the samples were checked by hand picking under a stereo-microscope and was found to be about 99%.

The major elements were analysed by conventional wet chemical techniques and trace elements by atomic absorption spectrophotometer (Perkin-Elmer-4000), calibrated using internal standards.

2. Geochemistry of biotite

The chemical analyses of biotite samples from Ambalavayal and their structural formulae (based on 22 atoms, anhydrous) are presented in table 1. Si cations range from 5.570 to 5.923 per formula unit compared to 6.000 for ideal phlogopite-annite series.

Table 1. Chemical analyses and structural formulae of biotite from Ambalavayal.

	A/BT/1	A/BT/2	A/BT/3	A/BT/4	A/BT/5	A/BT/6
<i>Chemical analyses</i>						
SiO ₂	35.01	36.10	36.28	37.10	38.18	37.51
Al ₂ O ₃	13.77	13.26	14.62	12.75	14.07	12.82
TiO ₂	2.80	2.88	2.23	2.60	1.96	2.14
Fe ₂ O ₃	5.02	5.44	5.21	8.39	7.46	6.47
FeO	29.21	28.10	26.28	26.05	21.37	25.86
MnO	0.33	0.42	0.46	0.18	0.53	0.34
MgO	0.96	1.12	1.42	0.65	2.02	0.84
CaO	1.57	1.84	1.13	1.12	1.48	1.12
Na ₂ O	0.80	0.76	0.74	0.65	0.58	0.63
K ₂ O	8.51	7.89	9.12	8.10	8.98	8.42
P ₂ O ₅	0.43	0.52	0.59	0.57	0.54	0.58
Moisture	0.44	0.66	0.25	0.18	0.28	0.18
LOI	0.81	0.98	0.73	1.68	0.56	1.64
Total	99.66	99.97	99.06	100.02	98.01	98.55
<i>Structural formulae*</i>						
Si	5.570	5.697	5.732	5.830	5.923	5.955
Al ^{iv}	2.430	2.303	2.268	2.170	2.077	2.045
Al ^{vi}	0.153	0.164	0.455	0.192	0.496	0.356
Ti	0.336	0.343	0.265	0.307	0.229	0.256
Fe ³⁺	0.601	0.647	0.619	0.991	0.871	0.773
Fe ²⁺	3.886	3.709	3.472	3.423	2.772	3.434
Mn	0.045	0.056	0.062	0.024	0.070	0.046
Mg	0.228	0.264	0.334	0.150	0.467	0.198
Ca	0.268	0.311	0.191	0.189	0.246	0.191
Na	0.246	0.234	0.036	0.198	0.176	0.194
K	1.726	1.592	0.919	1.624	1.776	1.706
Sum Y	5.249	5.183	5.207	5.087	4.905	5.063
Sum X	2.240	2.137	2.065	2.011	2.198	2.091
Mg/Mg + Fe ²⁺	0.055	0.067	0.088	0.042	0.209	0.055

*Based on 22 oxygens per formula unit; LOI—loss on ignition.

There is sufficient Al in the sample to fill the tetrahedral sites not occupied by Si. The octahedral sites are occupied by 4.905 to 5.249 Y group cations compared with 6.000 in the trioctahedral mica. The sum of the inter-layer X group cations (K, Na, Ca) ranges from 2.011 to 2.240, compared with the ideal 2.000 cations per formula unit. Plots of Fe/Fe + Mg ratios of biotite against Al atoms/22 oxygens define a field close to the annite-phlogopite join (figure 1), with Al atoms indicating composition close to that of annite (2.2–2.8).

The most striking feature of the biotites is the very low magnesium content of the octahedral layers (0.150–0.467). Figure 2 depicts a comparison of the composition of these biotites with those delineated for biotites from elsewhere. The Ambalavayal biotites lie outside Foster's (1960) field, away from the Mg apex and are comparable

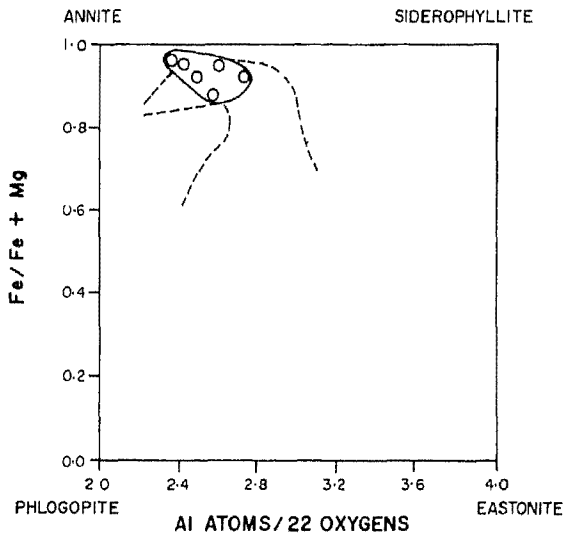


Figure 1. Composition of Ambalavayal biotite in terms of Fe/Fe + Mg vs Al atoms/22 oxygens. The broken lines represent the field of biotites as given by Anderson (1980).

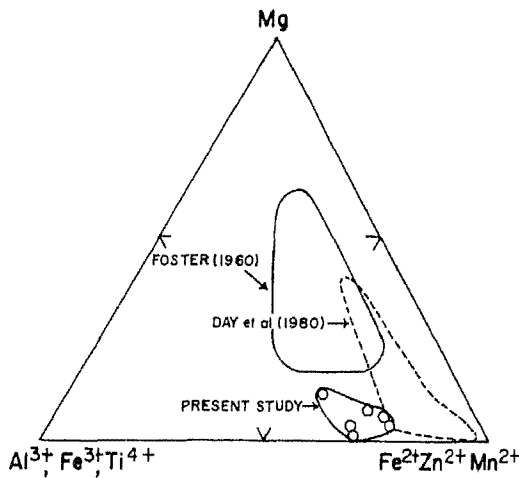


Figure 2. Composition of Ambalavayal biotites compared with those from elsewhere (note the low Mg-content).

with low Mg biotites from alkaline environments reported by Day *et al* (1980). The biotites show low sodium content in the alkali site varying from 0.036 to 0.246. These characters are comparable with those for biotites from alkaline rocks (*cf.* Czamanske *et al* 1977).

3. Geochemistry of hornblende

Chemical analyses and structural formulae (based on 23 oxygen atoms, anhydrous) of hornblende separates from Ambalavayal granite are presented in table 2. The analyses and structural formulae overall satisfy the requirements for 'superior analyses' and indicate an edenitic composition (Leake 1978). Si cations range from 6.306 to 6.920 per formula unit with sufficient Al in all the samples to fill the tetrahedral sites not occupied

Table 2. Chemical analyses and structural formulae of hornblende from Ambalavayal.

	A/HB/1	A/HB/2	A/HB/3	A/HB/4	A/HB/5	A/HB/6
<i>Chemical analyses</i>						
SiO ₂	39.83	40.23	39.45	39.83	41.21	39.78
Al ₂ O ₃	10.20	10.67	11.89	10.71	10.71	9.69
TiO ₂	1.42	1.41	1.35	1.53	1.58	1.53
FeO ₃	5.58	5.11	4.96	6.80	6.56	6.68
FeO	20.20	20.42	20.61	22.85	19.80	23.40
MnO	0.53	0.64	0.61	0.55	0.42	0.56
MgO	2.72	4.01	3.86	2.56	2.56	2.56
CaO	10.53	9.22	8.78	9.41	7.51	10.30
Na ₂ O	1.87	1.79	1.94	2.15	2.01	2.13
K ₂ O	2.41	1.98	2.21	1.78	2.48	1.78
P ₂ O ₅	0.31	0.28	0.12	0.22	0.16	0.15
Moisture	2.21	1.02	1.97	1.08	1.85	1.97
LOI	1.95	1.95	2.22	0.97	2.56	2.65
Total	99.76	98.53	99.97	100.44	99.41	98.41
<i>Structural formulae*</i>						
Si	6.947	6.443	6.337	6.306	6.716	6.371
Al ^{iv}	1.053	1.557	1.663	1.694	1.784	1.629
Al ^{vi}	0.894	0.442	0.526	0.306	0.774	0.154
Ti	0.175	0.170	0.163	0.182	0.191	0.135
Fe ³⁺	0.673	0.616	0.601	0.811	0.805	0.809
Fe ²⁺	2.734	2.735	2.769	3.025	2.700	3.137
Mn	0.073	0.086	0.083	0.074	0.058	0.077
Mg	0.656	0.957	0.924	0.604	0.622	0.606
Ca	1.826	1.582	1.512	1.596	1.322	1.771
K	0.588	0.556	0.604	0.660	0.634	0.654
Na	0.498	0.404	0.454	0.360	0.514	0.366
Sum Y	5.205	5.019	5.066	5.002	5.150	4.918
Sum W + X	2.912	2.542	2.570	2.616	2.472	2.791
Mg/Mg + Fe ²⁺	0.194	0.259	0.250	0.166	0.187	0.162

*Based on 23 oxygens per formula unit; LOI—loss on ignition

by Si. The total number of Y group cations range from 4.891 to 5.205 per formula unit compared with 5.0 in the ideal hornblende formula.

A notable aspect is the high Al-content of the hornblende ($\text{Al}_2\text{O}_3 = 9.69 - 11.89\%$), which compares with the characteristic high Al_2O_3 values of hornblendes from anorogenic granites (9–11 weight %) and contrast with the low Al values for hornblendes from calc-alkaline plutons associated with orogenic belts (Anderson 1980). In all samples except one, the sum of W and X group cations (Ca, Na, K) exceed the theoretical maximum of 2.000 cations per formula unit in the M_4 site and suggests partial occupation of the A sites. The $\text{Mg}/\text{Mg} + \text{Fe}^{2+}$ values are fairly uniform, ranging between 0.162 and 0.259.

4. Distribution of major elements

For coexisting minerals α and β , the distribution coefficient of element A is defined as:

$$K_{D(A)}^{\alpha-\beta} = \frac{X_A^\alpha}{1 - X_A^\alpha} \frac{1 - X_A^\beta}{X_A^\beta}$$

where X_A is the atomic ratio of element A to the sum of major elements occupying the same site or sites in phases α and β . If the elements considered behave as ideal mixtures and reach chemical equilibrium under uniform P - T conditions, then the distribution coefficient, $K_{D(A)}$ is constant (cf. Kretz 1959, 1960; Stephenson 1977). The distribution coefficient, $K_{D(\text{Fe}^{2+}-\text{Mg})}^{B-H}$ was calculated using the atomic ratio, $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$. $K_{D(\text{Al}^{\text{iv}})}^{B-H}$ was calculated using the atomic ratio, $\text{Al}^{\text{iv}}/(\text{Al}^{\text{iv}} + \text{Si})$. For the remaining distribution coefficients, the atomic ratio of the element considered is based on the total number of octahedral cations, e.g., for $K_{D(\text{Ca})}^{B-H}$, $X_{\text{Ca}} = \text{Ca}/\Sigma$ octahedral cations. The calculated atomic ratios of elements to the sum of major elements occupying the

Table 3. Atomic ratio of elements to the sum of major elements occupying the respective sites in hornblende and biotite from Ambalavayal.

	$X_{\text{Al}^{\text{iv}}}^H$	$X_{\text{Al}^{\text{vi}}}^H$	X_{Ti}^H	$X_{\text{Fe}^{2+}}^H$	$X_{\text{Fe}^{3+}}^H$	X_{Mn}^H	X_{Mg}^H	X_{Ca}^H
<i>Hornblende</i>								
A/HB/1	0.132	0.172	0.034	0.129	0.525	0.014	0.126	0.670
A/HB/2	0.195	0.088	0.034	0.123	0.545	0.017	0.191	0.622
A/HB/3	0.209	0.104	0.032	0.119	0.547	0.017	0.182	0.588
A/HB/4	0.212	0.061	0.036	0.162	0.605	0.015	0.121	0.610
A/HB/5	0.223	0.150	0.037	0.156	0.524	0.011	0.121	0.535
A/HB/6	0.204	0.031	0.028	0.165	0.638	0.016	0.123	0.635
	$X_{\text{Al}^{\text{iv}}}^B$	$X_{\text{Al}^{\text{vi}}}^B$	X_{Ti}^B	$X_{\text{Fe}^{2+}}^B$	$X_{\text{Fe}^{3+}}^B$	X_{Mn}^B	X_{Mg}^B	X_{Ca}^B
<i>Biotite</i>								
A/BT/1	0.304	0.029	0.114	0.115	0.740	0.009	0.043	0.120
A/BT/2	0.288	0.032	0.066	0.125	0.716	0.011	0.051	0.146
A/BT/3	0.284	0.087	0.051	0.119	0.667	0.012	0.064	0.093
A/BT/4	0.271	0.038	0.060	0.195	0.673	0.005	0.030	0.094
A/BT/5	0.260	0.101	0.047	0.178	0.565	0.014	0.095	0.112
A/BT/6	0.256	0.070	0.051	0.153	0.524	0.009	0.039	0.091

respective sites in coexisting hornblendes and biotites from Ambalavayal are given in table 3 and the distribution coefficients are given in table 4. The variations in K_D values of each element are shown in figure 3, where the linear to curvilinear trends depict near-chemical equilibrium conditions of crystallization of the two minerals.

Among the tetrahedrally coordinated cations, Al and Si show variable distribution with $K_{D(\text{Al}^{\text{IV}})}^{B-H}$ ranging from 1.255 to 2.303. The distribution of Al^{IV} and Si between coexisting hornblende and biotite is shown to be non-ideal with their K_D values systematically related to the Al^{IV} contents of hornblende (Gorbatshev 1970). The linear distribution pattern of $X_{\text{Al}^{\text{IV}}}^{\text{H}}$ and the curvilinear trend of $X_{\text{Al}^{\text{IV}}}^{\text{B}}$ and $K_{D(\text{Al}^{\text{IV}})}^{B-H}$ depicts that the Al-Si distribution coefficient is related to compositional variables (Stephenson 1977). A check on the trend defined by Al^{IV} and Si between the coexisting minerals as per the equation of Gorbatshev (1970) indicate near-chemical equilibrium conditions.

Among the octahedral cations (table 4), $K_{D(\text{Fe}^{2+})}^{B-H}$ ranges from 1.063 to 1.410 and $K_{D(\text{Mg})}^{B-H}$ ranges from 0.248 to 0.785. $K_{D(\text{Fe}^{2+}-\text{Mg})}^{B-H}$ relationship was also checked and found to be uniform, consistent with the observations of other workers (cf. Saxena 1966; Leelanandam 1970). The variation trends of Al^{VI} in biotite and Al^{VI} , Fe^{3+} , Ca, Mn and Ti in hornblende are rather ambiguous and the trend lines drawn are only overall estimates.

The higher charged octahedral cations like Fe^{3+} , Al^{VI} and Ti show overall uniform distribution. The increase in $K_{D(\text{Mn})}^{B-H}$ values against increasing Mn content in biotite (figure 4a) and their negative correlation in hornblende are consistent with similar observations of Saxena (1966) and Kretz (1959). The non-ideal distribution of Ti and Al^{VI} between hornblende and biotite also correlates with their observations with the feature attributed to be a result of variation in Al^{IV} , Al^{VI} , Fe^{3+} and alkalis in hornblende (Kretz 1960). Fe^{2+} and Ca in biotite show good fit against their respective K_D values, whereas in hornblende, the Ca distribution is not strictly regular.

5. Distribution of trace elements

The trace element geochemistry of hornblendes and biotites from Ambalavayal is presented in table 5 and the distribution coefficients are given in table 6. The pattern of distribution of elements between the coexisting minerals are shown in figure 4, where the K_D values are plotted against the respective $K_{D(\text{Mg}-\text{Fe})}^{B-H}$ value. Systematic relationship

Table 4. Distribution coefficients for coexisting hornblende and biotites from Ambalavayal.

K^{B-H}	$D(\text{Al}^{\text{IV}})$	$D(\text{Al}^{\text{VI}})$	$D(\text{Fe}^{3+})$	$D(\text{Fe}^{2+})$	$D(\text{Ti})$	$D(\text{Mn})$	$D(\text{Mg})$	$D(\text{Ca})$
1	2.303	0.169	0.891	1.410	3.353	1.614	0.341	0.179
2	1.477	0.364	1.016	1.314	1.941	0.647	0.267	0.235
3	1.359	0.837	1.000	1.219	1.594	0.727	0.352	0.158
4	1.278	0.623	1.203	1.112	1.607	0.313	0.248	0.154
5	1.666	0.673	1.141	1.078	1.270	1.273	0.785	0.209
6	1.255	2.258	0.927	1.063	1.821	0.130	0.317	0.143
Mean	1.468	0.821	1.030	1.199	1.931	0.784	0.385	0.180

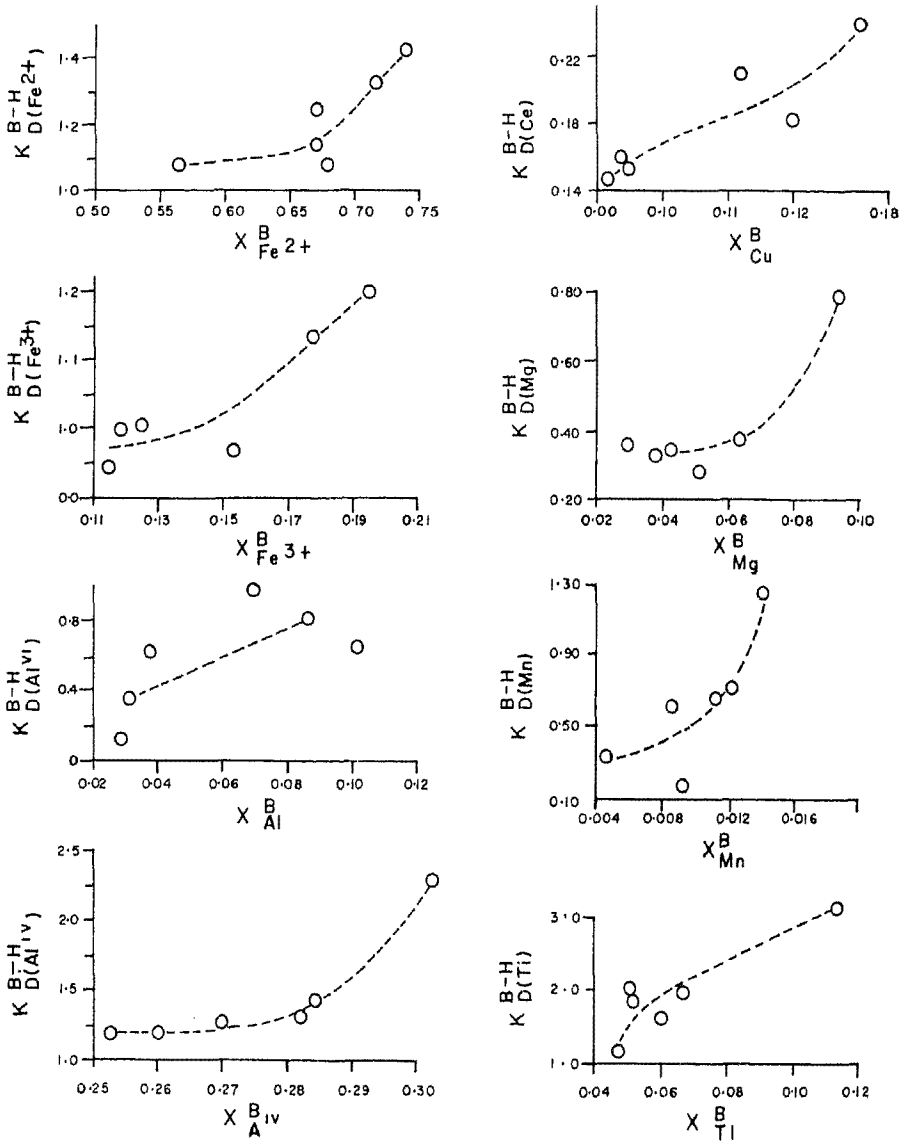


Figure 3. Variations of K_D values of major elements between coexisting biotite and hornblende from Ambalavayal.

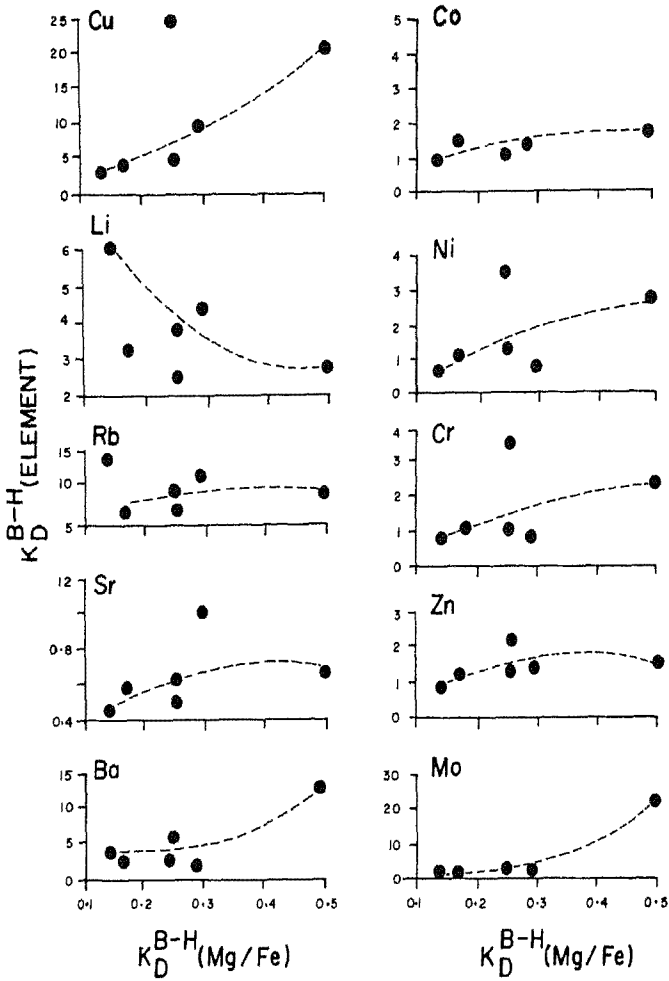


Figure 4. Variations of trace element K_D values between coexisting hornblende and biotite from Ambalavayal.

is observed in the distribution of Ba, Cu, Mo and Co, whereas Sr, Li, Zn, Cr, Ni and Rb show an overall correlation, suggesting the maintenance of near-chemical equilibrium during the crystallization of the minerals. The increase in Li and the decrease in other trace elements like Cu, Ni, Co, Zn, Sr and Cr with decreasing Mg/Fe values correspond with the crystal-chemical characters.

6. Intensive parameters

As shown by Wones and Eugster (1965), the dominant factors that influence the conditions of crystallization of biotite are temperature and fO_2 . Calculations based on the composition of biotite will hence give the minimum values of fO_2 . The most important elements to be considered are Fe^{2+} and Mg as the variations of these elements are largely temperature dependent. Also, Fe^{3+} and Fe^{2+} give an indication of

Table 5. Trace element analyses of hornblendes and biotites from Ambalavayal.

	Ba	Bi	Co	Cr	Cu	Li	Mo	Ni	Pb	Rb	Sr	V	Zn	Zr
<i>Hornblende</i>														
A/HB/1	72	50	136	122	2	89	24	86	40	62	54	120	1272	180
A/HB/2	64	58	128	128	4	88	22	98	34	56	66	130	1310	170
A/HB/3	76	48	132	116	6	92	38	80	48	72	48	110	1344	280
A/HB/4	22	74	148	128	4	42	24	104	60	24	27	100	1210	260
A/HB/5	30	60	146	116	2	72	2	122	46	50	39	140	1360	160
A/HB/6	60	78	153	124	4	48	14	102	38	30	15	100	1284	460
Mean	54	61	141	122	4	72	21	99	44	49	42	117	1297	252
<i>Biotite</i>														
A/BT/1	426	170	529	426	50	350	44	310	108	582	33	60	2600	300
A/BT/2	176	78	175	152	18	284	16	105	50	315	38	10	1530	100
A/BT/3	224	141	144	118	32	216	28	98	84	462	24	52	1840	220
A/BT/4	88	64	154	98	14	260	24	84	38	342	12	20	1142	400
A/BT/5	418	86	235	268	42	204	46	320	96	468	26	24	1860	280
A/BT/6	84	152	220	86	39	212	26	78	34	320	16	58	1780	360
Mean	236	115	243	191	33	254	31	166	68	415	25	37	1792	277

Table 6. Distribution coefficients of elements between coexisting biotite and hornblende from Ambalavayal.

K_D^{B-H}	Mg/Fe	Ba	Bi	Co	Cr	Cu	Li	Mo	Ni	Pb	Rb	Sr	V	Zn
1	0.25	5.9	3.4	3.9	3.5	2.5	3.9	1.8	3.6	2.7	9.4	0.6	0.5	2.1
2	0.17	2.3	1.3	1.4	1.2	4.5	3.2	0.7	1.1	1.5	3.2	0.6	0.1	1.2
3	0.25	2.9	2.9	1.1	1.0	5.4	2.4	0.7	1.2	1.8	2.4	0.5	0.5	1.4
4	0.14	4.0	0.9	1.0	0.8	3.5	6.2	1	0.8	0.6	6.2	0.4	0.2	0.9
5	0.50	13.9	1.4	1.6	2.3	21	2.8	23	2.6	2.1	2.8	0.7	0.2	1.4
6	0.29	1.4	2.0	1.4	0.7	9.8	4.4	1.9	0.8	0.9	4.4	1.1	0.6	1.4
Mean	0.32	5.2	2.0	1.7	1.6	11.5	3.8	4.9	1.7	1.6	4.7	0.7	0.4	1.4

the degree of oxidation. Composition of the Ambalavayal biotite when related to Wones and Eugster's (1965) experimental system suggest that oxygen fugacities during biotite crystallization were slightly higher than that defined by the Ni-NiO buffer and that the granite magma was buffered with respect to oxygen by oxides existing within the magma (Dodge *et al* 1969; Dodge and Ross 1971). If buffering continued during the crystallization of both biotite and hornblende, the tie lines between coexisting biotite and hornblende tend to be parallel to Wones and Eugster's estimated trends of buffered biotites. This is the case with Ambalavayal, where tie lines between coexisting biotites and hornblendes lie almost parallel to the trends of buffered biotite in the compositional triangle, $Fe^{3+}-Fe^{2+}-Mg$ (figure 5). Although ferric iron plays different structural roles in the micas and amphiboles, the parallelism of the biotite-hornblende tie lines with those of the buffered biotites indicate that the effect of oxygen pressure with respect to ferrous-ferric iron distribution is almost the same for biotite and hornblende. This is consistent with the observation that hornblende and biotite of

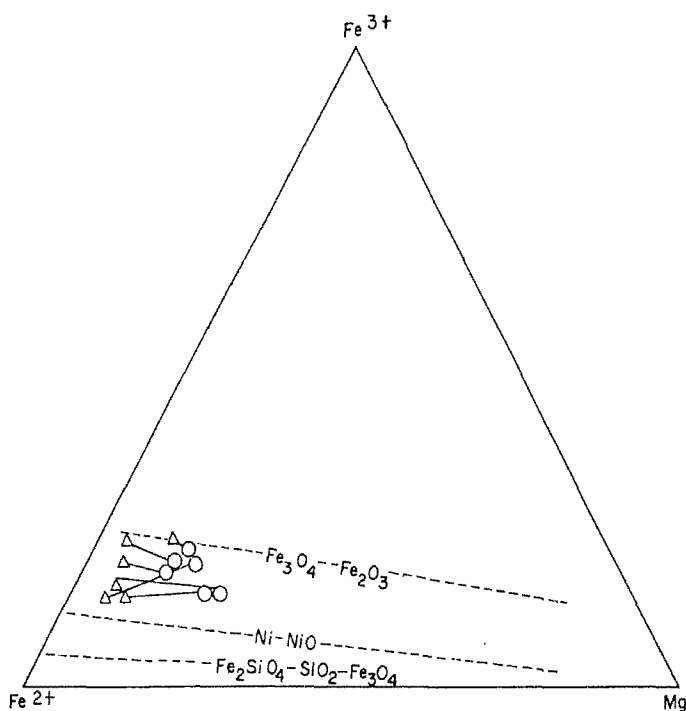


Figure 5. Fe^{3+} - Fe^{2+} -Mg plots of coexisting biotite (circles) and hornblende (triangles) from Ambalavayal. The buffer limits are after Wones and Eugster (1965).

plutonic rocks commonly formed in an environment closed to oxygen with oxygen fugacities determined by buffer reactions (Wones and Eugster 1965).

Qualitative aspects of intensive variables such as T , P , $f\text{H}_2\text{O}$ and $f\text{O}_2$ can be deduced from the sequence of crystallization of constituent minerals. The sequence of crystallization at T - $f\text{O}_2$ constrained to the Ni-NiO buffer for a rock of adamellitic composition was determined by Maaloe and Wyllie (1975). Their data show that hydrous minerals like biotite crystallize early under wet conditions and late under dry conditions. Hornblende and biotite are texturally late crystallized minerals in the Ambalavayal granite. This, together with the presence of pegmatites and aplites in the granite suggest an increase in $f\text{H}_2\text{O}$ to a probable saturation towards the final stages of crystallization.

Ishihara (1977) noted that Fe-Ti oxides indicate the relative levels of oxygen fugacity. His 'magnetite-series' refers to granites with high total Fe-Ti oxides with higher proportion of magnetite to ilmenite. The high $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios of coexisting biotites and hornblendes indicate higher oxygen fugacities during their crystallization ($f\text{O}_2 > \text{Ni-NiO}$). An estimate of $f\text{O}_2$ is depicted in figure 6 with the aid of an independent geothermometer obtained from coexisting feldspar pairs. Santosh (1986) estimated crystallization temperatures of 704–740°C for the coexisting alkali feldspar-plagioclase pairs from Ambalavayal, based on the mole % Ab content following Brown and Parsons' (1981) method. For granitic plutons, the lower limit of temperature is their wet solidus. As each stability field has pressure contours, the solidus for granitic melts in

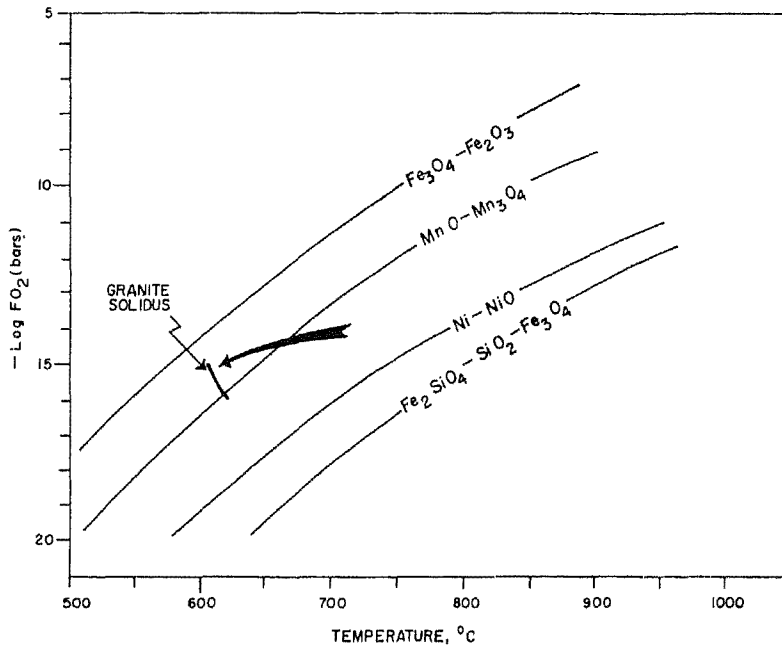


Figure 6. Log fO_2 vs temperature diagram with buffer limits, after Wones and Eugster (1965), showing the stability field of biotites from Ambalavayal. The upper limit of solidus temperature has been estimated from independent two-feldspar geothermometer (see text for further discussion).

equilibrium with biotite can be plotted. Thus, the stability fields depicted in figure 6 are derived from the two-feldspar geothermometer, which defines a window in P - T - fO_2 space, denoting high fO_2 conditions of crystallization of about 10^{-15} bars. The result is consistent with the qualitative estimate that the magnetite series granites crystallize at higher levels of fO_2 , well above the Ni-NiO buffer.

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