

Pyroxene and biotite from the charnockitic rocks of Garbham area, Srikakulam district, Andhra Pradesh, India

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SUMMARY. Chemical analyses and optical properties of ten orthopyroxenes, two clinopyroxenes, and six biotites (partial analyses) are presented from basic to intermediate charnockites of the Garbham area. The orthopyroxene is hypersthene to ferrohypersthene and the clinopyroxene is sahlite. Biotite has secondarily formed from pyroxene, particularly orthopyroxene, as a result of injection of potassic fluid in the basic charnockite. By combining the data of Srikakulam with those from other areas of the world it is shown that during the transformation of pyroxene to biotite in charnockitic rocks, in general, Mg and Fe²⁺ attain near-equilibrium distribution between orthopyroxene and biotite as well as between clinopyroxene and biotite. The magnesium distribution coefficient (K_D) of coexisting orthopyroxene and biotite is found to increase with the increase of temperature of biotite formation. A tentative geothermometric scale has been proposed plotting temperature of biotite formation against magnesium distribution coefficient of coexisting orthopyroxene and biotite. According to this scale, biotite in basic and semibasic charnockites from Garbham has formed between 285 and 465 °C.

THE Precambrian rocks of the area around Garbham (18° 22' N.; 83° 27.5' E.) are composed mainly of khondalites (garnet-sillimanite gneisses and schists), quartzites, calc-granulites, leptynites, and charnockites (basic to acid members). These rocks were metamorphosed to granulite facies and subsequently were feldspathized (potash feldspar) in places, to varying degrees, by a potash-rich fluid, leading towards granitization. The present author thinks that the basic charnockite of this area is metasediment and the intermediate and acid charnockites, in general, are the results of increasing feldspathization of the basic member (a detailed paper will be published later on).

The basic charnockite consists of orthopyroxene with or without clinopyroxene, plagioclase (An₅₀ to An₆₃), biotite, and accessories including opaque minerals (mainly ilmenite), apatite, and rutile. As a result of feldspathization some micropertthite is frequently present in the basic member. The potash-feldspar-bearing variety of basic charnockite is hereafter called migmatitic basic charnockite, and in that sense most of the basic charnockites studied are migmatitic. The intermediate and acid charnockites consist of plagioclase, micropertthite, biotite, garnet, opaques (mostly ilmenite), apatite, and zircon. Biotite has formed secondarily from pyroxene, particularly orthopyroxene in basic charnockite, and from orthopyroxene, garnet, and opaque minerals in intermediate and acid charnockites. The formation of biotite from pyroxene in basic charnockite, as a result of later injection of potassic fluid, can be justified as follows: In places, where there is no evidence for injection of potassic fluid (feldspathization) in basic charnockite, the latter does not contain any biotite; on the

other hand, basic charnockite occurring in the feldspathized zones and showing feldspathization almost invariably contains biotite. In fact, in basic charnockite as well as in other members of the charnockite series of this area, no potash feldspar, no biotite is the general rule. The textural relation strongly suggests that biotite has formed replacing pyroxene (fig. 1). The silica released during this transformation is frequently found as quartz along with the biotitized pyroxene.

Garnet is increasingly present from intermediate to acid charnockite while it is practically absent in the basic member. This paper deals with the chemistry of pyroxene and biotite occurring in basic to intermediate charnockites.

For simplicity of study of the distribution of elements in coexisting pyroxene and biotite, only those samples were selected that contain two or three principal ferromagnesian minerals (e.g. orthopyroxene, clinopyroxene, and biotite). In two samples, however, garnet is present in minor proportion.

The mineral separation was done by Frantz Isodynamic Separator, heavy liquids, tapping on art paper (for biotite), and finally by hand-picking under the microscope. The final purity of the samples was 99 %. The chemical analyses were done by conventional classical methods.

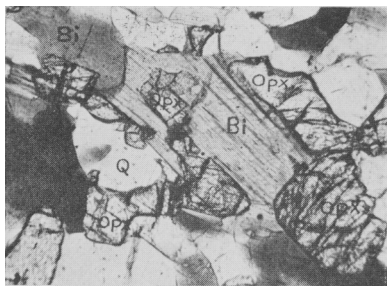


FIG. 1. Orthopyroxene (Opx) being transformed into biotite (Bi) in basic charnockite. Q, quartz (0.5 mm long).

Orthopyroxene. Table I shows the chemical analyses, structural formulae, compositions in terms of end-members, and optical properties of ten orthopyroxenes from basic to intermediate charnockites of Srikakulam. With the exception of 434, the orthopyroxenes vary in composition within narrow limits (En_{45} to $En_{57.7}$) and are, according to the classification of Hess and Phillips (1940), ferrohypersthene to iron-rich hypersthene. Alumina in 455, 529, and 434 is low for granulite facies orthopyroxenes, and lime is higher than that in most of the Madras orthopyroxenes (Howie, 1955; Howie and Subramaniam, 1957; Subramaniam, 1962). Table II shows a comparison of the compositional ranges of the orthopyroxenes from basic and intermediate charnockites of Srikakulam, Madras, and Kondapalli.

Structural formulae calculated on the basis of six oxygen atoms fit the theoretical structural formulae fairly closely in most of the analyses. A marked departure from the theoretical formulae, in which Z (Si+Al) is 2.00, is shown by two analyses (529, 434).

The intensity of pleochroism of orthopyroxenes in pink and green shades can be satisfactorily correlated with the TiO_2 contents of these minerals (Bhattacharyya, 1969). This concurs with the suggestion of Kuno (1954) and Hess (1960), and is opposed by Howie (1964a, 1965b).

Clinopyroxene is confined to the basic members of the charnockite series. Table I shows two analyses of clinopyroxene from migmatitic basic charnockites. Optical data indicate that both the pyroxenes are sahlite. Analysis 120 is closely comparable,

TABLE I. Chemical analyses, structural formulae, end-member compositions, and optical properties of pyroxenes from Srikakulam. Anal. B. P. Gupta

Orthopyroxene	Clinopyroxene										
	No.	204	455	126	120	524	201	178	529	281	434
SiO ₂	49.06	50.92	50.00	49.61	50.01	50.01	51.13	50.01	49.10	48.65	48.65
Al ₂ O ₃	2.19	0.72	1.42	1.46	1.88	1.88	2.38	2.13	0.26	1.63	0.34
TiO ₂	0.85	0.68	0.28	0.80	0.73	0.73	0.26	0.35	0.39	0.60	0.47
Fe ₂ O ₃	1.18	4.53	0.71	1.69	1.69	1.69	1.56	1.48	3.07	0.95	2.73
FeO	23.54	23.77	26.00	26.38	27.00	27.00	27.72	28.61	29.00	30.88	32.47
MnO	0.14	0.23	0.40	0.22	0.31	0.31	0.23	0.36	0.28	0.18	0.07
MgO	19.71	15.67	19.70	18.36	16.47	16.47	17.19	16.11	15.78	15.43	11.88
CaO	0.87	4.01	1.26	2.31	1.54	1.54	1.14	1.31	2.06	1.44	20.12
Na ₂ O	0.08	0.09	n.d.	0.10	0.11	0.11	n.d.	n.d.	n.d.	0.11	n.d.
K ₂ O	0.13	0.10	n.d.	0.12	0.21	0.21	n.d.	n.d.	n.d.	0.19	n.d.
H ₂ O ⁺	0.09	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H ₂ O ⁻	0.11	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.02	100.72	99.77	99.68	99.95	99.95	99.56	100.37	100.94	100.47	100.72
<i>Structural formulae on the basis of 6 (O)</i>											
Si	1.901	1.945	1.917	1.913	1.928	1.928	1.933	1.927	1.926	1.909	1.930
Al	0.099	0.033	0.064	0.066	0.072	0.072	0.067	0.073	0.012	0.075	0.016
Al	0.001	—	—	—	0.014	0.014	0.035	0.024	0.011	—	—
Ti	0.025	0.020	0.001	0.033	0.021	0.021	0.007	0.010	0.028	0.017	0.057
Fe ³⁺	0.035	0.130	0.020	0.009	0.049	0.049	0.045	0.043	0.091	0.081	0.081
Fe ²⁺	0.763	0.759	0.834	0.851	0.871	0.871	0.877	0.922	0.932	1.015	1.077
Mn	0.001	0.007	0.013	0.007	0.010	0.010	0.007	0.012	0.009	0.006	0.008
Mg	1.138	0.892	1.125	1.055	0.947	0.947	0.969	0.926	0.923	0.902	0.702
Ca	0.036	0.164	0.052	0.095	0.064	0.064	0.046	0.054	0.086	0.061	0.088
Na	0.006	0.006	—	0.008	0.008	0.008	—	—	—	0.008	0.008
K	0.006	0.004	—	0.006	0.010	0.010	—	—	0.010	0.006	0.006
Z	2.000	1.978	1.981	1.979	2.000	2.000	2.000	2.000	1.938	1.984	1.946
XY	2.010	1.983	2.045	2.054	1.994	1.994	1.986	1.991	2.072	2.047	2.027
<i>Composition in terms of end-members</i>											
Mg	1.8	8.5	2.6	4.7	3.3	3.3	2.4	2.8	4.2	3.0	4.5
Ca	57.7	45.8	55.4	52.5	49.0	49.0	50.0	47.6	45.0	45.0	36.0
Fe*	40.5	45.7	42.0	42.8	47.7	47.7	47.6	49.6	50.8	52.0	59.5
β	1.700	1.706	1.700	1.707	1.707	1.707	1.707	1.708	1.700	1.706	1.713
α	1.704	1.714	—	—	1.715	1.715	—	1.718	1.704	1.714	1.717
γ	1.716	1.725	1.716	1.725	1.725	1.725	1.725	1.728	1.716	1.725	1.728
2V _α	51 to 54	50 to 55	54 to 56	54 to 55	53	54	54	52 to 55	51 to 53	55 to 56	56
Pleochroism	++	++	++	+++	+++	+++	++	++	++	+++	+++
* Fe total.											
204 Xenolithic semibasic rock (between basic and intermediate charnockites)											
455 in biotite granodiorite gneiss, Srikakulam.											
126 Migmatitic basic charnockite, Srikakulam.											
120 Migmatitic basic charnockite, Srikakulam.											
524 Semibasic charnockite, Srikakulam.											
201 Intermediate charnockite, Srikakulam.											
178 Semibasic charnockite, Srikakulam.											
529 Migmatitic basic charnockite, Srikakulam.											
281 Xenolithic semibasic charnockite in intermediate-acid charnockites Srikakulam.											
434 Non-migmatitic basic charnockite, Srikakulam.											

* Fe total.

204 Xenolithic semibasic rock (between basic and intermediate charnockites)

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434 Non-migmatitic basic charnockite, Srikakulam.

both optically and chemically, with that of the sahlite described by Murty (1965) from the basic charnockite of the adjacent Visakhapatnam area. Analysis 529, however, falls in the augite field but near the sahlite side (Poldervaart and Hess, 1951). The measured refractive indices are very close to those obtained by plotting number of $(\text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mn})$ atoms on the curve of synthetic diopside-hedenbergite (Deer *et al.*, 1963, p. 62).

TABLE II. Comparison of the compositional variation of Srikakulam, Madras, and Kondapalli orthopyroxenes from basic and intermediate charnockites

	Srikakulam*	Madras†	Kondapalli‡
SiO ₂	48.65-51.13	47.23-52.54	50.45-51.42
Al ₂ O ₃	0.26-2.38	1.47-3.55	1.34-3.20
TiO ₂	0.26-1.90	0.11-1.02	0.24-0.38
Fe ₂ O ₃	0.32-4.53	0.59-1.93	0.14-1.19
FeO	23.54-32.47	22.70-34.03	24.36-28.89
MnO	0.14-0.40	0.32-1.03	0.52-0.98
MgO	11.88-19.71	11.14-21.08	16.17-19.51
CaO	0.87-4.01	0.10-1.66	0.18-1.02

* Ten analyses, this work.

† Nine analyses. Data from Howie, 1955; Howie and Subramaniam, 1957; Subramaniam, 1962.

‡ Six analyses. Data from Leelanandam, 1967. Orthopyroxene from anorthosite (no. 61) not considered. Orthopyroxene analyses from intermediate charnockites also could not be considered because specimen numbers of intermediate charnockites are not specifically mentioned in Leelanandam's paper.

Coexisting pyroxenes. There is a considerable overlap between igneous and metamorphic pyroxene pairs in their tie-line intersection points on the En-Wo side, for which reason, as voiced by many, these points of intersection have little practical significance for distinction between igneous and metamorphic pyroxenes. The intersection points of eight pairs of coexisting pyroxenes from the present area (compositions of two pairs by chemical analysis, one pair by optics and, for the rest orthopyroxene compositions obtained by chemical analysis and those of clinopyroxene by optics) seem to have a closer affinity to the pyroxenes equilibrated under metamorphic condition.

Considering the two analysed pyroxene pairs, it is seen that Ca-rich pyroxene has a higher Al and $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratio and lower Mn relative to the coexisting orthopyroxene. K_D of the two pyroxene pairs is anomalous and comes to be 0.81 (no. 120) and 0.54 (no. 529), where $K_D = X_{op}(1 - X_{cp})/X_{cp}(1 - X_{op})$, X_{op} and X_{cp} being $\text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Ti} + \text{Mn})$ atomic fractions in orthopyroxene and clinopyroxene respectively.

Biotite in all the members of the charnockite series is strongly pleochroic with α straw yellow, β dark brown, γ reddish-brown. The grains fringing clinopyroxene show a somewhat different pleochroism: α straw yellow with a faint greenish tinge, β dark

brown, γ dark with a faint greenish tinge. Refractive index β (1.623 to 1.642, more commonly 1.638) is more or less consistent in all the divisions, exceptions being, however, shown by some of the samples from the acid division where it is lower (β 1.618). Hall (1941) calculated that an increase of 1 % TiO_2 increases the refractive index of biotite by 0.0046. Following Hall's method the calculated refractive index γ of two biotites (table III, nos. 455 and 524) is 1.6518 and 1.6513 respectively. These values are very close to the observed values (γ 1.6501, 1.6495). Heinrich (1946, p. 847) obtained a positive correlation between γ and $\text{FeO}+2(\text{Fe}_2\text{O}_3+\text{TiO}_2)$ content of biotite. From the plots in Heinrich's diagram γ for these two biotites comes to be 1.670 and 1.675 respectively. These values are obviously higher than the observed γ and hence Hall's method gives a better approximation to the observed values.

Table III shows six partial analyses of biotite from migmatitic basic and semibasic (i.e. between basic and intermediate) charnockites. As expected from the mineralogical

TABLE III. *Partial chemical analysis of biotite from the basic and semibasic charnockites of Srikakulam. Anal. B. P. Gupta*

Biotite coexisting with	Op, Cp, Ga*						Structural formulae on the basis of 22 oxygen		
	Op, Ga	Op, Cp	Op, Cp	Op	Op	Op	455	524	
Ref. no.†	1	2	3	4	5	6			
	455	524	120	126	281	529			
SiO_2	35.33	34.30	n.d.	n.d.	n.d.	n.d.	Si	5.307	5.156
Al_2O_3	9.88	10.93	n.d.	n.d.	n.d.	n.d.	Al^{IV}	1.746	1.933
TiO_2	5.83	5.70	2.50	4.80	4.80	5.60	Al^{VI}	-	---
Fe_2O_3	2.89	6.04	n.d.	n.d.	n.d.	n.d.	Ti	0.658	0.642
FeO	19.52	17.49	13.09	12.36	13.82	14.91	Fe^{3+}	0.328	0.649
MnO	0.06	0.05	0.02	0.02	0.02	0.03	Fe^{2+}	2.448	2.194
MgO	15.73	14.18	14.53	17.23	15.00	16.00	Mn	0.008	0.006
CaO	0.41	0.53	n.d.	n.d.	n.d.	n.d.	Mg	3.517	3.170
Na_2O	0.40	0.65	n.d.	n.d.	n.d.	n.d.	Ca	0.068	0.085
K_2O	8.16	9.63	n.d.	n.d.	n.d.	n.d.	Na	0.090	0.188
							K	1.569	1.839
β	1.642	1.640	1.643	1.638	1.638	1.638			
γ	1.650	1.650	1.648	1.648	1.648	1.648			

For brief notes of the rocks see Table IV.

* Op, Orthopyroxene; Cp, Clinopyroxene; Ga, Garnet.

† Numbers as used in figs. 2-7.

assemblage, these biotites are high in MgO and TiO_2 and low in Al_2O_3 . Biotites coexisting with both ortho- and clinopyroxene have 4.80 % TiO_2 or less, but when coexisting with orthopyroxene with or without garnet, they have 4.80 % TiO_2 or more than this. There is a tendency for negative correlation between the amount of clinopyroxene and TiO_2 content of coexisting biotite. This, together with the observation that high-titanium biotite is associated with rocks richer in orthopyroxene and that the ilmenite content of the rock does not show any correlation with TiO_2 content of their

biotites, goes in favour of suggesting orthopyroxene to be a more important source than clinopyroxene for the TiO_2 content of the biotites. It may be observed at the same time that the analysed clinopyroxenes of the present area have lower titania than that of the coexisting orthopyroxenes. MnO is very low compared to the average MnO of biotites coexisting with pyroxene or olivine in calc-alkaline igneous rocks (Nockolds, 1947, p. 417). $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of biotite from nos. 455 and 524 are nearer to the average ratio in biotite coexisting with hornblende in calc-alkaline igneous rocks (0.09, Nockolds, 1947).

Two biotites from Srikakulam fall in the MgO-rich side of the diorite-tonalite field of Heinrich's (1946) diagram. Since the Srikakulam biotites have formed as a result of granitization of basic charnockites by the injection of a potassic fluid, one may expect to find the shift of biotite field from gabbro proper to more acidic rocks such as diorite-tonalite. This, together with the observation that the pleochroism (and, therefore, composition) of biotite replacing orthopyroxene is dissimilar to that of biotite replacing clinopyroxene, confirms that the composition of biotite is sensitive to the nature of the host rock as well as to the coexisting phases (cf. Atherton, 1965, p. 179).

Distribution of elements in coexisting pyroxene and biotite. If equilibrium is attained, the distribution diagrams of elements from coexisting minerals show smooth curves. In figs. 2-6 are shown the distribution of Mg and Fe^{2+} in coexisting pyroxene and biotite from Srikakulam and other areas. It is thought that biotite in Srikakulam charnockites as well as in similar rocks from Madras (cf. Howie, personal communication regarding the specimen 2270 from Madras), Vellore, and Uganda (Howie, 1964*b*) has formed secondarily from pyroxene or amphibole, regardless of whether its formation was facilitated by the introduction of potassium and aluminium from outside or from within the system. The similar mineralogical assemblage of the charnockitic rocks of these different areas and the similar mode of formation of biotite in all of them certainly justify combining the chemical data of pyroxene and biotite of Srikakulam with those from the charnockitic rocks of the other areas in a single distribution diagram to test whether Mg and Fe^{2+} attain equilibrium distribution between coexisting pyroxene and biotite. Two plots of clinopyroxene-biotite pairs included in table IV, nos. 13, 14, and fig. 6, however, do not represent charnockitic mineral assemblages.

Distribution of Mg between: Orthopyroxene and biotite (fig. 2). It is interesting to note that 3, 4, 5, and 6 from basic and semibasic charnockites of Srikakulam lie on a smooth curve (not shown) sufficiently apart from another moderately well-defined curve on which lie 1 and 2 from Srikakulam and 7, 8, 9, and 10 from Madras and Uganda. The point 11 at the lower end of the curve represents a mineral pair from coarse granite of Rubideaux Mountain, California. Another point 12 from magmatic norite of Vista, California, lies sufficiently apart from this curve near the upper left-hand side.

Clinopyroxene and biotite (fig. 3). The plots of Srikakulam together with 7, 10, and 13 from charnockites of Madras and Uganda, and from a calc-gneiss inclusion in Tيرة marble have a tendency to lie on a smooth curve.

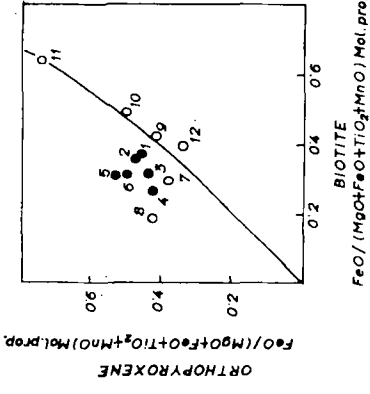


FIG. 2

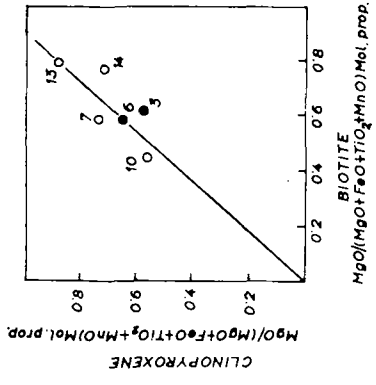


FIG. 3

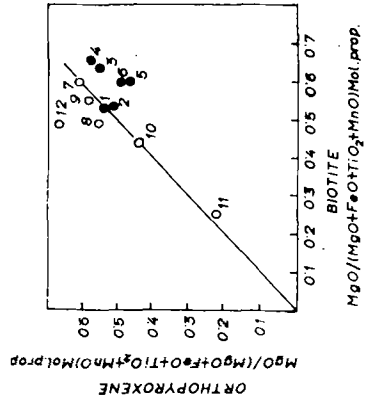


FIG. 4

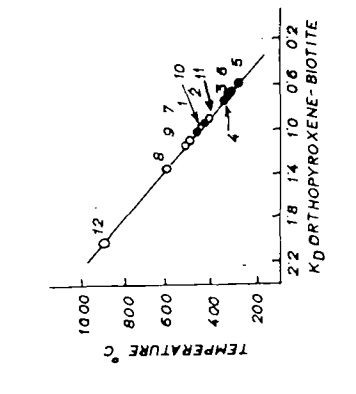


FIG. 5

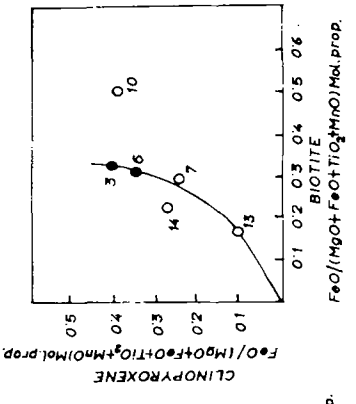


FIG. 6

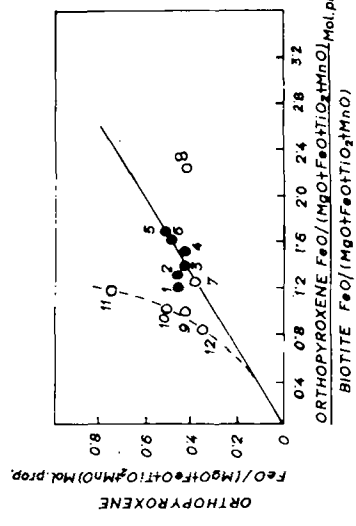


FIG. 7

FIGS. 2-7: numbers refer to Tables III and IV. Solid symbols, Skrikulam rocks, Fig. 2. Distribution of magnesium between orthopyroxene and biotite. Fig. 3. Distribution of magnesium between clinopyroxene and biotite. Fig. 4. Distribution of iron between orthopyroxene and biotite. Fig. 5. A slight increase of Fe²⁺ in orthopyroxene relative to that in biotite causes a more rapid increase of Fe²⁺ in those orthopyroxenes that are more aluminous (9, 10, 11, 12). Fig. 6. Distribution of iron between clinopyroxene and biotite. Fig. 7. Tentative relationship between magnesium distribution coefficient (K_D) and temperature of biotite formation.

TABLE IV. *Magnesium distribution coefficients (K_D) of coexisting pyroxene-biotite pairs from Srikakulam and other areas*

Ref. no.*	Spec. no.	K_D	T†
<i>Orthopyroxene-biotite</i>			
1	455	1.01	465 °C
2	524	0.94	430
3	120	0.70	330
4	126	0.72	350
5	281	0.59	285
6	529	0.66	315
7	2270	1.07	500
8	J 32	1.33	600
9	G 80	1.13	515
10	S 347	0.98	450
11	E 138-67	0.91	420
12	SLRM 334/E1-230	2.04	900
<i>Clinopyroxene-biotite</i>			
3	120	0.77	
6	529	1.25	
7	2270	1.99	
10	S 347	1.61	
13	S 32451	2.05	
14	—	0.79	

* Numbers as used in figs. 2-7.

† Inferred equilibrium temperature for orthopyroxene-biotite pairs.

1, 3, 4, and 6. Migmatitic basic charnockite, Srikakulam.

2 and 5. Semibasic (between basic and intermediate) charnockite, Srikakulam.

7. Intermediate charnockite, Salem, Madras; Howie, 1955.

8. Oligoclase-antiperthite-hypersthene granulite, Vellore, South India; Naidu, 1955.

9. Charnockite, Bunyoro district, Uganda; Groves, 1935.

10. Intermediate charnockite, Mt. Wati, West Nile district, Uganda; Groves 1935; orthopyroxene anal. Howie in Howie and Subramaniam, 1957, biotite composition based on the estimated composition by Howie (1965a, p. 74).

11. Coarse granite, Rubideaux Mtn., California; Larsen and Draisin, 1950.

12. Norite, Vista, California; Larsen and Draisin, 1950. The analyses are not from a strictly coexisting pair, the hypersthene being from SLRM 334 and the biotite from E 1-230, but both are from the same rock, norite.

13. Calc-gneiss inclusion in Tiree marble; Hallimond, 1947.

14. Diopside granulite, Visakhapatnam; L. N. Rao, 1960.

Distribution of Fe²⁺ between: Orthopyroxene and biotite (fig. 4). The plots are scattered compared to fig. 2 and, therefore, it is not possible to say whether they show equilibrium distribution; more data are necessary. But, when considered with the points 7, 9, and 10 from charnockitic rocks of other areas, the points 1, 2, and 3 from Srikakulam have a tendency to lie on a smooth curve. Orthopyroxene has more affinity for Fe²⁺ when it has a higher Al content; this is shown in fig. 5, which indicates that a slight increase of Fe²⁺ in orthopyroxene relative to biotite causes a rapid increase of Fe²⁺ generally in more aluminous orthopyroxenes (points 9 to 12).

Clinopyroxene and biotite (fig. 6). The data from Srikakulam are insufficient to draw any conclusion as to the attainment or non-attainment of equilibrium. The points 3 and 6 from Srikakulam together with 7, 13, and 14 appear to lie on a smooth curve.

The *magnesium distribution coefficient* (K_D) (table IV) was calculated from 12 orthopyroxene-biotite pairs using the equation: $K_D = X_{op}(1-X_{bi})/X_{bi}(1-X_{op})$, where $X_{op} = \text{MgO}/(\text{MgO} + \text{FeO} + \text{TiO}_2 + \text{MnO})$ molecular proportions in orthopyroxene, $X_{bi} = \text{MgO}/(\text{MgO} + \text{FeO} + \text{TiO}_2 + \text{MnO})$ molecular proportions in biotite. It may be noted that four pairs from Srikakulam (3, 4, 5, 6) having K_D varying from 0.59 to 0.72 fall on a smooth curve (not shown) in fig. 1, while seven pairs including two from Srikakulam (1, 2) having K_D of 0.91 and 1.33 lie on another curve. This difference is not due to the attainment of equilibrium under isochemical metamorphism on the one hand and allochemical metamorphism on the other, because Srikakulam biotites have all formed by K-metasomatism (allochemical metamorphism) yet K_D is characteristically different for two pairs and K_D of these two pairs is nearer to those of isochemically metamorphosed mineral pairs from Madras and Uganda (nos. 2270, G. 80, S. 347).

Biotite from the Uganda charnockite is said to have formed secondarily mainly from pyroxene (also amphibole) under conditions of granulite facies while biotite from Vellore, South India, has formed at upper amphibolite to lower granulite facies condition (Naidu, pers. comm.). Howie (1955, p. 763) estimated the temperature of metamorphism of the Madras charnockite series as approximately 660 °C, but later on Buddington and Lindsley (1964) estimated the temperature as 500–600 °C (using the composition of coexisting magnetite and ilmenite). Now, if the temperature of crystallization of the magmatic norite of Vista, California (Larsen and Draisin, 1950), is assumed to be approximately 900 °C, the higher K_D (2.06) of its orthopyroxene-biotite pair in comparison with that from Madras indicates temperature dependence of K_D . This temperature dependence of K_D is further evident from the Srikakulam charnockites: nos. 455 and 524 having K_D 1.01 and 0.94 contain an additional ferromagnesian silicate, garnet, unlike others having K_D from 0.59 to 0.72. The appearance of garnet in these two specimens is due to more intense migmatization and metasomatism with consequently more intense recrystallization, which is reflected in their coarser grain size. Since the $\text{Al}_2\text{O}_3/\text{CaO}$ ratio does not differ significantly in the garnetiferous and non-garnetiferous migmatitic basic and semi-basic charnockites under consideration, it may be inferred, as was done by Buddington (1965) that Al_2O_3 , though critical, is not the only factor for the development of garnet. Buddington says that the garnetiferous facies of the Adirondack quartz syenite gneisses experienced higher temperatures than their non-garnetiferous counterpart. Similarly, garnetiferous basic and semibasic charnockites of Srikakulam suffered higher temperatures during later metasomatism; K_D of two pairs (nos. 455, 524) of coexisting orthopyroxene and biotite from Srikakulam is very near to that from Madras specimen 2270, and hence the temperature at which the equilibrium for Mg distribution was attained in the mineral pairs of these two rocks from Srikakulam due to later metasomatism would be

very near to that for the Madras specimen. The temperature of formation of Madras specimen 2270 is known to be 500 °C by the interpolation method or 480 °C by the direct method of feldspar geothermometry (L. N. Rao, 1967, p. 98). From the K_D of coexisting pyroxenes in this rock the equilibrium temperature becomes 650 °C using Kretz's curve (Kretz, 1963, fig. 3) or 533 °C using the curve of Engel *et al.* (1964, fig. 8). Howie (pers. comm.) favours a temperature of 600 ± 50 °C for the metamorphic episode of Madras charnockite; but, according to him, the specimen 2270 is very different in having abundant biotite, possibly of a second metamorphic episode. The present writer thinks that this second episode is represented by retrogression giving rise to abundant secondary biotite and, therefore, a lower temperature of 500 °C, which is the minimum temperature of metamorphism of the Madras charnockites, determined by Buddington and Lindsley (1964), seems reasonable as the equilibrium temperature for the orthopyroxene–biotite pair.

In fig. 7 is shown a tentative relation between Mg distribution coefficient (K_D) of coexisting orthopyroxene–biotite and temperature of formation of biotite. This is based on the data from the two rocks, one from the Madras intermediate charnockite (no. 2270, K_D 1.07; temperature of formation 500 °C) and the other from the norite of California (no. SLRM 334/EL-230, K_D 2.04; temperature of biotite crystallization assumed to be 900 °C). The inferred temperatures of crystallization of biotite from the rocks of Srikakulam and other areas are included in table IV.

Magnesium distribution coefficient in coexisting clinopyroxene and biotite. Table IV also shows the Mg distribution coefficient of six pairs of coexisting clinopyroxene and biotite. K_D from two pairs (nos. 120, 529) from Srikakulam is distinctly lower than that of the mineral pairs from granulite facies rocks of Madras and Uganda (nos. 2270, S.347). This possibly indicates temperature dependence of K_D , because Srikakulam biotite has been shown to have formed at lower temperatures than the biotites from Madras and Uganda.

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