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# Minerals of Charnockites from India

By *P. R. Jagapathi Naidu*, Bangalore

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### Preface

The rock specimens on which the present work is based were collected between the years 1940 and 1943, during geological excursions conducted into the various charnockitic areas of India, under the auspices of the University of Mysore. With the kind permission of Professor L. Rama Rao, Head of the Department of Geology, Mysore University, I brought over these specimens for investigation in the Mineralogical Institute of the University of Basel in September 1949. From September 1949 to June 1951, the minerals contained in these specimens have been investigated under the guidance of Professor M. Reinhard.

My students, Messrs. M. S. Sadasiviah and S. V. Parthasarathy Iyengar, who have since obtained their doctor's degrees at the University of London, have given me great assistance in the field. Dr. O. Grütter, Prof. Reinhard's Assistant, has throughout helped me in the setting up of apparatus and in the determination of the plagioclase feldspars. P. D. Dr. E. Wenk has offered valuable criticism on every aspect dealt with in this paper: he cited useful references, checked my calculations and suggested improvements, by all of which I have considerably profited. To Mr. H. Schwander I am indebted for the chemical analyses of rock-forming minerals, and Mr. E. Glauser has made excellent preparations of rock slices and mineral powders for my optical studies. Mrs. N. Bächlin and Miss M. Caveng have carefully and neatly typed my manuscript. I render them all my best thanks.

Finally, my unfailing gratitude is due to Prof. M. Reinhard. His extremely painstaking criticism of my manuscript, his detailed instruction and scrutiny of my optical and chemical data, and his very careful editing of my work, have vastly enhanced the quality of my paper. I offer him my most heartfelt thanks.

Basel, 15th June, 1951.

P. R. J. NAIDU

### Introduction

In 1900, SIR THOMAS HOLLAND, Director of the Geological Survey of India, established the "Charnockite Series of India". He described them as a series of Archæan hypersthenic rocks, constituting an igneous series of consanguineous members, ranging from acid through intermediate to basic rocks. He enumerated geological, structural, mineralogical and chemical characters, which are distinctive of these rocks.

Since then, representatives of this series have been identified in and described from various Archæan terrains of the world. Thus ARNO SCHÜLLER (1949) p. 573, could remark, "Heute, und besonders im letzten Jahrzehnt, sind sie nahezu aus allen 'alten Kernen' der Kontinente beschrieben worden".

Among the papers published outside India, that of A. W. GROVES (1935) on the Uganda charnockites is a noteworthy contribution. He has marshalled evidence to show that the charnockite series are due to plutonic metamorphism of normal plutonic rocks (p. 198—200). In India, P. K. GHOSH (1941), of the Geological Survey of India (p. 52—53), and B. RAMA RAO (1945), Director of the Mysore Geological Department (p. 141—163), have likewise cited evidence in favour of a metamorphic origin for these rocks.

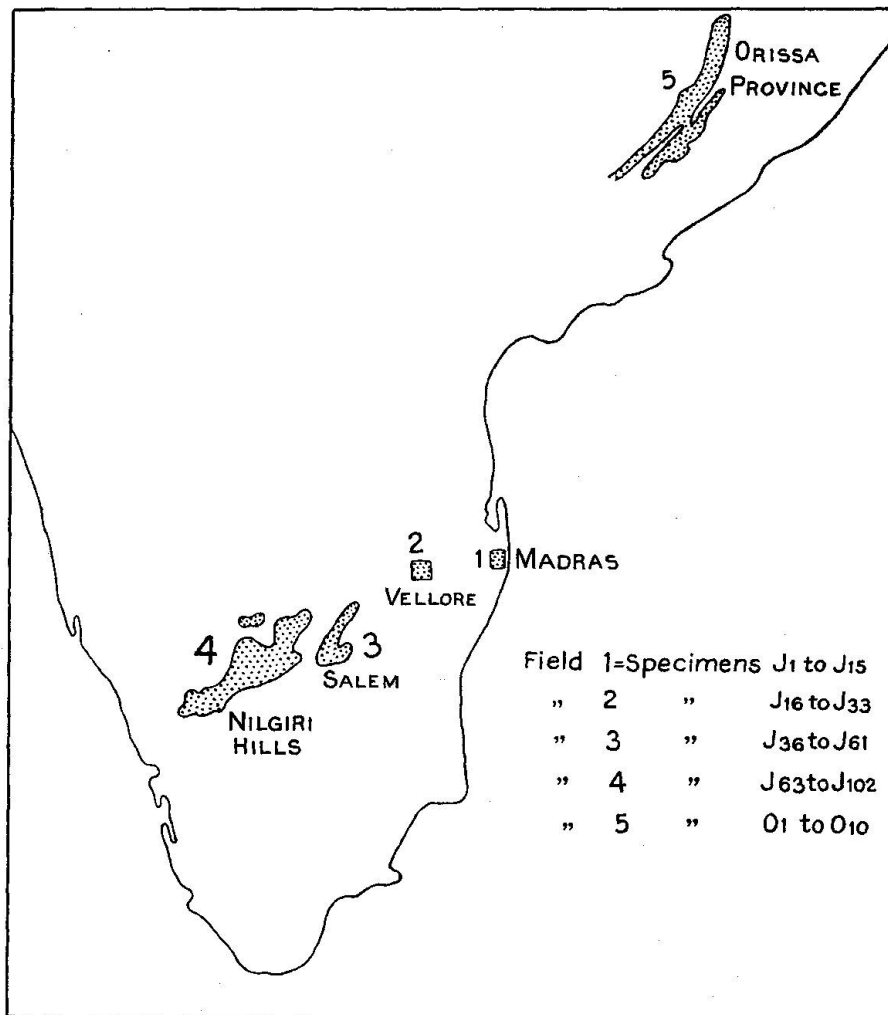


Fig. 1. The occurrences of charnockites in India.

The minerals of the charnockites of India have not been re-examined since SIR THOMAS HOLLAND gave their distinctive optical characters in his classical description of the charnockites. He noted particularly the blueness of the quartz, the absence of inclined extinction in the hypersthene, and the perthitic nature of the potash feldspars.

The various charnockitic areas in India are indicated in Fig. 1. During geological excursions conducted from 1940 to 1943 into various parts of these areas, a number of specimens of charnockites were collected. The localities are indicated in Fig. 1, and the micrometric analyses of thin slides of some of the specimens are given in Appendix 1. Exhaustive field and microscopic descriptions of these rock types have been given by SIR THOMAS HOLLAND and subsequent workers. No attempt shall here be made to redescribe these rocks.

The present paper deals mainly with the optical and chemical characters of the minerals contained in these rock types.

The results are treated under the following headings: (1) The determination of the plagioclase feldspars, (a) by the Fedorow method, (b) by the single-variation method, (2) Perthitic feldspars, (3) Mafic minerals: hypersthene, clinopyroxene, green and blue amphiboles, mica, garnet, and (4) The chemical relationship of these minerals to the rocks in which they occur. As already mentioned, the micrometric analyses of some of the examined thin slides of the rock specimens are given in appendix 1; in appendix 2 the petrofabric analyses of these rock types are shown.

### **Felspar group**

#### **Plagioclase feldspars**

##### **Nature of twinning**

SIR THOMAS HOLLAND has remarked that the plagioclase feldspars of charnockites are generally poorly twinned. The examination of about 100 thin slides enables us to confirm his statement. Some twinned plagioclase grains are sketched in figure 2.

Three characteristics of these twinning lamellæ are noticeable; (1) they are well developed in the basic granulites, (2) the lamellæ tend to be discontinuous in the acid granulites, and (3) sometimes they are curved. DONNAY (1943) regards such discontinuous lamellæ as characteristic of metamorphic and hybrid rocks. KÖHLER (1948) cites such poor development of lamellæ as characteristic of feldspars formed at a low temperature.

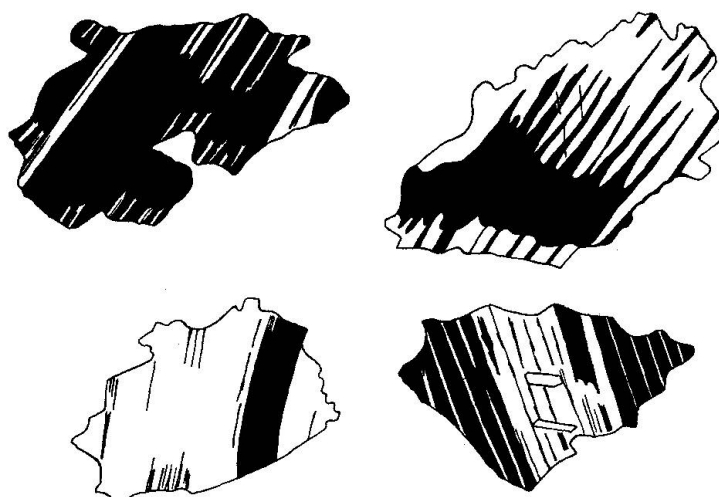


Fig. 2. Twinned plagioclase grains (albite law) from labradorite-amphibole-hypersthene-granulite.

#### Determination of plagioclase-felspars by the universal-stage method

The determination was carried out in accordance with the method of Prof. REINHARD (1931). The rock sections examined were about .06 mm thick.

72 feldspar grains from 28 rock sections were measured on the Fedorow stage. The results were interpreted according to tables 2, 3, and 4 of REINHARD (1931), slightly modified in part by SPAENHAUER (1933). In cases of doubtful interpretation, the construction of the twin axis was resorted to, and the result interpreted by means of Reinhard's table 5. In all the 72 cases, the pole of the twin plane was located by the NIKITIN method, and its position in the triangle of error determined by BEREK's method of locating the twin plane and therefrom the twin axis.

The results of this determination are shown in table I.

The twin laws that have been noticed are: albite, Manebach, acline, pericline, and albite-Ala. Carlsbad and albite-Carlsbad twins are typically absent and so are the Baveno and Ala twins. Albite and albite-Carlsbad twins however, were found in an augite-diorite (J. 16, J. 69 and J. 81), that occurs among the charnockite rocks, but does not constitute a member of the series.

Of the five laws occurring in the plagioclase felspars of charnockites the albite and the pericline are the most frequent. Out of the 72 determinations, 36 are albite law and 20 pericline. These two laws preponderate in the andesines (20 albite law, and 16 pericline). The albite-Ala seems

Table I. *Plagioclase Twins*

Nature of plagioclase	Percentage of anorthite	Normal law		Parallel law		Complex law	Rock types as described by Holland
		Albite	Manebach	Accline	Pericline	Albite-Ala	
Oligoclase	15—25%	—	—	1	—	—	Acid charnockites
Oligoclase to Andesine	25—35%	9	1	—	4	8	Gneisses
Andesine	35—50%	20	—	—	16	—	Intermediate charnockites, Gneisses, hypersthene-granulites (norite after Holland) Granulites, Amphibolites
Labradorite	50—70%	6	2	2	—	1	Hypersthene-granulites (norite after Holland)
Bytownite	70—90%	1	—	—	—	1	Basic charnockites
All plagioclases		36	3	3	20	10	
Twin laws in %		49	5	7	25	14	

to be distinctive of the basic oligoclase (8 out of the 10 recorded cases being in basic oligoclases). According to KÖHLER (1948) the albite and pericline laws dominate in rocks formed at low temperature, whereas the albite law together with Carlsbad are characteristic of rocks formed at a high temperature.

Of the five recorded twin laws none seems to be characteristic of any rock type of the charnockite series. All the types of twin laws, normal, parallel and complex, are represented in the basic charnockites (Norites after HOLLAND). (010) as a twinning plane is more common in the charnockite series than (001). In 46 instances the twinning plane is (010) and in only 6 instances it is (001). The width of the albite lamellæ measured from oligoclase to bytownite in this series generally accords with the theoretical deductions of DONNAY (1940).

On the basis of the plagioclases determined, the charnockites can be divided into the acid group with oligoclase to andesine (25 to 35% An), and the intermediate group with andesine (35 to 50% An). The gneisses correspond to these acid and intermediate divisions. The hypersthene granulites have andesine (40 to 50% An) and rarely labradorite to bytownite. The amphibole-bearing granulites and amphibolites have an anorthite content of from 40 to 80%.

The poles of the association plane are plotted in the cumulative stereogram (Fig. 4)<sup>1</sup>.

The poles show a remarkable dispersal from the curves, though not of the magnitude noticed by HOMMA (1932) and PALIUC (1932) in effusive rocks. BARBER (1936, p. 239) has suggested that this dispersal may be rectified by locating the optical symmetry plane, instead of the morphological composition face, in normal twins. Accordingly, this was tried in several instances, but the dispersal of the poles was found to be of the same order in both cases.

CAMPBELL SMITH (1928) has remarked that "the results for the poles of the twin axes are of a higher degree of accuracy than those for the planes of association". The poles of the twin axes of parallel and complex twins, located by NIKITIN's and BEREK's constructions, are plotted in Fig. 5.

The order of dispersal is about the same as that noticed when poles of composition faces are plotted.

### Optic axial angles

The optic axial angles determined are plotted in Fig. 3. The points show a very pronounced dispersion.

### Determination of the anorthite content by the immersion method

The determination of the refractive indices of minerals by the immersion method of Schroeder van der Kolk consists in matching the refractive indices of the principal vibration directions of a mineral with the refractive indices of liquids in which they are immersed, the wavelength of the source of light and the temperature being kept constant. This method has since been modified (1) by varying the wavelength of the source of light — the single-variation method of TSUBOI

<sup>1</sup>) Remark: In all stereograms, the signs  $\odot$  +  $\triangle$  indicate the position of X, Y and Z.



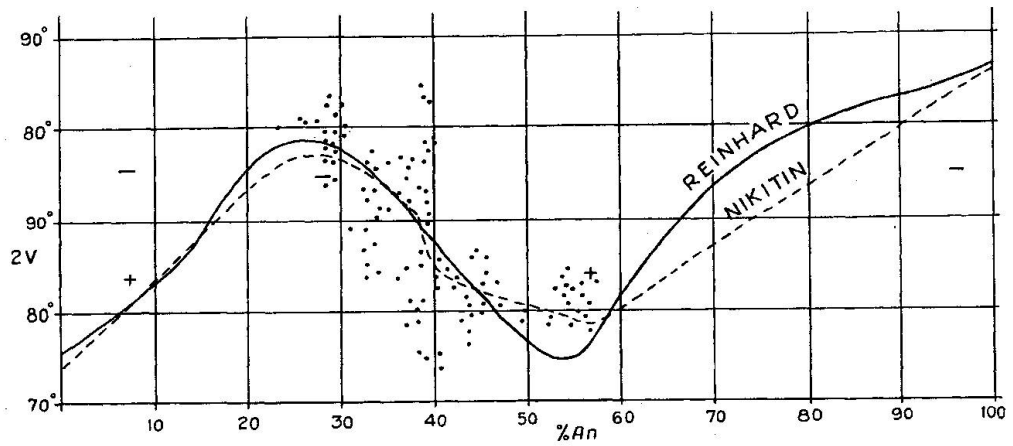


Fig. 3. Optical axial angles of plagioclase feldspars. The points show a very pronounced dispersion.

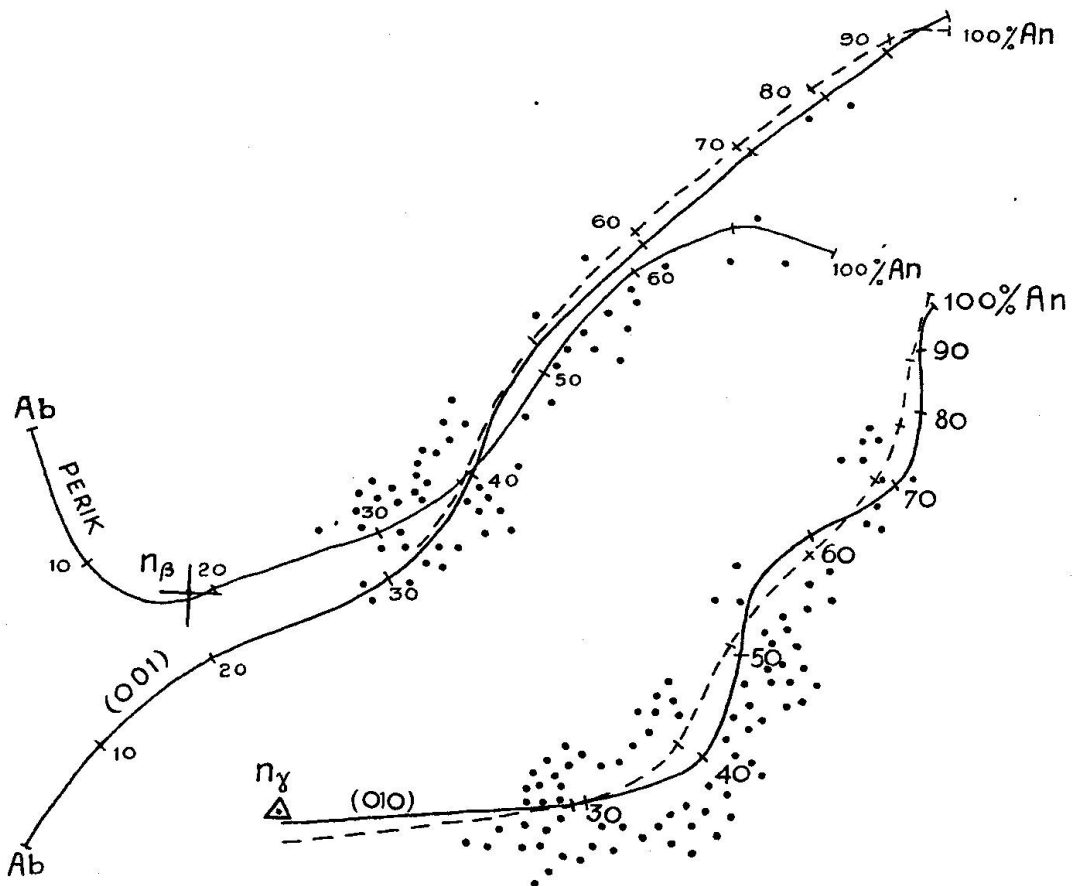


Fig. 4. Cumulative stereogram, showing the distribution of the poles of the composition planes of 72 plagioclase twins. Curves of Reinhard (drawn) and Spaenhauer (dotted).

and MERWIN, and (2) by varying the indices of the liquid by change both of wave-length of the source of light and of temperature — the double-variation method of EMMONS.

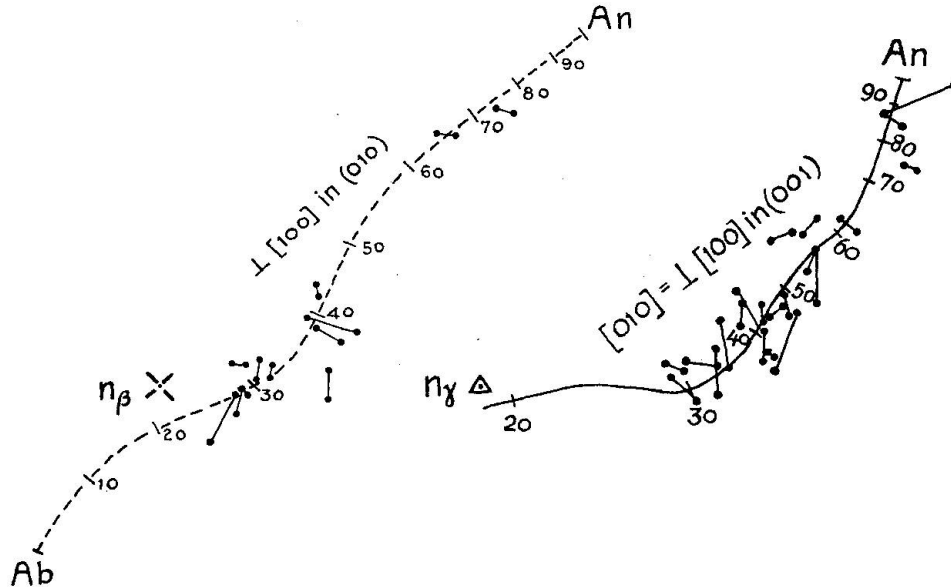


Fig. 5. Poles of the twin axes of complex and parallel twins located by Berek's and Nikitin's constructions. The two individuals of any twin are joined by a line.

Dr. E. WENK (1945) has extensively reviewed the applicability of these methods and has found the single-variation method best suited for the determination of feldspars.

*The single variation method of Tsuboi and Merwin*

The method consists in varying the refractive indices of the immersion media by varying the wavelength of the source of light. This procedure eliminates the inconvenience of employing more than a few liquids. Nitrobenzol was found to be suitable for the determination since it has a dispersion corresponding to the range of refractive indices of the plagioclase feldspars under examination, i. e. from 1.543 to 1.571. In the case of some sodic feldspars the matching for  $n_{\alpha}'$  occurred beyond the red ( $700\mu\mu$ ), and, in the case of some calcic feldspars, the matching for  $n_{\gamma}'$  was beyond  $500\mu\mu$ .

Clove oil was therefore used for the determination of the refractive indices of sodic plagioclases and mixtures of clove oil and cinnamon oil were made use of for the determination of calcic plagioclases. The dis-

persion of the mixtures was determined by the method indicated by Tsuboi. On a graph paper the refractive indices for different wavelengths of clove oil and cinnamon oil were plotted. The refractive indices for the D line of the mixtures was determined and a vertical drawn through these points.

The disposition of the apparatus required for this method — the electric lamp, the monochromator, microscope, and refractometer — is shown in the photograph Fig. 6.

By this arrangement the mirror of the refractometer can be swung out when not in use, and the light passes directly to the mirror of the microscope. The refractometer, and also the monochromator, may be used without disturbing their relative positions.

The results of the measurement of refractive indices and the determination of the corresponding anorthite content from the  $n_{\alpha}'$  curve of Tsuboi are as follows:

Rock No.	Wave length of matching (in $\mu\mu$ )	Anorthite content of plagioclases according to:	
		Immersion method	Fedorow method
J <sub>3</sub>	552—521 Nitrobenzol	51—61%	42—53%
J <sub>4</sub>	622—578 Clove oil	16—20%	26—32%
J <sub>15</sub>	610—582 Nitrobenzol	35—41%	35—42%
J <sub>23</sub>	604—567 Nitrobenzol	37—46%	50—59%
J <sub>24</sub>	650—552 Mixture 2	30—50%	27—30%
J <sub>27</sub>	642—563 Nitrobenzol	29—48%	30—40%
J <sub>31</sub>	690—570 Nitrobenzol	24—56%	26—35%
J <sub>39</sub>	652—582 Mixture 2	28—41%	36—46%
J <sub>74</sub>	518—512 Mixture 2	61—65%	53%
J <sub>90</sub>	568—522 Mixture 1	56—71%	58—62%
J <sub>98</sub>	593—553 Mixture 1	49—60%	48—54%

A comparison of the values obtained by the immersion method with those obtained by the Fedorow method, reveals a discrepancy particularly in the upper limit of the anorthite content. This is due to the fact that the cleavages are poorly developed in the feldspars of charnockites, and the grains examined were mostly of a rounded shape and had no straight edges. — Therefore, they were mostly not cleavage flakes but grains with a random orientation.

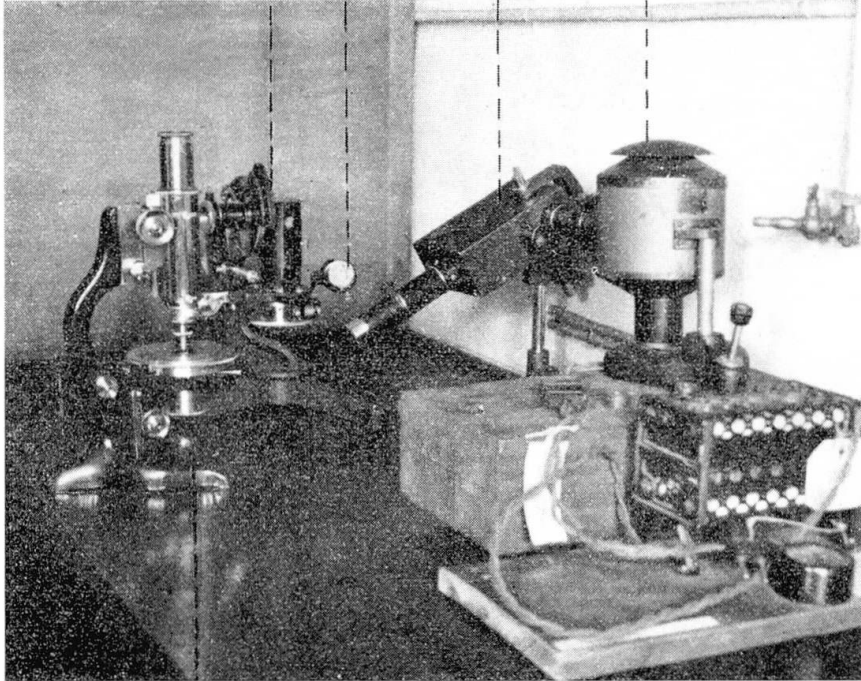


Fig. 6. Disposition of instruments for the immersion (single-variation) method.

E. WENK (1945) has commented on this difficulty: “Die Immersionsmethode liefert ungenaue Resultate, wenn die Plagioklaskörner schlecht spalten.”

To test if the grains examined were cleavage flakes, the following method was employed:

A stereographic projection of the axes of the indicatrix of about ten grains in each rock powder, mounted in canada balsam, was made and compared with REINHARD's determinative plates 3 and 4. Most of them coincided with varying values of anorthite content for  $n_{\alpha}$  (X),  $n_{\beta}$  (Y) and  $n_{\gamma}$  (Z). This is illustrated in the case of rock powder from  $J_{15}$ .

It is evident from the above list, that, out of the ten grains examined, only three (Grains nos 3,6 and 8) are cleavage flakes after (001).

Orientation of grains in rock powder J<sub>15</sub>

Grain No.	Position on REINHARD'S plates			Reference to REINHARD'S plates
	n <sub>α</sub> (Y)	n <sub>β</sub> (Y)	n <sub>γ</sub> (Z)	
1.	Dispersed at 60% An	60	Dispersed at 60	plate 4 (001)
2.	Far dispersed	80	Far dispersed	id.
3.	29	30	32	id.
4.	52	55	64	plate 3 (010)
5.	Dispersed at 40	40	35	plate 4 (001)
6.	35	35	30	id.
7.	Dispersed at 40	35	35	id.
8.	40	40	40	id.
9.	—	—	—	No coincidence in either of the plates 3 and 4
10.	—	—	—	id.

The examination of the other determinations also showed that the grains are but exceptionally cleavage flakes. The single-variation method of Tsuboi has for this reason been difficult to use for determining the anorthite content of plagioclase feldspars of charnockites.

## Chemical composition

The plagioclase from the andesine-hypersthene-diopside granulite of Pallavaram (J<sub>3</sub>) was analysed. The proportion of minerals by volume, as estimated in a thin slice of the rock, is given in Appendix I.

WILLIAM PARRISH (1941) has proposed the following formula for plagioclases:  $(Na_x, Ca_{1-x})(Si_xAl_{1-x})AlSi_2O_8$ , where  $x=1$  for albite and  $x=0$  for anorthite.

Computed according to this formula, the analysed plagioclase may be written as  $(Na_{.38}Ca_{.49}K_{.03})(Si_{.57}Al_{.45})(AlSi_2O_8)$ . The proportion in molecular % of Or : Ab : An is as 3 : 41 : 56. The mean value, determined on 5 grains after the Fedorow method, is 53% An.

A plagioclase of the ratio Or<sub>3</sub>Ab<sub>41</sub>An<sub>56</sub> has the following calculated chemical composition:

SiO <sub>2</sub>	54.2
Al <sub>2</sub> O <sub>3</sub>	29.1
CaO	11.4
Na <sub>2</sub> O	4.8
K <sub>2</sub> O	0.5
	100.0

## Chemical analysis of plagioclase

	Weight %	Mol. number	Metal atoms	O.OH.F. atoms	Basis 8(O.OH.F)
SiO <sub>2</sub>	56.80	946	946	1892	2.57
TiO <sub>2</sub>	—	—	—	—	—
Al <sub>2</sub> O <sub>3</sub>	27.10	266	532	798	1.45
Fe <sub>2</sub> O <sub>3</sub>	.70	4	—	—	—
FeO	.11	1	—	—	—
MnO	—	—	—	—	—
MgO	.34	7	—	—	—
CaO	10.15	179	179	179	.49
Na <sub>2</sub> O	4.28	70	140	70	.38
K <sub>2</sub> O	.49	5	10	5	.03
H <sub>2</sub> O+	.05	—	1807	2944	
H <sub>2</sub> O—	.05	—			
P <sub>2</sub> O <sub>5</sub>	.02	—			
	<u>100.09</u>				

$$F = \frac{8}{2.944} = 2.717$$

Sp. Gr. 2.66

Analyst: H. SCHWANDER

The chemical composition determined by analysis differs from this ideal composition by an excess of SiO<sub>2</sub> and a deficiency in Al<sub>2</sub>O<sub>3</sub>.

**Microcline-perthite and antiperthite**

## Shape and occurrence

HOLLAND (1900) described them as microperthite-microcline regularly intergrown with a plagioclase.

M. S. SADASIVIAH (1943) has studied the microcline-perthites of charnockites from Vellore, South India, and Halagur, Mysore, on the lines indicated by ALLING (1938) for the study of plutonic perthites. He came to the conclusion that the microcline-perthites are due to exsolution.

The microcline-perthites are best developed in the acid charnockites of the type area at St. Thomas Mount, Madras, and to a lesser extent in Kailasgarh, Vellore, Nagaramalai in Salem, and Dimbhum in Coimbatore District. They occur as allotriomorphic grains, sometimes 1.5 cm long, with crushed borders. The border is composed of grains of quartz, fresh plagioclase felspar, fine cross-hatched microcline without spindles, antiperthite and myrmekite ranging in size from .5 mm to .04 mm. The rocks show undoubted evidence of cataclasis, mylonitization, myrmekitization and lineation of the mineral constituents.

The antiperthites occur as big grains between 1.70 mm to .80 mm in diameter and are generally surrounded by cataclastic grains of  $\frac{1}{4}$  mm or less in size of quartz, antiperthite, twinned and untwinned plagioclase, and, occasionally, of cross-hatched microcline. They occur most abundantly in mylonitised quartz-felspar rocks, and, in subordinate amounts, with microcline-perthites, in acid and intermediate charnockites. Some grains are also present in basic charnockites. They occasionally show patches of microcline-perthites, and are invariably crowded with opaque dust and needles. The needles sometimes show a regular crystallographic orientation. In some, apatite grains are abundant, and in a few grains inclusions of biotite are noticed. The antiperthites are the dominant feldspars in charnockites of Vellore, Salem, and the Nilgiri range of hills. They are subordinate to microcline-perthites in the Madras area.

### Microcline-perthites Optical properties

Most of the grains show the cross-hatched structure, but some are untwinned. The twinning lamellæ are very fine in grains, which show no perthitic intergrowth, but become broader and irregular with the increase in size of the perthitic spindles. The position of the axes of the indicatrix and of morphological directions was determined on 82 grains in 33 rock sections on the Fedorow Stage, and transformed to the stereogram of NIKITIN, with  $n_\beta$  as the centre of projection. The results collected in this stereogram show the emergences of (001) poles between those of orthoclase and microcline.

The optic axial angles are generally comprised between  $-83^\circ$  and  $-86^\circ$ . Values between  $-83^\circ$  and  $-69^\circ$  occur only exceptionally. KÖHLER (1948) regards angles above  $80^\circ$  as characteristic of microclines formed at high pressure and low temperature.

The extinction angle  $X \wedge 001$  cleavage, measured on grains in slide  $J_{10}$ , on sections perpendicular to Z, gave an average value of  $+10^\circ$ .

The birefringences of the microcline-perthite hosts ranged from .006 to .007. The refractive indices as determined in sodium light are:

$$\left. \begin{array}{l} n_\alpha = 1.522 \\ n_\beta = 1.526 \\ n_\gamma = 1.528 \end{array} \right\} \pm .001 \quad n_\gamma - n_\alpha = .006$$

*Shape and nature of spindles*

They are of the shape of spindles in the zone [001], and appear as irregular blebs or patches on the (001) face.

One of these grains is shown in Fig. 7.

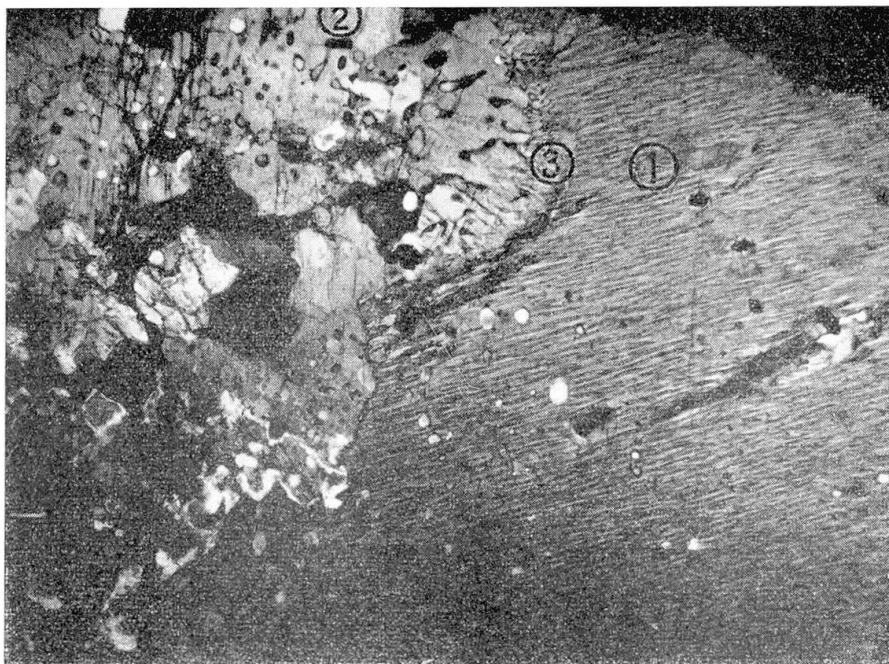


Fig. 7. Microcline-perthite (1); plagioclase with quartz-drops (2); rim of myrmekite at the border towards the microcline-perthite (3).

To judge from the optical properties, the spindles correspond to a potash felspar rich in the soda molecule.

### Antiperthite Optical properties

The host grains have a varying anorthite content of 20% to 37%, as was determined on REINHARD'S plates. The optic axial angles range from  $-74^\circ$  to  $-86^\circ$ . The values of the birefringences are:

$$\begin{aligned}(n_\beta - n_\alpha) &= .0048, .0035, \text{ and } .0042 \\(n_\gamma - n_\beta) &= .0037, .0033, .0034, \text{ and } .0032 \\(n_\gamma - n_\alpha) &= .0085, .0076, .0069, \text{ and } .0084\end{aligned}$$

The twinning is on the pericline and albite laws. The felspars show strain shadows.



Refractive indices were determined by the single-variation method. These are:

$$\left. \begin{array}{l} n_{\alpha} = 1.544 \quad 1.547 \quad 1.541 \\ n_{\beta} = 1.548 \quad 1.552 \quad 1.545 \\ n_{\gamma} = 1.552 \quad 1.555 \quad 1.549 \end{array} \right\} \pm .001$$

These values give for the anorthite content a range of 24% to 36% on curves given by WINCHELL and the data of TSUBOI.

*Shape of the spindles*

In the [001] zone they appear as long rods of lengths varying from .05 mm to .35 mm. Their breadth extends from .0008 mm to .0166 mm. They are variously inclined to the (001) cleavage. On (010) faces, angles like 72°, 76°, 84°, 86°, and 87° have been measured. In sample J<sub>39</sub>, there are two sets of spindles. On the (010) face they intersect each other at 71°, on (001) at 70°. On the (010) face one is at an angle of 87° with (001) cleavages, and another at an angle of 17°. One set of spindles is roughly parallel to albite lamellæ. On the (100) face the two sets of spindles intersect each other at right angles.

Some photographs of the antiperthites were taken and are shown in figures 8 to 10.

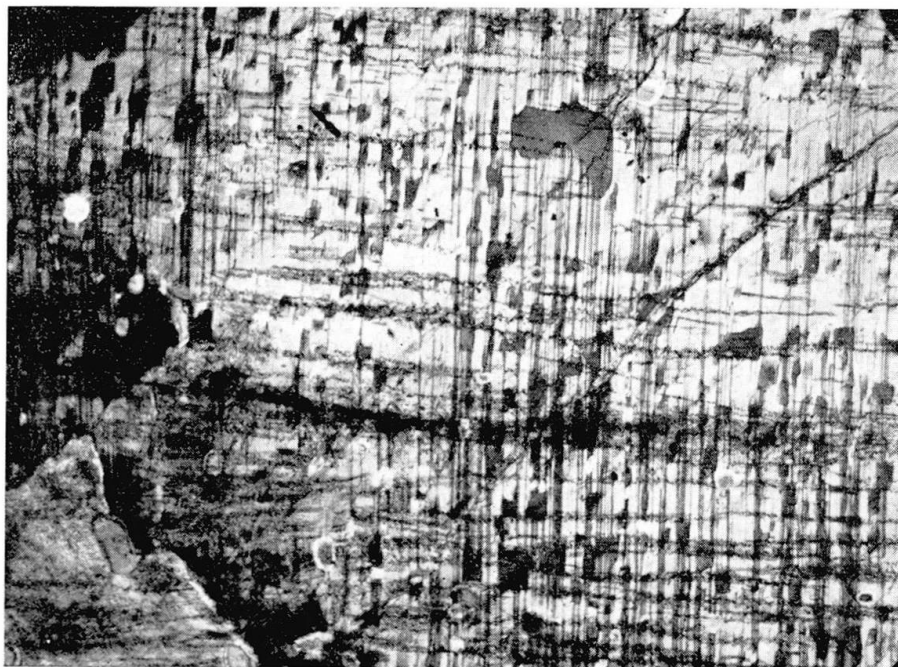


Fig. 8. Section of antiperthite.

The photograph Fig. 8 is of a grain cut nearly parallel to (100). The angle between the spindles and the trace of (001) is  $90^\circ$ . The small

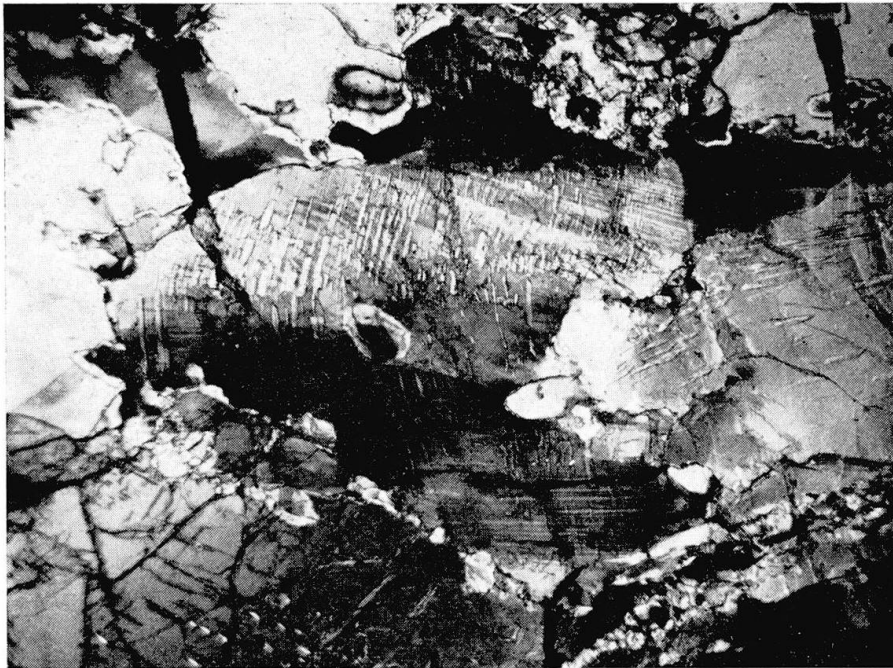


Fig. 9. Antiperthite. The spindles follow the curvatures in the very fine albite lamellae produced by shearing. The lamellae approximately  $\perp$  to the spindles are pericline twins.

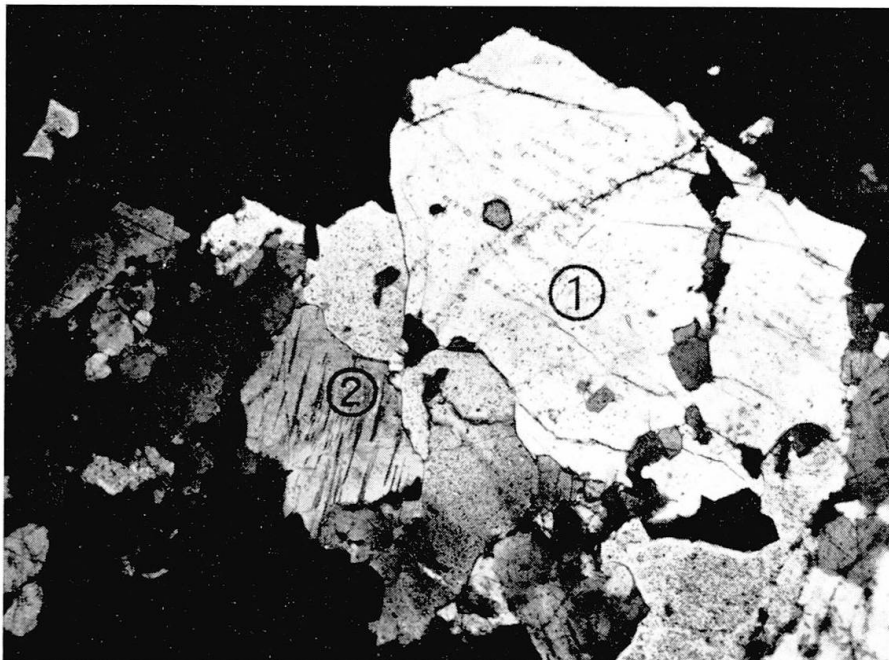


Fig. 10. Antiperthite. 1. Grain cut parallel to (001). 2. Grain cut parallel to (110).

spindles have the same orientation as the host, but the bigger ones have a slightly different orientation.

In photograph Fig. 9 the spindles are parallel to the albite lamellæ and follow the curvatures caused by shearing. The photograph is of a section cut nearly perpendicular to the *a* axis of the host.

In photograph Fig. 10 appear two grains. The big light-grey grain with minute square spots, is a grain parallel to (001). The spindle spots are arranged in rods parallel to (110). The smaller medium-grey grain with long narrow spindles, is cut parallel to (110). Here the spindles are elongated and parallel to the *c* axis. Each of these grains, when tilted through a big angle on the Fedorow stage, has the appearance of the other.

The optic axial angles of some of these spindles were measured. They give the values  $-2V = 40^\circ, 46^\circ, 60^\circ, 74^\circ, \text{ and } 83^\circ$ . The large spindle in the grain of Fig. 8 was the best of the spindles in antiperthites, whose optical constants could be measured in detail. The optic axial angle is  $2V = -46^\circ$ ,  $(n_\gamma - n_\beta) = .0008$ , and  $(n_\gamma - n_\alpha) = .0052$ .

#### Chemical composition of microcline-perthites and antiperthites

The rock powders were separated into heavy and light fractions in bromoform. The light fraction was treated in a mixture of bromoform and benzol to separate microcline-perthite and antiperthite from the rest of the felsic constituents.

Microcline-perthite was separated from rock specimen J<sub>10</sub>-Leptite from Pallavaram, Madras. A planimetric analysis of a thin slide of the rock gave in volume %:

Quartz	14
Microcline-perthite	76
Plagioclase	7
Hypersthene	2
Iron ore	.5
Apatite	.5

Antiperthite was separated from rock specimen J<sub>85</sub>, an oligoclase-antiperthite-gneiss from Hasanur, Nilgiri hills. A planimetric analysis of a thin slide of the rock gave:

Quartz	9
Antiperthite	69
Plagioclase	11
Hypersthene	6
Biotite	3
Iron ore	1.5
Apatite	1.5

Both the rocks are crushed and every grain of microcline-perthite is surrounded by a zone of minute grains of felspar and of quartz. At the contact between microcline-perthite and plagioclase, myrmekite is well developed.

Since no pure fraction of antiperthite could be obtained, only a partial analysis of it was made. The chemical analyses of the perthite and antiperthite are given below and compared with those given by ANDERSEN and WARREN.

## Chemical analyses of perthite and antiperthite

	1 J <sub>10</sub> Microcline- perthite	2 J <sub>85</sub> Anti- perthite	3 ANDERSEN 29	4 WARREN 1
SiO <sub>2</sub>	66.20	—	60.83	66.50
TiO <sub>2</sub>	—	—	—	—
Al <sub>2</sub> O <sub>3</sub>	17.57	—	23.36	18.40
Fe <sub>2</sub> O <sub>3</sub>	1.27	—	0.16	1.05
FeO	—	—	—	—
MnO	Tr	—	Tr	Tr
MgO	0.34	—	0.02	0.07
CaO	1.78	7.10	5.05	0.30
Na <sub>2</sub> O	3.28	7.34	4.38	5.40
K <sub>2</sub> O	10.00	1.36	6.09	8.77
H <sub>2</sub> O +	—	—	0.07	—
H <sub>2</sub> O -	—	—	0.14	—
P <sub>2</sub> O <sub>5</sub>	Tr	—	—	—
BaO	—	—	0.05	—
	<hr/> 100.44	—	<hr/> 100.15	<hr/> 100.69
Sp. Gr.	2.58	2.66	—	2.597

1. Microcline-perthite from Leptite, Pallavaram, Madras, Analyst H. SCHWANDER.
2. Antiperthite from oligoclase-antiperthite-gneiss, Hasanur, Nilgiri Hills, partial analysis, Analyst H. SCHWANDER.

3. O. ANDERSEN, "The genesis of some types of feldspar from Granite pegmatites", Norsk geologisk tidsskrift Vol. X, 1928, p. 147, Analysis No. 29, Analyst E. KLÜVER.
4. C. H. WARREN, "A quantitative study of certain perthitic feldspars". Proc. Amer. Acad. of Arts and Sc. Vol. 51, No. 3, 1915, p. 139, Analysis No. 1, Analyst C. H. WARREN.

The chemical analysis of microcline-perthite resembles analysis No. 1 of WARREN, and that of antiperthite resembles No. 29 of ANDERSEN in possessing a high content of lime. The total amount of alkalis in the analysis of microcline-perthite, i.e. 13.28, is near the average of 14 of perthite analyses. Alumina in the analysis of microcline-perthite is distinctly lower than the alumina in the analyses of perthites, cited both by ANDERSEN and by WARREN. The percentage of anorthite in the antiperthite is 33, which is above the average 20 to 24%, determined on REINHARD'S plates.

In the analysis of microcline-perthite the anorthite content is only 4%, and if this percentage is assumed as present in the microcline host, then the perthite spindles should be albite, which is, however, not revealed by the optical properties determined.

The calculation of the norm of the microcline-perthite gave the following result:

Orthoclase	58.94
Albite	27.71
Anorthite	3.89
Enstatite	1.80
Wollastonite	2.09
Hæmatite	1.28
Quartz	5.70
	101.41

### Origin of perthites

To ascertain the origin of perthites in the present case, estimates were made to determine the proportion of the spindles to the host in both microcline-perthites and antiperthites. The proportions are:

	Microcline-perthites						Antiperthites								
	J <sub>4</sub>	J <sub>5</sub>	J <sub>7</sub>	J <sub>9</sub>	J <sub>10</sub>	J <sub>22</sub>	J <sub>3</sub>	J <sub>7</sub>	J <sub>19</sub>	J <sub>26</sub>	J <sub>38</sub>	J <sub>51</sub>	J <sub>52</sub>	J <sub>85</sub>	J <sub>101</sub>
Spindles	44	44	45	31	48	45	22	9	26	30	29	36	30	20	31
Host	56	56	55	69	52	55	78	91	74	70	71	64	70	80	69

VOGT's ratio (as quoted by WARREN 1915) for eutectic composition of the two crystal phases in cryptoperthites is Or 40—44% to (Ab + An) 60—56. The ratios of the spindles to host in the cryptoperthite under study do not correspond to this ratio and can not be regarded as eutectic mixtures.

In the charnockites there is no evidence of alkalic solutions because the spindles do not extend into the grains from the margins, but group together towards the centre of the crystal. There are no plume-perthites or vein-perthites as have been cited as an evidence of replacement. The smaller grains, representing the last phase of crystallization, were examined on the Fedorow stage, to find out if there is evidence of pure albite and potash felspar having crystallized as the last residue.

The plagioclase grains have the same anorthite content as indicated by the host grains of the antiperthites, i.e. 20 to 30% An. They look untwinned, but, on being tilted on the Fedorow stage, the twin lamellæ appear in some of them. The ratio of twinned to untwinned plagioclase is 1 : 3. The microclines in the last phase of crystallization are non-perthitic. There is, therefore, evidence of the magma having differentiated in the last phase to a potash-rich liquid.

That the perthites are in the normal trend of crystallization of the charnockites is illustrated from the Or-Ab-An diagram (Fig. 11), in which the analyses of the charnockite series (by WASHINGTON) and of the analysed perthites are plotted.

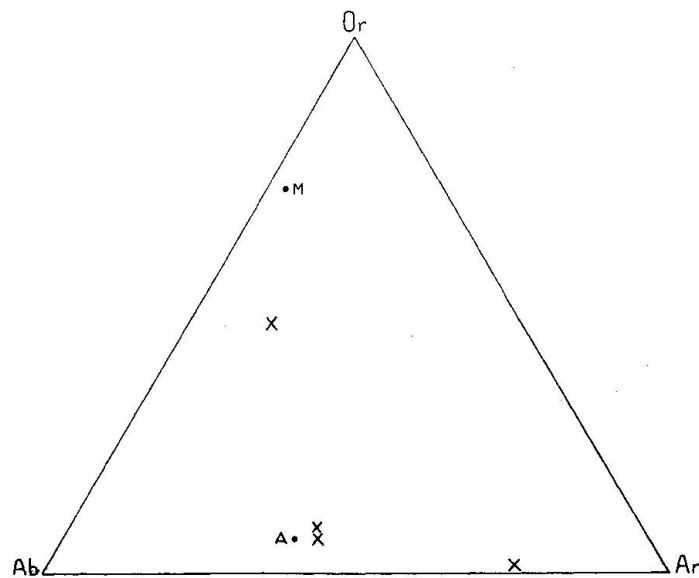


Fig. 11

Fig. 11. Ab-An-Or diagram. X = Analyses of charnockites by Washington; M = Analysis of microcline-perthite; A = Analysis of antiperthite.

It is necessary to examine what possibilities there have been for obtaining a potash-rich liquid as the last residue in the charnockite series.

Analyses by WASHINGTON of charnockites from South-India are plotted in Fig. 12.

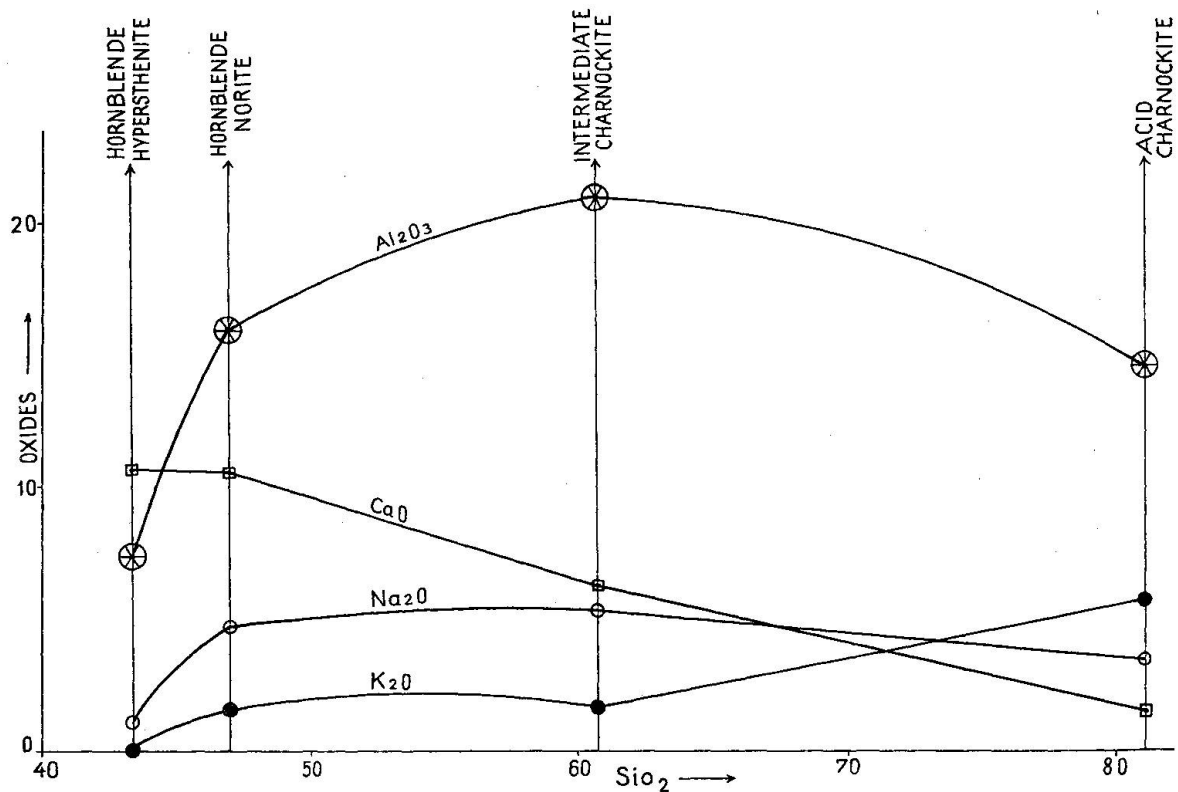


Fig. 12. Variation diagram of charnockites constructed from Washington's analyses. Plot of  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  curves in weight percentages. — Illustrates the upward trend of the potash curve and the intersection of the lime curve with the alkali curves near 70%  $\text{SiO}_2$ .

The curves do not correspond entirely with the trends of either the alkalic or the calc-alkalic suite of rocks. ARTHUR HOLMES (1921) has observed that the most significant factor of the two suites is the  $\text{SiO}_2$  % at the intersection of the lime curve with those of the alkalis. For the alkalic suite it is at 54%  $\text{SiO}_2$ , and for the calc-alkalic suite it is at 66% (HOLMES 1921, p. 452). In the charnockites the intersection is near 70%. They are, therefore, of extreme calc-alkalic character as is shown by the following comparison:

1. The alkali curves in the charnockites lie well below the alkali curves of the alkalic suite. Their total alkalic content is low.
2. The lime curve is well above the lime curve of the alkalic suite. Therefore, lime and soda are about equal in the feldspars formed at this

silica percentage, as is, for example, estimated in the antiperthites, namely  $\text{CaO} = 7.10\%$  and  $\text{Na}_2\text{O} = 7.34\%$ . At  $80\%$   $\text{SiO}_2$ ,  $\text{CaO}$  is half that of soda, and the plagioclase has the composition  $\text{Ab}_{70}\text{An}_{30}$ . A sodic residuum is never reached. On the other hand, the potash curve displays an upward trend. A potash residuum can form, if the liquid is fractionated at this stage. Therefore there is a possibility of replacement by a potash-rich liquid and not by a soda-rich residuum.

This process cannot account for the formation of perthites, as these show no such access of solution from outside, and particularly so, since there have been no albite solutions for the formation of microcline-perthites.

VOGT believes that there are two mixed crystal phases of orthoclase and plagioclase, namely (1) Or  $72\%$  and  $(\text{Ab} + \text{An}) 28\%$ , and (2) Or  $12\%$  and  $(\text{Ab} + \text{An}) 88\%$ , and that these would unmix to perthites on the lowering of temperature. The microcline-perthite and antiperthite analysed, have the proportions of 65 Or 35 Pl and 8 Or 92 Pl respectively, which are near the proportions cited by VOGT. It is therefore held that the formation of perthite in charnockites is due to exsolution.

### Mafic minerals

#### Introduction

SIR THOMAS HOLLAND has described in detail the various mafic minerals occurring in the charnockites of India. Some of these minerals have now been chemically analysed, and their optical characters determined in greater detail.

**Separation of minerals.** The crushed mineral powders passed through .02 mm mesh were first separated in bromoform. Iron ores were removed from the heavy residues by an electromagnet.

**Hypersthene, garnet and biotite.** These three minerals occur in an oligoclase-antiperthite-hypersthene-granulite ( $J_{32}$ ). Neither amphibole nor augite was present. The heavy residue from bromoform was treated with Clerici's solution diluted to 3.2 Sp. Gr. The mica floated and hypersthene and garnet sank. The mica was crushed again and passed through .01 mm mesh to remove hypersthene grains that were entangled in mica flakes. The flakes were then tapped on a finely-ruled paper-pad, when the hypersthene grains rolled off, and the mica flakes adhering to the pad were tapped and removed. After repeated sieving and tapping, and final treatment in Clerici's solution, the flakes had still about  $5\%$  by volume of impurity (plagioclase).



The mixture of hypersthene and garnet was treated with Clerici's solution of 3.6 Sp. Gr., when garnet sank and hypersthene floated. After repeated treatment, pure samples of hypersthene and garnet were obtained.

Green amphibole. This mineral occurs in a hypersthene-augite-hornblende-plagioclase-granulite (hornblende-norite after Holland). The heavy residue could not be separated into its mineral constituents, neither in heavy liquids nor in a centrifuge. The mixture was therefore repeatedly concentrated in an electromagnetic separator, by varying the strength both in homogeneous and in heterogeneous fields, and the less magnetic concentration, about 80% green amphibole, was treated in Clerici's solution in the following manner. The powder was poured into Brögger's separating funnel, half filled with Clerici's solution (Sp. Gr. 4.0), and with the addition of a few drops of water at a time the solution was stirred, until a few grains sank. After the liquid had stood for six hours, there was a concentration of green amphibole in the upper part, but there were still grains of pyroxenes in this fraction. Repeated attempts with the electromagnet and Clerici's solution produced a residue of green amphibole with approximately 8% impurity, consisting mainly of hypersthene and diopside. The mineral with the impurity has been analysed, as it gives a general indication of the amphibole present in these rocks. ESKOLA (1950) has had an amphibole with impurity analysed and remarks: "Although the separation was not complete, the result is sufficient to show some essential features in the composition . . ."

Blue-green amphibole. In an amphibolite consisting of plagioclase, iron ore, and apatite, 63% of blue-green amphibole occur. It did not require any further treatment beyond a repeated separation in bromoform. The grains (about .01 mm in size) of the blue-green amphibole, however, contain minute grains of iron ore.

#### Methods of optical examination

Refractive indices.  $n_{\beta}$  was determined by the immersion method in sodium light. Mixtures of monobromnaphthalene and methylene iodide, and monobromnaphthalene and chlornaphthalene were prepared on the spot, and the refractive index read on a Jelly refractometer. When matching occurred, the precise values were read on an Abbe refractometer.  $n_{\alpha}$  and  $n_{\gamma}$  values of amphiboles and pyroxenes were determined from the birefringences,  $(n_{\beta} - n_{\alpha})$ , and  $(n_{\gamma} - n_{\beta})$ . The retardation was determined with a Berek compensator. Special slides were prepared for determining birefringences. Quartz was mixed with each mafic mineral,

and the mount ground down until the minerals showed flat surfaces, — a method recommended by HESS (1949) for determining the thickness of the mineral.

$n_\gamma : c$ : These values for clinopyroxenes of pyroxene-granulites were determined on sections || to (010). For augites and pigeonites of augite-diorites the values were determined on simple twins by the method of NEMOTO and TURNER, recommended by HESS (1949).

2 V: These values were determined by the Fedorow method as described by REINHARD, and the angles were measured on the control K axis, whenever both the optic axes were within the field of view. These angles were corrected from the curves of TRÖGER (1939).

Density was determined on 2 to 5 grams of mineral with a 10 c. c. pycnometer, care being taken to drive out all air bubbles by gentle heating, and ultimately in an air pump.

## Pyroxenes

### Orthopyroxenes

Orthopyroxenes occur in all the rock types of the charnockite series, and are regarded by SIR THOMAS HOLLAND as distinctive of the series. They are granular and pleochroic; sometimes their pleochroism is weak when greenish-brown hornblende occurs with them. A clinopyroxene, also green in colour, is present, but the pinkish tinge parallel to X, characteristic of the orthopyroxenes, is absent in it. The two pyroxenes occur together in pyroxene-granulites in fairly equal proportions, but the clinopyroxene diminishes towards the acid charnockites, and in the most acid members it is absent. Lamellar structure is present in both. The optic axial plane is parallel to (100) lamellæ in the orthopyroxenes, and is perpendicular to them in clinopyroxenes. The sections of maximum birefringence have, therefore, a straight extinction for the orthopyroxenes and an inclined extinction for the clinopyroxenes.

The optical characters determined on the analysed specimen of hypersthene are:

$$\left. \begin{array}{l} n_\alpha = 1.710 \\ n_\beta = 1.721 \\ n_\gamma = 1.724 \end{array} \right\} \pm .001 \quad n_\gamma - n_\alpha = .024$$

The optic axial angle, as determined by direct measurement on the universal stage, where both the optic axes appear within the field of view

gave the values  $48^\circ$ ,  $55\frac{1}{2}^\circ$  and  $57\frac{1}{2}^\circ$  on different grains. Applying TRÖGER's corrections for segment 1.650, that was used, the true angles are  $-2V = 46^\circ$ ,  $53^\circ$  and  $55^\circ$ . Dispersion  $2V = \rho > v$ . The pleochroic scheme is:

Section (.03 mm thick)	Section (.07 mm thick)
X = tinge of pink	intense pink
Y = colourless	shade of green
Z = shade of bluish-green	bluish-green
Absorption $Y < X < Z$	

*Chemical composition of orthopyroxenes*

The chemical analysis of hypersthene from a granulite, specimen J<sub>32</sub>, from Kailasgarh, Vellore, having the modal composition:

Quartz	1.0
Microcline	2.5
Plagioclase	43.0
Antiperthite	26.0
Hypersthene	16.5
Biotite	7.0
Garnet	2.5
Iron ore	1.5

is as follows:

Chemical analysis of orthopyroxene

	Weight %	Mol. number	Metal atoms	O, OH, F atoms	Basis 6 (O, OH, F)
SiO <sub>2</sub>	48.65	810	810	1620	1.869
TiO <sub>2</sub>	1.60	20	20	40	.046
Al <sub>2</sub> O <sub>3</sub>	1.66	16	32	48	.074
Fe <sub>2</sub> O <sub>3</sub>	5.55	35	70	105	.162
FeO	24.40	339	339	339	.762
MnO	.30	4	4	4	.010
MgO	17.65	438	438	438	1.011
CaO	.12	2	2	2	.005
Na <sub>2</sub> O	.27	5	10	5	.025
K <sub>2</sub> O	Tr		1725	2601	
H <sub>2</sub> O+	.03				
H <sub>2</sub> O-	.01				
P <sub>2</sub> O <sub>5</sub>	.05				
	<u>100.29</u>				
Sp. Gr.	3.33				

MgSiO<sub>3</sub> : FeSiO<sub>3</sub> = 56.4 : 43.6  
(En) (Fs)

Analyst: H. SCHWANDER

The formula of the mineral on the basis of 6 (O, OH, F) atoms is  $(\text{Mg}, \text{Fe}^{\text{II}}, \text{Fe}^{\text{III}}, \text{Mn}, \text{Na})_{1.995} [\text{Si}_{1.989} \text{O}_6]$ . Titanium and aluminium are here regarded as replacing silica. The bases and silica fall short of the ideal 2 atoms by .005, and .011 respectively, a deficiency that is noticed in many analyses of pyroxenes.

HESS (1949) gives the general structural formula of WARREN and BERMAN for any pyroxene:

$(\text{W})_{1-p} (\text{X}, \text{Y})_{1+p} \text{Z}_2 \text{O}_6$ , with the values of  $p=1$  and  $W=0$  in orthopyroxenes, the formula then simplifying to  $(\text{X}, \text{Y})_2 \text{Z}_2 \text{O}_6$ . But in the balancing of electrical charges, he is in favour of Ti going with the bases. The atoms in the above analysis may be distributed according to his scheme in the following way:

Chemical composition of orthopyroxene calculated after the method of HESS

	Weight %	Mol. number	Atomic ratios	Na	Fe	Na	Al	W Y Z	Cations to Six O
SiO <sub>2</sub>	48.65	810	Si 810						
Al <sub>2</sub> O <sub>3</sub>	1.66	16	Al 32				32	842 Z	1.95
Fe <sub>2</sub> O <sub>3</sub>	5.55	35	Fe 70	10					
FeO	24.40	339	Fe 339						
MgO	17.65	438	Mg 438						
CaO	.12	2	Ca 2						
Na <sub>2</sub> O	.27	5	Na 10						
K <sub>2</sub> O	Tr	—	K —					W X Y 883	
H <sub>2</sub> O +	.03								2.04
H <sub>2</sub> O -	.01								
TiO <sub>2</sub>	1.60	20	Ti 20						
MnO	.30	4	Mn 4						
P <sub>2</sub> O <sub>5</sub>									

The proportion of cations to six O, Z : W X Y = 1.95 : 2.04, is within the limit of 2% error prescribed by him.

Nomenclature: HESS (1940) p. 285, has proposed the following scheme for the nomenclature of orthopyroxenes.

Optically +	En <sub>100</sub> - En <sub>88½</sub>	Enstatite
,,	- En <sub>88½</sub> - En <sub>80</sub>	Bronzite
,,	- En <sub>80</sub> - En <sub>50</sub>	Hypersthene
,,	- En <sub>50</sub> - En <sub>12</sub>	Ferrohypersthene
,,	+ En <sub>12</sub> ± to En <sub>0</sub>	Orthoferrosilite

Here the ratio of En is 56.4 (see p. 228), and therefore the mineral is well within the limit of hypersthene.

NIGGLI (1943) has made an exhaustive study of the pyroxenes, and has given a scheme of classification according to his system of calculating the basic standard molecules.

Plotted in his diagram for orthopyroxenes (Cs, FaFs, Fo subsidiary diagram, NIGGLI 1943 Fig. 8 p. 597), the analysed hypersthene has  $-2V = 54^\circ$ , and  $n_\gamma = 1.72 - 1.73$ ,  $\mu = .51$ ,  $\gamma = 0$ , all of which agree with the values determined.

#### *Comparison with other analyses*

The analysis of the hypersthene is compared with analyses of other hypersthene from charnockites of Mysore and Uganda, and two analyses of hypersthene (Stillwater and Bushveld), inverted from pigeonites, and one from the Moore County meteorite.

#### Analyses of hypersthene

	1	2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	48.65	45.90	54.37	55.15	53.16	51.16	52.66	51.40	50.24	49.37
TiO <sub>2</sub>	1.60	1.10	0.07	0.03	1.35	nil	Tr	.30	.69	0.62
Al <sub>2</sub> O <sub>3</sub>	1.66	7.00	9.39	6.50	10.55	3.44	1.28	1.78	4.52	1.55
Fe <sub>2</sub> O <sub>3</sub>	5.55	2.90	.95	2.10	4.30	5.20	5.47	1.40	.41	1.83
FeO	24.40	18.90	18.82	17.68	17.10	35.75	9.34	20.68	21.81	26.44
MnO	.30	—	.27	.34	nil	nil	.89	.48	.43	.37
MgO	17.65	14.90	14.44	16.62	11.95	4.51	26.58	19.37	15.81	15.54
CaO	.12	9.30	1.69	1.58	nil	nil	3.30	4.07	4.39	—
Na <sub>2</sub> O	.27	—	—	—	Tr	—	.84	.11	.18	—
K <sub>2</sub> O	Tr	—	—	—	nil	—	.18	—	.04	—
H <sub>2</sub> O+	.03	—	—	—	2.00	nil	.19	.37	1.42	—
H <sub>2</sub> O-	.01	—	—	—	—	—	—	.04	.04	—
P <sub>2</sub> O <sub>5</sub>	.05	—	—	—	—	—	—	—	—	—
	100.29	100.00	100.00	100.00	100.41	100.06	100.73	100.00	99.98	100.32
	South India	Uganda, East Africa			Mysore, India			Stillwater complex	Moore County	

1. From oligoclase-antiperthite-hypersthene-granulite, J<sub>32</sub>, Vellore, South India, Analyst: H. SCHWANDER.
2. From metadolerite, 3 and 4 from charnockites, Uganda, British East Africa; Quarterly Journal of the Geological Society of London, Vol. 91, 1935, p. 156, Analyst: A. W. GROVES.
5. Aluminous hypersthene, 6 iron-rich hypersthene, 7 normal hypersthene; B. RAMA RAO, The Charnockite rocks of Mysore. Bulletin No. 18 of the Mysore Geological Department, 1945, p. 21. Analyst: E. R. TIRUMALACHAR.

8. and 9. Hypersthene inverted from pigeonites. H. H. HESS, Pyroxenes of common mafic magmas, *American Mineralogist* Vol. 26, 1941, p. 579. Analyst: R. B. ELLESTAD. 8 Bushveld, 9 Stillwater.
10. From Moore County meteorite, *American Mineralogist* Vol. 21, 1936, p. 219. Analyst: E. P. HENDERSON.

The South Indian hypersthene is nearest in composition to that of the Moore County meteorite except that iron is in a more oxidised condition. It differs from hypersthene inverted from pigeonites (Stillwater complex) in being poor in lime. It is less aluminous than the Uganda hypersthene. The Mysore hypersthene is varied in character, but, as in the South Indian hypersthene, the iron is in a more oxidised condition.

Since the distinction between the different members of the orthopyroxenes is based on the relative proportion of En and Fs molecules, these have been calculated for the analyses set out above. The following are the ratios, neglecting  $\text{Al}_2\text{O}_3$ , and recalculating to 100, of  $\text{MgSiO}_3$ ,  $\text{FeSiO}_3$  and  $\text{CaSiO}_3$ .

	1	2	3	4	5	6	7	8	9	10
$\text{MgSiO}_3$ (En)	56.4	46.5	60.2	55.4	55.4	18.2	77.7	45.4	50.2	49.0
$\text{FeSiO}_3$ (Fs)	43.6	32.8	35.6	40.0	44.6	81.8	15.3	43.0	36.9	51.0
$\text{CaSiO}_3$ (Wo)	nil	20.7	4.2	4.6	nil	nil	7.0	11.5	12.9	nil

These values are plotted in the En-Fs-Wo triangular diagram of HESS (1940), Fig. 13, and their intercepts determined on the linear diagram of POLDERVAART (neglecting the Wo-component). Two hypersthene from Uganda, and those from Stillwater, and from Bushveld, lie within the pigeonite field. One from Uganda is near the augite field. The South-Indian hypersthene is on the direct line of variation of hypersthene from enstatite to orthoferrosilite and shows no "inversion relation" to pigeonites. Two of the three Mysore hypersthene are in the direct line of variation from enstatite to orthoferrosilite, and, like the South Indian hypersthene, show no "inversion relation" to pigeonites.

The Indian, Stillwater, Bushveld, and Uganda orthopyroxenes fall within the limit 50 En to 70 En of Poldervaart's diagram, for normal hypersthene, but some of them differ from normal hypersthene in having  $\text{Al}_2\text{O}_3$  and CaO. One from Mysore is bronzite and another eulite. The hypersthene from Moore County meteorite is ferrohypersthene.

The optical characters of orthopyroxenes investigated, but not analysed, are as follows:

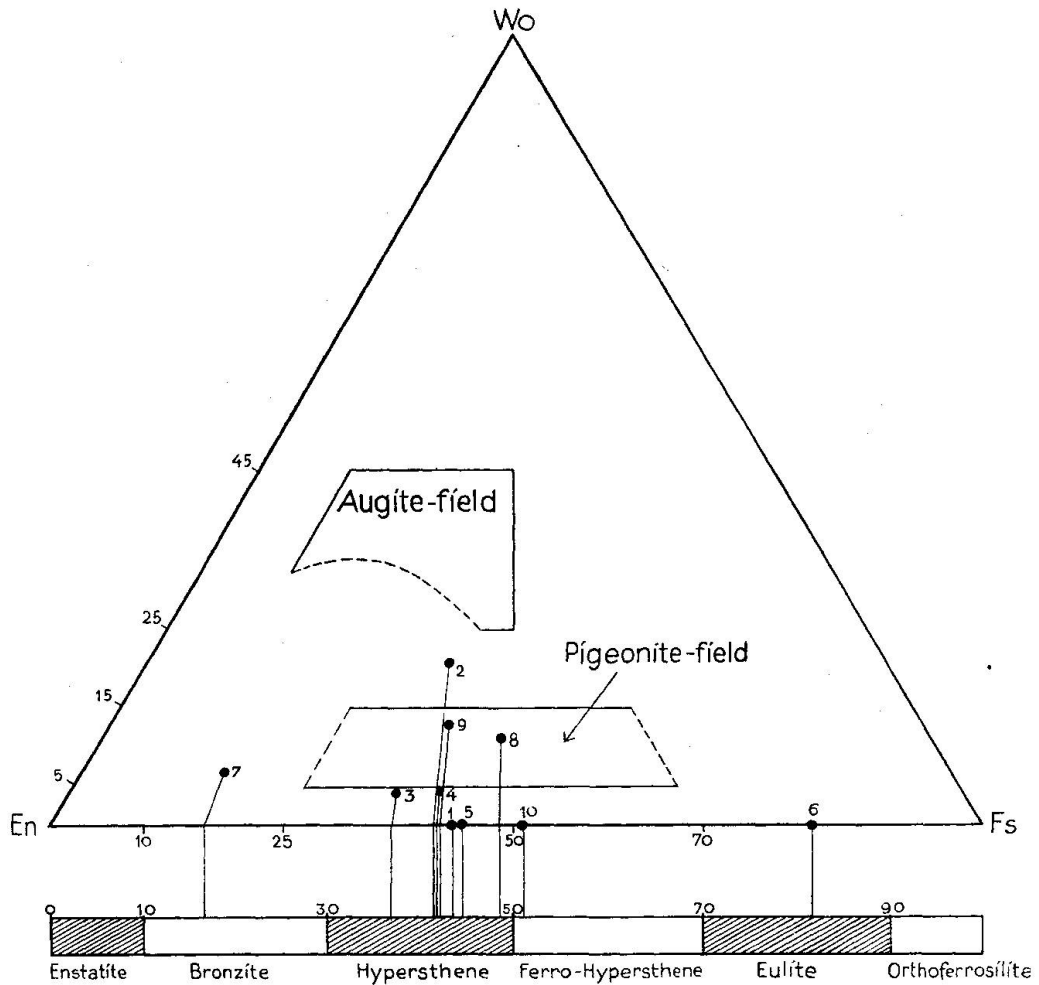


Fig. 13. The orthopyroxenes in the triangular diagram after Hess (above) and the linear diagram after Poldervaart (below). 1 = from South India; 2, 3, and 4 = from Uganda; 5, 6, and 7 = from Mysore; 8 = from Stillwater; 9 = from Bushveld; 10 = from Moore County meteorite.

#### Optical properties of Orthopyroxenes of Charnockites

	Pyroxene-granulites		Intermediate charnockites		Acid charnockites
	$J_3$	$J_{36}$	$J_4$	$J_{39}$	$J_{24}$
$n_\alpha^*$	1.688	1.694	1.689	1.696	1.695
$n_\beta$	1.704	1.706	1.705	1.708	1.708
$n_\gamma^*$	1.707	1.709	1.709	1.714	1.711
$n_\gamma - n_\beta$	.003	.003	.004	.006	.003
$n_\beta - n_\alpha$	.016	.012	.016	.012	.013
$-2V$	$44\frac{1}{2}, 46\frac{1}{2}$	48	$46\frac{1}{2}, 48$	55, 57	$53\frac{1}{2}, 54, 55$
(measured)	49, $52\frac{1}{2}$	55			
$-2V$	$47^\circ$	$53^\circ$	$53^\circ$	$60^\circ$	$51^\circ$

(calculated from  $n_\alpha$ ,  $n_\beta$ , and  $n_\gamma$ )

\* Values calculated from the birefringences  $n_\gamma - n_\beta$  and  $n_\beta - n_\alpha$ .

The range of composition in Poldervaart's curves (1947) is  $En_{72}$  to  $En_{66}$  (for  $n_\alpha$  values) and  $En_{73}$  to  $En_{58}$  (for  $n_\gamma$  values). The  $n_\gamma$  values are more reliable and lie within the upper and lower limits of the En ratio for hypersthene. The  $n_\beta$  values give on Winchell's curves a range of  $En_{73}$  to  $En_{68}$ . The most common  $2V$  value, 53 to 55, gives a En ratio of  $En_{56}$  to  $En_{60}$  on Poldervaart's  $2V$  curves.

The pleochroic scheme in all these hypersthene is X = tinge of pink, Y = shade of green and Z = green with tinge of blue. Grains without a tinge of pink along X were invariably ascertained to be clinopyroxene. In no instance was there an optic axial angle greater than  $62^\circ$ . All were negative in optical character.

*Inclined extinction in the hypersthene of charnockites*

B. RAMA RAO (1945) remarks (p. 22): "Many of these orthopyroxenes differ from the typical hypersthene in one essential respect, namely, — in the extinction inclined considerably from the pronounced vertical cleavage. Though HOLLAND states that he never found a pyroxene in the charnockites giving the pleochroism of hypersthene without at the same time, when definite cleavages are exhibited, showing straight extinction, in any of the hundreds of microsections of charnockites he examined from the Salem district and all other parts of the Madras Presidency, most of the subsequent investigators, including myself, have found however such pleochroic pyroxenes showing clearly inclined extinctions from well-marked cleavage traces. It is worth while studying whether those formed from the replacement of the monoclinic minerals (hornblende and diopside) have really attained the orthorhombic symmetry or still retain their original monoclinic symmetry. It is also desirable to see whether any of these correspond actually to the clinohypersthene though that species is stated to be known only in meteorites."

HENRY (1940) remarks (p. 23): "In recent years several occurrences of clinoenstatite and of clinohypersthene have been recorded the identification depending on the oblique extinctions measured from a prominent cleavage, and much fuller data would be necessary before most of these occurrences could be accepted as monoclinic Mg-Fe pyroxenes."

In view of these remarks of HENRY and B. RAMA RAO it seemed desirable that the question of inclined extinction in the hypersthene of charnockites should be re-examined. This was done on theoretical and statistical grounds in 1943, and the opinion was then expressed that the inclined extinction of the hypersthene is usually observed on sections of



orthorhombic crystals, which are inclined to all the three crystallographic axes. S. RAY and S. K. ROY (1944) found in fact that, when such sections were tilted on the Fedorow stage, the inclined extinction disappeared, and that straight extinction resulted.

The only relevant question, regarding the possibility of the occurrence of clinohypersthene in charnockites of India, is whether it can be established that the crystallographic directions, *a*, *b*, *c* (as determined by traces of cleavages or other morphological directions) are not coincident with axes of the optical indicatrix, *X*, *Y*, *Z*. More specifically, in this case, it should be established that *Z* is not coincident with the crystallographic *c* axis.

A number of stereograms (62 in number) were drawn for grains showing inclined extinction on any of the prominent cleavage traces. These grains originated from charnockites from all parts of India. The stereograms were invariably of the kind where *Z* coincided with *c*.

Sir THOMAS HOLLAND refers to an identification by LACROIX of a monoclinic pyroxene, in the pyroxene gneisses of Salem, with a pleochroism similar to that of hypersthene, namely, *Z* = sea green, *Y* = bright pink and *X* = yellowish green; with an extinction of  $45^\circ$  on the clinopinacoid (010), and remarks, "I have to confess my inability to discover a single instance of such a pleochroic monoclinic pyroxene".

This monoclinic pyroxene, though not so markedly pleochroic as hypersthene, but faintly pleochroic in pink and green, does occur, — not only in Salem, from where LACROIX described it —, but in several other charnockitic areas in India, and is referred to in the paragraph on monoclinic pyroxenes.

The question of amphibole cleavages in hypersthene was examined. None of the sections examined showed the typical cleavage of hornblende. The angular interval of the prismatic cleavage is very near  $90^\circ$ , which is the angle characteristic for pyroxenes. However, on sections parallel to the *b* axis, but inclined to the crystallographic *c* axis, their traces appear acute and obtuse and suggest angles near  $120^\circ$  and  $60^\circ$ . Several sections which showed such angles between cleavages, suggesting amphibole, were tilted to their proper azimuth on the Fedorow stage, and in all instances the real angle proved to be  $90^\circ$ .

#### Lamellar Structure

Both hypersthene and clinopyroxene show lamellar structure of the type sketched in Fig. 14. In clinopyroxenes it is very clear, in hypersthene less pronounced.

In the discussion of lamellar structure in hypersthene, HESS and PHILLIPS (1940, p. 272) have suggested that the crystal be set so that the *a* axis is longer than the *b* axis, as is the practice in Europe. Accordingly, throughout this paper, hypersthene is described with this setting. The lamellæ and optic axial plane are both parallel to (100) in hypersthene, whereas in clinopyroxene, the optic axial plane is parallel to (010) and the lamellæ are parallel to (100).

The appearance of the lamellæ in the hypersthene is somewhat similar to what has been described by HESS and PHILLIPS (1938, p. 452) in the orthopyroxenes of the Bushveld complex. On (001) and (010) the parting is poor, and the lamellæ have a breadth of about .004 mm. They are discontinuous and when the optic axial plane is tilted perpendicular to the control axis (*K*), on the Fedorow stage, the appearance of dark and clear bands vanishes at a tilt of about  $10^\circ$  on the *K* axis, and the bands appear equally light. If, with the *K* axis at  $0^\circ$ , they are tilted around the *H* axis, the lamellæ disappear at a tilt of  $10^\circ$  and equal illumination results. When the Fedorow stage is rotated about the *M* axis towards the  $45^\circ$  position, and the grain is tilted around the *K* axis with the association plane of the lamellæ perpendicular to *K*, the lamellæ are equally bright and extinguish together near an optic axis, as observed by SUNDIUS (1932).

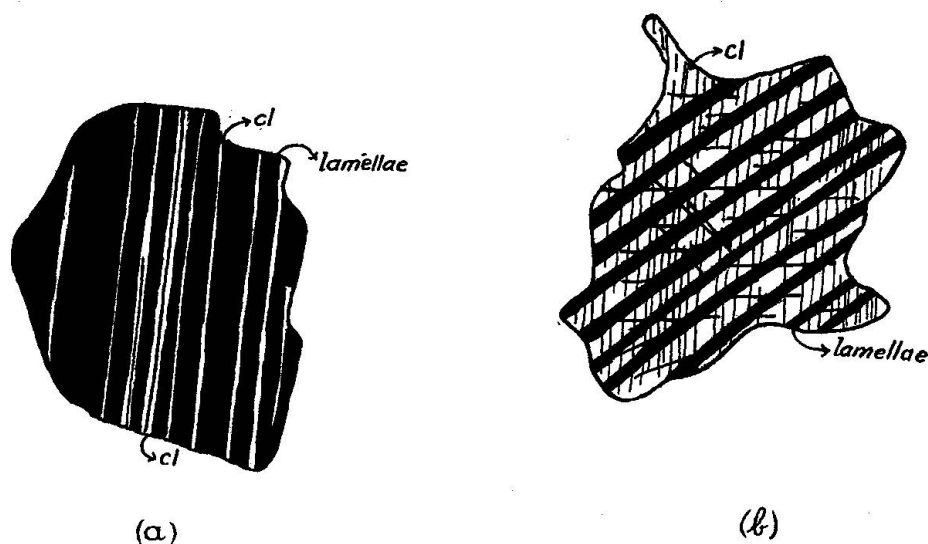


Fig. 14. Lamellar structure in clinopyroxenes. a = grain || (010); b = grain || (101).

The lamellæ thus behave like polysynthetic twins twinned on a normal twin law, but their very narrow development makes it impossible to ascertain, whether in projection the optical elements are symmetrically placed on either side of the twin plane.

HESS and PHILLIPS (1938, p. 456) explain these lamellæ as due to intergrowth of monoclinic pyroxene with hypersthene. But the lime in the analysed hypersthene of charnockite is below 2% (.12%), and yet the lamellæ are present. WAHL (1907, p. 22) also assumes a similar origin of the lamellæ in hypersthene studied by him, and draws a parallel to such intergrowths in perthites. But, in the case of perthites, there is a difference in the refractive indices and birefringences of the host and the inclusions, however minute or narrow these may be. And, although host and guest are very close to each other in their chemical composition, they differ in this respect also. In the case of the lamellæ of hypersthene, there is no difference in refractive indices or birefringences.

HENRY (1941, p. 187) has suggested that they are due to gliding planes — “Biegegleitung” of MÜGGE — whereby there is a translation in (100) in the direction [001] accompanied by bending about [010]. There seems to be gliding of two types: (1) simple gliding, with only a movement of molecules in one direction, sometimes accompanied by bending round an axis, and (2) gliding, resulting in the twinning of the individuals.

HESS (1941, p. 520) explains such lamellæ in diopsides as due to the exsolution of hypersthene. In the clinopyroxenes of charnockites, these lamellæ which are polysynthetic after (100) are sometimes accompanied by simple twinning after (100). Since (100) is a possible twinning plane in monoclinic crystals, there seems to be no difficulty in accepting them as true twin lamellæ.

#### *Herring-bone twins*

Two herring-bone twins, one of hypersthene and another of augite, from the charnockites of India are shown in Fig. 15a and b. They were examined on the Fedorow stage and from their stereograms it could be ascertained that in the hypersthene the twinning plane of simple twins is (201). In the augite (or pigeonite) the twinning-plane of simple twins is (100) and the fine lamellæ of the individuals are parallel to (001). The angular interval between the fine lamellæ of the two individuals in hypersthene is 80°, and the corresponding value in augite (or pigeonite) is 148°. It seems difficult to explain these two sets of lamellæ as resulting one from the other by inversion. The hypersthene in charnockites, therefore, have no inversion relation to pigeonite; and the fine lamellæ could not be due to this cause.

BUERGER (1945 and 1948) has formulated a general theory of twinning in crystals on structural grounds and draws a contrast between his theory and the theory of the French school, which is based on geometri-

cal grounds. He distinguishes between growth twins, transformation twins and gliding twins. The growth twins occur in stable forms, transformation twins in high-low temperature transformations, and gliding twins during deformation.

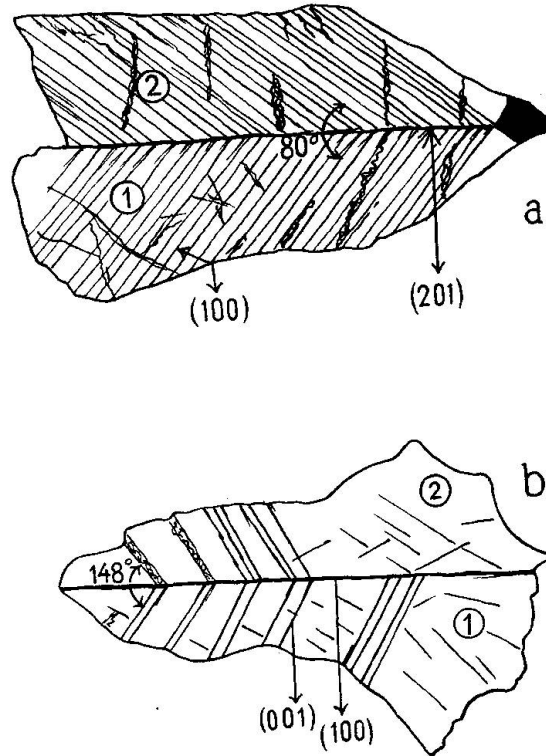


Fig. 15. Herringbone twins in pyroxenes. a) Hypersthene. b) Clinopyroxene.

The gliding twins have the special character of minute lamellæ and are polysynthetic. This is a character displayed by hypersthene in charnockites, and therefore, they can be regarded as gliding twins according to the suggestion of HENRY. In a herring-bone twin, the simple twin after (201) is likely to have occurred during crystallization at high temperature. On slow cooling and with deformation, the atomic layers in the two individuals of the simple twin would have sheared and formed polysynthetic twins parallel to (100).

### Clinopyroxenes

Clinopyroxenes are of the ferroaugite, augite and pigeonite types. The ferroaugites occur with orthopyroxene in the typical granulites of the charnockite series. But augites, which are faintly pleochroic in pinks and greens, and pigeonites, are confined to a rock which has a typical igneous texture, unlike the members of the charnockite series, and the

pyroxenes show a sub-ophitic relationship to the feldspars. Hypersthene is not always present in this rock.

### *Ferroaugite*

The ferroaugite from the andesine-hypersthene-augite-granulite (J<sub>3</sub>) of Pallavaram has the following optical properties:

$$\begin{array}{l}
 n_{\alpha}^* = 1.701 \\
 n_{\beta} = 1.706 \\
 n_{\gamma}^* = 1.722
 \end{array}
 \left.
 \begin{array}{l}
 \\
 \\
 \end{array}
 \right\}
 \pm .001
 \begin{array}{l}
 + 2V = 49^{\circ}, 51^{\circ}, 52^{\circ} \text{ and } 61^{\circ} \\
 \text{Dispersion } 2V = \rho > v
 \end{array}$$
  

$$\begin{array}{l}
 n_{\gamma} - n_{\beta} = .016 \\
 n_{\beta} - n_{\alpha} = .005 \\
 n_{\gamma} - n_{\alpha} = .021 \\
 Z \wedge c = 44^{\circ}, 45^{\circ}, 44^{\circ}, 46^{\circ}
 \end{array}
 \left.
 \begin{array}{l}
 X = \text{colourless to faint green} \\
 Y = \text{colourless to faint green} \\
 Z = \text{green with a tinge of blue}
 \end{array}
 \right\}
 \begin{array}{l}
 \text{In sections of} \\
 \text{thickness} \\
 .03 \text{ mm}
 \end{array}$$

\* Values determined from birefringences  $n_{\beta} - n_{\alpha}$  and  $n_{\gamma} - n_{\beta}$ .

The proportions of  $\text{MgSiO}_3$ ,  $\text{FeSiO}_3$ , and  $\text{CaSiO}_3$  for the ferroaugite as well as these for salites of the Uganda charnockites were plotted in the trilinear variation diagram of HESS (1941, p. 518).

	$\text{MgSiO}_3$	$\text{FeSiO}_3$	$\text{CaSiO}_3$	
South-Indian ferroaugite	26.7	34.9	38.4	From DEER and WAGER's $Z \wedge c$ and $2V$ curves
	29.0	28.0	43.0	From HESS's $2V$ and $n_{\beta}$ curves, $2V = 54^{\circ}$ , $n_{\beta} = 1.706$
Uganda No. 7	34.0	23.4	42.6	From chemical analysis by A. W. GROVES (1935)
	41.9	23.4	34.7	

The Uganda clinopyroxenes are salites and augites. The South Indian clinopyroxenes are augites according to the  $2V$  and  $n_{\beta}$  curves of HESS. The pyroxenes of both provinces lie within the two-pyroxene field of Tsuboi (HESS 1941, Fig. 12, p. 586) and when the corresponding hypersthene and clinopyroxenes of the two provinces are joined, they do not intersect at H, the common point of intersection of the two pyroxene joins (HESS 1941, Fig. 11, p. 586). The pyroxenes of the charnockite series differ therefore from the pyroxenes of igneous rocks.

### *Augite and pigeonite*

These minerals occur in a rock which is apparently the one to which LACROIX refers in his identification and description of a pleochroic monoclinic pyroxene. This rock is found, as mentioned above, in all the charnockitic areas of India, including Mysore. Pigeonite from such a rock,

met with in Halagur, Mysore, was described by the present author in 1943. The rock was described as dolerite, following the description used by B. RAMA RAO. A specimen of this type of rock is found in the collection of charnockites presented by Dr. A. L. COULSON to the Mineralogical Institute of the University of Basel. It is labelled as augite-diorite and comes from Shevroy Hills, Salem. The specimen under description is also from Shevroy Hills, Salem, but similar rock types have also been collected from the Nilgiri Hill Range, from Vellore, and from Pallavaram. Though these rocks are associated with the charnockite series, we consider them as being genetically different.

A sketch of a thin slide of the augite-diorite  $J_{81}$  is given in Fig. 16 both, under crossed nicols, and without the analyser. The plagioclase feldspars have a composition  $An_{40}$  to  $An_{53}$ , and the mafic mineral is augite. Following ROSENBUSCH, the rock is described as augite-diorite.

Unlike the charnockites, which are of a typical granulitic texture, this rock has a typical igneous texture. The feldspars are lath-shaped, and the mafic minerals tend to be sub-ophitic. The feldspars are cloudy. MCGREGOR (1931) has reviewed the literature on clouded feldspars. He



Fig. 16. Thin section of augite-diorite  $J_{81}$ . A = crossed nicols; B = without analyser. P = pigeonite, Pl = plagioclase, Au = augite, M.P. = Micropegmatite, Ke = kelyphitic border (green amphibole), Bi = biotite, I.O. = iron ore.

comes to the conclusion that the cloudiness is due to thermal metamorphism. Whether this is also the case in the Indian rocks is yet an open question. Twinning on the Carlsbad and albite-Carlsbad laws is well developed. Both these laws are absent in the feldspars of granulitic charnockites.

A rock of the latter type has been described by Sir THOMAS HOLLAND (1900, p. 159). He concludes, "Although the association of this rock with the normal members of the charnockite series, and the presence in it of considerable quantities of rhombic pyroxene, necessitates its inclusion in the series, I am unable at present to recognize any peculiar conditions in its occurrence, which would account for the distinct departure from the normal characters which it shows under the microscope".

His petrographic description can as well be applied to the rocks under study, except that a rhombic pyroxene is not always present in these specimens.

#### *Augite*

The augite has the following optical properties:

$n_{\alpha}^*$	= 1.684	X = tinge of pink	}	Section .07 mm thick
$n_{\beta}$	= 1.686	Y = colourless		
$n_{\gamma}^*$	= 1.704	Z = tinge of green		
$n_{\beta} - n_{\alpha}$	= .002			
$n_{\gamma} - n_{\beta}$	= .018			
$n_{\gamma} - n_{\alpha}$	= .020			

\* These values are determined from birefringences  $n_{\beta} - n_{\alpha}$  and  $n_{\gamma} - n_{\beta}$ .

+2V = 38°, 41°, 39°, 44°, 37°, 51°, 52° (by direct measurement on the Fedorow stage).

Z  $\wedge$  c = 37°, 38°, 40°, 42° (measured on twins by the method of NEMATO).

On DEER and WAGER's diagram of  $n_{\alpha}$  and  $n_{\gamma}$  indices (1937, p. 20) the augite under discussion has the chemical composition En 60.6, Fs 28.8 and Wo 10.6. On the Z  $\wedge$  c and 2V diagram (1937, p. 22) the range of composition is En 60, Fs 10.6, Wo 29.4; En 51.8, Fs 8.2, Wo 40.0; and En 64.8, Fs 7.0, Wo 28.2. The values determined on Z  $\wedge$  c and 2V have a composition ranging between about Wo<sub>30</sub> (En, Fs)<sub>70</sub> and Wo<sub>40</sub> (En, Fs)<sub>60</sub>. These are the limits of calcium-rich clinopyroxenes of basalts (HESS 1941, p. 583). Therefore, this mineral has the character of a derivative from a basaltic magma.

The augite has borders of a green amphibole.  $Z \wedge c = 15^\circ$ , and  $n_\gamma - n_\alpha = .020$ . A reddish-brown biotite, of the type found in charnockites, develops around grains of iron ore.

### *Pigeonite*

Pigeonite occurs sparingly. It is present both as individual grains in the fine-grained matrix and as a mantle around augite, suggestive of zoning, which is now obscured by contact metamorphism with the gneisses of the area. The mantle is almost uniaxial and the core has an optic axial angle of  $38^\circ$  to  $40^\circ$ . When the rim of the mantled grains is examined on the Fedorow stage, with the optic axial plane perpendicular to the control axis (K), a tilt around the K axis, in the  $45^\circ$  position, produces a prolonged extinction in a few cases. Such grains must have a small optic axial angle, but, since there is no emergence of light between the extremities of extinction (in this case the angle between the first appearance of extinction and its disappearance is about  $20^\circ$ ), the optic axial angle should be below  $10^\circ$  (TURNER 1940).

To ascertain the position of the optic axial plane in such apparently biaxial pigeonites, two methods were applied, (1) the classical method of locating the optical elements, as described by REINHARD, and (2) the tracing of the XY plane and locating Z polar to it, as described by TURNER (1940). Both methods gave nearly the same results. The optic axial plane is parallel to (010).

The birefringences of pigeonite, determined on grains whose thickness was ascertained, on the assumption of a maximum birefringence of .0075 for a neighbouring grain of feldspar ( $An_{45}Ab_{55}$ ) are  $(n_\beta - n_\alpha) = .0005$  and  $(n_\gamma - n_\alpha) = .018$ . On BOLDIREFF's diagram (NIKITIN 1914), the optic axial angle, corresponding to these values of birefringence, is about  $+18^\circ$ .  $Z \wedge c$  values, by NEMOTO's method are  $39^\circ$ — $40^\circ$ . With these data, the composition of pigeonite, read on the curves of HESS (1949, p. 643), is 33 to 35%  $FeSiO_3$  (on  $Z \wedge c$  curve) and 26%  $FeSiO_3$  on the curve of birefringences. On DEER and WAGER's curves the range of composition is (En 64 Fs 29 Wo 7) to (En 61 Fs 23 Wo 16).

### **Amphiboles**

The typical amphibole of charnockites is olive-green. Occasionally in ultrabasic members, a bluish-green hornblende is present.



## Green hornblende (Uralite)

The green hornblende develops at the expense of both ortho- and clinopyroxenes. In some slides the hornblende is seen growing at the expense of hypersthene, with exsolution of iron ore; others show the hornblende developing at the expense of minute granules of hypersthene surrounding it. At the same time quartz is exsolved, producing a sieve-structure in the hornblende.

The optical characters are:

$n_{\alpha}^*$	= 1.657	X = yellow	} Section .03 mm thick.
$n_{\beta}$	= 1.668	Y = brown	
$n_{\gamma}^*$	= 1.676	Z = brown	
$n_{\beta} - n_{\alpha}$	= .011	Absorption X < Y = Z	
$n_{\gamma} - n_{\beta}$	= .008		
$n_{\gamma} - n_{\alpha}$	= .019		

\* Values determined from birefringences  $n_{\beta} - n_{\alpha}$  and  $n_{\gamma} - n_{\beta}$ .

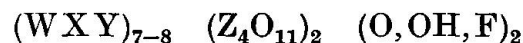
$$Z \wedge c = 16^{\circ}, -2V = 74\frac{1}{2}^{\circ}. \rho < v.$$

$$\text{Sp. Gr.} = 3.20.$$

The chemical analysis of the mineral is given below. The mineral was taken from a sample of granulite, J<sub>23</sub> Kailasgarh, Vellore. The modal composition is:

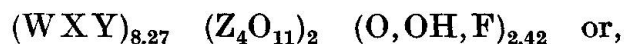
Plagioclase	36
Hypersthene and diopside	23
Green amphibole	31
Iron ore	9
Apatite	1

In the allotment of atoms, Ti is reckoned with Si, after KUNITZ. KUNITZ remarks (1930, p. 217), "In diesen titanreichen (basaltischen Hornblenden, Turmalinen und Glimmern) und wasserhaltigen komplexen Silikaten tritt das Titan an die Stelle des Siliciums". BERMAN (after WARREN) (1937, p. 354) gives the general formula for hornblendes as:

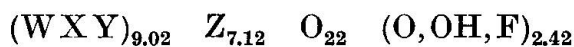


where W = Ca, Na, K; X = Mg, Fe, Mn, Al in part; Y = Al, Fe, Ti, and Z = Si, and Al in part.

According to KUNITZ the formula of the mineral is:



(Ca, Na, K, Fe<sup>''</sup>, Fe<sup>'''</sup>, Mg, Mn, Al)<sub>8.27</sub> (Si, Ti, Al)<sub>7.87</sub> O<sub>22</sub> (O, OH, F)<sub>2.42</sub>, and according to BERMAN, the formula is:



(Ca, Na, K, Fe<sup>''</sup>, Fe<sup>'''</sup>, Mg, Mn, Al, Ti)<sub>9.02</sub> (Si, Al)<sub>7.12</sub> (O, OH, F)<sub>2.42</sub>.

Chemical analysis of a green hornblende

	Wt %	Mol. number	Metal atoms	(O, OH, F)	Basis 24 (O, OH, F)	Ti replac- ing Si	Ti replac- ing Fe, Mg
SiO <sub>2</sub>	40.29	671	671	1342	6.10	7.87	7.12
TiO <sub>2</sub>	6.60	82	82	164	.75		
Al <sub>2</sub> O <sub>3</sub>	5.72	56	112	168	1.02		
Fe <sub>2</sub> O <sub>3</sub>	.63	4	8	12	.07	4.73	5.48
FeO	12.65	176	176	176	1.61		
MnO	.10	1	1	1	.01		
MgO	13.51	335	335	335	3.04	3.54	3.54
CaO	12.82	228	228	228	2.07		
Na <sub>2</sub> O	4.18	68	136	68	1.23		
K <sub>2</sub> O	1.22	13	26	13	.24	2.42	—
H <sub>2</sub> O +	2.40	133	266	133	2.42		
H <sub>2</sub> O -	.01	—	—	—	—	—	—
			2041	2640			
			4681				
P <sub>2</sub> O <sub>5</sub>	nil						
F	Tr						
Sum	100.13		$F = \frac{24}{2.640} = 9.091$				

$$V = \frac{2400}{2.688 \times 3.195} = 279$$

Analyst: H. SCHWANDER

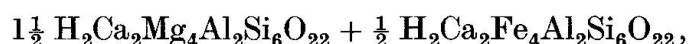
According to KUNITZ's mode of classification, there is a small deficiency of silica and alumina and a little excess in the bases owing to the impurity present in the analysed mineral (pyroxene). According to BERMAN's formula there is a large deficiency in silica and a corresponding excess in the bases.

BERMAN (1937, p. 355) classifies the hornblende series as follows:

X	Y	Z = Si : Al	
5	0	7 : 1	Hornblende-edenite
4	1	6 : 2	Hastingsite
3	2	8 : 0	Glaucophane
4.20	2.33	6 : 1.53	(Ratios in green hornblende of charnockites)

These figures indicate that the analysed green hornblende has the bulk character of hastingsites with alkalic affinities. But the refractive indices agree with those of common green hornblendes.

Refractive indices and titanium dioxide. The refractive indices determined are checked with curves given by KUNITZ for common hornblendes (1930, p. 208). For this purpose the green hornblende may be regarded as a mixture of  $H_2Ca_2Mg_4Al_2Si_6O_{22}$  (syntagmatite molecule) and  $H_2Ca_2Fe_4Al_2Si_6O_{22}$  (basaltic hornblende molecule). The green hornblende of charnockites has roughly the formula  $2 H_2Ca_2(Mg, Fe)_4Al_2Si_6O_{22}$ . This may be regarded as,



or 3 : 1 of syntagmatite molecule to basaltic hornblende. This composition on the curves of KUNITZ has the value  $n_\alpha = 1.646$  and  $n_\gamma = 1.665$ . The values here determined are  $n_\alpha = 1.657$  and  $n_\gamma = 1.676$ . The higher values determined are due to the titanium present in the mineral. The rate of increase of refractive index given by KUNITZ for titaniferous hornblendes is .008 for 1%  $TiO_2$ . At this rate the brown hornblende with its 6.6% titanium dioxide should show the following values:  $n_\alpha = 1.689$ , and  $n_\gamma = 1.708$ . These are far above the values determined.

The rate of increase has been calculated by KUNITZ for basaltic hornblendes, kärsutite, etc. However, within the common hornblendes themselves, the rate is entirely different.

The rate can be determined from the following two analyses of common hornblendes by DEER (1937, p. 58).

SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O + H <sub>2</sub> O-	Sum	F
44.15	3.73	10.59	5.02	8.89	.7	12.30	11.8	1.26	1.1	.95	100.91	.84
47.14	1.74	9.44	3.66	8.38	.11	14.44	10.53	1.15	1.3	2.0	100.42	—

The respective refractive indices are:

$n_\alpha$	$n_\beta$	$n_\gamma$
1.654	1.665	1.673
1.651	1.661	1.669

These analyses have practically the same content of FeO, and therefore the difference of the refractive indices may be taken as due to the difference in content of  $TiO_2$  — a difference of 2% titanium accounting for a difference of .003 in  $n_\alpha$  value and a difference of .004 in  $n_\gamma$  value. Assuming this rate for the hornblendes of Indian charnockites, the

refractive index should be  $1.646 + .010 = 1.656$  (for  $n_\alpha$ ) and  $1.665 + .013 = 1.678$  (for  $n_\gamma$ ). These values are nearer the values  $1.657$  ( $n_\alpha$ ) and  $1.676$  ( $n_\gamma$ ) here determined. Therefore the higher values shown by green hornblendes of charnockites are due to the presence of a considerable amount of titanium dioxide.

*Blue-green hornblende*

The analysed blue-green hornblende comes from amphibolite J<sub>48</sub> Kusumalai, Salem. The modal composition is:

Plagioclase	24.5
Blue-green hornblende	63
Epidote	6
Iron ore	6.5

The optical characters of the mineral are as follows:

$n_\alpha^*$	= 1.662	X = yellow	} Section .03 mm thick.
$n_\beta$	= 1.673	Y = green	
$n_\gamma^*$	= 1.679	Z = blue	
$n_\beta - n_\alpha$	= .011		
$n_\gamma - n_\beta$	= .006		
$n_\gamma - n_\alpha$	= .017		

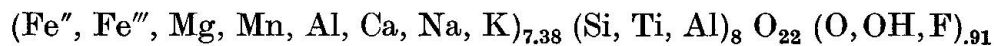
\* Values determined from birefringences  $n_\beta - n_\alpha$  and  $n_\gamma - n_\beta$ .

$$-2V = 72^\circ \rho > v$$

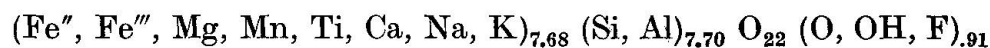
$$Z \wedge c = 15\frac{1}{2}^\circ$$

$$\text{Sp. Gr.} = 3.05$$

According to KUNITZ, the formula of the mineral is (with Ti replacing Si):



According to BERMAN (Ti replacing Mg):



The mineral has the character of common hornblende, with alkalic affinities.

## Chemical analysis of a blue-green hornblende

	Wt %	Mol. number	Metal atoms	O, OH, F	Basis 24 (O, OH, F)	Ti replacing Si	Ti replacing Fe, Mg
SiO <sub>2</sub>	43.23	719	719	1438	6.43	8.00	7.70
TiO <sub>2</sub>	5.70	71	71	142	.63		
Al <sub>2</sub> O <sub>3</sub>	7.23	71	142	213	1.27		
Fe <sub>2</sub> O <sub>3</sub>	6.92	43	86	129	.77		
FeO	10.72	149	149	149	1.33		
MnO	0.15	2	2	2	.02	7.38	5.34
MgO	11.68	290	290	290	2.59		
CaO	10.06	178	178	178	1.59		
Na <sub>2</sub> O	2.38	38	76	38	.68		
K <sub>2</sub> O	.42	4	8	4	.07		
H <sub>2</sub> O +	1.84	102	204	102	.91		2.34
H <sub>2</sub> O -	0.01		1925	2685			.91
			4610				
P <sub>2</sub> O <sub>5</sub>	0		4610				
F	Tr		4800—4610 = 190				
Sum	100.34						

$$F = \frac{24}{2.685} = 8.939$$

$$V = \frac{2400}{2.685 \times 3.055} = 292$$

Analyst: H. SCHWANDER

*General character of the amphiboles in charnockites from India*

Dr. E. WENK has collected about 150 analyses of hornblendes (alkali-hornblendes excepted) found in the literature, and has calculated Niggli values for all of them (not yet published). The Fo, FaFs, and Cs values are plotted in a trilinear diagram. This diagram is reproduced in Fig. 17 with his kind permission.

The bulk of the hornblende analyses lies in a field parallel to the line FaFs—Fo and between about 17% Cs to 28% Cs. This corresponds to a variation of 6% to 10% CaO in the analyses. In this diagram the chief variation in the hornblendes is in the relative proportion of MgO and FeO, the hastingsites lying close to the (Fa, Fs) corner, and the hornblendes of melanocratic rocks lying nearer the Fo corner. The Niggli values calculated for the hornblendes of charnockites are as follows:

	Kp	Ne	Cal	Ns	Cs	Fo	Fa	Fs	Q	Ru
Green amphibole	4.4	14.5	—	4.2	19.3	28.3	14.9	.7	9.1	4.6
Blue-green amphibole	1.6	13.5	4.8	—	13.3	25.4	13.3	7.6	16.3	4.2

The above values of Fo, FaFs, and Cs are entered in Fig. 17. The green hornblende is in line with k arsutites in chemical composition. The blue-green hornblende lies within the field of common hornblende, and represents a type rich in iron.

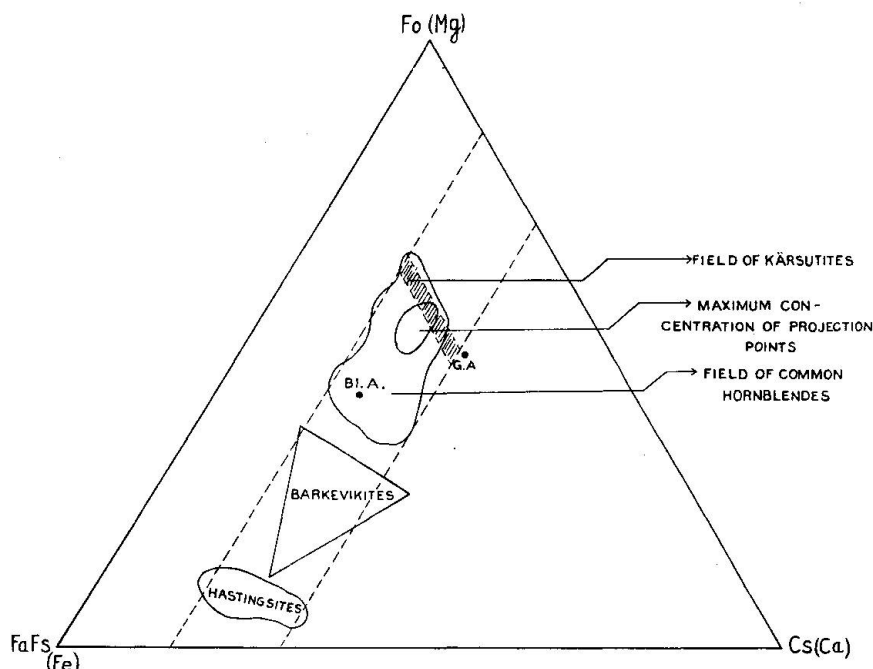


Fig. 17. Fo, FaFs, Cs diagram of amphiboles. G.A. = green hornblende of South Indian charnockite. Bl. A. = blue-green hornblende from amphibolite, Kusumalai, Salem.

### Biotite

Biotite in charnockites is of two kinds: (1) reddish-brown that occurs with basic and intermediate granulites, and (2) greenish-brown, which occurs mainly in the gneisses.

Biotite develops at the expense of iron ore, hornblende, hypersthene, or garnet.

The biotite was separated from the same granulite from which hypersthene had been separated (for modes see J<sub>32</sub> Appendix I). It was impossible to remove the plagioclase completely and the powder therefore still contained 5% feldspar of the composition Ab<sub>70</sub>An<sub>30</sub>. 5% of this plagioclase have the weight percentages CaO = 0.3; Na<sub>2</sub>O = .4, Al<sub>2</sub>O<sub>3</sub> = 1.2 and SiO<sub>2</sub> = 3.10. This has been deducted from the analysis of biotite.

Since the CaO was suspected to result from the 5% impurity present (mostly plagioclase) another attempt at separating was made in the

centrifuge (with Clerici's solution) and in Wülfing's funnel, in which the mica flakes could be shaken to remove the plagioclase particles adhering to them. The powder thus purified showed only a trace of CaO.

Analysis of biotite from granulite J<sub>32</sub>

	Wt %	Less 5% pl. of comp. Ab <sub>70</sub> An <sub>30</sub>	Recalcu- lated to 100	Mol. num- ber	Metal atoms	O, OH, F	Basis 600 (Si, Ti)O <sub>2</sub>	Basis 12 O, OH, F
SiO <sub>2</sub>	37.96	34.86	36.71	611	611	1222	—	2.67
Al <sub>2</sub> O <sub>3</sub>	16.02	14.82	15.60	153	306	459	115 R <sub>2</sub> O <sub>3</sub>	1.33
Fe <sub>2</sub> O <sub>3</sub>	nil	—	—	—	—	—	—	—
FeO	8.14	8.14	8.56	119	119	119	—	.52
MnO	nil	—	—	—	—	—	313 RO	—
MgO	11.42	11.42	12.01	297	297	297	—	1.30
CaO	1.82	1.52	1.60	28	28	28	—	.13
BaO	.14	.14	.15	1	1	1	91 R <sub>2</sub> O	—
Na <sub>2</sub> O	1.57	1.17	1.23	20	40	20	—	.17
K <sub>2</sub> O	6.47	6.47	6.81	72	144	72	—	.63
H <sub>2</sub> O +	2.26	2.25	2.36	131	262	131	99 H <sub>2</sub> O	1.14
H <sub>2</sub> O -	.10	.10	.10	—	—	—	—	—
TiO <sub>2</sub>	13.95	13.95	14.68	184	184	368	—	.80
P <sub>2</sub> O <sub>5</sub>	.18	.18	.19	1	2	5	—	—
F	Tr	—	—	—	—	—	—	—
	100.02	95.02	100.00			2722		

$$F = \frac{12}{2.722} = 4.41$$

Analyst: H. SCHWANDER  
Sp. Gr. 3.13

(F = factor obtained by dividing the Basis 12 oxygen atoms by the oxygen atoms in the analysed mineral.)

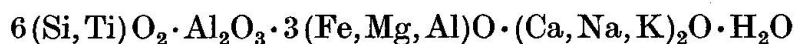
$n_\gamma = 1.657$  (determined by immersion method).

$n_\alpha = 1.593$  to  $1.595$  (determined by the method of FERGUSON and PEACOCK 1943).

Uniaxial to small axial angle.

X = brownish-yellow, Y = reddish-brown, Z = dark brown.

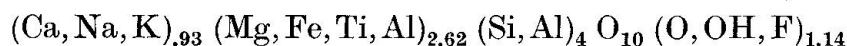
Formulae. HALLIMOND (1925) has proposed the general formula for micas as  $6\text{SiO}_2 \cdot \text{K}_2\text{O} \cdot m\text{RO} \cdot n\text{R}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ , and that Ti should be considered as replacing Si. The titaniferous biotite has approximately the formula



The water content is deficient by one molecule. BERMAN (1937, p. 385) gives the formula for biotites on structural basis as,



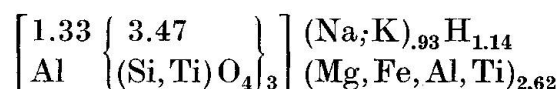
where the ratio of Si : Al in Z is 5 : 3 to 7 : 1. Cast into this form, the formula of biotite is



There is a deficiency of .07 in W; (X, Y) is within the limit 2—3, and (O, OH, F) is deficient by .86, and the ratio of Si to Al is 2 : 1, which is within the limit prescribed by BERMAN. The deficiencies in the W group and the (O, OH, F) group are the common deficiencies noted by WINCHELL (1935).

KUNITZ (1924), after reviewing the analyses of biotites, gives an ideal formula for biotites, which is in agreement with the later work of HALLIMOND, but provides for the following isomorphous substitutions, Fe for Mg, hydroxyl-fluor, K-Na (partly), Si-Ti (partly), and remarks as follows (1924, p. 409): "Alle Glimmer lassen sich in die gemeinsame Grundkomponente  $K Al SiO_4$  (Kaliophilitsilikat) zerlegen; man erhält bei den Muscoviten und Biotiten noch die Restsilikate  $H_2Al_2[SiO_4]_2$  und  $H_2Mg_3[SiO_4]_2$ , welche den glimmerähnlichen Mineralien der Kaolin-, Serpentin- und Chloritgruppe zugrunde liegen. Ersetzt man in der Muscovitformel  $[Al(SiO_4)_3]_{Al_2}^{KH_2}$ , die von CLARKE und JAKOB aufgestellt wurde, die beiden äusseren Aluminiumatome substituierend durch 3 Mg (3 Fe) oder die Gruppe "Le", so erhält man die empirische Zusammensetzung der Biotite und Lithionite."

Expressed in this form, and allowing for the substitutions proposed by KUNITZ, the formula of the mineral is



There is a deficiency in the alkali, water, and (Mg, Fe) groups, and an excess of .33 in Al and .47 in the (Si, Ti) group.

The substitutional relation of titanium. JAKOB (1931) gives the method of calculating the sesquioxide (S) and the non-sesquioxide molecules (M), in a biotite analysis, as follows:

$$S_4 = \frac{200 Al_2O_3}{SiO_2} \text{ and } M_4 = \frac{100 (SiO_2 - 2 Al_2O_3)}{SiO_2}, \text{ and}$$

$$M_5 = \frac{100 [(\sum MgO, K_2O, H_2O) + 3 Al_2O_3 - 2 SiO_2]}{SiO_2}$$



JAKOB and PARGA-PONDAL suggest (1932) that these molecules for the analyses of biotites should be calculated successively on three assumptions, namely that Ti replaces (1) Si, (2) Al, and (3) Mg. Whichever of these results is exactly divisible by 2, such that the total number of molecules  $(S + M) = 50$ , denotes the proper relationship. According to these three assumptions, the following molecules were obtained for the biotites investigated.

	$S_4$	$M_4$	$M_5$
1. Assuming that Ti replaces Mg (1 Ti = 2 Mg)	50.01	10.00	39.92
2. Assumption - Ti replaces Si	38.49	61.51	-61.2
3. Assumption - Ti replaces Al	110.30	-10.81	70.05

The molecules obtained on the first assumption are those most exactly divisible by 2 and such that the total of S and M molecules respectively = 50. Therefore in this biotite Ti replaces Mg. This accords with the general finding of JAKOB and PARGA-PONDAL. They remark (1932, p. 281), "Man könnte auch dieses als eine Stütze dafür ansehen, dass Titan in den Phlogopiten immer nur Magnesium ersetzt und nie Aluminium oder Silicium".

HALLIMOND (1926) determined the volume relations (observed and calculated) on the assumption that Ti replaces (1) Si and (2) Mg, and of the differences between the two values, he regards the smaller one as the proper indication of replacement. Accordingly, for the titaniferous biotites he finds that the observed and calculated volumes differ less if Ti goes with Mg, and that the differences are larger when Ti is considered as replacing Si. On the other hand, in normal biotites the differences are small when Ti is treated as replacing Si.

The volume relations for the investigated biotite are as follows:

	Observed volume	Calculated volume	
1. Assumption Ti replacing Si	232	270	Difference 38
2. Assumption Ti replacing Mg	313	325	Difference 12
3. Assumption Ti present independently	313	298	Difference 15

The volume relations are such that they appear in favour of regarding Ti as replacing Mg. The data are certainly not in favour of Ti replacing Si because the volume numbers 232 and 270 are those of phengites,

whereas the figures 313, 298 and 325 are those of biotites, and are thus in accordance with the optical and physical characters determined.

**Refractive index.** According to HALL (1941a), KUNITZ (1935), and JAKOB (1931), the chief factors that seem to influence the value of the refractive index in biotites are the amounts of the oxides — FeO, TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub> — and of F. In the analysed biotite F and Fe<sub>2</sub>O<sub>3</sub> are absent. Therefore the effect should depend only on the amount of FeO and TiO<sub>2</sub> present. On the curve of FeO given by KUNITZ (1924, p. 380) the value of the refractive index  $n_{\gamma}$  for 8% FeO present in the mineral should be 1.600. But the value determined is 1.657. This higher value should be due to the presence of TiO<sub>2</sub>. The rate of increase of refractive index due to the increase of TiO<sub>2</sub>, as read from the curve of KUNITZ (1936, p. 402), is .01 for 1% TiO<sub>2</sub>. For 13.95% TiO<sub>2</sub> present, the value at this rate should be  $n_{\gamma} = 1.740$ , which is far above the value determined. HALL (1941a) calculates the rate to be .0046. At this rate, the  $n_{\gamma}$  value for 13.95% TiO<sub>2</sub> is 1.660, which is nearer the value observed.

Density and refractive index agree with the data furnished by KUNITZ (1924, p. 387).

LARSEN and others (1937) have studied the biotites of the San Juan region. The titanium content and total iron content are practically the same, and yet the refractive indices show large variations. They comment on the variations as follows (p. 901): "The biotites of the extrusive rocks have variable indices of refraction, which, except in a few rhyolites, are considerably higher than those of the granular rocks: 1.70 to 1.73 (large optic axial angles) in the extrusives, 1.629 to 1.641 in the granular rocks (very small 2V)."

From their study it is evident that temperature and pressure have a large influence on the refractive indices of biotites — a conclusion that was arrived at by KUNITZ (1935). The biotite investigated shares the character of the biotites of the granular rocks of the San Juan region in its refractive index and optic axial angle, denoting formation at great depth and low temperature.

**Colour.** According to HALL (1941) the reddish-brown colour of biotites is due to high titanium and iron, and low magnesia, but, he adds (p. 32): "If the proportion of titania is sufficiently high, the biotite will still be red-brown even though the magnesia is high and the iron low." Here the proportion of TiO<sub>2</sub> : FeO : MgO is 41 : 24 : 35. The magnesia is high and the iron low, but titania is higher and masks the influence of magnesia. The reddish-brown colour of the investigated biotite is in keeping with the explanation of HALL.

## Garnet

Garnet occurs in the basic, intermediate, and acid charnockites. It is often shaped after the hypersthene grains as has been noted by both Sir THOMAS HOLLAND and Dr. A. W. GROVES. Mica develops around the borders as well as in the interior. Garnet exsolves quartz and presents a sieve-structure like the green amphiboles.

The garnet analysed is from leptite J<sub>1</sub> Pallavaram, Madras. The modal composition is:

Quartz	54 %
Microcline	2.5%
Plagioclase	2 %
Garnet	31.5%
Iron ore	4 %
Apatite	6 %

Chemical analysis of garnet from leptite J<sub>1</sub>

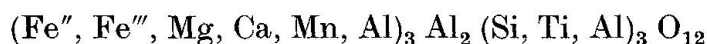
	Wt %	Mol number	Metal atoms	(O, OH, F)	Recalculated to 100	Mol number	Metal atoms	(O, OH, F)	Basis 12 (O, OH, F)	
SiO <sub>2</sub>	36.20	603	603	1206	36.46	607	607	1214	2.81	} 3.00
TiO <sub>2</sub>	1.04	13	13	26	1.05	13	26	26	.12	
Al <sub>2</sub> O <sub>3</sub>	26.26	257	514	771	26.45	260	520	780	2.41	} 2.00
Fe <sub>2</sub> O <sub>3</sub>	.88	6	12	18	.89	5	10	15	.06	
FeO	26.46	368	368	368	26.65	371	371	371	1.72	} 3.00
MnO	.42	5	5	5	.43	6	6	6	.03	
MgO	5.60	139	139	139	5.64	140	140	140	.65	} 3.00
CaO	2.42	43	43	43	2.43	43	43	43	.20	
Na <sub>2</sub> O	0.06	1	—	—	—	—	—	—	—	
			1697	2576	100.00			2595		
K <sub>2</sub> O	.41	4								
H <sub>2</sub> O +	.18	11								
H <sub>2</sub> O -	.01									
P <sub>2</sub> O <sub>5</sub>	.07									
	100.01									

$$F = \frac{12}{2.595} = 4.624$$

Sp. Gr. 4.14                      Analyst: H. SCHWANDER

$n = 1.795$  for sodium light (determined by immersion in methylene iodide, in which sulphur was dissolved).

Neglecting .73 (Na<sub>2</sub>O, K<sub>2</sub>O, H<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>), present in the analysis, and recalculating to a total of 100, and allowing .07 Al to replace Si, and .34 to replace the bases, the formula of the mineral is:



The Ti is regarded as replacing Si after KUNITZ (1935, p. 396). Calculated in terms of standard molecules, it has the composition:

Almandite	66.3%
Pyrope	25.0%
Grossularite	7.8%
Spessartite	.9%

**Specific Gravity.** The specific gravity determined is 4.14. The calculated specific gravity using the data of FLEISCHER (1937) is 4.074. KUNITZ calculates that the rate of increase of specific gravity is .005 for .5% of  $\text{TiO}_2$ . This gives in our case an increase of .01%, and the calculated specific gravity becomes  $4.074 + .010 = 4.084$ . The difference between observed and calculated value is .056, which lies within the maximum difference that FLEISCHER has recorded from published data on garnets.

**Refractive index.** The observed refractive index is 1.795 for sodium light. The calculated refractive index, from FORD's data (1915), is 1.791. The difference between the observed and calculated values is .004, which is within the average of differences observed by FLEISCHER (1937) in 57 published analyses of garnets.

PHILLIPSBORN (1928) has published 4-component diagrams for garnets. The refractive index, read from his diagram No. 3, and corresponding to the composition of the garnet from charnockites, lies at 1.797, which is .002 above the observed value.

*Comparison with garnets of other areas*

This garnet rather closely resembles No. 16 cited by HERITSCH (1927, p. 63). The standard molecules for the two garnets are:

	South Indian from leptite	No. 16 cited by Heritsch
Almandite	66.3	62.2
Pyrope	25.0	27.4
Grossularite	7.8	8.0
Spessartite	.9	2.4
Andradite	—	—

HERITSCH has prepared tables showing the paragenesis of garnets and rock types. The following paragenesis has data lying close to those of the Indian garnet.

Glimmerschiefergranaten  
3. Abt.: Granulit und Kinzigit

Spessartit	0— 3
Grossularit	3— 8
Pyrop	27—33
Almandin	62—65
Andradit	0— 0

This similarity denotes a metamorphic origin for the Indian garnet.

WRIGHT (1938, p. 441) has also given the average proportion of the major standard molecules of garnets in several rock types as follows:

Composition of garnets in different rock types after WRIGHT

Rock type	Spessar- tite	Grossu- larite	Pyrope	Alman- dite	Andra- dite
Pegmatite	47.1	—	—	41.8	—
Granite	36.0	—	—	56.8	—
Garnets associated with contact action on siliceous rocks	30.7	—	—	56.4	—
Biotite schists	—	6.0	13.8	73.0	—
Leptite, South India	.9	7.8	25.0	66.3	—
Amphibole schists	—	20.7	20.3	53.6	—
Eclogites	—	18.5	37.4	39.1	—
Kimberlite and peridotites	—	9.0	72.3	13.4	—
Various basic rocks	—	28.7	20.7	34.4	15.6
Charnockite, Uganda	1.3	—	35.8	41.2	21.7
Calcareous contact rocks	—	51.5	—	—	40.8

In the above table, the South Indian garnet can be placed between those of the biotite and the amphibole schists. This is in accordance with the paragenesis given by HERITSCH.

An analysed garnet from an intermediate charnockite gave a refractive index of 1.783, and the specific gravity 4.01. On FORD's diagram (1915) the composition is 57 Almandite, 20 Pyrope, 20 Grossularite, 3 Spessartite. Though the composition of all garnets in charnockites does not seem to be the same, they nevertheless belong to the schist group.

**Genetic relationship of the analysed minerals and the rock types**

The chemical analyses of the minerals and their corresponding NIGGLI molecular base values are collected in table II (p. 258). Table III (p. 259) gives the chemical composition of the rock types analysed by WASHINGTON (1916). The molecular base values for these rock analyses have been calculated by the present author. Their QLM values are plotted in Fig. 18.

The curve of variation connecting the four rock types of WASHINGTON resembles the trend of differentiation of an igneous series of the Pacific suite (e.g. Lassen Peak, see Fig. 23, p. 79, in BURRI and NIGGLI 1945). The NIGGLI molecular values calculated from WASHINGTON's analyses in fact agree with those of common magma types of the Pacific suite (viz. engadinite-granitic, quartz-dioritic, mela-gabbrodioritic, websteritic), as is shown by the following figures:

## Comparison of charnockites with magma types of Niggli

	Acid Charnock- kite	Enga- dinite grani- tic	Int. charnock- kite	Quartz- diori- tic	Horn- blende Norite	Mela- gabbro- diori- tic	Horn- blende Hyper- sthenite	Webs- teri- tic
si	483	380	222	225	118	130	87	95
al	40.5	43	30.5	32	16	19	6	1
fm	19	13	38	31	55.5	51	78	80
c	6.5	8	16.5	19	20	21	15	18
alk	34	36	15	18	10	9	1	1
ti	1.5	—	2.0	—	3.4	—	1.8	—
k	.48	.5	.17	.25	.16	.25	.11	—
mg	.20	.25	.45	.45	.35	.50	.70	.80
t	0	-1	-1	-5	-14	-11	-10	-18

Figure 19 shows the NIGGLI values given above plotted in a variation diagram. The curves resemble those of Lassen Peak as given by BURRI and NIGGLI (1945, p. 47).

The intersection of the al with the fm curve (isofalic point) is at the si value 272 (refer Fig. 19), which is far above the limit for the igneous series. The values fm and al are 33 and correspond with that of the Pacific suite. BURRI and NIGGLI (1945, p. 50) give the following isofalic and corresponding si values for the various provinces:

	al = fm	si
Lassen Peak (Pacific)	32	176
Highwood Mts (Mediterranean)	29	148
Tristan da Cunha (Atlantic)	30	135

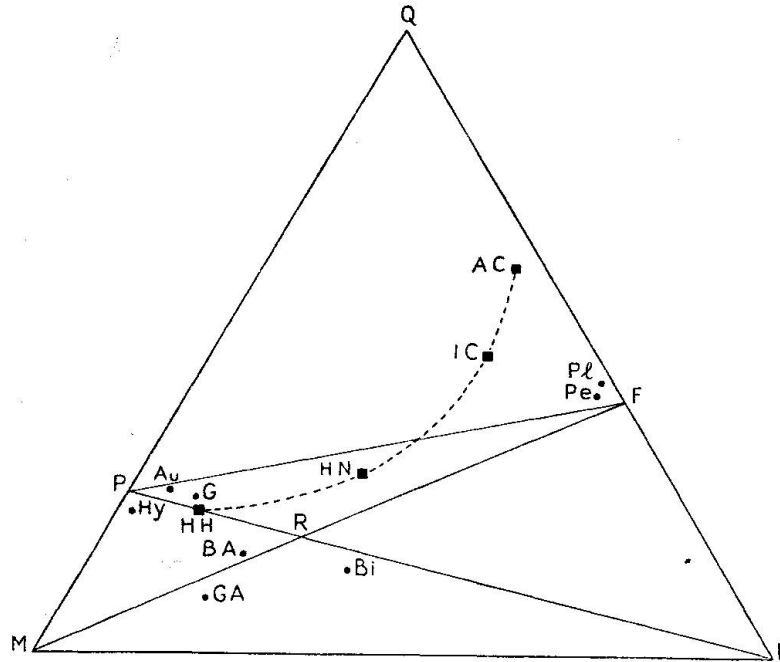


Fig. 18. Q-L-M diagram of the analysed minerals and of the charnockite series of rocks analysed by Washington. Hy = hypersthene, Au = augite, G = garnet, GA = green amphibole, BA = blue amphibole, Bi = biotite, Pl = plagioclase, Pe = perthite, AC = acid charnockite, IC = intermediate charnockite, HN = hornblende-norite, and HH = hornblende-hypersthene.

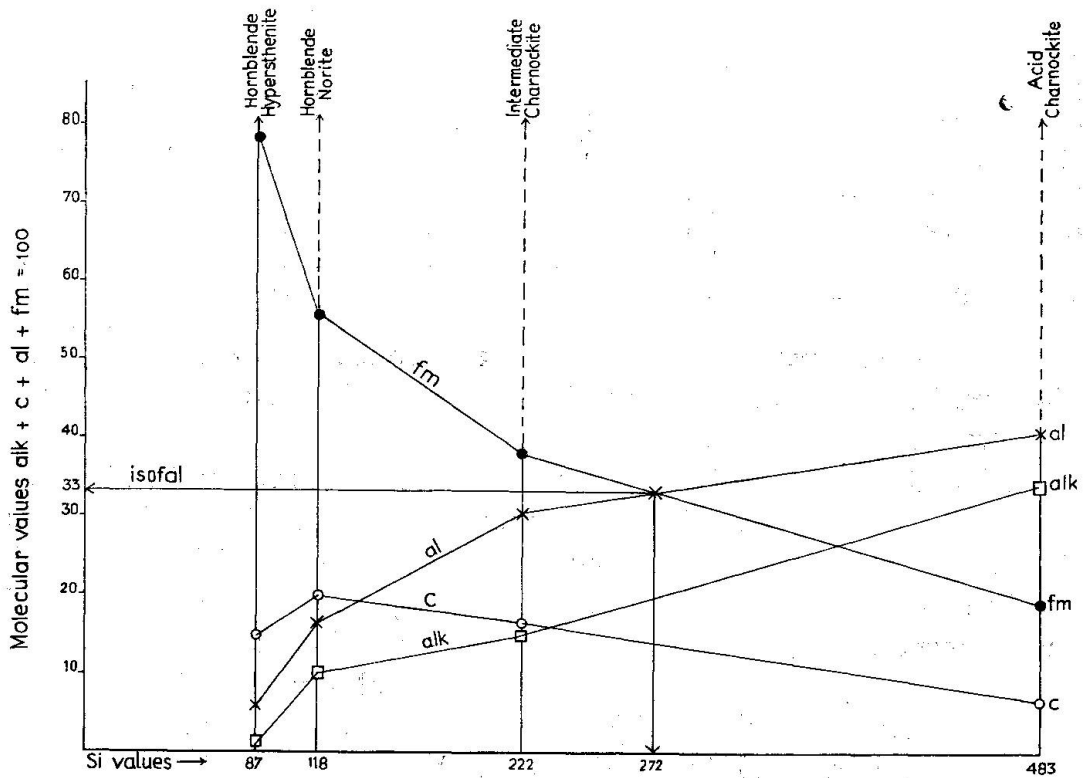


Fig. 19. Variation diagram of the charnockite series. al = fm at 33, for Si = 272.

The k-mg, k- $\pi$  and mg- $\gamma$  values are plotted in the corresponding diagrams of Lassen Peak. In the k-mg diagram (Fig. 20) the intermediate charnockite lies near the field of concentration of points for Lassen Peak,

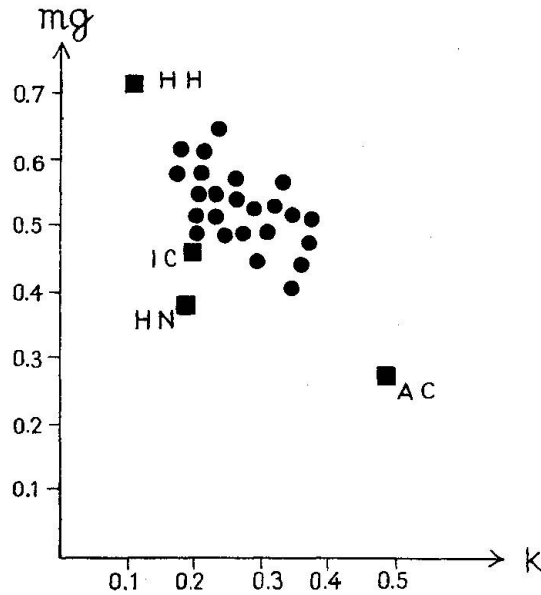


Fig. 20. mg-k diagram of Lassen Peak (after Niggli). ■ = Indian charnockites. AC = acid charn.; HN = hornbl.-norite; IC = interm. charn.; HH = hornbl.-hypersthene.

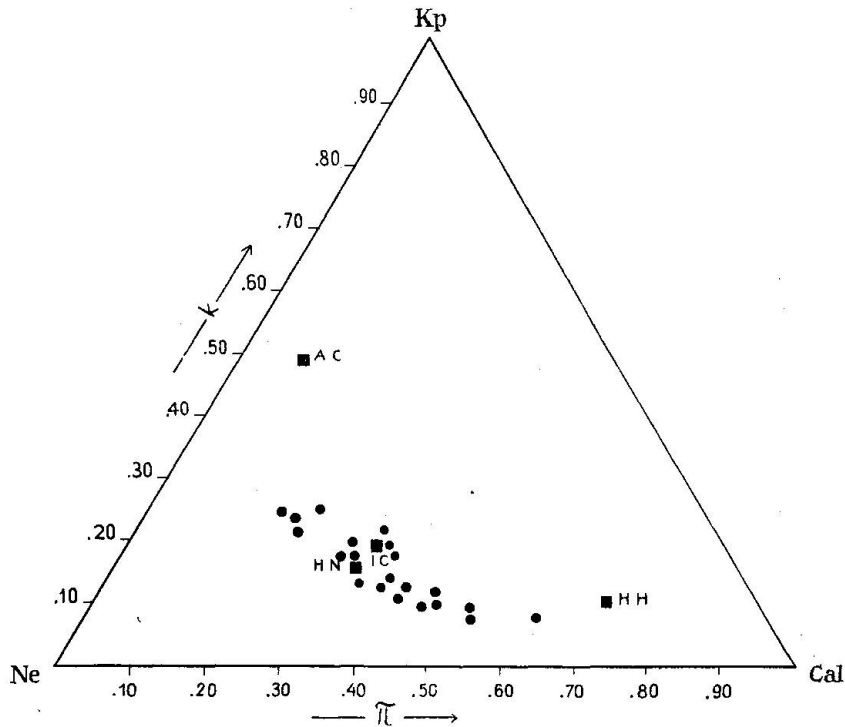


Fig. 21. k- $\pi$  diagram of Lassen Peak (after Niggli). ■ = Indian charnockites.



Weight percent and molecular base values according to  
NIGGLI of analysed minerals

Table II

	Weight percent							
	Hyper- sthene	Green Amphi- bole	Blue Amphi- bole	Bio- tite	Garnet	Plagio- clase	Per- thite	Anti- per- thite
SiO <sub>2</sub>	48.65	40.29	43.23	37.96	36.20	56.80	66.20	—
Al <sub>2</sub> O <sub>3</sub>	1.66	5.72	7.23	16.02	26.26	27.10	17.57	—
Fe <sub>2</sub> O <sub>3</sub>	5.55	.63	6.92	.00	.88	.70	1.27	—
FeO	24.40	12.65	10.72	8.14	26.46	.11	.00	—
MnO	.30	.10	.15	.00	.42	—	Tr	—
MgO	17.65	13.51	11.68	11.42	5.60	.34	.34	—
CaO	.12	12.82	10.06	1.84	2.42	10.15	1.78	7.10
BaO	—	—	—	.12	—	—	—	.11
Na <sub>2</sub> O	.27	4.18	2.38	1.57	.06	4.28	3.28	7.34
K <sub>2</sub> O	Tr	1.22	.42	6.47	.41	.49	10.00	1.36
H <sub>2</sub> O+	.03	2.40	1.84	2.25	.18	.05	.00	—
H <sub>2</sub> O-	.01	.01	.01	.10	.01	.05	.00	—
TiO <sub>2</sub>	1.60	6.60	5.70	13.95	1.04	—	—	—
P <sub>2</sub> O <sub>5</sub>	.05	.00	.00	.18	.07	.02	Tr	—
F	—	Tr	Tr	Tr	—	—	—	—
	100.29	100.13	100.34	100.02	100.01	100.09	100.44	—
	Molecular base values							
Cp	—	—	—	.3	—	—	—	—
Kp	—	4.4	1.6	24.9	1.4	1.6	35.0	—
Ne	1.6	14.5	13.5	6.9	.4	22.8	17.3	—
Cal	.3	—	4.8	4.5	7.5	29.7	2.2	—
Cs	—	19.3	13.3	—	—	—	1.4	—
Ns	—	4.2	—	—	—	—	—	—
Sp	1.6	—	—	6.1	24.4	1.2	—	—
Hz	—	—	—	—	12.4	.1	—	—
Fo	37.3	28.3	25.4	22.7	—	.1 (C)	.7	—
Fa	29.8	14.9	13.3	10.3	26.7	—	—	—
Fs	6.2	.7	7.6	—	1.0	.8	1.4	—
Ru	1.2	4.6	4.2	10.7	.7	—	—	—
Q	22.0	9.1	16.3	13.6	25.5	43.7	42.0	—
L	1.9	18.9	19.9	36.3	9.3	54.1	54.5	—
M	76.1	72.0	63.8	50.1	65.2	2.2	3.5	—
Q	22.0	9.1	16.3	13.6	25.5	43.7	42.0	—
π	.18	.00	.24	.16	.81	.55	.04	—
γ	.00	.31	.22	.00	.00	.00	.40	—
k	.00	.16	.10	.73	.73	.07	.67	—
mg'	.51	.65	.55	.69	.00	.00	.33	—

Weight percent and molecular base values according to NIGGLI of charnockites analysed by WASHINGTON (1916)

Table III

## Weight percent

	Acid charnockite	Intermediate charnockite	Hornblende- norite	Hornblende- hypersthene
SiO <sub>2</sub>	77.47	63.85	50.04	47.44
Al <sub>2</sub> O <sub>3</sub>	11.00	14.87	11.65	5.36
Fe <sub>2</sub> O <sub>3</sub>	1.04	2.32	2.63	3.13
FeO	2.02	5.07	15.76	12.42
MnO	—	.05	—	.15
MgO	.43	3.29	5.58	19.96
CaO	1.02	4.48	7.89	7.60
Na <sub>2</sub> O	2.86	3.72	3.08	.48
K <sub>2</sub> O	4.14	1.09	.89	.10
H <sub>2</sub> O +	.20	—	—	—
H <sub>2</sub> O -	.05	.11	.19	.08
TiO <sub>2</sub>	.26	.83	1.93	1.29
P <sub>2</sub> O <sub>5</sub>	—	.08	.20	.27
S	—	.15	—	.34
Cr <sub>2</sub> O <sub>3</sub>	—	—	—	.07
SrO	—	.04	—	—
	100.59	99.95	99.64	100.69
		-0 for S	0.06	
			99.89	

## Molecular base values

Cp	—	.3	.8	1.1
Kp	14.7	4.1	3.1	.3
Ne	15.7	20.3	16.6	2.7
Cal	3.1	12.5	9.8	7.4
Cs	—	.3	6.5	6.8
Sp	.2	—	—	—
Pr	—	.3	—	.8
Fo	.8	6.9	12.1	41.4
Fa	2.4	5.7	19.0	14.1
Fs	1.0	2.5	2.8	3.3
Ru	.2	.6	1.4	.9
Q	61.9	46.5	27.9	21.2
L	33.5	36.8	29.6	10.4
M	4.6	16.7	42.5	68.4
Q	61.9	46.5	27.9	21.2
π	.09	.34	.33	.71
γ	.00	.07	.16	.10
k	.48	.17	.16	.10
mg'	.23	.46	.36	.70

but the hornblende-hypersthene and hornblende-norite are dispersed, and the acid charnockite is far dispersed. In the  $k-\pi$  diagram (Fig. 21), the intermediate charnockite and the hornblende-norite lie within the field of concentration of points, but the points for acid charnockite and hornblende-hypersthene are far dispersed. In the  $mg-\gamma$  diagram (Fig. 22) the points for intermediate charnockite and hornblende-norite are within or near the field of concentration of points, but the points for acid charnockites and hornblende-hypersthene are far dispersed.

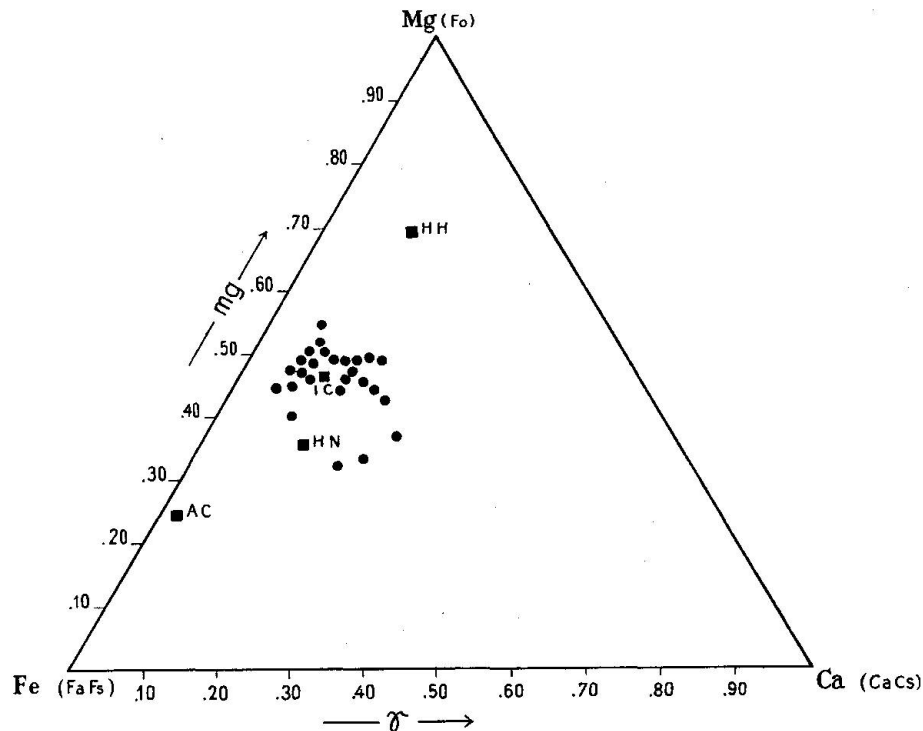


Fig. 22.  $mg-\gamma$  diagram of Lassen Peak (after Niggli). ■ = Indian charnockites.

Disregarding some distinctive mineralogical characters, the different rock types could be explained by withdrawal from a postulated magma of the minerals analysed, as is well evidenced by Fig. 18. The projection points of biotite, intermediate and acid charnockite are situated on an almost straight line. From a magma of the composition of intermediate charnockites which is believed by HOLLAND to represent the parent magma, biotite could crystallize and the trend of differentiation would lead to the development of the acid charnockite. As the projection points of hornblende, hornblende-norite and intermediate charnockite lie also on a straight line, the same argument could be offered for the development of these rocks by crystallization of amphibole. Finally, the crystallization of preponderent pyroxene and subordinate amphibole from a melt

of the composition of hornblende-norite and the squeezing out of a liquid rich in felspar molecules, would lead to hornblende-hypersthenites.

However, this assumed development disregards the important role played by hypersthene which is by far the most common mafic mineral of the rock series, persisting up to the most acid members of the suite. Compared with ortho- and clinopyroxene, amphibole and biotite are of subordinate importance. The crystallization of hypersthene from a melt of the composition of hornblende-norite does not lead to an intermediate charnockite nor does its early crystallization lead towards the acid charnockite. In fact, the formation of rocks oversaturated in silica, lying above the PF-line of Fig. 18, cannot be explained in this way. Only ample crystallization of hornblende and biotite could produce such acid rocks; but there is no evidence of an accumulation of these minerals.

There seem to be two trends of variation in the charnockite series: (1) magmatic differentiation: hornblende-norite — hornblende-hypersthene by predominant crystallization of pyroxene, yielding a residual liquid rich in felspar (gabbrodioritic). (2) development of intermediate and acid charnockites: This second trend can possibly be explained in two ways. (a) By assimilation of quartzo-felspatic rocks (gneiss, leptite, leptynite = basement of charnockite areas) in a gabbroic magma. (b) By injection of granitic material. These questions are best decided by field evidence. They will therefore be discussed no further in this paper.

### **Anorthite content of plagioclase feldspars and mode of parent rocks**

About 40 rock sections have been analysed micrometrically (refer Appendix 1). With these data diagrams of the modes have been prepared for the four regions: Madras, Vellore, Salem and Nilgiris. These diagrams are compared with the diagrams representing anorthite content of the plagioclase feldspars. The following facts emerge from the comparison:

1. In the rocks of the Vellore district (Fig. 23a) there is a general parallel relation between the colour index and the anorthite content. Rocks with a higher colour index contain plagioclase feldspars with gradually increasing anorthite content. The plagioclases of this rock series cover the range from calcic oligoclase to calcic bytownite. In the rocks of the Nilgiris area (Fig. 23b), however, there is no such relationship. Here, rocks with a colour index ranging from 30 to 77%, contain labradorite. Neither do the diagrams drawn up for the Madras and Salem areas show a parallel increase of colour index and modal anorthite content; there is, rather, a

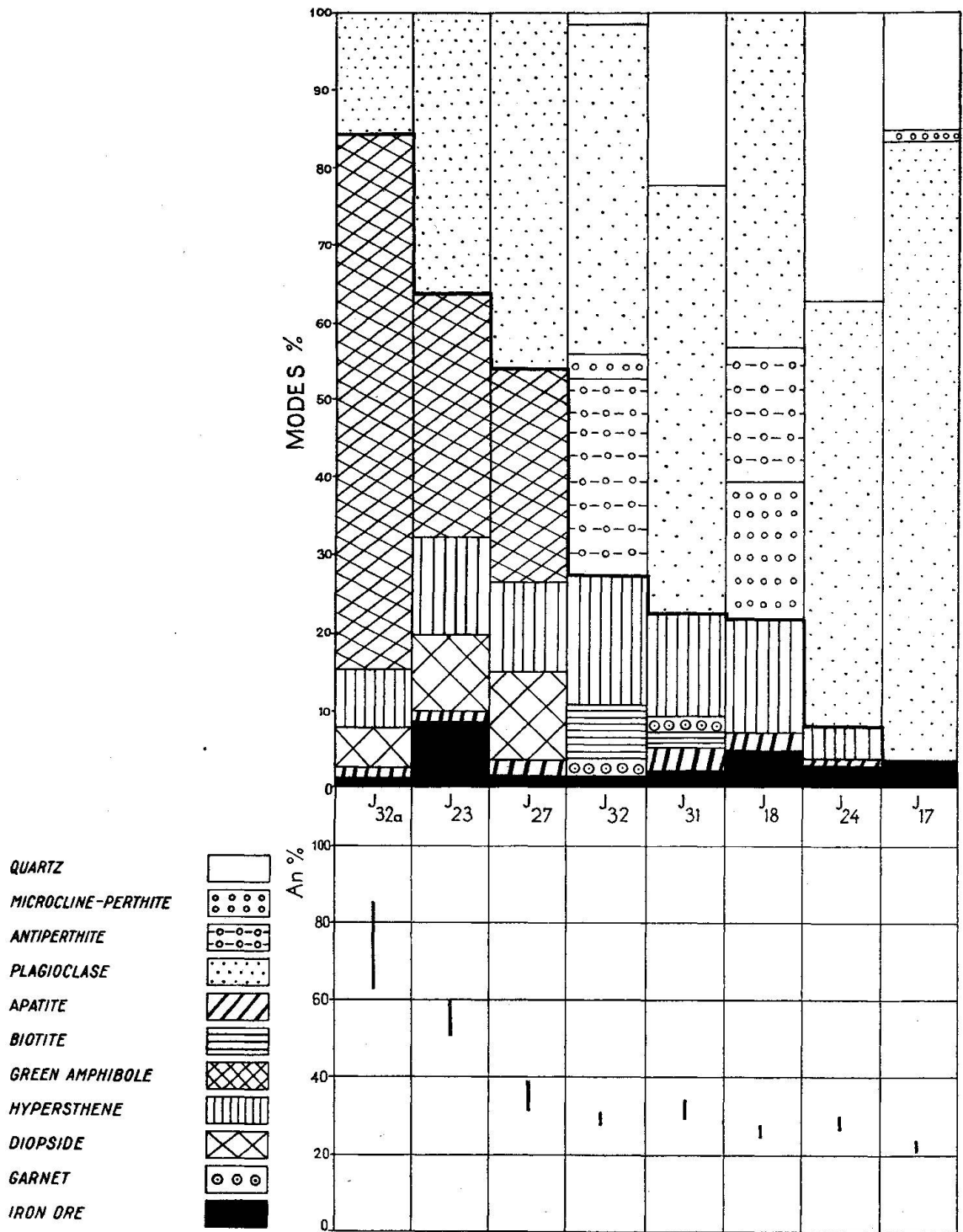


Fig. 23a and b. Diagrams illustrating the relationship of An content of plagioclase felspar and mode of parent rocks.

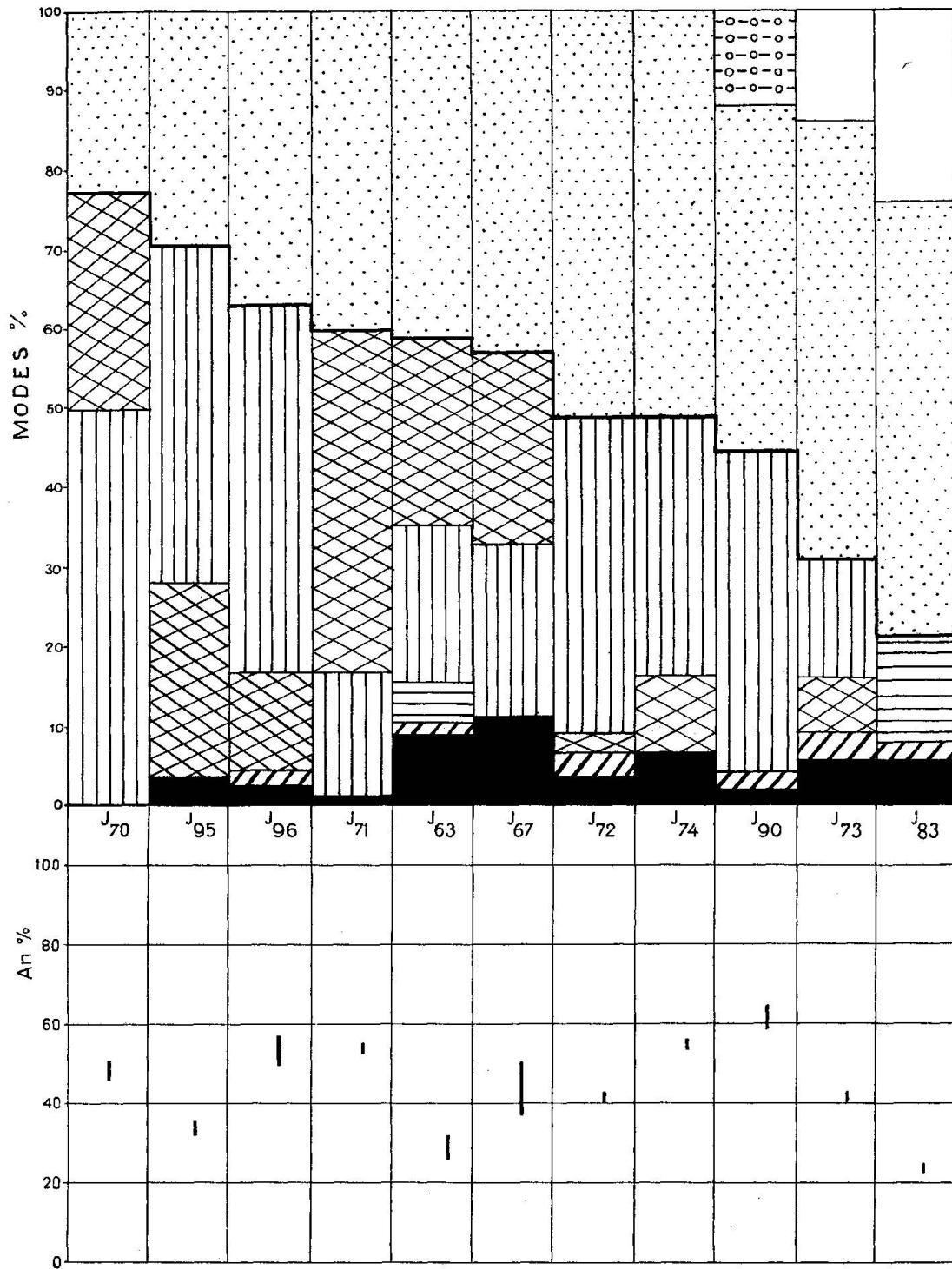


Fig. 23b.

stepwise relation, as is found in metamorphic rock series. Calcic oligoclase and andesine-labradorite are the main plagioclase phases occurring. Even melanocratic rocks with a colour index as high as 91%, such as sample Salem J<sub>53</sub>, carry acid labradorite and not a bytownite/anorthite as might have been expected.

2. From rock type to rock type, however, this parallel relationship does not hold good in all the four regions. Madras J<sub>7</sub> has a higher anorthite content than the four rock types on either side of it. In Salem area, J<sub>67</sub> has a higher anorthite content than the two rock types on either side of it. In Vellore, J<sub>31</sub> and J<sub>24</sub> have anorthite percentages higher than the rock types on either side of them. In the Nilgiris area the anorthite content varies from high to low throughout.

3. In the Vellore area the anorthite content is highest in rock types which contain the largest percentage of green amphibole.

Thus the relation between modal anorthite content and rock composition, found in the charnockite series described, is quite different from that found in igneous rocks. Furthermore two facts, not characteristic of igneous rocks, can be deduced from this comparison, namely, (1) green amphibole and hypersthene crystallize with plagioclase feldspars of the same anorthite content, and no line can be drawn between the points where one ceases to crystallize and the other commences. (2) Orthopyroxene, which is one of the earliest minerals to crystallize (according to BOWEN'S reaction series), continues to crystallize even in the most acid members, whereas green amphibole does not.

## Appendix 1

### Modal composition and anorthite content of the charnockite series and some associated rocks

The following list gives the number of the specimen, the micrometric analysis by volume when it could be ascertained, the anorthite content of the feldspar, the name of the rock, and the locality of the rock type examined.

The micrometric analyses by volume of only 37 specimens have been made on the integrating stage. It was impossible to ascertain the mode of the finely granulated rocks of the Orissa field on the integrating table, and it could only be roughly estimated. The majority of the gneisses and the leptites, and some gneissose granulites, are so fine-grained on account

of the cataclasis to which they have been subjected, that even a rough estimate of the modal mineral composition was not possible. The micro-metric analyses were made from rock sections that had been ground by hand in India, and which were, on an average, .06 mm thick. Lengths of about 100 mm were measured in each rock slice. Only one slide was used for each rock type.

The anorthite content of the feldspar was determined on 2 to 3 grains in each slide.

In the naming of the rocks, the terms employed by former writers have been considered. Earlier descriptions of them as hypersthene-granites, norites, hornblende-norites, and hornblende-hypersthenites have not been found suitable, since the rocks are now considered to be metamorphic. HOLLAND's general description of these rocks as basic, intermediate, and acid charnockites does not serve to distinguish the individual types from each other. The term granulite, as defined by HOLMES (1920), describes the textural and mineralogical features of these rocks more adequately. Therefore, the term granulite has been given preference. The names of minerals occurring in them are prefixed if they constitute above 10% in the mode. Where, however, in the granulites, a pronounced lineation is visible in the hand specimen, the term gneissose has been subscribed within brackets. The term leptite has been defined by HOLMES as a "fine-grained, granular, metamorphic rock composed mainly of quartz and feldspar with subordinate mafic minerals = granulite = Hällefintagneiss". This term has been employed here to describe rocks which have mafic minerals below 10% by volume. The minerals are both granular and crushed to fine-grain size. No restriction has therefore been made as to the size of the grain.

Some of the rocks, like  $J_{83}$  and  $J_{85}$ , are foliated and of gneissose structure. Their grains are distinctly anisometric and show dimensional orientation. For these rocks the term gneiss has been adopted. Most of them do not belong to the charnockite series and constitute the old peninsular gneissic basement rocks.

Rock type  $J_{81}$  is considered on textural grounds to be an igneous rock type not belonging to the charnockite series. It has been described as diorite following the classification by ROSENBUSCH.



## Appendix F

Modal composition and anorthite content in plagioclase of the charnockite series and of some associated rocks.

J<sub>1</sub>–J<sub>15</sub> Madras field. J<sub>17</sub>–J<sub>32a</sub> Vellore field. J<sub>39</sub>–J<sub>61</sub> Salem field. J<sub>63</sub>–J<sub>96</sub> Nilgiris field. O<sub>1</sub>–O<sub>10</sub> Orissa field. (For location of field occurrences see Fig. 1.)

No. of Specimens	Mineral	Vol. %	Percentage of anorthite in plagioclase and type of rock	Locality
1	2	3	4	5
J <sub>1</sub>	Quartz	–54.0		Pallavaram
	Microcline	– 2.5		A few yards east of the
	Plagioclase	– 2.0	An <sub>22</sub>	Pallavaram Railway
	Garnet	–31.5	Garnetiferous	station
	Iron ore	– 4.0	Leptite	
	Apatite	– 6.0		
J <sub>3</sub>	Plagioclase	–35.0	An <sub>42</sub> to An <sub>53</sub>	Pallavaram
	Hypersthene	–38.0	Andesine-hypersthene-	Western slope of the hill
	Augite	–17.5	augite-granulite	rise 500'
	Iron ore	– 8.0		
	Apatite	– 1.5		
J <sub>4</sub>	Quartz	–13.0		Pallavaram
	Plagioclase	–75.5	An <sub>21</sub> to An <sub>26</sub>	Top of the hill rise 500'
	Hypersthene	– 9.0	Quartz-oligoclase-	
	Iron ore	– .5	hypersthene-granulite	
	Apatite	– 2.0		
J <sub>7</sub>	Quartz	–26.0		Pallavaram
	Microcline-perthite	–35.0		On the eastern slope of
	Plagioclase	–25.0	An <sub>29</sub> to An <sub>32</sub>	hill rise 500'
	Hypersthene	– 6.5	Leptite	about 100 yards from
	Iron ore	– .5		top
	Apatite	– 7.0		
J <sub>9</sub>	Quartz	–38.5		Pallavaram
	Plagioclase	–51.0	An <sub>23</sub> to An <sub>24</sub>	Western slope of the
	Hypersthene	– 6.5	Leptite	hills to the east of hill
	Iron ore	– 2.0		rise 500' (in quarries
	Apatite	– 2.0		opened by the South- Indian Railway)
J <sub>10</sub>	Quartz	–14.0		Pallavaram
	Microcline-perthite	–76.0		In another quarry nearer
	Plagioclase	– 7.0	An <sub>23</sub>	the Railway Station of
	Hypersthene	– 2.0	Leptite	Pallavaram
	Iron ore	– .5		
	Apatite	– .5		

1	2	3	4	5
J <sub>15</sub>	Plagioclase Diopside and hypersthene Green amphibole Iron ore Apatite	-31.5 -26.5 -27.0 -14.0 - 1.0	An <sub>32</sub> to An <sub>48</sub> Andesine-hypersthene- amphibole-granulite	St. Thomas Mount (Top of the hill to the west of St. Thomas Mount, sketched by Holland (1900, p. 136))
J <sub>17</sub>	Quartz Plagioclase Microcline-perthite Iron ore	-15.0 -80.0 - 1.5 - 3.5	An <sub>23</sub> Leptite	Kailasgarh A few yards south of augite-diorite at the milestone 8/7 on the mount to the top of Kailasgarh hill (Δ 1242)
J <sub>18</sub>	Plagioclase Antiperthite Microcline-perthite Hypersthene Iron ore Apatite	-42.5 -17.5 -18.0 -14.5 - 5.0 - 2.5	An <sub>25</sub> Oligoclase-microcline- hypersthene-granulite	Kailasgarh A patch in J <sub>17</sub>
J <sub>23</sub>	Plagioclase Green amphibole Diopside and Hypersthene Iron ore Apatite	-36.0 -31.0 -23.0 - 9.0 - 1.0	An <sub>50</sub> to An <sub>60</sub> Labradorite-amphibole- hypersthene-granulite	Kailasgarh At the milestone 0/4 on the bridle-path leading to the crest of Kailas- garh
J <sub>24</sub>	Quartz Plagioclase Hypersthene Iron ore Apatite	-36.5 -54.5 - 5.0 - 3.5 - .5	An <sub>27</sub> to An <sub>30</sub> Leptite	Kailasgarh 50 yards east of 0/4 milestone
J <sub>27</sub>	Plagioclase Green amphibole Diopside and hypersthene Iron ore Apatite	-46.0 -27.5 -23.0 - 2.0 - 1.5	An <sub>32</sub> to An <sub>38</sub> Andesine-amphibole- pyroxene-granulite	Kailasgarh Milestone 2
J <sub>31</sub>	Quartz Plagioclase Hypersthene Garnet Biotite Iron ore Apatite	-22.0 -55.0 -13.5 - 2.0 - 2.0 - 3.5 - 2.0	An <sub>29</sub> to An <sub>33</sub> Quartz-andesine- hypersthene-granulite	Kailasgarh Milestone 2/4 up the rise to Kailasgarh sum- mit (Δ 2028)

1	2	3	4	5
J <sub>32</sub>	Plagioclase Quartz Microcline Antiperthite Hypersthene Biotite Garnet Iron ore	-43.0 - 1.0 - 2.5 -26.0 -16.5 - 7.0 - 2.5 - 1.5	An <sub>28</sub> to An <sub>30</sub> Oligoclase-antiperthite-hypersthene-granulite	Kailasgarh Main mass of the hill (Δ 2739)
J <sub>32a</sub>	Plagioclase Green amphibole Hypersthene and diopside Iron ore Apatite	-16.5 -68.5 -12.5 - 1.5 - 1.0	An <sub>62</sub> to An <sub>86</sub> Labradorite-amphibole-pyroxene-granulite	Kailasgarh Crest of the Kailasgarh hill to the east of the temple (Δ 2739)
J <sub>39</sub>	Plagioclase Hypersthene and diopside Iron ore Apatite	-43.0 -36.0 -17.5 - 3.5	An <sub>30</sub> to An <sub>39</sub> Andesine-pyroxene-granulite	Kusamalai From the northern slope of Kusamalai hill
J <sub>48</sub>	Plagioclase Blue-green hornblende Epidote Iron ore	-24.5 -63.0 - 6.0 - 6.5	Amphibolite	Kusamalai
J <sub>52</sub>	Plagioclase Green amphibole Diopside	- 7.5 - 8.5 -84.0	An <sub>30</sub> Andesine-diopside-granulite	Yercaud Crest of hill rise Δ 1441. West of Milestone 6/5
J <sub>53</sub>	Plagioclase Green amphibole Hypersthene Iron ore	- 9.0 -74.0 -10.0 - 7.0	An <sub>54</sub> Hornblendite	Yercaud A segregation in J <sub>52</sub>
J <sub>54</sub>	Plagioclase Hypersthene Iron ore Apatite	-59.5 -29.0 - 7.5 - 4.0	An <sub>33</sub> Andesine-hypersthene-granulite	Yercaud Crest of hill rise Δ 1446
J <sub>55</sub>	Plagioclase Garnet Diopside Iron ore	-12.0 -54.0 -29.0 - 5.0	An <sub>45</sub> Andesine-diopside-garnet-granulite	Yercaud Crest of hill rise Δ 1673
J <sub>56</sub>	Antiperthite and plagioclase Hypersthene Iron ore	-67.0 -28.0 - 5.0	An <sub>25</sub> Oligoclase-hypersthene-granulite	Yercaud Crest of hill rise Δ 2456

1	2	3	4	5
J <sub>57</sub>	Quartz Plagioclase Hypersthene and diopside Iron ore	-29.5 -39.5 -25.0 - 6.0	An <sub>25</sub> Quartz-oligoclase- pyroxene-granulite	Yercaud Base of the Southern slope of hill rise Δ 2546
J <sub>61</sub>	Plagioclase Green amphibole Hypersthene Iron ore Apatite	-18.0 -47.5 -25.5 - 6.0 - 3.0	An <sub>41</sub> Andesine-amphibole- hypersthene-granulite	Mettur Basic segregation in hypersthene-oligoclase- granulite from the wes- tern flank of the Mettur dam
J <sub>63</sub>	Plagioclase Green amphibole Hypersthene Biotite Iron ore Apatite	-42.0 -23.5 -19.0 5.5 - 9.0 - 1.0	An <sub>25</sub> to An <sub>30</sub> Oligoclase-amphibole- hypersthene-granulite	Dimbam, Coimbatore Dt. At Dimbam Cross Milestone 60, Δ 3613
J <sub>67</sub>	Plagioclase Green amphibole Hypersthene Iron ore	-43.5 -23.5 -22.0 -11.0	An <sub>37</sub> to An <sub>50</sub> Andesine-amphibole- hypersthene-granulite	Dimbam, Coimbatore Dt. Milestone 59
J <sub>70</sub>	Plagioclase Green amphibole Hypersthene	-23.0 -27.0 -50.0	An <sub>46</sub> to An <sub>50</sub> Andesine-amphibole- hypersthene-granulite	Gaddesol, Coimbatore Dt. From crest of Δ 4891, south of Doddabetta
J <sub>71</sub>	Plagioclase Green amphibole Hypersthene Iron ore	-40.5 -43.0 -15.5 - 1.0	An <sub>53</sub> Labradorite-amphi- bole-hypersthene- granulite	Gaddesol, Coimbatore Dt. Crest of Δ 4459, south of Doddabetta
J <sub>72</sub>	Plagioclase Diopside and hypersthene Green amphibole Iron ore Apatite	-51.5 -40.5 - 2.0 - 3.5 - 2.5	An <sub>40</sub> Andesine-pyroxene- granulite	Gaddesol, Coimbatore Dt. Southern slope of Δ 4459
J <sub>73</sub>	Quartz Plagioclase Hypersthene Green amphibole Iron ore Apatite	-14.0 -55.5 -15.0 - 7.5 - 5.0 - 3.0	An <sub>40</sub> Quartz-andesine- hypersthene-granulite	Gaddesol, Coimbatore Dt. Crest of Δ 4244

1	2	3	4	5
J <sub>74</sub>	Plagioclase Hypersthene and diopside Green amphibole Iron ore	-51.0 -33.0 - 9.5 - 6.5	A <sub>53</sub> Labradorite-pyroxene- granulite	Gaddesol, Coimbatore Dt. Northern slope of $\Delta$ 4158
J <sub>81</sub>	Clouded plagioclase Augite and pigeonite Green amphibole Biotite Iron ore Micropegmatite	-45.0 -36.5 - 4.5 - 3.0 - 2.0 - 9.0	An <sub>44</sub> to An <sub>58</sub> Augite-diorite	Hasanur, Coimbatore Dt. An included boulder in andesine-hypersthene- granulite from the mile- stone 47 leading from Hasanur to Gaddesol
J <sub>83</sub>	Quartz Plagioclase Hypersthene Biotite Iron ore Apatite	-24.0 -51.0 - 4.5 -13.0 - 5.5 - 2.0	An <sub>22</sub> Oligoclase-biotite- gneiss	Hasanur, Coimbatore Dt. Behind the Forest Ins- pection bungalow, Hasanur
J <sub>85</sub>	Quartz Antiperthite Plagioclase Hypersthene Biotite Iron ore Apatite	- 9.0 -69.0 -11.0 - 6.0 - 3.0 - 1.5 - .5	An <sub>23</sub> Oligoclase-anti- perthite-gneiss	Hasanur, Coimbatore Dt. From the eastern slope of hill rise $\Delta$ 4278, at milestone 1 on the road to Talamalai
J <sub>90</sub>	Plagioclase Antiperthite Hypersthene Iron ore Apatite	-44.0 -12.0 -41.0 - 1.0 - 2.0	An <sub>53</sub> to An <sub>63</sub> Labradorite-hyper- sthene-antiperthite- granulite	Doddanebetta, Mysore State; dyke in oligoclase- antiperthite-gneiss from low rise east of Punajur near bridlepath to Dod- danebetta
J <sub>95</sub>	Plagioclase Diopside and hypersthene Green amphibole Iron ore	-30.5 -41.0 -25.5 - 3.0	An <sub>33</sub> Andesine-hypersthene- amphibole-granulite (gneissose)	Doddanebetta, Mysore State Near the crest of Dod- danebetta $\Delta$ 5780
J <sub>96</sub>	Plagioclase Diopside and hypersthene Green amphibole Iron ore Apatite	-37.0 -46.5 -13.0 - 2.5 - 1.0	An <sub>48</sub> to An <sub>56</sub> Labradorite-pyroxene- amphibole-granulite	Doddanebetta, Mysore State Another specimen of J <sub>95</sub>

1	2	3	4	5
O <sub>1</sub> *	Quartz	-19.0		Balliguda
	Microcline-perthite	-56.0	An <sub>18</sub> to An <sub>30</sub>	
	Plagioclase	- 9.0	Biotite-perthite-gneiss	
	Biotite	-14.5	(cataclastic)	
	Apatite	- 1.5		
O <sub>3</sub> *	Quartz	-31.5		Barsingh Parbhat
	Plagioclase	-15.5	An <sub>28</sub> to An <sub>31</sub>	½ mile to the south of
	Microcline-perthite	-39.0	Microcline-perthite-	Nuagam on the path to
	Biotite	-14.0	oligoclase-biotite-	Barsingh Parbhat
			gneiss	
O <sub>4</sub> *	Quartz	-22.0		Barsingh Parbhat
	Plagioclase	-10.0	An <sub>18</sub>	1 mile to the south-east
	Microcline-perthite	-31.5	Oligoclase-perthite-	of Nuagam on the path
	Garnet	-21.0	gneiss	to Barsingh Parbhat
	Biotite	-14.0		
	Apatite	- 1.5		
O <sub>7</sub> *	Quartz	-44.5		Udayagiri
	Plagioclase	- 6.5	An <sub>30</sub>	Crest of Papkadi
	Microcline	-34.5	Microcline-oligoclase-	Parbhat Δ 3399
	Hypersthene	-13.0	hypersthene-granulite-	
	Biotite	- .5	(gneissose)	
	Iron ore	- 1.0		
O <sub>10</sub> *	Quartz	-28.0		Ballipadar, Aska
	Plagioclase	-46.0	An <sub>44</sub> to An <sub>50</sub>	Crest of Δ 1266 to the
	Hypersthene	-15.0		south-east of Ballipadar
	Garnet	- 4.0	Andesine-hypersthene-	
	Biotite	- 1.0	granulite (gneissose)	
	Iron ore	- 2.0		
	Apatite	- 4.0		

\* Mode roughly estimated

## Appendix II

### Petrofabric analysis

Although the specimens were not oriented in the field, petrofabric diagrams were prepared from slides of the following rock types to ascertain whether preferred orientations are present.

1. Andesine-hypersthene-augite-granulite (Norite of HOLLAND), from the type area — Pallavaram, Madras —  $J_3$ .
2. Oligoclase-antiperthite-hypersthene-granulite, biotite- and garnet-bearing from Kailasgarh, Vellore —  $J_{32}$ .
3. Oligoclase-antiperthite-gneiss from Kailasgarh, Vellore —  $J_{22}$ .

$J_3$ : In a slide cut parallel to the hardly recognisable foliation of this granular rock, the orientation of 200 grains of hypersthene was determined. The elemental diagrams Figs. 24a-c show the orientation of X (crystallographic axis b), Y (crystallographic axis a) and Z (crystallographic axis c). Evidently Y shows the best concentration of points. This well-pronounced maximum in the centre of Fig. 24b forms part of a girdle perpendicular to the projection plane (= a b plane of the fabric). The direction Z of the 200 grains is arranged along part of the periphery of the diagram (Fig. 24c), forming an incoherent girdle with several minor maxima. X is scattered over almost all the diagram (Fig. 24a), but nevertheless a distinct maximum can be made out near the centre. This result appears to contradict the Y maximum. But, during the measurements on the

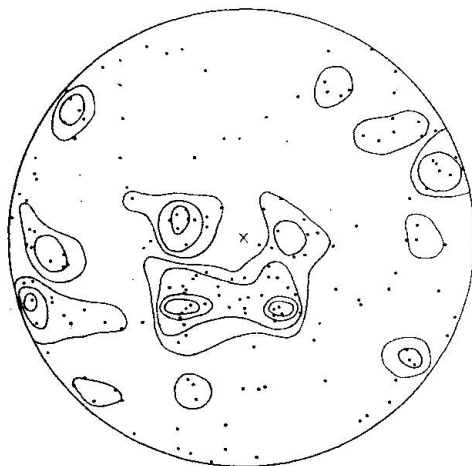


Fig. 24a. Diagram of the b (= X) crystallographic axes of hypersthene in  $J_3$ .

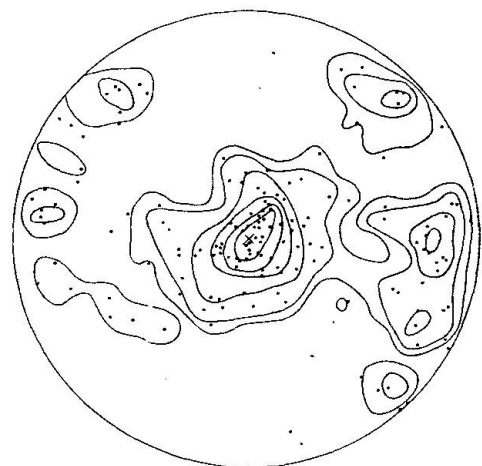


Fig. 24b. Diagram of the a (= Y) crystallographic axes of hypersthene in  $J_3$ .

universal stage, it became evident that one group of hypersthene crystals, forming clusters, is oriented with Y, another, less important group, with X in the centre of the projection. Thus it is evident that hypersthene shows preferred orientation, the crystal axis a (Y) being arranged parallel to one direction of the fabric. The girdles are indicative of differential movement during crystallization. But the complex character of the orientation does not allow further conclusions.

$J_{32}$ : 100 hypersthene grains of this granulite are plotted showing the emergence of the axes of the indicatrix (Fig. 25a-c). In contrast to  $J_3$ , the a, b and c crystallographic axes here show a marked concentration.

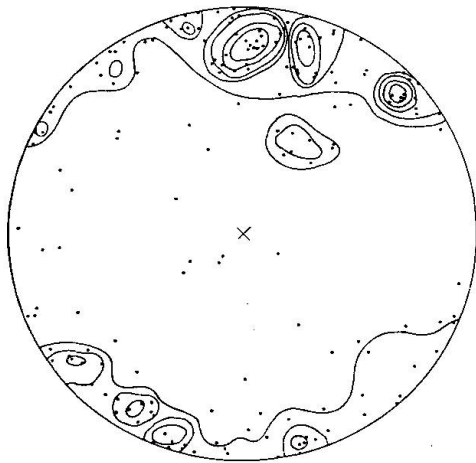


Fig. 24c. Diagram of the c (= Z) crystallographic axes of hypersthene in  $J_3$ .

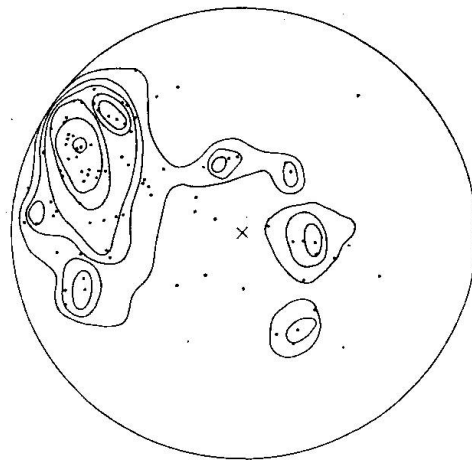


Fig. 25a. Diagram of the b (= X) crystallographic axes of hypersthene in  $J_{32}$ .

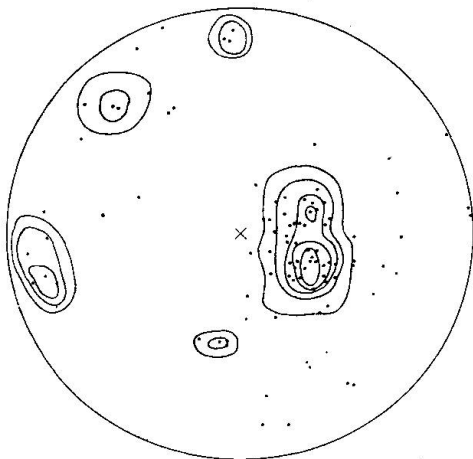


Fig. 25b. Diagram of the a (= Y) crystallographic axes of hypersthene in  $J_{32}$ .

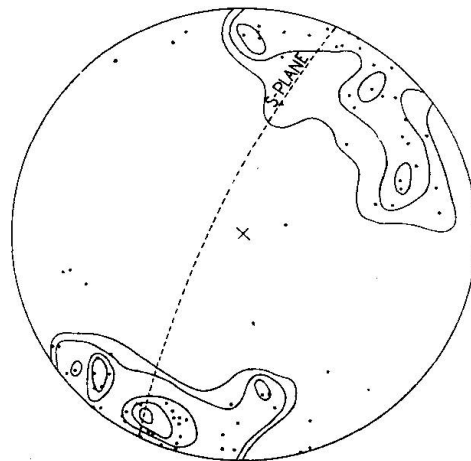


Fig. 25c. Diagram of the c (= Z) crystallographic axes of hypersthene in  $J_{32}$ .



A mica diagram was also prepared from the same slide. The petrofabric diagram (Fig. 26) shows a single maximum. A comparison of Fig. 25c (petrofabric diagram of c axes of hypersthene) with Fig. 26 (petrofabric diagram of c axes of mica flakes) reveals the fact that the two maxima are almost perpendicular to each other, and are so situated that the crystallographic c-axial directions of hypersthene are parallel to the elongation of the mica flakes — a fact easily seen in the slide, where the elongation of hypersthene is parallel to that of mica. Both minerals show homoaxial orientation. The girdle perpendicular to the fabric axis in mica is not well developed.

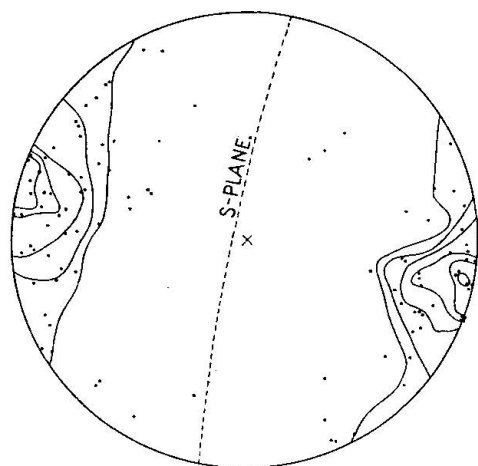


Fig. 26. Diagram of c (= X) axes of biotite in  $J_{32}$ .

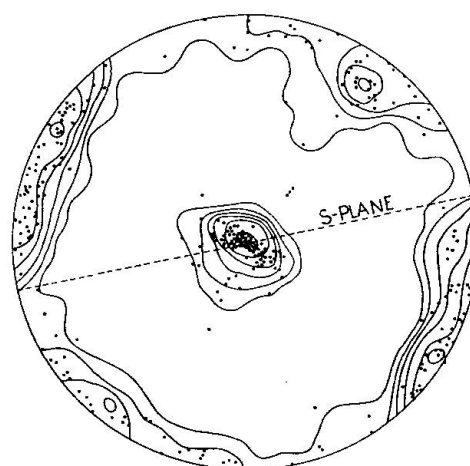


Fig. 27. Diagram of c (= Z) axes of quartz in  $J_{22}$ .

$J_{22}$ : In this well-foliated, leucocratic, oligoclase-antiperthite-gneiss, the crystallographic c-axes of 400 quartz grains were measured in a slide cut perpendicular to the foliation. The resulting diagram Fig. 27 shows a well-pronounced maximum in the centre, which appears to represent the a-axis of the fabric (maximum I of SANDER (1930)). Two minor maxima, situated at the periphery of the diagram, are perpendicular to each other and perpendicular also to the main maximum. As they occur at an inclination of about  $45^\circ$  to the s-plane, they can easily be identified as the well-known symmetrical pair of maxima III. This combination of maximum I with two maxima III is typical for granulites and is described from German and Finnish rocks. (SANDER 1930, SCHMIDT 1926, ANDREATTA 1933, CLOOS 1935, SAHAMA 1936, SANDER 1950). SANDER (1950, p. 143) remarks: "Die Maxima I, II, III und IV sind statistisch deutlich lagenkonstant. Sie treten alle sowohl einzeln als in jeder Kombination miteinander auf, mit oder ohne die (a b) und (a c) als Symmetrie-

ebenen entsprechenden Wiederholungen." In diagram Fig. 27 the maxima III are connected by a weakly pronounced girdle; a cross-girdle connecting maxima I and III is not developed here, though it is common in European granulites and gneisses.

The distinctly preferred orientation of quartz in the rock  $J_{22}$  shows that we are dealing with a tectonite. This conclusion is supported also by the shape of the quartz grains, which are flattened parallel to the s-plane, by their undulose extinction, and by the streaks of microgranules of quartz and feldspar.

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