AMPHIBOLITE-GRANULITE FACIES CHARNOCKITES

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Introduction

The Problem

The problem of the origin of the charnockites has been a much disputed one. Holland considered that the charnockites formed a magmatic series varying from acid to ultrabasic types and unified the series into a petrographic province. Vredenburg held the view that the charnockites were metamorphosed Dharwars. A detailed study of the type area affords enough evidence to consider that the rocks constitute a high grade metamorphic suite approaching the granulite facies. There have been oscillations in the P.T. conditions as shown by the prograde and retrograde mineral reactions. The type area itself shows rock-types which have resulted by allo-chemical metamorphism. The same theory may possibly hold good for the charnockites of batholithic dimensions, particularly in the light of modern ideas that the pegmatites and cross-cutting dykes, can be formed by metasomatic replacement.

Geological Setting

Cherimalai (sheet 66 D/15; Lat. 80° 10′ 55″: Long. 12° 57′ 25″) and Parvattai malai to its west, situated barely two miles to the south-east of the Mosque Hill Pallavaram, the type area for charnockites affords a very interesting study. The prominent rock-type not hitherto observed is a band of garnetiferous-diopside-granulite with a thickness varying from a few feet to a maximum of sixty feet making up nearly one-third of the southern flank of the hill. This rock occurs interbanded with the leptynites and gradually disappears into the norites. Detailed mapping (Fig. 1) resolves the charnockites in the area into noritic-boulders, and bands of varying sizes of biotite-norite, hornblende-garnet-spinel rocks and garnetiferous-diopside-granulite already referred to. This last member shows thin bands of scapolite-calc-granulite which formed the subject of a paper (Muthuswami, 1951). The calc-scapolite bands of thickness varying from half to one inch have also been observed in the Mosque Hill Pallavaram, described in Holland's Memoir (1900). There are stringers of norite in the garnetiferous-diopside-granulite; some of these spread out into irregular patches. All gradations of rock-types with hypersthene to those without hypersthene are fairly common. There is no definite cross-cutting relationship of the norite to consider it as intrusive; neither are there clear evidences of recrystallization of minerals at the contacts of norite bands.

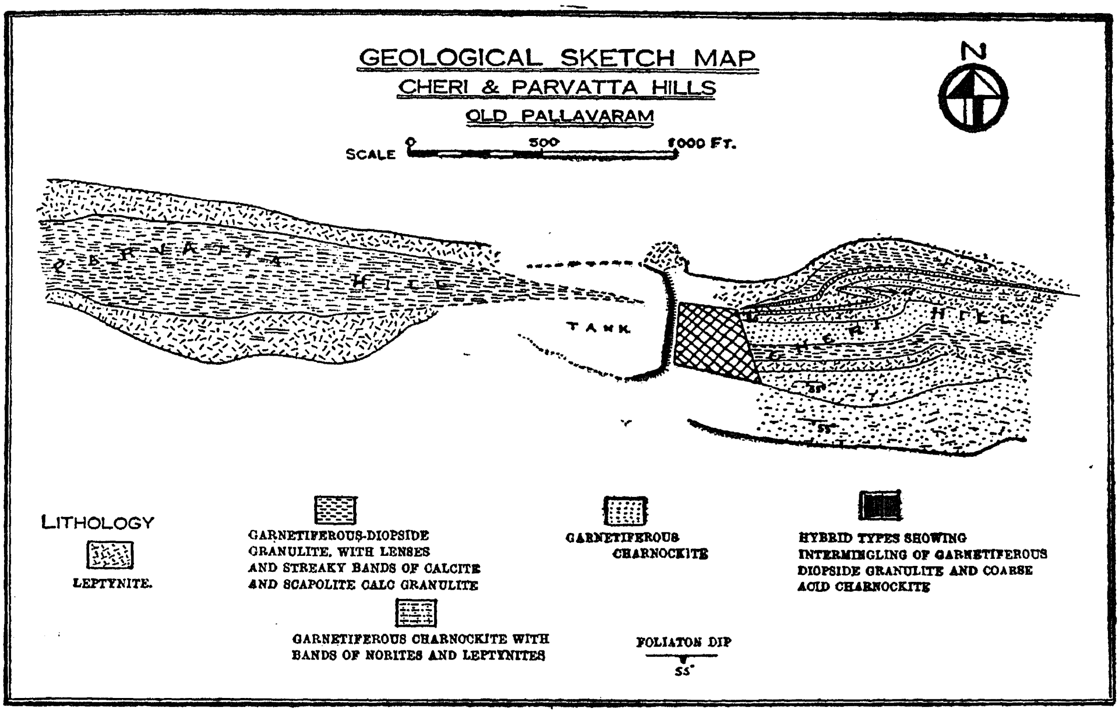

FIG. 1

There are indications of minor pitching folds of bands of basic granulite and leptynite on the northern flank towards the east. One could observe long-drawn-out bands of blue quartz. The lineation is 35 to 40 degrees to east-south-east. The basic rock-types include:

(i) Garnetiferous-diopside-granulite.
(ii) Hornblende-norite.
(iii) Biotite-norite.
(iv) Garnet-hornblende-spinel-rock.
(v) Norite.

MINERALOGY

General Statement

The most important minerals are plagioclase, pyroxene, hornblende, garnet, biotite, spinel, apatite and ores. Calcite occurs associated with scapolite and sphene, in scapolite-calc-granulite. It also occurs sparingly in some of the associated rock-types. Quartz is present in subordinate quantities.

Methods of Study

Indices of Refraction.—Refractive indices were obtained by immersion methods using white light. The R.I. of liquids were simultaneously determined by Abbé Refractometer or Leitz-Jelley Micro-Refractometer. Estimated possible errors are ± ·002. Optic axial angles and the twin laws of the plagioclases were found on the five-axis universal stage. The anorthitic content was estimated not only from the 2 V values but also from sections normal to the composition plane (010) and normal to the $\breve{a}$ axis. The specific gravity of garnet was determined by the pyknometer.

Micro-Petrography

Garnetiferous-diopside-granulite

Plagioclase.—The twins are mostly albite-normal with pericline striations; the twin bands are sometimes wedge-shaped and extinction undulose. The mean R.I. is 1·559; 2 V_z is 80°. The composition is $Ab_{50}An_{50}$. Sub-calcic plagioclases occur as inclusions in the calcic ones and sometimes the former cut across the twin bands of the latter. Such grains are mostly irregular in outline with diopsidic inclusions. Small anhedra of plagioclase also occur as inclusions in the pyroxene grains that show lamellar growths of diopside and hypersthene. Blebs of released quartz are fairly common.

Pyroxenes.—Both rhombic and monoclinic varieties are present. There is much variation in the 2 V and R.I. values; however the orthopyroxene of the intergrowth is eulite and the monoclinic variety is augite or salite. The minerals that have intergrown have the following characteristics:—

		Intergrowth: Orthorhombic pyroxene	Intergrowth: Monoclinic pyroxene
Pleochroism	X	Pink	Green
	Y	Yellow	Green with a tinge of brown
	Z	Green	Green
Ref. Indices	*nx*	1·701	..
	ny	..	1·704
Birefringence		..	·028
	2 V	63°	59°
Sign		Negative	Positive
Parting		‖ to (001)	‖ to (001)
Composition		Eulite (of 70 en 30)	20% Fe atoms in 50% Ca + Mg + Fe atoms augite or salite
		(Poldervaart, 1947)	(Hess, 1949)

The intergrowth produces a blurred colour effect on rotating the stage when the nicols are not crossed, an effect which is clearly seen in thick sections where the pleochroism of hypersthene dominates. The intergrowth is interrupted by salite veins and by hypidiomorphic grains (Micro-photo 1). The crystallographic (Hess, 1940) and optical orientations are given in Fig. 2.

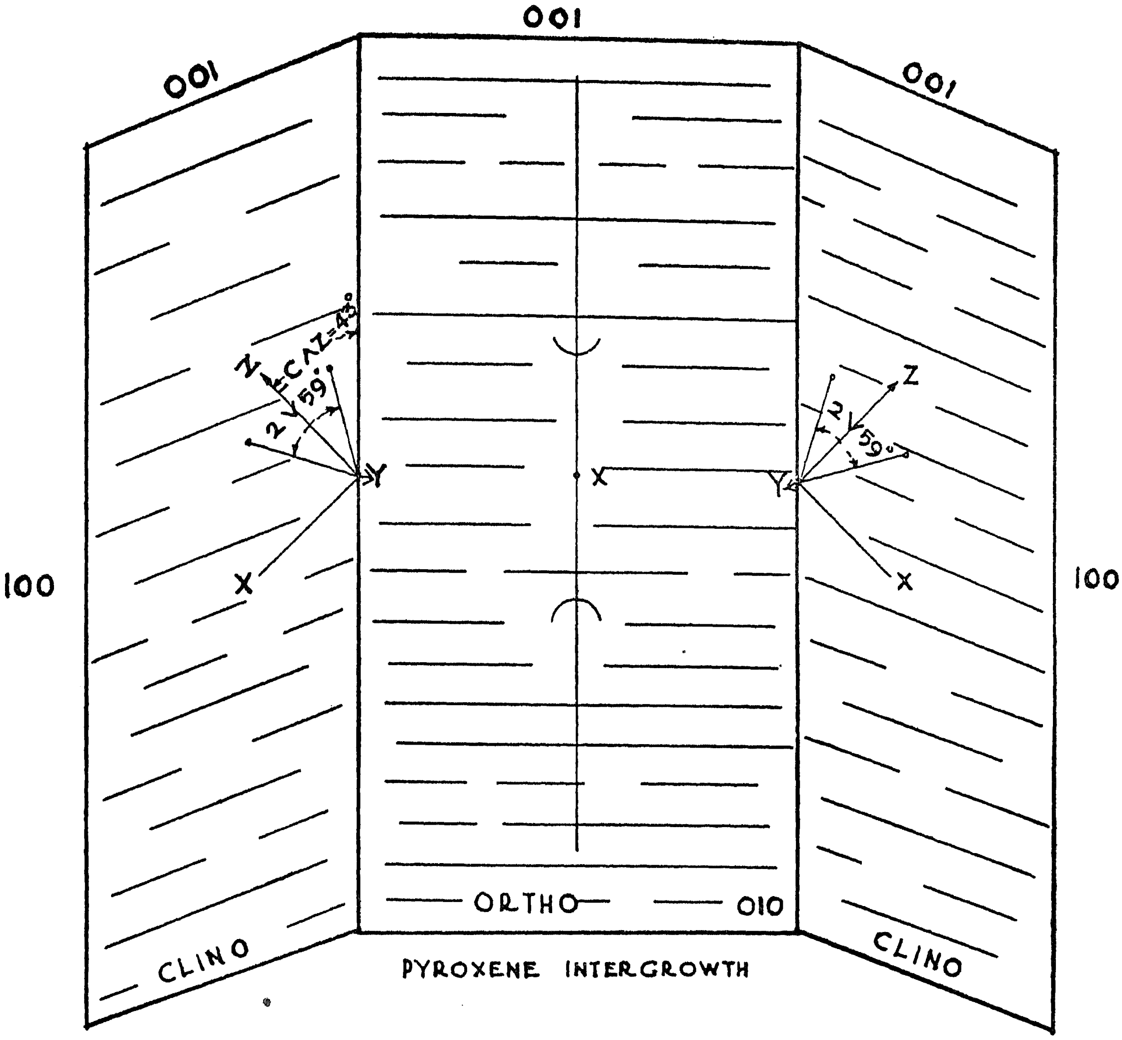

FIG. 2

The orthopyroxene crystallographic orientation is after Hess (1940); (100) is the junction plane of the two minerals; the X of hypersthene and Y of salite coincide; (001) salite lamellæ, make an angle of 20 degrees with (001) of the orthopyroxene.

Some hypersthene grains give inclined extinction up to 20 degrees. Hess (1938) explains this, as due to a composite effect brought about by the lamellæ dipping at low angles to the plane of the section. Under crossed nicols such sections simulate polysynthetic twinning. Sections parallel to (100) of the hypersthene reveal the sharp lamellæ of salite in the extinction position of the orthopyroxene. Occasionally the herring-bone structure (Micro-photo 2) associated with clinopyroxene is also observed in combination with lamellar structure. Inclusions of plagioclase are common in the lamellar intergrowths.

Hypersthene is also observed as a reaction mineral at the junction of ore and salite (Micro-photo 3). The rhombic pyroxene completely surrounds the ore and merges insensibly into salite. This is feebly pleochroic and has $2V_x = 65°$.

Garnet.—The mineral is mostly anhedral, embayed by plagioclase giving rise to irregular dented outlines. Euhedral crystals indicating a centrifugal growth are also present.

Refractive index	.. ..	1·794
Specific gravity	.. ..	4·06
Composition	.. ..	Grossularite 33%
		Almandite 67%

The mineral shows vermicular inclusions of quartz, plagioclase and relicts of pyroxene intergrowths (Micro-photo 4).

Garnet is developed fringing (1) iron ores (Micro-photo 5), (2) salite and (3) intergrowths of hypersthene and salites when these are at contacts with plagioclase (Micro-photo 6). The reaction equations are given in pages 739–40.

Hornblende.—The mineral is sparingly present.

Quartz.—This also occurs in minor quantities mostly as released mineral.

Texture.—The texture is granulitic; the crystalloblastic fabric, the bent and wedge-shaped twinning lamellæ, the undulose extinction, the veins of salite cutting across the intergrowths are evidences of recrystallization in a solid environment.

The chemical analysis of a representative specimen is recorded in Table I with some geochemical data.

Hornblende-norite.—The micro-characters of the important constituents plagioclase, hypersthene and diopside are in all respects similar to those already described.

TABLE I

Garnetiferous-diopside-granulite, Cheri Hill, Pallavaram

Constituents	Weight percentages	Niggli values	Basis molecules	Katanorm	CIPW norm.
SiO_2 ..	47·66	..	..	..	..
Al_2O_3 ..	19·51	si −107·40	Kp − 0·9	Q− 0·54	Q − 4·74
Fe_2O_3 ..	3·50	al − 25·86	Ne − 3·8	Or− 1·50	Or − 1·11
FeO ..	9·36	fm− 37·95	Cal −30·5	Ab− 6·33	Ab − 5·76
MnO ..	..	c − 34·35	Cs − 6·5	An−54·16	An −49·48
MgO ..	4·30	alk − 1·84	Fs − 3·8	Wo− 7·47	Di { Wo− 8·82, En − 4·00, Fs − 4·75
CaO ..	14·18	ti − 1·49	Fa −11·1	En−12·13	
Na_2O ..	0·66	k − 0·19	Fo − 9·1	Hy−12·27	Hy { En − 6·80
K_2O ..	0·25	mg− 0·38	Ru − 0·6	Tn− 1·80	Fs − 8·05
TiO_2 ..	0·87	..	Q −33·7	Mt− 3·80	Mt − 5·10
P_2O_5 ..	..	..	..	..	Il − 1·67
H_2O ..	+0·16	..	..	..	Water − 0·16
	100·45			100·00	100·44

Analysis : Department of Geology, Presidency College, Madras.

Hornblende is greenish brown and is present in appreciable quantities. Its characters are:—

$Z > Y > X$

nx ..	..	..	1·672
ny ..	..	..	1·679
nz ..	..	..	1·693
$2V_x$ ..	..	..	72°
$C \wedge Z$	..	..	− 12°

Biotite is observed and calcite is of rare occurrence.

Washington's (1916) analyses of the rock is reproduced with geochemical data in Table II.

Biotite-norite.—Plagioclase is of the andesine variety; the rhombic pyroxene is enstatite; diopside is practically colourless. Biotite is formed secondarily along the cleavage cracks and sometimes shoots itself into the cleavages of felspars (Micro-photo 7). The mineral is deeply pleochroic from brown to colourless and contains numerous pleochroic haloes. Hornblende is observed only in small quantities. Apatite and iron ores are fairly common. The chemical analysis and the calculated data are given in Table III.

TABLE II

Hornblende-Norite, St. Thomas Mount, Madras

Constituents	Weight percentages	Niggli values	Basis molecules	Katanorm	CIPW norm
SiO_2 ..	50·04	si – 118·00	Kp – 3·43	Or – 5·72	Or – 5·00
Al_2O_3 ..	11·65	al – 16·27	Ne – 17·23	Ab – 28·72	Ab – 26·20
Fe_2O_3 ..	2·63	fm – 55·30	Cal – 9·49	An – 15·81	An – 15·29
FeO ..	15·76	c – 19·95	Cs – 7·40	Wo – 7·10	Di { Wo – 9·40
					Di { En – 3·54
MnO ..	..	alk – 8·48	Fs – 2·83	En – 10·21	Di { Fs – 6·07
MgO ..	5·58	ti – 3·40	Fa – 18·72	Hy – 14·54	Hy { En – 7·74
CaO ..	7·89	k – 0·17	Fo – 12·13	Fo – 4·48	Hy { Fs – 13·20
Na_2O ..	3·08	mg – 0·36	Ru – 1·38	Fa – 6·40	Ol { Fo – 1·82
K_2O ..	0·89	..	Q – 27·33	Tn – 4·14	Ol { Fa – 3·36
TiO_2 ..	1·93	..	..	Mt – 2·83	Mt – 3·82
P_2O_5 ..	0·20	..	..	..	Il – 3·65
H_3O^+ ..	0·19	..	..	..	Ap – 0·50
	99·84		99·94	99·95	99·59

Analyst: Washington.

TABLE III

Biotite Norite, Pallavaram

Constituents	Weight percentages	Niggli values	Basis molecules	Katanorm	CIPW norm
SiO_2 ..	49·76	si – 128·10	Kp – 13·07	Or 21·78	Or – 20·90
Al_2O_3 ..	18·27	al – 27·67	Ne – 16·51	Ab 25·00	Ab – 21·36
Fe_2O_3 ..	2·68	fm – 37·71	Cal – 15·42	Ne 1·51	Ne – 2·18
FeO ..	9·35	c – 21·33	Cs – 4·73	An 25·70	An – 25·76
					Di { Wo – 5·29
MnO ..	..	alk – 13·30	Fs – 2·92	Wo – 6·30	Di { En – 2·03
					Di { Fs – 3·33
MgO ..	3·21	ti – 2·16	Fa – 11·18	Fa – 9·72	Ol { Fo – 4·20
CaO ..	7·73	k – 0·40	Fo – 6·88	Fo – 6·88	Ol { Fa – 7·65
					Mt – 3·87
Na_2O ..	3·02	mg – 0·30	Ru – 0·23	Ru – 0·23	Il – 1·98
K_2O ..	3·56	..	Q – 29·09	Mt – 2·92	Water – 1·19
H_2O+ ..	0·12	..	..	..	..
H_2O- ..	1·07	..	..	..	..
	99·77		100·03	100·04	99·74

Analysis : Department of Geology, Presidency College, Madras.

Garnet-hornblende-spinel-rock.—Plagioclase is $Ab_{35}An_{65}$. Garnet hornblende and spinel are the conspicuous minerals. Hornblende is formed along the cracks in garnets. The garnet contains inclusions of hornblende, spinel and plagioclase derived from the disintegration of the mineral (Microphoto 8). Hornblende has the following characters:—

$Z > Y > X$

X	Yellow
Y	Pale Yellow
Z	Brown
$2V_x$	71°

Biotite is clearly secondary after hornblende; pleochroic haloes are rare.

The chemical composition and the chemical values are given in Table IV.

TABLE IV

Garnet-hornblende-spinel rock, Cheri Hill

Constituents	Weight percentages	Niggli values	Basis molecules	Katanorm	CIPW norm
SiO_2 ..	40·84	si – 82·94	kp – 1·70	Or – 3·97	Or – 2·78
Al_2O_3 ..	27·21	al – 32·52	Ne – 7·00	Ab – 4·42	Ab – 5·40
Fe_2O_3 ..	2·16	fm – 37·64	Cal – 36·40	An – 60·66	An – 60·88
FeO ..	7·87	c – 26·67	Sp – 3·70	Ne – 4·15	Ne – 3·01
MnO ..	..	alk – 3·17	Fo – 12·40	Sp – 3·70	C – 2·24
MgO ..	6·83	ti – 0·97	Fa – 9·10	Fo – 12·40	Or {Fo – 11·97
CaO ..	12·25	k – 0·19	Fs – 2·40	Fa – 7·90	Or {Fa – 8·98
Na_2O ..	1·27	mg – 0·55	Ru – 0·40	Ru – 0·40	Mt – 3·25
K_2O ..	0·52	..	Q – 26·90	Mt – 2·40	Il – 1·22
TiO ..	0·60	..	..	..	..
H_2O^+ ..	0·97	..	..	..	..
H_2O ..	0·08	..	..	..	..
	100·60		100·00	100·00	99·73

Mode

Plagioclase ..	33·0
Garnet ..	35·0
Hornblende ..	28·0
Spinel ..	2·0
Quartz ..	1·0

Analysis : Department of Geology, Presidency College, Madras.

Norite.—Plagioclase ($Ab_{52}An_{48}$), hypersthene and diopside are present. But the intergrowth of the ortho and clinopyroxenes so distinguishing a feature of the latter is completely absent. Further garnet is also absent. Hornblende is of rare occurrence and quartz when present is a released mineral. The texture is granulitic.

The chemical analysis of norite with the chemical data is recorded in Table V.

TABLE V

Norite, Cheri Hill

Constituents	Weight percentages	Niggli values	Basis molecules	Katanorm	CIPW norm
SiO_2 ..	50·87	si – 122·36	Kp – 2·04	Q – 4·34	Q – 5·10
Al_2O_3 ..	18·88	al – 26·70	Ne – 9·19	Or – 3·40	Or – 2·78
Fe_2O_3 ..	2·83	fm – 42·86	Cal – 25·86	Ab – 15·32	Ab – 14·15
FeO ..	8·99	c – 25·68	Cs – 2·21	An – 43·10	An – 42·53
MnO ..	..	alk – 4·76	Fs – 3·06	Wo – 2·49	Di Wo – 3·02
					Di En – 1·50
MgO ..	5·43	ti – 1·15	Fa – 10·65	En – 15·44	Di Fs – 1·45
CaO ..	9·98	k – 0·18	Fo – 11·58	Hy – 12·16	Hy En – 12·10
Na_2O ..	1·72	mg – 0·46	Ru – 0·23	Tn – 0·69	Hy Fs – 12·14
K_2O ..	0·56	..	Q – 35·18	Mt – 3·06	Mt – 4·18
TiO_2 ..	0·36	..	..	..	Il – 0·61
H_2O ..	0·06	..	..	..	..
	99·68		100·00	100·00	99·56

Analysis : Department of Geology, Presidency College, Madras.

There are also types with plagioclase, garnet, diopside without hypersthene and with small quantities of brown hornblende, calcite, biotite and apatite.

A study of Niggli data shows that:—

(i) there is a close similarity in the Niggli values of the garnetiferous diopside-granulite and norite that they may be considered to have a genetic relationship;

(ii) that the hornblendic and biotite-norites have had possibly differences in original chemical composition;

(iii) that in these, the group of basis molecules are the same since $K + Na < Al$, and $K + Na + 2\,Ca > Al$; and

(iv) that the garnet-spinel-rock shows a clear difference in the bulk composition, as spinel is present in the katanorm.

METAMORPHIC FACIES

The equilibrium assemblages of the three associated phases with quartz as a fourth one are shown in Fig. 3. Hornblende and biotite are additional ones. The former makes its appearance in calcic-rich rocks while the latter in potash-rich rocks.

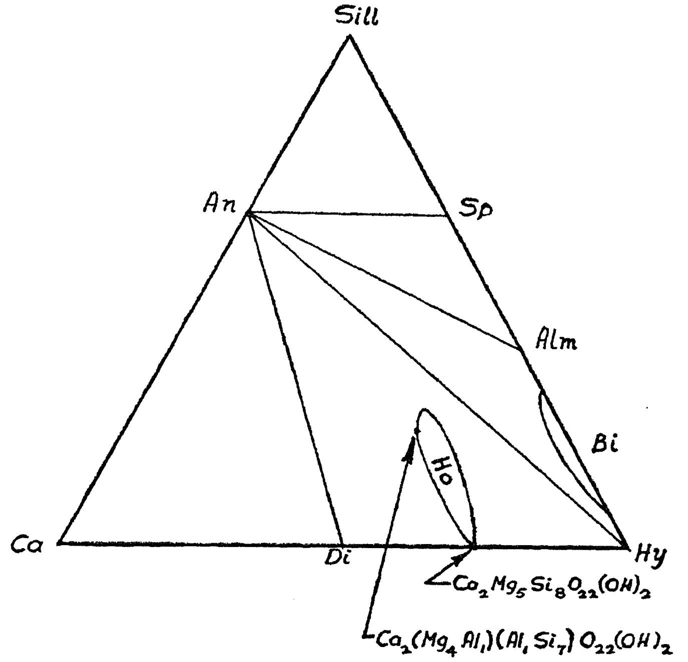

FIG. 3. ACF Diagram—on the basis of atoms Al, Ca and Mg

Rocks with the association

(*a*) diopside-plagioclase-hypersthene;

(*b*) almandite-plagioclase-hypersthene, conform to the usual paragenesis. Diopside and almandite do not occur together in stable equilibrium in the granulite facies. Such an association in the garnetiferous-diopside-granulite should be considered as a state of chemical dis-equilibrium. Exceptional occurrences of this kind have also been reported from Adelie Land (Stillwell, 1918), Uganda (Groves, 1935) and Sweden (Quensel, 1951).

The garnetiferous-diopside-granulite is a passage rock between these two facies, as revealed by its paragenesis-diopside, garnet, hypersthene and plagioclase.

The reactions may be indicated by the following equations:—

$$15\,[CaO\,(Mg, Fe)\,O \cdot 2\,SiO_2] + \begin{bmatrix} 6\,(CaO \cdot Al_2O_3 \cdot 2\,SiO_2) \\ 3\,(Na_2O \cdot Al_2O_3 \cdot 6\,SiO_2) \end{bmatrix} + 4\,Al_2O_3 \rightarrow$$

Diopside + Calcic plagioclase + Alumina →

$$\begin{bmatrix} 4\,(3\,CaO \cdot Al_2O_3 \cdot 3\,SiO_2) \\ 3\,(3Mg, Fe)O \cdot Al_2O_3 \cdot 3\,SiO_2 \end{bmatrix} + 6\,[(Mg, Fe)\,O \cdot SiO_2] + \begin{bmatrix} 3\,(CaO \cdot Al_2O_3 \cdot 2\,SiO_2) \\ 3\,(Na_2O \cdot Al_2O_3 \cdot 6\,SiO_2) \end{bmatrix}$$

Garnet + Hypersthene + Sub-calcic plagioclase

$$+\,6\,CaO \quad +\,9\,SiO_2$$

+ lime + quartz (1)

If the recrystallization process is not complete the paragenesis diopside, garnet, hypersthene and plagioclase would result.

The occurrence of hornblende in a water-deficient system such as the granulite facies is an interesting feature. The small quantities of hornblende in association with garnet and blebs of quartz is explained thus:

$7\,(Mg, Fe)\,SiO_3 + Ca_2Na\cdot Al_5Si_7O_{24} + H_2O \rightarrow$
Hypersthene + Plagioclase + Water
$Ca_2Na\,(Mg, Fe)_4Al_3Si_6O_{22}\,(OH)_2 + (Mg, Fe)_3Al_2Si_3O_{12} + 5\,SiO_2$
Hornblende + Garnet + Quartz (2)

Also,

$NaCaAl_3Si_5O_{16} + Ca\,(Mg, Fe)\,Si_2O_6 + 3\,(Mg, Fe)\,SiO_3 + H_2O \rightarrow$
Plagioclase + Diopside + Hypersthene + Water
$NaCa_2\,(Mg, Fe)_4Al_3Si_6O_{22}\,(OH)_2 + 4\,SiO_2$
Hornblende + Quartz (3)

In equations (2) and (3) water is a component in the reactions. In the practically anhydrous system such as the granulite facies " water itself constitutes an additional component permitting crystallization of an additional hydrous phase, namely hornblende, in appropriate mineral assemblages " (Turner, 1949).

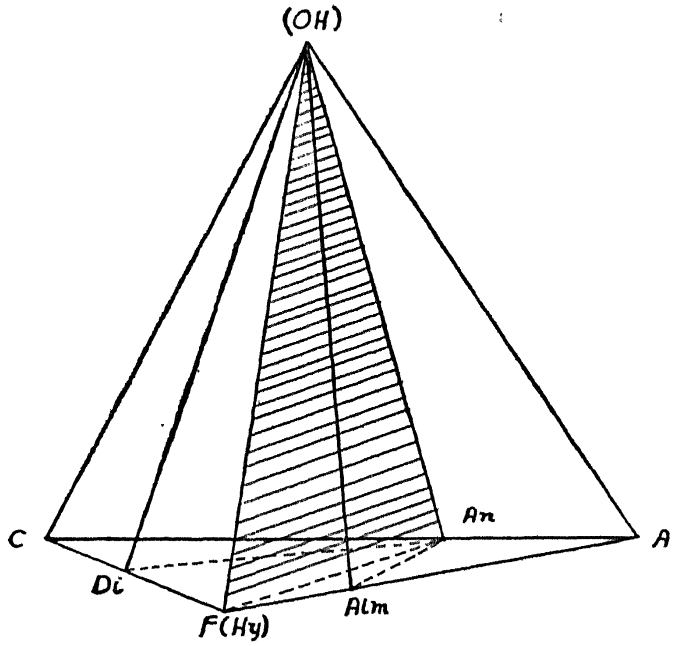

FIG. 4. Tetrahedral projection-ACF, with H_2O at the apex

In the tetrahedral projection (Fig. 4) using the ACF triangle as the base, and with water at the apex as the fourth component the following paragenesis are admissible:—

(*a*) Diopside-plagioclase-hypersthene-hornblende.

(*b*) Almandite-plagioclase-hypersthene-hornblende.

It is clear that almandite and diopside that are not stable together are separated by the "wall" hypersthene-plagioclase-hornblende. But due to chemical disequilibrium, as already said, diopside and garnet occur in the rock under description.

The presence of biotite may be explained in a similar way.

The synantectic formation of garnet at contacts of plagioclase with hypersthene or iron ore, the inclusion of released quartz in diopside, relict lamellar intergrowths of diopside-hypersthene in garnet, the anomalous double refraction of garnet in the intimately associated lime-rich granulite are evidences to show that there have been incipient adjustment of the rock-mass to conditions of slow cooling and release of load. The retrograde metamorphism, it may be inferred, has just reached a stage transitional between the typical granulite facies as exemplified by the norite and the almandine-diopside-hornblende subfacies of the amphibolite facies.

It is interesting as shown below that the scapolite-calc-granulite is also isofacial with the garnetiferous-diopside-granulite. Where the original rocks have been calcareous, plagioclase, pyroxene and calcite have been developed with quartz. The presence of calcite and quartz in the calc-granulite suggests that the prevailing pressures should have been high enough to permit the formation of calcite or dolomite and inhibit the formation of wollastonite. The rock cannot be classified under the granulite facies (plutonic metamorphism without stress) as sphene which is invariably absent in the granulite facies, is present in the rock. So it has to find a place high up in the amphibolite facies, namely the diopside-almandine-amphibole subfacies, which corresponds to the sillimanite zone of regional metamorphism.

A general retrograde metamorphic effect is inferred from the presence of the lamellar intergrowths of salite and hypersthene. These intergrowths do not seem to be contemporaneous; the two parts may be considered as exsolved products of a single phase on cooling. An alternative explanation also suggests itself. These intergrowths are combined occasionally with the herring-bone structure which is characteristic of clinopyroxene. The factors favourable for the solution of CaO in the clinopyroxenes are the availability of lime not only in the calcic plagioclase (Equation 1) but also in the closely associated bands of calc-granulite. Calcium has greater mobility under depth conditions and its solubility increases in the presence of CO_2. With fall of temperature and escape of CO_2 that follows the retrograde process, favourable conditions set in for CaO, which has a high velocity of diffusion, to get into the weak spots of the lime-free clinopyroxenic constituents and give rise to the diopsidic lamellæ; the hypersthene lamellæ are probably due to inversion.

It is also possible that the presence of fluorine and chlorine, as evidenced by the scapolitization of the plagioclases and occurrence of apatite, may disturb the bonding of the mineral phases and aid the intergrowth formations.

The two other basic rock-types hornblende-norite and hornblende-garnet-spinel-rock are also practically isofacial with the other types. They are unsaturated and the CIPW norm and Niggli katanorm do not show normative quartz. As under such conditions, hornblende can be stable in the granulite facies, the two rocks can be considered to belong to the granulite facies. Ramberg (1949) points out that hornblende can be present abundantly in the basic members of the charnockite series, provided there is an increase of anorthite in the plagioclase molecule. The reaction is given by equation

$7\,(Mg, Fe)\,SiO_3 + NaCa_2Al_5Si_7O_{24} \rightarrow$
Hypersthene + Plagioclase

$NaCa_2\,(Mg, Fe)_4Al_3Si_6O_{22}\,(OH)_2 + (M, Fe)_3Al_2Si_3O_{12} + 5\,SiO_2$
Hornblende + Garnet + Quartz (4)

The anorthitic content of 65 per cent. is sufficiently high to bring about such a displacement and the assemblage garnet, hornblende and spinel as shown below:—

$12\,(Mg, Fe)\,SiO_3 + 3\,NaCa_2Al_5Si_7O_{24} + 2\,H_2O \rightarrow$
Hypersthene + Plagioclase + Water

$2\,NaCa_2\,(Mg, Fe)_4Al_3Si_6O_{22}\,(OH)_2 + (Mg, Fe)_3Al_2Si_3O_{12} + (Mg, Fe)\,O \cdot Al_2O_3$
Hornblende + Garnet + Spinel

$+ NaCa_2Al_5Si_7O_{24} + 11\,SiO_2$
+ Plagioclase + Quartz (5)

The formation of biotite in the hornblende-norite and biotite-norite is dependent on the proportion of $K_2O/(Mg, Fe)\,O$ and Al_2O_3. The potash content in biotite-norite is 3·56 per cent., much higher than that in hornblende-norite which is 0·89 per cent.

Thus the rock-types show the paragenesis of the granulite facies with however a general tendency to approach the almandine-diopside-hornblende subfacies of the amphibolite facies.

The granulitic facies exemplifies the highest grade in regional metamorphism. The norite belongs to this grade. The other rock-types show a retrograde metamorphic character. It is not likely that the chemical composition of the premetasomatic complex was so uniform in character that all the types could have been derived entirely by diffusion from norite in a regional metamorphic environment.

However the microscopic and petrochemical evidences tend to indicate that the garnetiferous-diopside-granulite has been essentially derived by metasomatic diffusion in the said environment, the necessary heat for metamorphism being obviously obtained from the emanations that carry the material.

A quantitative idea of the extent of the diffusion effect has been rendered possible by Barth's Standard Cell Method. The underlying principles of this method are:

(1) That metasomatic replacement of rock takes place under isovolumetric conditions.

(2) In the majority of rocks 94 per cent. by volume is made up of oxygen and 6 per cent. by cations (silicon and metals).

(3) Since metasomatism takes place volume for volume, under the conditions that 94 per cent. of any rock is made of oxygen ions, it follows that the number of oxygen ions in all rocks is about the same.

(4) It would therefore be appropriate in metamorphic studies, where there are evidences of say, a rock *A* getting metasomatized to *B*, to determine the inflow and outflow of the stream of cations in terms of oxygen ion standard. Such a quantitative study with reference to a suite of isofacial rocks would give a clear picture of the fundamental aspects of the problem. It is obvious that one of the rock-types should be considered the mother rock, for purposes of tracing the descent of the other associated types.

(5) The constitution of most rocks is such that for 160 oxygen ions there are approximately 100 cations. Hence the number of cations linked up with 160 oxygen ions, gives directly the approximate percentage of the constituent cations. It would therefore be appropriate to take 160 oxygen

ions, *i.e.*, 320 valences as a morphological unit of a rock in determining the percentage of cations for that rock. This morphological unit is called the 'Standard Cell'. Its chemical content defines the chemical formula of the rock.

(6) Since 320 valences bind the cations, the number of valences must clearly balance in the exchange of cations in metasomatic diffusion.

Table VI gives the mode of calculation of the Standard Cell for the mother rock norite and its chemical formula.

TABLE VI

Cheri Hill-Norite

1	2	3	4	5	6	7	8
Constituents	Weight percentage	Molecular weight	Mol. prop. ×1,000	Cations prop. ×1,000	(5) × 100 / 1761·5 (5) × ·0567	Number of oxygen ions for 100 cations	No. of cations in the standard cell (6) × 160 / 161·545 (6) × ·99040
SiO_2 ..	50·87	60·06	847·0	847·000	48·024	96·048	47·563
Al_2O_3 ..	18·88	101·97	185·1	370·200	21·090	31·635	20·887
Fe_2O_3 ..	2·83	160·00	17·69	35·380	2·006	3·009	1·987
FeO ..	8·99	72·00	124·0	124·000	7·030	7·030	6·693
MgO ..	5·43	40·32	134·7	134·700	7·637	7·637	7·564
CaO ..	9·98	56·00	178·2	178·200	10·103	10·103	10·006
Na_2O ..	1·72	62·00	27·74	55·580	3·151	1·575	3·121
K_2O ..	0·56	94·00	5·958	11·916	0·699	0·349	0·692
TiO_2 ..	0·36	80·00	4·500	4·500	0·255	0·127	0·252
				1,761·476	99·995	157·513	99·035
H_2O ..	0·64	18·00	35·550	71·100	4·032	4·032	(3·993)
	100·26	..		..		161·545	

$K_{0\cdot09}Na_{3\cdot12}Ca_{10\cdot01}Mg_{7\cdot56}Fe_{8\cdot95}Al_{20\cdot89}Si_{47\cdot56}Ti_{0\cdot25}[O_{152}(OH)_8]_{160}$.

In a similar way the chemical formula of the garnetiferous-diopside-granulite is found to be:—

$$K_{0\cdot30}Na_{1\cdot32}Ca_{14\cdot69}Mg_{6\cdot18}Fe_{10\cdot02}Al_{22\cdot18}Ti_{0\cdot60}Si_{46\cdot00}[O_{158\cdot84}(OH)_{1\cdot16}]_{160}$$

The transfer of cations in the formation of garnetiferous diopside-granulite from norite is given in Table VII.

It would be reasonable to expect variations in the composition in the metasomatized rocks also due to the physical factors of cohesion, cleavage, lattice structure of the minerals. Further the energy of activation and the mobility of the activating medium may vary from place to place. This perhaps explains why the valences cannot be balanced to the exactitude demanded by theory, from the chemical data of average specimens.

TABLE VII

Norite passes into granetiferous-diopside-granulite by

Addition of cations	Valences	Removal of cations	Valences
Fe 1·07	7·03	K 0·39	0·39
Al 1·29	3·87	Na 1·80	1·80
Ca 4·68	9·36	Mg 1·38	2·76
Ti 0·35	1·40	Si 1·56	6·24
			H in (OH) 6·84
7·39	21·66	5·13	18·03

CONCLUSION

Stillwell (1911) after a critical examination of Holland's (1900) views considered that the characters form and structure, dykes and apophyses, as well as the chemical and mineralogical evidences can be explained on the basis of recrystallization under katazone conditions equivalent to the granulite facies. Fermor (1936) has considered the possibility of hypersthene of charnockites not being magmatic but as due to " a signature tune of common high grade metamorphism effected at unusual depths below the surface ". Ghosh (1941) has also shown that the breakdown of hypersthene into diopside and hornblende or to biotite is effected under the influence of alkaline fluids. B. Rama Rao (1945) considers that " the combined effects of a repeated series of alterations under different periods of metamorphism of a composite series of rock-formations of *different ages*, have given rise to a series of hypersthene-granulites of very variable composition ". He is a supporter, though with reserve of Vredenburg's (1918) view that the charnockites represent a series of the igneous members of the Dharwars.

This type area near Madras—a classic ground for the study of charnockites, affords enough data for the metamorphic origin of the suite of rocks. The norites of the area might have resulted from calc-alkaline-shale in the deep-seated folds of a precambrian orogenic phase, where depth and temperature combined to expel the water—a feature of the granulite facies.

SUMMARY

The Cheri Hill in the Madras type area of charnockites, shows on careful mapping the folding of bands of leptynite and basic charnockites. The mineralogy of the basic types gives striking evidences of the metamorphic origin of charnockites. The rocks have been subjected to some little retro-

grade metamorphism and are ascribed to the almandine-diopside-hornblende subfacies of the amphibolite facies. A quantitative idea of the influx and efflux of ions is worked out on the lines of Barth, in the process of replacement of the norite to the associated garnetiferous-diopside-granulite.

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EXPLANATION OF MICRO-PHOTOGRAPHS

1. Salite veins (Di) cutting across the hypersthene-salite intergrowth (IG).
2. Herring-bone structure of intergrowth (IG); Quartz (Q); Salite (Sa).
3. Hypersthene (Hy.) rim round ore; Salite (Sa).
4. Relicts of intergrowth (IG) and salite (Sa) in garnet.
5. Garnet (Ga) round ore; Plagioclase (Pl); Salite (Sa) and Quartz (Q).
6. Garnet (Ga) at contact of intergrowth (IG) and Plagioclase (Pl).
7. Biotite (Bi) shooting into plagioclase (Pl).
8. Amphibolization of garnet. Garnet (Ga); Hornblende (Ho); Spinel (Sp); Plagioclase (Pl).

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