A. INTRODUCTION

Holland (1900) used the term "Charnockite" for hypersthene bearing quartzofeldspathic rock. He meant by the charnockite series a common name for the eocamagmatic series of hypersthene bearing igneous rocks which form well defined petrographic province and show intrusive relation to the associated older schists and gneisses. In petrographic descriptions the nomenclature is mainly on the quantitative mineralogy and texture. Holland further observed that "there are some features which are sufficiently unusual in normal igneous rocks". The charnockites are commonly associated with norites and anorthosites and are restricted mainly to pre cambrian terrains. Their mineralogy indicates that they are originated in a deep seated 'dry' environment of granulite facies. They often show deformation and recrystallization phenomena. Their origin whether magmatic or metamorphic is debated. With reference to their peculiar characters and mineralogy of this suite of rocks they were called by several special names in various places and especially the Norwegian petrographers introduced several new names e.g. birkramite, mangerite, opdalite and acondolite.

Pichamuthu (1969) opines that in a polymetamorphic assemblage it is impossible to differentiate the individual rock series, suites and sequences and he is very much against
in using the terms like 'acid', 'basic' and 'ultrabasic'. He proposes felsic, intermediate, mafic and ultramafic with subdivisions in each depending upon the variation in mineral assemblage in each of them.

**Nomenclature of plutonic rocks**

At the I.G.C. meeting at Montreal (1972) the I.U.G.S. subcommission agreed upon the recommendations on plutonic rocks. The main points of agreements as given by Streckeisen are as follows. Plutonic rocks are classified and named according to the modal mineral assemblage (Vol.4). The following mineral groups are taken into account for the nomenclature, quartz (Q), alkali feldspar (A), plagioclase (P), feldspathoids (F), and mafic minerals including accessories (M). Rocks with M less than 90 are named according to their positions in the Q-A-F double triangular diagram, the light coloured constituents being calculated to the sum of 100.

The I.U.G.S. agreed that the Q-A-F diagram is also used for classifying charnockitic rocks, but divergent views came about the limitations of the fields in the triangle. Streckeisen (1973) summarised the views regarding the number of fields and their limits. In order to reduce the number of fields it was considered either to limit at \( \theta = 5 \) or \( \theta = 20 \) could be eliminated or a single limit should be drawn at \( \theta = 10 \), and the working group decided to retain the
subdivisions of the general scheme (Fig. 3) also for charnockitic rocks.

Perthitic feldspars

Many perthitic feldspars are transitional in composition between alkali-feldspar and plagioclase. Therefore their classification either to A or P was discussed. Johannsen (1957) suggested to include microperthite under A and antiperthite under P. The problem was complicated by the discovery of Na-K feldspars that consist of stringers of K-feldspars and plagioclase phases of nearly equal size and in nearly equal amounts. Michot (1961) used the term mesoperthite, consequently including mesoperthite entirely to A or to P and that would not convey an accurate picture of the real situation.

For treating perthitic feldspars the working group considered two possibilities. (i) For reasons of simplicity perthites and mesoperthites could be grouped under A and antiperthites under P (It is questionable for mesoperthite). (ii) All perthitic fields could be distributed over A and P according to their actual content of potash feldspar and plagioclase phases as determined by optical studies or diffractometry. As such determinations are now possible and the working group decided by majority for solution (ii) which was favoured by all those especially concerned with
charnockitic rocks.

Mesoperthitic rocks

Rocks that contain mesoperthite constitute the mangerite facies of P. Michot (1964). Belgian school suggested to designate corresponding rocks by prefix the term mangerite as follows:

Mangerite: It is intermediate between diorite and monzonite, which contains mesoperthite as the only feldspar.

Mangerocyanite: Which contains mesoperthite besides potash feldspar as the abundant mineral and hypersthene without quartz.

Mangeronorite: Which contains mesoperthite besides plagioclase and hypersthene.

Mangeromonzonite: Which contain mesoperthite besides potash and plagioclase feldspars, in equal amounts with little quartz.

Mangorocharnockite: Which contains mesoperthite and about more than 20% quartz, in addition to hypersthene.

Except mangerite the rest are not recommended by working group, because they erroneously would suggest rocks intermediate between mangerite and the fields to which
FIG. 3: Q A P DIAGRAM FOR NOMENCLATURE OF CHARNOCKITES
Mangerite is attached. Tobi (1971) proposed mesoperthite in place of mangerite and the prefix M on the places of mangerite, as for example mesoperthite charnockite or M-charnockite and hyperthene M-syenite etc.

Nomenclature of charnockitic rocks

For naming charnockitic rocks the working group considered two possibilities

(a) Names of general system could be used by adding the qualifier hyperthene e.g. hyperthene-granite for field 3, hyperthene tonalite for field 5, hyperthene-monzonite for field 8 etc.

(b) Special names could be applied as are in current usage e.g. charnockite, enderbite mangerite.

DeWaard (1969) has defined charnockite, "as a plutonic rock magmatic or metamorphic which has the composition of a granite and contains hyperthene". The fields noted as 6° to 10° are with prefix quartz e.g. for 7° it is hyperthene-quartz-syenite and for 10° quartz-norite etc.

Special names have been discussed by the W.G. and has recommended to abandon the following as they are ambiguous.

1. Birkramite of Koldurup, as it reveals mesoperthite
and it is K-charnockite (Field 3).

2. Farsundite used for hyperthene adammellite.

3. Ankeranendite.

4. Jotun norite is similar to hyperthene monzodiorite or monzonite. Other names like Arendalite, Bugite, Kata bugite, sabarovite etc. should not be used.

To designate the textural features the terms such as gneiss, granulite, granofels etc. may be used in relation to corresponding rocks, e.g. charnockitic gneiss or gneissose charnockite and charnockitic granulite (or granulitic charnockite) etc.

Sakola (1939) has proposed the term granulite facies to a group of metamorphic rocks recrystallised under high P-T conditions. Now it has become common to call all the rocks of this facies by the term granulite; but all the rocks of this facies do not have a granulitic texture. An ad hoc group of petrologists discussed for a definition and characterisation of granulites and opined as follows “Granulite is a fine to medium grained metamorphic rock composed essentially of feldspar with or without quartz. Ferromagnesian minerals are predominantly anhydrous. The texture is mainly granoblastic with gneissose to massive structure. The composition of the minerals correspond to granulite facies conditions."
The grain size is $<3 \text{ mm}$, otherwise the rock should be called as granofels. The granulites rich in ferromagnesian minerals (30% by volume) should be termed pyriclasite, pyribolite or pyrigarnitite depending on their composition.

Winkler and Sen (1973) have put forth another system of nomenclature on the basis of the following:

1. A rock should be named on its own merit and not through association with other rocks.

2. Mineral assemblage with textural and structural term is used for the nomenclature.

3. Instead of redefining an old name and in order to minimise confusion the term granulite can be used with further details as A or AB granulite etc.

In this thesis the author has used the term charnockite, a metamorphic rock formed under granulite facies conditions and instead of charnockite series the term "charnockites" is used for whole assemblage. Charnockite sensu stricto or birkramite occurrence is not seen in present area and the acid type is represented by the enderbite variety.

Field occurrence

The charnockites of Sivasamudram-Malvalli area range
in composition from acid to ultrabasic types. The characteristic minerals besides rhombic pyroxene are diopside, hornblende, plagioclase, quartz and biotite. The acid intermediate variety resembles the associated biotite gneiss in so much that it becomes impossible to demarcate the two in the field. The distribution of charnockites of mappable size is shown in the geological sketch map of the area (Map No.1). They are well developed in the south eastern part of the area. The endorbitic and intermediate type is widespread accounting for about 75% of the total area occupied by the charnockites. The basic and intermediate and ultrabasic types comprise the rest. The ultrabasic variety occupies the negligible area in the northern portion of the area 1.5 km east of Nariteswaranahalli and it is seen as small leucocratic inclusions in acid charnockite near Gramdevathipura. The ultrabasic type is not represented in the geological sketch map as these are not of mappable size. The basic and the ultrabasic varieties bear the same relation as the acid intermediate type.

The association of basic charnockite with the pyroxene-quartz-magnetite rock is noticed all along the C-V flanks of the hill south west of Sivasamudram. The basic charnockites occur as patches, lenses, ribbons and pods in the acid-intermediate types and also in the gneisses with sharp contacts. At some places hornblende gneiss appears to be similar to the acid intermediate charnockite and the basic
and ultrabasic types resemble the amphibolite and hornblende. Structurally, texturally and mineralogically the intermediate charnockite resembles the enderbit and these two occur in close contact with each other in the field. At many places it is difficult to demarcate these two on the geological map. Therefore a common symbol is used for these rocks on the geological map. The prominent exposures of acid-intermediate type are seen in Head work hill near Malagahalli, Gramadwathipura, Dhanagur and around Sivagamudram. They also occur as inclusions and lenses in the associated gneisses in the southern portion of the area. Most of the acid and intermediate charnockites of the area show distinct banding. The banding is due to the variation in the grain size, colour and relative proportion of the constituent minerals in alternate layers. Individual bands are usually less than a few millimeters and not traceable for considerable distances. Generally the light bands are more wider containing large amounts of feldspar and quartz while the dark bands consist of ferromagnesian minerals. The contacts between these bands are often gradational.

Charnockite-gneiss- metamorphism relation

The acid and intermediate charnockites grade with hornblende gneiss imperceptibly. The degree of foliation increases from former to later. Similarly high grade
metasediments of various kinds occur in intimate association with charnockites. The meta-siliceous sediments (quartzites) often containing sillimanite occur in contact with charnockites without any interaction. Similarly ferruginous metasediments with ferrohypersthene-sulite, hasdernbergite, garnet, magnetite and quartz occur in close association with the charnockites. The trend is almost same for both but they are never observed to merge with each other and they bear sharp contacts. The intimate association, similarity in structure and texture and of minerals formed under similar metamorphic condition suggest that the metasediments and the charnockites had the same metamorphic history.

B. PETROGRAPHY

The charnockites of Valvalli-Divasamudram area are divided into four groups - acid, intermediate, basic and ultrabasic, depending on mainly the petrographic characters. The division, however is arbitrary and the individual group is not sharply demarcated. Further while describing the assemblages some common igneous rock names (e.g. norite and diorite) are used without giving any significance to the igneous origin for these rocks. Those names denote only the conventional mineral assemblages in petrographic descriptions.

Detailed petrographic investigation of charnockites of Divasamudram area has been made by Mahabaleswar and
Sadashivaiah (1976). Most of the recent investigators agree that charnockites as they are found at present are high grade metamorphic rocks formed under granulite facies conditions. The detailed petrographic studies in terrains such as the Adirondack Highlands and the type area for charnockites (Madras) show that the hornblende-pyroxene granulites are the most common assemblages (De Waard 1967; Sen and Ray 1971). Many petrographers believe that hornblende is a retrograde phase in basic granulites. In Sivasamudran area also the charnockites are invariably containing a notable amount of hornblende in all the types (acidic to basic). In the present collection of about 150 samples of charnockites of this area the acid intermediate members predominate over the other types and the ultrabasic one is the least developed.

**Acid and acid intermediate charnockites**

Both the acid and acid intermediate charnockites are light to dark coloured medium to coarse grained and massive to gneissose rocks. The gneissose varieties show distinct foliation and banding is conspicuous, the individual bands being made up of acidic hypersthene and hornblende granulite (dark) and leptynite (light). The banding is occasionally due to the alternate arrangement of felsic and mafic segregations. The acid variety is mainly represented by enderbites and the enderbites vary considerably in their
Megaloscopic characters, some exhibiting dark greasy grey colour containing blue quartz and brownish feldspar and others with light greasy grey colour containing greyish yellow feldspar and quartz. These are a few which look like hornblendes and biotite gneisses containing whitish feldspars and colourless quartz. The intermediate charnockites have usually all the minerals characteristic of the endorhitic variety as well as the dioritic variety of basic charnockite.

In thin sections the rocks exhibit monomorphic granular texture and the ferromagnesian minerals occur in groups. Both the types constitute chiefly plagioclase (anorthitic), quartz, hypersthene, hornblende, biotite, magnetite, ilmenite and apatite. Potash feldspar occurs in subordinate amounts. Some sections of acid charnockite contain subordinate amount of garnets. Following are the typical assemblages of the acid and acid intermediate charnockites of the area.

1. Quartz-plagioclase-hypersthene
2. Quartz-plagioclase-hornblende-hypersthene
3. Quartz-plagioclase-hornblende-hypersthene-diopside
4. Quartz-plagioclase-hornblende-hypersthene-biotite
5. Quartz-plagioclase-hypersthene-diopside.

Usually the individual assemblages mentioned above
occur side by side and grade into one another. Many thin sections exhibit evidences of strain, like undulose extinction, peripheral granulation of quartz and feldspar, banding of prisms of pyroxenes and twin lamellae of plagioclase. In some rocks where cataclasism has advanced, porphyroclasts of feldspar are seen in the pulverised matrix made up of crushed quartz, feldspar and biotite (altering). Thin fracture 'planes' traversing through all the minerals of the section have also been observed.

**Basic charnockites**

The basic charnockites occur as bands, lenses, ribbons, clots and irregular inclusions in the acid intermediate type and also as large out crops in the associated gneisses and metasedimentary rocks. These are dark green to black, medium to coarse grained granular rocks. The foliation is defined by dimensional parallelism of ferromagnesian minerals. On the weathered surface of the rock a crude banding is observed.

Under the microscope the rock is fresh and exhibits xenomorphic granular texture. The conspicuous banding is clear in thin section and the orientation of the hornblende as elongated clusters in alternate layers is responsible for the banding. Depending on the mineralogy and the anorthite content of the plagioclase, the basic charnockites have been divided into two main classes one as noritic and the other
as dioritic type.

The norite variety mainly consists of brown green pleochroic hornblende, pale green diopside, purple coloured hypersthene and plagioclase (An 54-59%). Magnetite and apatite are the common accessories. The dioritic type has the following assemblages.

1) Diopside-hypersthene-diorite
2) Hornblende-diopside-hypersthene-diorite.

The anorthite content of the plagioclase of these two assemblages range in composition from 30 to 45% An. The hypersthene is pale pink and is weakly pleochroic. It occurs as discrete grains and patches. At places diopside forms inclusions in hypersthene and vice-versa. Dark brown hornblende occurs as big plates and prisms some times as edgings to pyroxenes. Quartz is seen occupying the interstices of plagioclase and hornblende or exhibits undulose extinction and some times Schmidt lamellae. Magnetite and ilmenite occur as granules bordering the hornblende. Acicular apatite is seen within the plagioclase.

The noritic and dioritic types occur side by side as separate bands.
Ultrabasic charnockites

It is quite restricted in occurrence and found at only one place occurring as inclusions in the basic charnockites around Gramadevathipura. It is black in colour, medium-grained and schistose with a Sp. Gr. of 3.00.

In this section it exhibits signs of crushing granulation and recrystallization. The main mineral assemblage is hypersthene, brown hornblende, diopside, and plagioclase in minor amounts. Hypersthene is feebly pleochroic, shows schiller inclusions and is surrounded by granular aggregates of diopside and hornblende. Hornblende forms the granular aggregates and also replacing pyroxenes. It is the most abundant mineral in this variety of charnockite. Diopside and plagioclase constitute about 20% mode. The plagioclase is lesser than diopside in its abundance, with an anorthite content ranging from 40-45%. Magnetite and ilmenite occur as thin rim all along the contact of hypersthene and hornblende.

Salient petrographic features of charnockites

1. The charnockites of Salvalli-Givasamudram range in composition from acid to ultrabasic.

2. Due to the invariable presence of hornblende and schistose nature, the basic charnockites of the
area resemble the amphibolites, while the ultrabasic resemble hornblendites.

3. Banding is more conspicuous in the acid intermediate type than in the basic and ultrabasic type.

4. All exhibit xenomorphic granular texture. The grains are invariably elongated parallel to the banding and foliation of the rock.

5. Hornblende is invariably present in all the members.

6. The minerals are frequently sieved and each mineral occurs as an inclusion in the other mineral.

7. There is a replacement relationship between the potash feldspar and plagioclase and between feldspars and quartz.

8. All the members exhibit the evidences of strain like undulose extinction (shown by quartz and feldspar), peripheral granulation, fracturing and bonding of twin lamellae and cleavages and formation of thin fracture planes throughout the rock.

9. The greasy grey or pale brownish colour of acid-intermediate charnockite is mainly due to the colour of feldspar but quartz does not show blue colour. It is mainly pale yellow or grey in colour.
10. The acid-intermediate members are generally more coarser in grain size than the basic and the ultrabasic members.

C. PETROCHEMISTRY

In terms of major elemental chemistry the charnockites resemble the calc-alkali series of plutonic rocks. The "charnockite suite" as defined by Subramanian (1959), comprises petrographic types corresponding to granite, tonalite, syenite and alaskite. In Melvalli-Sivassamudram area the granodioritic and enderbitic varieties of charnockites are common and the other varieties like syenitic and monzonitic are rare. In some respects these enderbites differ from those of Pallavaram e.g. these are having lesser modal proportion of potash feldspar which is reflected in the $K_2O$ content in the analyses. The close chemical similarity between the associated gneisses and the charnockites at Satnur (N.E. of this area) led Pichamuthu (1965) to conclude isochronous transformation of gneiss to charnockite. Mahabaleswar (1970) has shown that the petrochemistry of Sivassamudram charnockites (Major element) is comparable with Madras, Langoy and Satnur-Holagur charnockites.

In the present investigation, seventeen samples of...
Charnockites from Malvalli-Sivasamudran area have been analyzed for major and selected elements, of which ten basic five acid and two are intermediate charnockites. It is pertinent to note that the quality of the earlier analyses were not satisfactory because of imperfections in the determination methods (e.g., alkalies). The chemical analyses are presented in Table III, together with the calculated C.I.O. norm and Niggli values. To know the distinctive chemical features of the basic charnockites and the chemical variations within them triangular plots employing the important Niggli values and ratios have been presented in Figs. 4, 5, 6A and 6B.

Walker et al. (1960) have shown that the fields of para- and ortho-amphibolites can be separated in A-C-P and CaO-MgO-FesO diagrams. The charnockites of Malvalli-Sivasamudran have been plotted in such diagram (Fig. 7 and 8). These fall within the fields delineated for basic igneous rocks. According to Heier (1962), these graphical methods are not satisfactory as metasomatic alterations can affect the plot significantly. The average chemical composition of Sivasamudran charnockites and the type area charnockites is as follows.
From the above data it is clear that the charnockites of Melvalli-Sivasamudram are having more $\text{Al}_2\text{O}_3$ and total iron, but lesser $\text{TiO}_2$, $\text{MgO}$, $\text{Na}_2\text{O}$ and $\text{K}_2\text{O}$ than the corresponding varieties of Madras area. In acid charnockites of present area $\text{Na}_2\text{O}$ contents are generally higher than the $\text{K}_2\text{O}$ contents. The $\text{CaO}$ content of acid charnockites is also higher than the type area acid charnockites. It is also to be noted that the analytical comparison of charnockites of different areas will not help much unless accurate trace element data is available.
A comparison of the normative values of the charnockites of Sivasamudram will reveal following characteristic features.

a) Quartz appears in all but one sample of charnockites (basic). It ranges from 1 to 6% in basic and upto 40% in acidic types. But the basic charnockites do not exhibit any modal quartz. This is due to the abundance of hornblende which is reflected in the enrichment of normative hypersthene and quartz. Except this and the appearance of normative corundum for a few samples, the C.I.P.W. norms and the modes have correlative values. The Niggli K-mg plots of these charnockites though indicate calc-alkaline suite some samples of enderbites fall outside the field (Fig. 4) because of their lower values of mg. Therefore it is evident that these rocks can not be linked with an ideal magmatic differentiation process. Similarly the plots of Niggli Mg-C diagram of Leake (1969) exhibits a wide scatter giving no clue as to the original nature of these rocks (Fig. 5).

The chemical analyses of $\text{SiO}_2 - \text{Al}_2\text{O}_3 - \text{Fe}_2\text{O}_3 + \text{TiO}_2 + \text{CaO}$ when plotted in a triangular diagram devised by De la Roche (quoted in Holland and Lambert 1975) these charnockites cluster around the field of diorite and granite (Fig. No. 9).

The comparison of Niggli values and ratios will show
still greater diversity in these rocks. It is noteworthy that Niggli Mg values are not distinctive of any group, either basic or acidic.

In petrochemical characters, the basic charnockites are similar to the type area basic charnockites. They fall in salientic class and porfolic order of C.I.P.W. classification. In general the titania and soda contents are rather less in Solavasamudran rocks. To have a clear picture of the general behaviour of elements in charnockites it is worthwhile to discuss all the charnockite varieties together instead of discussing the petrochemistry of basic intermediate and acidic types separately. Therefore correlation coefficient values of some significant oxides of major elements like SiO₂, TiO₂, Fe₂O₃, FeO, MgO and MnO as well as a few trace elements like Co, Ni, Zn, Cu, Cr and Zr from different varieties (but most of them come from basic ones) are determined and given in Table V.

From the Table V it is clear, that SiO₂ has strong negative correlation with respect to Fe₂O₃, FeO and MgO and this is significant at 5% level, whereas TiO₂ and MnO also bear antipathetic relation with SiO₂ and they have lower negative values. Except Zr which has strong positive correlation, the other trace elements have strong negative correlation with respect to SiO₂. The oxides like TiO₂, Fe₂O₃,
FeO, MgO and MnO have again positive correlation values for each other and it is interesting to note that FeO has got +0.724 value of correlation coefficient with MgO which is uncommon if we consider their distribution only among the ferromagnesian minerals. This positive value indicates that these oxides when considered among the minerals donot have the same type of ratio or the other phases of FeO which donot contain magnesium, have bearing on the correlation coefficient values. During petrographic study of the thin sections the inclusions of ilmenite and magnetite were noticed more in basic charnockites and also this is reflected from 5 to 6: ilm + aqt in the C.I.P.M norm of basic charnockites.

TRACE ELEMENTS

Cobalt $^{2+}$ 0.84$^{\circ}$

Cobalt is generally enriched in basic igneous rocks. Goldschmidt assumed 40 ppm to be the crustal abundance of Co. In Sivasamudram charnockites, cobalt content is rather uniform and it is about 100 ppm, whereas cobalt is slightly enriched relative to Mg in acid charnockites of Madras (Howe 1955), the maximum value being 50 ppm Co. This is also found to be the case for the charnockites of southwest Finland (Farras 1958). This minor element follows Fe$^{2+}$ and Ni follows Mg. In the exogenic cycle both Co and
Ni are enriched in hydrolysates.

\[ \text{Ni}^{2+} \text{ 0.78 Å} \]

Nickel is camouflaged in the minerals containing Mg.

The average abundance of Ni in the crustal rocks is 100 ppm and it tends to be concentrated in the basic rocks. In the charnockites of Sivasamudram this is clearly seen as the basic rocks have upto 210 ppm Ni and the acid charnockites have as low as 63 ppm. These values are greater than the similar values given by Hoadie (1955) for charnockites of type area Madras.

\[ \text{Cr}^{3+} \text{ 0.64 Å} \]

Chromium occurs as independent constituent in early formed minerals of crystallization and also it replaces Fe\(^{3+}\) and Al\(^{3+}\) in silicate structures. In the area investigated, the distribution of Cr is regular. It is more in basic rocks, to about 140 ppm, whereas in acid charnockites it is as low as 17 ppm. Similar trend and values are noticed in the type area Madras (Hoadie 1955). But the charnockites of Tanjore (Heier 1960) show rather irregular distribution of Cr and generally they contain higher amount of Cr (Cr varying from 75 to 1030 ppm).
Copper \( \text{Cu}^{2+} (0.33 \text{Å}) \)

The copper content of Sivasamudram chernockites ranges between 21 ppm in acidic to 147 ppm in basic varieties, while the copper content of the acid igneous rocks is 15 ppm and basic ones being 149 ppm (Rankama 1950).

It is one of the mobile elements even during metamorphism but whether copper occurs as sulphides or replacing the major element in the silicate crystal lattice is not clearly understood. Haier (1960) opines that the low values of copper in Langoy rocks (amphibolite) are due to metamorphism where copper is driven off and the intermediate rocks are commonly higher in Cu content than the basic types.

Lead \( \text{Pb}^{2+} (1.33 \text{Å}) \)

The average concentration of lead in the ultrabasic to granitic rocks was found to be 3 to 20 ppm (Wedepohl 1956). It substitutes potassium in the potassium bearing minerals. Wedepohl has shown up to 27 ppm Pb in K-feldspars. In some pegmatites it is as high as 160 ppm. According to Goldschmidt Pb is captured and concentrated in the early formed potassium minerals (high temperature). Haier and Taylor (1959) show that Pb tends to be enriched in the most fractionated (low temperature) K-feldspars. This is due to covalent nature of Pb-O bonds, and they have opined that Pb content increases with increasing metamorphic grade i.e., with
increasing temperature.

In Sivasamudram charnockites the Pb content is rather uniform ranging from 30 to 40 ppm irrespective of silica content. Similar is the case with the type area rocks (Howie 1955) and Tengoy (Helor 1960), but the rocks of two areas have slightly lower values (about 25 ppm).

Zinc (Zn$^{2+}$ 0.83)

Zinc content in these charnockites is about 90 ppm and there is no regular variation in the different varieties. The pyroxenite rock has a maximum content of 171 ppm Zn. This sample also shows high Pb content (150 ppm).

Zirconium (Zr$^{4+}$ 0.87)

In igneous rocks, it is enriched in the late crystallizes as zircon. This trace element has a strong negative correlation with other trace elements, so far described here. In acidic varieties Zr content is from 100 to 150 ppm. In basic it ranges from 15 to 40 ppm. The type area (Kadras) charnockites show slightly higher values (Howie 1955). The higher content of zirconium could also be explained by assuming the granitic material to be igneous. In Sivasamudram charnockites the zirconium content has got a good correlation with the SiO$_2$ contents, having a significant positive correlation ($r = + 0.92$).
Discussion of the results

The values of concentration of trace elements in these rocks are within the limits known for such rocks. The purpose of correlating and determining the abundance of these elements was mainly to (a) investigate whether or not the element concentrations could be related to the origin of these rocks. (b) To investigate how variations in different variations are taking place; in other words the mobility and concentration of these trace elements with metamorphism or the physical and chemical changes. Igneous geochemistry is better understood than the metamorphic and the role of major elements is well known in petrogenesis but the trace element geochemistry gives confirmative tests and are more sensitive to the P.T.X. conditions, than the major elements. This also holds good in knowing the parentage of the charnockites, whether they have been formed from igneous or sedimentary source. Hence the trace elements in these two types should vary in nature and abundance.

When compared to the type area (Madras), the charnockites of Sivagangais contain greater abundance of cobalt, nickel, chromium, copper, lead and zinc. Zirconium content is slightly lesser in these rocks than the type area charnockites. In addition, they have strong correlation indicating that the mineral assemblages represented in these rocks have attained the chemical equilibrium.
D. MINERALOGY

The minerals charnockites of Malvalli-Givasamudram area are described here with emphasis on the mode of occurrence and paragenetic implications.

The microscopic study of the several thin sections of the charnockites was thoroughly carried out. For a few critical minerals the refractive indices by immersion method and optic axial angle and anorthite content and twin laws of plagioclases were determined on the four axes universal stage. The infrared spectra and X-ray powder pattern for several minerals (which have been chemically analysed) are described in order to interpret the structural and other characters. The detailed optical investigation data by Mahabaleswar and Sadashivaiah (1976) have been checked. As the chemical analyses of the minerals were not carried out by those investigators in detail, the present study is mainly intended to correlate the physical properties with the chemistry of the minerals.

The main mineral assemblage of the present study is quartz, plagioclase, clino- and ortho pyroxene, hornblende, potash feldspar, garnet, biotite and accessory minerals like magnetite, ilmenite, apatite and zircon. The individual minerals of the charnockites are described in the following account.
Quartz

Quartz is quite common in acid intermediate variety. It occurs as discrete grains, anhedral patches and sometimes as rounded inclusions in other minerals. In acid intermediate charnockites the colour of quartz is greasy grey to bluish but in banded types it is mostly colourless or pale grey. Undulose extinction is common in prismatic sections which consist of several optically oriented lamellar bodies, with their longest axis parallel to 'c' crystallographic axis. According to Holland (1900) the characteristic blue colour of quartz is due to small inclusions oriented to this crystallographic axis. Jayaraman (1930) concluded that the colour may not be due to visible inclusions but due to the amount of colloidal titanium. Hsueh (1955) also recognised the absence of relationship between the colour and inclusions and stated that the blue colour may be due to fine ultra microscopic material exsolved when the quartz was held at a moderately high temperature following its crystallization or during subsequent metamorphism.

Hollander (1964) considered that the blue colour of quartz is due to presence of titanium, supporting the views expressed by Jayaraman (op. cit.). Generally the quartz of the acid intermediate charnockites of the area is having dusty material evenly distributed throughout the grain and
the author of the thesis opines that the colour of quartz is due to these materials.

**Plagioclase**

This is the most common and abundant mineral occurring on laths of various sizes. It is dark grey to brownish yellow in acid intermediate types and pale grey to colourless in foliated varieties. Under the microscope it is colourless, fresh and unzoned. The anorthite content ranges from 25 to 55% An. The plagioclase in acid intermediate varieties commonly occurs as antiperthite with numerous oriented blobs of K-splints. The blobs are mostly of rod, bead and patchy type. The plagioclase with An. content varying from 25 to 38% An. is present in acid intermediate and dioritic varieties. Multiple twinning is also common. In the basic varieties the plagioclase with An. content ranging from 10 to 60% An. is common and generally twinned.

Tilley (1937) regarded the strong development of antiperthitic nature of plagioclase in oenobite as "Symptomatic of a high temperature consolidation of magma with low water content". Pararas (1958) considers the antiperthite as an exsolution phenomena, while Naidu (1963) describes a metasomatic and replacement origin. Generally the blobs in the antiperthitic plagioclase of the present samples exhibit the crystallographic orientation suggesting an exsolution
phenomena. The host plagioclase invariably shows undulose extinction and bent twin lamellae indicating that the deformation probably accompanied development of an antiperthitic character.

Twin laws of plagioclase feldspars have received great attention of many investigators. Some authors opine that the twinning is a diagnostic character in understanding the history of a rock whether igneous or metamorphic.

Gorei (1951), after statistical analysis of thousands of plagioclase twins of common igneous and metamorphic rocks, classified them into 'A' and 'C' types. He included that albite pericline, acline and other simple twins under 'A' and carlsbad, albite-carlsbad, albite-ala, manebach-ala and other complex twins under 'C'. He considered the later to be characteristic of rocks crystallised from a melt and former to the metamorphic and metasomatic rocks.

Turner (1951) points out that the carlsbad and albite-carlsbad laws of twinning of plagioclase are distinctive of igneous rocks. Naidu (1963) concluded that:

a) The carlsbad and albite-carlsbad laws are dominant in dolerites while albite and albite-ala are common in various rocks of different origin.

b) The incidence of carlsbad and albite-carlsbad laws
has no relation whatsoever to the anorthite content of the plagioclase.

c) The frequent incidence of carlsbad and albitecarlsbad laws in plagioclases of dolerites has no direct relationship to the igneous nature of the rocks in which they occur, but depends on its cooling history i.e. carlsbad and albitecarlsbad laws are common where rapid crystallization and relief of pressure. When there is slow crystallization under pressure, low temperature and dry conditions, there is a tendency for a crystal to grow in all directions and these two laws are inhibited in such crystal growth.

It is generally accepted, that in metamorphic rocks plagioclases are more commonly untwinned or twinned according to simple laws, while twinning according to carlsbad and albitecarlsbad law is absent.

The twin laws of plagioclase of the charnockites of Sivasamudram area are presented in Table VII. The twin laws noted are albitc, manebach-ala, albitc-ala, manebach and pericline, thereby suggesting the metamorphic nature of these rocks.
Calcic pyroxene

Calcic pyroxene is quite common ferromagnesian mineral in basic to intermediate charnockites. It is rare in acid varieties. It has similar shape and size as that of orthopyroxene. Exsolution lamellae parallel to (100) are common and they are slightly coarser than those in orthopyroxene. Oriented schiller inclusions are rare.

The optical characters of the calcic pyroxene are given in Table VIII. The $2V$ ranges from $50^\circ$ to $58^\circ$, $(Y - \alpha)$ from 0.024 to 0.029, $Z\alpha$ from $38^\circ$ to $44^\circ$ and $n_\beta$ varies from 1.69 to 1.70. The optical properties and the chemical analyses of the calcic pyroxenes show that they fall in the saite-augite compositions. The wollastonite/mol. varies from 34 to 44%, $En$ mol. from 27 to 37% and $Fe$ mol. from 19 to 30%. The $n_\beta$ refractive indices of the coexisting calcic pyroxene (determined by plotting Ca, Fe, Mg in Hess's diagram) when plotted against $n_\gamma$ of the orthopyroxene (Beer et al. 1963, Table IX and Fig. 21 A) a correlative picture is seen and these are compared with the similar plots of the type area charnockites (Madras) and Broken Hill (Binns 1962) where two isograds A and B are drawn through Broken Hill plots. It is seen that the plots of the pyroxenes of the charnockites of Sivasamudram as well as Madras lie between the isograds A and B of Binns (op cit).
Relation between ortho and calcic pyroxene has been discussed by many investigators. Chooh (1941), Sutton and Watson (1951) and Cooray (1962) have found the evidences of formation of hypersthene chiefly from diopside but in the charnockites of Nagarnoil, Jacob (1962) has observed exactly the opposite relation and some consider that the two pyroxenes are independent and constitute a happy combination of coexisting mineral phases. It is interesting to note that in basic granulites devoid of orthopyroxene, of the area, the calcic pyroxene is just the same as seen in the basic charnockite in all its characters.

**Orthopyroxene**

Orthopyroxene is the characteristic mineral in all the varieties of the charnockites of the area. In hand specimen it is brown to greenish brown in colour. The mineral is distinctly pleochroic with X = rose or bright pink, Y = pinkish yellow and Z = bluish green. The intensity is however variable. Quensel (1951) reports that the orthopyroxene of basic granulites is more strongly pleochroic than the orthopyroxene in the rocks of intermediate composition. Eskola (1952) stated that in the Lapland granulites the most strongly pleochroic orthopyroxene occurs in the more acid rock types. Kuno (1954) has suggested a possible relationship of pleochroism with the titanium content. Howie (1955) has contradicted this in
the type area charnockites and has attributed pleochroism to exsolution and oriented inclusions. Parras (1958) believes that the intensity of pleochroism is proportional to the abundance of exsolution lamellae. Mahabaleswar (1970) after careful study of the charnockites of Sivassamudram area concluded that the pleochroism of orthopyroxenes is not only related to the composition and also to exsolution lamellae. Therefore it is due to a combination of the above mentioned factors with which the author is in agreement. The compositional factors for pleochroism in orthopyroxene are namely:

a) Ordering of Fe$^{2+}$ ions in $M_2$ positions.
b) Entry of Al$^{3+}$ ions into $M_1$ positions.
c) Substitution of Si by Al in SiO$_4$ tetrahedra.
d) The concentration of Fe$^{2+}$ ion should be generally at least 15 mol. % Fe.

Therefore the crystal growth under granulite facies temperature and pressure fulfills these conditions.

Twinning

The orthopyroxenes possess thin hair like lamellae which are parallel to (100) and are prominent in sections perpendicular to the acute bisectrix. These lamellae are occasionally accompanied by simple twinning on (100). Hess and Phillips (1938) account these lamellae as due to the
intergrowth of monoclinic pyroxene with hypersthene. Henry (1941) suggests that they are due to gliding. Similar lamellae have been observed by Hovis (1953), Parras (1959) and others in the orthopyroxenes of charnockites. The refractive indices and the optic axial angles of the different lamellae are almost same in present samples and the author is of the opinion that it may be either due to translation gliding or twinning.

**Inclined extinction**

The inclined extinction by orthopyroxene of charnockites has been reported by Sen Gupta (1916), Washington (1916), Grooves (1938) Johansen (1957), Haïdu (1943) Ram Rao (1945), Ouessal (1951) and Parras (1958) and they have given a number of explanations.

Inclined extinction shown by orthopyroxene of charnockites was studied by Sadasivaiah (1943) and he concluded that the inclined extinctions are observed on domal and pyramidal sections, and not on pinacoidal and prismatic faces. This is also confirmed in the present study.

The optical properties of the orthopyroxenes of Sivasamudram area are given in Table VIII. These optical properties as well as the chemical analyses of the orthopyroxenes gave the composition ranging from an mol. 36% to 60% and
Fs mol. 46 to 60%. The X-ray powder data of orthopyroxene from Sivasamudram charnockite is given in Table X. The acid charnockite with Fe_{39.3} W_{0.45} gave the cell dimensions as $a = 13.22$, $b = 8.9$, $c = 5.2$ $\text{Å}$ with cell volume of $841.3$ $\text{Å}^3$.

A noteworthy feature of the orthopyroxenes of the Sivasamudram charnockites is their comparatively high alumina content (up to $3.2\% \text{Al}_2\text{O}_3$). Generally metamorphic orthopyroxenes have a greater spread of alumina contents. This depends mainly on the availability of Al during the formation of this pyroxene and secondly on the $P-T$ conditions of the formation. The nature of distribution of Al in tetrahedral and octahedral positions is discussed in detail while dealing with the chemistry of the minerals, later in Chapter IV.

**Hornblende**

Hornblende is one of the common constituents of Sivasamudram charnockites. It is more abundant in basic and intermediate varieties. In hand specimen it is dark green to black in colour with metallic lustre. Under microscope it exhibits brown, yellow and green pleochroic colours and it occurs as discrete grains and laths with well developed one or two sets of prismatic cleavages. Exsolution iron ore crystals (ilmenite) occur all along the contact between the hornblende and pyroxene. The bluish green hornblende is not common but it is found in acidic varieties of charnockites.
as thin fringes to the main greenish brown type. The optical properties are presented in Table VIII. The optical and X-ray powder pattern show that the hornblende is paragentic to ferruchosite in composition. The variations in composition are discussed in detail while dealing with the chemistry of the hornblendes.

**Biotite**

Biotite is common mineral found in acidic to intermediate charnockites. It is generally found as marginal fringes and scales penetrating along the grain boundaries of pyroxenes and hornblendes. It is strongly pleochroic with X = pale yellow, Y = Z = brown to dark brown.

**Relation of hornblende and biotite to pyroxene**

Grooven (1935) from the study of Uganda charnockites opined that the hornblende and biotite occurring in those rocks are original and the associated pyroxene is secondary, formed after the former, similar opinions have been expressed by RamyRao (1945), Barth (1952), Pichamuthu (1965) and others, who regard this as one of the evidences of metamorphic and metasomatic origin of charnockites. But Sutton and Watson (1951), Sutton et al. (1954) Morel (1958), Cooray (1962) and others regard hornblende and biotite as secondary after pyroxenes. Howie (1964) states that "Another recent advance
is the recognition that in many charnockite rocks any hornblende and biotite represent not the unaltered normal granitic material but the products of retrograde metamorphism or degradation of charnockites.

In Sivasarudram area the brown hornblende which has the uninterrupted continuation of cleavages to the pyroxenes, as the amount of hornblende decreases the pyroxene increases and the orthopyroxene appears. Another noteworthy feature is the concentration of ilmenite granules along the borders and cracks of hornblende and interlocking of pyroxene and ilmenite. The presence of opaques in higher modal proportions in hornblende-poor charnockites support that the reaction,

$$\text{hbl} + \text{qtz} \cong \text{opx} + \text{opx} + \text{plagioclase} + \text{opaques} + \text{water}$$

is from left to right.

The author opines that the formation of biotite and bluish green hornblende seen as shreds and patches is due to retro-grade metamorphism of the charnockites under amphibolite facies conditions.

**Potash feldspar**

Potash feldspar is present in subordinate amounts in the endorbitic and dioritic varieties of charnockites. In thin section it is fresh and perthitic. The perthitic blebs are generally spindle shaped and can be included under the
string perthites of Alling (1938). The optic axial angle varies from -80° to -90°. Cross hatching is common, some grains show wavy extinction. The optical properties indicate that the potash feldspar is microcline. Kohler (1948) opines that the optic axial angles above 80° as characteristic of microclines formed at high pressure and low temperature.

Garnet

The occurrence of garnet is restricted only to some crushed varieties of the charnockites. This observation is quite contradictory to the observations of Howie and Subramaniyan (1957), who stated that garnet is as consistent mineral as hypersthene. In Sivagangadram charnockites it occurs as pink discrete anhedral grains, often fractured and sieved with rounded inclusions of granular quartz and magnetite. It is relatively fresh and isotropic and has a refractive index varying from 1.76 to 1.78. The density is 3.66. The X-ray powder pattern gave the unit cell edge a = 11.640 Å and the chemical analyses indicates that the end member mol. composition to be Almandine 55 to 60%.

Pyrope 10 to 25%
Spessartite 1 to 2%
Grossular 10 to 15%

Holland (1900) did not consider garnet as a primary
mineral but described it as a secondary mineral formed from pyroxene as a result of metamorphism. This is a common constituent of varieties of charnockites which have suffered nanodymo metamorphism.

Accessory minerals

Apatite

It is a common accessory mineral in all the members of the series excepting a few basic types. It forms needles, slender prisms and anhedral to subhedral grains and it commonly occurs among plagioclase and quartz.

Iron ores

Magnetite and ilmenite is ubiquitous in almost all varieties of the charnockites constituting 6 to 8% of the mode. It occurs as irregular grains mostly in association with ferromagnesian minerals.

Secondary minerals

Pale green, nonpleochroic chlorite and calcite sometimes occur filling the fracture planes that cut through the rocks. Sericite and muscovite are the usual alteration products of feldspars.