CHARNOCKITES AND GRANULITES OF SOUTHERN INDIA. A REVIEW

by

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Abstract

The southern half of Peninsular India is one of the shield areas of the world occupied by a variety of metamorphic and igneous rocks, dating from 500 M.Y. to 2750 M.Y. These metamorphic rocks referable to the greenschist, amphibolite and granulite facies of regional metamorphism, display two major tectonic trends paralleling the western and eastern coast lines called the Dharwar trend and Eastern Ghats trend respectively. Charnockites were first described from the Madras area by HOLLAND in the early part of this century, following which such rocks have been described from many parts of the region. FERMOR divided Peninsular India into charnockite and non charnockite regions based on the prevalence or absence of Catazonal rocks such as charnockites. The various ideas which have been published with regard to the origin of charnockites are presented including those of HOWIE and the author based on comprehensive mineralogical, petrographical, chemical and field studies. It is emphasized that the term Charnockite should be restricted to the hypersthene granites with blue quartz and bluish green felspars; and the term charnockite suite applied to rocks ranging from such a hypersthene granite to hypersthene quartz syenite or enderbite. The 'basic' and 'intermediate' divisions of HOLLAND apparently represent pyroxene granulites of the basement, and hybrid types formed during the emplacement of the charnockite suite. The leptynites of HOLLAND are migmatized or recrystallized Khondalite (Quartz-felspathic garnet sillimanite gneiss) occurring in the basement, interstratified with the pyroxene granulites. It is considered that the charnockite suite of rocks crystallized under conditions of granulite facies. Subsequently, these together with the basement rocks appear to have undergone high grade regional metamorphism and subsequent retrograde metamorphism with the formation of transitional types along certain segments.

INTRODUCTION

The southern half of Peninsular India is one of the important shield areas of the world. It is from this region that Sir THOMAS HOLLAND towards the beginning of the present century described Charnockites and the Charnockite series of rocks. Except for segments occupied by Proterozoic, Mesozoic and Tertiary rocks including lava flows related to the Deccan volcanism, much of this area is occupied by metamorphic rocks displaying different facies of regional metamorphism. Granite bodies of batholithic dimensions and plutons of mafic, basic and alkaline rocks, such as pyroxenites, dunites, gabbros, norites, anorthosites (Adirondack type), syenites and nepheline syenites occur in this region besides some rare metamorphic assemblages containing sapphirine and kornerupine. A metamorphosed stratiform sheet containing meta-anorthosites carrying almost pure anorthite, with layers of

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chromitite and eclogitic rocks, occuring in the Salem district of Madras is also of special interest. This has been described by the writer as the Sittampundi Complex (SUBRAMANIAM, 1956). To a large extent our present knowledge of the petrology, tectonic setting and distribution of these rocks of Peninsular India is due to the work of the early pioneers. Among them may be mentioned, BRUCE FOOTE, KING, MIDDLEMISS, WALKER, VREDENBURG, HOLLAND and others of the Geological Survey of India, and SMEETH, SAMPAT IYENGAR and JAYARAM of the Mysore Geological Department. Since then many important contributions have been made on the geology of this region by FERMOR, KRISHNAN, RAMA RAO, PICHAMUTHU and other geologists who have in several papers presented interpretations on the complex geological problems of this region. The charnockites and the charnockitic rocks from this region have also been studied by several workers in recent years, one of the most important being the work of HOWIE (1955) on the geochemistry of the Madras charnockites.

CHARNOCKITE AND NON CHARNOCKITE REGION

Sir L. L. FERMOR (1936) based on a study of the literature and visits to sections of this vast tract proposed a division of Peninsular India into a 'Charnockite region' where rocks of the Charnockite series of HOLLAND were developed in force and 'Non-Charnockite region' where such rocks are rare; these are shown in the accompanying map (Fig. 1) as 1 and 2, divided by a heavy line. PICHAMUTHU (1962) has also discussed the evolution of metamorphic provinces in Peninsular India. S. NARAYANASWAMI (1966) on the basis of his traverses in southern India has recently elaborated on this and provided some details on these two regions, which are tabulated below with some modifications by the writer. The data are confined to the area under discussion.

Charnockite region	*Non Charnockite region*
Lithology	*Lithology*
Dolerite dykes Granites and pegmatites Charnockite suite Hybrid charnockitic rocks Peninsular gneiss and migmatites Garnetiferous Sillimanite K.Felspar gneisses and schists (khondalite) and their recrystallized facies (leptynite) Two pyroxene granulites, hornblende granulites, garnetiferous mafic granulites, amphibolites, and variants Calc granulites, marbles, magnetite quartzites and quartzites	Dolerite dykes Granites and pegmatites Peninsular gneiss and migmatites Shales, sericitic and ferruginous phyllites, cherts and impure quartzites, local conglomerates; sheared granite porphyry and granite, banded hematite quartzites with iron ore, argillites, limestones and clays; intercalated meta-volcanics, etc. Quartz schists, micaceous gneiss, greenstones, amphibolites, schists, etc.
Metamorphic facies	*Metamorphic facies*
Granulite and amphibolite and transitional type	Greenschist and amphibolite

Folding	*Folding*
Tight isoclinal folds with plunging and overturned axes, cross folding and refoliation at some places	Tight isoclinal folds with plunging and overturned axes, cross folding and refoliation at some places
Granite emplacement and migmatization	*Granite emplacement and migmatization*
Perhaps two or even three periods	Perhaps two periods
Ultramafic, basic, mafic and alkaline rock emplacement	*Ultramafic, basic, mafic and alkaline rock emplacement*
Perhaps during two periods	Ultramafic and basic intrusions perhaps restricted to one period

TECTONICS AND METAMORPHISM

The rocks of the Peninsular shield display certain broad regional trends. As early as 1943, KRISHNAN (1960) recognised these trend lines and called them by local names. In the region under discussion the Dharwar trend and Eastern Ghats trend are prominent. These are shown in the map (fig. 1). The Dharwar trend is generally NNW-SSE in region (1) in the map, swinging and veering to NNE-SSW in Southern Mysore. The NE-SW Eastern Ghats trend follows the eastern coast of the Indian Peninsula from north of Madras. There are areas in the region under discussion where there is an intermingling of the two trends. In recent times dating of rocks and minerals in them has received much attention. A wealth of data is fast coming in and it would require considerable analysis to interpret and use them to decipher the orogenic and metamorphic episodes in which the rocks of Peninsular India were involved. Available geochronological data show that the oldest crystalline rocks in Peninsular India are over 2750 M..Y and the youngest 500–600 M.Y. (See KRISHNAN, 1965).

The non-charnockite region is in part occupied by metasediments with interstratified volcanics, referred to as the Dharwar system, which is divided into three divisions. The lower division is mainly of basic volcanic rocks, ultramafites, hornblende schists, etc., whereas the upper two divisions comprise rocks formed during several cycles of sedimentation. The emplacement of the large batholithic granite (Closepet Granite) was perhaps the most important event in this region. Several bands of Dharwar pelitic and semi pelitic schists trending NNW-SSE are exposed as strips within the Peninsular gneisses and migmatites. These are interpreted to be infolded remnants of a major synclinorial structure in the Dharwars plunging NNW. Consequently, the upper part of the fold structure is exposed in the north and the deeper portion towards the south. There is a progressive change in metamorphic grade from north to south, the rocks of northern portion being referable to the greenschist facies, whereas towards the south they grade to the amphibolite and even granulite facies. The common rock types in the northern half are argillites, phyllites and schists containing muscovite, chlorite, tremolite, actinolite, epidote, sodic plagioclase etc. The limestones in this area contain chlorite and the quartzites are sericitic. Some of the schists which carry talc, tremolite, chlorite and serpentine are altered ultramafites. Towards the south the rocks tend to be of the amphibolite facies

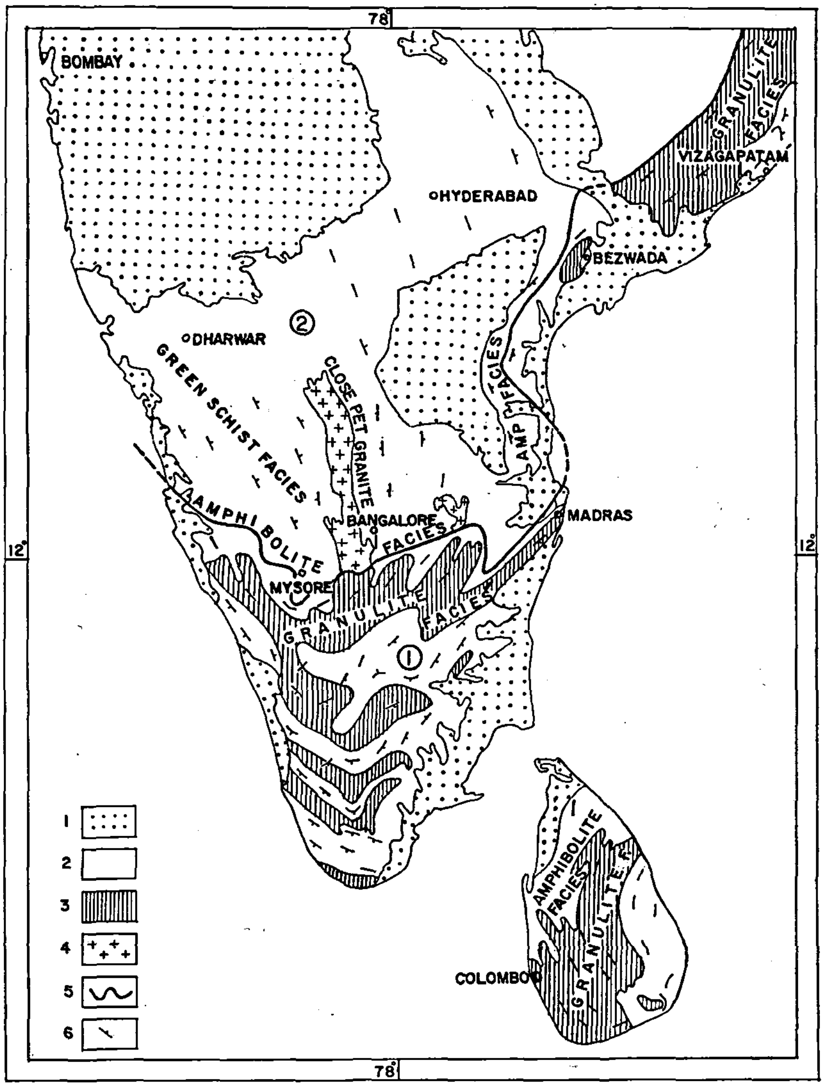

Fig. 1. Southern part of Peninsular India, and Ceylon showing broad tectonic and metamorphic features.
Legend: 1. Proterozoic to recent. 2. Migmatites and Peninsular gneiss complex. 3. Granulite facies. 4. Closepet granite. 5. Boundary of (1) Charnockite Region and (2) non-charnockite Region of FERMOR (slightly modified). 6. Regional trend lines.

with development of hornblende, biotite, garnet, staurolite, sillimanite, kyanite, etc. Beyond this we enter into the charnockite province where rocks of the granulite facies are developed in force at places showing retrogression to the amphibolite facies. Here the rocks exhibit ENE-WSW strike trend.

The charnockite region is characterised by the prescence of rocks of the granulite facies which are products of high pressure high temperature regional metamorphism. At places these rocks show retrograde characters by development of hornblende, biotite and cordierite. The regional strike trend veers from ENE-WSW to NNE-SSW and ultimately follows the Eastern Ghats trend paralleling the east coast of India. The main rock types in the region are migmatised gneises, granites, charnockite suite *sensu stricto*, two pyroxene granulites, metagabbros, metanorites, garnetiferous granulites, hornblende granulites, calc silicate marbles, amphibolites, khondalites, leptynites (stronalite), etc. In much of the Indian literature the two pyroxene and other mafic granulites are often referred to as basic or intermediate charnockites, as there has not been a proper appreciation of the mutual relationship of charnockite suite *sensu stricto* with the mafic and acid granulites of the basement. The following mineral assemblages are common in this tract.

Garnet-sillimanite-graphite-K felspar-quartz	(Granulite facies rocks)
Garnet-sillimanite-K felspar-quartz-spinel	
Garnet-K felspar-quartz-plagioclase	
Hypersthene-diopside-perthite-plagioclase-quartz	
Hypersthene-diopside-plagioclase	
Hypersthene-diopside-biotite-plagioclase	
Hypersthene-diopside-hornblende-biotite-plagioclase	
Hypersthene-diopside-garnet-hornblende-plagioclase	
Hypersthene-diopside-biotite-garnet-plagioclase	
Garnet-calcic plagioclase-scapolite-quartz	(Granulite facies rocks)
Garnet-calcic plagioclase-sphene-quartz	
Calcite-dolomite-diopside-phlogopite	
Hypersthene-garnet-K felspar-plagioclase-quartz	(Charnockite suite)
Hypersthene-quartz-K felspar	
K felspar-quartz-garnet	
Hypersthene-quartz-K felspar-garnet	
Ferro hypersthene-quartz-K felspar-plagioclase	

It should be mentioned here that within the charnockite region, large areas show development of lower facies of metamorphism viz. hornblende granulite facies, and almandine amphibolite facies. This must be attributed to a later cycle of metamorphism with lowering of temperature and access of water. This association of large segments of charnockites and granulite facies rocks with those of the hornblende granulite and amphibolite facies would suggest polymetamorphism. At places the Peninsular gneisses and migmatites show certain features of the higher grade rocks as by the presence of hypersthene; these may represent degraded transitional rocks similar to those recorded in Ceylon (COORAY, 1962). Several rare complex metamorphic assemblages containing sapphirine, orthopyroxene, sillimanite, cordierite, anthophyllite, kornerupine, corundum, spinel, rutile, etc. are also found in this region. Among interesting igneous rocks found in this region are the layered meta-anorthosite complex at Sittampundi in Madras containing a unique assemblage of minerals, the Adirondack type anorthosites of Madras and Orissa, the nepheline and corundum syenites of Madras, Andhra and Orissa and masses of dunite and peridotite found at some places in Mysore, Madras and Andhra.

In a recent contribution, WENK (1965) has discussed the terms khondalite, leptynite and stronalite. It would appear that WALKER (1902) who coined the term khondalite for a garnet-sillimanite-quartz-K felspar-graphite schist was not aware that such rocks had been described earlier from the Strona valley in Italy. The Italian rocks are schistose quartzo felspathic garnetiferous rocks generally rich in sillimanite with graphite, spinel and rutile, occurring in association with granulites. BERTOLANI (1964) has recognized acid stronalites which will be equivalent to khondalite and leptynite, and basic stronalites similar to the pyroxene granulites of south India in the Alps. It would appear therefore that the association of the two types of granulites is not limited to the Indian shield but is perhaps more widespread. WENK has suggested that the khondalites could be degranitized rocks consequent on high grade metamorphism. He further suggests that in the basement of an anatectic complex, mobilized masses rich in water, alkalies and silica rice leaving behind Al, Mg, Fe and Ca rich rocks such as stronalite (khondalite-leptynite) and pyroxene granulite. This suggestion merits careful consideration. The terms khondalite and leptynite are however too deeply entrenched in Indian petrological parlance to be displaced by the term stronalite. The writer regards leptynites to be recrystallized or migmatised khondalites, generally occurring at the contact zones of the Charnockite suite (see also HOWIE, 1965). Wenk regards khondalite and stronalite identical in their mineralogy, and draws attention to their association with basic granular rocks in the granulite facies in the Ivrea zone of the Alps.

The charnockite region of Peninsular India contains several hill ranges and high plateaux and in general is more elevated than the non-charnockite region. As several peaks in southern India ranging in height from 5000–8800 feet are composed of these high grade granulite facies rocks and charnockites, FERMOR suggested that the region must have undergone an uplift. This according to him must have taken place after the isogeotherms in the crust had been lowered prior to lowering of pressure thus retaining the deep seated character of the rocks in spite of being raised to a zone of low pressure. FERMOR proposed that a gentle tilt of one degree of the region would provide a relative uplift of the eastern and southern portions, of approximately over 9000 feet for 100 miles. Uplift by the above mechanism does not satisfactorily explain the presence of lower facies rocks embaying into the charnockite region or the abrupt termination of the charnockites in Orissa along the northeastern margin. FERMOR's alternative suggestion is a vertical uplift along a zone of weakness presumably following the junction of the charnockite and non-charnockite regions. Though there is no positive evidence for such a major uplifts, the presence of zones of mylonites around the margins of large charnockite massifs such

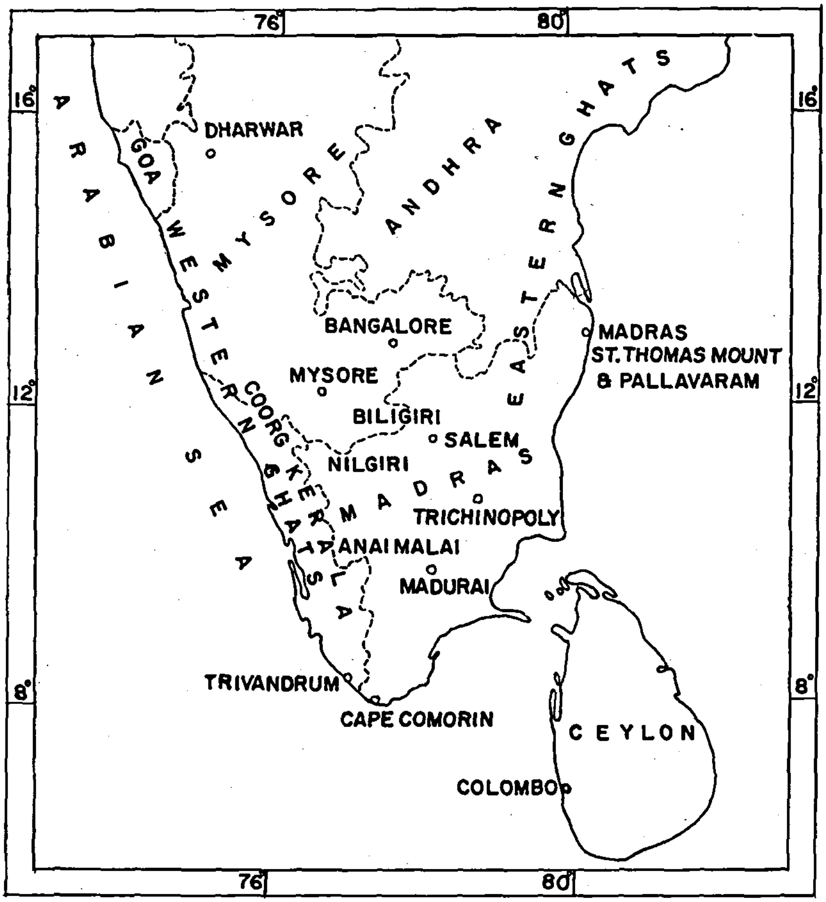

Fig. 2. Southern part of Peninsular India and Ceylon.

as those of Nilgiri, Madurai and Salem districts of Madras and the Biligirirangan hills of Mysore (see fig. 2) suggest faults and it would appear that large blocks have been uplifted several thousands of feet along zones marked by mylonite and intensely sheared rocks. To some extent there must have been changes in physical conditions along the margins of such uplifted blocks as evidenced by the presence of transitional rock types in such zones showing characteristics of the granulite and lower facies.

COMMENTS ON CHARNOCKITES AND GRANULITES

Some of the early European travellers in the Indian Peninsula (see PICHAMUTHU, 1953) noticed the dark coloured charnockites and granulites in the Nilgiri-Salem region of the present Madras State and in fact Captain Ouchterlony as early as 1848 observed the differences between the gneissic rocks of the plains and the dark coloured rocks in the Nilgiri massif. In 1885 JUDD (see HOLLAND, 1900) described the rocks of the Nilgiri mountains as *Nilgiri gneiss* and recognized in them the presence of orthopyroxene. Sir THOMAS HOLLAND's descriptions of similar rocks from the Salem district appeared in the trimonthly note of the Geological Survey of India in 1892. HOLLAND (1897) referred to the Pyroxene granulites and gneisses in southern India cut by dykes of Augite diorite. In 1893 he examined the tombstone of Job Charnock at St. John's Churchyard, Calcutta, and found it to be a hypersthene granite composed of blue quartz and felspars besides hypersthene and garnet. Regarding this rock as a petrographic type not previously reported from elsewhere, HOLLAND named this rock *Charnockite* in honour of JOB CHARNOCK. His detailed studies on the rocks from the type area near Madras city together with observations on similar rocks in other parts of Southern India appeared in 1900 as Memoir entitled *"The Charnockite series—a group of Archaean Hypersthenic rocks in Peninsular India"*. This famous Memoir should be regarded a classic in petrological literature in view of the remarkably lucid petrographic and mineralogical descriptions made in the early days of microscopic petrography. The contents of this classic paper are too well known to students of petrology, more particularly to those keenly interested in the charnockite problem.

HOLLAND proposed the term *Charnockite series* for a group of rocks genetically related to charnockite, which he defined as a hypersthene granite composed of quartz, microcline, hypersthene and accessory iron ores. He regarded the series to vary from acid charnockite to ultrabasic pyroxenite, characterised by even-grained granulitic texture and by the constant presence of highly pleochroic orthorhombic pyroxene hypersthene. HOLLAND however cautioned that the name Charnockite should not be used for any hypersthene granite in other petrographical provinces. He writes (1900, p. 131):

> The much complained of burdens of petrographical nomenclature are not due to the creation of specific names for local types but to irresponsible and unwarranted extension of such names to include unrelated members of different and widely separated petrographic provinces in which the accidents of differentiation and segregative consolidation may have produced by chance similar mineral assemblages.

The writer has presented a reinterpretation of the charnockites of the type area near Madras (SUBRAMANIAM, 1959) and discussed various features described by HOLLAND in support of his calling the 'Charnockite series' a petrographic province formed by differentiation. These will be referred to later; but the following observation of HOLLAND is significant.

> *We are not yet in a possession of sufficient facts to define the precise difference between the old norites and the pyroxene granulites.* Most probably they were *originally similar formations* which on account of secondary changes indicated *in the presumably older pyroxene granulites* are now distinguishable by differences more easily recognized than described. However the one important point to be considered by us at present is that between the norites which are certainly eruptive and the pyroxene granulites whose origin is doubtful

there are so many points of resemblance still left that we have good prima facie reasons for expecting evidences which will show that the two groups of rocks are really similar in origin. (HOLLAND, 1900, p. 209 – Italics author's).

MYSORE

JAJARAM, SMEETH, SLATER, SAMPAT IYENGAR and other Geologists of the Mysore Geological Department recognized the presence of charnockites and *mafic garnetiferous granulites in the Mysore area, soon after the publication* of HOLLAND's memoir. SMEETH of that Department described a banded sequence of such rocks in southern Mysore and regarded them as part of the Charnockite series. The term 'pseudo charnockites' and 'quasi charnockites' were applied to rocks which had a megascopic similarity to the charnockites, and included a variety of pyroxene and hornblende granulites and even cordierite garnet granulites. SAMPAT IYENGAR went to the extent of regarding some quartz-magnetite bodies as "Gravitative differentiates of the Charnockite magma".

VREDENBURG (1918) suggested that charnockites might represent an intensely metamorphosed facies of the igneous rocks of the Dharwar basement. He noticed also the constant association of charnockites and khondalites outcropping in alternate bands in the Eastern Ghats region. He believed that the charnockites represented the metamorphosed equivalents of original volcanic or igneous material occurring interstratified in a metasedimentary sequence. In so far as the pyroxene granulites are concerned, the writer would accept the interpretation of VREDENBURG, as in fact such a sequence forms the basement into which the charnockite suite has been emplaced as sheets and lenses. The related metasediments rich in alumina have been metamorphosed at the same time under granulite facies together with basic rocks forming khondalites and pyroxene granulites respectively.

B. RAMA RAO (1945) made an extensive study of the charnockitic rocks of the Mysore and has elaborated his views in his paper. According to him the charnockites do not belong to a petrographic province, due to magmatic differentiation under plutonic conditions. He ascribed the combined effect of a repeated series of metamorphic transformations of a sequence of rock units of different ages to the formation of hypersthene granulites of variable composition. He has attributed much importance to the batholithic Closepet granite which he considers to have intruded and reacted with older sheets and dykes of norites and pyroxenite, resulting in the formation of intermediate and acid charnockites. It appears to the writer that here again the various granulites, regarded by RAMA RAO as basic charnockites, belong to the basement into which charnockites *sensu stricto* have been emplaced. In fact PICHAMUTHU (1953, 119) reports the presence of numerous patches of basic rocks included in the acid charnockites of Biligiri hills in Mysore. He (PICHAMUTHU, 1962) recognises two types of charnockite, a granulitic foliated or mylonitised type conformable to the regional foliation of the gneisses, and a granitic coarse grained type which at places is porphyritic with transgressive relation to the gneisses. PICHAMUTHU (1960) has also reported the transformation of localised areas of Peninsular gneiss to charnockite in an area SSW of Bangalore. According to him the first type is older and has resulted from high grade regional metamorphism of pre-existing rocks, whereas the granitic type has resulted from palingenetic fusion of the former and widespread clouded feldspars demarcated these two periods of metamorphism during which the charnockites of different types were formed. He attributes the clouding of plagioclase in these dykes to a high temperature gradient related to the metamorphism and attendant rheomorphism connected with the formation of the coarse granitic charnockites. According to him these dykes were emplaced after the first regional metamorphism when the granulitic charnockites were formed. The present writer however contends that the first type of charnockites of PICHAMUTHU comprises essentially pyroxene granulites and their degraded variants found in the basement and should be clearly recognised as such. With regard to the second type, this would fit in with what the writer considers to be the Charnockite suite *sensu stricto*. Whether they have resulted from a plutonic intrusion under granulite facies conditions or whether they have been generated by crustal fusion, is a matter yet to be resolved.

THE EASTERN GHATS

P. K. GHOSH of the Geological Survey presented the results of his study of the charnockites of the Eastern Ghat region of Orissa, in which he considered the rocks of the charnockite series to have been derived from impure calcareous sediments by a sequence of metamorphic transformations. His views are largely based on field and petrographic studies but supporting mineralogical and chemical data are not available. According to him (GHOSH, 1941, p. 52–53):

1. Regional metamorphism of cafemic sediments resulted in diopside gneisses
2. a) Increase in temperature resulted in formation of hypersthene from diopside (basic charnockite stage)
   b) Further elevation of temperature and pressure resulted in the formation of hypersthene and garnet from diopside and plagioclase
   c) Increase of stress and fall in temperature caused the formation of hornblendes from pyroxene and plagioclase
   d) Oscillations in metamorphism caused the conversion of hornblende into hypersthene and possible formation of diopside from hypersthene with rock transformation to earlier types
   e) Increasing stress resulted in the disappearance of plagioclase and development of hornblende (ultrabasic charnockite stage)
3. Influx of alkaline fluids
   a) Formation of blue-green hornblende, minor biotite and sodic plagioclase (intermediate charnockite stage) through influx of soda rich fluids
   b) Influx of potassic fluids (hypersthene granodiorite stage)
   c) Dominance of potassic influx with formation of K feldspar and biotite

According to GHOSH, the ultrabasic, basic and some of the intermediate members of his Charnockite series do not have any intrusive relationship to the country rocks. The basic and ultrabasic types are considered by him to have been intruded by granitic rocks, resulting in the acid varieties of charnockite grading into them. The writer would, here again, regard much of the charnockites of GHOSH to be regionally metamorphosed rocks of the granulite facies, whereas his acid charnockite may be an intrusive into such a sequence. In this context the views of CROOKSHANK (1938) are significant. Working in the same general area as GHOSH, he considers the charnockites to be igneous in view of their showing a porphyritic texture and intrusive relationship to the gneisses. He also attributes albitization and myrmekitization of the gneisses adjacent to the charnockites, to alkalic fluids generated by the intrusive charnockite.

CEYLON

It may be of interest to mention here about the charnockites of Ceylon which is now an island but which presumably formed part of the Indian Peninsula. ADAMS (1929) has described the association of charnockites with pyroxene granulites, leptynites and khondalites of Ceylon. Until recently the geologists of Ceylon held the view that the charnockites have intrusive relationship to the biotite gneisses and the older metasediments (FERNANDO, 1948). In recent years COORAY (1954, 1962, 1963) has carried out geological mapping and petrographic studies on the charnockites of Ceylon, contributing to our better understanding of these rocks. According to him (COORAY, 1963) the following features are significant.

1. The charnockites are generally interbanded and interbedded with a variety of metasediments such as garnet sillimanite schists, garnet cordierite gneisses, quartzites, crystalline limestones and calc gneisses.
2. The mineralogy and petrology of the Ceylon charnockites closely simulate those of charnockites from other regions of granulite facies metamorphism.
3. The charnockites of Ceylon have minor structures concordant with those of the surrounding rocks and structurally conformable.
4. Charnockites of Ceylon are all metamorphic irrespective of their primary origin.
5. Differences in the charnockites of Ceylon from place to place are to be regarded as a reflection of variations in regional plutonic histories.
6. Anatectic granite pegmatites and small bodies of porphyritic hypersthene granite are similar to acid charnockite.

It would appear from the field relationship and petrography that the basic charnockites of COORAY were formed under the pyroxene granulite sub-facies of regional metamorphism, irrespective of their being of sedimentary or igneous origin. It is also noted that the 'intermediate' charnockites developed in force have resulted from interaction of basic material with the acid charnockite which carry streaks and patches of the former. Furthermore, due to retrograde metamorphism during a subsequent metamorphic episode referable to the almandine-amphibolite facies, charnockitic biotite gneisses transitional to gneisses and migmatites have been formed.

It may be seen from above that in Ceylon, as in India, the basic charnockites are essentially pyroxene granulites of an older cycle; the intermediate members are of hybrid origin; the charnockites *sensu stricto* are intrusive, whether palingenetic or igneous.

RECENT WORK IN SOUTHERN MADRAS

RAJAGOPALAN (1946 & 1947) made a petrochemical study of the charnockite of St. Thomas Mount and interpreted his chemical data on the rocks and minerals, following the methods of NIGGLI. Based on his studies he considered the rocks to be of igneous origin, formed by differentiation of a calc-alkaline magma. Some years later the rocks of the type area around Pallavaram and St. Thomas Mount near Madras City and from areas in south Madras were subjected to detailed chemical, mineralogical and petrographic studies by R. A. HOWIE at the Cambridge University and the results of this exhaustive study published in 1955. Later, the present writer made an exhaustive field study of the type area and utilised the valuable data of HOWIE (SUBRAMANIAM, 1959, 1960, 1962, 1963) in arriving at certain conclusions which will be discussed later. MUTHUSWAMI (1953) came to the conclusion that the basic charnockites of the type area were metamorphic types derived from a norite and had suffered retrograde metamorphism and now belong to the almandine diopside hornblende subfacies. NAIDU (1955) has detailed the mineralogy and petrography of charnockites from the Madras and contiguous areas to the west. NARAYANAN et al. (1955) have suggested that charnockites had been formed by syntectonic migmatisation of granulites. LEELANANDA RAO (1956) considered that charnockites and enderbites were intruded into khondalite and related metasediments. RAMANATHAN (1956), as a result of his studies in the Salem area in Madras, considers the basic pyroxene granulites to be early igneous intrusives, which were migmatised during the intrusion of a leptite magma, giving rise to the intermediate charnockites. NARAYANASWAMI (1963) and NARAYANASWAMI and LAKSHMI (1963) regard the charnockitic rocks to be products of compositional differences in geosynclinal rocks subjected to repeated cycles of magmatism and deformation, under deep-seated conditions. They envisage a geosynclinal association of sediments, basic volcanics and intrusives, which was involved in two periods of deformation, accompanied by granitic and migmatitic activity and deep seated palingenetic recrystallization.

RECENT WORK IN TYPE AREA NEAR MADRAS

The type area of charnockites near Madras City (see fig. 2) has been investigated in some detail by HOWIE (1955) and SUBRAMANIAM (1959, 1960, 1962). Several rock types and component minerals have been chemically analysed and detailed mineralogical and petrographic examination made. The writer (SUBRAMANIAM, 1962) redefined charnockite as *an orthopyroxene-quartz-feldspar rock, with or without garnet, characterised by greenish blue feldspars and greyish blue quartz.* He also proposed the term Charnockite suite for the genetically related alaskites, charnockites, enderbites and hypersthene quartz syenites initially of magmatic origin, later subject to conditions of granulite facies with formation of garnet and concomitant textural variations. HOWIE (1955), based on his extensive geochemical studies of rocks and minerals, agreed with the earlier interpretations of HOLLAND (1900) and WASHINGTON (1916) and concluded that the acid, intermediate and basic rocks of the type area were products of differentiation. The following sequence of rocks was established for the type area by the writer (SUBRAMANIAM, 1959).

Sequence of rocks in Type area

SUBRAMANIAM (1959)	HOLLAND (1900)
Dolerite	Dolerite dykes
Charnockite suite of alaskites, charnockites quartz syenites, enderbites, their variants and reconstituted facies	'Acid Division' of Charnockite series and leptynite
Syntectonic lenses of Norite with Pyroxenitic schlieren	'Ultrabasic Division' of Charnockite series
Hybrid rocks formed by reaction of Charnockite magma with Pyroxene granulites of the basement	'Intermediate Division' of Charnockite series
Pyroxene granulites and variants of the basement	'Basic Division' of Charnockite series
Schistose garnetiferous sillimanite gneisses and their recrystallized facies (leptynite)	Not reported (but association generally recognised)

The above sequence of rocks outcrops as a series of small hills with a general foliation trend of NE-SW to NNE-SSW corresponding to the Eastern Ghats trend, with steep easterly dips or tending to be vertical. A visible lineation parallel or sub parallel to the foliation caused by stretching of quartz grains and the dimensional orientation of aggregates of mafic minerals is noticed at places more particularly on weathered surfaces. This is a 'b' lineation at places showing a gentle plunge to the NE, indicating the regional fold axes of isoclinally folded units. The steep easterly dips suggest overturning of the isoclinally folded units to the west. The folding may be considered to have taken place after the emplacement of the charnockite suite of rocks as thick sheets and lenses in a gently folded sequence of quartzo-felspathic granulites (khondalite) with interstratified pyroxene granulites.

The rocks of the charnockite suite vary from fine grained bluish grey types in which the component minerals are readily recognised. Coarse alaskitic veins traverse the charnockite suite of rocks; these alaskites carrying blue quartz and pinkish felspar grade to charnockite *sensu stricto*, quartz syenite and their garnetiferous facies at many points. It is indeed difficult to distinguish the petrographic types within this suite by megascopic examination, but the syenitic types may be recognized by the paucity of quartz and the enderbites generally by their display of intense recrystallization; there is often a composite migmatite developed due to alternation of granulite and charnockite (SUBRAMANIAM, 1959, p. 344, pl. 3). It is believed that the intermediate division of HOLLAND represents hybrid types resulting from the intermingling of the charnockite and the older granulites, a fact recognized by HOLLAND who wrote (HOLLAND, 1900, p. 147):

> Even in hand specimen, the composite nature of the intermediate rocks is generally very noticeable, basic and *the acid portions being either distributed in irregular patches or arranged in parallel bands*. The fact makes it very difficult to place any one specimen in the commonly employed system of rock classifications.

On a later page (p. 149) in the same monograph he added:

It seems evident that these intermediate forms *are composed of half norites and half charnockite*. (Italics author's).

HOWIE's earlier conclusion that all the rocks of the type area are comagmatic was based on his laboratory studies, but after visiting the type area in 1964 during the International Geological Congress, he agrees with the reinterpretation of the writer (HOWIE, 1965).

COMMENTS ON MINERALOGY

The mineralogy of the charnockite suite of rocks is of considerable interest in elucidating their origin. The mineralogical differences between the rocks of the charnockite suite and those of the pyroxene granulites are tabulated.

Mineralogical Contrasts

Charnockite	*Mafic Granulites*
Quartz: Bluish grey or blue with acicular inclusions; in recrystallized types the quartz is clear	*Quartz:* Colourless or honey yellow quartz in minor amounts
Feldspars: Bluish green. Plagioclase An 25–30 with peculiar Ab–Ala twinning, antiperthites, microclineperthites and mesoperthites; potash feldspars are rich in Barium, symptomatic of high temperature	*Feldspars:* Dominantly greyish or bluish. Plagioclase An 35–70; untwinned plates abundant, generally clear due to recrystallization. Potash feldspars rare
Orthopyroxenes: Hypersthene-Eulite; exsolution lamellae of clinopyroxene observed in non recrystallized types	*Orthopyroxenes:* Hypersthene-Eulite; exsolution lamellae perhaps due to translation gliding
Clinopyroxene: Very rare in type area	*Clinopyroxene:* Augites, ferro augites and diopsidic augites; lamellar structure due to multiple twinning
Varietal: Garnet (almandines with low grossular and high pyrope components). Hornblende, biotite	*Varietal:* Garnets (almandines with almost equal proportion of grossular and pyrope component) strongly pleochroic brown hornblende secondary after pyroxenes and biotite
Accessory: Apatite, zircon, ilmenite, magnetite, titanomagnetite, pyrrhotite; the last two minerals suggest magmatic temperatures	*Accessory:* Apatite, calcite, ores, sphene

The orthopyroxene, an essential mineral of the rocks of the Charnockite suite, varies in composition from hypersthene through ferrohypersthene to eulite (SUBRAMANIAM, 1962). They are occasionally lamellar and contain oriented pleochroic inclusions which are characteristic of igneous orthopyroxenes. Furthermore they show a systematic compositional variation within the rocks of the charnockite suite, reflecting magmatic crystallization. Some of the granulites contain orthopyroxenes less magnesian than those in the acid members of the charnockite suite; this feature is not consistent with their being members of a common differentiation series. A similar compositional behaviour of the garnets in these types of rocks is evident in that the garnets of basic granulites are less magnesian than those of the charnockites. The orthopyroxenes from charnockites are noteworthy for their high Al_2O_3 content (see SUBRAMANIAM, 1962, p. 23), being as much as 4.08, averaging about 3%. ESKOLA (1957, p. 101) has ascribed this to extended diadochy of cations, due to high pressure; in fact in the analyzed samples half the alumina replaces silica in the SiO_4 tetrahedra. A characteristic feature of these orthopyroxenes is their strong pleochroism in salmon pink (α) and bluish green (γ). The intensity of the pleochroism which seems to be unrelated to the FE/Mg ratio has been correlated with entry of appreciable aluminium to the octahedral position in the structure, replacing the larger Mg and Fe^2 ions with consequent decrease in cell dimensions (HOWIE, 1963). It is also possible that the high alumina content of the orthopyroxenes in charnockites may be due to the enrichment of their parent magma in this oxide by assimilation of alumina-rich rocks such as the khondalites of the basement.

Though HOLLAND refers to the occurrence of garnets in the rocks of charnockite series he has not discussed the paragenesis of this important mineral in various rock types. He however considered the garnets in leptynite to have formed from hypersthene during the dynamic metamorphism related to the formation of leptynite from charnockite. Later work (HOWIE and SUBRAMANIAM, 1957) has proved the invalidity of this suggestion as the garnet in the leptynite and the hypersthene in charnockite are chemically dissimilar. Furthermore, the garnets from charnockite have a trace element composition quite different from those of the garnets from leptynite and khondalite (see HOWIE and SUBRAMANIAM, 1957, p. 576). The garnets in the charnockites have apparently been formed by reaction between the primary orthopyroxene ore minerals and the anorthite component of the plagioclase; the progressive increase of garnet with concomitant paucity of orthopyroxene and its sporadic occurrence in some rocks, supports this inference. In contrast to the garnets of charnockite which carry as much as 70 per cent almandine with 20 to 30 per cent pyrope and small amounts of spessartite, andradite and grossularite, the garnets from the granulites have a lower content of pyrope and higher proportion of grossularite. The garnets of khondalites and leptynites are very low in grossular, and are essentially pyralmandites.

The general dark or bluish colour of the charnockite suite of rocks is largely governed by the colour of the quartz and prevalent felspars. BUDDINGTON and LEONARD (1953, p. 893) have recorded this peculiarity in the rocks of the Diana quartzsyenitic complex in the Adirondacks, wherein the pyroxenic rocks are green in colour, and the hornblendic types pink. It seems to the writer that rocks consolidated under exceptionally dry conditions would have this bluish colour as oxidiation of iron oxide present in a diffused state in the felspars would be minimum. The bluish grey colour of the quartz in these rocks may be also due to their high pressure environment. It may be mentioned that chips of fresh charnockite when heated at 600–700° C for a few hours turned pink, simulating a typical pink granite.

HOWIE (1963) has attributed the overall colour of these rock to be related to greenish yellow veinlets of a mineralogically unidentified constituent present in the rock and particularly in the feldspars. He subjected

Table I.

Chemical compositions of the charnockite suite of rocks from the type area near Madras.

	1	2	3	4	5	6	7	8	9
SiO_2	77.32	76.92	77.47	71.97	70.65	72.21	70.94	71.32	71.98
TiO_2	0.56	0.38	0.26	0.40	0.46	0.20	0.32	0.27	0.74
Al_2O_3	9.81	10.86	11.00	13.30	15.09	15.05	14.15	14.31	12.49
Fe_2O_3	0.41	1.44	1.04	1.29	0.80	0.50	0.72	0.88	1.43
FeO	3.33	2.30	2.02	2.30	1.53	1.26	2.87	1.18	2.84
MnO	0.03	0.07	–	0.04	0.02	0.02	0.05	0.07	0.07
MgO	1.21	0.15	0.43	0.58	0.53	0.10	0.14	0.52	0.30
CaO	1.14	0.65	1.02	2.10	2.66	1.53	1.55	1.05	1.53
Na_2O	1.94	2.74	2.86	2.78	2.99	3.21	2.84	2.61	3.94
K_2O	3.87	4.16	4.14	4.24	4.69	5.80	6.38	6.87	3.99
H_2O+	0.25	0.24	0.20	–	0.43	0.16	0.24	0.65	0.58
$H_2O\div$	0.07	0.04	0.05	0.27	0.22	0.13	0.11	0.15	0.30
P_2O_5	0.11	n.d.	–	0.14	0.08	n.d.	n.d.	0.03	0.05
S	–	–	–	0.05	–	–	–	–	–
S =	–	–	–	0.33	–	–	–	–	–
Total	100.05	99.95	100.49	99.43	100.15	100.17	100.31	99.91	100.24
Density	2.70	2.72	2.67	2.72	2.65	2.66	2.71	2.71	2.71

Explanation to Table I.

Rocks of the Charnockite Suite.

1. 4639 Charnockite, Pallavaram, Madras; Anal. J. H. SCOON, (R. A. HOWIE, 1955, page: 782).
2. Ch. 96 Alaskite, from knoll S of Jalladampettai, Madras: Anal. M. S. JOSHI.
3. 9.658 Charnockite, Magazine Hill. St. Thomas Mount, Madras; Anal. H. S. WASHINGTON, (1916, page: 325).
4. 6436 Charnockite, Tirusulam Hill, Minambakkam, Madras; Anal J. H. SCOON, (R. A. HOWIE, 1955, page: 732).
5. 3705 Charnockite (GSI.9.658), Anal. J. H. SCOON, (R. A. HOWIE, 1955, page: 732).
6. Ch. 212 Charnockite, Tattankunnu quarry between the two rifle ranges south of Minambakkam Rly Station, Madras; Anal. A. PURUSHOTTAM.
7. Ch. 1 Charnockite, SSW corner of Hill. 500, Vandalur, Madras; Anal. A. PURUSHOTTAM.
8. Ch. 182 Charnockite, from quarry NW of Cowl Bazaar, Pallavaram, Madras; Anal T. KATSURA, (A. P. SUBRAMANIAM, 1959, page: 348).
9. Ch. 60 Charnockite (Enderbitic), small knoll south of mile 24.6, WNW of Melkottaiyur, Madras; Anal. T. KATSURA (A. P. SUBRAMANIAM, 1959, page 348).
10. Ch. 100 Charnockite (Hypersthene quartz syenite) from knoll SW of Jalladampetai, Madras; Anal. A. PURUSHOTTAM.
11. Ch. 112 Charnockite (Hypersthene quartz syenite), west of Hasanapuram quarry, south of Pallavaram, Madras; Anal. T. KATSURA, (A. P. SUBRAMANIAM, 1959, page: 348).
12. Ch. 217 Charnockite (Hypersthene biotite quartz syenite), Tattankunnu quarry between the two rifle ranges south of Minambakkam Rly Station, Madras; Anal T. KATSURA, (A. P. SUBRAMANIIAM, 1959, page: 348).
13. Ch. 22 Charnockite (Syenodiorite), from northern margin of hill. 349, Nedungunram, Madras; Anal. M. S. JOSHI.
14. 36218 Enderbite, Pallavaram, Madras; Anal. R. A. HOWIE (1955, page: 732).

Table I. Continued.

10	11	12	13	14	15	16	17	18	19
67.38	64.73	55.08	56.07	78.53	75.28	67.49	65.95	64.24	64.18
0.19	0.40	0.72	0.98	0.09	0.37	0.54	0.99	1.51	1.12
15.93	15.16	20.46	17.50	12.49	12.95	16.13	15.27	13.57	16.40
0.66	1.36	1.42	2.35	0.53	0.30	1.14	1.12	5.97	0.95
2.83	2.99	7.02	7.86	0.61	2.61	4.47	4.86	7.10	5.21
0.06	0.12	0.27	0.15	0.01	0.04	0.12	0.22	0.24	5.07
0.23	2.14	3.99	5.24	0.26	0.51	1.60	2.70	1.36	2.41
1.91	1.92	2.41	4.51	2.38	3.87	3.44	2.95	5.16	3.26
3.52	3.67	2.58	3.70	3.78	3.52	3.13	3.74	4.00	3.64
6.70	6.97	4.69	1.84	1.33	0.50	1.47	2.06	1.27	2.52
0.24	0.58	0.78	0.25	0.04	0.26	0.27	0.25	0.43	0.14
0.22	0.30	0.20	0.18	0.05	0.12	0.40	0.20	0.13	0.28
n. d.	0.19	0.10	n. d.	0.03	n. d.	0.04	tr	0.17	0.08
99.87	100.53	99.72	100.63	100.13	100.33	100.24	100.31	100.24	100.26
2.60	2.58	2.79	2.75	2.68	2.72	2.77	2.84	2.77	2.66

15. Ch. 53 Enderbite, southern margin of hill. 367 west of Nallambakkam; Anal. A. PURUSHOTTAM.
16. Ch. 219 Garnetiferous granulite (reconstituted enderbite), Tattankunnu quarry between the two rifle ranges south of Minambakkam Rly Station, Madras; Anal. R. A. HOWIE (HOWIE and SUBRAMANIAM, 1957, page: 572).
17. Ch. 113 Garnetiferous Enderbite, west of Hasanapuram quarry, south of Pallavaram, Madras; Anal. A. KATSURA, K_2O, H_2O- and H_2O- by R. A. HOWIE (HOWIE and SUBRAMANIAM, 1957, page: 572).
18. Ch. 29 Enderbite, northern slopes of Vandalur Hill. 563 in quarry East of Standard Motors; Anal. T. KATSURA, (A. P. SUBRAMANIAM, 1959, page: 348).
19. 56 Garnetiferous Enderbite, Pallavaram, Anal. R. A. HOWIE, (HOWIE and SUBRAMANIAM, 1957, page: 572).

Data from the report of the International Geological Congress, XXI, 1960, Part XIII, Page 398.

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slices of charnockite to leaching in warm hydrochloric acid for a few hours when the rock turned lighter in colour resembling a normal granite (HOWIE, 1963, p. 632). Chemical analysis of rock chips before and after leaching has revealed a loss in total iron. It may be stated here that in large exposures of charnockites the weathered surface is bleached to a pale hue and the fresh bluish grey rock is encountered only on breaking through this altered or bleached crust which at places is as much as a foot thick. In fact, in an exposure of charnockite lying at the base of the Cretaceous rocks of Trichinopoly (S.W. of Madras) which has been leached by the waters of the Cretaceous sea, the rock looks like any other weathered granite.

CHEMICAL PETROLOGY AND METAMORPHISM

In earlier papers the writer and HOWIE have discussed the chemistry of the charnockites and associated granulites and the component minerals in them. It has been demonstrated that leptynite, which HOLLAND regarded as a member of the charnockite series, is a recrystallized metasediment. WENK (1965) has also come to a similar conclusion and considered leptynite or khondalite to be identical to stronalites. The similarity of the chemistry of the garnets in the leptynite and khondalite and their dissimilarity to the garnets in charnockite suite of rocks has also been emphasized by HOWIE and SUBRAMANIAM (1957). It will be seen from the chemical compositions of 19 rocks of the charnockite suite presented in Table I (SUBRAMANIAM, 1960, p. 398) that they represent a fairly wide compositional range. In this Table rocks 1 to 8 are charnockites *sensu stricto,* 9 a transitional type from charnockite to enderbite, 10 to 12 quartz syenites, 13 a syenodiorite and 14 to 19 enderbites. The prevalence of enderbites in the charnockite suite of the type area is also clear. Furthermore the normative rations of these rocks suggest a magmatic origin as they plot within the compositional fields of proven igneous rocks in a Qz-Or-(Ab + An) ternary diagram (SUBRAMANIAM, 1960, p. 402). The enderbites appear to follow a granodioritic trend and the quartz syenites a syenitic trend of differentiation. The garnets in the reconstituted rocks of the charnockite suite have a higher (FeO + MnO/MgO) ratio than the co-existing orthopyroxenes which suggest their formation through reaction of orthopyroxene and magnetite. The inverse proportions of orthopyroxenes and garnets in the reconstituted types confirm their genetic relationship. Some of the analysed garnetiferous rocks of this suite fall in the appropriate fields of the granulite facies (see HOWIE and SUBRAMANIAN, 1957). The presence or absence of garnet appears to be related to the host rock composition, garnetiferous types being richer in Al_2O_3 + (FeO + MnO). The chemical compositions of the basic granulites and the hybrid types have been discussed previously by the writer (SUBRAMANIAN, 1959). The differences in trace element compositions of charnockites *sensu stricto* and their minerals as compared to those of the granulites and component minerals have also been shown in the above cited paper.

The plagioclase felspars in the charnockite suite of rocks are often antiperthitic and exhibit twinning normally found in magmatic rocks. The mesoperthitic nature of the potash feldspars in these rocks of the charnockite suite and their high Barium content are symptomatic of high temperatures of consolidation. Based on the compositions of co-existing magnetite and ferrian ilmenite from the Madras charnockites, BUDDINGTON and LINDSLEM (1964) estimate their temperatures of formation to be in the range 500°–600° C.

GEOLOGICAL SETTING OF CHARNOCKITE

The universal occurrence of the charnockite suite of rocks in the ancient shield areas dominantly of granulite facies rocks is a noteworthy feature. Hypersthene is a typomorphic mineral of charnockites and of the pyroxene granulite facies; this has resulted in much confusion of the nomenclature of the rocks. Examination of published literature shows that in most areas where 'charnockite series' of rocks are reported, an intrusive acid charnockite has also been observed. These acid charnockites have been grouped together with hybrid rocks, the basement granulites and retrograde types as "Charnockite series" in many areas all over the world. The occurrence of hornblende and biotite-bearing hypersthenic rocks associated with the charnockites is now being rightly recognized by many workers as due to retrograde metamorphism or degradation of pyroxene granulites and charnockites. The writer ventured to suggest (SUBRAMANIAM, 1963) that a granitic magma generated at lower crustal levels would at depths assimilate the granulites forming the present basement, and on differentiation, give rise to the charnockite suite of rocks. It may therefore be considered that charnockites are hypersthene granites and variants found in regions of granulite facies which have undergone magmatic crystallization under high pressure environments. WINKLER (1965) considers that the temperatures of formation of the charnockites were very high, with very low amounts of H_2O, and very high operative pressure, irrespective of their being magmatic or metamorphic. The present writer feels that segments of the crust containing granulite facies rocks including charnockites may have been tectonically brought to higher levels with consequent lowering of the metamorphic facies along the margins. Rocks of hornblende granulite and almandine-amphibolite sub-facies transitional to granulite facies found in several areas all over the world where charnockites occur may perhaps be attributed to such changes. The possibility of progressive metamorphism to the granulite facies should also be borne in mind, the problem becomes complex to unravel in areas which have undergone polymetamorphism. High pressures and temperatures involved in granulite facies metamorphism may often induce mobilization or melting, with consequent convergence of metamorphism and magmatism. HOWIE (1964) has rightly stated that the regional setting of the charnockites is of greater petrological significance than the exact details of their origin. Recent geochronological data shows disparity in ages of charnockites of Peninsular India (PICHAMUTHU, 1966). It seems therefore possible that rocks of the charnockite suite may have been emplaced, as any other granites during different orogenic epochs but under very dry conditions and high rock pressures. HOLLAND (1900, p. 131) has stated:

> It is possible therefore that we may be including under the name 'charnockite series' hypersthene bearing rocks derived from more than one magma, though all of very great antiquity.

The significance of this observation merits close attention of all students of the charnockite problem.

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PALAEOZOIC LOW-PRESSURE REGIONAL METAMORPHISM IN SOUTHEASTERN AUSTRALIA

by

T. G. VALLANCE*)

Abstract

Regional metamorphic rocks (chiefly aluminous pelites to psammites) of Ordovician age occur in two sub-parallel meridional belts, each more than 300 km long, which extend from N.E. Victoria into New South Wales. With increasing grade, the typical metamorphic sequence is from low-grade white mica + chlorite phyllites through biotite + muscovite schists and mica schists with porphyroblastic andalusite and/or cordierite to gneisses carrying first andalusite + K-feldspar and, finally, sillimanite + K-feldspar. Mineralogical evidence of a low-pressure metamorphic regime accords with the relatively modest cover indicated by stratigraphy. Granitic bodies, believed to be largely anatectic in origin, occur in close association especially with migmatitic high-grade gneisses. Both in chemistry and geological context, these anatectic granites stand in marked contrast with the later plutonic masses of S.E. Australia.

Information about the metamorphic geology of Australia is spread about as irregularly, and as thinly, as its human population. Large areas of the continent are still known only from reconnaissance surveys. Because of its remoteness from Denmark, I feel I should offer some comment on Australia as a whole before proceeding to my announced subject.

In broad outline, the present Australian continent consists of an extensive Pre-Cambrian terrain in the central and western parts with a belt of Palaeozoic rocks extending along the eastern side from Tasmania to Cape York. Deposition of the Palaeozoic rocks of eastern Australia took place in a complex of troughs separated by relatively higher areas known collectively as the Tasman Geosyncline (PACKHAM, 1960). In South Australia, the less extensive Adelaide Geosyncline had an active sedimentational history from later Proterozoic to early Palaeozoic times. Warping at different times across various parts of the continent has led to formation of a number of broad sedimentary basins, some marine, others non-marine, the largest and perhaps the best known being the Mesozoic Great Artesian Basin.

Regional metamorphic characters in Australia are restricted to the Pre-Cambrian and Palaeozoic terrains though by no means all such older rocks are metamorphic. Even in the early Pre-Cambrian regions great metamorphic variety has been noted. Thus the greenstones of the West Australian goldfield areas (PRIDER, 1961) may retain igneous textural relics with greenschist facies mineral assemblages. At the other extreme, many occurrences of high-grade gneisses and granulites are known in western and central Australia chiefly through the work of R. T. PRIDER, A. F. WILSON

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and their students (e.g. PRIDER, 1958; WILSON, 1960). A brief resumé of Archaean metamorphic associations in South Australia will be found in GLAESSNER and PARKIN (1958). BINNS (1964) has provided valuable details on the Broken Hill area of New South Wales. Despite these, and other fine studies, our knowledge of Pre-Cambrian metamorphic regions in Australia is still too fragmentary to provide a satisfactory basis for discussion on facies series in the sense of MIYASHIRO (1961). I am inclined to think, however, that most of our known examples will be found to belong to intermediate- and even low-pressure rather than high-pressure types. The World Metamorphic Mapproject which has brought us together here at Aarhus will undoubtedly serve to focus attention on the gaps in our knowledge. Regarding low-pressure metamorphism I should like to draw attention briefly to a recent study of the Pre-Cambrian Lamboo Complex in N.W. Australia by a former student of mine, Mr. I. GEMUTS. He has recognized wollastonite + Ca plagioclase in calcareous rocks and pelites with andalusite, sillimanite and K-feldspar isofacial with basic rocks some of which contain two pyroxenes. The work has some connection with what I am going to discuss shortly; I look forward to early publication of GEMUTS' detailed results by the Bureau of Mineral Resources, Canberra.

From Tasmania to northern Queensland, regionally metamorphosed Palaeozoic rocks occur in various places over the site of the Tasman Geosyncline. As yet not much is known of the southernmost examples (SPRY, 1962). Examples from N.E. New South Wales (BINNS, 1966) and Queensland (DE KEYSER, 1965) are known only from introductory studies which, however, indicate the presence of low-pressure metamorphic characters. The cases I wish to discuss as the main subject of my talk occur in N.E. Victoria and S.E. New South Wales. They have the advantage of a longer period of petrological study than any other metamorphic areas in Australia. The metamorphic area in the Wedderburn district of western Victoria may be similar but little is known of it.

Palaeozoic metamorphic rocks occupy two belts, roughly 100 km apart, both extending into New South Wales from the Gippsland region of Victoria. Apart from its occurrence at Cooma, the narrow eastern belt is imperfectly known though it appears to extend in a direction rather east of north for at least 300 km. Outcrop of the western belt is in places of the order of 150 km wide. Its extent along strike is still unknown though it must be greater than that of the eastern belt. Neither belt displays anything like continuous outcrop; both have been extensively faulted and invaded by post-metamorphic granitic bodies as well as granites which appear to belong to the regional metamorphic cycle. Parts of the eastern belt are covered by extensive Tertiary basaltic flows. The western belt passes northwards into a region of low relief and deep soil cover.

The Victorian end of the western belt was the first portion studied and much of the early work was done by a gifted amateur, A. W. HOWITT. By 1890 the metamorphic rocks had been recognized as stratigraphic equivalents of so-called Silurian (Ordovician) sediments, some metamorphic features being attributed to local contact effects, others to true regional metamorphism. To some extent the latter problem is still with us. The progressive nature of the metamorphism was clearly seen by HOWITT who also noted evidence of the early generation of chlorite minerals from the "original argillaceous paste" of the sediments (HOWITT, 1889). In this regard he had anticipated the work af BARROW and, later, TILLEY in the Dalradian of Scotland. HOWITT, however, did not attempt to plot details of metamorphic variety on his maps. Zonal mapping is a more recent development, as yet largely confined to New South Wales and first applied by JOPLIN (1942) at Cooma. Zoning in the western belt has been done at Albury (JOPLIN, 1947) and in the area between Wantabadgery and Tumbarumba (VALLANCE, 1953a), the latter work being extended southwards along strike to the Upper Murray country by GUY (1964). TATTAM (1929) and CROHN (1950) have contributed to metamorphic knowledge in N.E. Victoria.

Before turning to details of the zonal sequences, it is necessary to comment on the nature of the metamorphic rocks involved. In both belts the materials are predominantly metasediments of pelitic to psammitic types. Ca-rich rocks and contemporaneous igneous bodies occur but are of quite minor importance in the bulk. Many chemical data are now available for the main sedimentary suite (Figs. 1, 2) which displays the characters of Ca-poor K-rich clay/quartz mixtures. Low-grade psammites usually contain detrital grains of oligoclase as well as quartz. Chemically, the sediments are marked by high $K_2O/K_2O + Na_2O$ ratios (avge. 0.74 for 56 samples)

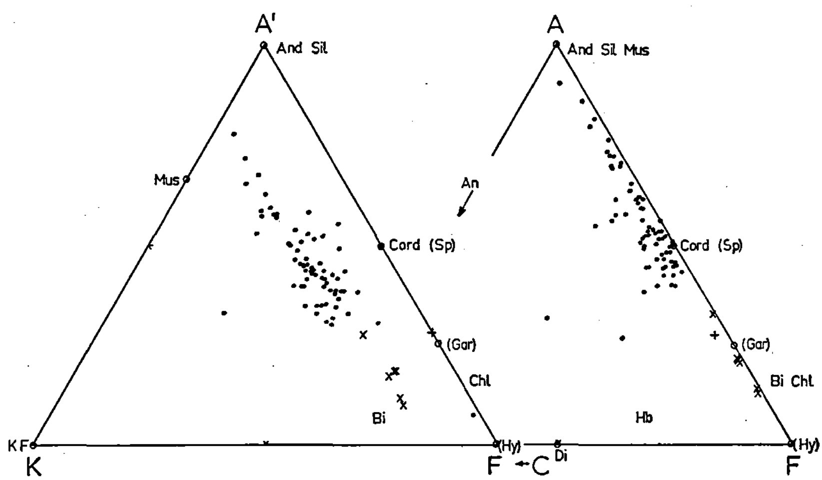

Fig. 1 and 2.
Plots (mol. proportions) showing compositional variety among metasediments and analysed phases from the S.E. Australian metamorphic areas. Phases present in the metamorphic associations are indicated, those of rare occurrence in brackets.
Key: metasediments •, biotites x, garnet +.
Fig. 1. A' = $Al_3O_3 + Fe_2O_3 \div (CaO + Na_2O + K_2O)$; $K = K_2O$; $F = FeO + MgO + MnO$.
Fig. 2. A = $Al_2O_3 + Fe_2O_3 \div (Na_2O + K_2O)$; $C = CaO$; $F = FeO + MgO + MnO$.

and high $Al_2O_3/K_2O + Na_2O + CaO$ (avge. 2.63). I have suggested that the association was miogeosynclinal (VALLANCE, 1953a).

The zonal patterns recognized in different localities are similar though various schemes of terminology have been used. With increasing grade the sequence is (1) low-grade zone (largely equivalent to the chlorite zone of JOPLIN, 1942), (2) biotite zone, (3) knotted schist zone (= JOPLIN's permeation zone and injection zone or zone of sills). I prefer this simple pattern because it avoids genetic concepts. It is difficult to assign outer limits to the low-grade zone; probably the greatest part of the metamorphic belts belongs to this grade. The higher grade zones are more readily defined on the ground. At Cooma, the biotite zone ranges to about 2.5 km in outcrop, the knotted schist zone usually less than 1 km whereas the high-grade rocks appear over a belt as much as 6.5 km wide. Comparable maximum widths of outcrop in the Wantabadgery-Adelong-Tumbarumba district are biotite zone 5 km, knotted schist zone 3.5 km, and high-grade zone 8 km. The width of zones is, however, a highly variable business. Near Wantabadgery, for instance, the high-grade zone is measured in centimetres rather than kilometres.

The low-grade pelites are typically phyllitic with a distinct metamorphic fabric defined by preferred orientation of white mica and chlorite. Their composition is such that, as a rule, mica appears in excess of chlorite. The more psammitic rocks commonly carry a few unadjusted detrital oligoclase grains. At the biotite isograd, a greenish brown biotite appears first, followed promptly by a more distinctly brown variety as grade increases. Biotite evidently forms from the reaction of white mica and chlorite. Chlorite does not normally persist far into the biotite zone although evidence of retrogressive generation of chlorite is widespread. The excess white mica by this stage exists as well-defined small flakes of muscovite. Detrital feldspar in the psammites has adjusted to albite. With the development of porphyroblasts of andalusite and/or cordierite in pelites the zone of knotted schists is reached. Fresh andalusite is found in the knotted schists at Cooma; elsewhere the porphyroblasts are now usually mica-chlorite aggregates. From the bulk chemistry one would expect cordierite to be at least as abundant as andalusite. GUY (1964) has, in fact, found relatively unaltered cordierite (ca. 40% Fe/Mg + Fe) porphyroblasts in the knotted schists of the Upper Murray area.

With increase in grade beyond the knotted schist zone, the metasediments tend to lose their well-defined planar mica fabrics and become more granoblastic – a change associated with development of K-feldspar poikiloblasts (optically orthoclase, but of unknown triclinicity). The typical high-grade zone rocks carry K-feldspar with Al-silicates. At Cooma, it has been demonstrated (JOPLIN, 1942; HOPWOOD, 1966) that, initially, K-feldspar co-exists with andalusite; the sillimanite isograd appears within the high-grade zone. Sillimanite forms at the expense of both andalusite and micas (in particular, it appears to nucleate in biotite). Cordierite commonly persists through the high-grade rocks and in a number of cases not all the andalusite is converted to sillimanite. The term granulite, formerly applied in the old British sense to some of the high-grade rocks because of their granoblastic character (JOPLIN, 1942; VALLANCE, 1953) has now been abandoned in favour of the term gneiss. The rocks do not belong to the normal granulite facies. Typical lithologies are termed spotted or mottled gneiss and banded gneiss, the former having dark biotite-rich patches (to ca. 10 cm diam.) set in a lighter matrix rich in quartz. One type of banded gneiss found in the outer part of the high-grade zone at Cooma is worthy of special comment, namely that marked in outcrop by a fine but distinct ribbing to which the descriptive term corduroy is applied. This corduroy feature, first recognized and named by BROWNE (1914) and described in some detail by JOPLIN (1942), has been taken to represent original sedimentary layering in a rock with the bulk composition of a psammopelite. Certainly the contrasts between the dark layers (with ca. 45% biotite, 20% quartz, 20% K-feldspar, 15% andalusite) and light layers (ca. 70% quartz, 15% biotite, 15% feldspars with minor andalusite) are akin to those found between recognizable pelites and psammites. In fact, the corduroy layering is an axial-plane structure in folds and the banding reflects a sort of metamorphic differentiation into fractions representative of the limiting sedimentary types. HOPWOOD (1966), in a detailed structural analysis, has shown that transposition of fine bedding features is common at Cooma. Only gross sedimentary characters may be retained in the higher grades. His mapping indicates a general consistency of the distribution patterns of banded and mottled gneisses with structural data suggestive of a stratigraphical relation between the different types of gneiss.

Well within the high-grade zone the gneisses, and especially the banded gneisses, acquire a migmatitic character. Patches and ptygmatically folded veins of quartzo-feldspathic material occur in a darker-coloured host. While sillimanite is more abundant in the host, it is not rare in the veins and patches. Granitic rocks are closely related spatially with these migmatic rocks which also occur as inclusions within the granites. The original terminology (permeation and injection zones) used by JOPLIN (1942) for the highgrade areas at Cooma involved the concept of addition of material from the associated granitic rocks. The evidence now available suggests that the high-grade metasediments are generally isochemical with the lower-grade schists though there may be a slight drop in Al_2O_3/K_2O + Na_2O + CaO values with increasing grade. A more apparent feature is the decline of Fe_2O_3/Fe_2O_3 + FeO with increase in grade for both metasediments and their biotites (VALLANCE, 1960).

Throughout the metamorphic progression, the metasediments normally carry no garnet, staurolite or kyanite. Instead there is andalusite and/or cordierite. With respect to garnet there are, in fact, a few exceptions. Minor pale pink garnet was found by JOPLIN (1942) in a biotite zone rock of unusual composition (higher CaO and MnO contents, 7.73% and 0.55% respectively). Amphibole also appears in these low-grade calcareous rocks. At high grades they contain diopside-hornblende-labradorite (TATTAM, 1929; JOPLIN, 1942). A few of the high-grade Ca-poor pelitic gneisses of N.E. Victoria carry garnet (TATTAM, 1929; BEAVIS, 1961). These garnetiferous rocks may contain rather more MnO than the common pelites (avge. of 35 pelites MnO = 0.05%); one of BEAVIS's gneisses has 0.20%

MnO. However, there are insufficient data here to establish whether garnet is rare for compositional or physical reasons. The only analysed garnet is a high-grade example—from a garnet-sillimanite-cordierite fragment in cordierite-bearing gneiss—which is not especially manganiferous (JOPLIN, 1947). A single example of a staurolite-bearing schist is known in the much-faulted terrain of the Kosciusko area; its metamorphic status is still uncertain. Staurolite is, in fact, not to be expected in many of our metasediments which, though Ca-poor, have notable amounts of alkalis and fairly high MgO contents relative to FeO. However, in the areas studied in some detail, no staurolite (or chloritoid) has been found in any of the rocks with favourable compositions.

The complete absence of kyanite and the occurrence of K-feldspar with andalusite in the high-grade pelites before the appearance of sillimanite suggests a distinctly low-pressure metamorphic pattern. In fact, the mineral assemblages are those of contact thermal metamorphism though the extent of the terrain declares the metamorphism to be regional. While the predominant pelite-psammite association allows us information about the distribution of various aluminous phases, it is necessary to consider briefly the situation regarding the very minor amounts of calcareous and mafic rocks found. Diopside-hornblende-labradorite in some calcareous rocks of the high-grade zone has been mentioned. Isogradal rocks, interpreted variously as basic igneous derivatives (JOPLIN, 1942) or sedimentary (SNELLING, 1959) carry similar assemblages or simply hornblende-plagioclase. In the Wantabadgery-Adelong-Tumbarumba district (VALLANCE, 1953b) mafic rocks range from types with albite-epidote-chlorite-calcite in the chlorite zone to hornblende-plagioclase amphibolites. The area where the more intensely metamorphosed mafic rocks occur is complicated by the intrusion of a later granite but the likely position of the amphibolites is outer high-grade zone. Further southwards, in what should be the sense of increasing regional grade, mafic rocks contain hypersthene-diopside-plagioclase. From this I suggested a possible peak for the metamorphic succession within a two-pyroxene facies. The range is, at least, clear from greenschist facies to the facies of cordierite amphibolites (VALLANCE, 1953a).

The regularity of the zonal sequences led me to think of the metamorphic patterns as representative in a given region of a single, though possibly complex, metamorphic cycle. It has to be recognized, however, that some have tended to follow HOWITT and postulate a high-grade thermal metamorphism superimposed on lower-grade regional metamorphic rocks, the porphyroblastic schists representing the outer influence of contact action. The geochronological study of PUDGEON and COMPSTON (1965) at Cooma perhaps offers some support to this view in that the high-grade rocks give slightly younger ages than the lower-grade samples. HOPWOOD's (1966) work on metamorphic fabrics in the same area has demonstrated discontinuities in degree of preferred orientation (Regelungsgrad) of quartz within the metamorphic sequence. From the chlorite zone a steady increase in degree of preferred orientation leads to a maximum within the knotted schist zone. Passage through the high-grade zone is marked by a systematic drop in degree of preferred orientation. The pattern is complicated by superimposition of a second set of fabric elements over an area of transition from knotted schists to high-grade rocks. Against these complications, the arithmetic mean grainsize of quartz throughout the *whole* metamorphic sequence shows a regular pattern of increase (HOPWOOD, 1966).

In both metamorphic belts in S.E. Australia, there is a close spatial connection between metamorphism and a distinctive suite of Ca-poor granites. To develop the picture, I must point out that three broad groups of plutonic rocks are recognized in this region (JOPLIN, 1962; VALLANCE, 1967). The first group, which I have called the Cooma type, comprises mainly true granites and adamellites, some massive, others foliated, emplaced in the metamorphic terrains discussed here. Migmatites are frequent associates and in a given locality granite of this type appears in the area of highest-grade metamorphism. The second group (Murrumbidgee type) ranges from granites to granodiorites; minor diorites and more basic rocks are not uncommon. Murrumbidgee type granitic bodies are frequently gneissic, at least near the margins, and occur as a rule in low-grade metamorphic (slate) terrains; contact influence is often slight. True hornfelses are either rare or quite lacking against both these types of plutonic rocks but are characteristic of contacts of the third group (Bathurst type). The latter group embraces mainly granites to granodiorites with subordinate monzonites and diorites. Minor gabbroic intrusions in some places have been invaded by the granitic bodies with resultant hybridism. Our best examples of plutonic complexes belong to this third type.

A progression in time appears to be represented by the three groups. The Cooma type is found only in Ordovician terrains, the Murrumbidgee granites, may have affected some Silurian successions. The third group bodies typically intrude Devonian rocks; some are demonstrably pre-Upper Devonian, others are younger but pre-Permian. Chemical data are summarized in Fig. 3. A clear separation of the Cooma type from the other plutonic associations is evident as is the broad compositional similarity of Cooma type granites with the rocks in which they are emplaced. The Ordovician metasediments tend to have lower Ca contents and Na/K ratios than the associated granites; these characters are strongly reversed in the minor volcanic contributions to the pile. It seems to me likely that the Cooma type granites were derived locally and represent one product of the metamorphism (VALLANCE, 1953c; 1960).*) Studies on strontium isotope ratios in the high-grade rocks and associated granites (PIDGEON and COMPSTON, 1965) and geochemical work by KOLBE and TAYLOR (1966) support this view. A distinct chemical similarity exists among the biotites of both high-grade rocks and granites (VALLANCE, 1960; GUY, 1964). PIDGEON and COMPSTON have argued that the Cooma gneiss could well have been formed *in situ* but there seems to be no reason why the anatectic material, once formed, should not have been able to migrate within the crust. Indeed,

*) An alternative scheme was proposed by JOPLIN (1952) who regarded the granites as syntectic products of reaction between more deeply-derived oligoclase granite melt and the metasediments. The same author is now inclined to favour a greater contribution from melting of metasediments (JOPLIN, 1962).

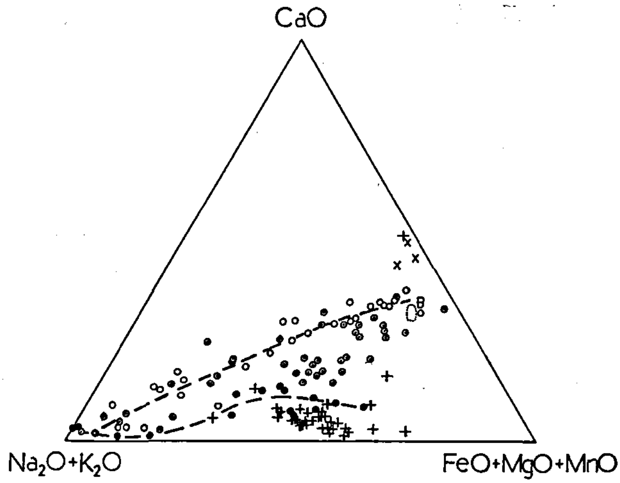

Fig. 3.
Diagram showing relations between CaO – Na_2O+K_2O – FeO+MgO+ MnO (wt. %) in plutonic and selected metamorphic rocks in S.E. Australia. Plutonic rocks (all from N.S.W) are distinguished thus: Cooma type •, Murrumbidgee type ⊙, and Bathurst type o. Variation traces are shown for the Cooma and Bathurst types. To avoid the complication of higher oxidation ratios, only higher-grade metasediments (+) and metabasics (x) associated with the Cooma type plutonic rocks are indicated. The dotted area B represents average basalt compositions after NOCKOLDS (Bull. geol. Soc. Amer, 65, (1954), 1007–1032).

field evidence in some areas clearly suggests such mobility. Lithologically and chemically identical granites are, in fact, now found in various metamorphic situations. The Cooma gneiss occurs against migmatitic high-grade rocks. In the Wantabadgery-Adelong-Tumbarumba district, as one goes from south to north, granites strikingly similar to the Cooma gneiss appear first within high-grade rocks and then among knotted schists (VALLANCE, 1953a, c). In both situations, inclusions in the granites have high-grade metamorphic characters. The granites have moved upwards (?) in a terrain, which despite the metamorphism, has yielded a few preserved Upper Ordovician graptolites. What slight stratigraphical evidence we have suggests that the regional metamorphism and the granite activity must have been accomplished under relatively little cover—an observation in harmony with the low-pressure assemblages in the metasediments.

I shall conclude with a comment on the later plutonic groups. With notably higher Ca-contents than the Cooma type (Fig. 3), these rocks seem to be more evidently linked with basaltic (mantle?) compositions. I am attracted to the idea that the Palaeozoic granites of this part of S.E. Australia developed first as crust-derived materials and that with passage of time there has been an increasing addition of mantle material to the crust perhaps much of it by volcanism. Within the tectonically more active belts in this part of the Tasman Geosyncline, important volcanic contributions to the accumulating piles were made until at least Middle Devonian time. These eugeosynclinal belts (the Cowra and Hill End Troughs of PACKHAM, 1960) are the sites of many of the later plutonic rocks.

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