Placed on: Osaka City University Repository

Journal of Geosciences, Osaka City University
Vol. 43, Art. 9, p.165-176, March, 2000

# Charnockite-enderbite rocks (orthopyroxene granulites) of northern Eastern Ghats Granulite Belt - a reconnaissance petrographic study and modal analysis

Kaushik DAS[1], Takamura TSUCHIYA[1], HOE Soeng Gi[2] and Masaru YOSHIDA[3]

1 Division of Earth and Planetary Sciences, Hokkaido University, Sapporo 060-0810, Japan
2 Raax Co. Ltd., Sapporo, Japan
3 Department of Geosciences, Faculty of Science, Osaka City University, Osaka 558-8585, Japan

## Abstract

Charnockite and enderbite with all kinds of intermediate varieties have been encountered in different parts of northern Eastern Ghats Granulite Belt. These orthpyroxene bearing granulites form one of the important voluminous members of the middle to lower crustal group. The problem is the nature of protolith for such rocks. During the post -conference field workshop several places across the high grade granulite terrain on the east coast of India were visited and samples were taken. The preliminary petrographic and modal analysis of all of these samples were carried out in this present study. This initial study shows a wide variation of these rocks. Merely, from the modal ratio of the respective feldspar species, a variation from the K-feldspar rich charnockitic end to plagioclage rich enderbitic end is conspicuous. From different parts of the world these granitoid rocks have been explained to have different affinities e.g. of igneous origin, metamorphic origin and also of metasomatic origin. Here in Eastern Ghats Granulite Belt, several events of metamorphism and deformation changed the protolith character of these rocks. Hence it is particularly very difficult to get any petrographic and chemical evidence of the early rock.

**Key words** : charnockite, enderbite, petrography, modal analysis, EGGB, India

## Introduction

The continental growth process by the accretion of crustal material - their chemical, magmatic and tectonic controls can best be understood through an extended characterization of granulites. That is why granulites exposed in high grade regional metamorphic belts and those exhumed as xenoliths in basaltic pipes are considered to be our window into the lower crust (Harley, 1989). This helps us to unravel the nature and composition of lower crust as well as their upbuilding processes. Granulites are typified by anhydrous mineral assemblages like garnet, orthopyroxene, plagioclase, K-feldspar and quartz. They appear to be crystallized or recrystallized under high temperature and low water pressure condition (as corroborated by their anhydrous assemblages). The marked depletion of large-ion-lithophile (LIL) elements, especially paucity of U, Th and Rb as against average crustal rocks indicates their lower crustal origin.

Apart from the Pressure-Temperature-Time history of the granulite terrains, the question of parentage of orthopyroxene granulite (both by igneous and metamorphic), a ubiquitously present rock type, is thought to be of utmost importance towards the understanding of such terrains (Newton, 1972). The available ideas regarding the origin of this kind of rocks from different parts of the world are as follows :

· as differentiation product of a mantle-derived granitoid magma intruded as a pluton of crustal dimension during the process of crustal accretion and formation of a stratified crust (Holland and Lambert, 1975 ; Drury, 1980).

· through large scale crustal melting by basaltic underplating (Bohlen, 1987).

· by the anatexis of the lower grade terrain towards a charnockitic trend in the tectonically overthickened crust (van Reenan et al., 1988)

· by possible deep crustal melting and metasomatism if $H_2O$-$CO_2$ volatiles are available in the deep crust, perhaps coming out from the deeply buried greenstone and limestone. In the Southern Granulite Belt, the fluid flux rich in $CO_2$ caused charnockitization (Janardan, 1982, Santosh et al., 1990, 1991).

From the Southern Marginal Zone of the Limpopo Belt, both the metamorphic and igneous charnockite have been reported by Bohlender et al., 1992. They proposed insitu biotite dehydration to form orthopyroxene in the presence of a fluid phase with locally different activity of $CO_2$ for the metamorphic charnockite and crystallization from calc-alkaline magmas derived by partial melting of lower crustal rocks for the igneous charnockite. Moreover, such magmatic rocks of broadly tonalitic chemistry have striking resemblance with the Precambrian TTGs (Young and Ellis, 1991 ; Kilpatric and Ellis, 1992, Keleman, 1995). The genesis of "charnockitic" magma is further complicated by the following hypothesis :

i) partial melting of a hornblende-free or poor but LILE enriched fertile granulite source (Kilpatric and Ellis, 1992).

ii) partial melting of the eclogites or basic granulites or amphibolites with or without garnet (Martin, 1988).

iii) fractionation of high Mg# andesites (Keleman, 1995).

This widely variable knowledge of the origin of charnockite-charnoenderbite-enderbite initiates the urge towards the careful characterization of this suite of rocks.

This has several varieties depending on the variation of the constituting mineral phases. Their chemical characters and structural dispositions are also varied. In the presently available publications different names are given for this group of rocks (acidic in nature) for which orthopyroxene granulite seems to be the all-inclusive term. Primarily, the orthopyroxene granulite can be divided into two groups, depending on the modal abundance of the dominant feldspar species. One is charnockite and the other is enderbite. The former one contains K-feldspar in excess of plagioclase. The later one has the opposite trend. The presence and absence of garnet can again be utilized to subdivide them. Obviously another variety having equal amount of both K-feldspar and plagioclase is present which can be termed as charno-enderbite.

The present work is to highlight the petrographic and modal variations among these varieties. The samples were taken during the post-conference (The Precambrian Crusts in eastern and central India, organized by UNESCO-IUGS-IGCP 368) fieldwork in 1998. Samples from several areas in the northern Eastern Ghats Granulite Belt had been taken

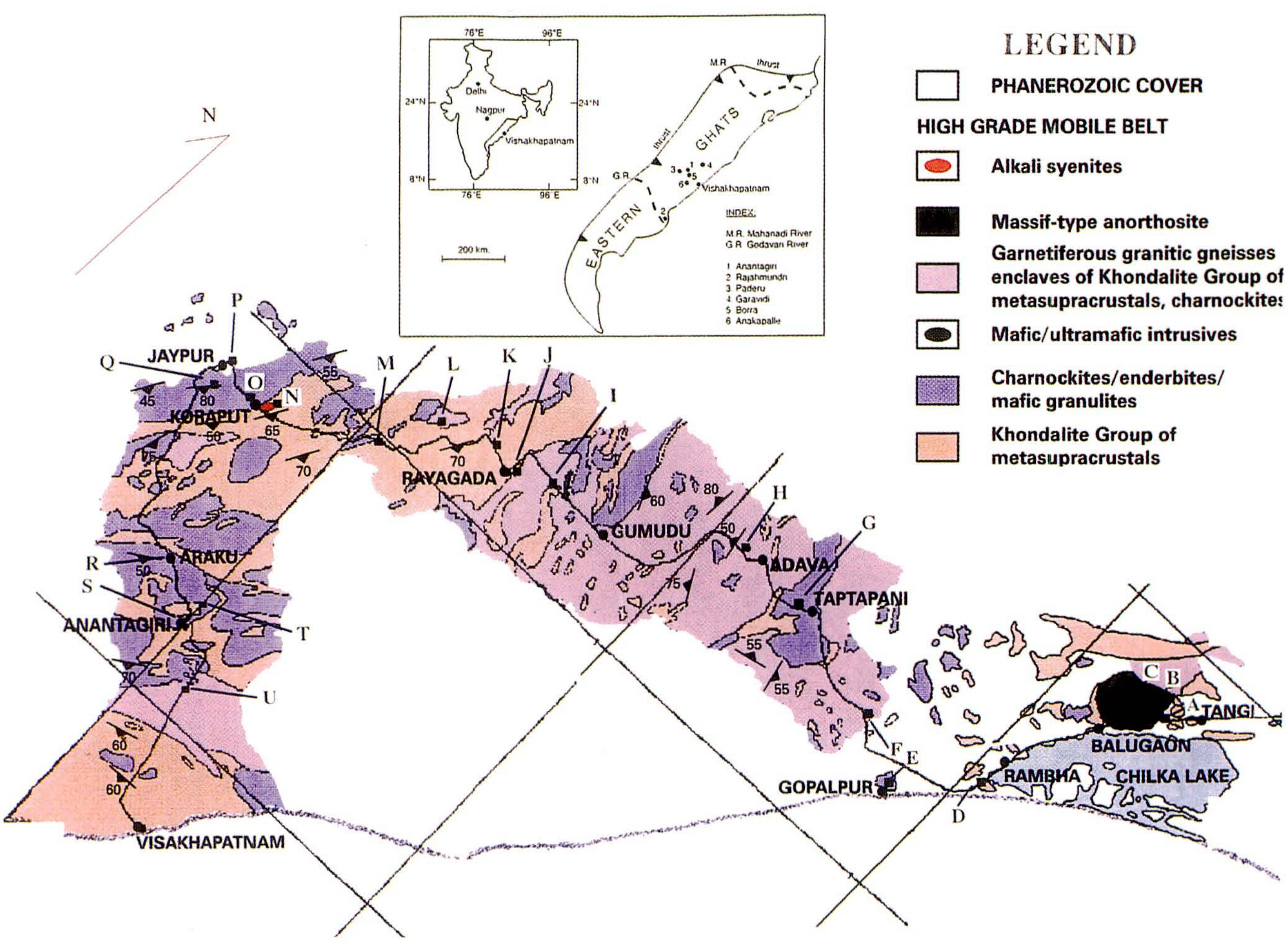



Fig. 1. The geological map and the route map of the post-conference field trip (modified from the guide book, Geological Survey of India, 1998). The alphabets indicate the visited exposures which are numbered as location numbers in the text of the guide book.

for the present study. The main areas include Araku, Anantagiri in the state of Andhra Pradesh and some exposures around the Chilka Lake area of the state of Orissa. Fig. 1 represents the modified geological map for the route of the post conference field work organized by GSI, India (Guide Book).

## Brief Outline of Regional Geology

The granulite terrain along the east coast of the Indian Peninsula, better known as Eastern Ghats Granulite Belt is an excellent area for granulite studies. This is a unique area in a sense that this exposes all possible mineral assemblages of granulite facies as well as several suites of anorthosites, alkaline rocks and chromitites. In most of the places, the most voluminous materials are khondalite (garnet-sillimanite-perthite-quartz gneiss), leptynite (garnet-perthite -quartz-plagioclase gneiss), orthopyroxene granulite and basic two-pyroxene granulites. Some areas have calc-silicate rocks, quartzites and high Mg-Al granulites having sapphirine-spinel bearing assemblages. Most of the information of the peak metamorphic condition had been derived from this sapphirine-spinel bearing metapelites that indicate a very high temperature event, nearly 10000℃ from the peak assemblages (Dasgupta and Sengupta, 1995 ; Sengupta et al., 1990, 1991 ; Lal et al., 1987 ; Kamineni and Rao, 1988 ; Dasgupta and Ehl, 1993). From this peak condition, evidences of both near isobaric cooling (Sengupta et al., 1990 ; Kamineni and Rao, 1988 ; Dasgupta and Ehl, 1993) and near isothermal decompression (Dasgupta et al., 1992, Dasgupta et al., 1994) are present. An anticlockwise P-T-t path has been advocated for the evolution of this terrain (Sengupta, 1990 ; Kamineni and Rao, 1988 ; Mukherjee, 1989). So far the geochronological data implies several events like a metamorphic event at 3100 Ma (Perraju et al., 1979), a basic and felsic magmatic event at 2900 Ma (Paul et al., 1990), a metamorphic event at 2600 Ma (Vinogradov et al., 1964 ; Perraju, 1979), a magmatic age related to the mafic granulites and leptynite (Shaw et al., 1997) a magmatic and metamorphic event at nearly 1000 Ma (Grew and Manton, 1986 ; Aftalion et al., 1988 ; Paul et al., 1990) and a Pan-African metamorphic event at 600 Ma (Aswanathanarayan, 1964, Yoshida, 1995).

## Petrography

Orthopyroxene granulite, in general, contains orthopyroxene, K-feldspar, plagioclase, quartz, opaque minerals, accessory minerals like sphene, apatite, rutile and monazite in variable amount with or without garnet and biotite. Sometimes, late amphiboles and rare spinels are also present. Development of late carbonate phases along fractures are also observed in some places. In the hand specimen scale, the rock is mesocratic. It shows gneissic foliation marked by alternate bands of felsic and mafic minerals. Such foliation is not always well developed. At places, the rock looks quite massive. Garnet does not occur everywhere but if present they show wide size variation. Mesoscopically, garnet occurs as separate grain and in a patchy disseminated clots as well.

However, all these mesoscopic variations can be observed in both the enderbite and charnockite members, even in a single area.

The important mineralogical and textural features of the individual phases are described below.

### Major Phases :

Orthopyroxene occurs in two distinct modes, as porphyroblastic phase and as small aggregates. In all the areas it usually occurs as porphyroblasts. The second variety is found in the rocks of some places. The porphyroblasts are anhedral to subhedral with one set of distinct cleavage. As far as the size is concerned, extreme variability is shown even in the scale of a thin section. Orthopyroxene grains are weakly to strongly pleochroic in nature, where X = pink, Y = greenish yellow, Z = green and the absorption formula is $X < Y < Z$. Usually they appear to be segregated as isolated patches floating in a matrix of quartz and feldspar. And where orthopyroxene is modally high, they define a crude foliation. These grains are elongated, highly fractured. Recrystallization and subgrain formation are widespread in such case. Occasionally, the porphyroblasts show undulose extinction and curved cleavage traces(Plate 3 C), sometimes with the conformably curved crystal boundaries. The boundary of the large stretched porphyroblasts is girdled by numerous small strain free grains are found to surround it. Locally, the porphyroblasts completely or partially enclose grains of biotite, ilmenite, plagioclase and quartz. At places late biotite replaces pyroxene grains to various extent (Plate 1 C). Replacing biotite sometimes pseudomorph the pyroxene grains. The porphyroblasts show non-interfering grain boundary relation with the adjacent quartz, K-feldspar and lobate garnet grains. But rarely there is direct contact with plagioclase grains except in a few microdomains where the adjacent plagioclase is found to be albitic in composition. Frequently, orthopyroxene is found to be separated from plagioclase by the coronal garnet (Plate 1 A). But in garnet free rocks, they are separated by interstitial quartz grains.

In Araku, the enderbite rock contains porphyroblasts of orthopyroxene crystallographic intergrowth of pigeonitic pyroxene. The intergrowths are exsolved in the form of streaks and they are oriented parallel to the trace of 100 plane.

The small aggregates orthopyroxene grains have been encountered in some of the rocks. The garnet-bearing enderbite shows the development of both the varieties of orthopyroxene. Such orthopyroxene develops along the boundary of the rugged porphyroblastic garnet. Here the plagioclase grains forming at the contact of garnet, are also of same variety. This kind of orthopyroxene grains are free from any inclusion.

Irrespective of their size, shape and mode of occurrence, the orthopyroxene grains are highly fractured and altered. Usually more sheared the rock more extensive is the alteration.

Plagioclase distinctly occurs in the following three different modes such as porphyroblasts of variable sizes, included phases and phases intergrown with quartz.

Porphyroblastic plagioclase grains are subhedral to anhedral in shape. They exhibit wide scale size variation ranging from coarse porphyroblasts to fine polygonised grains. The grain boundaries are straight to serrated in nature. Perfect polysynthetic twining is a common feature in all the plagioclase grains. Such twin lamellae are found to be kinked in many porphyroblasts (Plate 3 C). The development of spindle shaped deformation twin lamellae is widespread. Such deformed grains show undulose extinction. Interestingly enough, the sense of deformation can be delineated, even in a thin section scale, with the help of the orientation of the kinked lamellae and bent crystals. Recrystallization of plagioclase grains is a well conspicuous feature in this rock. Many porphyroblasts are surrounded by small recrystallized strain free grains (peripheral granulation?). In the annealed quartzofeldspathic portion polygonized plagioclase shows the triple point junction. Though rare, optical zoning is found in some porphyroblasts. Interestingly this feature is found in the garnet bearing enderbites of Anantagiri.

Smaller grains of anhedral plagioclase are found to be included in the grains of garnet and orthopyroxene. This is the second variety of plagioclase. Plagioclase lamellae of various shapes (streaks, spindles, blocks and strings) are exsolved in the host of K-feldspar forming different perthites. The charnockite rock contains such grains in profusion. Moreover, locally the plagioclase is found to be studded with lamellae of K-feldspar in the form of antiperthite (Plate 2 A).

Worm like intergrowths of plagioclase and quartz are found in all the areas (Plate 2 D). Such intergrowths are formed adjacent to large plagioclase porphyroblasts, perthites and along the fringe of exsolution free K-feldspar grains.

At places besides these three varieties, moat plagioclase also occurs as anhedral grains embaying the rugged grains of porphyroblastic garnet.

K-feldspar mostly occur as anhedral grains and like plagioclase they vary widely in grain size. Larger porphyroblasts are outnumbered by smaller grains. Coarse porphyroblasts are mostly perthitic. The crystallographic intergrowths of albitic plagioclase have been exsolved in the form of bleb, string, film and blocks (Plate 2 B). Sometimes stumpy blocks are also found. The core of the porphyroblastic K-feldspar contains plagioclase but the rim is free of any exsolution and the whole grain contains exsolved lamellae - both the occurrences are present in this rock. Moreover, the grains containing finer lamellae in the inner side and the coarse lamellae at the outer side are also encountered. Even there are lateral distributions of finer and coarse lamellae in a porphyroblast. Locally, perthitic porphyroblast includes small grains of plagioclase, orthopyroxene, biotite and opaque minerals. At the fringe, large grains are often replaced by a worm like intergrowth of quartz and plagioclase. As in the other feldspar species, plagioclase, the K-feldspar grains also show evidence of deformation. Undulose extinction is widespread. Recrystallizations of small strain-free subgrains around the larger grains are more extensive than that around plagioclase. Sometimes porphyroblasts are flattened conformably with the shape of flattened quartz ribbons. Though rare, antiperthite grains show exsolution of K-feldspar in the host of plagioclase.

At least in Anantagiri it is observed that exsolution free grains of K-feldspar occurring in the interstices of quartz and plagioclase. They are very irregular in shape and found to replace, at least partially, the plagioclase grains. So petrographic evidences might indicate a late K-feldspathization of an early plagioclase-rich enderbitic rock in this area.

The modal abundance of garnet is not uniform in this rock in all areas. Though sporadic in occurrence, garnet exhibits varied textural relationship with the associated phases. This pink colored isotropic phase with high refractive index occurs in the two modes as porphyroblast and as corona.

The porphyroblastic garnets (Plate 1 D) are again variable in amount from place to place. They are locally flattened and conform the crude foliation (Plate 3 A) defined by the elongated orthopyroxene and flattened quartz and K-feldspar. They sometimes poikiloblastically enclose different phases, such as biotite, orthopyroxene. They also include large grains of ilmenite and plagioclase as well. Such garnets show non-interfering grain boundary with orthopyroxene. At places garnet porphyroblasts are rugged in nature and resorption of such garnets to form small aggregate of orthopyroxene and plagioclase at the boundary is exhibited in the enderbites. In general garnet porphyroblasts are found to be partially replaced by patchy biotite. Usually the garnet porphyroblasts are highly fractured and late biotite replacement is extensive along these fractures. The other mode of garnet occurs in the form of corona (Plate 1 A and B). Such phase rims completely or partially the associated plagioclase, orthopyroxene and ilmenite (Plate 1 C). The thickness of corona is again widely variable. Coronal garnet is free from any inclusion. But where they rim around ilmenite some rutile grains are present occasionally at the contact of garnet and ilmenite. Coronal garnets are found to form separating the grains of orthopyroxene and plagioclase. Statistically, coronal garnets form more frequently along the contact of plagioclase and ilmenite than that between plagioclase and orthopyroxene. Though inclusion free, such garnets sometimes contain thread like intergrowth of quartz. This is observed as garnet-quartz symplectite. Both the porphyroblastic and coronal phases can be present in a microdomain.

Quartz occurs as an essential mineral in this rock but with varied grain size. It is usually anhedral to subhedral except in recrystallized polygonal grains. In the annealed quartzofeldspathic part quartz takes euhedral shape. The rock with overall gneissic foliation contains large porphyroblasts in the felsic portion. But in the mafic portion as well as in the massive rock grain size becomes smaller and they appears to occupy the interstices between mafic minerals. In all the places quartz grains are highly strained. They show undulose extinction. Sometimes flattened quartz ribbon imparts a strong foliation in the rock (Plate 3 B). Numerous small subgrains are found to form around large grains. Sometimes the grain boundary is serrated (Plate 2 C). Small quartz grains are found as inclusion in garnet. Thread like intergrowth of quartz is found with garnet to form garnet-quartz symplectite. Myrmekitic intergrowth with plagioclase is also found to replace K-feldspar and perthites marginally (Plate 2 D). Quartz has common non-interfering boundary contact with garnet, plagioclase, orthopyroxene, K-feldspar and opaque minerals.

Biotite most frequently occurs as euhedral to subhedral patchy grains. In many cases they have been found to be formed along the clevages and fractures of the ferromagnesian phases (Plate 1 C). Rarely another mode of biotite is present as an included phase. Actually they are of two different generations. The later type is rarely preserved. They are stumpy and included in porphyroblastic orthopyroxene and garnet. They show sharp contact with the surrounding phases, rather than diffused boundary. These are the relict prograde variety of biotite. The second variety is more common. But this is to be mentioned that they are not formed everywhere. They usually grow in expense of other ferromagnesian minerals like orthopyroxene, garnet and ilmenite. There are modal variations from place to place as far as this particular variety is concerned. Such grains are patchy in nature and sometimes show euhedral shape with one set of basal cleavage. Locally, orthopyroxene grains are found to be replaced and pseudomorphed by such biotite. In the highly sheared rock such biotite is developed extensively and sometimes conformable with the dominant fabric. This variety is termed as retrograde biotite which necessarily formed late i.e. after the formation of the other members of the assemblage.

Ilmenite is the dominant opaque mineral in this rock. It occurs both as coarse porphyroblast and as included phase. Porphyroblastic ilmenite grains are subhedral. It occurs in the vicinity of garnet and orthopyroxene. They are locally rimmed by coronal garnet (Plate 1 C) separating it from plagioclase and orthopyroxene. It also occurs in the interstices of a mosaic of orthopyroxene. The included ilmenite grains occur within porphyroblastic garnet and orthopyroxene as well as in coronal garnet. Along fractures, patchy biotite is found to replace ilmenite grains. Sometimes porphyroblastic grains contain numerous intergrown lamellae of magnetite along crystallographic planes.

The other scarcely occurring opaque mineral present in this rock is magnetite. They are mostly elliptical to rounded in shape and occur as scattered phase in the matrix of garnet, orthopyroxene, feldspar, ilmenite and quartz. Some grains, locally, are included in porphyroblastic garnet. As a second mode magnetite occurs as intergrown phase in the coarse porphyroblasts of ilmenite. There are both coarse and fine lamellae and both of them can occur together. The green variety of spinel occurs in a trace amount. The fine anhedral grains occur as inclusion within garnet, ilmenite and magnetite also.

**Accessory phases :**

Apatite, sphene, rutile and monazite are the accessory phases present in this rock. Their abundance is quite low. Moreover, in some places sphene and monazite are absent. As far as apatite is concerned, it is a ubiquitous phase. They are usually dumb bell shaped. Rutile occurs mostly in the garnet bearing rocks. The lobate shaped grains of rutile are occurring at or near the boundary of ilmenite and garnet. Well-rounded grains of sphene usually occur as droplets.

Table 1. Mineral modal analysis of some of the representative samples from the orthopyroxene granulite exposures of northern Eastern Ghats Granulite Belt, India.

| Sample number | Plagioclase | | | Potash feldspar | | | Myrmekite | Quartz | | Orthopyroxene | | Mica | | Hornblende | Garnet | Opaque | Accessory minerals | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Normal | Antiperthite | Other | Orthoclase | Twinned K-fs | Microcline | | coarse | fine | Normal | Pseudomorphed | Biotite | Muscovite | | | | Zircon | Apatite | Sphene | Epidote | Calcite | |
| | 6 | 279 | | 239 | | 10 | 8 | 24 | | 18 | | 54 | | | | 1 | 3 | 1 | | | | 643 |
| 98P02-2 | 0.9 | 43.4 | | 37.2 | | 1.6 | 1.2 | 3.7 | | 2.8 | | 8.4 | | | | 0.2 | 0.5 | 0.2 | | | | |
| | 101 | | 2 | 209 | 59 | 15 | 1 | 152 | | 43 | | 5 | | | 55 | 15 | 4 | 2 | | | | 663 |
| 98P06 | 15.2 | | 0.3 | 31.5 | 8.9 | 2.3 | 0.2 | 22.9 | | 6.5 | | 0.8 | | | 8.3 | 2.3 | 0.6 | 0.3 | | | | |
| | 101 | | 89 | 207 | | | 3 | 102 | | 121 | | 1 | | | | 11 | 1 | | | 1 | | 646 |
| 98P07 | 15.6 | | 13.8 | 32 | | | 0.5 | 15.8 | | 18.7 | | 0.2 | | | | 1.7 | 0.1 | | | 0.2 | | |
| | 23 | | 47 | 4 | | | | 6 | | 446 | | 23 | | | | 10 | | | 1 | | | 560 |
| 98P10 | 4.1 | | 8.4 | 2.7 | | | | 1.1 | | 79.6 | | 4.1 | | | | 1.8 | | | 0.2 | | | |
| | 114 | | 8 | 184 | | | 3 | 110 | | 10 | | 174 | 3 | | 37 | 3 | 5 | 3 | 1 | | | 647 |
| 98P08 | 17.6 | | 1.2 | 28.4 | | | 0.5 | 17 | | 1.6 | | 26.9 | 0.5 | | 5 | 0.5 | 0.8 | 0.5 | 0.2 | | | |
| | 60 | | 31 | 223 | | | 5 | 177 | | 18 | | 27 | 1 | | 18 | 1 | 3 | 1 | 1 | | | 566 |
| 98P9-10 | 10.5 | | 5.4 | 29.1 | | | 0.9 | 31 | | 3.2 | | 4.7 | 0.2 | | 3.2 | 0.2 | 0.5 | 0.2 | 0.2 | | | |
| | 140 | | 76 | 98 | | | | 120 | | 12 | 43 | 13 | 1 | | 90 | 18 | 3 | | | 1 | | 565 |
| 98P14 | 24.6 | | 4.6 | 17.2 | | | | 21.1 | | 2.1 | 7.6 | 2.3 | 0.2 | | 15.8 | 3.2 | 0.5 | | | 0.2 | | |
| | 23 | 291 | 21 | 191 | | | | 11 | | 1 | | 46 | | 40 | | 12 | | 1 | | | 9 | 646 |
| 98P15 | 3.5 | 44.7 | 3.2 | 29.3 | | | | 1.7 | | 0.2 | | 7.1 | | 6.1 | | 1.8 | | 0.2 | | | 1.4 | |
| | 36 | 55 | 28 | 422 | | | 15 | 52 | 48 | 49 | | 10 | | | | 1 | 2 | | | | 1 | 717 |
| 98P19-1 | 5 | 7.7 | 3.9 | 58.8 | | | 2.1 | 7.2 | 6.7 | 6.6 | | 1.4 | | | | 0.1 | 0.3 | | | | 0.1 | |
| | 139 | 200 | 2 | 63 | | | 2 | 41 | | 220 | | 2 | 1 | | | 12 | 2 | 1 | | | | 683 |
| 98P19-2 | 20.1 | 29.3 | 0.3 | 9.2 | | | 0.3 | 6 | | 32.2 | | 0.3 | 0.2 | | | 1.8 | 0.3 | 0.2 | | | | |
| | 14 | 261 | 6 | 71 | | | 20 | 19 | 41 | 88 | | 117 | | | | 1 | 3 | 1 | 1 | | | 643 |
| 98P02-1 | 2.2 | 40.6 | 1 | 11 | | | 3.1 | 3 | 6.4 | 13.7 | | 18.2 | | | | 0.2 | 0.5 | 0.2 | 0.2 | | | |
| | 88 | 194 | 1 | 111 | | | 25 | 41 | 62 | 50 | | 90 | | | | 1 | 2 | 1 | | | | 668 |
| 98P02-3 | 13.2 | 29 | 0.2 | 16.6 | | | 3.7 | 6.1 | 9.3 | 7.5 | | 13.5 | | | | 0.2 | 0.3 | 0.2 | | | | |
| | 200 | 124 | 6 | 72 | | | 5 | 210 | 62 | | 38 | 17 | | | | 6 | | | | | | 740 |
| 98P02-3' | 27 | 16.8 | 0.8 | 9.7 | | | 0.7 | 28.4 | 8.4 | | 5.1 | 2.3 | | | | 0.8 | | | | | | |
| | 143 | 28 | 40 | 44 | | | | 29 | 43 | 190 | | 29 | | | | 13 | | 1 | | | | 560 |
| 98P19-2 | 25.5 | 5 | 7.1 | 7.8 | | | | 5.2 | 7.7 | 33.9 | | 5.2 | | | | 2.3 | | 0.2 | | | | |
| | 2 | 5 | 20 | 356 | | | 12 | 61 | 42 | 7 | 10 | 11 | | | 85 | 10 | 2 | | | 2 | | 625 |
| 98P19-04 | 0.3 | 0.8 | 3.2 | 57 | | | 1.9 | 7.8 | 6.7 | 1.1 | 1.6 | 1.8 | | | 13.6 | 1.6 | 0.3 | | | 0.3 | | |
| | 24 | 141 | 34 | 187 | | | 28 | 81 | 49 | 3 | | 34 | | | 60 | 12 | | | | | | 653 |
| 98P19-b | 3.9 | 21.6 | 5.2 | 28.6 | | | 4.3 | 12.4 | 7.5 | 0.5 | | 5.2 | | | 9.2 | 1.8 | | | | | | |
| | 174 | 21 | 32 | 38 | | | 5 | 238 | 28 | 3 | 5 | 3 | | | 76 | 27 | 1 | | | | 4 | 653 |
| 98P19 | 26.7 | 3.2 | 4.9 | 5.8 | | | 0.8 | 36.1 | 4.3 | 0.5 | 0.8 | 0.5 | | | 11.6 | 4.1 | 0.2 | | | | 0.6 | |

Locally they are found to be present at the triple point junction of polygonised quartz and feldspar grains. Monazite, if present, occurs as rounded grains in orthopyroxene porphyroblasts showing distinct pleochroic hallo.

Amphibole is not present in all the areas. But if present, they are anhedral in shape and takes medium to coarse grain size. They are found to replace orthopyroxene grains along cleavage and fractures. Locally, they pseudomorph the pyroxene grains. Hence petrographically they are the products of late hydration.

Particularly in Anantagiri, clots of carbonate minerals are occurring along fracture planes. The feldspars are the prime victims of such mineralization. Sometimes euhedral calcite crystals are formed along the wider openings. For obvious reasons, these minerals are the consequence of the late carbonate input.

## Modal Analysis

A detailed modal analysis of nearly 30 samples taken during the fieldtrip from different parts of northern Eastern Ghats Granulite Belt have been carried out to differentiate the variations of the orthopyroxene granulites. Table 1 shows the results of some of the representative samples randomly taken from all the exposures visited. The sample numbers don't match with the exposure numbers on the route map. The problem with such exercise is to put properly the included phases and phases with exsolutions. Here such phases have been separately treated. For each sample, the first row indicates the absolute values of each type of grains and the second row is the percentage of such grains.

This study indicates presence of the two end members, a K-feldspar rich charnockitic variety and a plagioclase rich enderbitic variety with an intermediate variety of charno-enderbite that contains almost equal amount of K-feldspar and plagioclase. The results have been put together in two bar diagrams. Fig. 2 a shows the bar diagram where for each sample, plagioclase and K-feldspar modal percentage with respect to the total rock has been plotted. The left-hand side is obviously K-feldspar rich whether on the right-hand side, all the samples are plagioclase rich. In Fig. 2 b, this is explained more clearly. The K-feldspar and plagioclase modal percentages with respect to the total feldspar species have been plotted. Here also the end member charnockite and enderbite have been easily understood with an intermediate variety of charno-enderbite. To show the disposition of such varieties in terms of quartzofeldspathic part, a ternary diagram (Fig. 3) has been plotted. In this diagram, the modal values of quartz (both fine and coarse) are plotted at one apex and on the other two apices plagioclase and K-feldspar have been plotted. This diagram again shows the broad divisions of these rock types.

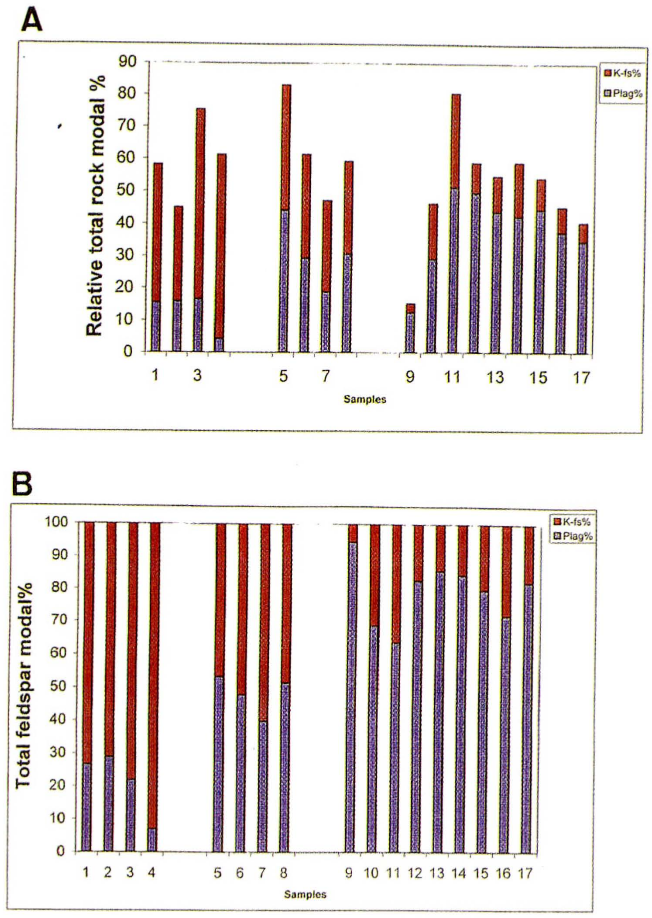



Fig. 2. The bar diagrams showing the modal variation of feldspar species. A. The modal percentage values of K-feldspar and plagioclase with respect of total rock modal values have been plotted for each sample. B. The modal percentages of the same samples as of A with respect to the total feldspar species have been plotted. In both the figures the sample numbers are according to that in Table 1.

## Discussion

The classification of the orthopyroxene granulite in terms of the origin is not clear until today. Different nomenclatures are problematic in the understanding of these rocks in most of the presently exposed granulite terrains of the world. Polyphase metamorphism and crustal defromation events posed the severe problem regarding this. Hence a detailed field survey to recognize the structural and lithologic relationships between the different types and with the surrounding materials, a very careful sampling of the rock types followed by modern petrographic and petrochemical studies is needed in a well-planned manner to lead to the petrogenesis of these rocks. Eastern Ghats Granulite Belt has several varieties of orthopyroxene bearing quartzofeldspathic gneiss. From this reconnaisance study, several varieties have been identified. In a terrain like EGGB, polyphase deformation and metamorphic events have blurred all the evidences of the nature of the protolith. From our trip, highly foliated to massive type of charnockitic rocks have been identified and sampled. The detailed petrographic analysis identified an initial modal variation of the feldspar species. Though these rocks have several names in the available publications, we have differentiated a K-feldspar rich charnockite end member and a plagioclase rich enderbitic endmember. There are intermediate varieties as well. And also from the modal analysis a spread in the modal values in each type is observed. From this study 3 different types of enderbite have been identified - massive enderbite with or without garnet, enderbitic augen gneiss (porphyritic enderbite?) with patchy occurrence of garnet and pegmatoidal enderbite. Charnockites and charno-enderbites are mostly foliated type with or without garnet. In some of the places massive variety is also present. These petrographically different varieties raise the possibility of difference in protolith or a later modification. A detailed study from diffrent point of view is needed to classify these rocks according to their origin. Though the enderbitic types have been thought to be of igneous origin, there may be charnockites of different origins (metamorphic or igneous). From the field observations some of the foliated rocks have late K-feldspar rich portions in apparently enderbitic rock which is also evident from the petrographic study. Due to intense deformation in most of the places these portions are parallel to the dominat gneissic foliation. Hence these charnockites are having mixed rock character in bulk. However, any other features typical of migmatites are not observed in this rock type. Moreover, in most of these rocks, the coronal garnet forming reaction texture indicating near isobaric cooling is preserved. These indicate that these rocks have metamorphic history that started from the near or late peak condition and they had definitely suffered the dominant deformation event. So the early history preceeding the dominant deformation and peak metamorphism is rather difficult to delineate. Enderbites of different degree of deformation indicate that there may be several emplacements at different times of this part of the lower crustal evolution.

A detailed study of the field relationships between these several types of orthopyroxene granulite and also with the other lithounits are of primary need. A more extensive petrographic analysis of the different varieties of orthopyroxene granulites (charnockite, enderbite and any intermediate varieties, if present) and petrochemical study of the carefully taken samples are needed.

The questions that have been identified as very important regarding this rock group are as follows :

1. From the petrographic and petrochemical studies,

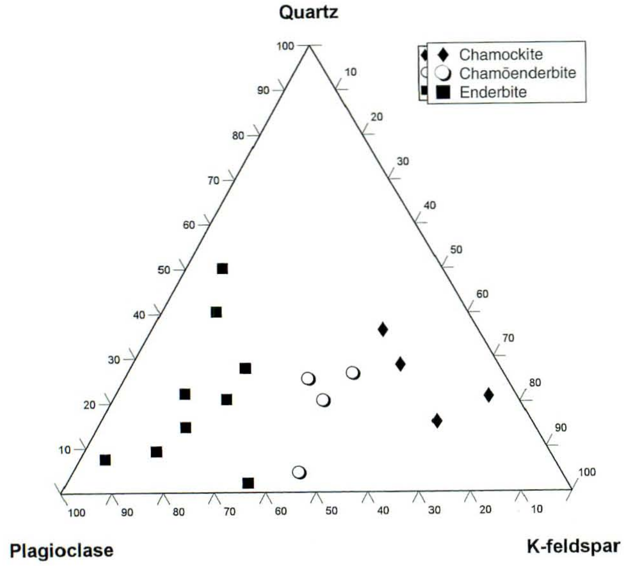



Fig. 3. Ternary diagram of quartz-plagioclase-K-feldspar modal values showing the relative disposition of the different varieties of orthopyroxene granulite.

particularly, from the modeling of different immobile trace elements and the patterns of REE, what could be the nature of the parent material of the orthopyroxene granulite of the Eastern Ghats Mobile Belt?

2. From the thermobarometric studies supported by the petrographic analysis, what are the possible P-T-t evolutionary path and their tectonic implication of these rock types?

3. What could be the answer to the enderbite-charnockite relationship?

4. Whether does the answer of thermal contribution lie under the genetic history of the charnockite and/or enderbitic magma?

This work is a preliminary investigation towards the much-asked question about the enderbite-charnockite relationship/problem.

## Acknowledgements

The authors are deeply thankful to Drs. R.N. Ghosh and Amitava Sarkar of Geological Survey of India for their guidance and help in field work. Thanks are due to all the participants of the post conference (The Precambrian Crusts in eastern and central India, organized by UNESCO-IUGS-IGCP 368) field trip, 1998 for their exciting discussions on the field. We acknowledge the comments and corrections of Prof. A.T. Rao on the initial version of this manuscript. Mr. T. Kuwajima and Mr. H. Nomura of the Faculty of Science, Hokkaido University helped a lot to prepare the thin sections. K.D. and T.T. are supported by IGCP 368 for this field trip.

## References

Aftalion, M., Bowes, D.R., Dash, B. and Dempster, T.J., 1988. Late Proterozoic charnockites in Orissa, India : A U-Pb and Rb-Sr isotopic study. *J. Geol*., **96**, 663-675.

Aswanathanarayana, U., 1964. Isotopic ages from the Eastern Ghats and Cuddapahs of India. *J. Gephys. Res*. **69**, 3479-3486.

Bohlen, S.R., 1987. Pressure-Temperature-time paths and a tectonic model for the evolution of granulites. *J. Geol*., **95**, 617-632.

Bohlender, F., van Reenan, D.D. and Barton, J,M,Jr., 1992. Metamorphic and igneous charnockites in the Souther Marginal zone of the Limpopo Belt, South Africa, *Precam. Res*., **55**, 429-449.

Dasgupta, S., 1993. Contrasting mineral parageneses in high-temperature calc-silicate granulites : examples from the Eastern Ghats, India. *J. Met. Geol*., **11**, 193-202.

Dasgupta, S. and Ehl, J., 1993. Reaction texures in a spinel-sapphirine granulite from the Eastern Ghats, India and their implications. *Eur. J. Min*., **5**, 537-543.

Dasgupta, S. and Sengupta, P., 1995. Ultrametamorphism in Precambrian granulite terranes : evidence from Mg -Al granulites and calc-silicate granulites of the Eastern Ghats, India. *Geol. Jour*., **30**, 307-318.

Dasgupta, S., Sengupta, P., Fukuoka, M. and Chakraborty S., 1992. Dehydration melting, fluid buffering and decompressional P-T path in a granulite complexfrom the Eastern Ghats, India. *J. Met. Geol*., **10**, 777-788.

Dasgupta, S., Sanyal, S., Sengupta, P., Fukuoka, M., 1993. Petrology of granulites from Anakapalle - evidence for Proterozoic decompression in the Eastern Ghats, India. *J. Petrol*., **35**, 113-120.

Drury, S.A., 1980. Lewisian pyroxene gneiss from Barra and the geochemistry of the Archean lower crust. Scott. *J. Geol*., **16**, 199-207.

Grew, E.S., and Manton, W.I., 1986. A new correlation of sapphirine granulites in the Indo - Antarctic metamorphism terrain : Late Proterozoic dates from the Eastern Ghats. *Precam. Res*., **33**, 123-139.

Geological Survery of India, 1998. *Guide book, post-seminar field workshop in parts of Orissa and Andhra Pradesh, India, Nov.1–3, 1998. International seminar and field workshop on the Precambrian continental crust in eastern and central India, UNESCO–IUGS–IGCP 368, Bhubaneswar, India, 22 nd October–3 rd November, 1998. Geological Survey of India.*

Harley, S., 1989. The origin of granulites : a metamorphic perspective. *Geol. Mag*., **126**, 215-247.

Holland, J.G. and Lambert, R.St.J., 1975. The chemistry and the origin of the Lewisian gneisses of the Scottish Minland : the Scourie and Inver assemblages and subcrustal accretion. *Precam. Res*., **2**, 161-188.

Janardan, A.S., Newton, R.C., Hansen, E.C., 1982. The transition from amphibolite facies to charnockite in southern Karnataka and northern Tamil Nadu. *Contrib. Miner. Petrol*., **79**, 130-149.

Kamineni, D.C. and Rao, A.T., 1988. Sapphirine granulites from Kakanuru area, Eastern Ghats, India. *Am. Min*., **73**, 692-700.

Keleman, P.B., 1995. Genesis of high Mg# andesites and the continental crust. *Contrib. Miner. Petrl.*, **120**, 1-19.

Kilpatrik, J.A., and Ellis, D.J., 1992. C-type magmas : igneous charnockites and their extrusive equivalents. *Trans. R. Soc.Edin. : Earth Sciences,* **83**, 155-161.

Lal, R.K., Ackermand, D., Upadhyay, H., 1987. P-T-X relationships deduced from corona textures in sapphirine-spinel-quartz assemblages from Paderu, southern India. *J. Petrol*., **28**, 1139-1168.

Martin, H., 1988. Petrogenesis of Archean trondhjemites, tonalites and granodiorites from Eastern Finland : major and trace element geochemistry. *J. Petrol*., **28**, 921-953.

Mukherjee, A., 1989. P-T-time history and thermal modelling of an anorthosite-granulite interface, Eastern Ghats metamorphic belt, India, *In J.S. Daly, R. A. Cliff and B.W.D. Yardley (eds), Evolution of metamorphic belts, Geol. Soc. Spec. publication,* **43**, 265-274.

Newton, R.C., 1992. An overview of charnockite. *Precam. Res*., **55**, 399-405.

Perraju, P., Kovach, A. and Svingor, E., 1979. Rubidium-strontium ages of some rocks from parts of the Eastern Ghats in Orissa and Andhra Paradesh, India. *J. Geol. Soc. India*, **20**, 290-296.

Paul, D.K., Ray Barman, T.K., Mcnaughton, N.J., Fletcher, I.R., Potts, P.J., Ramakrishnan, M., Augustine, P.F., 1990. Archean-Proterozoic evolution of Indian charnockites. Isotopic and geochemical evidence from granulites of the Eastern Ghats belt. *J. Geol*., **98**, 253-263.

Santosh, M., Harris, N.B.W., Jackson, D.H. and Mattey, D. P., 1990. Dehydration and incipient charnockite formation : a phase equilibria and fluid inclusion study from South India. *J. Geol*., **98**,915-926.

Santosh, M., Harris, N.B.W., Jackson, D.H. and Mattey, D. P., 1991. Carbonic fluid inclusions in South Indian granulites : evidence for entrapment during charnockite formation. *Contrib. Miner. Petrol*., **108**, 318-330.

Sengupta, P., Dasgupta, S., Bhattacharya, P.K., Fukuoka, M., Chakraborty, S. and Bhowmik, S., 1990. Petrotectonic imprints in the sapphirine granulites from Anantagiri, Eastern Ghats Mobile Belt, India. *J. Petrol*., **31**, 971-996.

Sengupta, P., Karmakar, S., Dasgupta, S., Fukuoka, M., 1991. Petrology of spinel granulites from Araku, Eastern Ghats, India and a petrogenetic grid for sapphirine free rocks in the system FMAS. *J. Met. Geol*., **9**, 451-459.

Shaw, R.K., Arima, M., Kagami, H., Fannings, C.M., Shiraishi and Motoyoshi, Y., 1997. Proterozoic events in the Eastern ghats Granulite Belt, India : evidence from Rb-Sr, Sm-Nd systematics and SHRIMP dating. *J. Geol*., **105**, 645-656.

Vinogradov, A., Tuganinov, A., Zhykov, C., Stapnikova, N., Bibikova, E. and Khorre, K., 1964. Geochemistry of Indian Precambrian. *International Geological Congress, 22 nd session, India, Reports, part 10*, 553-567.

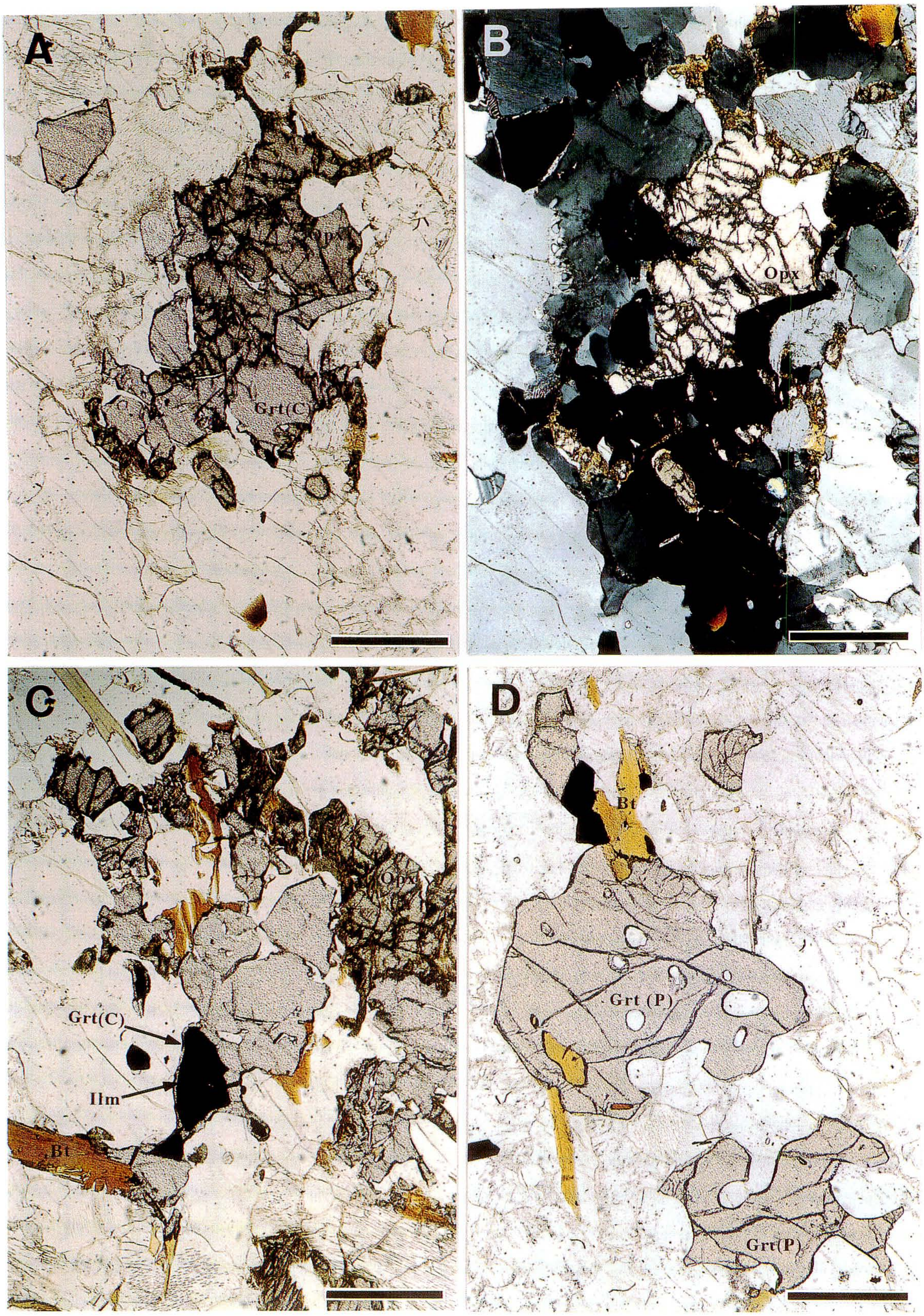
Yoshida, M., 1995. Assembly of East Gondwanaland during the Mesoproterozoic and its rejuvenation durion the Pan-African period. *In India and Antarctica during the Precambrian. Eds, Yoshida, M. and Santosh, M. Memoir Geol. Soc. India,* **34**, 25-45.

Young, D. N. and Ellis, D.J., 1991. The intrusive Mawson charnockites ; evidence for a compressional plate margin setting of the Proterozoic mobile belt of East Antarctica. *In Geological Evolution of Antarctica. eds. Thompson, M.R.A, Crame, J.A. and Thomson, J.W.,* Cambridge University Press, 25-31.

*Manuscript received August 31, 1999.*

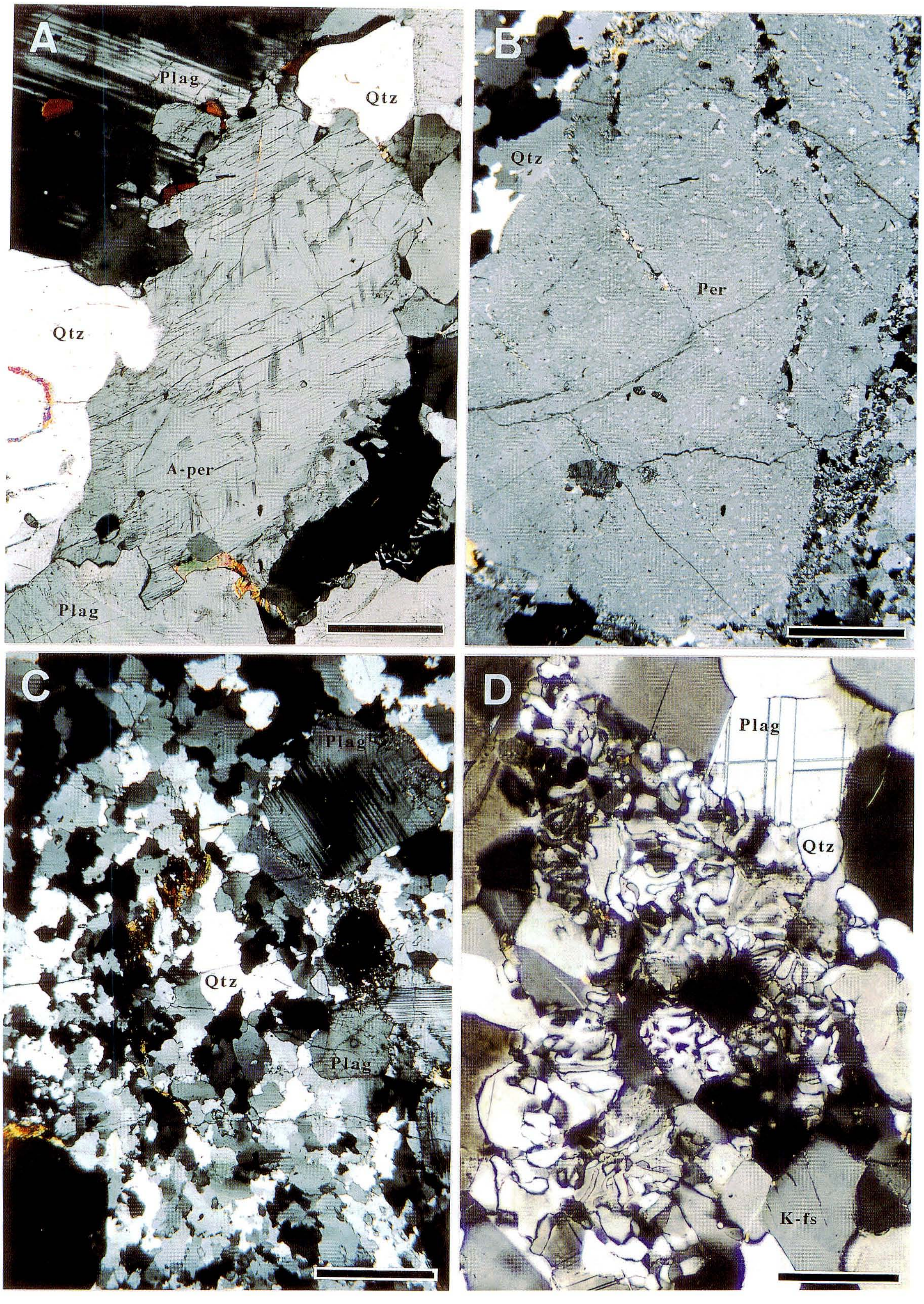
*Revised manuscript accepted March 13, 2000.*

Plate 1



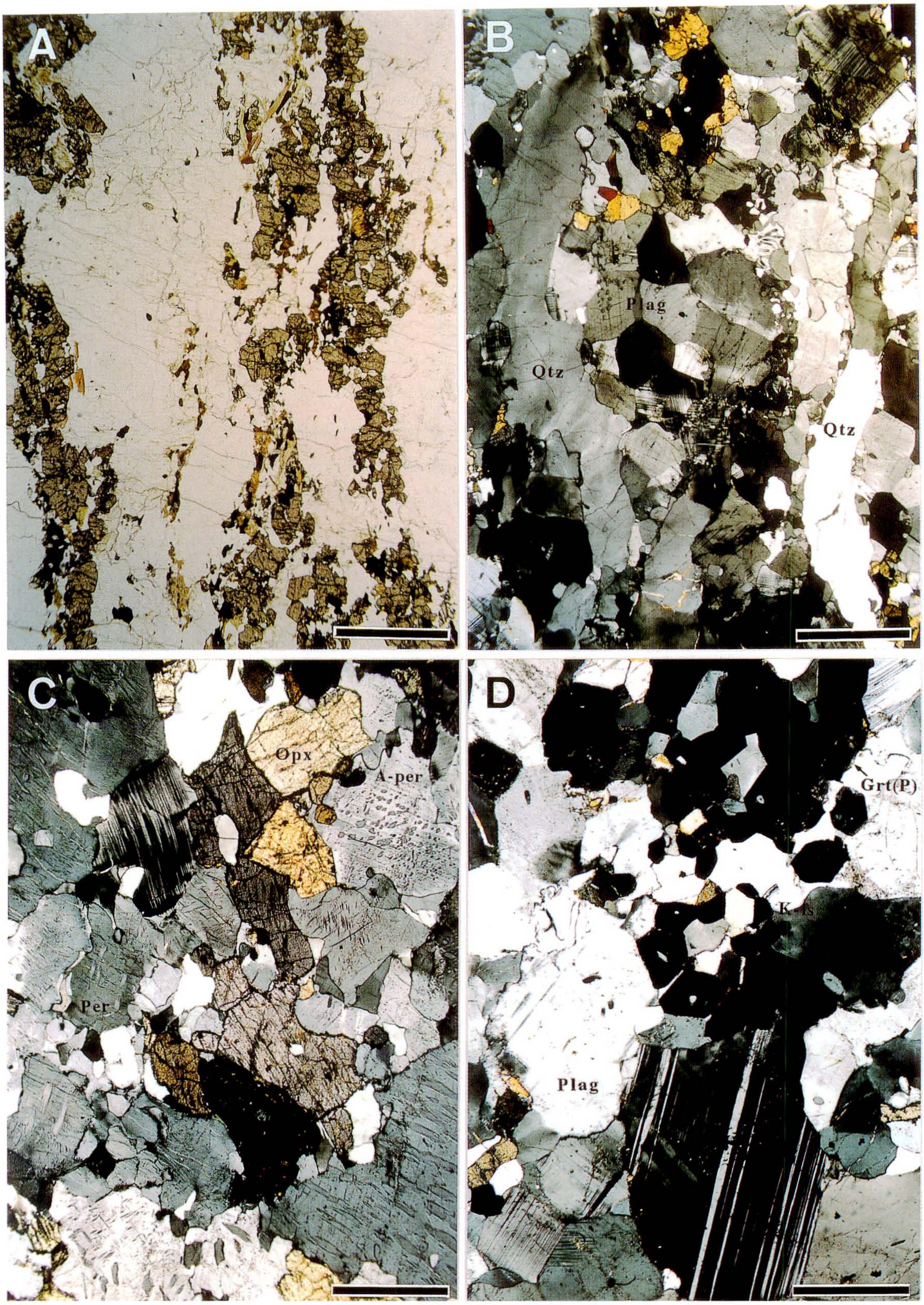

A. The photomicrograph showing the development of partial coronal garnet (Garnet (c)) around orthopyroxene in the charnockitic variety. Parallel nicols. Length of the scale bar is 0.5 mm. B. The same photomicrograph with crossed nicols. Length of the scale bar is 0.5 mm. C. Photomicrograph showing development of thin garnet corona (Garnet(c)) around ilmenite (Ilm). The development of patchy and euhedral biotite is also showed. Parallel nicols. Length of the scale bar is 0.5 mm. D. Photomicrograph showing the porphyroblastic garnets (Garnet (P)) with included quartz and the later biotite in the quartzofeldspathic portion. Parallel nicols. Length of the scale bar is 0.2 mm.

Plate 2




A. Photomicrograph showing antiperthites (A-per) in the quartzofeldspathic portion. Crossed nicols. Length of the scale bar is 0.5 mm. B. Photomicrograph showing coarse perthite (Per) grain with different sizes and orientation of exsolution lammela. Crossed nicols. Length of the scale bar is 0.5 mm. C. Extensive recrystallization of quartz grain showing serrated grain boundary. Crossed nicols. Length of the scale bar is 0.5 mm. D. Photomirograph showing worm like myrmekite intergrowth in the quartzofeldspathic portion. Crossed nicols. Length of the scale bar is 0.2 mm.

Plate 3




A. Photomicrograph showing the gneissic layering composed of garnet, pyroxene and biotite rich layer and quartzofeldspathic layers. Parallel nicols. Length of the scale bar is 2.0 mm. B. Deformed elongated ribbon shaped quartz and feldspar grains with polygonal plagioclase. Crossed nicols. Length of the scale bar is 2.0 mm. C. Deformed orthopyroxene (Opx) and defromed twin lamellae of plagioclase(Plag). Crossed nicols. Length of the scale bar is 1.0 mm. D. Photomicrograph of enderbite showing the relative abundance of plagioclase over K-feldspar. Crossed nicols. Length of the scale bar is 1.0 mm.