

Geological Survey in Southern to Eastern Peninsular India, 1992

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(With 11 Figures and 2 Tables)

Abstract

The field survey during October-November 1992 was accomplished, supported by the Monbusho Fund of Japanese Government. Participants were seven Japanese and three Indians, assisted by several Indian scientists from different organizations. Survey areas included surrounding Trivandrum, southern Karnataka, near Madras, near Hyderabad, surrounding Godavari Valley, surrounding Visakhapatnam, surrounding Bhubaneswar, and Singhbhum Craton area. Geologic outlines of these areas, some of the field observations along with themes to be studied by us in future are given. Total amount of rock samples collected were about 800 kg. Laboratory works are in progress mostly with regard to petrology, petrochemistry and geochronology.

Key Words: Dharwar Craton, Eastern Ghats, Granulite, India, Precambrian

Introduction

When and how did the East Gondwana form? This is one of the utmost attractive topics in the present-day researches on crustal history and global tectonics. Geology of Peninsular India is considered to provide one of the key resolution to the above question. The east coast of India has generally been considered to have juxtaposed with East Antarctica; but the detailed mode of juxtaposition differs according to researchers and continuation of geologic characteristics is not well constrained. Furthermore, there still remains a view that western Australia possibly juxtaposed with the east coast of India. Although extensive researches have been conducted on the Precambrian geology of Peninsular India, drastic progress of geosciences both in global tectonics as well as detailed structural, petrological and geochronological studies requires further work when we attempt to investigate the mode of juxtaposition of India with other continental fragments during Precambrian times.

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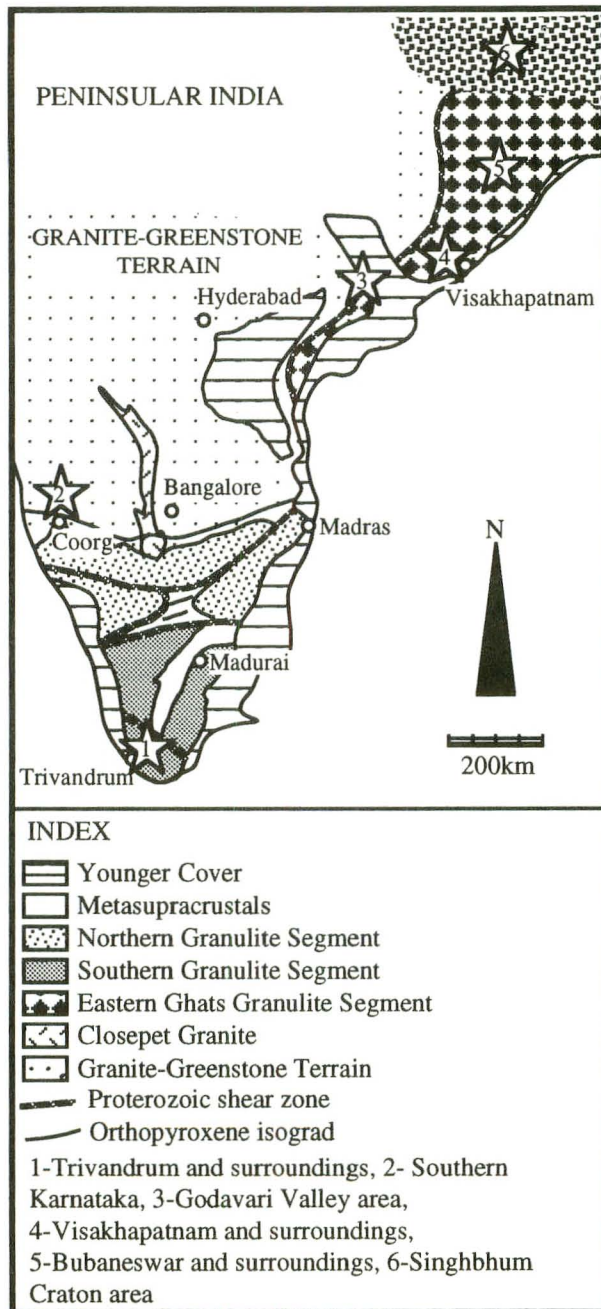


Fig. 1. Geologic outline of Peninsular India showing field survey areas during 1992 (the geologic outline is referred after UNNIKISHNAN-WARRIER *et al.*, 1993).

Table 1. Geological survey in southern to eastern Peninsular India

Survey area	Survey period	Scientists
Surrounding Trivandrum	Oct. 18-26	Kano, Kunugiza, Rao, Shirahata, Sohma, Unnikrishnan, Venkatesh, Yoshida (M. Santosh ¹ , V. Nanda-Kumar ¹)
Madras	Oct. 25-26	Rao, Unnikrishnan, Yoshida (K. C. Rajasekaran ² , V.R. Mohan ²)
West of Bangalore	Oct. 28	Kano, Kunugiza, Rao, Shirahata, Sohma, Venkatesh, Yoshida (A. S. Janardhan ³ , M. Jayananda ³ , B. Mahabaleswar ⁴)
Southern Karnataka	Oct. 29-Nov. 2	Kano, Kunugiza (A. S. Janardhan ³ , M. Jayananda ³)
Surrounding Godavari	Oct. 30-Nov. 2	Rao, Shirahata, Venkatesh, Yoshida, (R.K. Chakraborti ⁵ , T. Rajesham ⁵)
Hyderabad	Nov. 1-2	Sohma (H. Sarvothaman ⁵)
Surrounding Visakhapatnam	Nov. 5-9 Nov. 13-19	Kano, Kunugiza, Rao, Shirahata, Sohma, Yoshida (S.R. Divi ⁶ , A.T. Rao ⁷) Arima, Yamaguchi (A.T. Rao ⁷ , T.R. Rao ⁷)
Surrounding Bhubaneswar	Nov. 13-15	Kano, Kunugiza, Rao, Shirahata, Sohma, Yoshida (S. Acharya ⁸ , S. Bhattacharya ⁹ , M. Das ⁸ , N.K. Mahalik ⁸ , S.K. Sen ¹⁰)
Singhbhum Craton	Nov. 16-19	Kano, Kunugiza, Rao, Shirahata, Sohma, Yoshida (S.L. Ray ¹¹ , A.K. Saha ¹¹)

1: Centre for Earth Science Studies, Trivandrum, 2: Madras University, Madras, 3: Mysore University, Mysore, 4: Bangalore University, Bangalore, 5: Geological Survey of India, Hyderabad and Calcutta, 6: Osmania University, Hyderabad, 7: Andhra University, Visakhapatnam, 8: Utkal University, Bhubaneswar, 9: Indian Statistical Institute, Calcutta, 10: Jadavpur University, Calcutta, 11: Presidency College, Calcutta.

Thus, we started a new research project titled "Comparative Study of India and Antarctica during Precambrian" as a joint India-Japan research program for 1991-1994, so as to contribute to the IGCP288. The 1992-1993 program is funded by the Ministry of Education, Science and Culture, Japan (MONBUSHO).

Geological Survey in Southern to Eastern Peninsular India

The field survey was conducted during the period from 15th October to 26th

November, 1992, by the members of the Monbusho program including seven Japanese and three Indian scientists, assisted by several Indian scientists. Survey areas include five granulite areas including the areas surrounding Trivandrum, Visakhapatnam, Bhubaneswar etc. and three Archaean cratonic areas including the areas southern part of Karnataka state, south of Godavari Valley, and the Singhbhum Craton (Fig. 1, Table 1). Details of major areas of the survey are given below.

Surrounding Trivandrum

General. The extreme southern part of Peninsular India comprises a vast supracrustal sequence known as the Kerala Khondalite Belt (KKB), predominantly composed of charnockite*-khondalite-leptynite suits with minor amount of basic granulites, calc-silicates and quartzites (CHACKO *et al.* 1987). It is bounded in the north by the Achankovil Lineament whereas the southern part is composed of the Nagarcoil massive charnockite (Fig. 2). The Achankovil Lineament is believed to be late Proterozoic in age. Geochronological data are sparse from the KKB. Available ages show that the incipient charnockites were formed around ~500 Ma during the Pan-African extensional regime in this terrain (UNNIKRISHNAN-WARRIER *et al.* 1993).

The incipient charnockite. The incipient charnockites occur at many places in the KKB. They are mostly formed as veins and pods with some dominant orientations in the gneisses. Comprehensive studies in the last one decade have documented more than one mode of incipient charnockite formation from variety of quarries; in almost all cases from southern India, flushing of CO₂ has been considered instrumental for their formation (SANTOSH, 1991; YOSHIDA and SANTOSH, 1994). In Nellikala proximal to the Achankovil Lineament, cordierite-bearing charnockites are developed. They show symplectic intergrowth of cordierite and hypersthene at the expense of garnet, clearly indicating decompression suggesting the rapid uplift of the terrain (NANDA-KUMAR *et al.* 1991). Small exposures of augen gneiss cut by the incipient charnockite were noticed near Ayur proximal to the Achankovil Lineament. The incipient charnockite formation can also be seen at Mannantala near Trivandrum, and in Kottavattom south of the Achankovil Lineament. In the Mannantala Quarry, the incipient charnockite occurs in metasedimentary gneisses of upper amphibolite grade (Fig. 3A). The gneissic foliation in these areas are completely obliterated and younger pegmatitic charnockite veins are found to traverse these lithologies (YOSHIDA and SANTOSH 1987). At the Nuliyam Quarry about 40 km SE of Trivandrum, three lithological units are exposed; calc-silicate gneisses of unknown thickness at the bottom of the quarry immediately overlain by coarse-grained massive charnockite that is again overlain by gneiss-incipient charnockite association. Graphite-bearing pegmatite veins cut across both the massive charnockite and the gneiss-incipient charnockite association. In this quarry, CO₂ is

* Dark greyish rocks with intermediate to acid composition carrying orthopyroxene.

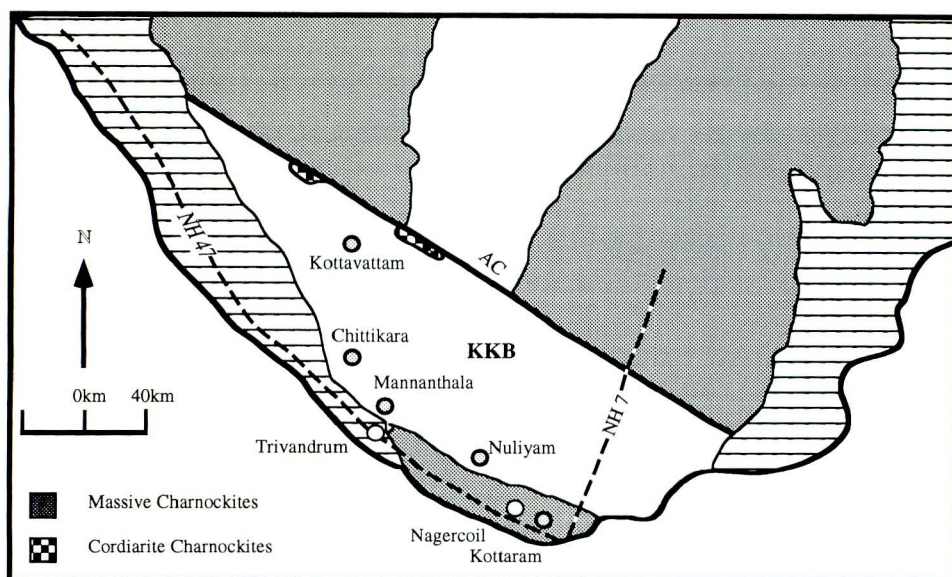


Fig. 2. Geologic outline and locations of field survey of the area surrounding Trivandrum (Geologic outline is modified from SANTOSH, 1991)

AC: Achankovil Lineament, KKB: Kerala Khondalite Belt, NH: National Highway.

considered to have been derived by the decarbonation of local calc-silicate lithology producing a total conversion of the gneiss into charnockite near the contact, and effecting a partial conversion away from the contact (JACKSON and SANTOSH 1992).

Khondalite. At another location north of Trivandrum in a quarry near Chittikara, the dominant lithology is garnet-biotite-sillimanite metapelite known as the khondalite having cordierite along compositional banding. They also contain cordierite-graphite veins and patches, thus suggesting two generations of cordierite. Stable carbon isotope studies of single graphite grains by SANTOSH and WADA (1993) showed strong isotopic zonation in single grains of graphite. This has been interpreted to show precipitation of graphite from the carbonic fluids.

The massive charnockites. The massive charnockites at Kottaram in the Nagarcoil Block show igneous texture within which xenolithic layers of metapelite are involved (Fig. 3B). A syenite pluton occurs nearby and are considered to be associated with the massive charnockites. This charnockite massif is reported as a separate geological unit from the KKB even though the relationship between the two units is not clear (SRIKANTAPPA *et al.*, 1985).

Conclusion. The KKB provides exciting themes on granulite petrogenesis as evidenced by numerous and varied occurrence of incipient charnockites. Detailed structural analysis appeared possible due to fresh quarry faces. Further, logistic conditions are convenient throughout the area. As a result, detailed studies may follow

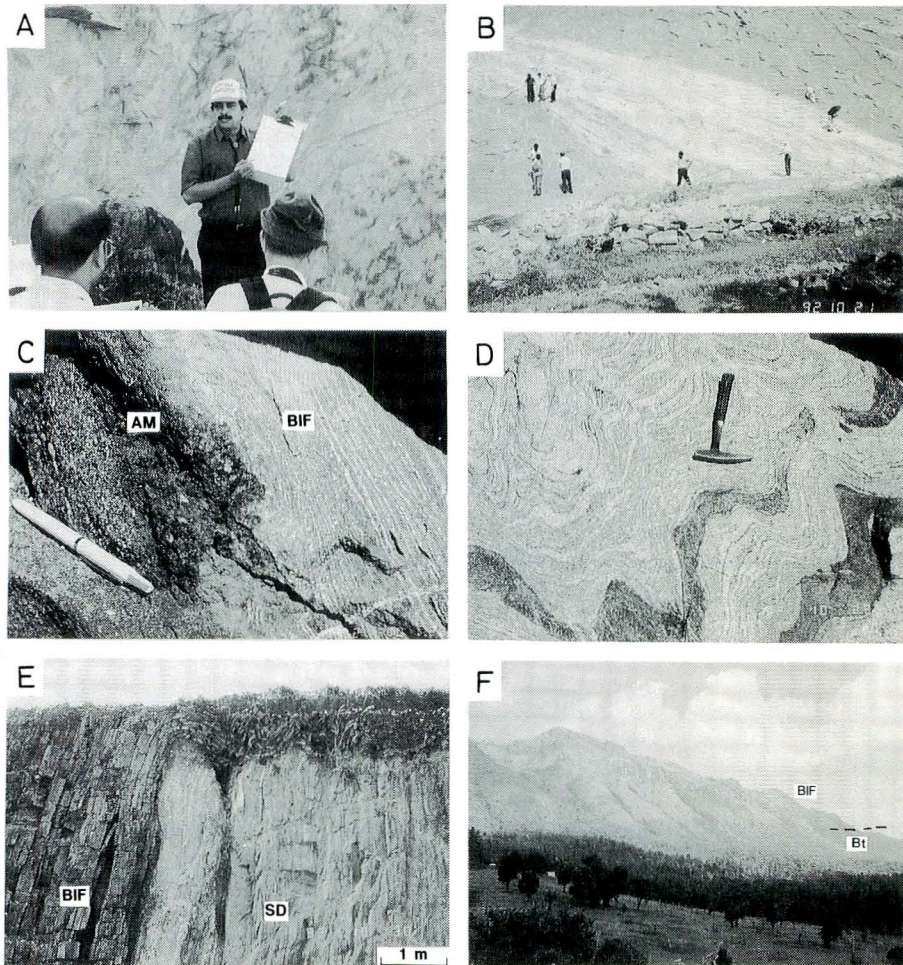


Fig. 3. Field pictures in areas surrounding Trivandrum and southern Karnataka. (A) An incipient charnockite outcrop at Mannanthala quarry guided by M. Santosh. (B) A xenolithic metapelite layer within the massive charnockite at Kottaram. (C) Boundary between BIF and garnet amphibolite (AM) at Nugu dam, Sargur area. (D) Highly folded TTG near Begur cross, Sargur area. (E) Folded BIF and associated sedimentogeneous schists (SD) in the Holenarsipur Belt near Hassan. (F) A distant view of Mt. Bababudan with a steep cliff where BIF contacts with basic volcanic rocks (Bt).

under the present joint research program.
(C.U.W.)

Southern Karnataka

General. The Dharwar Craton, known as a typical Archaean greenstone-granite terrain in the world, is well exposed in the Karnataka State in South India. Although the duration of the field survey was very short, we could see essential lithological constituents

Table 2. Classification and correlation of geologic units in southern Karnataka (referred after SWAMI NATH and RAMAKRISHNAN, 1990)

Middle to Late Proterozoic	Kaladgi, Badami, and Bhima Groups
~ Unconformity ~	
Late Archaean to Early Proterozoic (2400-2600 m.y.)	Dharwar Supergroup { Chitradurga Group Unconformity Bababudan Group
~ Unconformity ~	
Middle Archaean (2900-3000 m.y.)	Peninsular gneiss { Migmatites, gneisses, granitoids
Early to Middle Archaean (>3000 m.y.)	Sargur Group { Several unclassified associations of supracrustal rocks
Basement not seen (3400 m.y. old gneisses)	

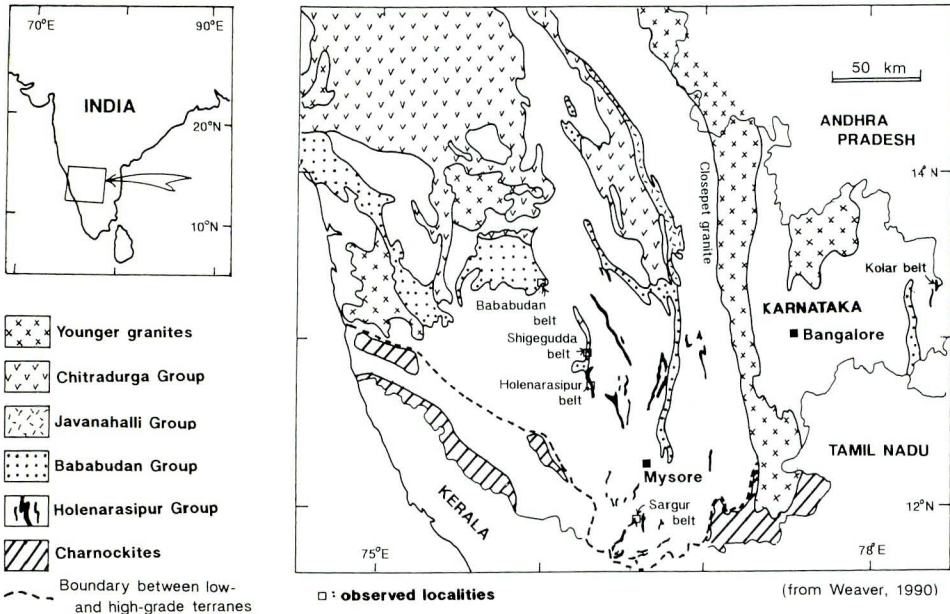


Fig. 4. Geologic outline and locations of field survey of southern Karnataka (the geologic outline is modified from WEAVER, 1990).

in several areas, such as the Sargur, Holenarsipur and Bababudan areas.

The southern part of the Dharwar Craton in southern Karnataka consists mainly of two major rock-units; (a) Peninsular Gneiss originated from tonalitic, trondhjemitic and granodioritic rocks (TTG), and (b) greenstone belts composed of basic to ultrabasic rocks, banded iron formation (BIF), quartzite and other supracrustals. The Peninsular gneiss is mostly tonalitic, trondhjemitic and granodioritic in composition (TTG) with

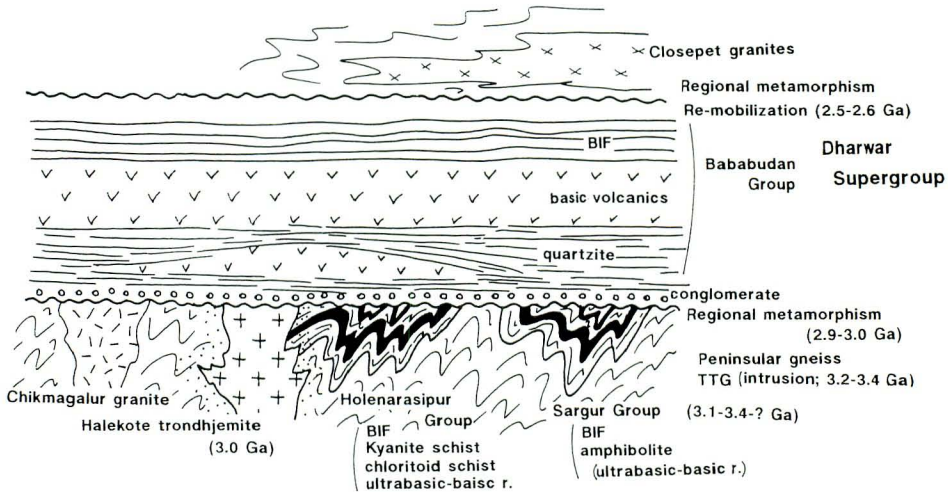


Fig. 5. Generalized geologic column of the southern part of Dharwar Craton (compiled from SWAMI-NATH and RAMAKRISHNANN; 1990, WEAVER, 1990 and personal communication by M. JAYANANDA).

minor gabbroic to dioritic inclusions and granitic to pegmatitic veins. The Peninsular gneiss shows highly folded and sheared nature with distinct foliation, but the petrographical features are widely uniform through vast areas. The greenstone belts crop out in several areas as narrow bands within the Peninsular Gneiss (Fig. 4). The relationship between the greenstones and Peninsular Gneiss has long been discussed by Indian geologists. Most of the researchers (e.g. VENKATA DASU *et al.*, 1991) recently agree with the general view that there are several stages in the formation of greenstone belts as summarized in Table 2 and Fig. 5. The Sargur and Holenarasipur belts and their equivalents are the oldest geologic units in South India. Rocks of these belts are intruded by TTG and occur as xenolithic masses within TTG, and their ages may be older than 3.0 Ga. The Bababudan and major part of the Dharwar Supergroup represent younger belts of late Archaean to early Proterozoic in age (<2.9 Ga.). These younger belts unconformably overlie the Peninsular Gneiss with distinct basal conglomerate. Overall the metamorphic grade increases from north to south in the Dharwar Craton, and reaches upper amphibolite to granulite facies conditions in the southern part of Karnataka (JANARDHAN *et al.*, 1982; HANSEN *et al.*, 1984).

Sargur area. The BIF and amphibolite at Nugu dam were observed at the outcrop situated at ca. 40 km south of Mysore (Fig. 4). Each band of BIF-bed ranges from 20 cm to 2-3 m in thickness, and is intercalated by massive to foliated amphibolite (Fig. 3C). The contact between them is clear, and shows no structural discontinuity. The BIF is composed mainly of magnetite, and the amphibolite sporadically carries garnet. Near Begur cross, an outcrop consisting of coarse- to medium-grained TTG including fine- to medium-grained metabasite was observed. They are totally well folded (Fig.

3D). The TATA Steel magnesite mine works network veins of magnesite in strongly weathered serpentinite at open pit.

Holenarsipur area. Ultramafic rocks (amphibolite) observed in this area are generally metamorphosed in the upper greenschist to lower amphibolite facies conditions. They are schistose and partly massive, and contain chromite. Their origin, whether volcanics or peridotites, is unknown, because original textures mostly disappear. Further, a continuous section consisting of TTG, BIF, mafic meta-volcanics and meta-sediments was also observed along the road-cutting south of Hassan (Fig. 4). In this section, TTG is directly in contact with mafic meta-volcanic rocks, and may be in an intrusive relationship with them. There are several bands of BIF (1 to 5 m thick) within the alternation of volcanic and sedimentary rocks. Some bands of BIF are distinctly folded (Fig. 3E). This outcrop is one of the target for 1993's field observation. An outcrop of Halekote Trondhjemite body is also studied. It is composed mainly of gneissic trondhjemitic rocks similar to TTG, and is a part of the intrusive body of ca. 3.0 Ga in the Holenarsipur belt. Both meta-rhyolite and basalt were observed at the same outcrop in the Holenarsipur belt, suggesting a bimodal volcanic activity in this belt. The meta-rhyolite is quartz blastoporphyrritic micaceous schist showing leptite-like feature, and is assumed to be originated from rhyolite. The schist belt units have undergone medium-pressure type metamorphism, and pelitic rocks have mineral assemblages such as chloritoid-garnet and kyanite-staurolite.

Shigegudda area. The Shigegudda belt, the equivalent of the Bababudan belt, consists of mafic meta-volcanic rocks (amphibolite), quartzite and quartzose conglomerate. The conglomerate overlies on TTG and contains many pebbles of rounded quartzite embedded in quartzose matrix, and grades into quartzite bed upward.

Bababudan area. The Bababudan belt near Chikmangalur is composed mainly of quartzose conglomerate, quartzite, mafic meta-volcanic rocks (amphibolite) and the BIF in a general ascending order from the TTG basement to the Bababudan hill top. The BIF at the hill top is well banded with magnetite-hematite rich bands and quartzite layers, and amounts to more than 200–300 m in total thickness (Fig. 3F).

Conclusion. We recognized two major problems in this area: (1) the origin and development of granitic rocks (TTG) including re-mobilization of them (Closepet Granite), and (2) the nature and tectonic setting of supracrustal rocks in greenstone belts consisting of BIF and mafic igneous rocks. Both the problems are connected with the crustal growth during the Archaean times. The problem concerned with granitic rocks has been discussed by many researchers on the basis of geochemical and isotopic data (e.g., JAYANANDA *et al.*, 1991).

Recently, several Japanese geologists have opined that the Archaean greenstone belts from Isua, Greenland and the Pilbara Craton in Australia were of accretionary complex. The BIF and associated chert and mafic-ultramafic rocks are considered to be the products at mid oceanic ridge, and the sandstones and conglomerates etc. at

subduction zone; greenstone belts represents a generalized travel history of the Archaean oceanic plate. From this point of view, we have several questions as follows; (1) is it also in the Dharwar Craton? And/or (2) what is the real geologic condition of evolving continents during Archaean times? Recent accumulation of geochemical and isotopic data on granitic rocks have shown that the Peninsular Gneiss of the Dharwar Craton is of primordial continental crust (TTG) formed by partial melting of basaltic crust. The Closepet Granite represents remelted product of the Peninsular Gneiss at a subduction zone (JAYANANDA *et al.*, 1991). Supracrustal rocks in this area, however, seem not to have been fully studied from this view point. Detailed geological, petrological and geochemical data are needed. To answer these questions, we plan to revisit the Archaean greenstone belts in the Karnataka State in near future.

(T.K. & K.K.)

Godavari Valley and Surrounding Area

General. The east coast of India is traversed by three major graben-like basins namely the Godavari, Mahanadi and the Damodar. These basins are considered to be of the Phanerozoic rift system. Further, there are evidences to suggest that these rift systems were active since Proterozoic times and are therefore crucial in Gondwana reconstruction models. Presently, the tectonic significance of these graben features remains to be fully understood. The Godavari Graben was considered to be a tectonic join between two cratonic blocks (RADHAKRISHNA and NAQVI, 1986) and as an intracratonic thrust zone by Rogers (1986). The recent report on granulite facies rocks along the southern flank of the Godavari Graben (RAJESHAM *et al.*, 1993) offers a new perspective to the tectonic evolution of the region dating back to the Archaean age (RAJESHAM and others, 1993 a, b). It is observed that the Godavari Valley (Fig. 7A) is piled with the Gondwana sediments of Palaeozoic-Mesozoic ages. These Gondwana sediments are flanked on either sides by mildly metamorphosed Proterozoic sediments which in turn are bordered with Archaean granulites. Their zonal distribution indicates episodic basinal tectonics along the valley. Since rocks covering a wide span of ages (Archaean-Mesozoic) are exposed in the lower reaches of the Godavari Valley, they are considered to be crucial in investigating tectono-thermal evolution in relation to the Precambrian tectonics of South India. This may have bearing in understanding the rift tectonics and its implication on the Gondwana breakup. As an initial effort, a four day reconnaissance fieldwork was carried out in the Godavari Valley and surrounding areas. Besides, several localities of geological importance in the Khammam District of Andhra Pradesh State were also visited (Figure 6).

The Peninsular Gneiss and Phakhal Formation. In the vicinity of Suryapet, a quarry outcrop of Peninsular Gneiss was studied (loc. 1 in Figure 6). The Peninsular Gneiss shows typical migmatitic structures with boudinaged and broken blocks of amphibolite. The pink granitic portions represent re-mobilized material and are

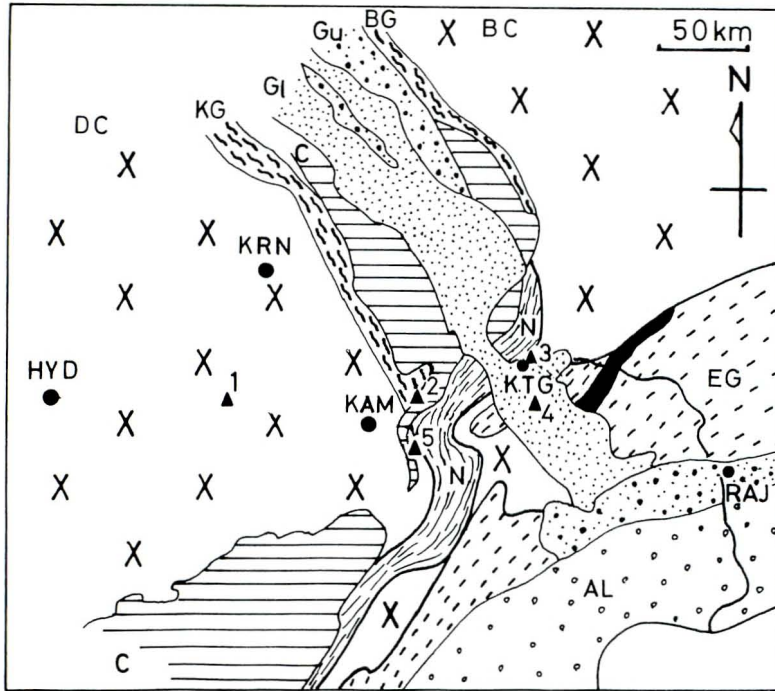


Fig. 6. Geologic outline and locations of field survey surrounding Godavari Valley (the geologic map is based on the Geological Survey of India, 1973 and RAJESHAM *et al.*, 1993 a, b).

Solid triangle with numerals: Location of field observations. AL: Alluvium, BC: Bastar Craton, BG: Bhupalapatana Granulite Belt, C: Cuddapah Super Group and equivalent, DC: Dharwar Craton, EG: Eastern Ghats Granulite Belt, GI: Lower Gondwana Sediments, Gu: Upper Gondwana Sediments, KG: Karimnagar Granulite Belt. HYD: Hyderabad, KAM: Khammam, KRN: Karimnagar, KTG: Kothagudem, RAJ: Rajahmundry.

considered to be equivalent to the Closepet Granites. Two kilometers east of Khammam, dolomitic rocks intercalated with cherty layers were observed (loc. 2 in Figure 6). These rocks belong to the Phakhal Formation that is considered to be the equivalent of the upper Cuddapah rocks. The cherty layers show tight (almost reclined) folded structures. These rocks are a part of the Sharanvala outlier consisting of the Phakhal basin which is surrounded by the Peninsular Gneiss. The dolomitic rocks show shear movement indicating crustal shortening.

The Nellore Schists. At some other outcrops near Kothagudem (loc. 3 in Figure 6), the basement rocks consisting of garnet-kaynite schists and garnet-muscovite schists, pebbly biotite schist etc. belonging to the Nellore Schist Belt were observed. They are intensely folded and carry dominant lineations. The Gondwana Sediments (Barakar Formation) overlie these rocks, although actual contact was not observed. Further, the basement rocks of the Nellore Schist Belt (garnet-sillimanite schist) overlain by the

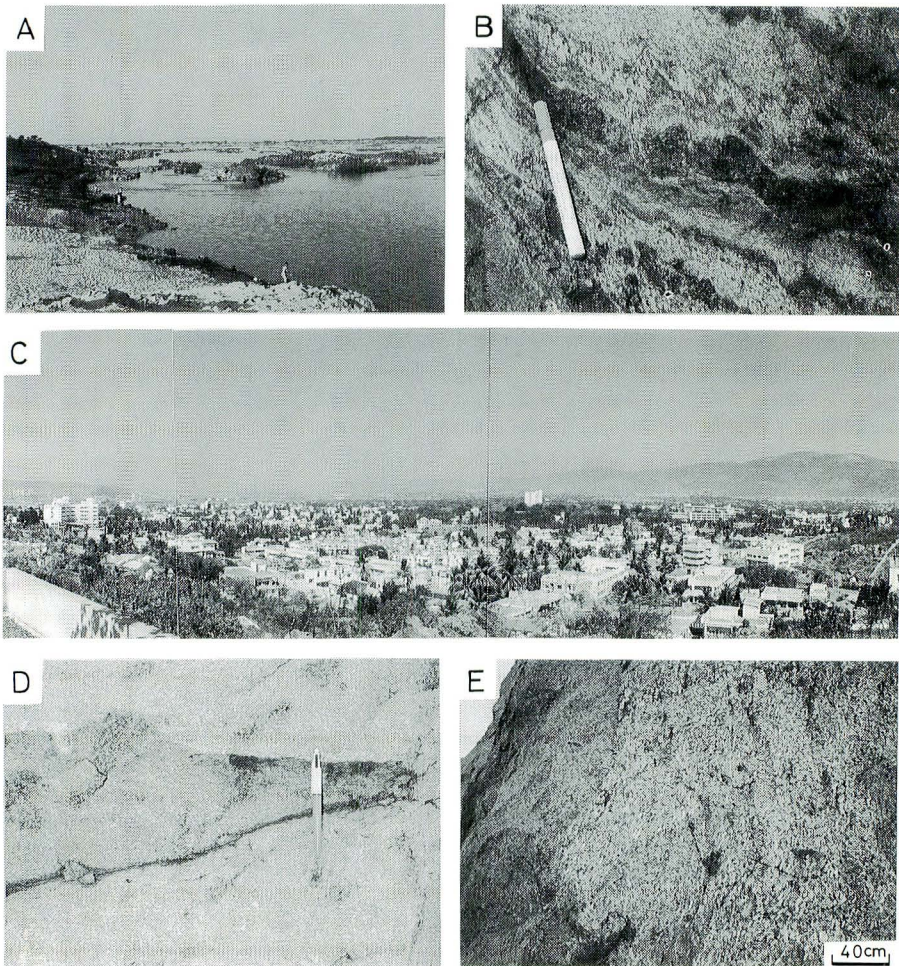


Fig. 7. Field pictures in areas surrounding the Godavari Valley and Visakhapatnam. (A) The Godavari River viewed from Bhadrachalam bridge. (B) Banded charnockite near Sabbavaram, Godavari Valley area. Later schistosity inclined from the banding is seen. (C) The town of Visakhapatnam with the Kailasa Hill in the back which is composed of khondalite. (D) Incipient charnockite developed directly within the pink leptynite (upper right) as well as within the pink pegmatite (lower right) that cuts the leptynites. (E) Porphyritic charnockite within non-porphyritic charnockites, at Airport Hill.

sediments belonging to the Talchir Formation were observed at a locality near Ramapuram (loc. 4 in Figure 6).

Granulites. A granulite quarry near Sabbavaram was visited (loc. 5 in Figure 6). Here, charnockite, garnetiferous gneiss and younger metabasic intrusives were observed. The charnockites are thinly banded and show folded structures in some outcrops (Fig. 7B). The meta-basic dykes have been intruded by quartzo-feldspathic veinlets which

represent the melt fraction during the dyke injection.

Conclusion. The area surrounding Godavari Valley is considered crucial to investigate the tectonics and tectonothermal history of Peninsular India. Characterization of structural and metamorphic features of different geologic units were the main objectives of the present study. However, short period of survey and scarcity of good outcrops in this area have been disappointing. Samples of important lithologies collected during the present survey will receive future laboratory studies and are expected to provide useful information for future. A possibility of future field investigations of this area is under consideration. (V.R.)

Surrounding Visakhapatnam

General. This area represents one of the type areas of the Eastern Ghats Granulite Belt and has been studied from various geoscientific points of view. Classic report of sapphirine from this area evinced keen interest among many petrologists to carry out advanced studies of this area (e.g., MIDDLEMISS 1904; GREW 1982; GREW and MANTON, 1986; KAMINENI and RAO, 1988; SENGUPTA *et al.*, 1990). Geochronological studies of the Eastern Ghats Granulite Belt also came mostly from this area (e.g., VINOGRADOV *et al.*, 1964; CRAWFORD, 1974; PERRAJU *et al.*, 1979; RAO *et al.*, 1980; PAUL *et al.*, 1990). Works by A.T. Rao and co-workers have given general geologic and structural features of this region (SRIRAMADAS and RAO, 1979; RAO and RAO, 1992). The area is underlain mostly by khondalites, leptynites and charnockites with minor quartzite, calc-silicate gneiss and pyroxene granulites. They trend NE-SW to E-W, having major isoclinal fold structures, superimposed by NW-SE or N-S cross folds (Fig. 8). The major isoclinal folds may correspond to the D₃ folds, and the later cross folds to the D_{late} fold of HALDEN *et al.* (1982) identified in the Angul area northwest of Bhubaneswar. Some of important observations in the field are given below.

The khondalites, leptynites and incipient charnockites. Khondalites and leptynites were observed at the road-cut along the eastern foot of the Kailasa Hill (Fig. 7-C) facing to the Bay of Bengal (Loc. 1, Fig. 8). The leptynite in the south changes gradually to the khondalite, the intercalation of the latter within the former increasing northward. At a hilly outcrop (Loc. 2, Fig. 8) in Vizianagaram circa 50 km northeast of Visakhapatnam, sapphirine-bearing quartzite reported by KAMINENI and RAO (1988) were observed. The rock is dark gray and appears as an ordinary pelitic gneiss. It is associated with the leptynites. The quartzite shows rootless isoclinal small folds plunging gently eastward, the mineral lineation paralleling it. These structures may be comparable with the D₂ structures of HALDEN *et al.* (1982) identified in the Angul area. It is worth noting that PERRAJU *et al.* (1979) obtained a ca 816 Ma Rb-Sr whole-rock age for quartz-feldspathic veins and the country gneissic rock from Sankili, about 130 km northeast of Visakhapatnam and interpreted the age as the age of granitic activity. In the town area of Visakhapatnam, leptynites were observed throughout. Small amount

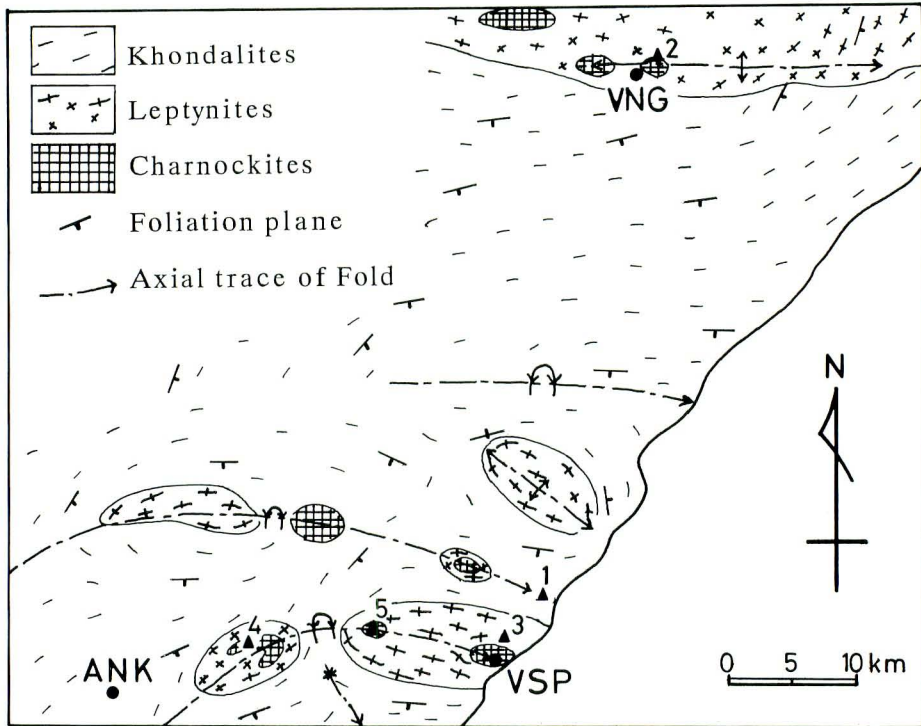


Fig. 8. Geologic outline and locations of field survey of the area surrounding Visakhapatnam (geologic sketch is compiled from SRIRAMADAS and RAO, 1979, and RAO, 1991). Solid triangle with numerals: Location of field observations. ANK: Anakapalle, VSP: Visakhapatnam, VNG: Vizianagaram.

of pyroxene granulites, charnockites, calc-silicate gneisses and khondalites were found sporadically, associated with the leptynites. At a cliff backside of a village in the Visakhapatnam town (Loc. 3, Fig. 8), the pink leptynite having E-W schistosity is cut by veins and pods of pink granitic pegmatite trending mostly NE-SW with a moderate southeasterly dip. Some part of the pegmatite as well as the leptynite are converted into hypersthene-bearing charnockitic pegmatite, appearing somewhat similar phenomena to that of the incipient charnockites observed in the area surrounding Trivandrum (Fig. 7-D).

Massive charnockite. Massive charnockites were observed at several outcrops. At the Aganampudi quarry (Loc. 4, Fig. 8), the charnockites are garnetiferous and dominantly porphyritic with elongated feldspar phenocrysts having elongation lineations plunging moderately west-southwestward. At the Airport Hill about 15 km west of the Visakhapatnam town (Loc. 5, Fig. 8), medium- and coarse-grained charnockites (tonalitic and granodioritic) are dominant, partly with shulieric layers of fine-grained charnockites. They all show a general NW-SE strike with near-vertical dip. Pegmatitic charnockite veins develop sporadically throughout, cutting all the above lithologies, trending

NNE-SSW with a near-vertical dip. Porphyritic charnockite with distinct euhedral feldspars is found to occur (Fig. 7-E), appearing to cut the non-porphyritic charnockite, although the foliation shown by the elongated feldspar is concordant to the general foliation of the charnockites. Allanite-bearing pegmatite occurs at this outcrop cutting charnockites and running NW-SE with a moderate dip northeastward. U-Pb dating of allanite for both the pegmatite and pegmatitic charnockite from this locality gave circa 2000 Ma (RAO *et al.*, 1980).

Conclusion. Through the present survey, a detailed structural analysis of khondalite from both macroscopic and microscopic points of view are considered important, especially in view of comparing with structural studies in Orissa (e.g., HALDEN *et al.*, 1982). Geochronological studies connected with the structural analysis is considered also very effective in this area. This area is also considered appropriate to investigate the stratigraphic succession as the massive charnockite in the base and the leptynites and khondalite overlying it, as was suggested by NARAYANASWAMI (1975) and RAO and RAO, (1992). We hope to carry out these studies in some detail during ensuing years.

(M.Y.)

Surrounding Bhubaneswar

General. The area surrounding Bhubaneswar has been studied from various points of view and it represents one of the type areas of the Eastern Ghats Granulite Belt. Structural and geochronological studies of the Angul area northwest of Bhubaneswar (HALDEN *et al.*, 1982; AFTALION *et al.*, 1988) provided important contributions to the understanding of the tectonothermal history of the Eastern Ghats Granulite Belt. In the Chilka Lake area, west of Bhubaneswar, a post-metamorphic anorthosite mass dated circa 1400 Ma occurs (SARKAR *et al.*, 1981). Structural studies of this area (SARKAR *et al.*, 1981; BHATTACHARYA *et al.*, 1994) are considered to provide a critical key to the tectonothermal history of this belt. The western and northwestern boundary of the Eastern Ghats Granulite Belt to the northwest of Bhubaneswar is reported to be a tectonic line called the Sukinda Thrust (PRASADA RAO *et al.*, 1964) and is thus important to an understanding of the tectonic evolution of Precambrian Peninsular India.

We spent in the latter two areas only three days for the field survey, of which one day was for the Sukinda Thrust and two days were for the Chilka Lake area (Fig. 9). Some details of the field observations are given below.

The Sukinda Thrust. The Eastern Ghats Granulite Belt is juxtaposed with the Shinghbhum Craton to the north, bounded by the Sukinda Thrust (Fig. 9). An outcrop near the Sukinda Thrust was visited. It is about 12 km north from the bridge crossing Maipura, along the highway from Dhanmandal to Palaspal. After several kilometers from the last outcrop of the Eastern Ghats Granulite Belt, composed of well-folded khondalite and charnockitic rocks, an outcrop composed of a heterogeneous peculiar rock was found (loc. 1, Fig. 9). The rock has the appearance of granite or granodiorite

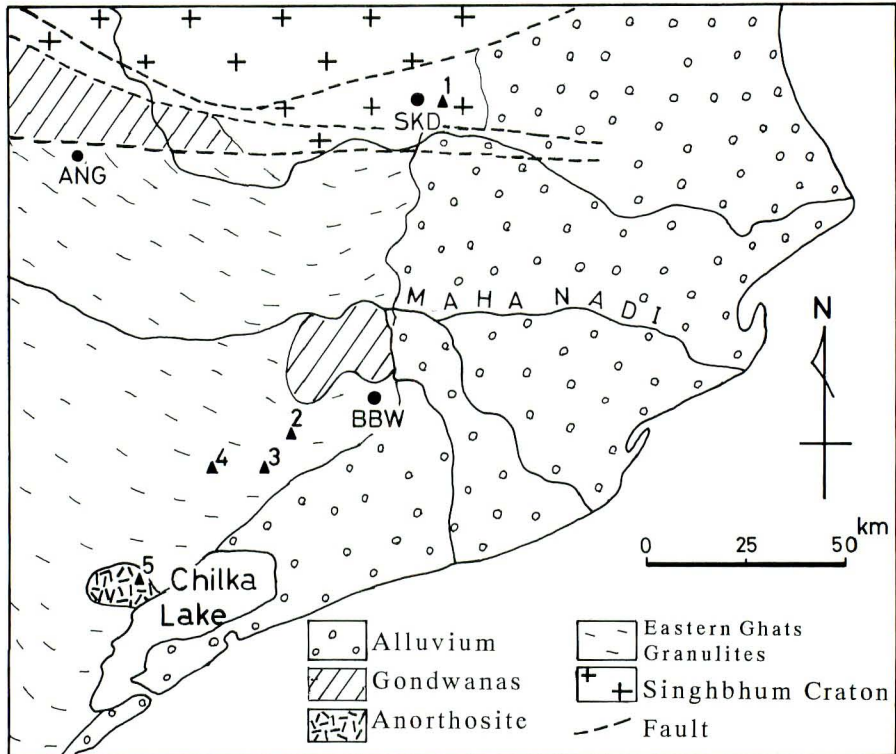


Fig. 9. Geologic outline and locations of field survey of the area surrounding Bhubaneswar (the geologic sketch is modified from MAHALIK, 1984 and 1990).

Solid triangle with numerals: Location of field observations. ANG: Angul, BBW: Bhubaneswar, SKD: Sukinda.

of a shallow emplacement, with numerous rounded to angular blocks of various lithologies, including greenrocks, granitic rocks and gneissic rocks (Fig. 10A). The rock has suffered chloritization, and bears a very faint schistosity trending NNE-SSW and dipping moderately west-southwestward. Some of the xenolithic blocks are also elongated in the same direction. The rock is considered, from a total consideration, to be a kind of intrusive rock having various country rocks as xenoliths, although opinions varied among us whether it is a conglomerate, migmatite or mylonite. A map by MAHALIK (1990) indicates that the outcrop lies on the Sukinda Thrust zone, which bounds the Singhbhum Craton to the north and the Eastern Ghats Granulite Belt to the south, and is underlain by Singhbhum granite having xenolithic blocks of the Iron Ore Group rocks.

Khondalite. In the area surrounding Chilka Lake west of Bhubaneswar, the khondalite-leptynite-charnockite association is well developed. Superimposed folding structures, associated foliations, and various linear structures were noticed at several outcrops (Fig. 10B). At an outcrop south of Khondha (loc. 2, Fig. 9), hinges of rootless isoclinal folds plunge moderately eastward, but the younger crenulation and sillimanite lineations plunge gently westward.

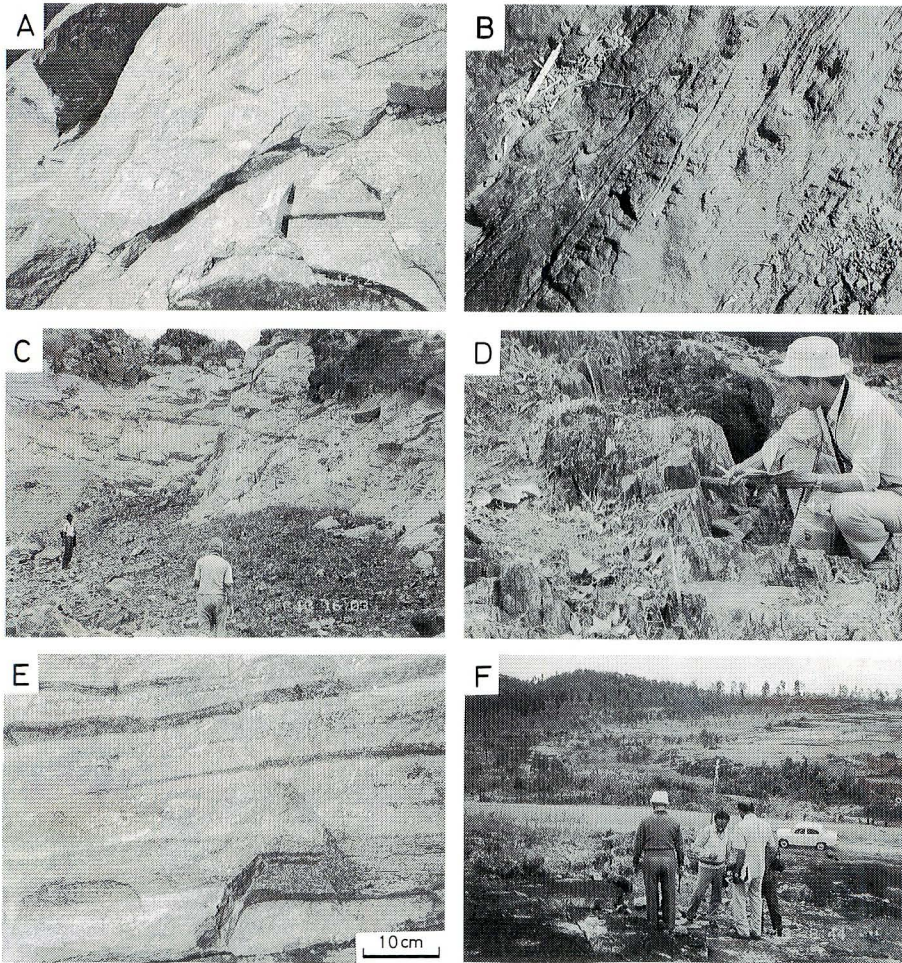


Fig. 10. Field pictures in the area surrounding Bhubaneswar and the Singhbhum Craton area. (A) Granitic rock with angular blocks of various kinds of rocks, near Sukinda. (B) Khondalite showing intrafolial rootless isoclinal fold, at an outcrop south of Khonda. (C) Occurrence of the incipient charnockite. Relict charnockite layers in the left is dispersed into numerous elongated pods (tubes) of incipient charnockite, at a quarry southwest of Khonda. (D) Para-amphibolite of OMG near Champua, the Singhbhum Craton. (E) Banded hornblende gneiss belonging either to OMG or OMTG. Southwest of Champua. (F) A hilly outcrop of the Singhbhum Granite, northeast of Keonjhar.

Charnockites. In some areas where leptynites are dominant, relicts and neozones of charnockite showing spectacular evidence of breaking and making of charnockite occur (BHATTACHARYA *et al.*, in press), although these authors insist that all charnockites within the leptynite are of relict nature. At an outcrop 10 km southwest of Khondha (loc. 3, Fig. 9), continuous layers of relict charnockite (under the breaking) occur within the leptynite. These layers are dispersed and change into numerous pods of the incipient

charnockite (under the making) (Fig. 10C). The leptynite shows faint foliation paralleling the charnockite layers, trending ENE-WSW and dipping steeply southward, and carry quartz elongation lineation plunging gently east-northeastward. Many of the pods have practically the tube shape, and their elongation plunges gently west-southwestward. At another quarry, 1 km southwest of loc. 3, similar phenomena shown by the leptynite and charnockite were observed. The incipient charnockite patches are more or less tabular, nearly paralleling the axial surface of a near-upright fold, which may belong to a later generation. Younger foliation and shear planes filled with biotite run also in nearly the same direction, hinges of the undulation of the shear plane plunging gently west-southwestward.

At a quarry east of Banpur (loc. 4 in Fig. 9), banded charnockite with sporadic thin, basic layers was observed. Pale pink pegmatite veins develop irregularly, altering the charnockite surrounding it. The basic layers show rootless isoclinal folds plunging gently east-northeastward, and a quartzo-feldspathic band cutting the basic layers carries mineral elongation lineation plunging gently west-southwestward.

Anorthosite. A characteristic post-metamorphic intrusion of nearly massive anorthosite, which was dated circa 1.4 Ga (SARKAR *et al.*, 1981), occurs on the west side of the Chilka Lake. At an outcrop in the field along Chilka Lake (loc. 5 in Fig. 9), the anorthosite shows locally a faint foliation trending NNE-SSW, with a gentle inclination westward. The relationship of this structure with that of the surrounding rocks was not examined, although this anorthosite is reported to be post D_1 - D_2 and suffered syn- D_3 deformations in this area (SARKAR *et al.*, 1981); thus the major tectogenesis of the Eastern Ghats Granulite Belt has been considered to be older than circa 1.4 Ga (e.g., RADHAKRISHNA and NAQVI, 1986).

Conclusion. A detailed field study of this area appears crucial to understand the tectonic relationship between the Eastern Ghats Granulite Belt and the Singhbhum Craton, as pointed out by MAHALIK (1990). However, because of the short visit and very limited observations, we could not provide productive views on the nature of the Sukinda Thrust. A detailed field survey is expected to be conducted in the near future.

In the area surrounding Chilka Lake, there is some difference in recognition of the D_1 and D_2 folds from previous studies (SARKER *et al.*, 1981; HALDEN *et al.*, 1982; BHATTACHARYA *et al.*, 1994). The coexistence of the earlier easterly lineation and the later westerly one was met with during the present survey at many outcrops, not only of khondalite but also of leptynites as well as charnockites. This observation is in contradiction to that of BHATTACHARYA *et al.* (1994) who identified l_2 plunging gently westward and l_3 gently northeastward. Our observation in this area is limited and therefore, needs further confirmation. Comparison of structures of this area with those of Visakhapatnam area may provide good information for constructing the structural sequence in the Eastern Ghats Granulite Belt. Spectacular occurrences of breaking and making of charnockite in this region are worth noting. This area is considered to

provide one of the critical examples of the incipient charnockite formation. The structural evidence that BATTACHARYA *et al.* (1994 and in press) described in this area is worth noting as it shows that not a small amount of incipient charnockite-like pods have a relict nature rather than a neozomic one. It is felt that the spectacular outcrops of this area may provide very good fields of study of the intimate relationship of the breaking and the making phenomena of charnockites. These phenomena now appear to the senior author to be genetically associated. It was felt throughout the present observations that charnockitization is associated with some later deformations, as pointed out by HALDEN *et al.* (1982). There is a possibility that the area is coeval in time with the incipient charnockite in the Angul area, about 100 km northwest from the Chilka Lake, which was dated at circa 950 Ma by AFTALION *et al.* (1990).

(M.Y.)

The Singhbhum Craton Area

General. The Singhbhum Craton (Singhbhum-Orissa Iron Ore Craton) is the oldest craton in India (BASU *et al.* 1981; SAHA *et al.*, 1988). A Proterozoic Singhbhum-Dhalbhum mobile belt runs to the north of the Singhbhum Craton, separated from the latter by the Singhbhum Thrust (Fig. 11) (RADHAKRISHNA and NAQVI, 1986). The Older Metamorphic Group (OMG) occupies an area of less than 100 km², and is situated in the western part of the craton. The mass is composed mainly of metapelites, with subordinate para-amphibolites and other supracrustals, which are older than the Older Metamorphic Tonalite-granodiorite Gneiss (OMTG) which has a Nd-Sm whole rock isochron age of ca 3.8 Ga. The OMTG occurs as several masses throughout the craton, the largest mass being in the centre of the northern part of the craton. The largest mass occupies over several hundreds square kilometers. The Singhbhum Granites are extensively developed throughout this craton, intruding into both OMG and OMTG. Three phases of intrusions, ranging in age from ca 3.1 Ga to 3.3 Ga, have been identified (SAHA *et al.*, 1988). The Iron Ore Group occupies mostly the western portion of the area. This group overlies the early phase intrusions but is intruded by the later phase one of the Singhbhum Granites (SAHA *et al.*, 1988). An outline of the geology and tectonic interpretation of the Singhbhum Craton area is given by SARKAR and SAHA (1983). SAHA *et al.* (1988) gave a "sink model" of mafic-ultramafic crust starting from circa 4.0 Ga in this area. Some of our field observations in this area are described below.

The Older Metamorphic Group (OMG) and the Older Metamorphic Tonalite-granodiorite Gneiss (OMTG). An outcrop of OMG was observed (loc. 1 in Fig. 11) near the bank of the Baitarani River near Champua. It is banded para-amphibolite (Fig. 9D) which has banding and schistosity of varying strikes and steep dips carrying steep easterly or westerly plunging mineral and undulation lineations. A small outcrop of OMTG (loc. 2 in Fig. 11) is situated in the paddy field about 17 km SSW of Champua along the road to Keonjhar. It is a mesocratic amphibolite with leucocratic bands. The banding trends NE-SW, with a steep dip. The rock carries an overall

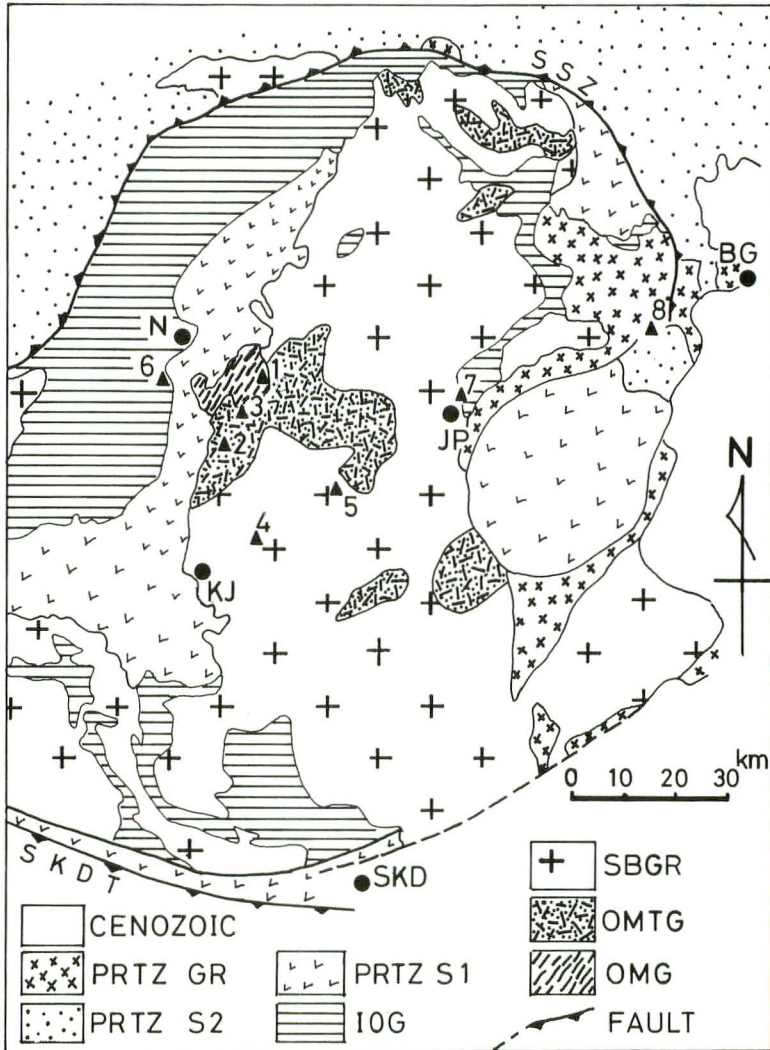


Fig. 11. Geologic outline and locations of field survey of the Singhbhum Craton area (the geologic sketch is modified after SARKAR and SAHA, 1983 and SAHA, unpubl.). Solid triangle with numerals: Location of field observations. PRTZ GR: Proterozoic granites including basic and ultrabasic intrusives, PRTZ S2: Proterozoic system belonging the Singhbhum mobile belt, PRTZ S1: Proterozoic basic lavas (Dhanjori Group) and sediments (Kolhan Group) in the Singhbhum Craton, IOG: Iron Ore Group (Middle Archaean), SBGR: Singhbhum Granites and equivalents (Middle Archaean), OMTG: Older Metamorphic Tonalitie-granodiorite Gneiss (Early Archaean), OMG: Older Metamorphic Group (Early Archaean). SSZ: Singhbhum Shear Zone, SKDT: Sukinda Thrust, BG: Baharagora, JP: Jashipur, KJ: Keonjhar, N: Noamundi, SK: Sukinda.

faint schistosity which becomes intense in some portions. At another outcrop (loc. 3) about 8 km NE of loc. 2, a well banded hornblende gneiss composed of mafic and

leucocratic layers (Fig. 10E) crops out. This rock may belong either to OMG or OMTG.

Singhbhum Granites. The Singhbhum Granites are the commonest rock type we met with throughout the craton. A hilly outcrop (Fig. 10F) with wide and fresh exposures lies about 13 km NE of Keonjhar, along the road to Jashipur (loc. 4, Fig. 11). Here the rock is composed mostly of a porphyritic hornblende-biotite granite with a moderate foliation trending NNW-SSE, with a vertical dip. At the Baitarani river bed, about 20 km NE from loc. 4 (loc. 5 in Fig. 11), leucocratic tonalitic rocks of fine- and coarse-grained lithologies, with later tonalitic small dikes, are observed. These rocks carry foliation trending NNW-SSE, with a vertical dip.

Iron Ore Group. Rocks of the Iron Ore Group were observed at two outcrops; one is southwest of Noamundi (loc. 6 in Fig. 11) and the other NE of Jashipur (loc. 7 in Fig. 11). At these outcrops, the rocks are iron-quartzite, with subordinate pelitic rocks. They are strongly schistose and carry lineations plunging moderately to gently north-northwestward.

Proterozoic metasediments. Proterozoic metasediments belonging to the Singhbhum Mobile Belt were observed at an outcrop near Bangriposhi (loc. 8 in Fig. 11). They are chlorite-epidote-albite schists of graywacke origin with thin layers of pelitic schist. The schistosity trends NNE-SSW with a moderate dip toward ESE; an intersection lineation plunges east.

Conclusion. In the Singhbhum Craton area, we could just observe several outcrops, as mentioned above, but they are too scarce to expect meaningful results. However, some important rock samples were collected for future laboratory studies. We may be able to utilize the existing knowledge and the forthcoming data in order to compare them with those of other early Archaean terrains when investigating the geotectonic environment during the early history of the earth.

(M.Y)

Conclusion and Future Studies

The field program during October-November, 1992, in the southern and eastern parts of Peninsular India, under the joint India-Japan Research Program, was accomplished. Participants included seven Japanese and three Indian scientists from Japan and twenty scientists from India. Several important Precambrian terrains were visited, critical outcrops were observed, and rock samples were collected for further laboratory works. We intend to study the tectonothermal history through the field and laboratory works and to compare them with those of East Antarctica.

Although observations were too limited to enable detailed studies on any of areas of the present survey, one of the valuable results we got is that we are now able to envisage the geology of several parts of India when contemplating the Gondwana tectonics. Other results that we may get in future are to be derived from laboratory analyses, e.g., geochronological and petrological, of rock samples collected during the present

survey. Although there are considerable amounts of reliable data to support metamorphic and plutonic events ranging from circa 1.2 Ga to 0.85 Ga from both the Visakhapatnam and Bhubaneswar areas, we believe that the major metamorphic events in these areas as well as in most areas of the Eastern Ghats Granulite Belt are sure to be older than 1400 Ma, and possibly more than circa 1900 Ma, as pointed out more precisely by GREW and MANTON (1986). On the other hand, effective structural analysis of the granulite terrains of Peninsular India can also be expected. A composite study of macroscopic structures identified throughout southern to southeastern Indian granulite terrains by NARAYANASWAMI (1975), and detailed structures demonstrated in the Angul area of the Eastern Ghats Granulite Belt by HALDEN *et al.* (1982), is considered necessary for this.

At the present stage, we can only realize the distinction between the rocks and structures of the cratonic areas and those of the granulite terrains in Peninsular India, as has been witnessed by FERMOR (1936) and many others. It is recognized that the granulite terrains appear to be monotonously similar, except for variations in the proportional amounts of charnockites throughout southern to eastern Peninsular India, as pointed out by NARAYANASWAMI (1975). Also, it is found that they resemble well with the Proterozoic granulite terrains of Sri Lanka as well as the Lützow-Holm Bay area, East Antarctica, as has also been witnessed by several geologists (e.g., FERMOR, 1936; KATZ, 1974).

In view of comparing the geology of India and Antarctica, we felt that the search for an Archaean cratonic component in subglacial areas to the south, apart from the coast of Lützow-Holm Bay, is considered necessary. Analysis of morainic boulders along the coast is considered valuable, in addition to geophysical researches, to verify the existence and to examine the characteristics of the Archaean cratonic blocks which were demarcated by GRIKUROV (1982), based mainly on geophysical data.

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