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Proterozoic Evolution of the Nellore-Khammam Schist Belt in the Khammam district, SE India

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Abstract

The Nellore-Khammam schist belt (NKSB), SE India, has been known as one of the oldest greenstone belts in Peninsular India, and is bounded by Proterozoic Eastern Ghats terrain on the east and the Proterozoic Cuddapah Supergroup overlying the Archean Dharwar-Bastar craton on the west. The NKSB has been divided into upper and lower structural units. The former is dominated by low-grade metamorphic rocks, derived from sedimentary rocks, occurring in southwestern part of the belt ; the latter consists mainly of high-grade metabasaltic rocks distributed in the eastern part.

The highest P-T conditions, derived from metabasic rocks (amphibolites) of the lower unit in the Khammam district, are 700±50℃ at 1.0±0.2 GPa. Based on the estimation in combination with previously reported P-T data, metamorphic P-T conditions of the rocks of the lower unit yield an array with positive slope in P-T space (dT/dP = ~ 0.4℃/MPa), which is equivalent to a geothermal gradient of ca. 10℃/km. Such a geothermal gradient is typical of a high-pressure P/T metamorphic belt formed at a subduction zone, a continent-continent collision zone or a terrain accretion zone. On the basis of geochemical characteristics of the bulk-chemistry of the amphibolites, they can be divided into two origins, such as modern oceanic arc and continental arc basalt affinities. Hence, rocks derived from different subduction zone systems have been mixed in the schist belt. Because it has been considered that the Eastern Ghats terrain accreted to the Dharwar-Bastar craton from late Mesoproterozoic to early Neoproterozoic, the high-pressure Nellore-Khammam metamorphism was probably related to the terrain accretion at this period.

Key words : Archean greenstone belt, Proterozoic high-pressure metamorphic belt, terrain accretion, India

1. Introduction

Archean greenstone belts are the oldest major belts of well-persevered volcano-sedimentary rocks on Earth and so they give us much direct evidence of early crustal conditions (Windley, 1995). The Nellore-Khammam schist belt (NKSB) forms a linear belt paralleling the east coast of India (Fig. 1). As the NKSB is considered to be equivalent to the Sargur schist belt within the Dharwar craton, which is the oldest (protolith age of ca. 3.3-2.5 Ga) supracrustal belt in India (e.g. Naqvi and Rogers, 1987 ; Peucat et al., 1995 ; Kunugiza et al., 1996), it is known as an Archean greenstone belt in India (e.g. Ramam and Murty, 1997). The NKSB has a length of about 600 km, with variable width from 30 to 130 km, and is bounded by the Proterozoic Eastern Ghats granulite terrain on the east and the Proterozoic basin sediments (Cuddapah Supergroup and Pakhal Supergroup) overlying the Archean Dharwar-Bastar craton on the west (e.g. Ramam and Murty, 1997 ; Babu, 1998 ; Gopalakrishnan, 1998). The terrane boundaries between the NKSB and Eastern Ghats terrain and between the NKSB and Proterozoic basin sediments have been considered to be eastward-dipping low-angle fault systems. Because the Eastern Ghats terrain accreted to the Dharwar-Bastar craton during Mesoproterozoic (e.g. Lakshminarayana, 1997) and the NKSB is sandwiched by them, information from rocks of the NKSB is a key to understanding terrain accretion and the crustal evolution of the Indian continent during Precambrian.

We have investigated rocks of the NKSB in the Khammam district (Fig. 1) from 1997, in order to determine their structural and petrological characteristics. In this paper we present : (1) a review of geological aspects of the Nellore-Khammam schist belt, (2) a summary of important results recently obtained by our research group from 1997, and (3) some consideration of the evolution of

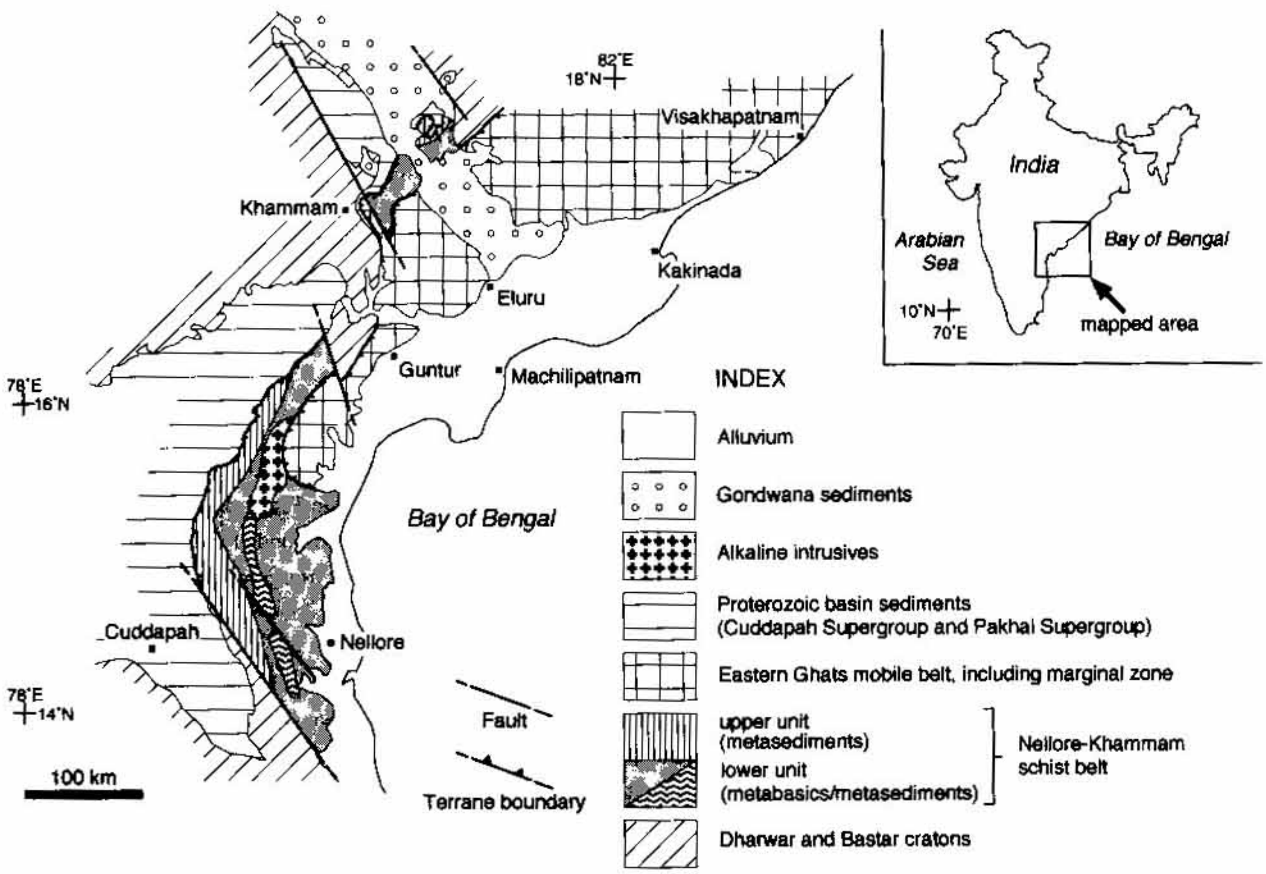

Fig. 1. Generalized geological map around the Nellore-Khammam schist belt, that are based mainly on the data of Ramam and Murty (1997) and Babu (1998). Location of the amphibolite samples described here is indicated.

the NKSB. The detailed field observations and descriptions of petrography and deformation structure of the rocks in the Khammam district are presented in the theses of Hari Prasad (2000) and Rajneesh Kumar (2000).

2. Outline of geology

As shown in Fig. 1, the NKSB has been divided into two structural units, that is, upper and lower units (e.g. Vasudevan and Rao, 1975 ; Narayana Rao, 1983 ; Ramam and Murty, 1997). They are juxtaposed along suspected low-angle faults. The former is dominated by low-grade metamorphic rocks derived from sediments (such as pelites, psammites, conglomerates, cherts, limestones and acidic volcanics) occurring in the southwestern part of the belt ; the latter consists mainly of high-grade metabasaltic rocks distributed in the eastern part. Such a subdivision into an upper metasedimentary unit and a lower metabasic unit is a common in many Archean greenstone belts (Windley, 1995). The rocks of the upper unit have been considered to be derived from trench sediments (Ramam and Murty, 1997). In the lower unit, subduction-related magmatism in

Table 1. Previously estimated $P-T$ conditions of the metamorphic rocks from the Nellore-Khammam schist belt. Mineral abbreviation area after Kretz (1983).

Rock type	Locality	Estimated $P-T$ conditions	Reference
Ms-St schist	Saidapuram-Podalakuru	550-700 ℃, 0.72 GPa	Babu (1970)
Hbl-Bt-Grt schist	*ditto*	600-710℃, 0.75 GPa	*ditto*
Bt-Ky schist	*ditto*	650-700 ℃, 0.8 GPa	*ditto*
unknown	unknown	595±10 ℃, 0.3-0.6 GPa	Parshad et al. (1979)
unknown	Uppalapadu	700±50 ℃, 0.7±0.1 GPa	Babu (1996)
Grt-Bt-Ms schist	Vinjamuru	715-765 ℃, 0.86-0.92 GPa	Moeen (1998)
Grt-St-Ky schist	*ditto*	520-570 ℃, 0.61-0.68 GPa	*ditto*

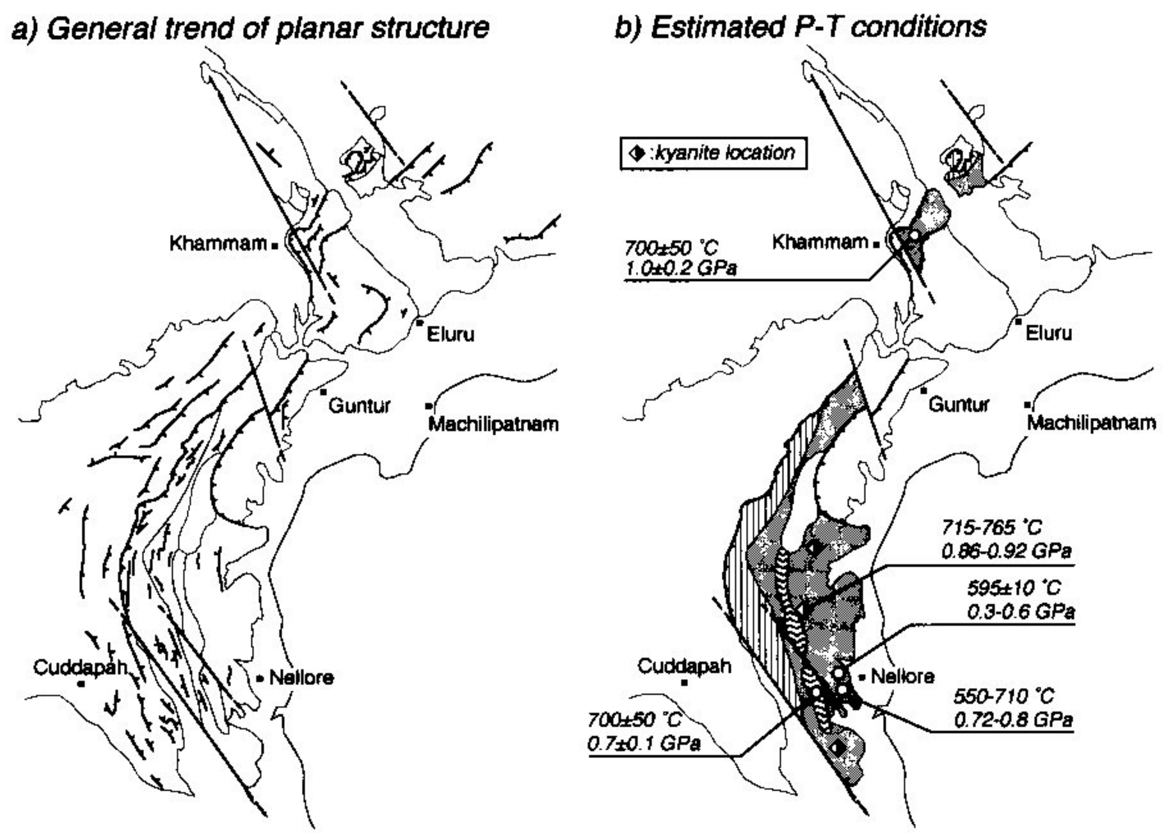

Fig. 2. a) General trend of the most distinct planar structure in the Nellore-Khammam schist belt, Cuddapah Supergroup, Pakhal Supergroup, and Eastern Ghats granulite terrain. Data source of Geological Survey of India (1973, 1975), Nagaraja Rao et al. (1987), Sreenivasa Rao (1987), Srinivasan et al., (1992, 1993, 1994), Sarvothaman (1995 a, b), Geological Survey of India (1998), Hari Prasad et al. (1999), and Rajneesh Kumar et al. (1999). b) P-T conditions of the rocks of the Nellore-Khammam schist belt. Data source : Babu (1970), Parshad et al. (1979), Babu (1996), Moeen (1998), and Hari Prasad et al. (1999).

different settings (that is, oceanic-island arc, continental margin or back arc) has been well recognized, and the affinities to within-plate basalt and N-MORB are absent (Satyanarayana et al., 1994 ; Hari Prasad et al., in press). Such geochemical characteristics of the bulk-chemistry of the greenstone succession are common in the Precambrian greenstone belts (Condie, 1989).

The general trend of the most distinct planar structure (lithologic banding or tectonic foliation) of the rocks of the NKSB is summarized in Fig. 2 a. As shown in this figure, general trends of the planar structure are roughly parallel to the trend of the terrane boundaries, and are comparable to the general trend of the planar structure of the rocks in the Cuddapah Supergroup, the Pakhal Supergroup and the Eastern Ghats granulite terrain. Overall, in the NKSB, the structure dips toward the west in the upper unit and toward the east in the lower unit.

Metamorphic grade generally changes from greenschist facies to upper amphibolite facies, from west to east (Vasudevan and Rao, 1975 ; Ramam and Murty, 1997 ; Babu, 1998 ; Moeen, 1998). It has been considered that there is a gap of metamorphic grade between the low-grade upper and the high-grade lower units. Because chlorite-bearing assemblages of metasediments in the upper unit has been reported (e.g. Vasudevan and Rao, 1975 ; Ramam and Murty, 1997 ; Babu, 1998). The metamorphic

Table 2. Geochronological data of the metamorphic rocks from the Nellore-Khammam schist belt

Rock type	Locality	Age (Ma)	Remarks	Reference
Metaquartzite	Nandivaya	536±14	K-Ar, Fuchsite	Sarkar et al. (1964)
Metabasalt	Kandra	989±23	K-Ar, W.R.	Ghosh et al. (1994)
Ky-St-mica schist	Kandra	806	K-Ar, Muscovite	*ditto*
Metasediment	Khammam	1126	Pb-Pb mineral isochron	Yoshida et al. (1995)

W.R. : whole rock

facies may be inferred to be greenschist. In the lower unit, because the mineral assemblages garnet + staurolite + muscovite + biotite ± kyanite ± sillimanite (+ plagioclase + quartz) have been reported (e.g. Vasudevan and Rao, 1975 ; Ramam and Murty, 1997 ; Babu, 1998 ; Moeen, 1998), metamorphic P-T conditions may be located near the phase boundary curve between kyanite and sillimanite. There is quantitative P-T data reported from the metapelites of the upper unit by Moeen (1998) and from the amphibolites of the lower unit by Hari Prasad et al. (in press). Previously reported peak P-T conditions are compiled in Table 1 and Fig. 2b.

Although geochronological data are very poor in the NKSB, previously published data are summarized in Table 2. Most of the data indicates a Neoproterozoic event in the NKSB rocks, but most of the data were obtained from a K-Ar system having a closure temperature lower than the peak metamorphic temperature.

3. The Nellore-Khammam schists in the Khammam district

In the Khammam district, both the rocks of the upper and lower units occur. Furthermore, the northern part of the district includes the terrane boundary between the NKSB and Mesoproterozoic Pakhal Supergroup (e.g. Sreenivasa, 1987). The boundary between them is characterized by the presence of a highly deformed conglomerate bed (e.g. Rajneesh Kumar et al., 1999, in press). The constituent rocks of the upper unit of the northern part of the Khammam district are greenschist to lower amphibolite facies-grade metasediments and meta-igneous rocks with various degrees of mylonitization. The southern part of the Khammam district is mainly composed of rocks of the lower unit, and is dominated by different type of amphibolites, varying from weakly foliated to well foliated and in some areas, of a banded nature. The rocks of the southern part are separated by a major fault from garnetiferous orthogneiss of the marginal zone of the Eastern Ghats granulite terrain.

3.1. Structures

The regional structural studies in NKSB were carried out by Geological Survey of India (1973, 1975), Subba Raju (1975), Sarvothaman (1995 a, b), and Srinivasan et al. (1992, 1993, 1994). According to Rajneesh Kumar et al. (1999), in the rocks of the upper units of the northern part of the Khammam district, four deformation phases (D1-D4) can be identified (Table 3). A tectonic foliation trending NE -SW is the most distinct structural element, and is called S1. Because the S1 foliation can be defined by preferential alignment of (001) plane of biotite and *c*−axis of hornblende, the formation of S1 is related to the peak metamorphism. Intrafolial folds of tight to isoclinal type can be recognized, and axial planes of the intrafolial folds are parallel to S1. Therefore, the intrafolial folds may be cogenetic with S1 during the first phase deformation (D1). Fold axes of the intrafolial folds are gently eastward plunging, although they are scattered, resulting from effects of later deformations. Macroscopic open folds with vertical axial surfaces and hinges plunging southeast are recognized. They fold the S1 foliation, so the deformation forming the open folds is recognized as the second generation (D2). Axial surfaces of the D 2-folds are further folded along E-W trending fold axes of the D3 deformation. The D3-folds are characterized by northward-vergent asymmetric folds with a horizontal axis. The last deformation phase (D4) is characterized by the development of macro- to mesoscopic upright folds, gently plunging southwest. The D4-folds are well recognized in the area near the boundary with the Pakhal Supergroup.

In the amphibolites of the southern part of the Khammam district, according to Hari Prasad et al. (1999), three deformational events (D1-D3) have been identified (Table 3). The amphibolites show compositional banding, called S0, developed by the alternation of plagioclase-rich bands and amphibole-rich bands. Because there is a district

Table 3. Deformation events in the Nellore-Khammam schist belt in the Khammam district*.

Upper unit		Lower Unit	
Phase	Characteristic structures	Phase	Characteristic structures
D 1	Bedding-parallel foliation Intrafolial folds	D 1	Bedding-subparallel foliation Intrafolial folds
D 2	Upright folds with fold axis plungintg to ESE	D 2	Reclined folds with fold axis plunging to SSW
D 3	North-verging close folds with horizontal fold axis trending EW	D 3	Local shear zones trending NW-SE
D 4	Upright folds gently plunging to SW		

* Structural data of the upper and lower unit are from Rajneesh Kumar et al. (1999) and Hari Prasad et al. (1999), respectively

foliation (S1) resulting from the preferential alignment of c-axis of amphibole grains formed during the first phase deformation (D1), S1 formed during the peak metamorphism. Intrafolial isoclinal to tight folds are also observed. The axial planes of the intrafolial folds are parallel to the S 1 foliation, indicating that these folds are cogenetic with S 1. The trend of S 1 is occasionally oblique to that of S 0, giving intersection lineations. The large-scale structure in the district is characterized by a map-scale reclined fold, with its fold axis plunging SSW. These large- to meso-scale folds are interpreted to belong to the second phase (D2), because the intrafolial D1 folds are refolded by this fold. Many local shear zones trending NW-SE are seen. The shear zones are associated with retrograde metamorphism, characterized by the development of retrograde minerals such as chlorite, epidote and actinolitic amphibole, which are stable under greenschist facies conditions. The retrograde shear deformation is of the last phase (D3).

In the two areas, characteristic structural features are comparable. These are : (1) distinct tectonic foliation (S1) defined by preferential alignment of metamorphic minerals formed by peak metamorphism, and (2) D4 folds plunging SW in the northern part and D2 folds plunging SSW in the southern part. The general trend of the foliation and fold axes in the Khammam district cannot be traced to other areas of the NKSB, because of the lack of fundamental structural data. However, the last phase folds, with axes plunging SSW-SW, are interpreted by Rajneesh Kumar et al. (1999) to be superimposed structures resulted form the accretion of the Eastern Ghats terrain to the Dharwar-Bastar craton during the Neoproterozoic.

3.2 .Metamorphism

The constituent rocks of the upper unit of the northern part of the Khammam district are characterized by the following mineral assemblages (Rajneesh Kumar et al., 1999, in press) :

Quartzo-feldspathic rocks :

quartz + plagioclase + chlorite + muscovite + biotite

quartz + plagioclase + muscovite + biotite ± titanite

Mafic rocks :

hornblende + plagioclase + quartz + garnet + retrograde chlorite.

Mineral assemblages of the quartzo-feldspathic rocks indicate that the rocks were metamorphosed under greenschist facies conditions.

In the lower units, according to Hari Prasad et al. (1999), the amphibolites can be divided, based on their mineralogy, into three rock types, namely, garnet (Grt) amphibolite, garnet-clinopyroxene (Grt-Cpx) amphibolite and clinopyroxene-titanite (Cpx-Ttn) amphibolite. Mineral assemblages of the three rock types are different, as shown below.

Garnet amphibolite :

oligoclase + pargasitic hornblende + garnet + quartz

Garnet-clinopyroxene amphibolite :

andesine + pargasitic hornblende + garnet + clinopyroxene + quartz

Clinopyroxene-titanite amphibolite :

labradorite + tremolitic hornblende + clinopyroxene + titanite + quartz

In the garnet-bearing amphibolites, plagioclase and amphibole compositions are more albitic and pargasitic, respectively, than those in the garnet-free amphibolites. Compositional zoning in plagioclase is not clear : the Grt amphibolite has core X_{An} = 0.22-0.26 and rim 0.23-0.27 ; the Grt-Cpx amphibolites core is 0.33-0.37, rim 0.30-0.38 ; the Cpx-Ttn amphibolite core is 0.55-0.64, rim 0.55-0.77. Amphiboles are calcic- subcalcic and fall into the range of tremolitic to pargasitic hornblende. The average values of Mg# [= Mg/(Mg+Fe)] of amphiboles are ~ 0.47 for the Grt

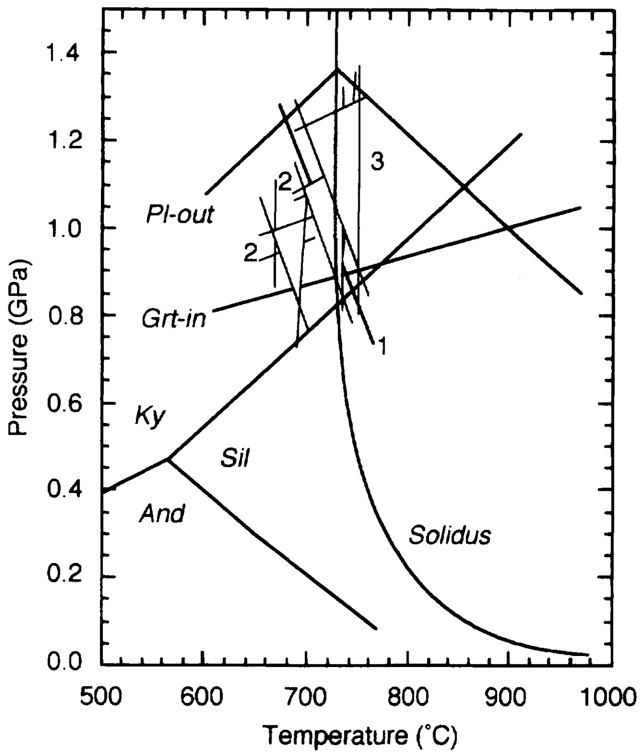

Fig. 3. Estimated P-T conditions for the amphibolites in the Khammam district (Hari Prasad et al., in press). Plagioclase-out, garnet-in and solidus lines for wet basalt are derived from the experimental data of Ernst and Liu (1998). Phase boundaries for aluminosilicate was calculated by using THERMOCALC ver. 2.3. Line 1 and areas 2 and 3 represent calculated P-T conditions of the Cpx-Ttn amphibolite, Grt-Cpx amphibolite and Grt amphibolite, respectively.

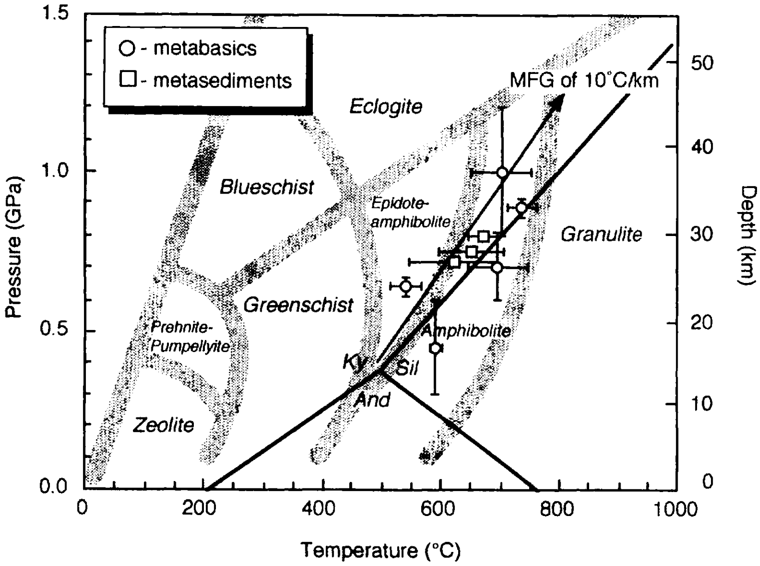

Fig. 4. Summarized peak P-T conditions of the rocks of the Nellore-Khammam schist belt. Data source: Babu (1970), Parshad et al. (1979), Babu (1996), Moeen (1998), and Hari Prasad et al. (in press). Boundary curves of metamorphic facies fields are after Spear (1993). Metamorphic field gradient (MFG) of 10℃/km, assuming the rock density of 2759 kg/m³, is also indicated.

amphibolite, ~ 0.6 for the Grt-Cpx amphibolite, and ~ 0.6 for the Cpx-Ttn amphibolite. Garnet is observed in the Grt amphibolite and the Grt-Cpx amphibolite, and is grossular-almandine of fairly constant composition in each rock type. (Grt amphibolite $X_{Alm} = 0.52$, $X_{Grs} = 0.33$, $X_{Prp} = 0.11$; Grt-Cpx amphibolite $X_{Alm} = 0.51$, $X_{Grs} = 0.31$, $X_{Prp} = 0.17$). Clinopyroxene is diopside (X_{Mg} = ~ 0.75 for the Grt-Cpx amphibolite ; 0.73 for the Cpx-Ttn amphibolite), and mole fractions of acmite and jadeite in the both amphibolites are less than 0.05.

According to Hari Prasad et al. (in press), for the amphibolites in the southern part of the Khammam district, metamorphic P-T condition can be estimated by using amphibole-plagioclase (Holland and Blundy, 1994) for all the three rock types and garnet-hornblende-plagioclase-quartz (Graham and Powell, 1984 ; Kohn and Spear, 1990) for garnet-bearing amphibolites ; and garnet-clinopyroxene-plagioclase-quartz (Ellis and Green, 1979 ; Newton and Perkins, 1982) can be used for the Grt-Cpx amphibolites. Because garnet, clinopyroxene, amphibole and plagioclase crystals in the amphibolites do not show a distinct compositional zoning and have nearly constant values in each rock type, average compositions of each mineral are used for the P-T calculation. As shown in Fig. 3, the P-T conditions of three rock types fall into the range between 650 and 750℃ around 1 GPa (Fig. 3). The estimated P-T conditions fall between the garnet-in and plagioclase-out field in the petrogenetic grid for the basaltic system of Ernst and Liu (1998), and occur within the kyanite-stability field.

Based on the result of the P-T estimate (Hari Prasad et al., in press) in combination with previous P-T data (Table 1), almost all the P-T data plot within the field of the amphibolite facies of Spear (1993), and they are located near the boundary of the phase transition from kyanite to sillimanite (Fig. 4). Overall, the P-T data yield an array with positive slope in P-T space, and dT/dP is estimated to be ~ 0.4℃/MPa. This is equivalent to the geothermal gradient (= metamorphic field gradient) of ca. 10℃/km, assuming the rock density of 2750 kg/m³. Such a metamorphic field gradient is of a high-pressure metamorphic belt (e.g. Spear, 1993). Archean and Proterozoic orogenic belts include dominantly intermediate to low pressure facies series regional metamorphic belts instead of high-P/T types (Grambling, 1981 ; Maruyama and Liou, 1998). Therefore, the P/T ratio of the NKSB are higher than those of many Archean and Proterozoic orogenic belts.

3.3. Bulk-rock chemistry

Geochemical characteristics of the amphibolites can be utilized to determine the tectonic environment of the protolith in comparison with modern plate-tectonic systems. Because major elements, especially large-ion lithophile elements (LILEs) can be mobilized during secondary processes such as high-grade metamorphism and alternation, the ratios of relatively immobile elements such as TiO_2/Zr and Nb/Y are used to clarify the geochemical characteristics of the amphibolites. In fact, the LILEs (Sr, K, Rb and Th) in the amphibolite samples are highly variable in abundance ; especially, the abundance in Sr and Th of some samples is less than the detection limit (Sr $\leq$ 2.7 ppm, Th $\leq$ 2.0 ppm). Based on the TiO_2-Zr diagram of Pharaoh and Pearce (1984), all samples fall in the arc field (Fig. 5 a). The Grt-Cpx amphibolite samples are plotted in the left hand side of the primitive-evolved boundary line, whereas the Grt amphibolites and Cpx-Ttn amphibolites are located to the right hand side of the boundary line. As shown in Fig. 5 b, on the basis of Zr/Y vs Zr diagram of Pearce (1983),

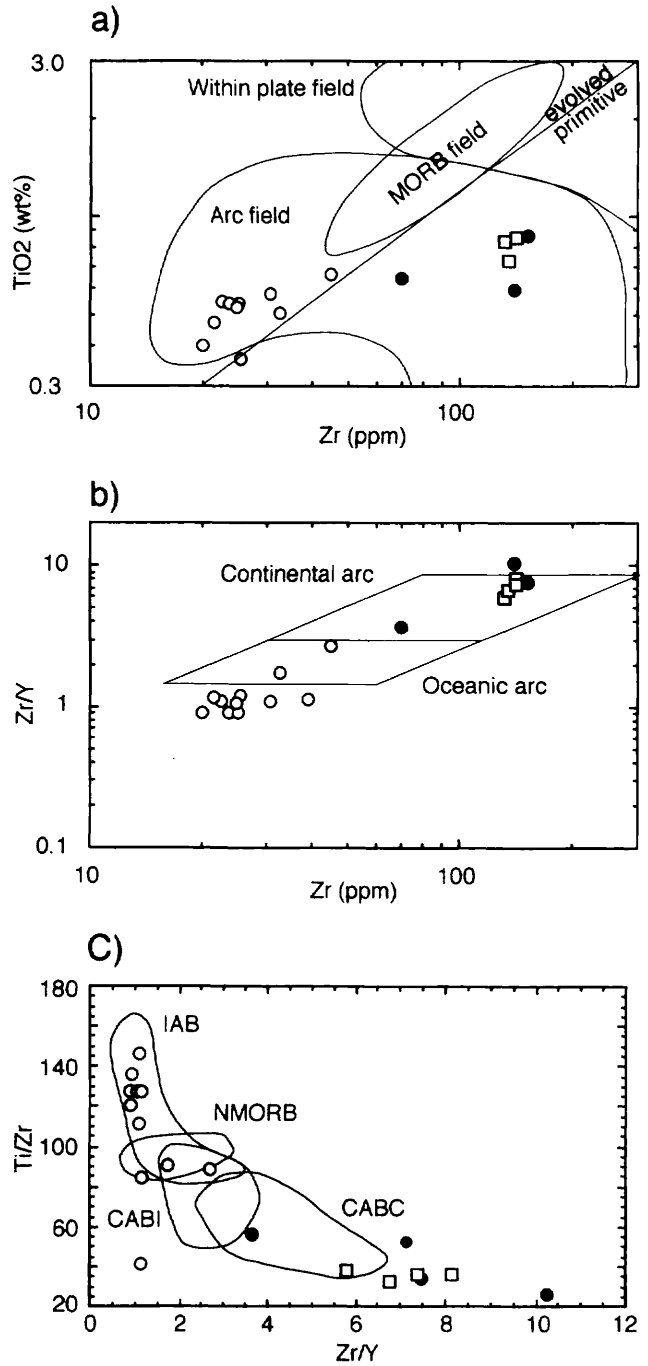

Fig. 5. Discriminant diagram of the bulk-rock chemistry for the amphibolites in the Khammam district (data source : Hari Prasad et al., in press). a) TiO 2 vs Zr diagram of Pharaoh and Pearce (1984). b) Zr/Y vs Zr diagram of Pearce (1983). c) Ti/Zr vs Zr/Y diagram of Pearce (1982). Open square : Grt amphibolites. Open circles : Grt-Cpx amphibolites. Solid circles : Cpx-Ttn amphibolites.

they are clearly divided into two different fields, that is, the Grt-Cpx amphibolites are plotted near the field of oceanic arc and the others are plotted in the field of the continental arc. Furthermore, in the diagram of Ti/Zr vs Zr/Y (Pearce, 1982), the rocks plotted in the island-arc basalt field are the Grt-Cpx amphibolites, whereas the samples plotted near the field of calc-alkaline basalt from continental-margin arcs (CABC) are the Grt amphibolites and Cpx-Ttn amphibolites (Fig. 5c). Consequently, on the basis of these discrimination diagrams, the amphibolite samples can be divided into two groups, that is, those with oceanic arc and those with continental arc basalt affinities.

4. Discussion

The amphibolites of the lower unit can be divided into two groups, based on their geochemical similarity, namely, the rocks having geochemical affinities to (a) modern oceanic island-arc basalt and (b) continental-arc basalt. This suggests that they have been derived from two different subduction-zone systems, and at present the rocks are mixed in the NKSB. The accretionary process by plate tectonics results in thick sequences of volcano-sedimentary rocks that have originated at different tectonic settings attributed to the shuffling of thrust piles consisting of both the continental and oceanic materials at a trench (Matsuda and Isozaki, 1991). The rocks of the NKSB originated mainly from basalt, chert, pelite, psammite, acidic clastic volcanic, banded iron formation and limestone (e.g. Vasudevan and Rao, 1975 ; Narayana Rao, 1983 ; Ramam and Murty, 1997). This lithological feature is similar to accretionary complexes through geological time (e.g. Matsuda and Isozaki, 1991). Furthermore, within the NKSB, an ophiolitic melange has been reported (Reddy et al., 1994). Ophiolitic melanges are characteristic rock bodies found along many active and ancient plate margins of the world and are also regarded as diagnostic products of subduction of oceanic lithosphere beneath continental lithosphere (e.g. Cloos, 1982). Therefore, there are many lines of evidence suggesting that the protoliths of the NKSB were formed by accretionary processes due to subduction of oceanic plate.

Timing of the high-pressure metamorphism in the NKSB is problematic. There are a few geochronologic data for the metamorphic rocks (Table 2), although many data for granitic rocks and pegmatites have been reported. Because K-Ar ages of the rocks of the NKSB may represent the timing at which temperature of the NKSB rocks passed to the closure temperature for a K-Ar isotopic system, the Neoproterozoic K-Ar age (~ 900 Ma) of Ghosh et al. (1994) do not indicate the timing of peak metamorphism but their exhumation. Furthermore, the K-Ar age of 536 Ma (Sarkar et al., 1964) in the NKSB may indicate the Pan-African thermal overprint on the rocks. If the high-pressure metamorphism with metamorphic field gradient of ca. 10 ℃/km resulted from the accretion of the Eastern Ghats terrain to the Dharwar-Bastar craton, the high-pressure metamorphism occurred during the accretion. According to Laksminarayana (1997), onset of the accretion of the Eastern Ghats terrain to the Dharwar-Bastar craton was ca. 1300 Ma, and the accretion had continued until Neoproterozoic, based on the analysis for the Pakhal Supergroup, which are identified as the collision-induced rift sediments. These geological circumstances suggest that the high-pressure metamorphism in the NKSB occurred during late Mesoproterozoic to early Neoproterozoic time. This suggestion is supported by the preliminary geochronologic data of Pb-Pb mineral isochron age from the metasediments in the Khammam district (1126 Ma : Yoshida et al., 1995).

The study of the rocks of the Nellore-Khammam schist belt has just commenced, and tectono-metamorphic history of the NKSB has to be further established, based on detailed petrological, structural and geochronological data.

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