Int. J. of Geology & Earth Sci., 2019

International Journal of Geology and Earth Sciences

ISSN 2395-647X www.ijges.com
Vol. 5, No. 3, September 2019

Research Paper

Field and Petrography of the Rocks from the Gobbagurthi Area in the Khammam Schist Belt, Khammam District, Telangana State, India

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Petrographic characterization of Amphibolites and associated rocks from the Gobbagurthi area in the Khammam Schist Belt covers an area about of 240 sq.km, scale 2cm =1km (1: 50000), the Survey of India Toposheet no 65 C/7 and 65 C/8 the latitude and longitudes are 17^0 10' - 17^0 21' N and 80^0 15' - 80^0 27' E. The area has been covered with 200 representative lithological samples and made 100 thin sections among the amphibolites, metabasalts, metadolerites, anorthosites, granulites, gneisses and schists. The modal analyses, geological settings of the area, field descriptions and petrographic characters of the rocks are investigated. The mineralogical and textural characteristic of the rocks from the Gobbagurthi area are describes in vary textural features from magmatic to metamorphic deformation. The original cumulate characters of mafic to ultramafic intrusives (layered complex), ophitic to sub-ophitic textures from meta-basalts and meta-dolerites. These are modified by the later metamorphic imprint and recrystellization under amphibolite and granulite facies of metamorphism. Due to recrystellization and basaltic processes the micro structures were formed as Coronal and sieved garnets.The KSB forms retrograde metamorphism from granulte to amphibolies, amphibolite to greenschist facies condition. The original mineral grains in each rock-units are modified by late dynamic deformations in which coarse-grained minerals (plagioclase, hornblende, clinopyroxene and Fe-Ti oxides) are broken-down to form undeformed smaller recrystallized grains by grain boundary migration and recrystallization (mortar texture) at low temperature conditions. Textural equilibrium between polygonal mineral grains with smooth planar boundaries and triple junctions in the rock-units of KSB suggest solid-state recrystallization due to grain boundary migration during plastic deformation at higher temperatures. This type of textural features is overprinted on early folded gneissose and schistose rocks, streaky amphibolites and metamorphosed mafic & ultramafic lavas. Hornblende coronas around clinopyroxene and Fe-Ti oxides, epitaxial overgrowth of hornblende over clinopyroxene, scapolite over plagioclase and zoisite / clinozoisite mineral growth over plagioclase and hornblende indicate replacement textures in the rocks of Gobbagurthi area in KSB.

Keywords: Amphibolites, Gneisses and schists, Modal analysis, Khammam Schist Belt

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Introduction

The Khammam Schist Belt (KSB) forms a curvilinear belt and it over 120 km from south of Nandigama in Krishna district, Andhra Pradesh to Bhadrachalam in north of Khammam district, Telangana with an average width of 25 km.This belt is inferred to be a tectonised belt sandwiched between the Dharwar Craton in the West and the Eastern Ghat Mobile Belt (EGMB) in the East. The KSB is considered to be as anorthern extension of the Nellore Schist Belt (NSB).Both KSB and NSB are collectively renamed as Nellore Khammam Schist belt (NKSB) in recent period byVijaya Kumar *et al.* (2006).

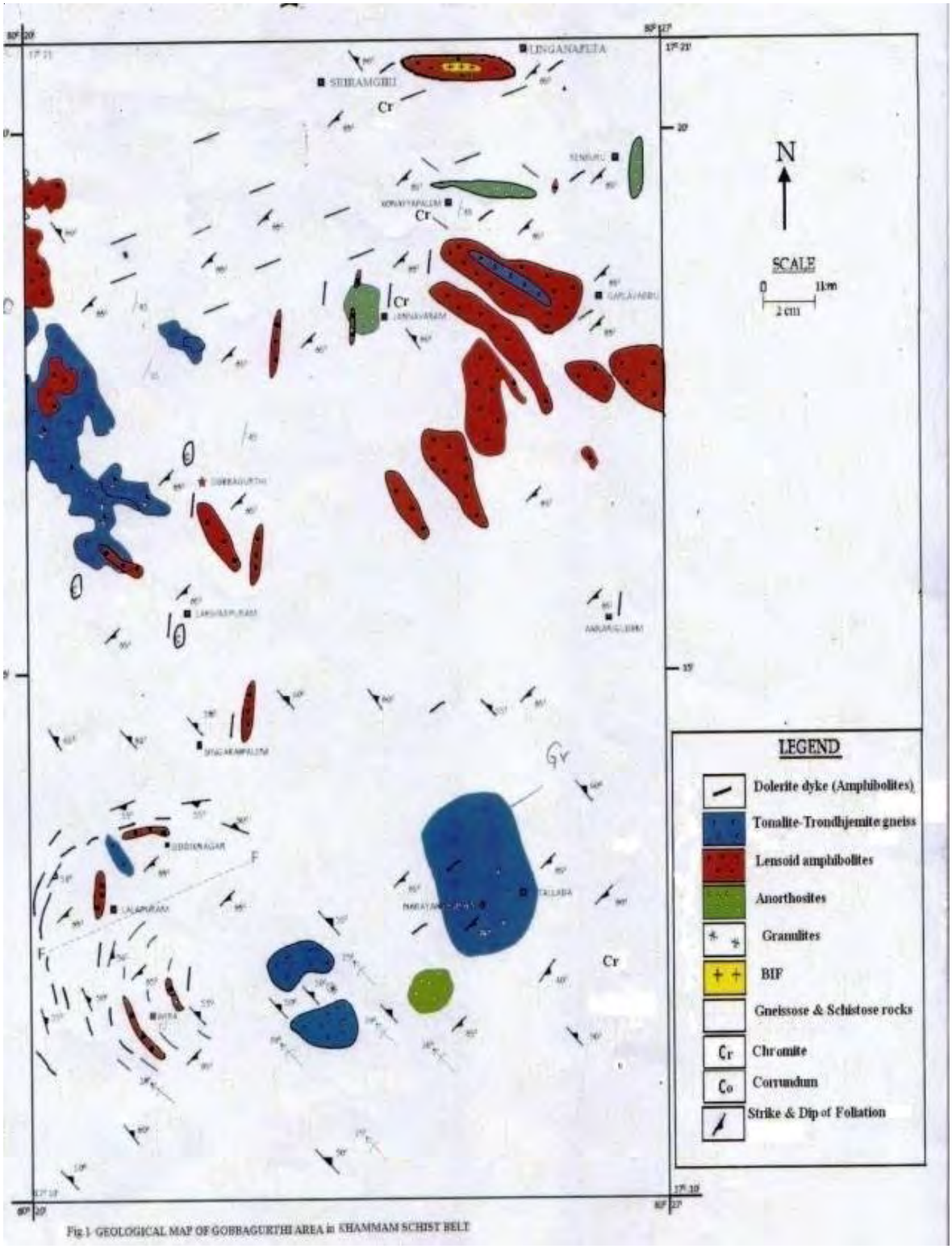
This belt is separated from NSB by a Prominent NNW-SSE crustal scale fault which facilitated to flow Krishna River in the eastern direction across the east coast of Andhra Pradesh (Ramamand Murty, 1997; Dobmeier and Raith, 2003)and KSB is also described as transcratonicsupracrustal belt within the marginal zone of the Eastern Dharwar Craton (Sarvothaman, 1995). The KSB is a highly deformed and metamorphosed belt and is bounded by Pakhals and Gondwana formations in the north, granitoids and Pakhals metasediments of Eastern Dharwar Craton in the West and Kannegiri granites in the East (Servothaman, 1995, Narsimha Reddy and Leelanandam, 2004).

The KSB is predominantly composed of schistose and gneissose rocks of the Precambrian age. These rocks occur as discontinuous deformed bands along with foliated amphibolites. Hornblende schists, Schistose amphibolites and Tremolite-actinolite-talc-chlorite schists occurs as dark bands, streaks and lenses within the tonalite gneisses and pelitic gneisses in the KSB, forming the basement for younger anorthosites, amphibolite dykes, mafic andfelsic granulites, meta-dolerites and granitoids. Intrusive dykes and sills and extrusive mafic rocks of roof – top rafts (now amphibolites) thrust over (1) gneissose and schistose rocks, and (2) layered and massive gabbro- anorthosite association.The Proterozoic pakhals and Phanerozoic Gondwanas form the cover sediments in the Northern part Appavadhanulu, 1976; and Sreenivasa Rao, 1987).

2. Geological Setting of the Rocks from Study Area

The Gobbagurthi area coverscentralpart of the Khammam schist belt (Figure 1).The dominant lithology comprises amphibolites, which are in the form of massive lenses, bands and foliated sheets. They are of garnetiferous and non – garnetiferous types and have cross- cutting relationships with associated gneisses, schists and anorthosites. The oldest and predominant rocks are ortho-and para-gneisses and schists (hornblende- plagioclase gneiss, quartz–plagioclase-hornblende gneiss, biotite-hornblende-plagioclase-quartz gneiss, kyanite-sillimanite- cordierite-gedrite-plagioclase-corundum± quartz rocks, garnetiferous biotite-kyanite schists, quartzo-feldspathic schists, fuchsite-and garnet-bearing quartzites, banded iron formations and calc- silicate rocks) are basement rocks in the study area (Figure 1).These rocks are affected by mainly intrusive and extrusive mafic and ultramafic rocks (now hornblende schists, schistose and streaky amphibolites and recrystallized ultramafic bands and lenses), minor granulites of different compositions (mafic, felsic and calcic), and a Prominent Chimalpahad Layered anorthosites

Figure 1: Geological Map of the Gobbagurthi area in the Khammam Schist Belt (After Sarvothaman H, 1995)



Complex which constitute both layered and massive anorthositic rocks,minor gabbroic rocks, and rare ultramafic rocks with Chromitites (Leelanandam and Narsimha Reddy 1983, 1985; Narsimha Reddy and Leelanandam, 2004 and Subba Raju,1987).

Themajor folds such as isoclinal antiforms and synforms are encountered with steep dipping in the directions of NE-SW in the study area. These folds are further overprinted by brittle and brittle-ductile fractures,en- echelon tension gashes and different vein-fibers with calcite, amphiboles and plagioclase in the directions of N-S, NW-SE, and ESE - WNW. The overall structural geometry and deformation history in KSB reflect the compressional and transitional tectonism (Narsimha Reddy and Leelanandam, 2004). Shear zones and thrust-imbricated structures within and between litho-units may be considered as last phase of Pan- African deformation in the KSB. In this case, the KSB is quite comparable with that of irregular distribution of metamorphic grade of the Yilgarn province Western Australia and the Yellowknife greenstone belt of the Slave province (Condie, 1981). The patchy or irregular distribution of metamorphic grade in these belts or provinces may be attributed to differential upliftment and erosion of crust that was subjected to an irregular distribution of thermal domes (Thompson, 1978).

3. Field Description of Rocks from the study area

3.1. Amphibolites

The amphibolites are medium grade regional metamorphic rocks, which are derived from metamorphosed mafic basaltic igneousrocks.

They are fine to coarse grained and dark colored rocks and occur as massive granular and foliated- bands. The massive granular varieties occur as dykes, sills, mounds and lenses (Figure 2a and 2b) and occasionally show garnet porphyroblasts (Figure 2c). The foliated amphibolite forms bands and sheets within gneisses.

The lensoid bodies of amphibolites (pillow basalts?) are thrusted (or) occur as roof- top rafts over tonalite-trondhjemite gneissic (TTG) rocks at Garlavaddu, Jannaram, Bagavannayakthanda, and Gobbagurthi hill areas (Figure 2d). They are also thrusted over Banded Iron Formations (BIF) (Figure 2e) at Sriramagiri-Lachiguda. The foliated amphibolites occur as intercalated bands (Figures 2f and 2g) with tonalite-trondhjemite gneisses on plain country andhill masses over basement portion of these rocks are referred to as ''supracrustal amphibolites'' by (Sarvothaman, 1995 and 1996).

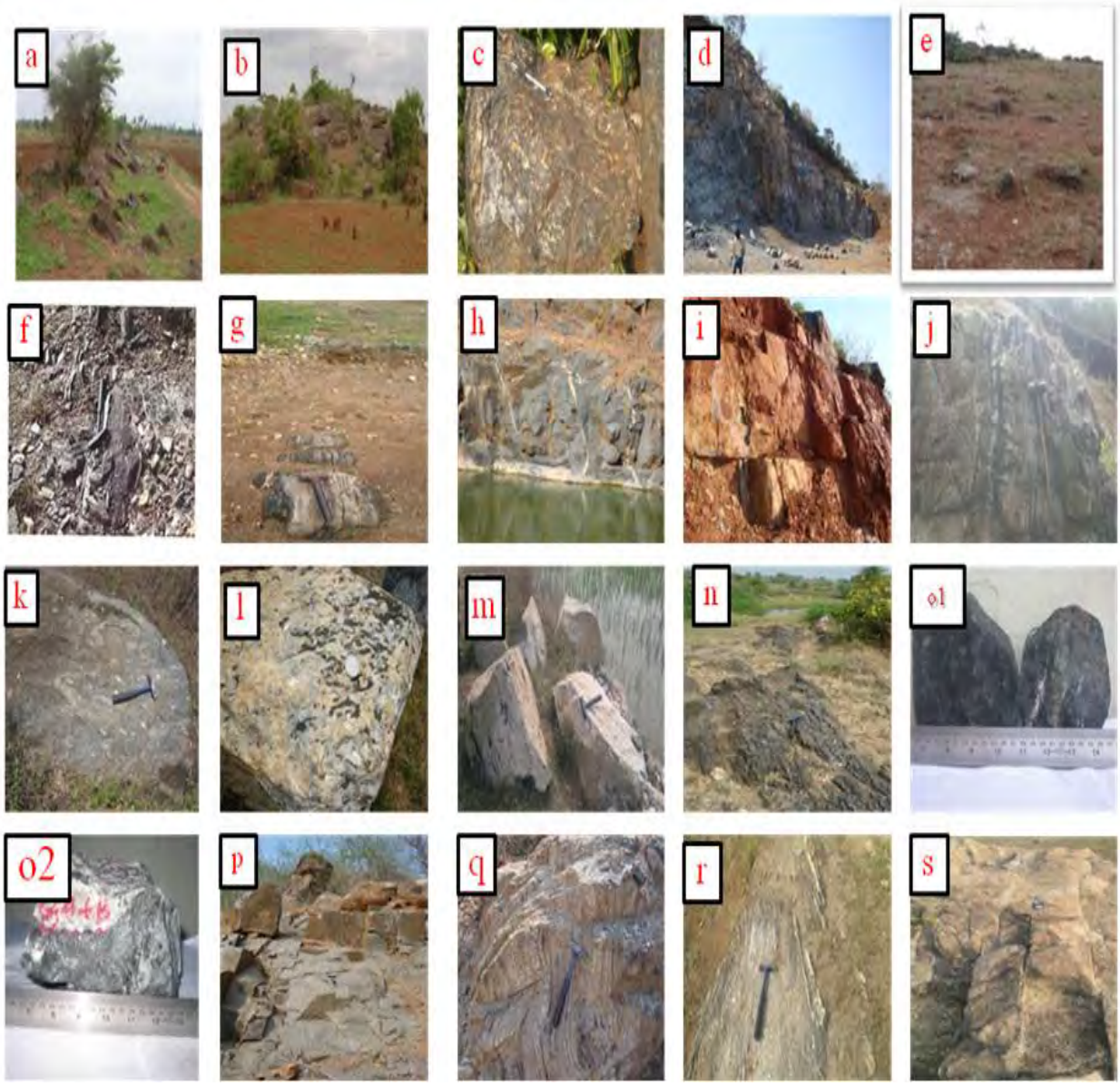
Amphibolites are traversed by quartz bands and veins (Figure 2h) and also displayed structural features like joints, fractures, folds and shear zones in the Gobbagurthi area (Figsures 2i and 2j). They are less in areal extent when compared to the schistose and gneissose rocks in the study area of KSB (Appavadhanulu, 1976). These rocks are considered as younger than the schistose and gneissose rocks and are either younger or older than the anorthositic rocks.

Megacrystic plagioclase is occasionally noticed in amphibolites (Figure 2k) at Lallapuram and Uttukuru places in KSB and hence, the amphibolites have petrogenetic link with the anorthosites in the area (Phinney *et al.*1985 and Sarvothaman, 1996).

The strike directions of amphibolites are oriented mainly in NE-SW and NW-SE with steep dips (60^0-85^0). These structural trends are very

Figure 2: Field Photographs from the Gobbagurthi area in the Khammam Schist Belt

(2a) Massive amphibolite occurring as inclined dyke with 40^0 at 1.5 km at Laxmipuram(2b) Lensoid bodies ofmassive amphibolites in a small mound at Gobbagurthi(2c) Massive amphibolite showing garnet porphyroblasts at Jannaram(2d) The lensoid bodies of amphibolites (pillow basalt?) occurring as roof- top rafts thrust over the tonalite-trondhjemite gneissic rocksat Garlavaddu(2e) Massive amphibolites occurring as roof-top rafts thrust over banded iron formation (BIF) at Sriramagiri(2f) Foliated amphibolite 1 km North of Lingannapet showing synformal structure. Note the trend of foliation is N 55^0 E with steep dipping on NW and SE directions (2g) Foliated amphibolite (dark) co-folded with tonalite-trondhjemite gneisses (white) 3 km north of Yenkuru. Note the gneissic bands display steep dipping (85^0) (2h) Quartz veins cutting the massive amphibolite at canal section 1 km west of Gobbagurthi(2i) Massive amphibolite showing horizontal joints at Gobbagurthi(2j) Deformed intercalated bands of amphibolite (dark) and tonalite-trondhjemite gneiss (white) at 2.5 km North of Yenkur. Note these bands trend in NE-SW direction with steep dipping towards NW direction (2k)Megacrystic plagioclase laden amphibolites at Lallapuram and Uttukuru places in KSB. Hammer is 30 cm (2l) Massive anorthosite showing garnet porphyroblasts and lenticular hornblendes at 1 km west of Jannaram. Coin is 2 cm diameter (2m) Massive anorthosite showing lenticular hornblende (dark) Nimmavagu near Jannaram. Hammer is 30 cm (2n) Massive anorthosite (white) showing intrusive contact relationship with foliated amphibolites (dark) in Nimmavagu near Jannaram ($2o_1$ & $2o_2$) Ultramafic lenses and bands within Tonalite- trondhjemite gneiss at Garlavaddu(2p) Felsic granulites showing vertical joints at Laxmipuram hill, 1.5 km NW of Laxmipuram village (2q) Deformed intercalated bands of amphibolite (dark) and tonalite-trondhjemite gneiss (white) beyond Laxminarsimha Swamy Temple at Garlavaddu. Note these bands trend in NW-SE direction with steep dipping towards SW direction. Hammer is 30 cm (2r) Foliated or streaky amphibolite showing steep dipping (80^0) at Himam Nagar. Hammer is 30 cm (2s) Deformed pink granite showing vertical joints at the bottom of Wyra tank-bund



common when compared to those of E-W and N-S trends which are transposed earlier ones in the study area. The rocks of the study area exhibit structural complexities due to multiple phases of deformation and metamorphism (Narsimha Reddy and Leelanandam, 2004 and Subbaraju, 1975). According to Subbaraju (1975) the rocks of KSB were affected by five periods of folding, two periods of metamorphism and three periods of igneous activity whereas three phases of brittle-ductile deformations were noticed in the Chimalpahad layered complex in KSB and itis just north of present study area(Narsimha Reddy and Leelanandam, 2004).

3.2. Anorthosites

Anorthositic rocks are coarse grained cumulates of Plutonic igneous rocks that have been crystallized from tholeiitic basalt magmas of mantle origin (Ashwa, 1993). They show massive as well as layered forms in the Khammam Schist Belt (Narsimha Reddy and Leelanandam, 2004).

The rocks are fresh, white or grayish white in colour. They occasionally show porphyroblasts of garnets and lenticular aggregates of hornblendes at Jannaram (Figs.2l & 2m). These rocks are relatively very restricted in the areal extent and they occur as bands and lenses in schistose & gneissose rocks of the KSB. They are prominently seen at Chimalpahad hill ranges north of study area; however, the small bodies of anorthosites have intrusive relationships with foliated amphibolites (Figure 2n) at Jannaram, Lingannapet, Yenkur, Wyra and Siripuram areas of the KSB. Though perfect layering and gneissosity are well developed at many places throughout the area, it is only in the northern part of the KSB where the layered characters are lavishly revealed and well-defined layering of plagioclase - and hornblende-rich layers on different scales and styles are very conspicuous in the gabbroic anorthosites and anorthositic gabbros which are the dominant rock types of the Chimalpahad layered anorthosite complex; zebra banding, inch-scale layering and rhythmic layering are seen in low strain areas(Narsimha Reddy and Leelanandam, 2004; Subba Raju, 1987; Ramamohan Rao and Satyanarayana Raju, 2000).

3.3. Mafic and Ultramafic Rocks

These are second larger group after gneissose and schistose rocks in the study area. They are in the form of amphibolites (both massive and foliated), meta-dolerites, and meta-gabbros and metamorphosed hornblendites, Pyroxenites, hornblende schists (Figs.2o_1&2o_2), chromite bearing talc – tremolite – actinolite schists and chromite- hornblende cumulates (chromitites) (Figure 1). These rocks occur as lenses, bands, and hillocks in the study area. All these rocks are underwent variable metamorphism and deformation from greenschist to amphibolite facies. However, lower granulite facies metamorphism is locally observed in these rocks.

The ultramafic rocks are now seen in varying stages of preservation as massive lensoid bodies and friable schistose bands with chromite float ores (Narsimha Reddy and Leelanandam, 2004and Dharma Rao *et al.* 2015). The original mineralogy and magmatic textures are rarely noticed in these rocks from low strain areas.

3.4. Granulites

The granulitic rocks of the Gobbagurthi area have limited areal extent (Figure 1) and are sparsely distributed in gneissose and schistose rocks. They are classified into threevarieties based on mineralogical characters, but they show common granoblastic to granulose texture and they are:

(1) mafic granulites, (2) felsic granulites and (3) calc granulites. They occur as intrusive hill masses (~ 5 sq.km), dykes (0.1 x 1 km), lenses (<1x2m) and bands amidst of schistose and gneissose rocks from the KSB. These rocks contain clinopyroxene, plagioclase and hornblende as essential minerals and quartz, orthopyroxene, biotite, garnet, zircon and opaques as accessory minerals (Table 2).

3.4.1. Mafic Granulites

Mafic granulites are coarse grained and dark in colour. They look like gabbroic rocks in the field, but they differ from the latter by their characteristic mineral assemblages, granoblastic texture and absence of cumulate characteristics. They occur as lenses, dykes and small hillocks in the KSB and are generally situated at the marginal portion of the Chimalpahad layered complex and other places at marginal zones and specifically noticed at Kannegiri hills in the eastern margin and Gobbagurthi hills in the western margin of the KSB.

The petrographic characteristics of mafic granulites are similar to those in high pressure retrograde granulites of Ungava orogen, Canada (St-Onge and Ijewliw, 1996). Therefore, these mafic granulites may be considered as high pressure retrogressive granulite facies metamorphic products of basalts or fine grained gabbros. Mafic granulites of KSB may be comparable with those of some greenstone belts of Canada based on their mineralogical, petrological and emplacement history (Ungava, Piikwitonei and Kapuskasing in Superior Province

Table 2: Approximate Modal Compositions (Vol. %) of the Anorthosites, Granulites and Gneissose and Schistose Rocks From The Gobbagurthi Area in the Khammam Schist Belt

	Anorthosites					Granulites			Gneisses			Schists		
	JN1	**JN2**	**WR7**	**YN2**	**SP10**	**GG1**	**LP1**	**YN1**	**GG10**	**NC26**	**GV27**	**GV28**	**JN19**	**GG5**
Hbl	13	20	1.5	1.5	4.5	20	16	18	25	15	5	10	-	-
Act	-	-	-	-	-	-	-	-	-	-	-	20	90	60
Plg	80	65	96.5	96.5	92.5	32	35	34	26	30	40	-	-	-
Grt	5	5	-	-	-	-	-	1	-	-	-	-	-	-
Cpx	-	10	-	-	1	40	36	38	-	-	-	58	-	-
Opx	-	-	-	-	-	1	5	3						
Qtz	-	-	-	1	1	5	6	4	33	40	35	5	5	30
Zrn	-	-	-	-	-	-	-	-	1	3	-	-	-	-
Bt	-	-	-	-	-	-	-	-	10	10	-	-	-	-
Acc	2	-	1	1	1	1	2	1	5	2	10	5	5	10
Total	**100**	**100**	**99**	**100**	**100**	**99**	**100**	**99**	**99**	**100**	**100**	**98**	**100**	**100**

Note: LP: Linganpeta; GV: Garlavaddu; LX: Laxmipuram; NC: Nacharam; GG:Gobbagurthi; JN: Jannaram; WR: Wyra; APJ: Anjanapuram; BNT: Nagaboinatigala banjara; Acc: Epidote, Biotite, Sphene, Scpolite, Calcite and Fe-Ti oxides. Mineral abbreviations after Ralph Kretz.

Source: [17]

of Canada, South Africa Kaapvaal Province and Rhodesian Province) and Wyoming& Montana of USA (Condie, 1982).

Mafic granulites have distinct mineralogy and textures when compared to other rock types of KSB. Pyroxenes are dominant over amphiboles and clinopyroxenes are greater in proportions than orthopyroxenes in these granulites. Plagioclase feldspar is only dominant felsic mineral enter into metamorphic reaction with mafic minerals (two pyroxenes, hornblendes and Fe-Ti oxides) to form two varieties of garnet such as coronas and porphyroblasts. Absence of epidote group minerals in granulites is a distinct mineralogic variant from that of anorthositic rocks and amphibolites of the KSB. Scapolite, quartz, biotite and Fe-Ti oxides form the accessories in these mafic granulites. The mineralogy and textures of mafic granulites of KSB (Narsimha Reddy and Leelanandam, 1999) are quite comparable to those of garnetiferous granulites of the Sittampundi complex (Janardhanaand Leake, 1975).

3.4.2. Felsic Granulites

Felsic granulites are light grayish white in colour and granular in form in hand specimen. They occur as small mounds in the field at 1.5 km north-western part of Laxmipuram in Gobbagurthi reserved forest area. Vertical joints (Figure 2p) are common in the direction of N 310^0 W in these rocks.These rocks contain mainly pyroxenes, plagioclase feldspar and quartz. Hornblende and Fe-Ti oxides occur as sub-ordinate minerals. Biotite forms the accessory. Garnets are totally absent and orthopyroxenes are more abundant than clinopyroxenes in felsic granulites. They show intergranular granoblastic texture with feeble foliation due to alignments of orthopyroxene and plagioclase (±quartz) minerals. Hornblende occurs as corona around Fe-Ti oxide and orthopyroxenes. Bent lamellae in plagioclase indicate that these felsic granulites are deformed and metamorphosed at granulite facies grade.

3.4.3. Calc Granulites

Calc granulitesoccur as narrow bands along with quartzites 2 km north of Gobbagurthi village. They are greenish grey in colour and show medium to coarse grained granulitic textures. The dominant minerals present in them are diopside, scapolite, wollastonite and sphene. Accessories include hornblende, actinolite, tremolite, apatite, quartz and Fe-Ti Oxides (Subbaraju, 1975).

3.5.1. Gneisses

The oldest and dominant rocks in the study area are gneisses of different petrological associations: ortho-gneisses (hornblende- plagioclase gneiss, quartz–plagioclase-hornblende gneiss and tonalite-trondhjemite gneiss) which form steep bands within the intercalated amphibolite bands, while para- gneisses are closely associated with corundum bearing rocks and biotite rich quartzo-feldspathic schists. These rocks are intruded by intrusive and extrusive mafic dykes and sills (now amphibolites) and layered and massive gabbro-anorthosite association. They occur as steep bands along with amphibolite bands with vertical and sub-vertical foliation and horizontal to vertical mineral stretching lineations in plain country as well as core portion of the amphibolite hills at Garlavaddu, Jannaram and Gobbagurti areas (Figure 2q). They show variable intensity of deformation with folds, fractures and shears.

These rocks show variable structural trends with moderate to steep dips (40^0-80^0) and have NE-SW foliation trend in the north of Jannaram and NW-SE foliation trend in the south of Garlavaddu, Jannaram, and Gobbagurthi areas

of KSB. These structural trends are locally cut by E-W trending of amphibolite dykes in the KSB (Figure 1).These rocksshows typically granular texture with equant mineral grains, and planar boundaries.

3.5.2. Schists

The common schists present in the KSB are kyanite-sillimanite- cordierite-gedrite-plagioclase-corundum± quartz rocks, garnetiferous biotite-kyanite schists, and quartzo-feldspathic schists. These Schists are essentially constituted by quartz, felspars, biotite, chlorite and sericite (Table 2).They occur as steep bands along with amphibolite bands with vertical and sub-vertical foliation and horizontal to vertical mineral stretching lineations in plain country (Figure 2r).

3.5.3. Pink Granites

Pink granites are medium to fine grained and homogeneous rocks. They are sparsely distributed in the study area, specifically at Siddinagar, Somulagadda and Wyra (Figure 1). They have intrusive as well as sheared contact relationships with schistose and gneissose rocks of the KSB. These rocks at Siddinagar show feeble foliation trend in E-W direction with steep dipping towards south, while at Somulagadda and Wyra areas, they display NNW-SSE trend with steep dip of 85^0 towards SW. These Pink granites are occasionally traversed by meta-dolerite (amphibolites) dykes. Both the rocks are cut by joints (Figure 2s).

4. Petrography

Mineralogy and Textures of amphibolites and associated rocks of the study area:

All the rock types are variably deformed and metamorphosed from greenschist to lower granulite facies grade. However, the amphibolite facies metamorphism was wide spread and most persistent in the KSB.

4.1. Amphibolites

These are of two types as (1) massive granular and (2) foliated/lineated ones. They are coarse to fine grain in hand specimen. They display granular and poikiloblastic/ porphyroblastic textures (Figs.3a, 3b and 3c) and gneissose and schistose textures (Figs.3d & 3e) under the microscope. Relict ophitic textures (Figure 3f) and garnet corona textures (Figure 3g) are occasionally seen in massive amphibolites.

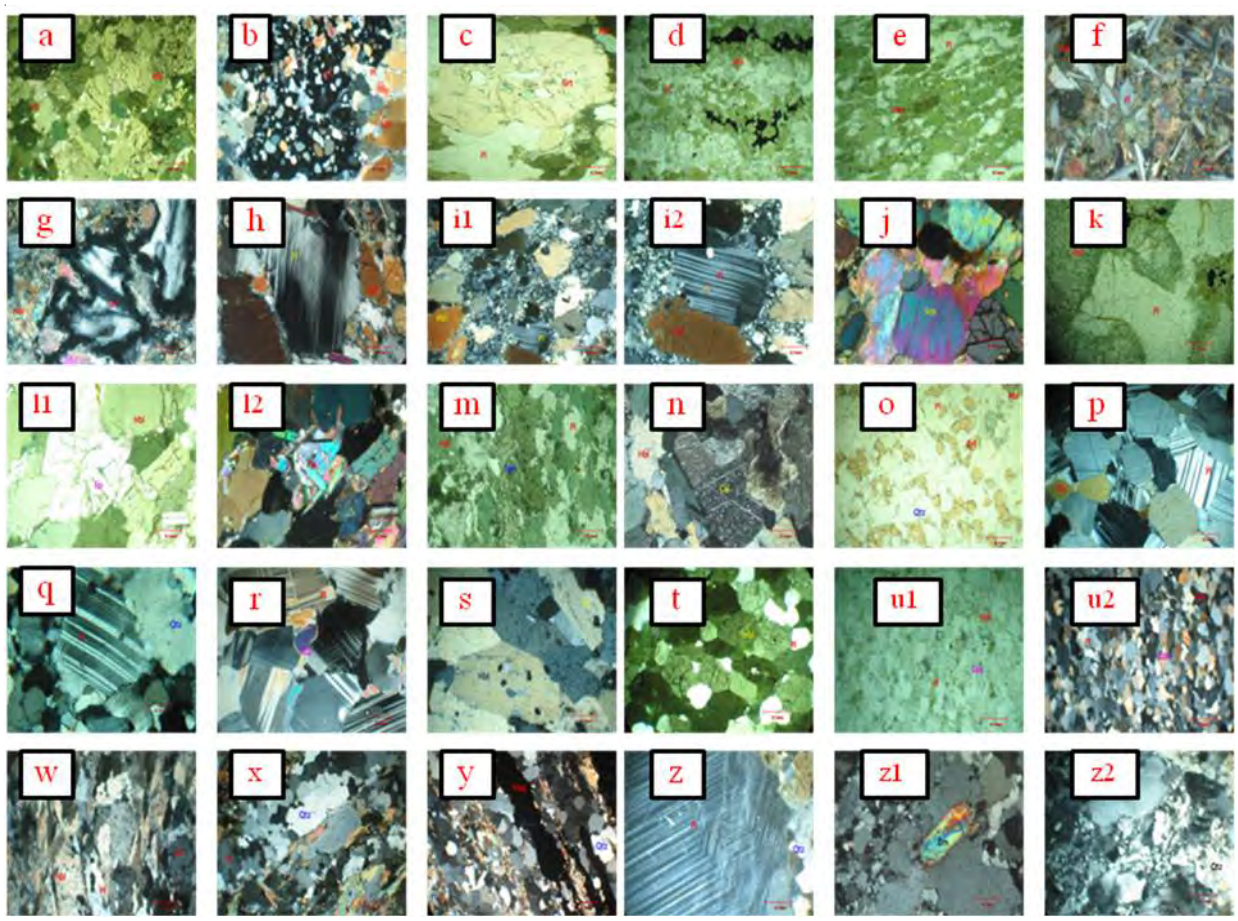
They essentially consist of hornblende and plagioclase. Epidote, zoisite, clinozoisite, scapolite, garnet and augite are present as sub-ordinate minerals. Quartz is occasionally present as inclusions in sieved-type garnet porphyroblasts (see Figure 3b). Sphene and magnetite are found in traces. The modal compositions of amphibolites are presented in the Table 1.

Plagioclases (An_{50-67}) are fine to medium grained with a length from 0.37 to 0.42 mm and a width from 0.22 to 0.3 mm. They generally exhibit subhedral to anhedral form with planar to sub-planar grain boundaries. In many rocks, the grains are equant; the presence of smaller equant grains around the margins of big deformed grains is not uncommon. They show dusty appearance and occur as lath-shaped grains in some of the amphibolite dikes (Figure 3e). Albite and combined Albite- Carlsbad twins are frequently observed and Pericline twinning is rare in them. The plagioclase grains occasionally show irregular outlines, and display strong zoning (Figure 3h) and bent lamellae with curved boundaries (Figure 3 i1& i2). The textures are generally modified by late dynamic deformations, in which the big coarse-grained plagioclase is

Figure 3: Photo Micrographs of Amphibolites and Associated Rock Types from the Gobbagurthi Area in the Khammam Schist Belt

(3a) Amphibolite lenses showing isotropic granoblastic texture (PPL)(3b) Garnetiferous amphiboliteshowing garnet Poikiloblastic texture with plagioclase, hornblende and quartz inclusions(XPL)(3c)Garnetiferous amphibolite showing garnet porphyroblastic texture. Note inclusions of plagioclase, quartz and hornblende at the core of garnet (PPL). (3d) Foliated amphibolite showing gneissose texture. Note alignment of hornblende (green), plagioclase (white) and Fe-Ti oxides (block)(PPL).(3e) schistose texture with alignment of hornblende and plagioclase in deformed foliated amphibolite. Note peripheral granulation around big crystals of hornblende and plagioclase (PPL). (3f)Garnetiferous amphibolite showing relict ophitic texture with randomly oriented plagioclase grains within hornblende matrix (XPL). (3g) Garnetiferous amphibolite showing garnet corona at interface between zoned plagioclase and hornblende (XPL).(3h) Amphibolite showing zoning and truncated twin lamellae in plagioclase.Note small epidote crystals at the margin of plagioclase(XPL). (3i1) Deformed amphibolite showing smaller recrystallized grains of plagioclase and hornblende around the margins of their bigger counterparts(XPL).(3i2) Bent twin lamellae in deformed plagioclase at the centre of photomicrograph of amphibolites (XPL).(3j) Amphibolite band showing granular texture with scapolite at bottom-center of photomicrograph(XPL).(3k) Meta-dolerite showing hornblende corona at interface between plagioclase and clinopyroxene (PPL).(3l1 & l2) Amphibolite band showing randomly oriented needles of epidote crystals within plagioclase at the centreof the photomicrographs (PPL&XPL). (3m) Photomicrograph showing aggregate grains of sphene lie parallel to the hornblende (green) and plagioclase (white) in foliated amphibolites (PPL). (3n) Amphibolite showing granulose texture.Note calcite with rhombus cleavage at bottom – centre of the photomicrograph (XPL). (3o) Garnetiferous gabbroic anorthosite showing aggregate crystals of garnet porphyroblasts (PPL). (3p) Photomicrograph of anorthosite showing cummulus texture(XPL).(3q) Deformed anorthosite showing cataclastic texture.Note the bent twin lamellae and curved boundaries of the plagioclase grains. Note also the fine grained untwinned inter-granular (recrystallized) plagioclase(XPL).(3r) Deformed anorthosite showing bent and truncated twin lamellae of plagioclase(XPL).(3s) Photomicrograph showing interlocking of inequant hornblende grains with planar boundaries and triple junctions of an isotropic decussate texture in a ultramafic schist (PPL). (3t) Amphibolite lens showing isotropic ''decussate'' granoblastic texture (PPL).(3u1 & u2)Photomicrograph of Granulite exhibiting gneissic texture with parallel alignment of plagioclase, quartz, pyroxene and hornblende (PPL).(3w) Chlorite- actinolite schist showing schistosity with strong foliation(PPL&XPL).(3x) Quartz- plagioclase-biotite-hornblende gneiss showing microfolds overprinted by plastic deformation(XPL).(3y) Banded iron formation showing oxide (magnetite, rutile) and silicate (quartz, plagioclase, hornblende and grunerite) bands with recrystallized grains under plastic deformation(XPL).(3z) Gneissic amphibolite showing deformed plagioclase with kink bands (XPL).(3z1) Photomicrograph of hornblende –plagioclase –quartz gneiss showing euhedral zircon crystal with resorption margin (XPL).(3z2)Pink granite (or) diorite showing deformed mortar texture (XPL)

Photomicrographs of Amphibolites and associated rocks from the Gobbagurthi area are shown in both PPL (Plane polarized light) and XPL (Crossed polarized light).



broken-down to form undeformed smaller recrystallized grains (Figure 3 i1 & i2). Inclusions of hornblende in plagioclases are occasionally observed in all types of amphibolites. Scapolite occurs as an altered product of plagioclase (Figure 3j).

The Hornblendes in general, are relatively fine grained, the boundaries of the hornblende grains are smooth, clean and clear, and no reaction products are observed along the hornblende-plagioclase contacts. They are dark green to brownish green in color and are fine to coarse grained, with a length from 1.1 to 1.7 mm and width from 0.86 to 0.50 mm. The grain size of hornblende in amphibolites is much coarser than that of the hornblendes in anorthositic rocks (Leelanandam & Narsimha Reddy, 1983; 1985). Simple twinning in hornblende is occasionally observed; sieved structure of hornblende with plagioclase inclusions is not an uncommon feature. Hornblende forms corona around clinopyroxene and Fe-Ti oxides in many massive granular amphibolites (Figure 3k).

Garnets in these rocks show sieved microstructure, with abundant inclusions of quartz, plagioclase, scapolite, hornblende and augite. In some of the garnetiferous varieties, augite is rarely present and is rimmed by hornblende (see Figure 3k). The close association of augite, hornblende and garnet, and the observed textural features suggest the augite is a “disappearing” phase and that garnet is a “growing” phase largely derived from the other two minerals.

Zoisite/clinozoisite in these rocks is colourless and it occurs as euhedral itself signify well developed crystal shapes. It shows anomalous blue, yellowish blue interference colors; it occasionally occurs as idioblasts with inclusions of plagioclase grains (Figure 3 l1 & l2).

Sphene is a major accessory mineral in the garnet free amphibolites, and gradually decreases in its amount with increase in the amount of garnet. It forms aggregate anhedral grains parallel to the foliation of schistose amphibolites (Figure 3m).

Calcite (Figure 3n) is rarely present in amphibolites and it shows rhombus cleavage, twinkling and bright polarization colours. Micro-shear zones are rarely seen in some foliated amphibolites and they show recrystallized fine grained material which are transposed to original mineral foliations of amphibolites.

4.2. Anorthosites

The rocks are fresh, white to grayish white in colour and are medium to coarse grained; the pegmatitic varieties are expectedly very coarse grained. They contain predominantly plagioclase (>90%) and subordinately hornblende (<10%). Pyroxenes are totally absent in pure anorthosites while clinipyroxene is occasionally present in mafic rich leuco-gabbros (Leelanandam and Narsimha Reddy, 1983); scapolite, zoisite /clino-zoisite and calcite are important accessories; garnet is present in insignificant amount, but in some it is found as porphyroblasts (Figure 3o). The modal compositions of anorthosites are presented in the Table. 2.

Plagioclase crystals are fresh and coarse grained, and rarely altered to scapolite. The size of the plagioclase varies from 2.3 mm to 3.0 mm in length and width from 1.7 mm to 1.8 mm in massive type anorthosites; and from 1.7 mm to 1.8 mm in length and from 1.3 mm to 1.4 mm in width in layered anorthosites. Twinning on albite and pericline laws is common, and Carlsbad,

combined albite-Carlsbad twinning is rare in them. In this respect these plagioclases resemble those from the Fiskenaesset complex (Windley *et al.*, 1973; Myers and Platt, 1977) and from the Quebec massif anorthosites(Suwa, 1979). Untwinned grains of plagioclases are frequently present. Planar boundaries, triple junctions and polygonal arrangement of plagioclases suggest that the typical 'equilibrium texture' is present in layered anorthosites (Figure 3p).

Some plagioclases in the massive deformed anorthosites, in contrast to the layered anorthosites, have irregular borders and show feeble zoning; bent and saw teeth lamellae, kink bands and peripheral granulation which are suggesting protoclastic or mortar texture (Figure 3q) with grain boundary migration and recrystallization at low temperature by dynamic deformation and there is no perceptible difference in composition between the fine-grained secondary recrysatallized grains and coarse-grained primary deformed grains of plagioclases from anorthositic rocks as in the Fiskenasset complex (Myers and Platt, 1977). This indicates that no significant change in plagioclase compositions occurred during metamorphism (Myers and Platt, 1977). All these features are conspicuously absent in the undeformed layered varieties. The plagioclases in the pegmatitic anorthosites are markedly more sodic than those in the layered anorthosites as pointed out by earlier workers and the former are more deformed than the latter (Leelanandam & Narsimha Reddy, 1983; 1985).

The decrease in the content of the plagioclase with increasing deformation and metamorphic recrystallization is a feature characteristic of plagioclases from other Archaean anorthosite complexes (Ashwal, 1993). Interestingly, it is in the pegmatitic deformed anorthosites only, garnet porphyroblasts occur and these features are similar with those of other places, especially in the Chimalpahad layered complex, north of present study (cf. Leelanandam and Narsimha Reddy, 1983 and 1985). Thus it appears to be a genetic connection between the lower content of the plagioclase, greater deformation and recrystallization and the appearance of garnet.

Hornblende crystals, in massive anorthosites at Jannaram are fine to medium grained, and they are of 0.6 mm to 0.7 mm in length, and 0.3 mm to 0.35 mm in width; their length (0.5 to 0.76 mm) and width (0.23 mm to 0.4 mm) are not very different in layered anorthosites at the Chimalpahad area noted by cf. Leelanandam and Narsimha Reddy, 1983 and 1985. Hornblendes are fresh and pale yellowish green in colour, with the absorption formula X < Y < Z. They show extinction angle (Z L c) of 12–20^0 and simple twinning is present in a few grains.

Inclusions of plagioclase in hornblende and hornblende inclusions in plagioclase grains indicate that these two minerals are formed simultaneously at equilibrium conditions. Scapolite occurs as small fresh independent grains and also as an alteration product of plagioclase (Figure 3r). Ziosite/clinozoisite occasionally occurs as euhedral crystals with well developed faces and is colourless in plane polarized light; it is generally tabular, but sometimes sub-rounded and prismatic in form. These textural habits of zoisite suggest that it is formed by breakup of plagioclase and hornblende grains (cf. Gibson, 1979); it shows anomalous blue or yellowish-blue interference colours. Calcite occurs as disseminations and is in trace amounts.

4.3. Mafic and Ultramafic Rocks

These rocks are occasionally preserved as cumulous igneous texture with cumulus hornblende and clinopyroxene. However, sometime the ultramafic rocks exhibit, by and large, metamorphic equilibrium textures with equant Polygonal grains and smooth planar boundaries with triple junctions (Figure 3s). These features indicate solid state recrystallization due to grain boundary migration during plastic deformation at higher temperature. In some mafic rocks in the study area a special type of metamorphic texture [decussate texture (Figure 3t)] is noticed with inequigranular, interlocking, randomly oriented platy, tabular, prismatic or elongated hornblende with planar boundaries and triple junctions.

4.4 Granulites

They display crude gneissic texture with recrystallized grain boundaries under the microscope (Figs.3 u1& u2).

4.4.1. Mafic Granulites

Typically show granoblastic texture with sieved as well as coronal garnet, flakes of biotite, rounded grains of sphene. Some of the mafic granulites exhibit exsolution lamellae of ilmenite in clinopyroxene, and these lamellae occur only in the core portion of clinopyroxene. Relict exsolution lamellae of thin clinopyroxene in orthopyroxene, orthopyroxene in clinopyroxene, and relict sub-ophitic textures are occasionally preserved in some of the mafic granulites. The mineralogical assemblage and textural features of the mafic granulites are distinctly different from those of the gabbroic rocks of the KSB.

Pyroxenes are dominant over amphiboles and clinopyroxenes are greater in proportions than orthopyroxenes in these granulites. Plagioclase feldspar is only dominant felsic mineral enter into metamorphic reaction with mafic minerals (two pyroxenes, hornblendes and Fe-Ti oxides) to form garnets of two varieties such as coronas and porphyroblasts absence of epidote group minerals in granulites is a distinct mineralogical variant from that of anorthositic rocks and amphibolites of the KSB. Scapolite, quartz, biotite and Fe-Ti oxides form the accessories in mafic granulites Table.2.

4.4.2. Felsicgranulites

These rocks contain mainly pyroxenes, plagioclase feldspar and quartz. Hornblende and Fe-Ti oxides occur as sub-ordinate minerals. Biotite forms the accessory. Garnets are totally absent and orthopyroxenes are more abundant than clinopyroxenes in felsic granulites. They show intergranular granoblastic texture with feeble foliation due to alignments of orthopyroxene and plagioclase (plus quartz) minerals. Hornblende occurs as corona around Fe-Ti oxide and orthopyroxenes. Bent lamellae in plagioclase indicate that these felsic granulites are deformed and metamorphosed at high grade conditions.

4.4.3. Calc Granulites

Display medium grained granulitic texture with dominant minerals of diopside, scapolite, wollastonite and sphene. Amphiboles, apatite, quartz and Fe-Ti oxides occur as accessories.

4.5. Gneissose and Schistose Rocks

These rocks are medium to coarse grained and are characterized by strong foliation and lineation. Chlorite schists (Figure 3v) quartzofeldspathic schists, hornblende schists, tremolite-actinolite schists, garnet-biotite-hornblende-plagioclase-quartz gneisses and hornblende-plagioclase-gneisses are the major rock types encountered in the study area. Mesoscopic to micro-folding is

a common feature in some of these rocks (Figure 3w). These deformed folded gneisses are later affected by solid-state recrystallization due to post-tectonic crystalloblastic process.

The gneissose rocks are medium to course grained, and show gneissosity in a pronounced way. They contain mainly quartz and plagioclase feldspars as dominant mineral in white bands, whereas in dark bands of gneisses, the hornblende and biotite form major minerals. Garnet, sillimanite, kyanite, cordierite, grunerite and corundum minerals are common in many para-gneisses (Figs.3x). Clinopyroxene, zoisite/ clinozoisite, scapolite, calcite, zircon and Fe-Ti oxides are found as accessories (Table. 2). Biotite is tabular in form, brown in color, and shows light brown to dark brown pleochroism and one set of basal cleavage. Hornblendes are green in colour, fine to medium grained. They show light yellowish green to dark green pleochroism and are marked with peripheral granulation. Two sets of cleavage at 56^0 angle and simple twinning are occasionally observed in the hornblendes.

Quartz is fine to coarse grained and anhedral in form. It occasionally occurs as elongated deformational bands shows wavy extinction. Plagioclase is fine to coarse grained and appears dusty in plane polarized light and it occasionally shows deformed kink bands in crossed polarized light (Figure 3y). Euhedral zircons with well developed faces are seen in hornblende-plagioclase-quartz gneisses from Garlavaddu (Figure 3z)

The schistose rocks essentially consist of chlorite in chlorite schist, quartz and feldspars in quartzofeldspathic schist and hornblende, tremolite and actinolite in hornblende schist and tremolite-actinolite schist. Plagioclase is common feldspar in all the schists. Sphene, zoisite/ clinozoisite and garnet are important accessories.

Chlorite is a fine to medium grained mineral and exhibits faint pleochroism with greyish green to light green in color and wavy extinction. Hornblende is medium grained and subhedral in form and shows yellowish green to light green pleochroism. Quartz is medium to coarse grained and is anhedral in form. It shows deformed lamellae and wavy extinction. Plagioclase is medium to coarse grained, and appears dusty; it is commonly altered to sericite. Lamellar twinning and zoning are common in many plagioclase grains. Twinning is generally on albite and pericline laws in them. Sphene is colourless and form aggregate anhedral grains and it shows bright polarization colours under crossed polarized light.

4.6. Pink Granites

These rocks contain deformed quartz and plagioclase feldspars and hypersthene as major minerals. Chlorite, biotite and hornblende are altered products from hypersthene, and anhedral garnet grains are locally developed in the shear planes. Pink granites (or) diorites are typically exhibit deformed and recrystallized textures under the microscope (Figure 3 z1).

Conclusion

Based on the field and petrographic characteristics of the various rock types from the KSB, we draw the following general conclusions.

1. The lithology of KSB is broadly classified into three main associations: (a) lower Ultramafic-mafic– leucogabbro- anorthosite- amphibolite1 association, (b) upper amphibolite2-tonalite-trondhjemite-ortho-gneiss association, and (c)

top most minor sub-marine (chemical) metasediments and pelitic paragneisses.

2. These lithological associations are described as thrust- imbricated panels of oceanic crust generated by opening and closing of sub-continental lithospheric mantle in the southeastern margin of Eastern Dharwar Craton and the different temporally and spatially extrusive and intrusive lithologies were tectonically juxtaposed, accreted and colloided during strike-slip transpressional tectononism operated in the KSB (Narsimha Reddy and Leelanandam, 2004 & Narsimha Reddy, 2016). Immobile trace element (Zr- Y-Ti) constraints of the amphibolites from the Nellore – Khammam Schist Belt explain about both Oceanic island arc and continental marginal arc setting for the rocks of KSB (Hari Prasad et. al, 2000).

3. These lithological variations of Gobbagurthi area are quite comparable with those of Arc-generated blocks of West Greenland by(Windley and Garde, 2009)ultramafic to mafic volcanic rocks (amphibolites) of SW Greenland (Polat *et al.* 2011) and subduction-accretion complexes of late Archaean Schreiber-Hemlo and White River-Dayohessarah greenstone belts in Superior province, Canada (Polat *et al.* 1998).

4. The amphibolites from the NKSB are formed from a melt generated by dynamic melting of Precambrian mantle (Vijaya Kumar *et al.* 2006).

5. Textural features of the rocks in the study area suggest that there are four types of imposed metamorphic fabrics namely (1) Cataclastic fabric (2) Plastic fabric (combined deformation and solid-state recrystallization) (3) Retrograde replacement fabric and (4) Crystalloblastic fabric that are overprinted on original cumulate, ophitic and inequigranular textures of the rocks in and around Gobbagurthi area. The original cumulate characters from mafic and ultramafic intrusives (layered complex) and ophitic to sub-ophitic textures from meta-basalts and meta-dolerites are modified by later metamorphic imprint and recrystallization under amphibolite and granulite facies metamorphism. Garnet corona and sieved microstructures are formed by sub-solidus recrystallization and blastic processes respectively retrograde metamorphism from granulite to amphibolite facies and from amphibolite to greenschist facies is uncommon and in Gobbagurthi area overprinted on original Protoliths.

6. The original mineral grains in each rock-units/ rock types are modified by late dynamic deformations in which the big / coarse-grained minerals (plagioclase, hornblende, clinopyroxene and Fe-Ti oxides) are broken-down to form undeformed smaller recrystallized grains along their margins by grain boundary migration and recrystallization (mortar texture) at low temperature conditions. Textural equilibrium between polygonal mineral grains with smooth planar boundaries and triple junctions in the rock-units of KSB suggest solid-state recrystallization due to grain boundary migration during plastic deformation at higher temperature. This type of textural features is overprinted on early folded gneissose and schistose rocks, streaky amphibolites and metamorphosed mafic & ultramafic lavas.

7. Hornblende coronas around clinopyroxene and Fe-Ti oxides, epitaxial overgrowth of hornblende over clinopyroxene, scapolite over

plagioclase and zoisite / clinozoisite mineral growth over plagioclase and hornblende indicate replacement textures in the rocks of Gobbagurthi area.

8. From the textural characteristics of mineral assemblages, and thermobarometric studies on amphibolites and anorthosites, the rocks of study area in particular and from the KSB in general have been equilibrated in two stages of metamorphism – at high pressure and temperatures (800-900 ^{0}C; 8-9 kbar) conditions of high pressure granulite facies and relatively low pressure and moderate temperatures (450-750 ^{0}C; 4-6 kbar) of amphibolites facies conditions (Narsimha Reddy and Leelanandam, 1999) and unpublished data of second author. The majority of mineral assemblages of amphibolites, anorthosites, and gneissose and schistose rocks from Gobbagurthi area equilibrated at transitional conditions between granulite facies to amphibolites facies (Hari Prasad et. al, 2000; Okudaira et.al, 2001).
9. Co-existence of high calcic plagioclase (An80-85) with igneous amphibole, occurrence of amphibole veins and megacrysts of amphiboles in a Ca-plagioclase matrix, micro-texural features like plagioclase inclusions in hornblende and hornblende inclusions in plagioclase in the rocks of the study area and adjoining CLC suggest a hydrous nature of the parental magma for the anorthosite-amphibolite-tonalite-trondhjemite gneiss association in the KSB.

Acknowledgment

The first author acknowledges University Grants Commission (UGC) for providing Rajiv Gandhi National Fellowship award. The second author expresses his sincere thanks to OU-DST-PURSE for providing financial assistance.

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