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Geochemical Characteristics of Mafic Granulites and Associated Websterites from the Sittampundi Complex, South India

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Abstract

Linear bands of garnetiferous mafic granulites composed of garnet, clinopyroxene, plagioclase with or without orthopyroxene occur all along the region in between the E-W trending Moyar Bhavani shear (MBS) and the Palghat cauvery shear (P-Ca). Dismembered units of these mafic granulites and websterites occurring in association with supracrustal sequences can be traced from the southern margin of Nilgiri massif to Sittampundi Complex, in the high grade terrain of south India. Field characteristics of these rocks in the Sittampundi Complex show that the mafic granulites are invariably associated with websterites indicating their genetic relationship. The mafic granulites occur as bands within anorthosites and as veins and lensoid patches within dunites. Petrographic studies reveal that mafic granulites with garnet + clinopyroxene + plagioclase assemblage and mafic granulites of similar assemblage with orthopyroxene as the additional phase are the most predominant. The assemblages do not occur as discrete bodies and are present as different bands in the rock. The major element chemistry of the rocks show that they have a basaltic chemistry. The rocks exhibit tholeiitic trend as seen from the AFM diagram and on a Jensen's cation plot, many of the analyzed samples fall in the field of komatiitic basalt. The rocks are rich in transition metals and are depleted in incompatible elements. Rb is generally lower than the primordial mantle value. Chondrite normalized transition metal plots show a progressive depletion from Ti to Ni with a positive Ti anomaly and a negative Cr anomaly. Whereas the websterites are enriched in transition metals and have low concentration of incompatible elements than the mafic granulites. The transition metal plots of websterites show a mild negative Ti anomaly and a positive Co anomaly. The differentiation trends observed in the bivariant plots of major and trace elements show that, the chemistry of the rocks are not modified by partial melting.

Key words : Mafic granulites, Websterites, Sittampundi Complex, Bhavani Shear Zone.

Introduction

Granulite facies terrains of Southern India have received considerable attention over the past two decades because of their bearing on crustal evolution. Perusal of literature reveals that two types of mafic granulites predominates in the South Indian high grade granulite facies terrain. The most predominant one is the mafic granulites associated with the charnockites, which contain an assemblage of Opx + Cpx + Plg + Hbl + accessory minerals ± garnet as a minor phase. The other less common variety is garnetiferous mafic granulites, which occur as linear bands and lenses within the retrograded reworked hornblende biotite gneisses of the region in between the E-W trending Moyar-Bhavani and Palghat-Cauvery shear systems (Fig. 1). Structurally these garnetiferous mafic granulites are conformable to the gneissic country rocks and are commonly associated with websterites, calcic-meta anorthosites (Selvan and Janardhan, 1990; Janardhan and Leake, 1975; Ramadurai et al., 1975) and serpentinised dunites. These mafic granulites contain Grt + Cpx ± Plg ± Opx ± Hbl. Such assemblages were earlier viewed as eclogite-gabbro series (Subramaniam, 1956) from the metamorphosed anorthositic igneous complex of Sittampundi, in the granulite facies terrain of south India and attain significance in view of their regional distribution.

Geological Setting

The Moyar-Bhavani shear (MBS) is formed due to the coalescence of WNW trending Moyar lineament and NE trending Bhavani lineament (Fig. 1). The two lineaments form the boundaries of Nilgiri massif. After coalescence in Bhavani Sagar, the lineament is named as Moyar-Bhavani lineament or shear which trends E-W to ENE-WNW. This lineament/shear belt is considered to extend further east into the Mesozoic sedimentary cover (Gopalakrishnan et al., 1975). However, Drury et al (1984) believed that the shear belt veers to a NNE direction 50 km east of Salem town and extends further along the eastern margin of Cuddapah basin. The shear belt extending further east of Salem is not related to Moyar-

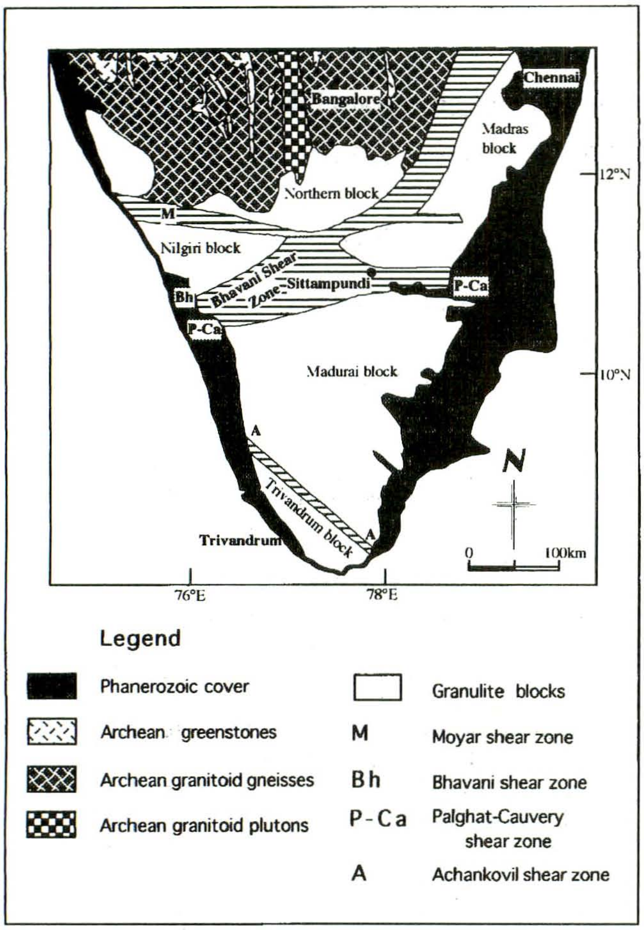

Fig. 1. Generalized geological map of Granulite facies terrain of south India showing the location of study area.

Bhavani shear and is a separate lineament named as Attur valley shear.

The Palghat-Cauvery lineament/shear belt, which is also called Noyil-Cauvery shear belt after a small river Noyil, is also a major shear belt in the region and extends across the subcontinent from the West coast to East coast. P-Ca has been recognized as a fundamental break in terms of lithological association and is considered to separate the Archaean granulite belt and the Proterozoic granulite belt of contrasting metamorphic history and ages.

These two shear zones (MBS and P-Ca) together form a dextral oblique-slip shear complex of Proterozoic supracrustal sequences (Drury and Holt, 1980; Mukhopadhyay, 1986). In this region, dismembered units of Archaean layered complexes comprising calcic-meta anorthosites, websterites, clinopyroxenite, pyroxenite, mafic granulites and serpentinised dunite occur as linear bands for a distance of more than 250 km., from the southern margin of Nilgiri massif to Sittampundi in the east.

Field Characteristics

Sittampundi Complex is well known for the occurrence of anorthosites and has been investigated in various geological aspects. It is located 75 km south west of Salem town. Since, mafic granulites are encountered mainly in the western part of the complex, only a part of the complex is taken up for the present study. The area examined is about 122 sq.km.

Sittampundi complex is a highly deformed Archaean anorthosite complex which forms an arcuate belt extending for a distance of 19 km (Fig. 2). The general width of the anorthosite body is about 700 m. To the south of the Sittampundi village, the anorthosites attain a maximum width of about 1 km and the thickening of anorthosites is attributed to NNW-SSE trending open fold (Ramadurai et al., 1975). In the crest of the fold, numerous elongate bodies of mafic granulites are seen. To the south east of Sittampundi, near Sirappalli, few ultramafic bodies contain veins and patches of mafic granulites, garnet amphibolites, garnet websterites and amphibolites. In places, small elongate bodies of mafic granulites and lensoid bodies of websterites occur within the gneisses. The well foliated hornblende biotite gneisses are mafic rich and banded. These gneisses carry older supracrustal rocks viz. ferruginous quartzite, calc-granulites, mafic granulites, websterites and anorthosites. The general trend of the gneisses (NW-SE) is conformable to that of the supracrustals. However, in the southern part of the area, the trend is almost east-west.

Mafic and serpentinised dunite ultramafic intrusive bodies of few hundred meters in length are located in the southern part of the area near Sirappalli (Fig. 2). The highly deformed Archaean anorthosites which host the mafic granulites contain calcic plagioclase (An85-An95), and are comparable to the anorthosites of Fiskenaesset complex, Greenland (Windley and Selvan, 1975). The banded anorthosites in this area are considered as layered anorthosites and are essentially composed of plagioclase and hornblende (5-50%). To the south of Sittampundi, true anorthosites (Fig. 3A) with 90% plagioclase feldspar are exposed in the thickened portion of the band. Corundum occurs in many places in this area and its origin is thought to be the result of incongruent melting of the plagioclase under high pressure and temperature (Yardley and Blacic, 1976; Janardhan and Leake, 1974). Occurrence of sapphirine in anorthosites close to the chromitite bodies was also reported by Janardhan and Leake (1974). Layers of chromitite ranging in length from few meters to few tens of meters occur within the anorthosites in the eastern part of the area. These chromitite layers contain

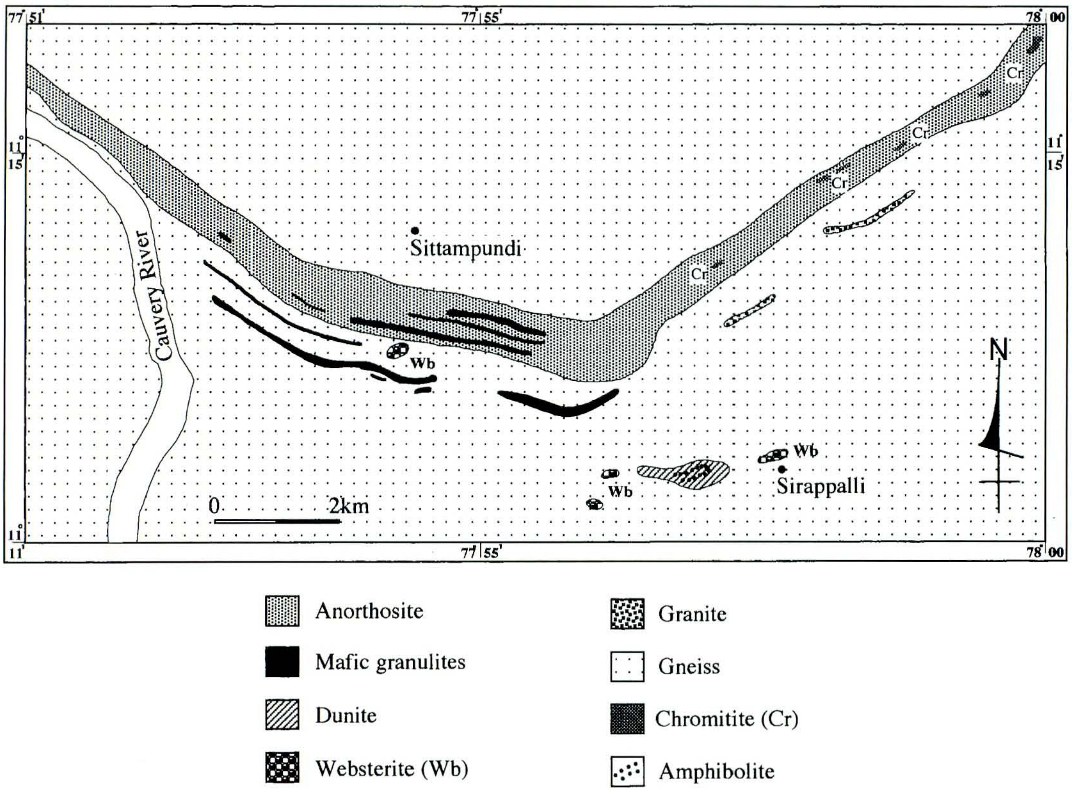

Fig. 2. Geological map of the Sittampundi Complex.

chromite and hornblende.

In the south of Sittampundi, three major bands of mafic granulites occur within the anorthosites. These bands are 2 to 3 km long forming low level ridges and are conformable to the anorthosites. However, they are sub-parallel in few places and the variation in the trend of the anorthosites (NW-SE) and mafic granulites is about 5-10%. The presence of minor folds and pinch and swell structures are characteristic of mafic granulites and such features are rare in the anorthosites. The mafic granulites are generally banded and based on the mineralogy, the layers can be classified into garnetiferous mafic granulites, garnet-websterites and garnet-amphibolites. In general, the garnetiferous rocks are medium grained with less amount of plagioclase and orthopyroxene is rarely present. Coarse grained rocks with garnet and pyroxene porphyroblasts (Fig. 3B) are rarely seen. To the south of Sittampundi, the mafic granulites contain segregations of garnet pyroxenites and garnet websterites. The size of these enclaves range from 10 meters to 100 meters. Websterite is locally associated with mafic granulites, anorthosites or gneisses (Fig. 3C).

In the southern part of the area, elongate bodies of magnesite bearing dunites are exposed near Sirappalli. The mafic granulites occurring within the ultramafic bodies in Sirappalli are smaller, rarely exceed 200 m in length and in places form smaller veins of about 1 to 2 m in width. These veins have been retrogressed resulting in the formation of amphiboles and can be considered as garnet amphibolites. Medium to coarse grained websterites which are bimineralic, poor in plagioclase and devoid of garnet form oval shaped patches within ultramafic rocks. Pegmatite and quartz vein intrusions mark the youngest intrusive activity in this region.

Petrography

Mafic granulites are characterised by centimeter to decimeter thick layers. The layers are defined by variations in grain size and in the abundance of garnet, clinopyroxene and plagioclase. In some layers orthopyroxene occurs as an additional mineral and these layers are typified by granulitic texture with equigranular, medium grained minerals. Where as the layers without orthopyroxene are medium to coarse grained, lacking granulite texture and frequently exhibit porphyroblastic texture. In thin sections garnet is observed as large subrounded idiomorphic grains and is 10 to 40 percent by volume. Garnet porphyroblasts often enclose clinopyroxene and plagioclase. Clinopyroxene which is 20 to 30 percent by volume is pale green typified by lamella structure. Plagioclase is always interstitial and is labradorite (An 50 to An 55). The orthopyroxene bearing assemblages

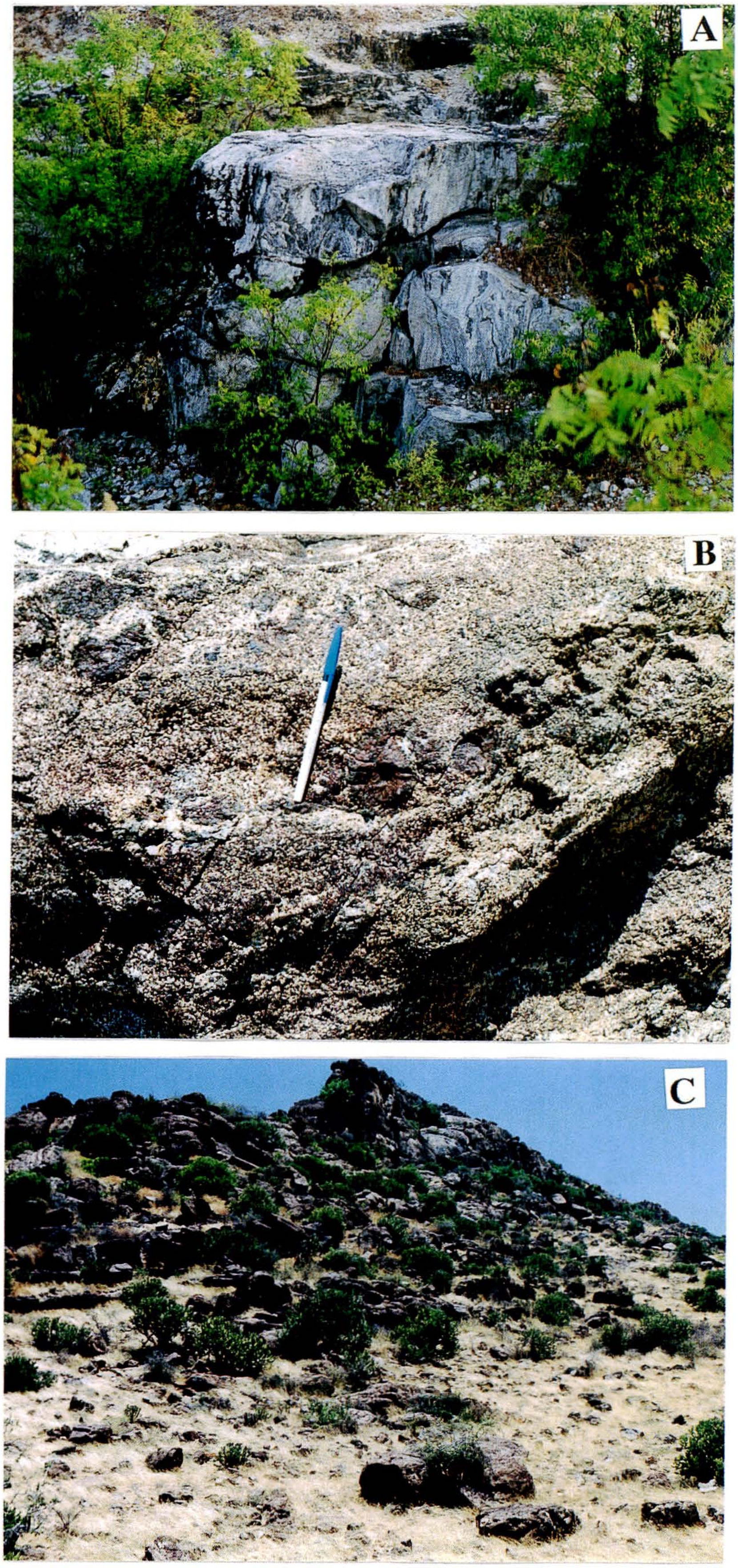

Fig. 3A. Corundum bearing anorthosite in Sittampundi.
B. Porphyroblasts of garnet and pyroxene in coarse grained mafic granulites occurring within the Sittampundi anorthosites.
C. A small hillock of websterites in the close proximity of southern margin of Sittampundi anorthosites.

characteristically have equant shaped minerals exhibiting triple junctions. The orthopyroxenes also contain faint exsolution lamellae of clinopyroxene. The plagioclase in the orthopyroxene bearing rocks is more calcic (An 80-85). The rocks have been subjected to alteration and formation of kelyphitic rims composed of aggregate of plagioclase and hornblende around garnet is common. Formation of granules of hypersthene are seen in few mafic granulites. Scapolite occurs in some rocks and appears to be secondary.

Extensive amphibolisation is noticed in the mafic granulites occurring as veins in the Sirappalli ultramafics and these rocks are typified by schistose texture with prismatic hornblende grains sweeping around porphyroblasts of garnet and interstitial plagioclase. Occasionally the garnets contain inclusions of clinopyroxene indicating that the primary assemblage contained clinopyroxene also. Kelyphitic rims of plagioclase and hornblende are occasional.

Websterites contain clinopyroxene and orthopyroxene in more or less equal proportion exhibiting cumulous texture. Both clino- and orthopyroxenes have exsolution lamellae. Plagioclase is generally absent and if present is in minor amounts. Secondary alteration resulting in the development of fibrous amphiboles is common. Garnet occurs in some rocks as subrounded grain.

Analytical Techniques

After careful examination of mineral assemblages, 20 samples were analyzed for major element chemistry using the wet chemical methods outlined by Shapiro (1975). Sodium and potassium were determined using flame photometry. Trace elements were determined in selected rock samples using ICP-MS at NGRI, Hyderabad. The ICP-Mass Spectrometer used for this work is a plasma Quad (VG Belemental, Winsford, U.K). The ion detection system and the data acquisition system consist of a Chaneltron Electron Multiplier (CEM) and a multichannel analyzer (Tract Northern). The details of the operation parameters of the instrument are summarized by Balaram (1991). For trace element analyses, rock samples solution (0.1%) were prepared using HF-$HC1O_4$-HNO_3 decomposition procedure in teflon beaker. An acid concentration of 5% (v/v) was maintained with respect to HNO_3 with an overall concentration of 0.1mg/ml Indium to serve as internal standard. To assess the accuracy of the procedure, few rock standards were analyzed. The analytical uncertainty for the Trace elements analyzed is better than 3% of the amount present.

Major Element Chemistry

The representative chemical analyses of major elements are presented in Table 1 along with the Mg numbers (Mg#) and C.I.P.W. Norm. The rocks from Sirappalli contain less amount of SiO_2 than the rocks which occur within anorthosites. Garnet amphibolites (T-1, T-4 & TS-8) are enriched in Al_2O_3 than the garnet websterites (T-8 & TS-5). The higher Al_2O_3 content in Sittampundi (8.36-15.78%) may be due to the abundance of garnet in these rocks. TiO_2 is fairly low, and in majority of the samples it is less than 1%. Mafic granulites from Sittampundi show significant variation in total Fe_2O_3 (9.62-17.49%) and MgO (4.42-12.61%). Alkali content is very low (<1%)in all the samples analyzed.

Websterites are bimineralic, consist of orthopyroxene and clinopyroxene in more or less equal proportion and are closely associated with mafic granulites. The analytical data (Table 1) indicate that the rocks are enriched in silica than the mafic granulites. The concentration of TiO_2 (0.24-0.45%) and Al_2O_3 (1.35-3.68 %) is found to be very low in these rocks. Fe_2O_3 (7.45-3.68%), MgO (18.59-21.15%) and CaO (13.34-17.45%) are fairly constant. Na_2O content is very less (0.60-0.72%) and the amount of K_2O present is negligible (0.03-0.20%).

The tholeiitic characteristics of the rocks are illustrated (Fig. 4) by the discriminatory diagram (AFM) proposed by Irvine and Baragar (1971). The more mafic rocks have certain chemical characters which differ from tholeiitic basalts and resemble more close to the komatiitic basalt which occur elsewhere (Ardndt et al 1977; Nisbet et al 1977; Nesbitt & Sun 1976).This has also been supported by the CaO/Al_2O_3 ratios, for many rocks have >0.9 of this ratio. However, no spinifex texture has been observed in these rocks. To understand the komatiitic affinity, the analyzed data were plotted on a Jensen's cation plot (Fig. 5). The Jensen's cation plot (Jensen,1976) can be effectively used for rocks which have suffered mild loss of alkalis during metamorphism (Rollinson, 1993). In this diagram, majority of the rocks plot in the field of basaltic komatiites apart from the websterites, which fall in the field of ultramafic komatiite.

Trace Elements

Analyzed data of the trace elements are presented in Table 2. and the plots of selected trace elements versus MgO (%), Zr and Ti (ppm) are not shown here for want of space. Transition metal abundances are high in the mafic granulites and the websterites have a higher concentration. Websterites are enriched in Sc (72.68-89.91ppm) than the mafic granulites. However, in the garnet websterites and garnet amphibolites,

Table 1. Representative analyses of major oxides (weight percent) along with C.I.P.W. Norm and Mg #.

Sample No.	SA-1	SA-2	SA-6	SA-7	SA-10	SM-1	SM-9	SM-11	SM-12	SM-14	SM-15	T-1	T-4	T-5	T-6	T-8
SiO_2	50.24	48.14	47.53	45.56	48.24	50.08	49.10	47.54	50.48	49.15	50.28	46.35	44.82	44.15	47.56	52.94
TiO_2	0.28	0.25	0.38	1.36	0.34	1.04	1.17	0.17	1.45	1.18	1.35	0.50	0.58	1.14	0.84	0.67
Al_2O_3	11.97	15.78	12.84	10.08	12.81	8.36	8.59	13.83	10.44	10.15	10.34	11.94	12.29	11.28	10.21	6.30
Fe_2O_3*	9.62	9.89	13.71	17.49	13.69	13.39	14.67	12.79	13.51	16.35	14.67	18.04	21.39	13.92	18.75	12.44
MnO	0.17	0.18	0.19	0.18	0.21	0.25	0.25	0.18	0.27	0.33	0.35	0.29	0.26	0.32	0.35	0.21
MgO	12.61	10.06	11.23	10.01	11.73	10.76	9.48	14.02	9.20	8.13	4.42	11.56	9.10	12.62	8.79	12.32
CaO	13.36	14.28	13.03	14.21	12.11	15.51	15.74	10.64	13.54	13.49	17.19	10.44	10.94	15.57	13.40	14.43
Na_2O	1.37	1.50	0.98	1.03	1.05	0.88	0.98	0.54	0.90	1.22	1.30	0.95	0.60	1.15	0.56	0.78
K_2O	0.03	0.04	0.03	0.14	0.03	0.06	0.06	0.05	0.05	0.06	0.07	0.14	0.09	0.16	0.03	0.07
Total	99.65	100.12	99.92	100.06	100.21	100.33	100.04	99.76	99.84	100.06	99.97	100.21	100.07	100.31	100.49	100.16
Mg#	72.19	66.83	61.86	53.13	62.92	61.41	56.13	68.46	57.42	49.61	36.37	55.93	45.73	64.23	48.14	66.23
C.I.P.W.Norm																
q							0.12		3.54	0.36	3.90					3.54
or				1.11		0.56	0.56	0.56	0.56	0.56	0.56	1.11	0.56	25.02		0.56
ab	11.53	12.58	8.38	8.91	8.91	7.34	8.38	4.72	7.86	11.40	11.00	7.86	5.24		4.72	6.81
an	26.41	36.42	30.58	22.24	30.30	18.63	18.63	35.03	23.91	21.96	21.96	27.80	30.58		25.30	13.34
le														0.87		
ne														5.40		
di	32.01	27.97	27.70	39.64	24.23	47.57	48.66	14.40	35.27	37.33	53.38	19.66	19.70	42.47	34.18	47.10
wo																
hy	20.04	7.01	17.86	3.05	23.24	20.92	18.83	30.63	22.67	23.31	3.08	22.89	24.82	21.07	29.57	24.51
ol	6.52	13.36	11.34	18.48	9.48			11.08				15.53	13.07		0.48	
mt	1.39	1.39	2.09	2.55	2.09	2.09	2.09	1.86		2.31	2.09	2.55	3.02	2.09	2.78	1.86
il	0.61	0.46	0.76	2.58	0.61	1.98	2.28	0.30		2.28	2.58	0.91	1.60	2.13	1.67	1.22

Notes : Fe_2O_3* is total iron ; Mg# = 100 MgO / MgO + 0.85 X FeO (total) ; Samples are denoted by the following prefixes :
SA & SM - Samples from Sittampundi ; T & TS - Samples from Sirappalli ; WB - Websterites from Sittampundi.

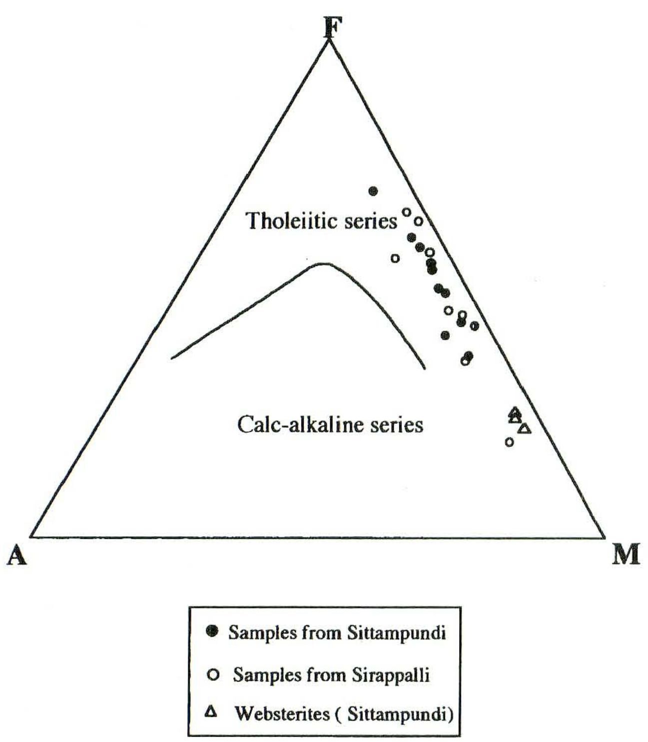

Fig. 4. AFM Diagram showing the tholeiitic trend of the rocks.

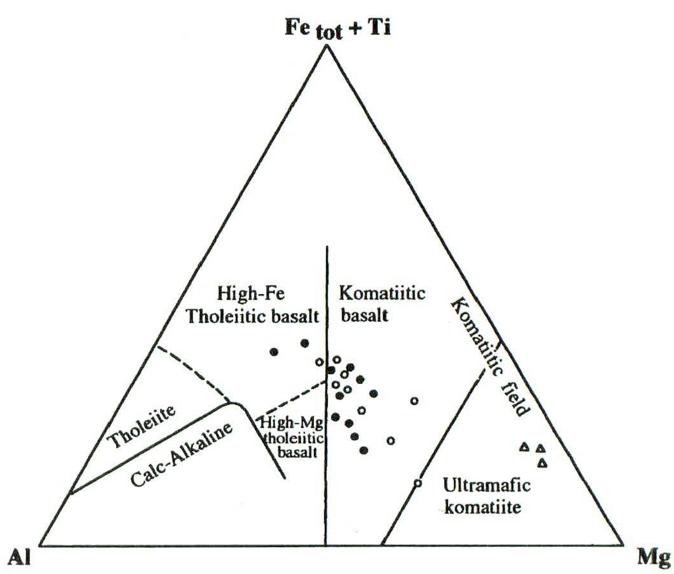

Fig. 5. Jensen's cation plot.(Symbols as in Fig. 4).

T-9	TS-5	TS-6	TS-8	WB-1	WB-2	WB-3
51.33	47.58	48.53	46.88	51.86	52.62	52.11
0.36	0.38	0.15	0.97	0.24	0.38	0.34
11.97	9.93	9.79	11.95	1.56	2.42	4.38
6.49	10.19	17.24	16.70	7.45	9.61	8.67
0.22	0.33	0.21	0.24	0.14	0.19	0.18
19.66	13.99	9.18	9.86	20.11	21.15	18.19
7.73	15.81	12.48	12.63	17.45	13.34	14.82
2.05	1.38	2.13	0.91	0.68	0.60	1.16
0.21	0.28	0.22	0.11	0.02	0.03	0.10
100.02	99.87	99.93	100.25	99.51	100.34	99.93
85.71	23.11	51.33	53.90	84.24	81.34	71.63
1.11	1.67	1.12	1.11			0.06
17.29	5.76	17.82	7.86	5.76	5.24	9.14
22.80	20.01	16.68	27.80	1.11	3.89	6.32
12.32	3.12	37.54	28.63	67.65	49.54	47.21
24.63	46.96	4.91	18.88	8.35	29.34	19.61
19.33	19.08	17.36	10.14	14.10	9.12	13.29
0.93	1.39	2.54	2.32	1.16	1.39	1.27
0.76	0.76	0.30	1.82	0.46	0.76	0.61

it is present in moderate amount (47.44-59.1%). The bivariant plot of MgO (%) versus Sc show a weak positive correlation. The concentration of V is more in garnet amphibolites, garnet websterites and websterites exhibit the highest concentration (205.34-296.43 ppm). Chromium is useful in the study of basic volcanic rocks and their metamorphosed equivalents. Mafic granulites granulites are rich in chromium (76.19-309.90 ppm) and the concentration of Cr in websterites is remarkably high (2592.88-6470.65 ppm). The mafic granulites are enriched in Cr relative to Group II basic granulites reported from Madras (Weaver et al., 1978). In this respect, the rocks differ markedly from the basic granulites occurring as enclaves within charnockites.

A significant variation in Co content (29.59-95.52 ppm) is observed in the mafic granulites and the websterites exhibit a higher concentration (95.88-190.40 ppm). The Co content in mafic granulites is comparable to that of the mafic granulites of Orissa (Bowes & Dash 1992). The rocks are enriched in Co than the average MORB (Shaw 1980). Mafic granulites show a significant variation in Ni content (42.07-255.85 ppm) and a similarity in Ni concentration is observed between these rocks and the basic granulites from Northern Kerala (Nambiar et al 1987) and group II granulites from Madras (Weaver et al 1978). The distribution of Cu and Zn are not uniform and Cu in particular exhibit a very wide range. The plot of Cu and Zn against MgO (%) do not show any variation and this may be due to the mobility of these elements during metamorphism (Rollinson, 1993).

Transition element plots are useful to explore the

Table 2. Representative analyses of trace elements (in ppm).

Sample No.	SM-1	SM-9	SM-11	T-4	T-6	T-8	TS-5	WB-1	WB-2	WB-3
Sc	20.00	27.82	8.78	47.44	47.63	59.11	58.77	72.68	89.91	79.19
V	74.54	151.63	67.93	106.95	85.22	192.08	224.79	205.34	296.43	218.10
Cr	309.90	244.41	76.19	51.26	144.54	1187.33	1021.15	3299.50	2592.88	6470.65
Co	32.93	48.42	84.05	32.32	29.59	95.52	89.57	95.88	183.02	190.40
Ni	47.95	42.07	255.85	37.92	74.30	129.48	356.46	582.21	962.85	550.91
Cu	31.44	18.10	121.62	30.37	47.87	29.42	8.42	20.73	175.17	83.67
Zn	51.73	39.84	46.66	48.40	45.42	35.08	67.55	58.61	92.31	129.93
Ga	11.73	10.01	7.30	10.98	15.52	15.37	16.32	6.73	15.98	13.71
Rb	1.83	0.92	0.51	1.20	0.43	1.33	2.56	0.49	1.32	0.73
Sr	59.38	77.62	58.56	82.07	50.14	133.26	83.49	78.09	77.07	104.48
Y	24.47	30.34	1.75	91.93	46.27	28.84	8.79	9.58	6.13	9.61
Zr	28.84	26.84	20.86	23.01	19.13	25.57	30.36	10.63	9.40	15.26
Nb	2.65	1.23	0.45	0.55	1.86	0.58	0.61	0.34	0.19	0.17
Ba	340.90	79.81	34.49	685.95	486.22	77.58	41.22	42.86	13.46	21.96
Hf	3.32	1.58	0.34	0.55	0.52	0.74	0.89	0.28	0.18	0.23
Ta	9.26	0.88	0.05	0.06	0.16	0.03	0.04	0.01	0.00	0.01
Th	0.64	0.12	0.22	0.67	0.73	0.31	0.58	0.17	0.02	0.02
U	0.16	0.06	0.17	0.16	0.26	0.14	0.10	0.04	0.03	0.01

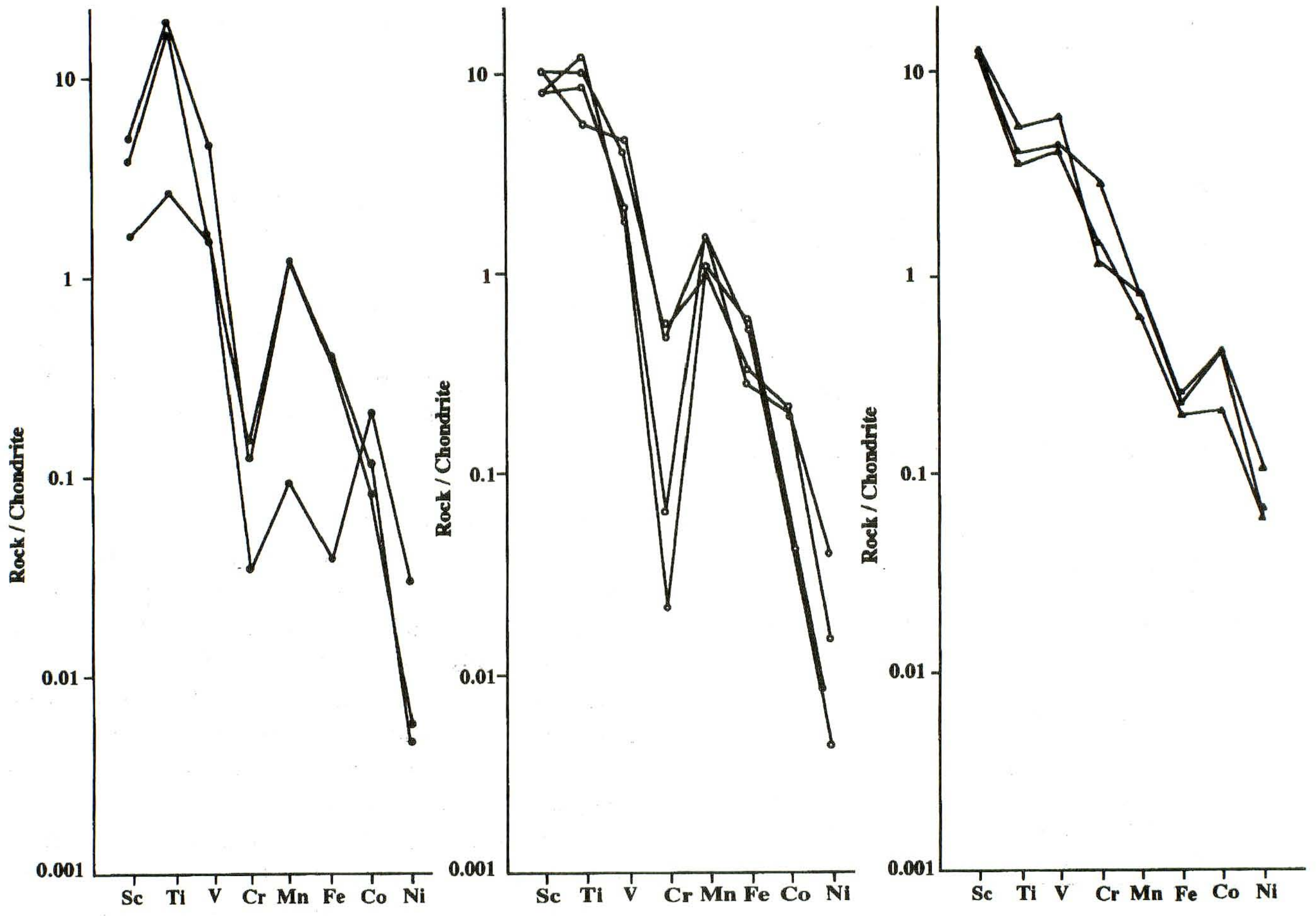

Fig. 6. Chondrite normalized transition metal plots of samples collected from Sittampundi, Sirappalli and websterites (Sittampundi). Normalizing values are taken from Langmuir et al. (1977) except for Fe, which was taken from Wood et al. (1977). (Symbols as in Figure 4).

geochemical behavior of the first transition series. In the present study, chondrite values of Langmuir et al. (1977) is used as normalizing values except for Fe, which was taken from Wood et al. (1979). Mafic granulites show consistent trends on chondrite normalized transition metal plots (Fig. 6). They show a progressive depletion from Ti to Ni, and have a positive Ti anomaly and a negative Cr anomaly. The garnet websterites and garnet amphibolites also behave in a similar way (Fig. 6). Where as the websterites exhibit a mild negative Ti anomaly and positive Co anomaly (Fig. 6). The negative Cr anomaly in the mafic granulites is attributed to the fractionation of chromite and clinopyroxene.

Among the large ion lithophile elements (LILE), Rb is significantly low in the mafic granulites and the websterites exhibit less concentration. The depletion of Rb may be attributed to the mobility of this element during metamorphism, absence of K-feldspar and potassium bearing minerals such as biotite and muscovite. While the garnet rich rocks are low in Sr, plagioclase rich rocks contain higher Sr concentration. The anomalous values in Ba content could not be explained properly. The LILE do not exhibit inter-elemental correlation and hence in the variation diagrams they show considerable scatter.

Zr, Hf, Th, U, Nb, Ta, Y, Sc and Ti are some of the high field strength elements analyzed. These elements are often used to understand the petrogenetic processes in metamorphosed rocks as they are less mobile and their distribution is not affected by metamorphism (Sun & Nesbitt, 1978; Condie et al,1977). The distribution of Sc and Ti has been already described under transition metals. Zr concentration is less than 30 ppm in all the samples analyzed, such lower values of Zr are reported from basaltic komatiites of Munro Township (Arndt & Nisbet, 1982). However the websterites have a very low Zr content (9.40-15.26 ppm) which is comparable to the average primitive mantle value of 11 ppm (Wood et al., 1979). When Zr is plotted against MgO (Plots are not shown), a weak negative correlation is observed. Significant variation is not observed in Hf and Nb. Similarly U and Th are highly depleted (<1ppm) in these rocks.

Discussion and Conclusions

The first report of mafic granulites was made by Iyer

(1933) and he considered that they were early stage differentiates of the basic magma which was parental to the anorthosites also. Subramaniam (1956) described the Sittampundi complex as anorthosite-eclogite-gabbro complex, consisting of meta-anorthosite and eclogite-gabbro series. He concluded that the anorthosite complex is a layered gravity-stratified sheet and the eclogite gabbro series are the original mafic gabbros of the complex. Janardhan and Leake (1975) on geochemical grounds believed that the complex is a highly metamorphosed layered igneous complex formed by crystal settling with the felsic layer represented by meta-anorthosite and the mafic layers by mafic granulites. However, Ramadurai et al. (1975) concluded that the anorthosites and the mafic granulites are genetically unrelated.

The banded mafic granulites display millimeter to centimeter wide mafic and felsic rich layers of different modal composition. Clinopyroxene is found to be rather uniform and orthopyroxene is seen in certain layers. The plagioclase poor layers grade in to garnet-clinopyroxenites and garnet websterites depending on the absence or presence of clinopyroxene and orthopyroxene respectively. Garnet-amphibolite veins within serpentinised dunites in Sirappalli are retrogressed and contain hornblende.

The major element chemistry of mafic granulites and garnet websterites show that, these rocks have evolved from a basaltic precursor slightly deficient in silica with normative quartz appearing in some samples. The range of Al_2O_3 (6.30-15.78 %) in these rocks differ from MORB which has Al_2O_3 content of 15-18 percent (Bence et al 1980). The MgO content of majority of the rocks fall in between 9.10 to 12.62 percent, which is marginally less than the high MgO basalts which have a MgO content of more than 13 percent (Hart and Davis, 1978). The range of Mg# in magmas derived by partial melting of mantle lherzolites is 72 to 74 (Green, 1971; Green et al., 1974; O'Hara, 1975; Ringwood, 1975). The low Mg# (45.73-68.46) in majority of the samples reveal that the rocks are not metamorphosed primary melts. Fractionation of olivine and pyroxenes might be the reason for the low Mg#. The concentration of CaO and Al_2O_3 indicate that plagioclase and clinopyroxene fractionation has played a limited role in the evolution of the melt. The range of CaO/Al_2O_3 ratio (0.65-2.29) widely vary in these rocks. Significant amount of CaO and Al_2O_3 will be removed from the melt during low pressure fractionation of plagioclase and may lead to the variation in CaO/Al_2O_3 ratios (Redman and Keays, 1985). This geochemical signature suggests that the magma has probably fractionated orthopyroxene and clinopyroxene which are present as websterites.

The higher concentration of Ni, Cr, Co and Mn in these rocks is attributed to high temperatures for the same degree of melting and, to a steeper geotherm, which has resulted in greater degree of partial melting in the upper mantle (Nesbitt and Sun,1976; Gill, 1979; Condie, 1985). Cr/Ni ratio of most basalts range from 1.3to 1.9 (Turekian, 1963). However, mafic granulites (except sample SM-11), garnet websterites and garnet-amphibolites show a wide range in Cr/Ni ratio (1.29-9.17). Such a variation in Cr/Ni ratio (1.1-9.1) is observed in metabasites of Kolar schist belt (Rajamani et al. 1985), Proterozoic oceanic crust of eastern New Foundland (Strong and Dostal, 1980) and Archaean metabasites of Eastern Gold fields Province, Western Australia (Redman and Keays, 1985).

Rb is highly depleted in these rocks, ultimately K is also found to be very low. Lewis and Spooner (1973) and Whitney (1969) have reported a marked depletion of K and Rb in the lower crust. The depletion of K and Rb is attributed to the high-grade regional metamorphism, influenced by the orogenic activity in this region. The concentration of LILE in the mafic granulites do not represent the composition of the basaltic precursor, and metamorphism has mobilized the elements (Weaver and Tarney, 1981). HFS elements are strongly depleted in the rocks in spite of their least mobility during metamorphism (Bodinier et al.,1987) indicating that the elements were depleted in the parent rocks (Dickin and Jones,1983; Evans et al., 1981). These elements show good negative correlation with MgO and the correlation is best observed in TiO2, Nb and Y (plots are not shown). The concentration of Y in the rocks is comparable with average MORB (Pearce, 1983) and is found to be more than the basic granulites of Madras (Weaver et al., 1978).

In the variation diagrams of the oxides against MgO (plots are not shown), websterites show a linear relationship with mafic granulites with the exception of CaO. Websterites are enriched in transition metals, particularly in Cr, Ni, Co, Cu and Sc relative to mafic granulites granulites. However, concentration of V and Zr is comparable to mafic granulites. Cr/Ni and Ni/Co values in websterites are much higher than the mafic granulites. Websterites exhibit similar geochemical characters to the rocks occur in the ultramafic complexes of Cabo Ortegal (Van Calsteren, 1978), Tinaquillo, Venezuela (Seyler and Mattson , 1993), Ronda (Suen and Frey,1987) and Zabargad peridotite (Picardo et al., 1988). These pyroxenites are thought to be the products of multistage events: 1. Crystallization of primary melts in the mantle, 2. High pressure cumulates, 3. Residues after partial melting of mafic layers (Piccardo et al., 1988; Suen and Frey, 1987).

The mafic granulites are found as bands within the anorthosites and the contact is sharp and lack gradation. Further, the anorthosites in immediate contact with the mafic granulites contain hornblende as the chief mafic mineral and garnet is absent while pyroxenes are rare. If the anorthosites and the precursors of the mafic granulites and websterites are to be formed by the differentiation of a single basic magma, it should be highly calcic to form a anorthite bearing plagioclase cumulate. Hence, we consider that the anorthosites are genetically unrelated to the mafic granulites. However field and geochemical characteristics indicate that the complex has been formed by the obduction of the ultramafic masses and partial melting due to decompression has emancipated in the generation of mafic melts which underwent subsequent differentiation producing the rocks of the complex. The garnetiferous mineralogy was resulted due to later high grade metamorphism in the region.

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