Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 97, No. 1, July 1988, pp. 1–10 © Printed in India.

Chemistry of calcic amphiboles from the area around Terakanambi, southern Karnataka

N SHADAKSHARA SWAMY and B MAHABALESWAR
Department of Geology, Bangalore University, Bangalore 560056, India

MS received 4 February 1987; revised 13 July 1988

Abstract. Chemial analyses of twelve amphiboles from the area around Terakanambi are presented. Results indicate that they are ferro-hornblende and ferro-pargasitic hornblende types in banded iron formations; magnesio hornblende in ultramafic rocks and edenite; and ferroan pargasite and ferroan pargasitic hornblende types in calcamphibolites. Titanium content in the amphiboles of the present study is relatively low compared to results from similar zones elsewhere. The lower titanium content of the amphiboles may be attributed to either bulk chemical composition or to low oxygen fugacity. Mg/Fe ratios vary considerably and it is mainly controlled by host rock composition. The plots of calcic amphiboles on (100 Na/Ca + Na)/(100 Al/Si + Al) and Al^{IV}/Al^{VI} diagrams indicate that they are of medium to low pressure type.

Keywords. Calcic amphiboles; Terakanambi; high grade terrain; chemical analyses.

1. Introduction

Amphiboles are ubiquitous in a wide variety of regionally metamorphosed rocks. They generally occur as recrystallised phases or as products of breakdown reaction between two different minerals. The study of the chemistry of amphiboles is considered crucial as it is related to the intensity of metamorphism under which they are formed (Raase 1974; Anantha Iyer and Narayanan Kutty 1976; Raase *et al* 1986; Boyle 1986). The present study attempts to elucidate the chemical characteristics of amphiboles occurring in different supracrustal lithounits of the Terakanambi area.

2. Geology of the area

The area around Terakanambi (figure 1) forms the southern part of the Sargur terrain in southern Karnataka (Shadakshara Swamy 1983). The supracrustal rocks occur as huge rafts within the gneisses of 2800 to 3400 Ma age (Janardhan *et al* 1986). The supracrustal rocks include varied sequence of metasediments like quartzites, iron formations, manganiferous horizons, calc-silicate rocks, amphibolites and components of layered complex. They are highly deformed and metamorphosed under upper amphibolite facies conditions. The amphiboles discussed in this paper are from banded iron formations, calc-amphibolites and olivine-bearing ultramafic rocks.

2.1 *Amphiboles*

In the Precambrian terrains calcic amphibole appears to be a common mineral in the metamorphosed impure calcareous sediments (Rice 1977; Krishnanath 1981; Siva-

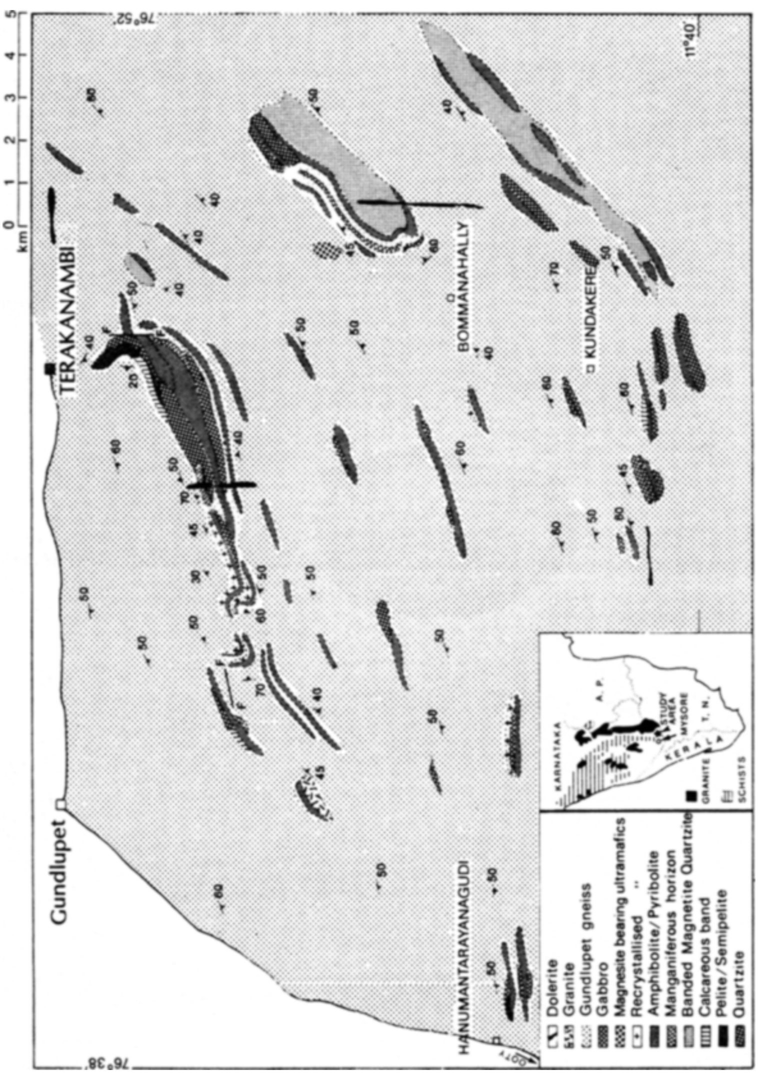


Figure 1. Geological map of the area around Terakanambi. Location of samples: 1 and 2—from BIF, 2·5 km NNE of Bommanahally; 3 and 4—from BIF, 3 km east of Kundagere; 5, 6 and 7—from calc-silicate rocks, 2 km south of Terakanambi; 8—from calc-silicate rock, 1·5 km south of Kundagere; 9 and 10—from calc-silicate rocks. 4·5 km S 35° east of Gundlupet; 11—from an ultramafic rock, 1·5 km south of Kundagere; 12—from an ultramafic rock, 6 km S 50 east of Gundlupet.

prakash 1981; Sharma 1982), banded iron formations (Klein 1983; Mahabaleshwar *et al* 1984; Hall 1985), and ultramafic rocks (Evans 1977; Srikantappa *et al* 1985). Amphiboles from the calc-amphibolites of the present study occur either as discrete grains or as grains rimming clinopyroxene. Green-coloured hornblende of the calcic type generally pseudomorphs grunerite in the banded iron formations. Tremolite is the other amphibole occurring in association with the green hornblende in the ultramafic rocks of the study area. Textural studies clearly indicate that the green hornblendes are after clino- or orthopyroxenes in the ultramafic rocks.

3. Analytical methods

Minerals were analysed with an ARL electron mircoprobe using energy dispersive detection at the Department of Geophysical Sciences, University of Chicago, Chicago by Prof. A S Janardhan. In each sample two to three grains were analysed and the average was taken. The operating voltage was 15 kV and the sample current was 10^{-7} amp with a 1 μm beam spot. Synthetic standards were used. Analyses of the standards were generally reproducible to $\pm 0{\cdot}1$ wt% of each oxide component, and analyses in the tables are given only to this precision.

4. Chemistry

The analyses of twelve amphiboles are listed in tables 1 and 2. The structural formulae are calculated on the basis of 23 oxygen atoms and they satisfy Leake's (1978) criteria for defining calcic amphiboles, having $(Ca + Na)_B \geqslant 1{\cdot}34$ and $Na_B < 0{\cdot}67$. Calcic amphiboles from the banded iron formations belong to ferrohornblende and ferropargasitic hornblende type; calcic amphiboles from the ultramafic rocks are magnesio hornblendes; and calcic amphiboles from the calc-amphibolites belong to edenite, ferroan pargasite and ferroan pargasitic hornblende types.

The Al substitution for the tetrahedral site ranges from 1·019 to 1·740 in the hornblendes of the present study. Leake (1971) documented calcic amphiboles with a maximum of about 1·4 Al in octahedral position. In the present study Al ranges from 0·524 to 0·748.

Titanium content of the hornblendes of the present study varies considerably. Many workers (Raase 1974; Raase *et al* 1986) have shown that the titanium content of the amphiboles increases systematically with the metamorphic grade. Ti ranges from 0·04 to 0·16 with an average of 0·1 in the hornblendes from the calc-amphibolites of the present study. In the hornblendes of the ultramafic rocks Ti averages 0·1 and, in banded iron formations, Ti is totally absent. The average Ti content of the calcic amphiboles from the Terakanambi area is distinctly lower compared to the Ti content of the amphiboles from the ultramafic rocks of the hornblende granulite zone reported by Raase *et al* (1986). The relatively lower value of Ti may possibly be due to the non-coexistence of hornblendes with the minerals having excess Ti phase as substantiated by Raase *et al* (1986). TiO_2 is totally absent in hornblendes of banded iron formations. This may be attributed either to bulk composition or to the preferential entry of Ti into magnetite during metamorphism under low oxygen fugacity conditions as explained by Coolen (1980) and Mahabaleswar and Vasant Kumar (1983).

Many workers (Raase 1974; Hormann *et al* 1980; Spear 1981) have suggested that the Ti content in calcic amphiboles is strongly temperature-dependent and nearly

Table 1. Chemistry of calcic amphiboles from the Terakanambi area.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	40·78	42·05	43·67	42·05	41·72	40·72	46·63	46·93	45·62	47·97	48·77	48·07
TiO_2	—	—	—	—	1·26	1·40	0·62	0·36	0·73	—	1·09	0·89
Al_2O_3	11·41	11·07	11·00	11·46	13·99	13·79	10·61	9·34	10·26	9·39	11·08	10·75
FeO^*	25·78	25·89	25·75	26·87	17·67	18·22	16·32	17·28	17·86	17·84	6·62	6·89
MnO	—	—	—	—	—	—	—	0·63	0·45	—	—	0·21
MgO	5·87	5·51	5·49	5·71	9·29	8·98	11·24	10·21	10·01	11·18	17·66	17·95
CaO	10·26	10·19	10·33	10·98	11·76	11·68	12·23	12·28	12·51	12·11	12·97	12·66
Na_2O	1·08	0·98	0·73	1·25	1·59	1·31	1·22	0·72	1·32	0·96	0·60	0·62
K_2O	0·81	0·80	0·96	0·85	0·73	0·77	0·22	0·76	0·51	—	0·15	0·15
Cr_2O_3	—	—	—	—	—	—	—	0·20	0·15	—	0·33	0·37
Total	95·99	96·49	97·93	99·17	98·01	96·87	99·09	98·71	99·42	99·45	99·27	98·56

FeO^* = Total iron as FeO.

Table 2. Structural formulae on the basis of 23 oxygen atoms.

	1	2	3	4	5	6	7	8	9	10	11	12
Si	6·486	6·628	6·745	6·494	6·260	6·178	6·797	6·934	6·730	6·981	6·775	6·746
Al	1·514	1·372	1·255	1·506	1·740	1·822	1·203	1·066	1·230	1·019	1·225	1·254
ΣT	8·000	8·000	8·000	8·000	8·000	8·000	8·000	8·000	8·000	8·000	8·000	8·000
Al	0·625	0·684	0·748	0·580	0·634	0·643	0·621	0·561	0·554	0·592	0·589	0·524
Ti	—	—	—	—	0·142	0·160	0·068	0·040	0·081	—	0·114	0·094
Cr	—	—	—	—	—	—	—	0·023	0·020	—	0·036	0·042
Mg	1·393	1·295	1·263	1·314	2·077	2·031	2·442	2·248	2·199	2·426	3·655	3·754
Fe	2·982	3·021	2·989	3·106	2·147	2·166	1·869	2·148	2·146	1·982	0·606	0·586
ΣC	5·000	5·000	5·000	5·000	5·000	5·000	5·000	5·000	5·000	5·000	5·000	5·000
Fe	0·447	0·392	0·342	0·363	0·070	0·146	0·120	0·003	0·058	0·189	0·163	0·223
Mn	—	—	—	—	—	—	—	0·078	0·057	—	—	0·024
Ca	1·749	1·721	1·709	1·817	1·890	1·899	1·910	1·944	1·977	1·889	1·931	1·905
Na	—	—	—	—	0·400	—	—	—	—	—	—	—
ΣB	2·196	2·113	2·051	2·180	2·000	2·045	2·030	2·025	2·092	2·078	2·094	2·152
Na	0·339	0·299	0·217	0·373	0·423	0·386	0·346	0·207	0·378	0·271	0·162	0·169
K	0·165	0·161	0·188	0·167	0·139	0·148	0·220	0·144	0·094	—	0·026	0·027
ΣA	0·504	0·460	0·405	0·540	0·562	0·534	0·566	0·351	0·472	0·271	0·188	0·196

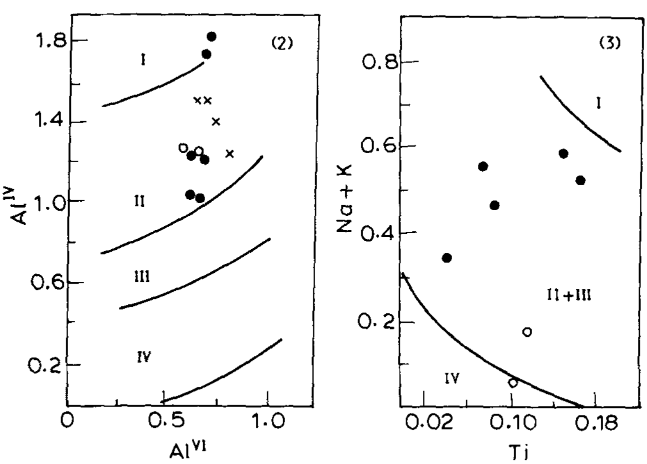
1 to 4 = Calcic amphiboles from banded iron formation.
5 to 10 = Calcic amphiboles from calc-amphibolite.
11 to 12 = Calcic amphiboles from ultramafic rocks.

independent of pressure. Helz (1973) showed from his experimental studies that the Ti content of hornblende will not increase with increase in temperature conditions. Therefore the variation in Ti content of hornblendes from different lithounits of the Terakanambi area, which are metamorphosed under the same PT conditions, may be a bulk compositional control or due to low fO_2 conditions. Hence, using Ti content as an indicator of grade of metamorphism needs a careful scrutiny.

The potassium content of the calcic hornblendes increases with the metamorphic grade and this may be attributed to the increase in temperature which favours the introduction of potassium into the amphibole structure (Raase *et al* 1986). The introduction of potassium may be either during metamorphism or metasomatism. The average potassium content in the hornblendes of the present study is 0·128, which is relatively higher compared to that in the amphiboles from the low grade terrains elsewhere.

The average $Mg/Mg + Fe^t$ values are 0·279, 0·505 and 0·826 respectively for the hornblendes of banded iron formations, calc-amphibolites and ultramafic rocks. The values clearly indicate that there is a close spatial relationship between the $Mg/Mg + Fe^t$ ratio of hornblendes and that of the host rock. This is in accordance with the observations made by Leake (1965), Grapes *et al* (1977) and Kamineni (1986) for the calcic amphiboles elsewhere. Leake (1968) reported that the low Mg/Fe ratio in Al-rich calcic amphiboles is mainly due to the change in the partitioning related to co-existing minerals, whereas Kamineni (1986) attributed the same to the amounts of Fe and Mg available in the host rock. In the hornblendes of the present study, Al_2O_3 ranges from 9·34 to 13·99% with an average of 11·29% and Mg/Fe ratios also vary considerably. It seems probable that the host rock composition must have played a dominant role in determining the Mg/Fe ratio of hornblendes of the present study and this is clearly substantiated by the presence of higher ratios in the hornblendes of the ultramafic rocks relative to that of hornblendes from the banded iron formations.

In terms of Al^{IV} and Al^{VI} (figure 2) the plots of the hornblendes of Terakanambi area



Figures 2 and 3. Al^{IV}–Al^{VI} and Ti/(Na + K) diagram. Fields after Yurkova *et al* (1985): I—Granulite facies, II—Amphibolite facies, III—Epidote amphibolite facies and IV—Greenschist facies, × —amphiboles from the banded iron formations, ● —amphiboles from calc-amphibolites and ○ —amphiboles from ultramafic rocks. In figure 3 amphiboles from the banded iron formations are not plotted as they do not contain Ti.

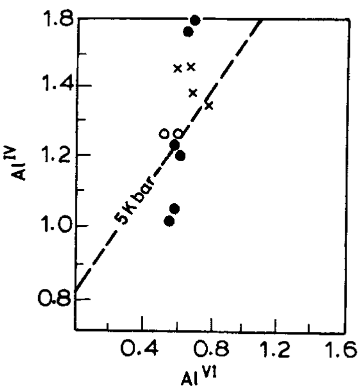


Figure 4. Al^{IV}–Al^{VI} diagram after Raase (1974). Note that the plots of amphiboles fall around the 5 kbar line.

fall well within the field of amphibolite facies of Yurkova *et al* (1985) except for the two plots which fall in the field I of granulite facies. On the (Na + K)/Ti diagram (figure 3) the plots fall in the field II + III assigned for the amphibolite and epidote amphibolite facies. One plot of hornblende from the ultramafic rock falls in the greenschist facies field and this may be attributed to the regressive metamorphic origin of hornblende by the replacement of high temperature orthopyroxene.

Leake (1965), Raase (1974), Brown (1977) and Raase *et al* (1986) have shown that the amphibole composition, in particular the Al and Na contents can be used as a pressure indicator. On the Al^{IV}/Al^{VI} diagram (figure 4) the plots fall around the 5 kbar line of Raase (1974) indicating that the hornblendes of the present study were formed under medium to low pressure conditions. It is generally argued that the Al^{IV} content of the calcic amphiboles increases with Al^{VI} with increasing grade of metamorphism. Plots of hornblendes of the study area on Al^{IV}/Al^{VI} diagram (figure 4) show no substantial increasing or decreasing trends. It also shows that the main governing factors are the amount of Si available and the total value of Al^{IV} substitution for the octahedral site. Spear (1981) suggested that higher Al^{IV} and Al^{VI} contents in hornblendic calcic amphiboles generally favour higher pressures. Though the Al^{IV} and Al^{VI} contents of the hornblendes of the present study are rather high they tend towards low to medium pressure fields on different diagrams (figures 4 and 5). On the diagram (figure 5) of Laird and Albee (1981) plots of hornblendes of the present study fall in and around the low to medium pressure fields.

Grapes and Graham (1978) and Kamineni (1986) have shown the compositional variations for a large number of calciferous amphiboles in terms of Si/Al^{VI}, (Na + K)/Al^{VI} and (Na + K)/Al^{IV}. Klein (1969) and Cooper and Lovering (1970) have used these plots to suggest a compositional miscibility gap in the calcic amphiboles. However, similar plots for the calcic hornblendes of the Terakanambi region show compositional continuity in the ($\sum$ Fe/($\sum$ Fe + Mg))/Al^{IV} (figure 6) and (Na + K)/Al^{IV} (figure 7) diagrams.

5. Conclusions

Calcic amphiboles of the present study are of metamorphic origin and they are of medium to low pressure type. The variation in the titanium content of the hornblendes

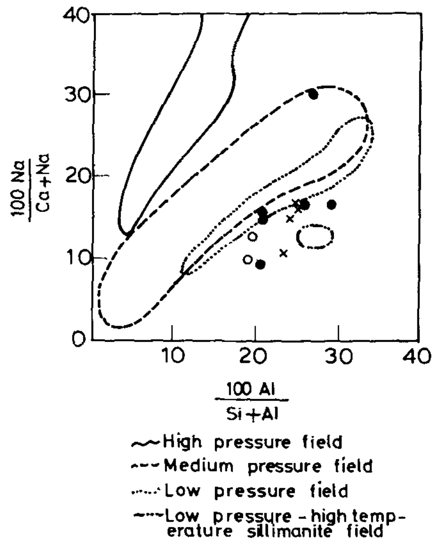
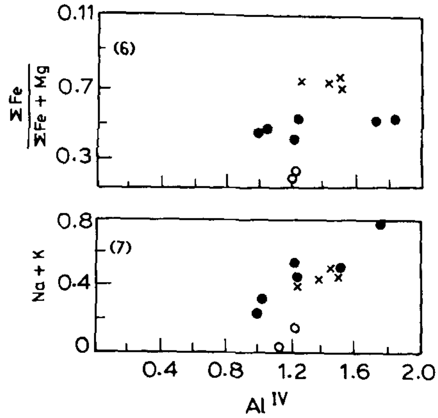


Figure 5. Plots of calcic amphiboles on 100 Na/(Ca + Na) – 100 Al/(Si + Al) diagram. Fields are after Laird and Albee (1981). All the plots fall in and around low to medium pressure fields.



Figures 6 and 7. Plots of amphiboles on $(\Sigma Fe/(\Sigma Fe + Mg))/Al^{IV}$ and $(Na + K)/Al^{IV}$ diagrams after Boyle (1986).

may be attributed to the bulk composition control or to the low fO_2 conditions. Potassium content of the amphiboles of the present study is relatively higher compared to that of the amphiboles from the low grade terrains elsewhere. Whole rock chemistry and temperature conditions of formation are the two important factors that govern the higher Al, Ti and K contents in the calcic amphiboles of the Terakanambi area.

Acknowledgements

The authors are thankful to Prof. C Naganna for encouragement and to Prof. A S Janardhan for the microprobe analyses.

References

Anantha Iyer G V and Narayanan Kutty T R 1976 Geochemistry of amphiboles from the Precambrian of Karnataka; *J. Geol. Soc. India* **17** 17–36

Boyle A P 1986 Metamorphism of basic and pelitic rocks at Sulitjelma, Norway; *Lithos* **19** 113–128

Brown E H 1977 The crossite content of Ca amphibole as a guide to pressure of metamorphism; *J. Petrol.* **18** 53–72

Coolen J J M 1980 Chemical petrology of the Furua granulite complex, southern Tanzania; *GUA pap. Geol. 1* **13** 1246

Cooper A F and Lovering J F 1970 Greenschist amphiboles from Haast river, New Zealand; *Contrib. Mineral. Petrol.* **27** 11–24.

Evans B W 1977 Metamorphism of Alpine peridotite and serpentinite; *Annu. Rev. Earth Planet. Sci.* **5** 397–447

Grapes R H and Graham C M 1978 The actinolitehornblende series in metabasites and the so-called miscibility gap: A review; *Lithos* **11** 85–97

Grapes R H, Hashimoto S and Miyashita S C 1977 Amphiboles of a metagabbro amphibolite sequence, Hidaka metamorphic belt, Hokkaido; *J. Petrol.* **18** 285–318

Hall R P 1985 Mg-Fe-Mn distribution in amphiboles, pyroxenes and garnets and implications for conditions of metamorphism of high grade early Archaean iron formation, Southernwest Greenland; *Mineral. Mag.* **49** 117–128

Helz R T 1973 Phase relations of the basalts in their melting range at pH_2O—5 kbar as a function of oxygen fugacity. Part I. Mafic phases; *J. Petröl.* **14** 249–306.

Hormann P K, Raith M, Raase P, Ackermand D and Seifert F 1980 The granulite complex of Finnish Lapland: Petrology and metamorphic conditions in the Ivalojoki-Inarijarvi area; *Geol. Surv. Finland Bull.* **308** 1–55

Janardhan A S, Shadakshara Swamy N and Capdevila R 1986 Banded iron formation and associated manganiferous horizons of the Sargur supracrustals, southern Karnataka; *J. Geol. Soc. India* **28** 179–188

Kamineni D C 1986 A petrochemical study of calcic amphiboles from the East Bull lake anorthositegabbro layered complex, District of Algoma, Ontario; *Contrib. Mineral. Petrol.* **93** 471–481

Klein C 1969 Two amphibole assemblages in the system actinolite-hornblende-glaucophane; *Am. Mineral.* **54** 212–237

Klein C 1983 Diagenesis and metamorphism of Precambrian banded iron formation in *Iron formations; Facts and problems* (eds) A F Trendall and R C Morris, (Amsterdam; Elsevier) 417–469

Krishnanath R 1981 Coexisting humite-chondrodite-spinel-magnesium calcite assemblages from the calc-silicate rocks of Ambasamudram, Tamil Nadu, India; *J. Geol. Soc. India* **22** 235–242

Laird J and Albee A L 1981 Pressure, temperature and the time indicators in mafic schists; their application to reconstructing the polymetamorphic history of Vermount; *Am. J. Sci.* **281** 127–175

Leake B E 1965 The relationship between tetrahedral aluminium and the maximum possible octahedral aluminium in natural calciferous and subcalciferous amphiboles; *Am. Mineral.* **50** 843–851

Leake B E 1968 A catalogue of analysed calciferous and subcalciferous amphiboles together with their nomenclature and associated minerals; *Geol. Soc. Am. Spec. paper* **68** 1–210

Leake B E 1971 On aluminous and edenitic hornblendes; *Mineral. Mag.* **38** 389–407

Leake B E 1978 Nomenclature of amphiboles; *Am. Mineral.* **63** 1023–1053

Mahabaleswar B and Vasant Kumar I R 1983 Mineral chemistry of hornblendes from the charnockites of Karnataka, India; *Acta Miner. Petrol.* **26** 115–123

Mahabaleswar B, Ananthamurthy K S and Basavanna M 1984 Pressure-temperature estimates of the iron formations of Sivasamudram area, Karnataka; *J. Geol. Soc. India* **25** 564–569

Raase P 1974 Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism; *Contrib. Mineral. Petrol.* **45** 179–203

Raase P, Raith M, Ackermand D and Lal R K 1986 Progressive metamorphism of mafic rocks from greenschist to granulite facies in the Dharwar craton of South India; *J. Geol.* **94** 261–282

Rice J M 1977 Progressive metamorphism of impure dolomitic limestone in the Marysville aureole, Montana; *Am. J. Sci.* **277** 1–24

Shadakshara Swamy N 1983 Petrology and structure of the metasediments and the associated gneisses around Terakanambi, southern Karnataka; Unpublished PhD thesis, University of Mysore

Sharma R S 1982 Petrology of a scapolite bearing rock from Karera, District Bhilwara, Rajasthan; *J. Geol. Soc. India* **23** 319–329

Sivaprakash C 1981 Petrology of calc-silicate rocks from Koduru, Andhra Pradesh, India; *Contrib. Mineral. Petrol.* **77** 121–128

Spear F S 1981 An experimental study of hornblende stability and compositional variability in amphibolite; *Am. J. Sci.* **281** 697–734

Srikantappa C, Raith M and Ackermand D 1985 High grade regional metamorphism of ultramafic and mafic rocks from the Archaean Sargur terrane, Karnataka, South India; *Precambrian Res.* **30** 189–219

Yurkova R M, Peyve A A, Zinkevich V P and Cherkashin V I 1985 Amphibolites of the Shirshov ridge, Bering Sea; *Int. Geol. Rev.* **27** 1051–1068