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MINERAL CHEMISTRY OF HORNBLENDES FROM THE CHARNOCKITES OF KARNATAKA, INDIA

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ABSTRACT

Calciferous amphiboles found in the charnockites of Karnataka have been analysed for major elements. The majority of the analysed amphiboles are contained within a narrow range of $Fe^{tot}/Fe^{tot}+Mg$ values. They show all the chemical characteristics of high alumina, high titanium and high alkali hornblendes from other granulite facies area. They can be termed ferroan pargasitic hornblendes according to the nomenclature of LEAKE [1978]. The variation of Si—Al in the hornblendes is attributed to influence of pressure, whereas the Ti variation is due to a combination of independant parameters namely, temperature of metamorphic crystallisation and oxygen fugacity. The Al^{iv} and Al^{vi} relationship in the hornblendes has been considered as a function of Ti substitutions.

INTRODUCTION

Calciferous amphiboles are formed in a wide range of temperature, pressure and chemical environment in both metamorphic and magmatic rocks. Their chemistry is complex because of numerous ionic substitutions. This factor hinders the specific identification of amphiboles by conventional petrographic methods. Furthermore, recent investigations in some metamorphic areas have shown that there are significant differences in hornblende chemistry between different regional metamorphic terrains i.e. different metamorphic facies series [SHIDO and MIYASHIRO, 1959; RASSE, 1974; FABRIES, 1968]. With this in mind the authors have undertaken the chemical investigation of amphiboles found in the charnockites from the Sivasamudram and Kanakapura areas. The charnockites of these areas are considered to be typical for these rocks and afford an opportunity to understand the chemical complexities of the amphiboles present. A comparison of chemistry of the amphiboles of the present study with those of others found in different metamorphic environments is made in an attempt to understand the differences between the chemistry of the amphiboles formed under different metamorphic environments.

LOCATION

The Sivasamudram and Kanakapura areas described in this investigation are located 65 to 115 km. southwest of Bangalore city. They are bounded by latitudes 12°15′ and 12°34′ and longitudes 77° and 77°34′. The area largely consists of charnockites, granulite and amphibolite facies gneisses and granites.

ANALYTICAL METHODS

Compositional determination of the amphiboles of charnockites were facilitated by energy dispersive spectrometry (EDS) at Department of Mineralogy and Petrology, University of Cambridge, Cambridge, U.K. Analysis were done on carboncoated polished thin sections an on energy dispersive spectrometry unit with a Harwell Si (Li) detector and pulse processor. The results were calculated using a computer programm employing iterative spectrum stripping techniques [STATHAM, 1976]. Correction procedures applied were those of SWEATMAN and LONG [1969].

CHEMICAL CHARACTERISTICS OF AMPHIBOLES

The analyses of 15 hornblendes are given in Table 1. The structural formula of the hornblendes have been calculated on the basis of 23 oxygen atoms, according to the methods of the Subcommittee on amphiboles [LEAKE, 1978]. Classification of the hornblendes, as suggested by the Subcommittee, is on the basis of the number of $(Ca+Na)_B$ and Na_B. Following this classification, the amphiboles of the areas belong to the calcic amphibole group, and on the basis of $Mg/Mg+Fe^{2+}$, fall within the field of ferroan pargasitic hornblendes *(Fig. 1)*.

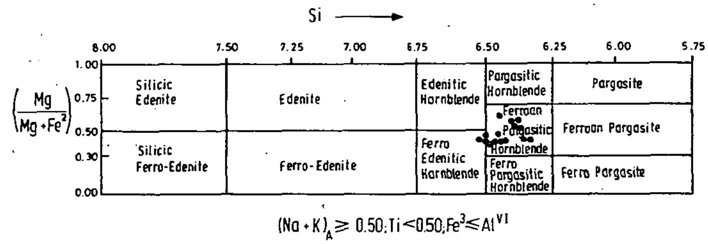

Fig. 1. Classification of amphiboles [after LEAKE, 1978]

Hornblendes from the charnockites show all chemical characteristics of well known high Ti, high Al and high alkali hornblendes from other granulite facies areas [ENGEL *et al.*, 1964; BINNS, 1965; LEELANANDAM, 1970; DAVIDSON, 1971 and COOLEN, 1980].

The majority of hornblendes represent a narrow range of $Fe^{tot}/Fe^{tot}+Mg$ values extending from 0.46 to 0.57. These hornblendes are olive green to brownish green and brown in colour.

The Ti content of the hornblendes vary considerably. The maximum Ti content of the hornblendes of the present study (3.09 wt% TiO_2) is higher than reported elsewhere from these areas [ANANTHA IYER *et al.*, 1976] but is slightly lower than the maximum Ti values reported from hornblende-pyroxenite xenoliths in basalt pipes [e.g. DAWSON and SMITH, 1973]. The variation in Ti values appears to depend upon the type of mineral adjacent to the hornblende; hornblende grains surrounding opaque oxides always contain less Ti than hornblendes which are associated with pyroxene [*c. f.* COOLEN, 1980].

The Al^{iv} values are close to 2.0 *(Fig. 2)* accompanied by low Al^{vi} values. Compositional zoning within individual grains of hornblende is generally lacking.

Al AND Si VARIATION AND THE INFLUENCE OF PRESSURE

LEAKE [1965, 1971] recognised that hornblendes in magmatic and contact metamorphic rocks generally have lower Al^{vi} and Si contents, than hornblendes in regional metamorphic rocks. He suggested that Al^{vi} content is pressure dependent and showed

TABLE 1

Chemical composition and structural formula of hornblendes

	CHR11	CHR	CHR3	326	326	121	540	110	141	139	183	56a	25	167	72
SiO_2	41.75	42.50	42.27	41.11	41.87	42.50	42.75	41.68	42.30	42.65	42.40	41.60	41.80	42.40	42.60
Al_2O_3	11.50	11.63	11.59	11.80	11.17	11.74	11.38	11.73	11.40	11.26	12.32	11.70	11.97	11.90	11.90
TiO_2	3.09	2.95	2.80	1.42	1.76	2.90	2.76	2.16	2.58	1.94	2.10	1.02	1.42	0.96	1.09
FeO	19.06	18.35	18.15	16.86	15.37	17.52	18.75	17.01	19.86	17.76	16.60	18.57	18.76	18.85	18.90
MnO	0.16	0.18	0.27	—	0.16	0.18	0.16	0.10	0.17	0.16	0.24	0.27	0.10	0.20	0.25
MgO	8.24	8.54	8.84	10.55	10.46	10.65	8.24	9.96	8.03	8.36	10.76	8.62	8.62	8.73	9.15
CaO	11.34	11.31	11.35	10.49	11.31	11.25	10.70	11.12	11.12	11.88	12.40	11.97	11.87	11.60	11.50
Na_2O	1.67	1.63	1.43	1.22	1.22	1.65	1.43	1.69	1.35	1.46	1.60	1.52	1.65	1.35	1.30
K_2O	1.35	1.30	1.29	1.35	1.30	0.70	0.92	1.15	0.85	1.20	0.65	0.80	1.05	1.10	1.30
Total	98.16	98.39	97.99	94.79	94.62	99.09	97.09	96.60	97.66	97.67	99.67	96.07	97.24	97.09	97.99

TABLE 1 contd.

Structural formula on the basis of 23 oxygens

	CHR11	CHR	CHR3	326	326	121	54B	110	141	139	183	56a	25	167	72
Si	6.360	6.391	6.511	6.381	6.469	6.376	6.502	6.363	6.440	6.523	6.352	6.414	6.400	6.466	6.439
Al^{iv}	1.640	1.609	1.489	1.619	1.531	1.624	1.498	1.637	1.560	1.477	1.648	1.586	1.600	1.534	1.561
T	8.000	8.000	8.000	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^{vi}	0.425	0.449	0.616	0.540	0.504	0.447	0.545	0.468	0.486	0.541	0.526	0.543	0.549	0.609	0.561
Ti	0.356	0.334	0.317	0.166	0.205	0.207	0.319	0.247	0.292	0.220	0.117	0.120	0.156	0.109	0.127
Mg	1.882	1.931	2.029	2.440	2.408	2.395	1.878	2.280	1.827	1.917	2.417	1.999	1.974	1.997	2.086
Fe^{2+}	2.337	2.286	2.038	1.854	1.883	1.951	2.258	2.005	2.395	2.266	1.940	2.338	2.321	2.285	2.226
C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	4.944	5.000	5.000	5.000	5.000	5.000
Fe^{2+}	0.084	0.016	0.300	0.312	0.103	0.237	0.113	0.155	0.126	—	0.135	0.068	0.066	0.115	0.159
Mn	0.027	0.027	0.035	—	0.021	0.027	0.019	—	0.018	0.018	0.027	0.037	0.009	0.027	0.036
Ca	1.846	1.823	1.873	1.745	1.986	1.810	1.742	1.822	1.818	1.945	1.986	1.981	1.947	1.896	1.859
Na	0.043	0.134	—	—	—	—	0.127	0.023	0.038	0.037	—	—	—	—	—
B	2.000	2.000	2.208	2.057	2.110	2.074	2.000	2.000	2.000	2.000	2.148	2.052	2.022	2.038	2.054
Na	0.450	0.330	0.428	0.363	0:366	0.486	0.293	0.471	0.364	0.403	0.468	0.463	0.496	0.403	0.381
K	0.274	0.253	0.254	0.268	0.256	0.063	0.167	0.220	0.164	0.239	0.126	0.167	0.184	0.220	0.253
A	0.724	0.583	0.682	0.631	0.622	0.559	0.457	0.691	0.528	0.642	0.594	0.630	0.680	0.623	0.634

that the maximum possible Al^{vi} in calciferous and sub-calciferous amphiboles increase regularly as Al^{iv} increases.

KOSTYUK and SOBOLEV [1969] on the basis of statistical analysis, distinguished a variety of paragenetic types of calciferous amphiboles in metamorphic rocks. They concluded that increasing pressure causes a slight increase in Al^{vi}, whereas increasing temperature causes a slight increase in Al^{iv} and alkalies. The postulated Al^{iv} increase with temperature is in contradiction to detailed investigations of SHIDO and MIYASHIRO [1959], ENGEL and ENGEL [1962], BINNS [1965] and BARD [1970]. These authors

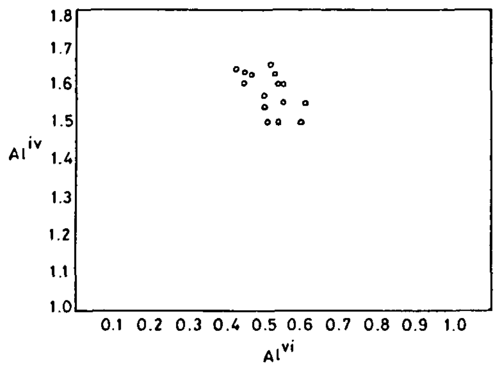

Fig. 2. Plots of Al^{iv} and Al^{vi} for the amphiboles

recognised slight increase of alkalies and Ti and sometimes significant decrease of Al^{vi} and Fe^{2+} with increasing metamorphic grade. This may be interpreted as a change from tschermakitic composition in the low grade amphibolite facies versus pargasitic composition in the hornblende granulite facies [RASSE, 1974]. From the above resume it is clear that the Al content has a complex dependence upon temperature, pressure and chemical environment, which makes it difficult to use it as an indicator of metamorphic grade. Nevertheless the Al^{vi} and Si contents together permit a rather good distinction between hornblendes of low pressure type and high pressure type of regional metamorphism.

The Al^{vi} and Si contents of the hornblendes of the present study are plotted in *Fig. 3* along with Al^{vi} and Si content of hornblendes from some petrographically well known regional metamorphic terrains. The diagonal solid line in *Fig. 3* is taken from LEAKE [1965] and indicate maximum possible Al^{vi}. It can be seen that the hornblendes of the present study are relatively low in Al^{vi} and Si and plot well below the line of maximum possible Al^{vi}, similar to the hornblendes from low pressure regional metamorphic facies series from the Central Abukuma Plateau, Japan [SHIDO and MIYASHIRO, 1959], Broken Hill district, New South Wales [BINNS, 1965] and Adirondack mountains, New York [ENGEL and ENGEL, 1962]. On the contrary, the hornblendes from the Grampian Highlands, Scotland [SHIDO and MIYASHIRO, 1959], the Sanbagawa belt, Japan [BANNO, 1964] and the Holenarsipur schist belt, Karnataka [ANANTHA IYER *et al.*, 1976] plot between the broken line and the line of maximum Al^{vi} in *Fig. 3,* which is indicative of their formation at higher pressures probably above 5 kbs [RASSE, 1974].

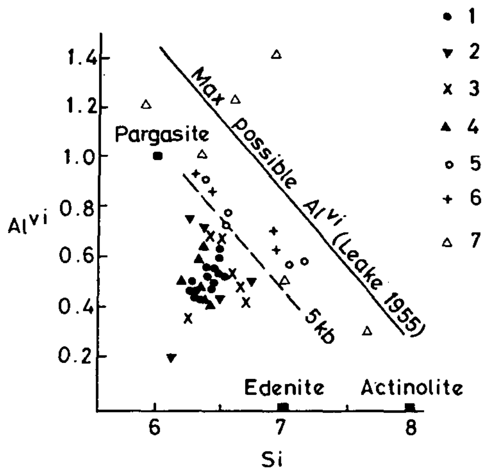

Fig. 3. Relation between Al^{vi} and Si of hornblendes of
1) the present study
2) Central Abukuma Plateau
3) Broken hill district
4) Adirondack Mountains
5) Grampian Highlands
6) Sanbagawa belt
7) Holenarsipur schist belt

Ti CONTENT OF HORNBLENDE AND ITS RELATION TO METAMORPHIC GRADE

Though KOSTYUK and SOBOLEV [1969] were able to distinguish different paragenetic types of hornblende corresponding to different metamorphic facies and rock composition by making use of the diagrams Al—Fe+Mn/Fe+Mg, Na+K−Al−(Na+K) and Al^{iv}−Al^{vi}, it is impossible to relate a hornblende of a definite composition to a definite paragenetic type, since overlapping of hornblende composition is large. So the most satisfactory parameter that can be used to distinguish different paragenetic hornblendes is the Ti content. A comparison of the Ti contents of hornblendes from rocks of different metamorphic facies has shown that variation in Ti content is related to metamorphic grade.

In *Fig. 4* the Ti content of the hornblendes of the present study and Ti content of hornblendes from rocks of different metamorphic facies is represented. Although there is some overlapping in Ti contents regarding neighbouring metamorphic facies, there is a clear trend of increasing Ti with metamorphic grade. The broken line in *Fig. 4,* indicates maximum possible Ti in hornblende of respective metamorphic facies.

Ti AND Al VARIATIONS AND THE INFLUENCE OF OXYGEN FUGACITY

Several authors have evaluated Ti and Al^{iv}/Al^{vi} variations in hornblende in terms of difference in bulk chemistry, modal content, T and P conditions of metamorphism [RASSE, 1974; BINNS, 1965; HELZ, 1973 and GRAPES *et al.,* 1977]. However, the observed features of the hornblendes of the present study, namely, *1.* no relationship between the whole rock Ti content and the Ti content of hornblendes; *2.* the consistency in the $Fe^{tot}/Fe^{tot}+Mg$ of the hornblendes; *3.* lower Ti content in hornblendes associated with Fe—Ti oxides than those associated with pyroxene; *4.* high whole rock oxidation ratios, defined as $Fe^{3+}/Fe^{3+}+Fe^{2+}$ molar ratios, tend to be related to relatively lower Ti values in the hornblendes *(Fig. 5)*, have made the authors to believe that the Ti variations in the hornblendes of the present study is due to a combination of independent parameters namely, temperature of metamorphic crystallisation and oxygen fugacity.

The influence of oxygen fugacity is noted on minor scale as shown by the low Ti contents of hornblende that surrounds Fe—Ti oxides but also much larger scale as shown by a correlation of low Ti with relatively high whole rock oxidation ratios. Both the relationships are consistent with data of HELZ [1973] who has demonstrated experimentally that an increase in fO_2 at constant whole rock oxidation ratio and

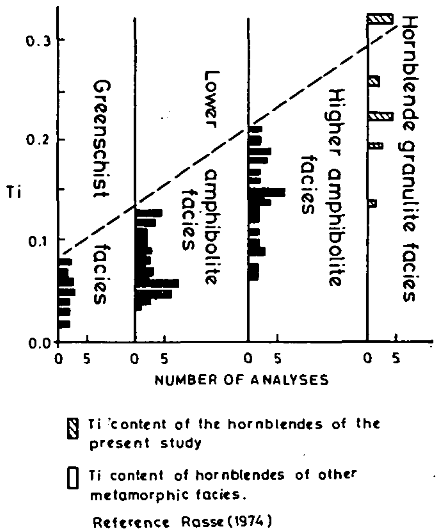

Fig. 4. Histogram of Ti content of hornblende of the present study and hornblendes in rocks of metamorphic facies

temperature reduces the Ti content of hornblende in favour of Fe—Ti oxides. Hornblende around Fe—Ti oxides in the charnockites of Sivasamudram and Kanakapura areas apperently form microdomains of relatively high fO_2. HELZ [1973] has also demonstrated that the Ti content of hornblende increase with rising temperature in the range of 700°—1000°, in agreement with the inferences of BINNS [1965] and RASSE [1974]. The relations between Ti and temperature, however, is shown to be highly dependent upon fO_2. HELZ [1973] observed distinct positive correlation in quartz-fayalite-magnetite buffered experiments. In hematite-magnetite buffered ones, on the other hand, the Ti content of hornblende was rather low, showing to increase with rising temperature.

The observed positive correlation between Ti and Na + K and Al^{iv} and Na + K in a near 1 : 2 and 1 : 1 cation ratio, respectively *(Figs. 6. and 7)* are consistent with a model of titanotschermakite substitutions in the hornblende structure expressed as Ti, 2Al, Mg, 2Si, coupled with an increasing occupation of the *A* site [ROBINSON *et al.*,

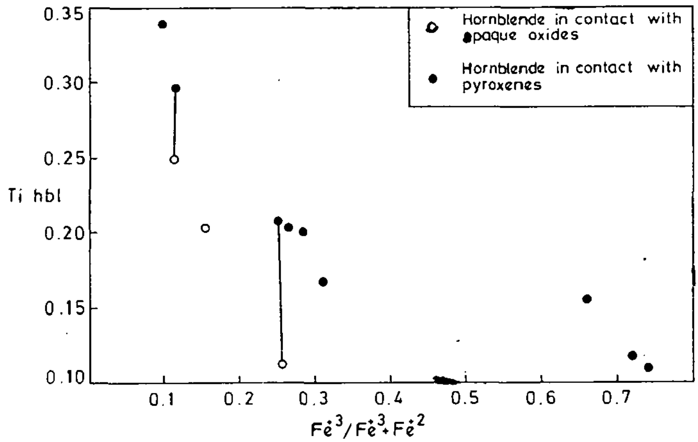

Fig. 5. Plot of Ti content of hornblende and whole rock oxidation ratio expressed as molar ratio $Fe^{3+}/Fe^{3+}+Fe^{2+}$

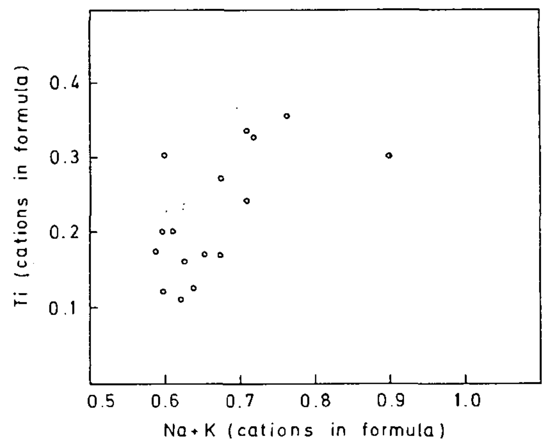

Fig. 6. Plot of Ti and total alkalies for hornblendes showing positive correlation in near 1:2 cation ratio

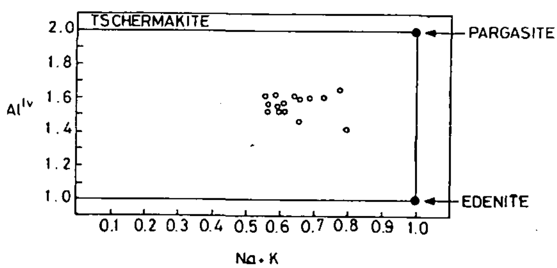

Fig. 7. Plot of Al^{iv} and total alkalies for hornblende

1971; GRAPES *et al.*, 1977; COOLEN, 1980 and VAN LAMOEN, 1980]. However, the above substitution is more complex than described above because of the generally complementary relation between Ti and Al^{vi}. Nevertheless, the $Al^{iv}-Al^{vi}$ relationship in the hornblendes of the present study may be regarded as essentially a function of Ti substitutions. Similar relationships are discussed by VAN LAMOEN [1980] and COOLEN [1980] who stressed the point that substitution of this type strongly influence the Al^{iv}/Al^{vi} ratio in hornblende, a ratio currently being used to indicate pressure estimates of metamorphism [RASSE, 1974 and MORTEANI, 1978].

CONCLUSIONS

Hornblendes from the charnockites of Karnataka show all the characteristics of previously published high Ti, high Al and high alkali hornblendes from other granulite facies areas. The hornblendes of the present study are of low pressure type which can be clearly demonstrated by $Al^{vi}-Si$ content of these hornblendes. The variation in Ti content of the hornblendes is due to a combination of independent parameters namely, temperature of metamorphic crystallisation and oxygen fugacity. The $Al^{iv}-Al^{vi}$ relationships in the hornblendes of the present study has been regarded as essentially a function of Ti substitutions.

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