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ARTICLE

Mineral Chemistry and Nomenclature of Amphiboles of Garnet Bearing Amphibolites From Thana Bhilwara, Rajasthan, India

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ABSTRACT

Amphiboles are frequently observed in the medium to high grade metamorphic rocks of garnet bearing amphibolites from Thana. In present work, authors have discussed the mineral chemistry and nomenclature of amphiboles. On the basis of mineral chemistry, the amphibole from garnet bearing amphibolite are normally varies from Hastingsite, Ferropargasite to Tschermakite variety.

1. Introduction

The study area exposes rocks of the Banded Gneissic Complex of the Proterozoic age [1,2], predominantly include basic granulites, pelitic granulites, and amphibolites etc, and constitute the main litho units of the gneissic complex (Figure 1) [1-12].

The Amphibolites occurs as isolated bands varying in width from a few centimeters to 20 meter, and also as lensoid bodies within the para-gneiss. At places the amphibolites are mixed with gneisses to form migmatite on mesoscopic and megascopic scales. This mixed rock is characterized by a conspicuous schistosity due to the presence of equidimensional hornblende in varying amounts.

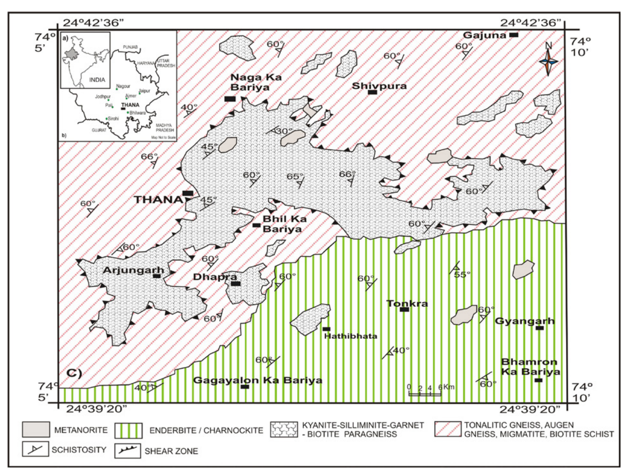

Figure 1. Geological map around Thana, Bhilwara, Rajasthan by author [1] , showing distribution of different litho units

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Several recent studies on amphibole chemistry have been carried out [13-20]. The main aim of this paper is to describe the mineral chemistry & nomenclature of these amphiboles using the [21] and [22] classification.

2. Amphibole

Ca–amphibole is present in garnet bearing amphibolite. In amphibolites, the hornblende forms a replacement zone or overgrowth on clinopyroxene. This can be considered a late tectonic occurrence of hornblende and the possible reaction is:

$$5CaMgSi_2O_6 + NaAlSi_3O_8 + H_2O = NaCa_2Mg_5Si_7AlO_{22}(OH)_2 + 6SiO_2 + 3Ca$$

3. Mineral Chemistry

Quantitative chemical analysis of mineral phases have been undertaken at the Mineralogisch Institute de Universitait, Weirzberg by Professor R.S.Sharma using Camera 5 X 50, operating at 15 kv with constant beam current and pulse height selection. The counting time was 100 seconds and 0.02 micro-ampere specimen current. ZAF and dead time corrections were applied with the computer programmed “FRAME”. The compositions of hornblende, is given in Table 1. The lower limit of detection ranges from about 0.004 to 0.010%. The total iron from microprobe analyses is reported as FeO^T.

The data of analyzed hornblende from garnet bearing amphibolite sample no. (H87/302 and H87/458) is shown in Table 1. The structural formula was recalculated on the basis of 23 oxygen basis. The structural formula corresponds closely to the generalized formula of the calcium-rich amphiboles which can be expressed as:

$A_{0-1}B_2C_5T_8O_{22}(OH)_2$

Where A= Na, K

B=Ca, Na, Mn

C= Mg, Fe^{+2}, Fe^{+3}, Al, Ti, Mn Cr, Li, Zn

T= Si, Al

[23-27]

Table 1. EPMA analysis and nomenclatures of garnet bearing amphiboles from Thana Bhilwara Rajasthan

Sample No	H87/458	H87/458	H87/458	H87/458	H87/458	H87/458	H87/458	H87/458	H87/302	H87/302
Circle No	2	2	2	2 Hb rim	2 Hb (small crystal)	1	1	1	1 (Hb/Pt 5) in carona	1 Hb(Pt-6) in carona of Hb-Plag
Point analysis	Hb Pt-36	Hb Pt-37	Pt-38	Pt-39	Pt-40	Pt-45	Pt-46	Pt-47	Pt-5	Pt-6
SiO_2	38.648	38.92	39.75	39.163	37.595	39.528	39.803	39.002	40.563	42.05
TiO_2	1.673	1.669	1.736	1.849	1.83	1.629	1.758	1.705	0.434	0.538
Al_2O_3	11.742	11.716	11.621	12.203	11.62	12.206	11.49	11.891	14.345	12.816
Cr_2O3	0.0057	0.04	-	-	0.017	-	-	0.04	0.023	0.012
MgO	6.6061	6.55	6.65	6.594	6.721	6.561	6.741	6.652	7.981	9.331
CaO	11.545	11.185	11.351	11.285	11.402	11.135	11.583	11.421	11.706	11.843
MnO	0.074	-	0.074	0.116	0.092	0.102	0.069	0.194	0.106	0.186
FeO	22.472	21.522	22.498	21.898	22.143	21.999	22.133	22.085	17.864	17.835
Na_2O	1.435	1.385	1.382	1.424	1.47	1.525	1.431	1.449	1.01	1.129
K_2O	2.267	2.1676	1.986	2.126	2.043	2.135	2.076	2.106	1.455	1.276
Cl^-	0.807	0.839	0.647	0.686	0.723	0.682	0.601	0.764	0.189	0.02
H_2O	1.671	1.649	1.735	1.718	1.66	1.724	1.748	1.69	1.886	1.965
Total	98.9458	97.6426	99.43	99.062	97.316	99.226	99.433	98.999	97.562	99.001
Cations based on 23 O	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen	23 Oxygen
Si	6.1841	6.2656	6.2765	6.2050	6.1130	6.2467	6.2793	6.2070	6.2877	6.3994
Ti	0.2011	0.2021	0.2061	0.2202	0.2237	0.1936	0.2085	0.204	0.0506	0.0616
Al	2.2124	2.2229	2.1626	2.2787	2.2268	2.2734	2.1364	2.2303	2.6208	2.2988
Cr	0.0007	0.0051	0	0	0.0022	0	0	0.005	0.0028	0.0014
Mg	1.5741	1.5717	1.565	1.5572	1.6289	1.5454	1.5851	1.5778	1.8441	2.1165
Fe	3.0043	2.8975	2.9709	2.9015	3.0111	2.9074	2.9201	2.9393	2.3158	2.2699
Mn	0.01	0	0.01	0.0155	0.0127	0.0136	0.0093	0.0262	0.0132	0.024

Ca	1.9773	1.9292	1.9202	1.9157	1.9863	1.8853	1.9579	1.9475	1.9442	1.9296
Na	0.4448	0.4324	0.4232	0.4374	0.4634	0.4671	0.4376	0.4471	0.3037	0.333
K	0.4623	0.4451	0.3999	0.4297	0.4237	0.4303	0.4178	0.4275	0.2877	0.2478
Total	16.0711	15.9716	15.9344	15.9609	16.0918	15.9628	15.952	16.0117	15.6706	15.682
Avg of Min and Max Fe^{+3}										
Si	6.106881	6.206829	6.207922	6.14379	6.02135	6.190462	6.226066	6.134278	6.238876	6.336272
Al -IV	1.893119	1.793171	1.792078	1.85621	1.97865	1.809538	1.773934	1.865722	1.761124	1.663728
SUM T	8.000000	8.000000	8.000000	8.00000	8.00000	8.000000	8.000000	8.000000	8.000000	8.000000
Al-VI	0.291656	0.408878	0.346893	0.400011	0.214764	0.443395	0.344354	0.338448	0.839325	0.612395
Fe^{+3}	0.423892	0.291386	0.403094	0.355121	0.541858	0.322894	0.306779	0.408197	0.485871	0.578181
Ti	0.198589	0.200204	0.203848	0.218028	0.220346	0.191857	0.206732	0.20161	0.050207	0.060992
Cr	0.000691	0.005052	0	0	0.002167	0	0	0.004941	0.002778	0.001386
Mg	1.554445	1.556957	1.547901	1.541839	1.604478	1.531487	1.571662	1.559314	1.82978	2.095621
Fe^{+2}	2.525797	2.537522	2.493337	2.477356	2.410142	2.50366	2.565872	2.474578	1.785506	1.639582
Mn	0.004929	0	0.004928	0.007645	0.006245	0.006707	0.004601	0.012912	0.006532	0.011844
Sum C	5	5	5	5	5	5	5	5	5	5
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{+2}	0.017096	0.041414	0.042008	0.040401	0.013956	0.054672	0.022694	0.022088	0.02644	0.029746
Mn	0.004946	0	0.004963	0.007702	0.006265	0.00677	0.00462	0.012981	0.006565	0.01192
Ca	1.919922	1.867675	1.863173	1.855135	1.932464	1.823665	1.90328	1.888212	1.839958	1.84569
Na	0.058036	0.090911	0.089856	0.096762	0.047315	0.114893	0.069406	0.076719	0.127036	0.112644
Sum B	2	2	2	2	2	2	2	2	2	2
Na	0.38121	0.337433	0.32872	0.336323	0.409137	0.348002	0.364484	0.365143	0.174306	0.217071
K	0.456527	0.440925	0.395531	0.425461	0.417348	0.426426	0.414258	0.422491	0.285466	0.245356
SUM A	0.837737	0.778358	0.724251	0.761784	0.826485	0.774428	0.778742	0.787634	0.459772	0.462427
Total	15.83774	15.77836	15.72425	15.76178	15.82648	15.77443	15.77874	15.78763	15.45977	15.46243
IMA Classification	**Hastingsite**	**Ferropargasite**	**Hastingsite**	**Ferropargasite**	**Hastingsite**	**Ferropargasite**	**Ferropargasite**	**Hastingsite**	**Tschermakite**	**Tschermakite**

The hydrous ion present in amphibole may be partially or wholly replaced by F and Cl. In case of garnet bearing amphibolite (Sample No H87/458 and H87/302; Table 1), the SiO_2 and Al_2O_3 content varies from 37.59 to 42.05% and from 11.49 to 14.34 respectively, FeO^T, MgO and CaO content varies from 17.83 to 22.49%, from 6.55 to 9.33% and from 11.13 to 11.84, respectively and the total oxide ranges from 97.31 to 99.43.

3.1 Substitutions

The analyzed hornblendes show several substitutions in the Y and Z positions accompanied by the introduction of Na (K) into the X sites. Owing to the variable substitutions the hornblende composition can be expressed in terms of four end members. Tremolite - actinolite $Ca_2(Mg,Fe^{+2})_5Si_8O_{22}(OH)_2$; edenite - ferroederite $NaCa_2(Mg_5,Fe^{+2})_5AlSi_7O_{22}(OH)_2$; tschermakite $Ca_2(Mg,Fe^{+2})_3\ Al_2Si_6Al_2O_{22}(OH)_2$ and Pargasite - hastingsite $NaCa_2(Mg_2,Fe^{+2})_4\ AlSi_6Al_2O_{22}(OH)_2$.

The edenite-ferroederite and tschermakite composition can be derived from tremolite-actinolite by the substitution Si $\rightleftharpoons$ Al^{VI}; Na and (Mg, Fe) Si $\rightleftharpoons$ Al^{IV}, Al^{VI}, respectively. The combination of both these types of substitution results in the pargasite-hastingsite composition.

Hence, the analysed hornblendes are plotted on these four end member composition diagram (Figure 2 and 3a) [23,24] and the analyses of the hornblende are also expressed by the relationship between Al^{IV} and (Na + K) atoms per formula unit (Figure 3a) [28]. TiO_2 varies from 0.434 to 1.84 wt%; Na_2O varies from 1.01 to 1.53 wt% and K_2O varies from 1.27 to 2.27 wt% (Table 1).

From the plot it is clear that the analysed hornblende contains a considerable amount of pargasite and tschermakite molecules, and the reaction between Al^{VI} and Si of the hornblendes are shown in the Figure 3b, the diagram after ([28] Figure 1). The hornblende of the area show relatively low Al^{VI} and Si, and plot below the broken line of 5 Kb drawn by [28] (*loc cit.*) parallel to the line of maximum Al^{VI} after [26].

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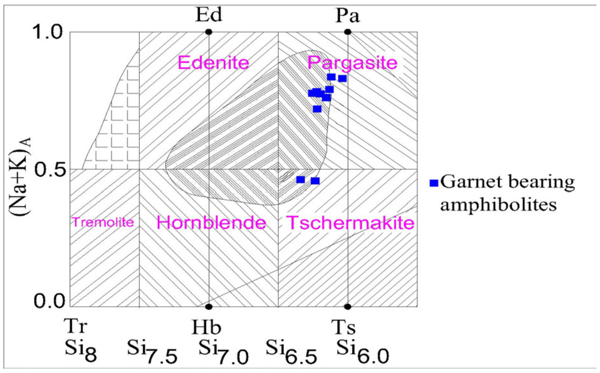

Figure 2. The chemical variation of calcic amphiboles expressed as number of (Na+K) in A-sites and Si atoms per formula units. End member are Tr-Tremolite, Hb-Hornblende (Sensu strico), Ed- Edenite, Pa-Pargasite, Ts-Tschermakite. The more densely stippled areas show the more commonly occurring compositions [24]

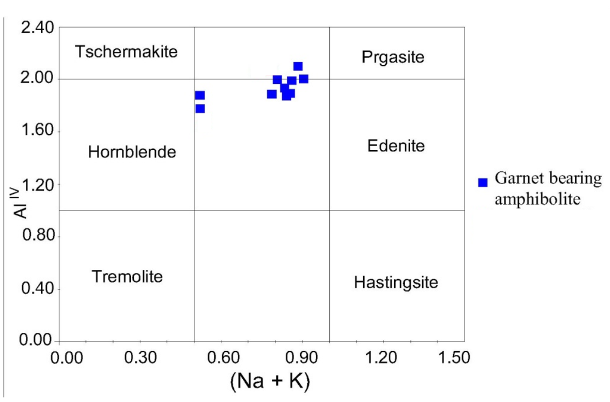

Figure 3a. Compositional variation diagram of Hornblende (after Raase, 1974) [28]

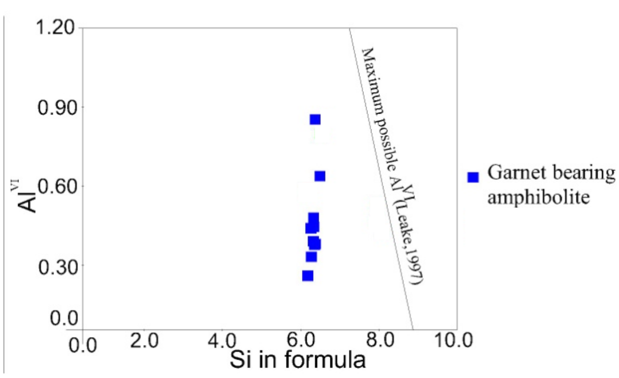

Figure 3b. Plot representing the maximum possible Al^{VI} position in Si Vs Al^{VI} ions of hornblende (after Raase, 1974)[28]

3.2 Compositional Variations

Several workers have attributed certain compositional variations in hornblende to the grade of metamorphism. [29]; [30]; [31] and [32] have suggested that Al/Si ratio in hornblendes increase with increasing temperatures of metamorphism. Increase in Ti content of hornblende with increasing grade of metamorphism has been noted by [3,28,30,33]. Increase in Na and decrease in amount of Mn(OH) and also in the ratios Fe_2O_3/FeO and Fe/Mg with increasing grade of metamorphism have been reported by [34].

4. Nomenclature

The amphibole group is a complex, compositionally diverse group among silicates, and exists in large varieties of rock types and P-T ranges making it very useful P-T and petrogenetic indicator. In [22] the International Mineralogical Association (IMA) revised its [21] nomenclature scheme for amphiboles to accommodate all known amphibole species including several species discovered after [21]. The main difference between the [21] and [22] a scheme is that amphiboles were divided into five groups in the [22] scheme instead of four groups in the [21] scheme, on the basis of B site occupancy, which is as follows:

Group 1 the sum of L type ions ^{B}(Mg, Fe, Mn, Li) ≥ 1.50 apfu, then the amphibole is member of the magnesium- iron-manganese-lithium group.

Group 2 ^{B}(Mg, Fe^{+2}, Mn^{+2}, Li) ≤0.50, ^{B}(Ca, Na) ≥ 1.00 and ^{B}Na<0.50 apfu, then the amphibole is a member of calcic group.

Group 3 ^{B}(Mg, Fe^{+2}, Mn^{+2}, Li) ≤0.50, ^{B}(Ca, Na) ≥ 1.00 and 0.50≤ ^{B}Na<1.50 apfu, then the amphibole is a member of sodic-calcic group.

Group 4 ^{B}(Mg, Fe^{+2}, Mn^{+2}, Li) ≤0.50, and ^{B}Na≥1.50 apfu, then the amphibole is a member of sodic group.

Group 5 0.50 < ^{B}(Mg, Fe^{+2}, Mn^{+2}, Li) <1.50 and 0.50≤ ^{B}(Ca, Na) < 1.50 apfu, then the amphibole is a member of sodium-calcium-magnesium-iron-manganese-lithium group.

4.1 Cations Substitution

There are a number of substitutions for the mechanism of amphiboles, which involve coupling of cations with different valence states to maintain charge balance [35].

Site/charge balance equation	Substitution	End member
$[A]_\square + {}^{[4]}Si = {}^{[A]}Na + {}^{[4]}Al$	Edenite	$NaCa_2Mg_5Si_7AlO_{22}(OH)_2$
$2^{[4]}Si + 2^{[6]}Mg = 2^{[4]}Na + 2^{[6]}Fe^{+3}$	Iron Tschermakite	$\square Ca_2(Mg_3Fe_2^{+3})Si_6Al_2O_{22}(OH)$
$2^{[4]}Si + 2^{[6]}Mg = 2^{[4]}Al + 2^{[6]}Al$	Aluminum Tschermakite	$\square Ca_2(Mg_3Al_2)Si_6Al_2O_{22}(OH)_2$
$2^{[4]}Si + {}^{[6]}Mg = 2^{[4]}Al + {}^{[6]}Ti$	Titanium Tschermakite	$\square Ca_2(Mg_4Ti)Si_6Al_2O_{22}(OH)_2$

$[A]_{\square}$ + $^{[6]}Mg+2^{[4]}$ Si = $^{[A]}$ Na+ $^{[6]}Fe^{+3}$ +2$^{[4]}$Al	Hastingsite	$NaCa_2(Fe_4^{+2}F^{+3})$ $Si_6Al_2O_{22}(OH)_2$
$[A]_{\square}$ + $^{[6]}Mg+2^{[4]}Si$ = $^{[A]}Na$ + $2^{[6]}Al$ + 2Al	Pargasite	$NaCa_2(Mg_4Al)$ $Si_6Al_2O_{22}(OH)_2$
$[A]_{\square}$ + $^{[M4]}Ca$= $^{[A]}Na$ + $^{[M4]}Na$	Richterite	$Na(CaNa)Mg_5Si_8O_{22}(OH)_2$
$^{[M4]}Ca$ + $2^{[6]}$ Mg= $2^{[M4]}Na$ + $2^{[6]}$ Fe^{3+}	Riebeckite	$\square Na_2(Fe_3^{2+}Fe_2^{3+})$ $Si_8O_{22}(OH)_2$
$^{[M4]}Ca$ + $2^{[6]}Mg$= $2^{[M4]}Na$ + $2^{[6]}Al$	Glaucophane	$\square Na_2(Mg_3Al_2)Si_8O_{22}(OH)_2$
$[A]_{\square}$ indicates vacancy in the A-site		

Note: Where [A]□ indicates vacancy in the A-site. Only the Edenite and aluminum Tschermakite substitutions are linearly independent.

4.2 Calcic Amphiboles

The calcic amphibole group is defined as monoclinic amphiboles in which (Ca + Na)*B* ³ 1.00, and Na*B* is between 0.50 and 1.50; usually, Ca*B* ³ 1.50. The number of subdivisions used in IMA 78 has been more than halved; silicic edenite and compound names like Tschermakite hornblende have been abolished, Sadanagaite [36] and Cannilloite [37] have been added, and the boundaries of the group have been revised. The Classification of calcic amphibole [21,22], in fig 4 (a) Si in formula against Mg/ (Mg + Fe^{+2}) of the garnet bearing amphiboles (Sample no H 87/458) occur in Hastingsite and Ferropargasite. In plot 4 (b) Si in formula against Mg/(Mg + Fe^{+2}) but few garnet bearing amphiboles (Sample no H87/302) occur in Tschermakite field.

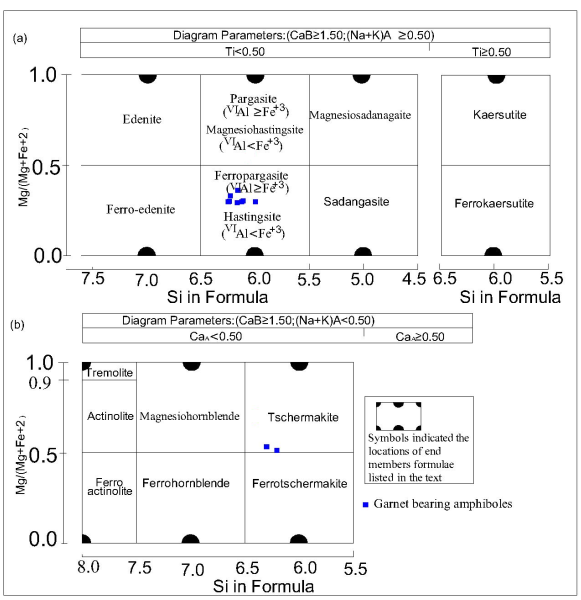

Figure 4. Classification of calcic amphibole [21, 22] (Leake et al 1997, 2004). In fig 4 (a) Si in formula against Mg/ (Mg + Fe $^{+2}$) most of the garnet bearing amphiboles (Sample No. H 87/458) occur in Hastingsite and Ferropargasite, field. In plot 4 (b) Si in formula against Mg/(Mg + Fe $^{+2}$) but few garnet bearing amphiboles (sample No. H 87/302) occur in Tschermakite field

5. Discussion

In present work mineral chemistry and nomenclature of amphiboles from Thana Bhilwara, Rajasthan, is based on the nomenclature of the amphiboles given by [21] and [22], where the chemical formula are calculated according to [38], in which the estimation of Fe^{+3} requires the evaluation of the all- ferrous iron anhydrous formula calculated on 23 oxygen atom basis. The stiochiometric limit for minimum estimation of the proportion of Fe^{+3} is Si ≤ 8, ∑Ca ≤ 15 & ∑ K ≤ 16. Similarly for the maximum estimation of the proportion of ferric iron is ∑ Al ≥ 8, ∑ Mn ≥ 13 & ∑ Na ≥ 15 with the normalization factor all the cations are recalculated (Table 1).

In the garnet bearing amphiboles (H87/458 & H87/302), the excess of CaO represent the calcic amphiboles mainly by Hastingsite and Ferropargasite. TiO_2 varies from 0.43-1.84 Wt% which indicates the increasing grade of metamorphism.

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