روابط فازی و تاریخچه واکنش‌های دگرگونی در سنگهای رسی دگرگون شده
کلریتوئیده‌دار و بدون کلریتوئید، منطقه ماهنشان، شمال‌غرب ایران

عادل ساکی، محسن موذر، منصور مجتهدي، روند اوبرهانسی

چکیده: مجموعه کانی‌ها، بافت‌های واکنشی و ترکیب کانی‌های سنگهای رسی دگرگون شده منطقه جنوب‌غرب ماهنشان واقع در شمال‌غرب ایران به منظور پاسارگار تاریخچه واکنش‌های دگرگونی، مورد بررسی قرار گرفته است. تاریخچه واکنش‌ها در سنگهای رسی دگرگون شده بدون کلریتوئید و کلریتوئیددار کمیکس ماهنشان جهت مطالعه روابط فازی با استفاده از نمودارهای فازی AFM، AFMn
واکنش‌های اصلی در سنگهای رسی دگرگون شده را کانی‌های بدون کلریتوئید و دگرگونی در بدل پرچین از گالری استارولیتی، آندالوزیت، کپثایت، ویبرولیت، بوته‌یه، مسکوت و کورتنت در این سنگ‌ها از آن‌ها جزء سری دگرگونی باروین هستند. سنگهای رسی دگرگون شده کلریتوئیددار منطقه دارای کانی‌های گرانی، استارولیتی، کلریت، مسکوت، کورتنتی و کورتنت در این سنگ‌ها از آن‌ها جزء سری دگرگونی باروین هستند. روآی شاخه واکنش‌های دگرگونی شکل‌دهنده کانی‌ها در هر دو سنگهای کلریتوئیده‌دار و بدون کلریتوئید مورد استفاده قرار گرفته‌اند.

واژه‌های کلیدی: کمیکس ماهنشان، سنگهای رسی دگرگون شده، کلریتوئید، روآی فازی، تاریخچه واکنش‌ها، سری باروین
Phase relations and reaction histories of chloritoid-free and chloritoid-bearing metapelites from the Mahneshan area, NW Iran

A. Saki 1, M. Moazzen2, M. Modjtahedi2, R. Oberhänsli 3

1- Department of Geology, Shahid Chamran University, Ahvaz, Iran
1- Department of Geology, University of Tabriz, 51664 Tabriz, Iran
3- Institut für Geowissenschaften, Universität Potsdam, Germany
E-mail: adel_saki@yahoo.com

Abstract: Mineral assemblages, reaction textures and mineral composition of the metapelitic rocks from the Mahneshan area in NW Iran are studied to reconstruct the reaction history of the rocks. The phase relation on the real mineral chemistry AFM, AFMn compatibility diagrams and mineral isograds in chloritoid-free and chloritoid-bearing metapelites of Mahneshan Complex were studied in order to determine the reaction history. The main minerals in the graphitic metapelites (chloritoid-free schist) of the Bolandparchin are garnet, staurolite, andalusite, kyanite, fibrolite, biotite, muscovite and quartz. The isograds are typical Barrovian. Chloritoid-bearing metapelites of the area contain the minerals garnet, staurolite, chlorite, muscovite, chloritoid and quartz. The isograds are not compatible with Barrovian type, but reflect the first appearance of chloritoid in the aluminous bulk compositions. Phase relations on the AFM and AFMn compatibility diagram are used to find the metamorphic reactions in both chloritoid-bearing and chloritoid-free rocks.

Keywords: Mahneshan Complex, metapelites, chloritoid, phase relation, reactions history, Barrovian type.

1- Introduction
The chemical system K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O (KFMA) is used to study the compatibility of the coexisting phases in the Mahneshan metapelites [1]. In this paper, we assume an equilibrium or at least a close to equilibrium condition for crystallization of different metamorphic minerals in the metapelitic rocks of the Mahneshan area.

The observed mineral assemblages, the analysis of reaction textures and the mineral compositions are used to reconstruct the reaction history of the rocks in the Mahneshan Complex. Based on field and petrography studies, four metamorphic phases have affected the area. The first phase (M₁) has been a regional metamorphic event, crystallizing garnet, biotite and muscovite. Inclusion trails within andalusite, staurolite and garnet are developed, which help to determine the relative chronology of the metamorphic and deformational phases. The second phase (M₂) has formed new minerals such as kyanite, fibrolite, staurolite, andalusite and garnet. The third phase (M₃) is contact metamorphism around younger igneous intrusions, which has produced post-deformational andalusite and garnet. The last metamorphic phase (M₄) is retrograde and post-magmatic, which has affected M₁, M₂ and M₃ metamorphic assemblages, overprinting schistosities (both S₁ and S₂) of the rocks.

2- Geological setting
The area chosen for this study is located in NW of Mahneshan town in Zanjan province of Iran. The area is limited to geographical Latitudes of 36° 30' to 37° 00'N and Longitudes of 47° 07' to 47° 45'E (Fig. 1). The Mahneshan Complex is located within the Alpine-Himalayan orogenic system of western Asia [2], [3]. Probably, the main geological
features of the area are formed during Pan African orogeny similar to central Iranian block (e.g. [4]).

In the northern part of the Takab quadrangle (Mahneshan Complex is the central part of the Takab quadrangle), a sedimentary sequence (more than 1300 m in thickness) is exposed and ranging in ages from Precambrian, Cretaceous, Eocene, Oligocene-Miocene to post-Miocene [5]. Emplacement of Precambrian and Palaeozoic rocks under the sedimentary and volcanic rocks with Oligo-Miocene age is brought up an old horst (Gor Gor - Belgheys and Ghebleh Dagh horst). This horst with a trend of NW-SE extends from N to S of the area (Fig.2). The western border of this horst is a reverse fault (Gainarjah- Chartag fault) with depression of Shirmard and Eastern border is Pari basin. The base complex is formed of Precambrian rocks which are exposed in the central part of the Mahneshan area.

3- Petrography and deformation
3.1. Structural relations and petrofabric features of pelitic rocks of the study area

Microstructure and petrographic features and field relations show that the formation of Mahneshan metamorphic complex is poly-metamorphic with four metamorphic phases (M₁, M₂, M₃ and M₄) and at least two deformational phases (D₁ and D₂). A poly-phase deformation can be considered based on two foliations, (S₁ and S₂) as well as by inclusion trails in porphyroblasts. D₁ (first deformational phase) is affected by D₂ (second and main deformational phase) with respect to the microscopic thin sections and field evidence. D₂ is the most obvious and pervasive deformation in the area while D₁ can be seen in some thin section, only.

**Fig.1.** Simplified structural map of Iran (compiled from [3]; [2]). MKDF = Main Kopeh-Dagh Fault, ZTZ = Zagros Thrust Zone.
3.2. Formation of foliations (S1 and S2)
The slaty cleavage $S_1$ (formed during the first deformation $D_1$) is best seen in samples from the Almalu schist where it is brought about by two mica (Bt, Ms) crystallized parallel to the slaty cleavage (Fig. 4c, 5b) and also in crenulation cleavage (Fig 5c). $S_2$ (formed during the second deformation $D_2$) is parallel to axial planes of micro-folds in intercalated quartz – feldspar rich and phyllosilicate-rich layers. This foliation represents the main regional foliation and can be recognized at all part of the metamorphic zone. $S_2$ foliation might have developed simultaneously with first generation of the folds and thrusts, superimposed on older structures.

3.3. Relation between deformation and metamorphism (Poly-metamorphism)
a) M1 metamorphism
The $M_1$ metamorphic phase formed during $D_1$ deformational phase is represented by fine to medium – grained (0.5-1mm) metamorphic minerals which are present in the weakly-deformed domains. The main minerals of this metamorphic phase (with respect to inclusion in porphyroblast) are garnet, white mica, biotite, chlorite, quartz and albite.
The mica flakes may have grown as crystals parallel to bedding due to diagenetic foliation under low-grade metamorphic condition, simultaneously to the D1 deformation.

b) M2 metamorphism

The M2 metamorphic phase is characterized by a strong crenulation cleavage and preferred alignment of mainly mica minerals (S2) and development of new porphyroblasts including Grt, Bt, Ctd, And, Ky, Sill and St. This phase was the major regional metamorphic phase in the studied area and affected the M1 metamorphic phase. Name abbreviations are after [6].

Two main mineral assemblages formed during M2 in the graphitic schists (Bolandparchin sub area Fig.4) and non-graphitic schist (Poshtuk sub area Fig.5). The graphitic schists assemblages (chloritoid-free) are (in addition to muscovite, quartz as KFMASH system minerals):

- Chl + Bt
- Bt + Grt
- Bt + Grt + And + St
- Bt + Grt + And + Ky
- Bt + Grt + Sill

The mineral assemblages in the non-graphitic schists are

- Grt + St + Chl
- Ctd + Grt + St + Chl

The crystallization of these minerals was found to be temporally related to the S2 fabric and D2 phase in all domains.

c) M3 metamorphism

The M3 metamorphic stage represents a contact metamorphic phase. This metamorphism is affected M1 and M2 regional metamorphic phases. Some minerals such as biotite and garnet are replaced the old regional metamorphic garnet due to contact metamorphism. Also and is formed in phyllosilicate-rich layers, overprinting both S1 and S2 (Fig.4h). The main assemblage of contact metamorphic phase is Grt + Bt + And + Crd + Ms.

d) M4 metamorphism

This metamorphism is retrograde and a postmagmatic event. M4 metamorphism has affected M1, M2 and M3 metamorphic assemblages, overprinting both S1 and S2 schistosities (Fig.4b). The mineral assemblage that formed during metamorphism (M4), is Chl + Ms. Retrograde reaction textures such as Chl after Bt and Grt are observed mainly in the regional Grt zone and St – And zone.

3.4. Metamorphic mineral growth

a) Chlorite

Primary chlorite is crystallized in the non-graphitic schists. The rocks containing primary chlorite are composed of fine-grained muscovite, chlorite, quartz and porphyroblasts of helsitic garnet and staurolite (Fig.5g). Chlorite and muscovite up to 0.3 mm long have developed in the rocks. Retrograde chlorite is crystallised after both M1 and M2 metamorphism (Fig.4b).

b) Biotite

Pelitic rocks from the Alemalu area (Fig.3) are phyllites or fine grained schists with lepidoblastic texture and are characterized by a slaty cleavage, which is affected by later crenulation cleavage. The mineral assemblage of these rocks is Chl + Ms + Bt + Qtz + Pl with opaque accessory minerals (Fig.4c).

c) Garnet

Garnet in the graphitic schists (1 up to 4 mm in diameter) usually forms idiomorphic to subidioblastic, sometimes inclusion-rich grains with Bt and/or Qtz inclusion. Texture of these schists is lepidoporphryoblastic. Grt, Bt and Ms are syntectonic (D3), because porphyroblasts of Ms and Bt lie parallel to S2 and wrap garnet (Fig.4f). Garnet predates D3 deformational phase in some sample (Fig.4e).

Most of the garnet crystals (in non-graphitic schists of Poshtuk) show spiral shape inclusion fabrics, which have traditionally been interpreted as developed during syn-tectonic (S2) growth of rotating porphyroblasts (Fig5d). Porphyroblasts of garnet up to 1.3 mm long have developed in the non-graphitic schists of the Poshtuk area (Fig.5a).

d) Andalusite

Andalusite exists in the chloritoid-free schists. With respect to the petrography studies, two types of andalusite can be distinguished in graphitic schists:

- The first generation of andalusite (And1) which is formed pre-tectonically to syn-tectonically (D3) in term of deformation in the crystals, pressure shadow and boudins (Fig.4e). Mica parallel to S2
wraps the andalusite. And$_1$ is formed during the M$_2$ metamorphic phase. Some of these andalusites have preserved garnet, graphite and staurolite as inclusion and show zoning under the microscope. The second generation of andalusite (And$_2$) is formed post-tectonically (M$_2$) and due to M$_3$ contact metamorphism. And$_2$ grows statically over pre-existing microfolds of S$_2$ foliations and phyllosilicate-rich layers (Fig.4h).

Two textural generations of biotite and garnet can be distinguished.

Mineral growth outlasted the deformation, as indicated by And$_2$, Grt$_2$ and Bt$_2$, porphyroblasts either growing statically over pre-existing microfolds of S$_2$ or replacing a former mineral that formed during regional metamorphism such as Grt$_1$.

e) Staurolite
Staurolite is crystallized in both chloritoid-free and chloritoid-bearing schists. There is no pressure shadow around this mineral. It seems that the staurolites are syn-D$_2$ (Fig.4h). S$_2$ schistosity wraps some staurolites. Staurolite usually forms idioblastic to sub-idioblastic, inclusion-free grains. Staurolite in chloritoid-bearing schists of Poshtuk often nucleated at the margin of garnet or in phyllosilicate-rich layers (Fig.5.e). Most of the garnet has already broken down in these rocks and staurolite is formed at the rim of garnet (Fig.5.f).

f) Chloritoid
Chloritoid was found in non-graphitic schists in the study area. It occurs in fine-grained rock matrix as lath-shaped crystals with bluish colour under the microscope (Fig.5g). These rocks consist of garnet (up to 1.3 mm) chloritoid, staurolite (up to 0.5 mm), chlorite and muscovite. Chloritoid, chlorite and muscovite are formed parallel to S$_2$ in non-graphitic schist that wraps spiral garnet. These minerals are syn-D$_2$. Therefore main mineral assemblage in these rocks, which are formed syn-M$_2$, is: Ctd + Grt + St + Ms + Chl + Qtz.
Fig. 4. a- sillimanite grows at the expense of biotite. b- Retrograde chlorite over printing both S1 and S2 foliation. c- A schistosity (S1) is defined by a preferred orientation of muscovite, and biotite affected by a crenulation schistosity with an axial plane cleavage (S2) defined by Bt and Ms. d- Kayanite porphyroblast formed during M2 regional metamorphism. e- Syn-tectonically andalusite (And1) and deformed porphyroblast formed during M2 main regional metamorphism and deformed S2 foliation with rotated andalusite porphyroblast. f- Syn-tectonic garnet porphyroblasts formed during M2 metamorphism. g- Staurolite is formed syn-tectonically in the chloritoid-free schists. h- Undeformed andalusite (And2) porphyroblast has overgrown D2 micro fold during M1 contact metamorphism.
Fig. 5. a. garnet porphyroblasts (Grt) with 0.5 to 1.5 cm diameter formed in chloritoid schists. b. folding of the S1 foliation leading to the development of a S2 foliation parallel to the axial plane. c. A schistosity (S1) is defined by a preferred orientation of muscovite, chloritoid and chlorite which is crenulated. d. Syn-tectonic helicitic garnet porphyroblasts (Grt1) formed during M2 metamorphism and garnet (Grt2) is formed during contact metamorphic phase. e. Staurolite and muscovite nucleated at the margin of garnet. f. garnet (pseudomorph) is replaced by staurolite (prograde metamorphism). g. Chlorite and chloritoid in textural equilibrium. h. staurolite pseudomorphed by muscovite.
g) Sillimanite
Pelitic rocks of Bolandparchin, which contain sillimanite, are medium – grained schists (Fig.4a). Sillimanite aggregates are associated with biotite and also are in contact with andalusite. The typical assemblage (in addition to muscovite + quartz + plagioclase) is Bt + Grt + And + Sill with minor Fe – Ti oxides.

4. Mineral chemistry of peak metamorphism
In order to identify the mineral composition of major phases of metapelites in the studied samples, minerals in five representative thin sections of the rocks were analysed with the electron microprobe in GeoForschungsZentrum (GFZ) Potsdam, Germany, using a CAMECA model SX100 microprobe in the wavelength-dispersive mode with 15 Kv acceleration Voltage, 3 nA beam current and 40 second acquisition time per analyses. The detection limit of the machine is approximately 0.1 wt%. The relative analytical errors are approximately 1%.

Sample locations are shown in Figure 3. Representative mineral analyses are provided in Tables 1, 2 and 3.

### Table 1. Representative Chlorite and muscovite analyses and the structural formulae

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pre</th>
<th>Post</th>
<th>15 Kv</th>
<th>Analytical</th>
<th>Structural</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorite</td>
<td>13E</td>
<td>13b</td>
<td>13a</td>
<td>49g</td>
<td>49g</td>
<td>43b1</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>K2O</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 2. Representative biotite and garnet analyses and the structural formulae.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pre</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>34.95</td>
<td>35.25</td>
<td>40.73</td>
<td>34.40</td>
<td>34.34</td>
<td>35.62</td>
<td>34.36</td>
<td>36.8</td>
<td>36.50</td>
<td>37.11</td>
<td>38.11</td>
<td>35.02</td>
<td>36.50</td>
</tr>
<tr>
<td>TiO2</td>
<td>2.05</td>
<td>1.55</td>
<td>2.45</td>
<td>1.36</td>
<td>1.57</td>
<td>1.62</td>
<td>0.04</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Fe2O3</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>1.88</td>
<td>1.85</td>
<td>1.36</td>
<td>0.825</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>CaO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

11 (O) 12 (O)

Si 2.62 2.62 2.90 2.61 2.67 2.70 2.65 2.94 2.93 2.94 3.027 2.94 2.96
Ti 0.11 0.11 0.08 0.14 0.08 0.09 0.09 0.00 0.00 0.00 0.00 0.00 0.00
Al 1.82 1.81 1.82 1.58 1.82 1.81 1.78 2.00 1.98 1.97 1.97 1.97 1.97
Cr 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Fe3+ 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.11 0.13 0.14 0.17 0.09 0.10
Table 3. Representative staurolite, chloritoid and plagioclase analyses and the structural formulæ

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Si</th>
<th>Ti</th>
<th>Mg</th>
<th>Fe(2+)</th>
<th>Fe(3+)</th>
<th>Al</th>
<th>Cr</th>
<th>Mn</th>
<th>Na</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inc</td>
<td>43c</td>
<td>43c</td>
<td>49g</td>
<td>13b</td>
<td>13b</td>
<td>13a</td>
<td>13a</td>
<td>49g</td>
<td>49g</td>
<td>49g</td>
</tr>
<tr>
<td>Core</td>
<td>55.60</td>
<td>57.34</td>
<td>57.14</td>
<td>53.60</td>
<td>54.36</td>
<td>54.83</td>
<td>54.82</td>
<td>41.35</td>
<td>41.26</td>
<td>41.00</td>
</tr>
<tr>
<td>Rim</td>
<td>63.64</td>
<td>62.94</td>
<td>62.00</td>
<td>59.87</td>
<td>59.48</td>
<td>59.55</td>
<td>59.57</td>
<td>56.00</td>
<td>55.76</td>
<td>55.10</td>
</tr>
<tr>
<td>Core</td>
<td>98.00</td>
<td>97.00</td>
<td>97.00</td>
<td>96.02</td>
<td>96.64</td>
<td>96.52</td>
<td>95.41</td>
<td>95.76</td>
<td>95.10</td>
<td>95.93</td>
</tr>
<tr>
<td>Rim</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
<td>89.83</td>
</tr>
</tbody>
</table>

a) Chlorite
Representative analyses of chlorite are shown in Table 1. The number of cations is calculated on the basis of 28 Oxygens. Prograde chlorite is only present in non-graphitic schists. Retrograde chlorite, formed as alteration product of biotite and garnet has almost the same composition as the prograde ones. The oxide totals are between 86.87 and 89.49. The amount of Ti is between 0.01 and 0.07 atom per formula unit (apfu). The chlorites are Mn-free. Na varies from 0.00 to 0.02 apfu, and K from 0.00 to 0.03 apfu. Substitution of Al\(^{3+}\) for Si\(^{2+}\) is calculated using stoichiometric approach. Figure 6a after [7] shows the classification of the studied chlorites. According to this figure, chlorites are of epidolite to daphnite type. This figure also shows the Fe-rich nature of the chlorites. According to Fig. 6b [8] retrograde chlorites plot on the Medium-/Low-pressure field and prograde chlorite plot close to this field.

b) Muscovite
Muscovite analyses are listed in Table 1. The number of cations is calculated on the basis of 11 oxygens. All samples of pelitic composition contain primary muscovite. There is no compositional difference between those lying parallel to the schistosity and those oblique to the S2 foliation. According to Figure 6c [9], muscovite is rich in the muscovite end-member Figure 6d, paragonite being the second dominant component. The mole fractions of other components are negligible. Reduction in the phengite component of muscovite with metamorphic grade has been described by several authors (e.g. [10]; [11]; [12]) in different low-to-medium pressure metamorphic terranes.

c) Biotite
Microprobe analyses of biotite are provided in Table 2. The number of cations is calculated on the basis of 11 oxygens. The amount of Ti is between 0.08 and 0.14 (apfu). Phlogopite-annite are the dominant constituents in the biotite (Fig.6d1). Ti versus Fe/(Fe+Mg) diagram for biotites from different metamorphic zones, is given in Figure 6e. Compositional ranges of biotite from various metamorphic zones in New England are from [13].
According to this figure, biotites in the studied samples plot in the Ky-St and Sil-St zones. This is in accordance with petrographical observation.

d) Garnet
Garnet compositions are listed in Table 2. In general, garnets are Fe-rich with almandine content varying between 80 and 90%. Ti is not presented or occurs in very low amounts. Figure 6g shows the chemical composition of the analysed garnets on the Alm, Pyp and (Grs+Sps) triangular diagram. Fe\(^{3+}\) content of garnet were calculated based on eight cations and 12 Oxygens. Zoning profiles are from rim to rim through the core of the garnets (Fig 6k). There is significant normal zoning in the garnet from sample 43b1.

![Figure 6a](image1)
![Figure 6b](image2)
![Figure 6c](image3)

**Fig. 6.** a. Classification of the analysed chlorites using Al\(^{3+}\) substitution for Si\(^{4+}\) versus Mg/(Mg+Fe\(^{2+}\)) diagram. Chlorites in all samples are ripidolite to daphnite in composition. b. Chlorite composition of Mahneshan metapelite on a formula proportion diagram (Al(VI)+2Ti+Cr-2 versus Al(IV)-2). Compositional variation along the 1:1 line represents the Tschermak substitution. Indicated field for different metamorphic condition after [8]. c. Chemical compositions of muscovites from metapelits of Mahneshan. Si (Per 11 oxygens) against Fe+Mg.
Fig. 6. d1. Plot of Ti (per 11 oxygens) as a function of Fe/(Fe+Mg) for biotite from different metamorphic zones.

5.e. Unshaded fields: compositional ranges of biotite from metapelites of Mahneshan ([13]). f. Composition of the studied chloritoids plotted on the Mn, Fe$^{2+}$, Mg and Fe$^{2+}$ + Mn, Al-Fe$^{3+}$, Mg triangular diagrams. Chloritoids are Fe-chloritoid. g. Composition of the studied garnet plotted on the Fe$^{2+}$, Mg and Ca, triangular diagrams. h. Composition of the studied staurolite plotted on the Fe$^{2+}$, Mg and Mn + Ca triangular diagrams. i. Composition of the Mahneshan igneous feldspars, plotted on the An-Ab-Or diagram.
Fig. 6. k. Zoning profiles from rim to rim through the core of the garnets. There is significant normal zoning in garnet from sample 43b1.

**e) Chloritoid**
Chloritoid is found only in Non-graphitic schists. Representative mineral compositions of chloritoids in the studied samples are given in Table 3. The number of cations is calculated on the basis of 12 Oxygenes. Chloritoids are iron rich, and the Fe/Mg ratio is much higher than in the coexisting chlorite. Fig.6f, illustrates the composition of chloritoids on the Al+Fe$^{3+}$, Fe$^{2+}$+Mn, Mg and Fe$^{2+}$, Mn, Mg triangular diagrams. According to the figure, Fe$^{2+}$ occupies the cubic site (i.e. chloritoids are Fe-rich).

**f) Staurolite**
Staurolite analyses are listed in Table 3. The number of cations is calculated on the basis of 22 Oxygenes. Staurolite in sample 49g, which is associated with chloritoid, has distinctly less MgO (~0.35% ) and ZnO(~0.30 %) than staurolite in sample 43c associated with andalusite and/or kyanite, with MgO(~1.22%) and ZnO(~1.78 %). Staurolite do not show any significant zoning. Fig.6h, shows compositional ranges of staurolite on the Fe, Mg and (Mn+Zn) triangular diagrams. According to the figure, staurolites are Fe-staurolite and MnO and ZnO contents are very low. Staurolite shows lower X$_{Fe}$-value than coexisting garnet.

**g) Feldspar**
Feldspar analyses are listed in Table 3. The number of cations is calculated on the basis of 8 Oxygenes. The anorthite content (XAn) of plagioclase is variable. For example in sample 44c XAn is 0.30 and in sample13f it is 0.10. Figure 6i, illustrates the composition of feldspars on the Ca,
Na, K triangular diagram. According to the figure, plagioclases are albite-rich.

5- Discussion
5-1- Phase relation and reaction history of peak metamorphism (M2) in the chloritoid-free metapelitic rocks of the Bolandparchin sub-area
AFM compatibility diagrams, constructed based on real minerals chemistry, show phase relation for the garnet zone to sillimanite zone in the chloritoid-free metapelites (Fig. 7).

a) The biotite-in isograd
The initial assemblage in the graphitic metapelitic rocks of the Bolandparchin sub area was probably, Kfs (detrial) + Chl + Ms + Qtz.

At the biotite-in isograd the first appearance of biotite in these rocks could be resulted from a KFMASH continuous reaction, such as
Kfs + Chl = Bt + Ms + Qtz + H2O  (1)
The appearance of biotite in semi-pelitic rocks with detrital K-feldspar can be explained by this reaction.

Reaction (1) is also proposed by [10] for pelitic rocks from the Scottish Dalradian. We adopt the generally assumed temperature for the biotite in isograd of 370-400°C.

Bucher and Frey [14] discuss the equilibrium condition of such a reaction as a function of XFeO. The pelites lacking K-feldspar, dominate the metasedimentary sequence. In these rocks biotite forms most probably by the continuous reaction
Phe + Chl = Bt + Phe-poor Ms + Qtz + H2O  (2)
According to Bucher and Frey [14] this reaction involves the progressive replacement of chlorite and the reduction of the phengite component in muscovite.

Fig. 7. a to e, Al2O3-FeO-MgO projection from quartz, muscovite and H2O for coexisting minerals in graphitic schists of the Bolandparchin sub-area.
b) The garnet-in isograd
The garnet-in isograd reaction is strongly depended on bulk-rock composition and MnO and CaO contents in the rocks. With high amount of these components, garnet could appear at temperatures below 450°C [15].

The appearance of garnet in the studied graphitic schists is most probably related to the two continuous reactions deduced from the AFM-phase compatibility diagrams (Fig. 7 a to e)

\[ \text{Chl} + \text{Qtz} = \text{Grt} + \text{H}_2\text{O} \quad \text{e.g.}[16] \]  
\[ \text{Chl} + \text{Ms} + \text{Qtz} = \text{Grt} + \text{Bt} + \text{H}_2\text{O} \]  

In Bolandparchin sub-area chloritoid dose not occur, due to the MnO content of garnet, which produces an expansion of the Grt-Chl stability field to lower temperatures or to Al-poor bulk composition that contain Grt + Chl assemblages rather than chloritoid + biotite [17]

c) The staurolite-Al2SiO5-in isograd
Staurolite is crystallized in both chloritoid-bearing and chloritoid-free rocks. Staurolite in the chloritoid-free, rocks could have been produced by the following discontinuous reaction.

\[ \text{Grt} + \text{MS} + \text{Chl} = \text{St} + \text{Bt} + \text{Qtz} + \text{H}_2\text{O} \quad [18] \]  

Garnet is partially resorbed by this reaction, and a significant amount of chlorite is removed, along with the production of abundant staurolite and new biotite.

According to [19], this reaction takes place at a fixed temperature for any given pressure, because it is discontinuous and proceeds until one of the three reactants has been consumed. When this reaction ceases, additional staurolite may be produced by a continuous reaction involving the remaining phase, for example

\[ \text{MS} + \text{Chl} = \text{St} + \text{Bt} + \text{Qtz} + \text{H}_2\text{O} \]  

This reaction may be deduced from AFM phase compatibilities and metamorphic textures, in that staurolites occurs mainly in phyllosilicates-rich layers [e.g.20]. These reactions account for the disappearance of primary chlorite in the staurolite-andalusite zone.

Staurolite does not appear in samples 13f and 44c (And +Grt + Bt + Ms) but exists as inclusions in andalusite, therefore, the following reaction can be considered for staurolite breakdown:

\[ \text{St} + \text{Ms} + \text{Qtz} = \text{Bt} + \text{And/Ky} + \text{H}_2\text{O} \]  
\[ \text{St} + \text{Bt} + \text{Qtz} = \text{Grt} + \text{Als} + \text{Ms} + \text{H}_2\text{O} \]  

The low pressure andalusite-bearing rocks are mainly exposed in the Bolandparchin area. The appearance of andalusite is most probably related to the reactions

\[ \text{Chl} + \text{Ms} = \text{And} + \text{Bt} + \text{H}_2\text{O} \]  

Chl + Ms = ky + Bt + H2O  

Reaction (12) generally occurs at low-pressure of the lower amphibolite facies, whereas reaction (13) occurs at medium-pressure of the lower amphibolite facies [5]. Two representative mineral assemblages formed during M2 metamorphic phase in the graphitic schists of the Bolandparchin sub-area are:

\[ \text{Bt} + \text{Ms} + \text{Grt} + \text{St} + \text{Ky} + \text{Qtz} + \text{Pl} \] (medium-pressure type)

\[ \text{Bt} + \text{Ms} + \text{Grt} + \text{St} + \text{And} + \text{Qtz} + \text{Pl} \] (low-pressure type)

d) The Sillimanite-in isograd
Sillimanite occurs as two types (i) aggregates of fibrolite, overgrowing biotite and muscovite (Fig 4p) (ii) prismatic sillimanite.

The fine- grained fibrolite may have resulted from the following reactions:

\[ 2\text{Ms} + 2\text{H}^+ = 3\text{Sil} + 3\text{Qtz} + 2\text{K}^+ + 3\text{H}_2\text{O} \]  
\[ 4\text{Bt} = 2\text{Sil} + 10\text{Qtz} + 12(\text{Mg,Fe})\text{O} + 2\text{K}_2\text{O} + 4\text{H}_2\text{O} \]

According to Carmichael [18], the development of fibrolite at the expense of micas may be related to a series of local metasomatic cation-exchang reactions.

Staurolite does not appear in this zone, it is preserved as inclusions in andalusite. It may disappear as a result of the discontinuous reaction (11) or continuous reaction (12):

\[ \text{St} + \text{Ms} + \text{Qtz} = \text{Sil} + \text{Grt} + \text{Bt} + \text{H}_2\text{O} \]  
\[ \text{St} + \text{Ms} + \text{Qtz} = \text{Al}_2\text{SiO}_5 + \text{Bt} + \text{H}_2\text{O} \]  

Reaction (12) reflects lower temperature than the discontinuous reaction (11) and P-T condition is nearly independent of the CaO and MnO content of the rock [21].

5-2- Phase relations and mineral reactions in the chloritoid metapelitic rocks of the Poshtuk sub-area
Sample 49g contains the assemblage garnet, staurolite, chlorite, muscovite, chloritoid, quartz. The isograds are not typical Barrovian isograds, but reflect the first appearance of chloritoid in these aluminous bulk compositions. Staurolite does not co-exist with biotite as it does in the classical Barrovian staurolite zone. Petrographical studies of the samples show obvious reaction rims around the garnet crystals.

a) The garnet-in isograd
Chloritoid is formed in non-graphitic schists of the Poshtuk sub-area, Chloritoid acts as a possible reactant for garnet formation in these rocks. This is
deduced from the AFM-phase compatibilities (Fig.8a, b, c)
\[ \text{Ctd} + \text{Chl} + \text{Qtz} = \text{Grt} + \text{H}_2\text{O} \]  
\[ \text{Fe-chloritoid} + \text{annite} = \text{almandine} + \text{muscovite} + \text{H}_2\text{O} \]  

b) The Staurolite-in isograd
In the chloritoid schists (non-graphitic rocks), textural relations show the formation of staurolite at the expense of garnet (Fig.5) suggesting the following reaction
\[ \text{Ctd} = \text{St} + \text{Grt (Alm)} + \text{Chl} + \text{H}_2\text{O} \]  

The appearance of staurolite in sample 49g is the result of the continuous Fe–Mg–Mn reaction.
The garnet in the garnet zone samples occurs as an extra phase, stabilized by Mn [e.g. 24] (Fig.8d, e, f, g). In the AFM system, the garnet zone samples at a given temperature (T₁) are characterized by co-existing chlorite and chloritoid. At higher metamorphic temperatures (T₂), the reaction:
\[ \text{chloritoid} = \text{garnet} + \text{staurolite} + \text{chlorite}, \] results in the demise of chloritoid in the higher grade rocks and the appearance of staurolite and continued garnet growth. These garnet-bearing rocks are better illustrated in the AFMn system when projected from chlorite. The stable garnet zone (T₁) sub-assemblage is chloritoid+garnet+chlorite (Sample 49g). As temperature increases to T₂, the three phase assemblage chloritoid + garnet + staurolite shifts to lower Mn until chloritoid is consumed leaving the garnet+staurolite+chlorite sub-assemblage (Sample 47b).

As it can be seen, the appearance of staurolite is not the result of a garnet consuming reaction such as garnet + chlorite = staurolite + biotite + H₂O, as in low-Al pelites (because biotite is not formed in the studied rocks). Therefore, we conclude that garnet in these samples did not experience any dissolution due to the appearance of staurolite.

---

**Fig. 8.** a,b,c, Al₂O₃–FeO–MgO projection from quartz, muscovite and H₂O of coexisting minerals in Non-graphitic schists of the Poshtuk sub-area. d,e,f,g, AFMn plots showing the phase relation for the garnet zone and staurolite zone samples.
6- Conclusion

The main mineral assemblage of peak metamorphism in the graphitic metapelites (chloritoid-free schist) of the Bolandparchin is garnet, fibrolite, biotite, muscovite and quartz. Chloritoid-bearing metapelites of the Poshtuk sub-area contain the assemblage of garnet, staurolite, chlorite, muscovite, chloritoid and quartz; AFM compatibility diagrams, constructed based on real minerals chemistry, show the phase relations for the garnet zone to sillimanite zone in the chloritoid-free metapelites. The isograds are typical Barrovian type.

AFM and AFMn compatibility diagrams show the phase relations for the garnet zone and staurolite zone samples in the chloritoid-bearing metapelites. The deduced isograds based on the field geology studies and petrographical inspection of the samples are not typical Barrovian type, but reflect the first appearance of chloritoid minerals in these aluminous bulk compositions.

Since biotite is not crystallized in the studied samples, the appearance of staurolite can not be attributed to the garnet consuming reactions as happens in most of the low Al-pelites of the world. Therefore there are two distinct mechanisms for staurolite crystallization in the chloritoid-bearing and chloritoid-free rock studied here.

The stable garnet zone assemblage is chloritoid + garnet + chlorite. As temperature increases the three phase assemblage chloritoid + garnet + staurolite shifts to lower Mn contents until chloritoid is consumed leaving the garnet + staurolite + chlorite assemblage.

Acknowledgements

The main analytical part of the research was carried out in the Geosciences Institute of Potsdam University and GFZ, Potsdam, Germany. We would like to thank fruitful discussions with A. Muller and P. O’Brien from Potsdam University. Dr. Rhede and O. Appelt are acknowledged for their generous help during microprobe sessions. Constructive comments by two anonymous referees of the journal improved the manuscript. We thank editorial efforts by Dr. Tajabor and Dr. Homam.

References


