Paragenesis of Cr-rich muscovite and chlorite in green-mica quartzites of Saigaon–Palasgaon area, Western Bastar Craton, India

K R RANDIVE^{1,*}, M M KORAKOPPA², S V MULEY³, A M VARADE¹, H W KHANDARE¹,
S G LANJEWAR¹, R R TIWARI¹ and K K ARADHI⁴

¹Post Graduate Department of Geology, RTM Nagpur University, Nagpur 440 001, India.

²National Centre of Excellence in Geoscience Research, GSI, Bengaluru 560 078, India.

³Groundwater Surveys and Development Agency (Zilla Parishad), Nagpur 440 001, India.

⁴National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India.

*Corresponding author. e-mail: randive101@yahoo.co.in

Green mica (fuchsite or chromian-muscovite) is reported worldwide in the Archaean metasedimentary rocks, especially quartzites. They are generally associated with a suite of heavy minerals and a range of phyllosilicates. We report the occurrence of green-mica quartzites in the Saigaon–Palasgaon area within Bastar Craton in central India. Mineralogical study has shown that there are two types of muscovites; the chromium-containing muscovite (Cr_2O_3 0.84–1.84%) and muscovite (Cr_2O_3 0.00–0.22%). Chlorites are chromium-containing chlorites (Cr_2O_3 3.66–5.39%) and low-chromium-containing chlorites (Cr_2O_3 0.56–2.62%), and as such represent ripidolite–brunsvigite varieties. Back scattered electron images and EPMA data has revealed that chlorite occurs in two forms, viz., parallel to subparallel stacks in the form of intergrowth with muscovite and independent crystals within the matrix. The present study indicates that the replacement of chromium-containing chlorite by chromium-containing muscovite is found to be due to increasing grade of metamorphism of chromium-rich sediments. However, the absence of significant compositional gap between aforementioned varieties indicates disparate substitution of cations, especially chromium, within matrix chlorites. The chromium-containing muscovite and muscovite are two separate varieties having distinct paragenesis.

1. Introduction

Green-mica quartzites, which are often referred to as ‘fuchsite’ quartzites occur profusely in the Archaean metasedimentary terrains. The green micas are commonly chromium-muscovites, their peculiar green colour is attributed to the concentration of chromium or iron in the micas. In most of the quartzites worldwide, occurrence of a variety of minerals such as zircon, rutile, tourmaline, Cr-spinels, pyrope, sphene, magnetite, hematite,

chlorite, biotite, pyrophyllite, andalusite, silliminite, kyanite, corundum, microcline, epidote, and zoisite have been reported (Whitemore *et al.* 1946; Clifford 1957; Ramiengar *et al.* 1978; Raase *et al.* 1983; Sinha-Roy and Ravindra Kumar 1984). Two types of origins are commonly envisaged for the formation of green-mica quartzites, namely: hydrothermal alteration, in which, mica is formed either due to replacement of pre-existing rocks or due to hydrothermal solution emanating from magmatic intrusions (Whitemore *et al.* 1946; Geijer

Keywords. Green mica; chromian muscovite; chromian chlorite; Bastar Craton; fuchsite quartzite.

Figure 1. Geological maps (a) showing location of Bastar Craton in India (redrawn from Meert *et al.* 2011); (b) Bastar Craton (redrawn from Ramakrishnan and Vaidyanadhan 2008); and (c) Saigaon-Palasgaon area (modified after GSI 2001).

1963; Morata *et al.* 2001; Arif and Moon 2007) or by metamorphism of chromium-rich minerals in the source rock (Leo *et al.* 1965; Argast 1995). Green mica quartzites are known to occur in Archaean rocks, e.g., Montana, USA (Heinrich 1965), Outokumpu, Finland (Treloar 1987), Dharwar Craton, India (Argast 1995).

We are presenting here a study of green-mica quartzites occurring in Bastar Craton (central India). Two localities, namely, Palasgaon and Saigaon, were selected for collecting the representative samples where small rock quarries were opened up. On the basis of this study, we discuss the origin of phyllosilicates associated with green-mica quartzites.

2. Geology of the area

The ENE–WSW trending mobile belt known as Central Indian Tectonic Zone (CITZ) divides the Precambrian shield of India into two major crustal blocks (figure 1a); the northern block is known

as Aravalli Protocontinent which is comprised of Aravalli–Delhi metasediments, Bundelkhand massif and Vindhyan sedimentary basin; whereas the southern block is referred to as the Dharwar Protocontinent comprising Dharwar, Bastar, and Singhbhum Cratons and South Indian Granulite Terrain (Naqvi *et al.* 1974; Drury 1984; Rogers 1986; Murthy 1987, 1995; Ramchandra *et al.* 1995, 2001; Zhao *et al.* 2003; Acharya 2003; Stein *et al.* 2004; French *et al.* 2008).

The Bastar Craton is a square-shaped ($\sim 500 \text{ km}^2$) crustal block in south-central India (figure 1b) bounded to the north by Central Indian Tectonic Zone, to the south by Eastern Ghat Mobile Belt, to the east by Mahanadi Rift and to the west by Godavari Rift (Bhadra *et al.* 2004; French *et al.* 2008; Ramakrishnan and Vaidyanadhan 2008; Meert *et al.* 2011). The oldest rock units in the Bastar Craton are undifferentiated tonalite–trondjemite gneisses. The high-grade gneissic terrain forms the basement for supracrustals represented by phyllite, schist, quartzite, and meta-carbonate interbedded with metabasalts. Ghosh

Figure 2. (a) A quarry section in Saigaon area. The ground level exposure dug for extracting green mica. The beds are dipping at $\sim 45^\circ$ at this location; the strata show little displacement due to folding. (b) A section of quartzite hill in Palasgaon area. Mica-poor quartzite is dominantly present in this area. (c) A bed of green-mica quartzite sandwiched between the mica-poor quartzites at Palasgaon section. Within the green quartzite, a brown layer of ferruginous quartzite is also seen. (d) Closer view of the green-mica quartzite bed at the level of current mining bench in Saigaon section.

(1941) grouped these supracrustal rocks as Bengpal Series, whereas Crookshank (1963) subdivided them into older Sukma Series and Younger Bengpal Series. Sarkar (1957–58) described the old supracrustal sequence around Bhandara as Amgaon Group that occurs as scattered enclaves within Amgaon Gneisses. The enclaves are mainly quartzites, garnet-staurolite-kyanite-sillimanite schists; cordierite-anthophyllite rocks with subordinate calc-silicate rocks and marbles. The Amgaon Gneisses are arguably co-relatable with the Sukma Gneisses occurring profusely in the Bastar Craton (Ramchandra *et al.* 2001). Although much before any such debate started, Ghosh (1941) stated that all the older supracrustal rocks of Bastar Craton are facies variants of one another and grouped them under one umbrella term – the Bengpal Series. Some of the recent publications subscribe to this view (e.g., Meert *et al.* 2011).

The gneissic complex of the Bastar Craton consists of TTG (tonalite-trondjemite-granodiorite) suite of rocks that are extensively exposed in the south and west of the Craton (Ghosh 2004). The TTG gneisses enclose rafts of ‘continental’ sediments of quartzite-carbonate-pelite (QCP) facies, together with minor BIF and mafic-ultramafic rocks (e.g., Sukma Group of Bastar and Amgaon Group of Bhandara). The fuchsite quartzites were reported from the Sukma Group, but not much information is available further. However, the green-mica quartzites from the Amgaon Group did not receive any attention.

3. Geology of Saigaon–Palasgaon area

The study area bounded between latitudes 20°16′–20°30′ and longitudes 79°35′–79°55′ covers an area of about ~200 km² (figure 1c). The area comprises Archaean to Paleoproterozoic rocks of Amgaon Gneissic Complex, which forms the basement into which quartzites, and banded hematite quartzites belonging to Bailadila group of Paleo-Proterozoic age occur (GSI 2001). Within the Amgaon Gneissic Complex enclaves of Amgaon group, viz., quartzites, green-mica quartzites and banded iron formations occur. Within the Archaean basement, outliers of sandstones of Neo-Proterozoic Vindhyan Supergroup are present. Several small lateritic capings of Cenozoic age also occur in the area (GSI 2001; figure 1c).

Several lenticular ridges of quartzites occur in the area, most of which are aligned in a north–south direction; smaller outcrops are disposed in E–W and NE–SW direction. Only few of these outcrops have green mica associated with them. Two such localities namely, Palasgaon and Saigaon were selected for sampling because the mining is

currently on at these places and therefore fresh samples were available for study. These outcrops are generally low lying, with a thick laterite cover (~1 m), and are rarely exposed above the ground (figure 2a–d).

Figure 3. Geological sections at Saigaon and Palasgaon quarries. Legend: 1a: lateritic soil cover, 1b: muscovite quartzite interlayered with ferruginous material limonite and kaolinite, 1c: closely spaced fractures often filled with ferruginous material and kaolinite within quartzite, 1d: green muscovite quartzite showing increasing iron content from bottom to top, 1e: closely spaced joints within quartzite often filled with ferruginous material and kaolinite, 1f: green-mica quartzite, 1g: white mica (paucity of green mica) with impregnation of Fe-oxide, and 1h: green-mica quartzite (current mining bench); 2a: ferruginous soil, 2b: weathered ferruginous quartzite, 2c: ferruginous quartzite (several dark bands of 2–4 cm thickness), 2d: quartzite with ferruginous material, 2e: green-mica quartzite (dip 40°–45°), 2f: white quartzite with impregnation of Fe-oxide, 2g: green-mica quartzite, and 2h: base not known.

The Saigaon section (figure 3) begins with the layer of green-mica quartzite (current mining bench), which is overlain by white quartzite impregnated by iron oxide. The strata are dipping at an angle varying between 40° and 50°. Another layer of green-mica quartzite occurs in the sequence. This layer shows greater variation in mica content; generally 2 to 3 bands of 2–4 cm thickness are interbedded with relatively mica-poor quartzites. Further up in the sequence Fe-content increases and the soil becomes completely lateritic.

At Palasgaon (figure 3), a hilly outcrop exposes dirty white quartzite which exhibits variegated colours such as green, yellowish-brown, ochre, chocolate brown, and reddish brown. At the

bottom, white quartzite is overlain by a layer of green-mica quartzite, followed by a layer of mica-poor quartzite, and another layer of green-mica quartzite. Towards the top of the section weathering becomes more pronounced and iron content increases, as has been noticed in the Saigaon section. On the whole it appears that the area represents a metasedimentary-type quartzite with alternate layers of mica-poor and mica-rich quartzites.

4. Analytical techniques

Mineralogical studies were carried out using petrological microscope Nikon 50i POL Trinocular

Figure 4. Various minerals and textures observed in the green-mica quartzites of Saigaon and Palasgaon areas [10X is magnification factor; XN is crossed polars; PPL is over polars; RT-2 and RT-3 are sample numbers]. (a) Small crystal of mica developed within the quartz matrix. Note the presence of innumerable fluid inclusions and cracks within quartz (RT-2; 10X; XN). (b) Flakes of muscovite within the matrix. Orientation is roughly perpendicular to the direction of stress (RT-3; 10X; XN). (c) A kink band within muscovite indicating deformation (RT-2; 10X, reflected light). (d) Chlorite crystal being intruded by the muscovite crystal (see also figure 5a; RT-2; 10X; XN). (e) Pyrophyllite aggregate within the rock (RT-3; 20X; XN). (f) Segregated crystals of euhedral chromian spinels within quartz matrix (RT-2; 10X; XN).

Polarizing Microscope at Post Graduate Department of Geology, RTM Nagpur University. The EPMA analyses were carried out at the National Centre of Excellence for Geoscience Research in the Geological Survey of India, Southern Region, Bangalore using CAMECA SX100 electron microprobe. Operating conditions were 15 keV–15 nA and beam size was 1 μm . Standards used for calibration were: Na on Jadeite, Si and Ca on Wollastonite, Mg on Diopside, Al on Corundum, K on Orthoclase, Ti on Rutile, Fe on Fe_2O_3 , and Cr on Cr_2O_3 .

5. Mineralogy and petrography

As mentioned above, quartzites can be distinguished separately as mica-poor and mica-rich. The sutured grains of quartz constitute about 95% of the rock mass, green mica 4–5%, and other minerals <1%. It commonly exhibits lepidogranoblastic texture.

The mica-rich quartzite can also be termed as micaceous quartzite or quartzitic mica schist or quartz mica schist, depending upon relative percentage of quartz and mica. However, these quartzites have been referred to as 'Fuchsite Quartzite' (GSI 2001). Due to preponderance of mica, this rock usually forms lepidoblastic or grano-lepidoblastic texture. Mineralogy of quartzites is discussed below.

Quartz is a ubiquitous mineral, though its concentration varies inversely with muscovite. The sutured quartz grains show deformation bands and initiation of neograin formation. Several fluid inclusions are also present. Mica occurs in two different microstructural sites, as small individual idiomorphic crystals within the quartz matrix with sharp outer margins and poorly-developed zones from core to rim (figure 4a). They show weak pleochroism and strong interference colours. Another one is represented by crystals which occur profusely in the mica-rich quartzites and mica schists; these are oriented perpendicular to the direction of stress (figure 4b). The chlorite crystals are small, idiomorphic, dark-green coloured and show middle order interference colours. It forms close intergrowth with muscovite in the form of chlorite-muscovite stacks (RT/2; figures 4c, 5a). At other places chromium-containing muscovite has intersected the low-chromium containing chlorite (RT/3; figure 4d, 5b), indicating that the former is younger than the latter. Pyrophyllite occurs in minor quantities with rutile and kaolinite (figure 4e). A majority of the phyllosilicates including chlorite, pyrophyllite and kaolinite were distinguished using SEM-EDS and EPMA. Opaque, euhedral crystals of chromian spinel occur in small clusters or even as independent crystals (figure 4f). Rutile shows a

Figure 5. (a) Back scattered electron image showing chromian-muscovite in the centre, which is cut by low-chromium-containing chlorite. (b) The back scattered electron image of chlorite-muscovite stack showing interleaved layers of light coloured chromian-chlorite and dark coloured chromian-muscovite. Other minerals sphalerite, monazite, pyrite, zircon and quartz are indicated in the diagram.

thick and sharp outline accentuated by high relief; its color is dark brown but varies from reddish to yellowish brown. It is often fractured and oriented along the direction of mica flakes. Well-developed crystals of zircon are present. They characteristically show growth zones and occur in small clusters, and are often aligned parallel to the foliation of mica. The SEM-EDS and EPMA analysis also indicated the presence of monazite, sphalerite, and pyrite.

6. Mineral chemistry

Totally 195 spot analyses of various mineral phases were carried out; the cations of the identified mineral phases were recalculated following standard procedures. Mineral chemistry of muscovite and chlorite is discussed below in detail.

Table 1. Representative EPMA analysis of chrom-muscovites from Saigaon and Palasgaon areas. Cations are calculated on the basis of 22 oxygens, and anions calculated assuming stoichiometry.

Sample	Chromium-containing muscovite							Muscovite				
	RT-2	RT-2	RT-2	RT-2	RT-2	RT-2	RT-3	RT-3	RT-3	RT-3	RT-3	RT-3
Point	5/1	6/1	7/1	26/1	33/1	35/1	50/1	54/1	55/1	57/1	7/1	8/1
SiO ₂	45.63	45.19	46.18	45.96	46.08	45.18	46.72	46.13	45.44	45.49	45.45	45.9
TiO ₂	1.43	1.48	1.1	0.9	0.78	0.84	0.01	0.02	0.05	0.02	0.03	0.01
Al ₂ O ₃	32.91	33.84	33.58	34.25	34.42	34.38	37.49	38.49	38.72	38.65	38.04	37.92
FeO	1.67	1.74	1.71	1.44	1.57	1.72	0.01	0.19	0.19	0.05	0.09	0.18
MnO	0	0.02	0	0.01	0	0.04	0.03	0	0.03	0	0	0
MgO	0.84	0.86	0.82	0.74	0.81	0.73	0.01	0	0.01	0	0.01	0.02
CaO	0.03	0	0.02	0.01	0.01	0	0.01	0	0	0.02	0.02	0
Na ₂ O	0.64	0.7	0.66	0.73	0.65	0.73	0.17	0.69	1.41	0.67	0.99	0.74
K ₂ O	10.19	10.35	10.22	10.15	10.24	10.36	10.27	10.04	9.22	10.18	9.89	10.18
Cr ₂ O ₃	1.42	1.31	1.48	1.08	0.95	1.43	1.01	0	0	0	0.01	0
H ₂ O*	4.445	4.471	4.497	4.487	4.497	4.469	4.571	4.567	4.548	4.540	4.513	4.531
Total	99.205	99.961	100.267	99.757	100.007	99.879	100.301	100.127	99.618	99.620	99.043	99.481
Si	6.156	6.061	6.158	6.142	6.144	6.061	6.129	6.056	5.991	6.009	6.038	6.074
Al iv	1.844	1.939	1.842	1.858	1.856	1.939	1.871	1.944	2.009	1.991	1.962	1.926
Al vi	3.389	3.411	3.437	3.537	3.553	3.498	3.925	4.012	4.008	4.027	3.995	3.989
Ti	0.145	0.149	0.110	0.090	0.078	0.085	0.001	0.002	0.005	0.002	0.003	0.001
Cr	0.151	0.139	0.156	0.114	0.100	0.152	0.105	0.000	0.000	0.000	0.001	0.000
Fe	0.188	0.195	0.191	0.161	0.175	0.193	0.001	0.021	0.021	0.006	0.010	0.020
Mn	0.000	0.002	0.000	0.001	0.000	0.005	0.003	0.000	0.003	0.000	0.000	0.000
Mg	0.169	0.172	0.163	0.147	0.161	0.146	0.002	0.000	0.002	0.000	0.002	0.004
Ca	0.004	0.000	0.003	0.001	0.001	0.000	0.001	0.000	0.000	0.003	0.003	0.000
Na	0.167	0.182	0.171	0.189	0.168	0.190	0.043	0.176	0.360	0.172	0.255	0.190
K	1.753	1.771	1.738	1.730	1.741	1.773	1.718	1.681	1.551	1.715	1.676	1.718

Figure 6. Al^{VI} vs. (Fe+Mg+Mn+Cr) diagram showing linear correlation with correlation coefficients for non-chromian as well as chromian-muscovites (see text for details).

6.1 Muscovite

Micas were calculated on the basis of 22 oxygens, results of analysis are given in table 1. Two types of micas occur in the studied samples. The green variety (with higher Cr, Fe and Mg) and the white variety (with lower Cr, Fe and Mg but higher Al and K) of the mica belonging to dioctahedral

mica group, which compares well with the composition of muscovite [KAl₂□AlSi₃O₁₀(OH)₂, where ^{IV}Si: 3.0–3.1; ^{VI}Al: 1.9–2.0; K: 0.7–1.0; ^{VI}Al/(^{VI}Al + ^{VI}Fe³⁺): 0.5–1.0 and ^{VI}R³⁺/(^{VI}R³⁺ + ^{VI}R²⁺): <0.25]. The formulae indicate that both micas are muscovite, the green micas show some concentration of octahedral alumina (Al^{VI}), which is replaced by Cr³⁺ and Fe; similarly, potash K⁺ and inter-layer cation (I, i.e., Ca+Na+K) are lower than white mica. Based on the stoichiometry, calculated mineral formulae are:

Chromium-containing muscovite (Green Mica)

Muscovite (White Mica)

Cations in the order of their decreasing abundance are $\text{Fe} \rightarrow \text{Mg} \rightarrow \text{Cr} \rightarrow \text{Ti} \rightarrow \text{Mn}$. Foster *et al.* (1960) studied the green-mica quartzites from Grandfather Mountain Range in North Carolina and concluded that the green colour acquired by this mica is due to substitution of Fe. However, in the present case we suggest that the green colouration of mica is due to Cr content, since the dioctahedral micas showing important phengitic substitutions, such as Fe and Mg, are not green.

Green and white muscovites differ in their relative cation percentages, but fall along a straight line on being plotted with octahedral ($^{\text{VI}}\text{Al}$) aluminum against ferromagnesian cations ($\text{Mg}+\text{Fe}+\text{Mn}+\text{Cr}$). The straight line correlation (figure 6) between the two indicates difference of ferromagnesian cations. In the Si – ($\text{Mg}+\text{Fe}+\text{Mn}+\text{Cr}$) diagram (figure 7a) the green mica analyses plot above the line of ideal Tschermark substitution indicating ferrimuscovitic substitution. The

Figure 7. (a) Si vs. (Fe+Mg+Mn+Cr) diagram indicating common Tschermark and ferrimuscovite substitutions in chromian-muscovites, (b) Si/Al vs. (Ca+Na+K) diagram showing dominant Tschermark substitution as against illitic substitution in chromian-chlorites. Cations for these diagrams are calculated on the basis of 11 oxygens.

Si/Al-interlayer charge diagram (figure 7b) confirms that the green micas show tschermakitic as well as ferrimuscovitic substitutions, which are lacking in the white micas.

6.2 Chlorites

Chlorites are associated with green micas in the Palasgaon–Saigaon area. EPMA analysis of the representative chlorites has been obtained. Cations were calculated on the basis of 28 oxygens, the analyses are given in table 2. On the basis of their mineral chemistry, chlorites can be distinguished as chromium-containing chlorites ($\text{Cr} \geq 0.4$ apfu and low-chromium-containing chlorite ($\text{Cr} \leq 0.4$ apfu). The formulae for chlorites of the study area are:

Chromian-chlorite

Low-chromium-containing chlorite

Three main substitutions occur in chlorites (Zane *et al.* 1998), namely, (i) the Tschermark substitution (TK), (ii) the dioctahedral substitution (AM), and (iii) the Fe– Mg_{-1} substitution (FM). In figure 8, a majority of the data points plot on the arrow indicating TK substitution, whereas those that are plotting above this arrow indicate increasing AM substitution. Significant Tschermark substitution appears to be $^{\text{IV}}\text{Al}^{\text{VI}}\text{AlSi}_{-1}\text{Mg}_{-1}$ and $^{\text{IV}}\text{AlCr}^{+3}\text{Si}_{-1}\text{Mg}_{-1}$ for Saigaon–Palasgaon chlorites. Whereas, the dominant cation in the FM substitution is Fe in comparison to Mg (Type-I), as shown in figure 9 (Zane and Weiss 1998).

Zane *et al.* (1998) compared chlorites occurring in metamorphic rocks. They discussed three possible parent rocks, namely: (1) metapelitic rocks, (2) metabasic rocks, and (3) felsic rocks. The data plotted in the $^{\text{IV}}\text{Al}$ vs. $^{\text{VI}}\text{Al}^{2+}+\text{Ti}+\text{Cr}$ diagram, in which the rectangular areas indicate the field in which 99% of chlorites occur (i.e., 2604 out of 2619 chlorite analyses). The relative spread of the data points within the rectangular area points towards metapelite field (figure 10a); similarly data plot in the metapelite and felsic fields in Fe^{2+} vs. Mg diagram (figure 10b). Moreover, the Mg–Al+ $\square$ –Fe diagram (figure 11) shows scatter of data points

Table 2. Representative EPMA analysis of chlorites. Cations are calculated on the basis of 28 oxygens, anions are calculated assuming stoichiometry.

	Chromium-containing chlorite							Low-chromium-containing chlorite				
	RT-2	RT-2	RT-2	RT-2	RT-2	RT-2	RT-3	RT-2	RT-2	RT-2	RT-3	RT-3
Sample	68/1	2/1	3/1	5/1	9/1	10/1	22/1	35/1	71/1	73/1	25/1	27/1
SiO ₂	23.760	23.050	25.090	23.690	24.160	24.850	27.940	25.02	25.520	25.820	26.190	26.380
TiO ₂	0.020	0.050	0.040	0.040	0.040	0.020	0.010	0	0.070	0.310	0.340	0.830
Al ₂ O ₃	17.510	17.060	18.210	17.420	17.150	16.490	19.050	19.44	20.190	19.100	18.760	17.830
Cr ₂ O ₃	4.440	5.290	3.660	4.900	4.410	4.320	4.100	2.62	1.940	1.300	1.270	1.640
FeO(T)	32.565	33.994	29.729	34.353	33.374	33.489	28.023	29.77	30.974	30.615	31.217	30.203
MnO	0.170	0.110	0.140	0.100	0.070	0.160	0.130	0.19	0.260	0.220	0.040	0.180
MgO	7.750	6.020	9.890	6.340	7.210	7.600	6.890	8.83	8.620	10.180	10.080	9.700
CaO	0.020	0.050	0.000	0.040	0.050	0.060	0.050	0.11	0.030	0.000	0.020	0.030
Na ₂ O	0.050	0.110	0.080	0.120	0.100	0.080	0.140	0.16	0.110	0.080	0.140	0.180
K ₂ O	0.130	0.190	0.140	0.170	0.120	0.120	1.170	0.26	0.180	0.160	0.140	0.170
H ₂ O*	10.518	10.307	10.841	10.494	10.519	10.589	11.037	10.8	10.983	11.004	11.040	10.922
Total	96.933	96.230	97.821	97.667	97.203	97.778	98.540	97.19	98.877	98.789	99.237	98.065
Si	5.398	5.340	5.522	5.389	5.484	5.603	5.959	5.52	5.534	5.600	5.659	5.748
Al iv	2.602	2.660	2.478	2.611	2.516	2.397	2.041	2.48	2.466	2.400	2.341	2.252
Al vi	2.105	2.019	2.271	2.082	2.093	2.006	2.839	2.608	2.731	2.507	2.464	2.363
Ti	0.003	0.009	0.007	0.007	0.007	0.003	0.002	0	0.011	0.051	0.055	0.136
Cr	0.798	0.969	0.637	0.881	0.791	0.770	0.691	0.457	0.333	0.223	0.217	0.283
Fe ³⁺	0.145	0.146	0.214	0.159	0.178	0.185	0.661	0.26	0.300	0.204	0.207	0.316
Fe ²⁺	6.027	6.425	5.235	6.360	6.138	6.110	4.264	5.202	5.284	5.326	5.412	5.153
Mn	0.033	0.022	0.026	0.019	0.013	0.031	0.023	0.035	0.048	0.040	0.007	0.033
Mg	2.625	2.079	3.245	2.150	2.440	2.555	2.191	2.903	2.786	3.291	3.247	3.151
Ca	0.005	0.012	0.000	0.010	0.012	0.014	0.011	0.026	0.007	0.000	0.005	0.007
Na	0.044	0.099	0.068	0.106	0.088	0.070	0.116	0.137	0.092	0.067	0.117	0.152
K	0.075	0.112	0.079	0.099	0.069	0.069	0.637	0.146	0.100	0.089	0.077	0.094
VAC	0.140	0.109	0.219	0.128	0.170	0.190	0.570	0.225	0.309	0.202	0.192	0.313
XMg	0.30	0.24	0.37	0.25	0.28	0.29	0.31	0.35	0.33	0.37	0.37	0.37

Figure 8. Mg-Al+□-Fe diagram showing data from Saigaon-Palasmaon chlorites, which fall within Type I category of Zane and Weiss (1998).

with increasing grade of metamorphism. Study of this diagram indicates that chlorites of greenschist facies metamorphism plot within the green shaded area and with the increased grade of metamorphism the data shifts to amphibolites facies metamorphism indicated by the orange coloured area. Whereas, the chlorites from metabasic rocks of greenschist facies occur within the orange coloured area, and the amphibolites facies chlorites of the metabasic rocks plot further towards Mg-end of the diagram. Since the data from Saigaon-Palasmaon area occur towards green shaded area, they represent chlorites from the metapelites of greenschist facies metamorphic conditions.

7. Discussion and conclusions

Muscovite and chlorite are often seen in intimate association in the form of intergrowths, ranging from parallel or subparallel packets (Jiang and Peacor 1994; Saxena *et al.* 2012) to fibrous intergrowths (Rustein 1979). Such intergrowths occur

Figure 9. Plot between octahedral aluminum and $\text{Al}^{\text{VI}} + \text{Cr} + 2 \cdot \text{Ti}$ from the chlorites. Red circles are data points from study area (see text for details).

more commonly in metapelites and typically display deformation features that imply an origin preceding or contemporaneous with deformation and metamorphism (Craig *et al.* 1982; Gregg 1986; Milodowski and Zalasiewicz 1991). Moreover, the chlorite-muscovite stacks show a general trend of increasing average size with increasing grade, which suggests that the phyllosilicate stacks are not only structurally and chemically altered but also affected by growth and overgrowth (Jiang and Peacor 1994).

The studied samples show muscovite and chlorite are interleaved at micron scale, although, the mixed layer sequences do not represent independent intermediate mineral phases, e.g., corrensitite. The diagram $(\text{Fe} + \text{Mg} + \text{Mn} + \text{Cr}) / \text{Si-interlayer Sum} / \text{Si}$ that discriminate between muscovite, chlorite, and mixed layers (figure 12), also shows that no intermediate component is formed.

The chlorite-muscovite intergrowth is formed due to various mechanisms, such as:

- (i) Diagenetic alteration of detrital biotite
- (ii) Retrograde diagenetic reactions
- (iii) Prograde metamorphic replacement of chlorite in stacks by dioctahedral mica layers.

The diagenetic alteration of detrital biotite can occur by two mechanisms, viz., (a) replacement of individual or multiple layers and (b) dissolution-transport-precipitation (Jiang and Peacor 1994). However, no traces of biotite are seen in the quartzites of Saigaon–Palasgaon area, which

Figure 10. (a) Plot between octahedral aluminum and $\text{Al}^{\text{VI}} + \text{Cr} + 2 \cdot \text{Ti}$ from the chlorites. Red circles are data points from study area (see text for details). (b) Plot between Fe^{2+} and Mg from the chlorites. The lower side of blue rectangle represent metapelite field (see Zane *et al.* 1998).

negates the possibility of diagenetic alteration of biotite. Another mechanism, that is, retrograde diagenetic reactions such as replacement of chlorite by vermiculite and replacement of muscovite by smectite as observed in Serra de Mojotoro (Do Campo and Neito 2003, 2005; Neito *et al.* 2005) or retrograde alteration of chlorite to smectite under oxidizing conditions due to the introduction of groundwater as observed in the slates of the subgreenschist facies in Sierra Espuna, Beltic

Figure 11. Triangular plot between Mg-Al+□-Fe from the chlorites. The trapezohedral blue area indicates field for majority of the chlorites from metamorphic parent. Green shaded area shows majority of the chlorites from green-schist facies metapelites, whereas orange coloured area shows field for green-schist facies metabasic parent or amphibolites-facies metapelite parent. All fields are from Zane *et al.* (1998). The Saigaon-Palargaon chlorites (red circles) indicate green-schist facies metapelite parent, except for Al+□ value, which is slightly higher than the average.

Cordillera, Spain (Neito *et al.* 1994) is known. However, again no evidence of retrograde diagenetic alteration was noticed during the present study. On the contrary, there are evidences of metamorphism. Giorgetti *et al.* (1997) observed that the replacement of chlorite in stacks of diocatahedral mica layers in the presence of aqueous fluids occurs due to prograde metamorphism. They quoted the significant chemical changes associated with these reactions such as loss of divalent cations (Mg^{2+} , Fe^{2+}) and H_2O , gain of K^+ , Si^{4+} , and textural features such as topotactic transformation of mica over chlorite. In addition to the divalent cations mentioned above, the trivalent cations (Cr^{3+} and probably Fe^{3+}) also show mobility from chlorite to muscovite in the Saigaon-Palargaon area. Chemical analyses of chlorite and mica (tables 1 and 2) indicate considerable loss of chromium by chlorite to muscovite during replacement of chlorite by mica.

Earlier the Cr-chlorites were classified on the basis of structural location of Cr^{3+} (Lapham 1958), as Kammererite (octahedral Cr^{3+}) and Kotschubeite (tetrahedral Cr^{3+}), e.g., the Cr-chlorites of Nuggihalli schist belt, Dharwar craton, India were identified as Kotschubeite (Damodaran and Somasekar 1976); which are now regarded simply as 'chromian' chlorites (Bayliss 1975; Bish 1977; Phillips *et al.* 1980). The chlorites occurring within green-mica quartzites of Saigaon-Palargaon area are therefore chromium-containing chlorites, especially those that occur as interlayer stacks by metamorphic replacement. On the other hand, the chlorites formed as independent crystals are

Figure 12. Interlayer cations per silica *vs.* octahedral cations per silica diagram for chlorites and muscovite occurring in stacks (figure 5b). The lines joining the two indicate field for intermediate compositions. For, this diagram cations were calculated on the basis of 25 oxygens (14 chlorite + 11 muscovite) following Do Campo and Neito (2005).

Figure 13. SiO_2 *vs.* Cr_2O_3 diagrams for muscovite (a) and chlorite (b). Note the compositional gap in muscovite varieties, whereas there is rather continuous variation in chromium content of chlorites.

relatively less Cr rich, and therefore may be called as low-chromium-containing chlorite instead of chromium-containing chlorites.

The photomicrograph and back scattered electron (BSE) image of a sample shows intersection of low-chromium containing chlorite by chromium-containing muscovite (figures 4d, 5a) indicating that chlorites have formed earlier to muscovite. Our observation indicates that chlorites occurring in stacks are richer in chromium ($\sim \text{Cr} > 0.6 \text{ afu}$), whereas those in the matrix show variation (0.1 to $> 0.7 \text{ afu}$). Therefore, no compositional gap is evident between chromium-containing and low-chromium-containing chlorites (figure 13a). Although, this negates the possibility of two chlorite varieties having formed separately, it necessitates a mechanism to account for variable loss of cations in the matrix chlorites. Among the possibilities, syn- or post-metamorphic hydrothermal or retrograde alteration of chlorite, as proposed for berthierine-chlorite stacks of Kidd Creek massive sulfide deposit, Ontario, Canada (Jiang *et al.* 1992), looks plausible in the present case. On the other hand, a remarkable compositional gap exists between muscovite and chromium-containing muscovite (figure 13b). We could not find any direct textural link such as epitaxial growth or topotectic association of one over the other of the two mica varieties. This indicates that these are two separate varieties. The paragenesis of chromium-bearing muscovite is attributed to the prograde metamorphic replacement of chlorite, whereas the origin of muscovite (chromium deficient) remains inconclusive.

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