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Characteristics of Cordierite (Iolite) of Bandarguha-Orabahala Area, Kalahandi District, Odisha, India

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Abstract

Optical microscopy, X-ray diffractometry, micro CT studies and mineral chemistry by SEM-EDS has been carried out on cordierite rich rock fragments from Bandarguha and Orabahala areas of Kalahandi district, Odisha. Macroscopically, cordierite grains exhibit distinct pleochroism in the shades of violet blue to light blue and colourless and are of gem quality (iolite). Biotite is the dominant associated mineral and Mg-Fe distribution coefficient (K_D) between coexisting cordierite and biotite varies from 1.71 to 2.76. The cordierite is low cordierite (distortion index, Δ=0.257). Mineral analyses indicate that cordierite is magnesian rich (X_{Mg}=0.82-0.88) with limited Fe^{2+} substitution for Mg^{2+} and dichroism is due to presence of part of iron in ferric form. Cordierite is formed during metamorphism by reactions: (a) orthopyroxene+sillimanite+quartz=cordierite+K-feldspar+water and (b) orthopyroxene+sillimanite=cordierite+corundum.

Keywords: Cordierite; Pleochroism; Pinitisation; Distortion index; Mg-Fe exchange; Odisha

Introduction

Cordierite mineral is predominantly a product of metamorphism. It was regarded high temperature-low pressure mineral typically developed in thermal aureoles (hornfels), as a major constituents of high grade regionally metamorphosed rocks of pelitic composition (shales and other argillaceous rocks), and as constituent of aluminium rich xenoliths in igneous rocks. Cordierite in small quantities occurs in magmatic rocks as well as in granite, pegmatites, gabbro, rhyolite and andesite. Cordierite is an index mineral for the anatectic origin of the rocks or contamination by Al-rich contact rocks (e.g., clay-rich sediments). In the regionally metamorphosed rocks, granulites and gneisses, cordierite coexists with other Mg-Fe mineral phases such as garnet, biotite, orthopyroxene, spinel, or staurolite as well as with other more aluminium bearing phases like sillimanite, sapphirine and corundum.

When transparent and of high clarity and pleochroic in shades of violet blue to blue, yellow and colourless, cordierite is used as a gemstone which is known as "iolite" in the gem and jewellery industry. India is an important market for iolite gem trading and iolite is extensively used in jewellery industry. Iolite occurrences have been reported from high grade metamorphic rocks of Eastern Ghat Mobile Belt of the states of Odisha and Andhra Pradesh and in metamorphic rocks of Karnataka and Tamil Nadu [1]. However, gem quality iolite deposits are found in few localities in Kalahandi district, Odisha which are: Orabahala (19°48'13"N/83°04'12"E), Dedar (19°47'30"N/83°02'30"E) and Bandarguha (19°48'26"N/83°02'30"E) (Figure 1a) [2-4]. The evolution of Eastern Ghat Mobile Belt occurring in eastern India (mainly in the states of Odisha and Andhra Pradesh) has been described by many authors [5-7]. The granulite facies Eastern Ghat Mobile Belt has been divided into four longitudinal zones which from east to west are: western charnockite zone, western khondalite zone, central migmatite-charnockite zone and eastern khondalite zone (Figure 1b). Samples from the present study fall in the leptynite and quartz-feldpathic lithounits of western khondalite zone, Kalahandi district, Odisha (Figure 1a).

During 2012, mining operation for iolite was being carried out from Bandarguha area. The mining area represents a flat terrain with gentle sloping topography. The cordierite schists and gneisses occur as discontinuous lensoid bodies within colluvial zone represented by highly weathered quartzo-feldspathic gneisses (leptynite). The major rock type is cordierite (iolite)-biotite schists (Figure 2), the total reserve of schist is about 8 million tonne and the plant capacity was 3.6 tonne cordierite (iolite) per year. Natural large gem quality cordierite crystals (iolite) are also found in the cordierite–phlogopite dominated Mg-Al rich rocks near Orabahala [2,3].

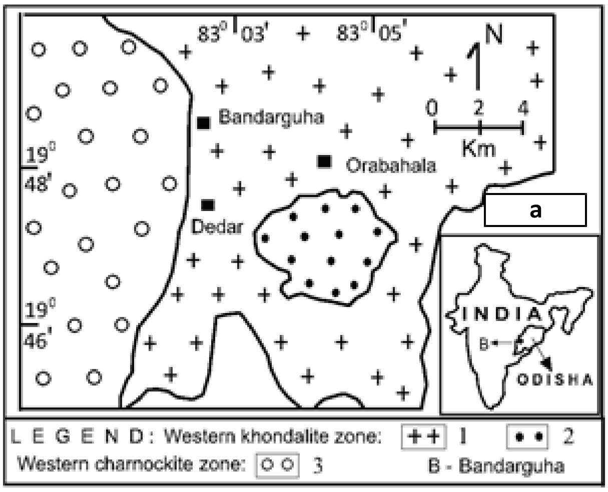

Figure 1a: Geological map around Bandarguha area [10]. 1: Quartz feldspathic gneisses and mafic granulites; 2: Mafic granulites and amphibolites with enclaves of cordierite-phlogopite rocks; 3: Mafic granulite, charnockite gneiss, garnet plagioclase dominated Fe-Al rich rocks and amphibole dominated Mg-Al rich rocks.

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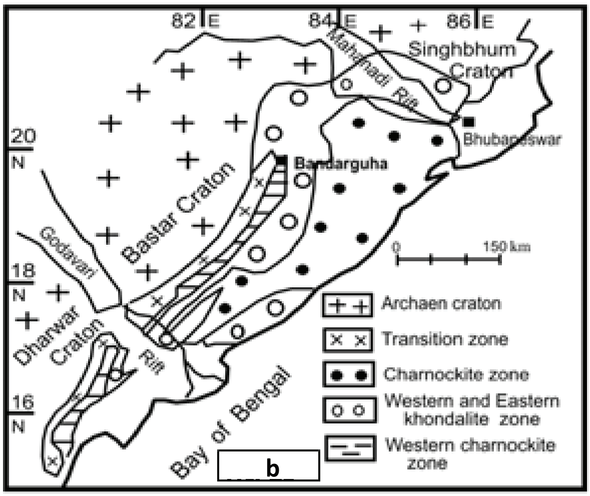

Figure 1b: Geological extension and different lithounits of Eastern Ghat Mobile Belt, India [10]. Bandarguha location is shown in this figure.

Figure 2: Cordierite-biotite rock boulder near the mine site, Bandarguha.

Materials and Methods

Semi-precious pure iolite samples and cordierite (iolite) rich rock fragments were collected by hand picking from the mining dumps of the cordierite mines at Bandarguha and from cordierite gneiss outcrops of Orabahala areas, Kalahandi district. The size of the samples ranges between 40 to 3 mm. In the laboratory the samples were cleaned with water in ultrasonic bath to remove loosely adhering soil particles. Thin and polished sections of the rocks and mineral fragments were prepared by adopting standard section preparation techniques. The thin sections were studied under petrographic microscope (model: DM2500P; M/s. Leica Microsystem Gmbh, Wetzler, Germany). The polished blocks were carbon coated and semi-quantitative analysis of the mineral phases was done by Energy Dispersive Spectrometer (M/s. Bruker AXS Microanalysis, Berlin, Germany) attached to scanning electron microscope (SEM; model: EVO-50; M/s. Zeiss, Germany). The pure cordierite fragments were powdered and heated to 900°C for one hour to determine the water content. Pure cordierite samples were handpicked and finely powdered in an agate mortar. The powdered sample was taken for X-ray diffraction analysis using an XRD unit (Philips PW 3710) with Cukα1 radiation operating at voltage of 40 kV, current of 20 mA and scan speed of 1/8 degree 2θ per minute. 3D characterization of small cordierite sample was performed with X-ray microcomputer tomography (microCT) (M/s. Bruker, Belgium; model: Sky Scan 2211) in combination with 3D analysis using Avizo 9.0 software.

Results and Discussions

Macroscopic description

The coarse cordierite bearing fragments are translucent to almost opaque and cordierite grains are clustered with each other (Figure 3a). The coarse cordierite bearing fragments/rocks mostly consist of cordierite and biotite and small amounts of quartz, feldspars and fine friable clay minerals along grain boundaries and fractures (Figures 3 b and 3c). Under naked eye, thin Iolite fragments exhibit strong to weak pleochroism that varies from colourless to violet blue to blue, greyish blue to light gray, and rarely with yellowish hue (Figures 3d-3f). It has duller somewhat greasy and vitreous lustre. Biotite flakes and sheets are dark brown in colour, translucent and vitreous and quartz grains are granular.

Figure 3a: Coarse fragment containing tightly packed cordierite grains.

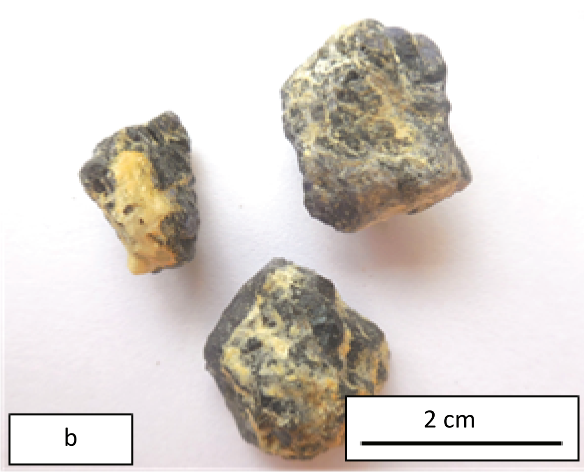

Figure 3b: Cordierite bearing fragments containing biotite, weathered feldspar, quartz and clays.`

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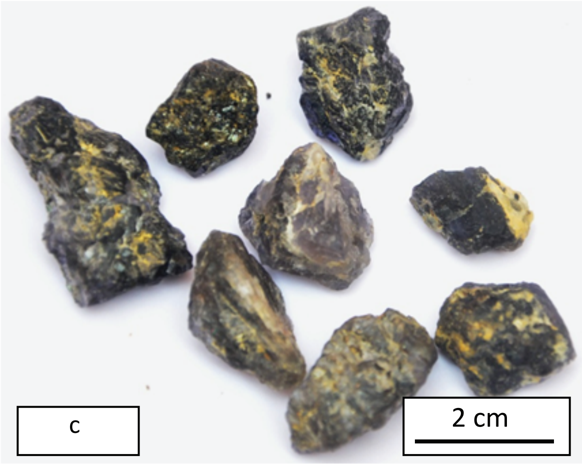

Figure 3c: Cordierite fragments contain biotite, quartz, feldspars.

Figure 3f: Translucent to opaque dark grey to dark blue cordierite fragments.

Figure 3d: Pure transparent grey white to pale bluish (dichroic) cordierite fragments.

Figure 3e: Pure transparent cordierite showing light and dark color bluish violet dichroism

Microscopic description

In thin section under plane polarised light, cordierite grains are colourless to very pale blue mostly with no pleochrosim, though grain mounts in R.I. liquid (1.53) are distinctly pleochroic. It occurs as idioblastic, subidioblastic to highly irregular porphyroblastic grains (Figures 4a, 4b and 4k). Under crossed nicols, cordierite grains are colourless to slightly blue. Twinning is common in the cordierite grains which are mostly lamellar and polysynthetic types; twin lamellae are mostly discontinuous and wedge out in the form of a tip of a knife or pen (Figures 4c and 4d). Some of the twins are abruptly stepped, irregularly distributed, at times coalesces with each other forming patchy twinning (Figure 4e). Some grains show two sets of twin lamellae which occur in 60° orientations (Figure 4f). Complex or multiple twinning features in cordierite are shown in Figures 4g and 4h. Cordierite showing simple and polysynthetic types of twinning are formed at a lower temperature growth condition [8]. Cordierite is at places altered to pinite, a fine-grained greenish or yellowish aggregate of chlorite, muscovite, serpentine, iron oxides and other silicates. Extensive alterations often lead to pinitized pseudomorph after cordierite (Figure 4i). The alteration is mostly prominent along cracks and grain margins (Figure 4j). The sericite bearing component is formed by the action of K-bearing solution on cordierite.

Biotite is abundant, occurs as weakly oriented tabular and flattened platy crystals along the grain boundaries of cordierite (Figures 4b and 4k) and as irregular massive bodies (Figures 4l and 4m). Biotite is brown, red-brown, brown-green and green in colour and strongly to weakly pleochroic in nature. The greenish biotite is secondary while the red brown biotite is primary in origin [3]. Corundum varies widely in shape and size from small euhedral to large subhedral grain (Figure 4n). Sillimanite occurs as bladed and acicular crystals up to 3 mm in length usually associated with masses of biotite and cordierite (Figure 4o). Sillimanite also occurs as fibrous masses (fibrolite) within cordierite grains (Figure 4p). Minute zircon, monazite, rutile, and pyrite grains are sometimes noted as inclusions within cordierite (Figure 4q). Perthite occurring as vein is also found in cordierite bearing fragments (Figure 4r). Cordierite grains often contain inclusions of fine quartz grains which occur as trails (Figure 4s). In cordierte fragments, orthopyroxene is rare and occurs as small stout grain.

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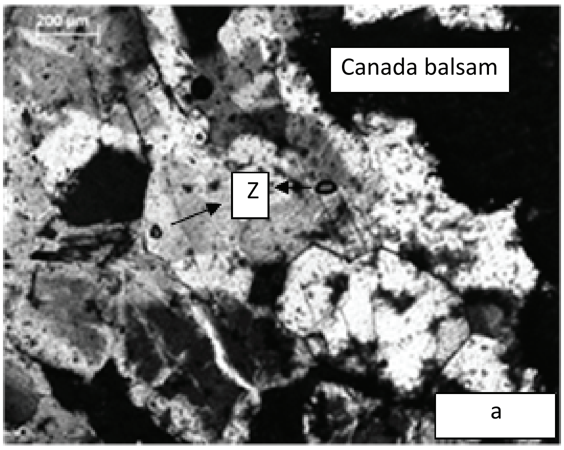

Figure 4a: Subhedral to anhedral cordierite grains showing undulose extinction, Z-Zircon.

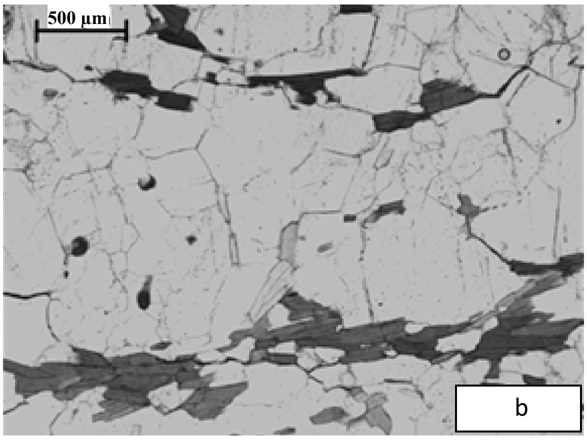

Figure 4b: Idioblastic cordierite grains with sealed grain boundary contact. Greenish biotite grains define distinct lamination.

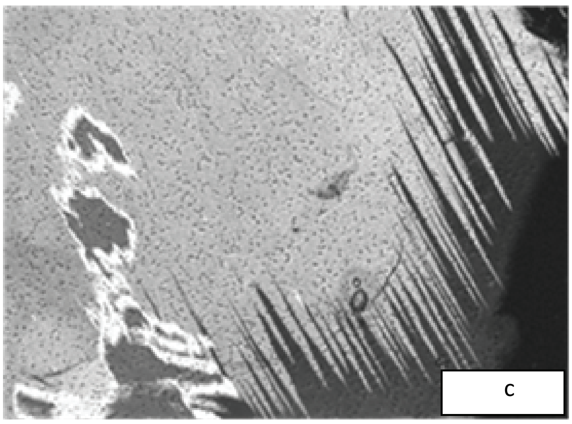

Figure 4c: Polysynthetic twin lamellae tapering within the grain and patchy extinction. Note zircon inclusion.

X-ray diffraction studies

The powder X-ray diffractogram of pure cordierite sample between 29 to 31 degree 2θ using CuKα1 radiations is given in Figure 5. The distortion index (Δ), calculated for this sample using the 2θ positions at (511), (421) and (131) planes, provided a value of 0.257 which is close to the distortion index of 0.25 reported by Majumder and Mathew [9]. This distortion index computes the deviation of the cell structure from a geometrically hexagonal unit and cordierite sample of the study area

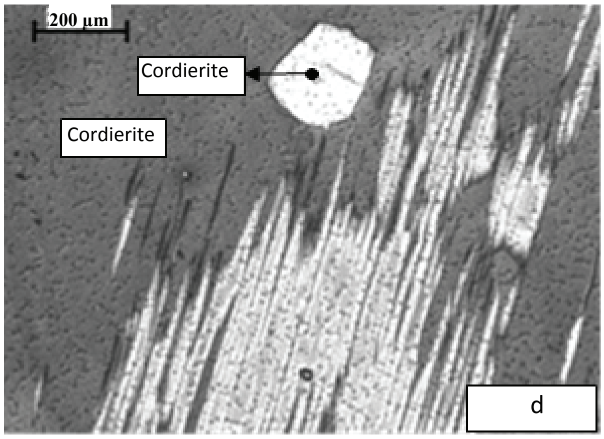

Figure 4d: Irregularly distributed tapering twin lamellae in cordierite grain. Euhedral cordierite inclusion within coarse cordierite grain.

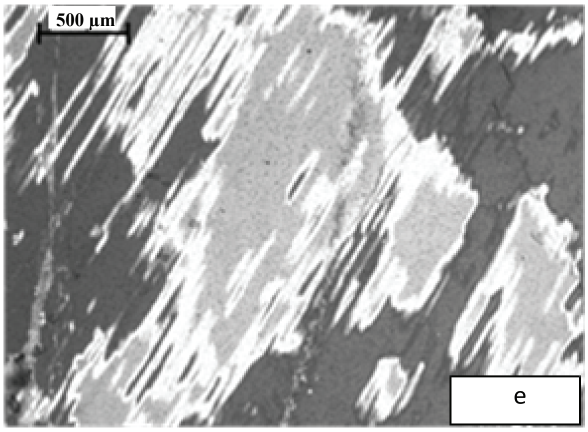

Figure 4e: Coalescence of twin lamellae within cordierite grain.

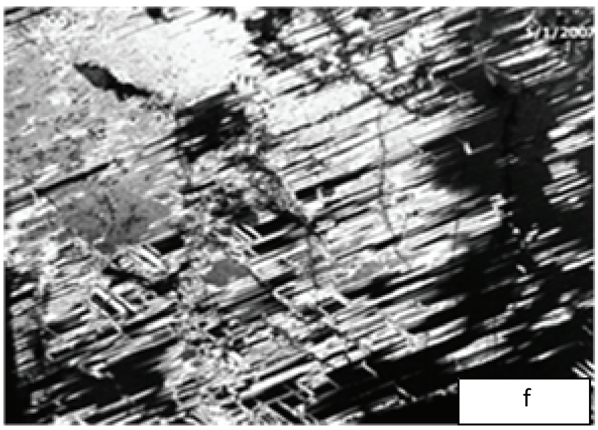

Figure 4f: Two sets of twin lamellae at 60° intersection within cordierite.

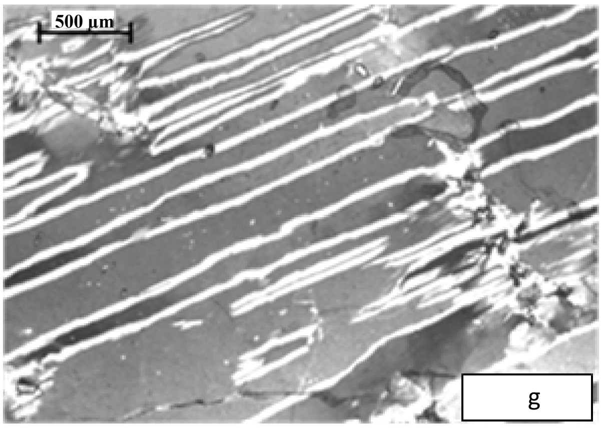

Figure 4g: Cordierite showing complex multiple twinning and twins are abruptly stepped.

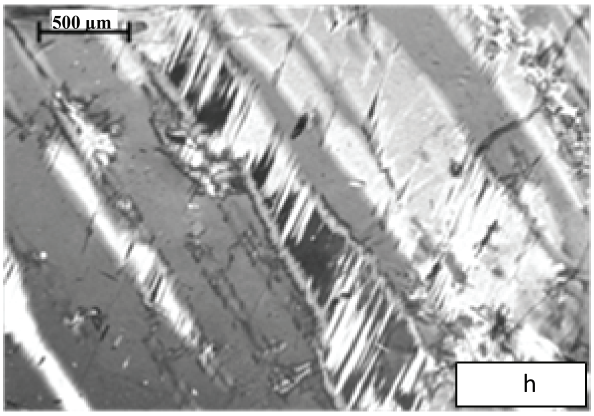

Figure 4h: Cordierite showing complex twinning.

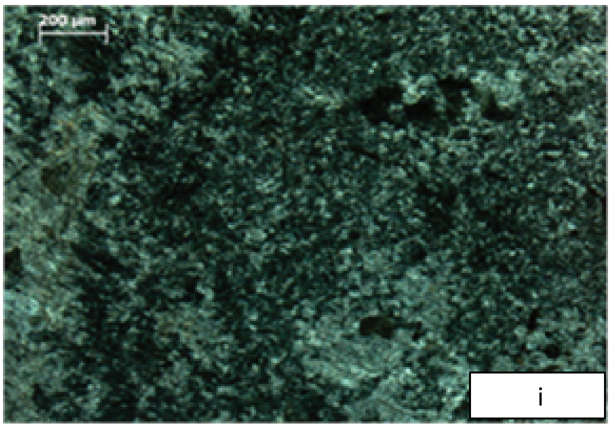

Figure 4i: Pinite pseudomorphed cordierite, pinite in fine grained aggregates.

is assigned as low cordierite with ordered structure. The interpretation assumes that cordierites with large distortion indices typically occur in regionally metamorphosed terrain characterized by slow heating and cooling [9].

X-ray microCT studies

X-ray microCT is a powerful non-destructive probing technique for 3D visualisation of the internal structure and composition of a wide range of objects. X-ray microCT images of cordierite sample in three

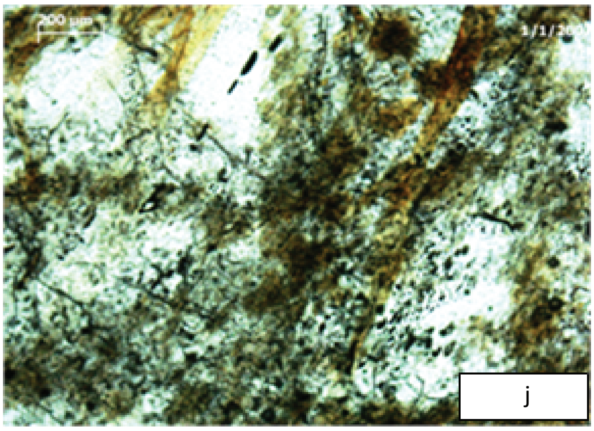

Figure 4j: Pinitisation of cordierite mostly along fractures and grain boundaries.

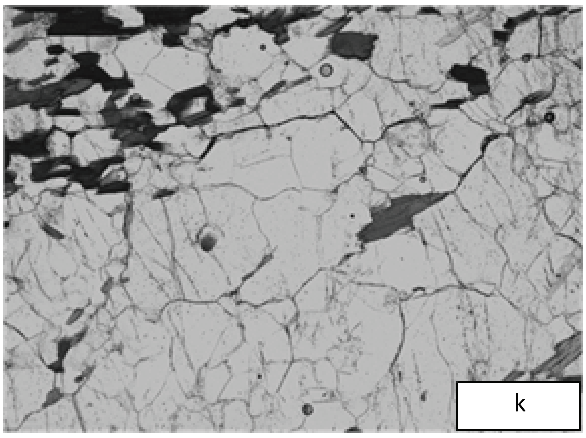

Figure 4k: Highly pleochroic green to dark green biotite along cordierite grain boundaries

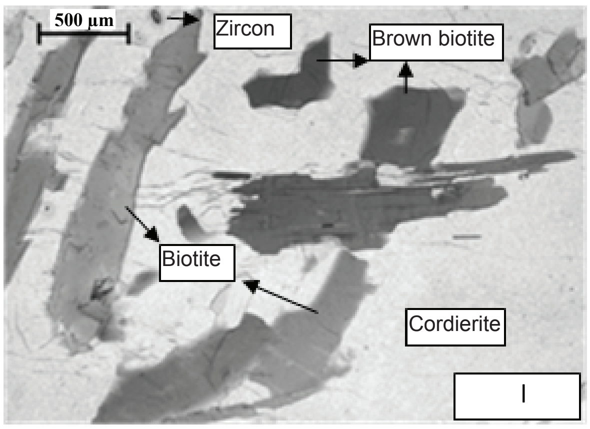

Figure 4l: Thick lamellar and massive brown biotite in association with cordierite.

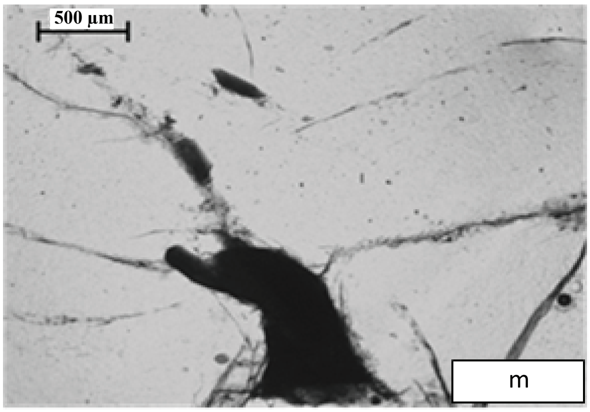

Figure 4m: Tabular and massive biotite (dark) in association with cordierite (white).

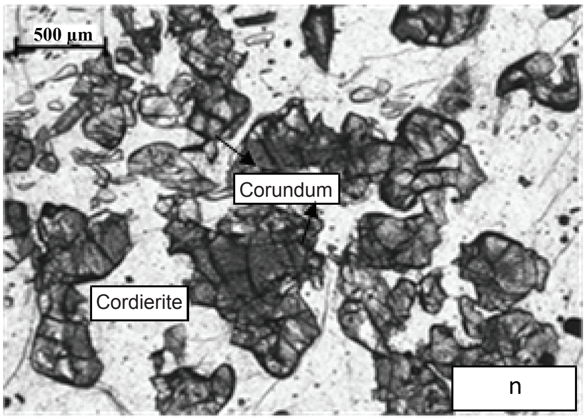

Figure 4n: Corundum grains as aggregates and isolated grains in association with cordierite (white).

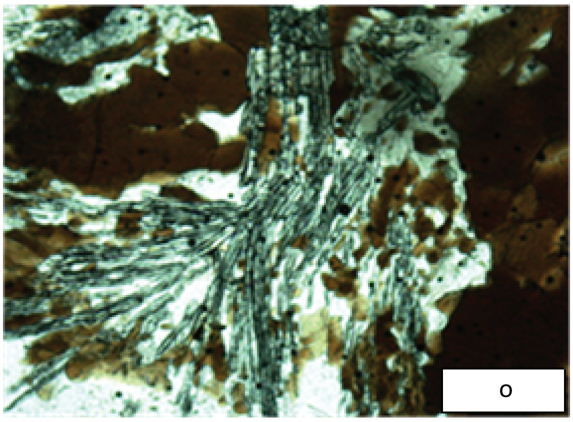

Figure 4o: Acicular radiating sillimanite grains in association with massive brown biotite and cordierite (white).

different slices in 2D sectional view are presented in Figures 6a-6c. Within the cordierite matrix, the included grains/mineral phases are unevenly distributed. Light grey mineral phase (Figures 6a and 6b) occurring as small platy and acicular grains are possibly biotite and altered minerals. The rounded and subrounded grains are possibly zircon, monazite, iron oxides and pinite. The cordierite grain is pore free.

Mineral Chemistry

The semi-quantitative analyses of the minerals (cordierite, biotite,

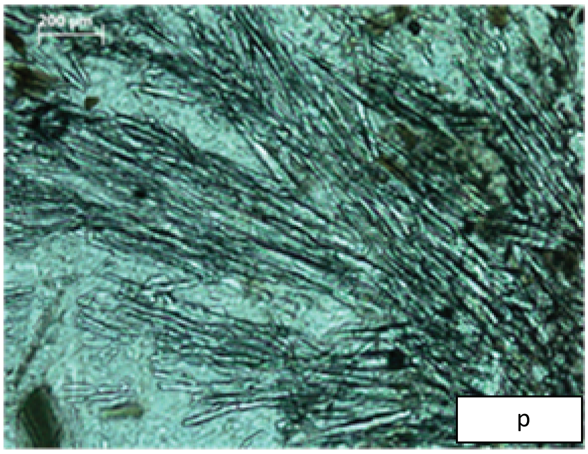

Figure 4p: Sillimanite flakes as partial inclusions within cordierite grains.

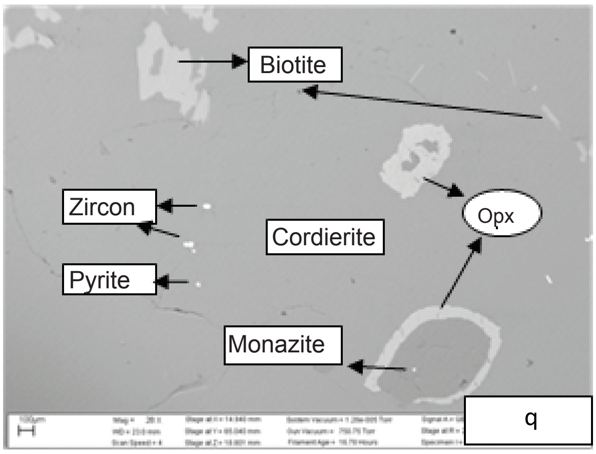

Figure 4q: Pyrite, zircon and monazite inclusion in cordierite. Note biotite and orthopyroxene (Opx). BSE- SEM image.

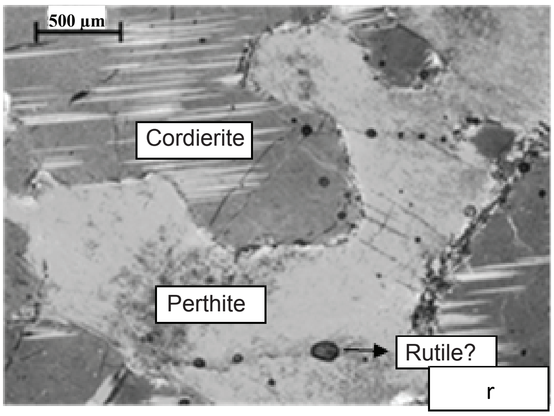

Figure 4r: Irregular coarse perthite grain.

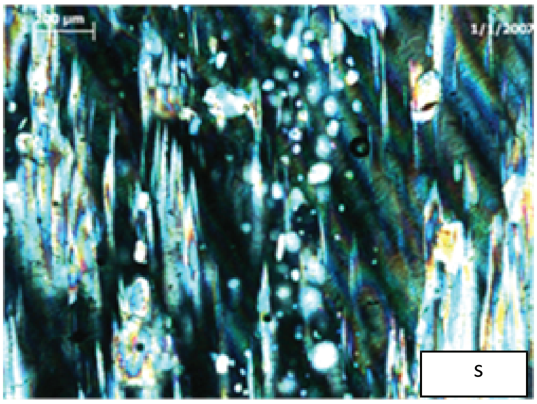

Figure 4s: Fine granular quartz within cordierite.

plagioclase feldspar, potash feldspar, corundum and orthopyroxene) are given in Table 1. The loss on ignition percent of pure cordierite sample was determined to be 1.85% which indicates presence of volatile matter (H_2O and CO_2) in the crystal structure. Cordierite shows restricted range of aluminium contents corresponding to 3.945 to 4.073 apfu (atoms per formula unit). The no. of silicon atoms (apfu) is close to five and a small part of silicon is possibly substituted by Al. The cordierite grains are magnesian rich and iron poor (Mg- 1.734–1.940; Fe- 0.273-0.380 apfu), Mg/Fe and Mg/(Mg+Fe) ratios varies between 4.63-7.11 and 0.82-0.88 respectively (Table 1). The data indicate that within cordierite structure replacement of Mg by Fe^{2+} is restricted which corroborates the views of earlier workers [3,10]. Biotite in the cordierite fragments/rocks has high TiO_2 (2.28-3.32%), high MgO (12.86-14.72%) and Al_2O_3 (16.65-18.88%) (Table 1). The Mg/Fe and Mg/Mg+Fe ratios in biotite varies from 1.85-2.72 and 0.65-0.73 respectively. The Mg/Fe distribution coefficient between coexisting cordierite and biotite (K_D) varies from 1.71 to 2.76 and is characteristic of low to high grade metamorphic

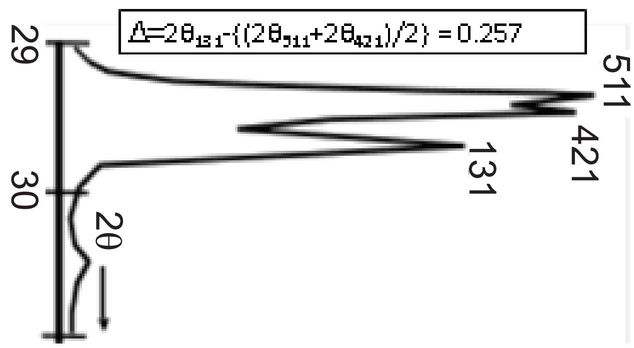

Figure 5: X-ray powder diffractogram of pure cordierite sample denoting distortion index (Δ).

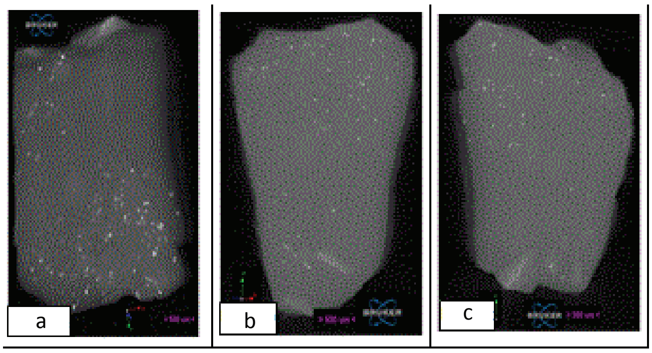

Figure 6: µ-CT image of internal surface of cordierite (2D section). (a), (b), (c): Irregular distribution of mineral phases in cordierite.

Minerals	Cordierite				Biotite		K-felds		Plag.	OPX	Crn
Wt.%	1	2	3	4	5	6	7	8	9	10	11
SiO_2	48.82	48.12	49.06	48.97	35.28	37.54	62.79	61.75	62.45	50.74	0.00
TiO_2	0.00	0.00	0.00	0.00	3.02	2.28	0.00	0.00	0.00	0.00	0.00
Al_2O_3	34.11	33.96	33.10	33.08	18.88	16.65	19.91	20.03	23.39	5.93	99.45
FeO	3.71	4.47	4.01	3.23	14.15	11.37	0.00	0.00	0.00	20.09	0.55
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	11.51	11.60	11.98	12.86	14.72	17.32	0.00	0.00	0.00	23.24	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.11	0.00	0.00
Na_2O	0.00	0.00	0.00	0.00	0.47	0.38	2.84	1.15	10.68	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	9.71	10.69	14.46	17.07	0.37	0.00	0.00
Number of ions on the basis of											
Basis	18(O)				22(O)		8(O)			6(O)	3(O)
Si	4.916	4.875	4.956	4.935	5.212	5.489	2.908	2.890	2.773	1.863	
Ti					0.336	0.251	0.00	0.00	0.00	0.00	
Al	4.064	4.073	3.958	3.945	3.287	2.869	0.00	1.105	1.224	0.257	1.995
Fe	0.339	0.380	0.340	0.273	1.748	1.390	1.087	0.00	0.00	0.617	0.008
Mn					0.00	0.00	0.00	0.00	0.00	0.00	
Mg	1.734	1.760	1.812	1.940	3.242	3.775	0.00	0.00	0.00	1.272	
Ca					0.00	0.00	0.00	0.00	0.148	0.00	
Na					0.135	0.108	0.255	0.104	0.919	0.00	
K					1.83	1.994	0.854	1.019	0.021	0.00	
Total	11.053	11.088	11.066	11.093	15.790	15.876	5.104	5.118	5.085	4.009	2.003
Mg/Fe	5.12	4.63	5.33	7.11	1.85	2.72				2.06	
Mg/Mg+Fe	0.84	0.82	0.84	0.88	1.85	2.72				1.89	

Table 1: Chemical analyses (wt.%) by SEM-EDS of different minerals. [Biotite (5 and 6) coexisting with cordierite (1 and 2) respectively; K-felds: K-feldspar in perthite, Plag-Plagioclase feldspar in perthite, OPX-Orthopyroxene, Crn-Corundum].

rocks [8]. The plagioclase feldspar is oligoclase in composition. The orthopyroxene has Mg/Mg+Fe ratio of 0.67 and the Al_2O_3 content 5.93 %.

Conclusions

(1) Cordierite grains are Mg rich with X_{Mg} values ranging between 0.82-0.88.

(2) Mineral chemistry of gem quality cordierite samples by SEM-EDS studies indicated the presence of a small amount of Fe in the crystal structure. A part of iron in the cordierite structure is possibly present in the form of Fe^{3+} that facilitate charge transfer process resulting in blue to violet pleochroism, hence, rendering these stones as gem quality cordierite (iolite) [10].

(3) Several reactions have been proposed for cordierite crystallisation in the metamorphic rocks [8]. Biotite, orthopyroxene, sillimanite, corundum, feldspars and quartz have been identified in the cordierite samples which corroborate the observations of [2,3,10]. One of the possible reactions for cordierite formation is: orthopyroxene+sil limanite+quartz=cordierite+K-feldspar+water. Further orthopyroxene can react with sillimanite to form cordierite and corundum as per reaction- orthopyroxene+sillimanite=cordierite+corundum.

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