

## Indialite from cordierite gneisses of Eastern Ghats Mobile Belt, India

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Indialite, a high temperature hexagonal modification of cordierite is reported for the first time associated with cordierite–sillimanite–monazite–spinel–quartz rock from the high grade metamorphic complexes of Eastern Ghats Mobile Belt, Vijayanagaram district, Andhra Pradesh. Based on  $\text{Fe}^{+2}/\text{Mg}$  ratio (33.02), the temperature of its crystallization is believed to reflect higher temperatures. The mineral is uniaxial negative,  $\epsilon = 1.538$ ,  $\omega = 1.542$ , dichroic ( $e$  = Pale blue and  $o$  = Violet blue), having chemical formula  $(\text{Mg}_{1.375}\text{Fe}^{+2}_{0.625}\text{Mn}_{0.053}\text{Ca}_{0.250})_{2.303}(\text{Al}_{3.908}\text{Fe}^{+3}_{0.206}\text{Ti}_{0.010})_{4.124}(\text{Si}_{4.193}\text{Al}_{0.807})_5\text{O}_{18}$ . These refined unit cell values obtained from powder diffraction data are  $a_0 = 9.790 \text{ \AA}$ ,  $c_0 = 9.353 \text{ \AA}$ ,  $V = 776.31 \text{ \AA}^3$ ,  $Z = 2$  and  $D_x = 2.522$ .

DURING an investigation of cordierite group of minerals from cordierite gneisses at Ayyanna Agraharam (Lat.  $18^\circ 10' 44''\text{N}$ ; Long.  $83^\circ 22' 43''\text{E}$ ), deep violet blue prismatic crystals (Figure 1a) associated with cordierite were noted from Eastern Ghats Mobile Belt (EGMB) of Vijayanagaram district, Andhra Pradesh. Cordierite gneisses occur as small lensoidal patches in khondalites with quartzites and pegmatitic veins exhibiting E–W and ENE–WSW trends. Optically pure, 1–1.5 cm long and 0.5–0.6 cm wide grains were separated from cordierite gneisses using the Frantz isodynamic separator and treating the fractions with heavy liquids and finally hand picked using a binocular microscope; the grains were assumed as 99.99% pure which were confirmed as indialite sensu stricto (JCPDS 13-293) through X-ray studies. The mineral indialite was found along with cordierite, sillimanite, monazite, magnetite–ilmenite, spinel, plagioclase and quartz.

The crystal habit of indialite was found to be prismatic parallel to (0110) with distinct basal cleavage. They occur as small symmetrical hexagonal grains and clusters of spiral-shaped grains. It has a marked deep violet blue colour in thin section and is optically negative. The mineral exhibits dichroism ( $e$  = pale blue and  $o$  = violet blue). The indices of refraction determined were  $\epsilon = 1.538$  and  $\omega = 1.542$ , with a birefringence of 0.004. It exhibits interpenetrating twin-like optical structure between crossed nicols (Figure 1b). This is the only mineral exhibiting strong to deep violet blue dichroism, in contrast to the cordierite. Hence, the mineral is distinct in its optical characteristics. The specific gravity was determined to be 2.53 g/cc and calculated as 2.522 from the X-ray data. X-ray powder patterns of

indialite and associated cordierite were taken on a Philips X-ray diffraction system PW 1730/PW 1390 with generator setting at 35 kV, 30 mA ( $\text{CuK}\alpha$  radiation having a wavelength of  $1.54184 \text{ \AA}$ ; scan speed fixed at  $0.04^\circ 2\theta/\text{s}$ ;  $2\theta$  range from  $5^\circ$  to  $90^\circ$ ) and the data is

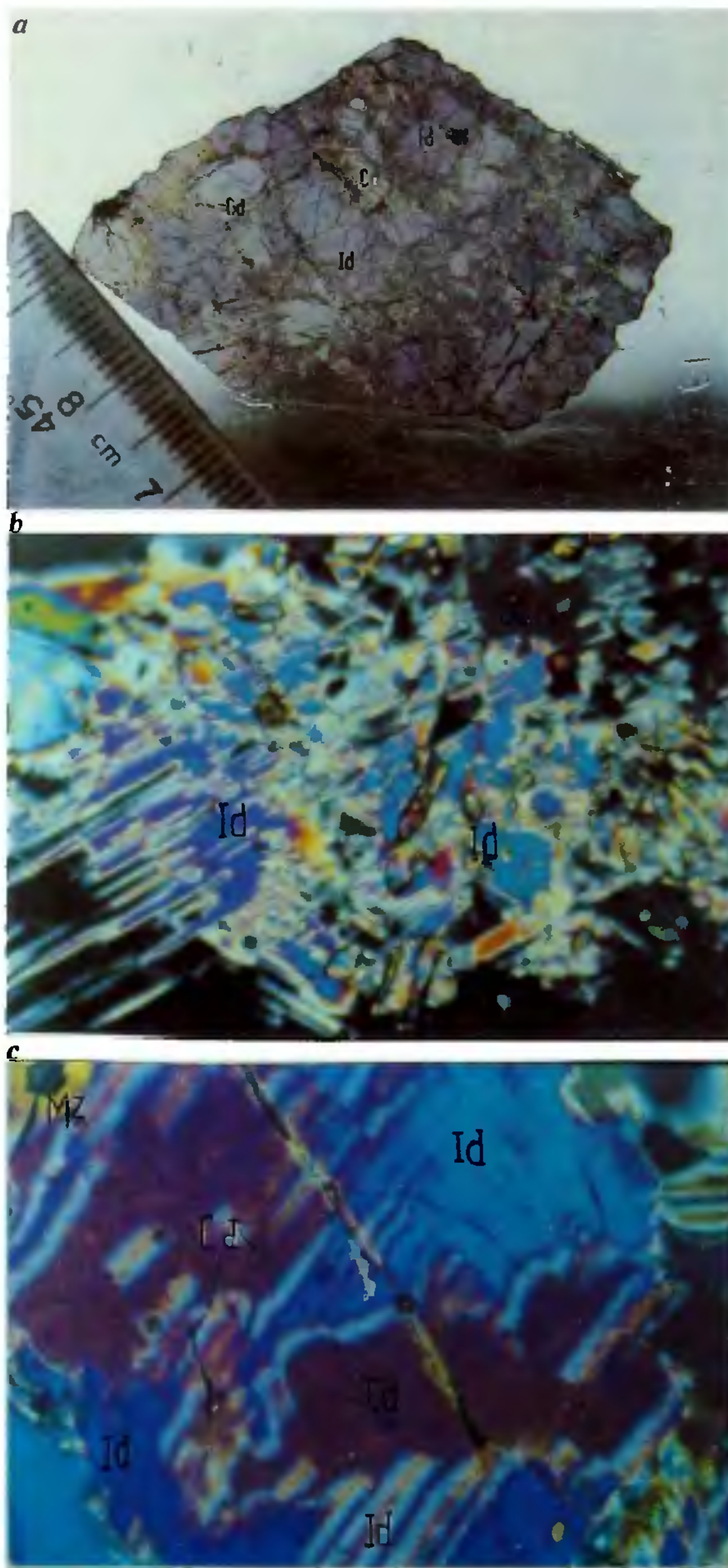


Figure 1. a, Thin section photograph showing crystalloblast indialite (Id) (measuring 1–1.5 cm) in violet blue colour with prismatic cleavage associated with cordierite (Cd) and minor magnetite, monazite, sillimanite; b, Photomicrograph showing indialite (Id) idioblast exhibiting interpenetration twin planes enclosed by cordierite (Cd) grains (under crossed nicols,  $20\times$ ); c, Photomicrograph showing embayed grains of cordierite (Cd) and monazite (Mz) with reaction rim enclosed within the indialite (Id) (under crossed nicols  $40\times$ ).



Table 1. X-ray diffraction data of indialite and associated cordierite

Indialite					Cordierite		
Present study			Miyashiro <i>et al.</i> <sup>3</sup>				
<i>hkl</i>	<i>d</i> Å	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i> Å	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i> Å	<i>I</i> / <i>I</i> <sub>0</sub>	<i>hkl</i>
100	8.4788	100	8.490	100	8.5412	75	020
110	4.9173	16	4.914	18	6.2701	2	111
102	4.0984	38	4.099	54	4.9125	30	130
—	—	—	3.476	18	4.8571	12	200
112	3.3882	37	3.387	43	4.6702	12	002
—	—	—	3.209	18	4.2669	10	040
202	3.1388	65	3.145	25	4.0910	60	112
211	3.0283	49	3.040	54	3.4012	73	132
—	—	—	2.651	21	3.3715	60	202
212	2.4617	24	—	—	3.1514	41	042
220	2.4404	6	—	—	3.1310	100	222
302	2.4110	2	—	—	3.0461	39	151
004	2.3382	8	2.340	14	3.0328	50	241
311	2.2760	2	—	—	3.0120	50	311
222	2.1610	—	—	—	2.6531	18	152
114	2.1081	5	—	—	2.4316	11	062
320	1.9378	3	—	—	2.3369	26	420
402	1.9260	2	—	—	2.2930	4	171
313	1.8747	8	—	—	2.2354	4	243
412	1.7190	2	—	—	2.1124	12	440
224	1.6549	14	1.6940	11	2.0491	21	224
420	1.5971	2	—	—	1.9951	3	280
413	1.580	3	—	—	1.9259	4	442
404	1.5694	2	—	—	1.8945	8	314
006	1.5581	3	—	—	1.8871	10	353
116	1.4861	4	—	—	1.8139	5	461
305	1.4629	5	—	—	1.6632	4	174
					1.5901	10	552

## Crystallographic constants

Crystal system	:	Hexagonal	Orthorhombic
Space group	:	P6/mcc	Cccm
<i>a</i> <sub>0</sub> (Å)	:	9.790	9.714
<i>b</i> <sub>0</sub> (Å)	:	—	17.082
<i>c</i> <sub>0</sub> (Å)	:	9.353	9.340
<i>V</i> (Å <sup>3</sup> )	:	776.31	1549.83
<i>Z</i>	:	2	4
Optically	:	Negative	Positive
<i>D</i> gm/cc (measured)	:	2.53	2.64
<i>D</i> <sub>x</sub> (X-ray)	:	2.522	2.651
		$\epsilon = 1.538$	$n\gamma = 1.553$
		$\omega = 1.542$	$2V_u = 77^\circ$

given in Table 1. The X-ray pattern shows the indialite to be hexagonal with possible space group P6/mcc. The refined cell parameters<sup>1</sup> were determined as  $a_0 = 9.790$  Å,  $c_0 = 9.353$  Å and  $V = 776.31$  Å<sup>3</sup> with  $Z = 2$ . The strongest lines are almost similar to those of indialite described by JCPDS and Miyashiro *et al.*<sup>3</sup>. Indialite is isostructural with beryl with a distortion index of zero. Optically pure, separated mineral grains of indialite and associated cordierite were chemically analysed using X-ray Fluorescence Spectrometer (XRF) [VXQ-150 A, Shimadzu (Japan model)] using LiF crystal, Rh target, acceleration voltage of 70 kV and 14 nA current. G<sub>2</sub> (USGS) was used as standard. Three pol-

ished rock specimens were also scanned at a number of points in the mineral grain (core to rim) to obtain analysis using multichannel simultaneous type scanner and associated software attached to XRF spectrometer. The carbon-coated samples were further checked with the aid of a wavelength dispersive spectrometer-X-ray counting system (WDS-XRCS) attached to a scanning electron microscope (SEM) (JEOL JSM-T 330 A) using accelerated voltage of 20 kV at the Department of Geology, Andhra University. The results of the complete chemical analysis are given in Table 2. The chemical formula of indialite calculated on the basis of 18 oxygen atoms is:

$(\text{Mg}_{1.375}\text{Fe}^{+2}_{0.625}\text{Mn}_{0.053}\text{Ca}_{0.250})_{2.303}(\text{Al}_{3.908}\text{Fe}^{+3}_{0.206}\text{Ti}_{0.010})_{4.124}(\text{Si}_{4.193}\text{Al}_{0.807})_5\text{O}_{18}$  with  $Z = 2$ . The amount brings the analytical total of sample to 99.33% and results show reasonable stoichiometry.

Miyashiro and Iiyama<sup>2</sup>, Miyashiro *et al.*<sup>3</sup> and Meagher and Gibbs<sup>4</sup> have reported and described the properties and existence of indialite from fused sediments of Bokaro coal fields of India. Chemistry indicates that there are a series of cation substitutions between Mg—(Fe—Mn—Ca) at octahedral site and Al—(Ti—Si) at tetrahedral site of the indialite. Substitution of a trivalent or bivalent cation for a similar charged cation does not require much compensating mechanism. Coupled substitutions are feasible because the charge compensations can occur in the VIII, VI and IV co-ordinations for elements like Mg, Fe, Mn and Al, which with higher ionic sizes can easily accommodate Ti in their respective vacant sites. Charge compensations in the tetrahedral Al site could have occurred via the exchange operation with Ti and  $\text{Fe}^{+3}$ . Schreyer and Scharier<sup>5</sup> have recorded high  $\text{Al}_2\text{O}_3/\text{SiO}_2$  ratios (more than 0.65) for stable high cordierite. The indialite from the study area has shown a ratio of 0.95, which is in concurrence with the ratio determined from the reported indialite analysis of Meagher

and Gibbs<sup>4</sup> [ $\text{SiO}_2 = 48.6$ ;  $\text{Al}_2\text{O}_3 = 34.7$ ; total iron as  $\text{FeO} = 7.8$ ;  $\text{MgO} = 9.3\%$ ]. Schreyer and Yoder<sup>6</sup> reported that the alumina enrichment in cordierites was due to the partial melting of sediments in deep-seated regional metamorphic environments where water pressure is no longer equal to the total pressure. Calcium present in the mineral structure was drawn from the associated pegmatite which might have partially melted as batch melting component along with cordierite. Ca ions are probably accommodated in the channels parallel to Z in the place of alkali and hydroxyl ions (which were originally present in the source cordierite channels parallel to Z) without much disturbance to the structure of indialite. Hence, coupled substitutions<sup>7</sup> might have occurred conveniently. Embayed cordierite grains with partial reaction rims were identified within the indialite crystals (Figure 1c). At places, altered cordierite occur around the indialite crystals. These textural evidences suggest that the indialite is a modified form of cordierite. Miyashiro<sup>8</sup> obtained the transformation relations from cordierite to the indialite. The temperature of structural changes and decomposition become lower with the increasing  $\text{Fe}^{+2}/\text{Mg}$  ratio. According to the experiments of Miyashiro<sup>8</sup>, at 1 atmospheric pressure, the Mg-rich indialite (11.1 ratio) formed at a temperature of  $1470^\circ\text{C}$  and iron rich varieties (70.3 ratio) formed between  $1200^\circ$  and  $1250^\circ\text{C}$ . The sample of the study area shows a ratio of 33.02, clearly suggesting that the mineral might have formed at high temperatures. Schreyer and Scharier<sup>5</sup> have given a range of temperatures for the formation of Mg-cordierites at  $1275^\circ\text{C}$  at 2 kb of  $P_{\text{H}_2\text{O}}$  and  $970^\circ\text{C}$  at 10 kb  $P_{\text{H}_2\text{O}}$  and has a liquidus above  $1300^\circ\text{C}$ . The high temperature stability relationship of cordierites was assessed by Waters<sup>9</sup>; Hensen and Green<sup>10</sup>. Ramesh Kumar<sup>11</sup> recorded the highest temperature of  $1250^\circ\text{C}$  at 10 kb assessed from the garnet-biotite thermometry in cordierite gneisses from the same location based on the models proposed by Perchuk and Lavrent'yeva<sup>12</sup> and Perchuk *et al.*<sup>13</sup> respectively for thermometry and barometry. Shaw and Arima<sup>14</sup> reported  $>1150^\circ\text{C}$  temperature at 13 kb pressure from adjacent parts of the study area location. Cordierite gneisses-associated pegmatites appear to be developed from the fractional crystallization of granites located 2 km away from the study area. This could be responsible for creation of higher temperature in the region. The indialite from the study area might have stabilized at temperatures in excess of  $1000^\circ\text{C}$  during the thermal metamorphism of cordierite gneisses belonging to the khondalite group of rocks.

Table 2. Chemical analysis and structural formulae of indialite and associated cordierite

	Indialite	Cordierite
	Wt%	Wt%
$\text{SiO}_2$	39.95	48.94
$\text{Al}_2\text{O}_3$	38.11	29.45
$\text{TiO}_2$	0.13	0.01
$\text{Fe}_2\text{O}_3$	—	0.50
$\text{FeO}$	9.47*	9.58
$\text{MgO}$	8.79	10.08
$\text{MnO}$	0.60	0.38
$\text{CaO}$	2.22	0.02
$\text{Na}_2\text{O}$	—	0.31
$\text{K}_2\text{O}$	—	0.01
$\text{P}_2\text{O}_5$	0.06	0.02
$\text{H}_2\text{O}^+$	—	0.42
$\text{H}_2\text{O}^-$	—	0.27
Total	99.33	99.99
Structural formulae on the basis of 18 (O)		
Si	4.193	4.969
$\text{Al}^{\text{VI}}$	0.807	1.031
$\text{Al}^{\text{IV}}$	3.908	2.494
Ti	0.010	0.0006
$\text{Fe}^{+3}$	0.206	0.038
$\text{Fe}^{+2}$	0.625	0.814
Mg	1.375	1.525
Mn	0.053	0.033
Ca	0.250	0.002
Na	—	0.060
K	—	0.001
P	0.005	0.002

\*Total iron as FeO.

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2. Miyashiro, A. and Iiyama, T., *Jpn. Acad. Proc.*, 1954, 30, 248–251.
3. Miyashiro, A., Iiyama, T., Yamasaki, M. and Miyashiro, T., *Am. J. Sci.*, 1955, 253, 195–208.



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