

## Manganese-bearing silicate minerals from metamorphosed manganese formations of India. I. Juddite

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**SUMMARY.** The manganese-bearing amphibole juddite has been reported by a number of workers from metamorphosed manganese formations of India. The mineral is developed at the contact of pegmatite and gondite, and associated characteristically with blanfordite (manganiferous aegirine-augite) and winchite (manganiferous richterite-tremolite). The range of the refractive indices of the mineral and the orientation of the optic axial plane normal to (010) suggest the mineral to be of magnesioriebeckite composition. The  $100 \text{ Mn}^{2+} : (\text{Mn}^{2+} + \text{Mg} + \text{Fe}^{2+})$  and  $100 \text{ Fe}^{3+} : (\text{Fe}^{3+} + \text{Al}^{\text{vi}} + \text{Ti})$  ratios plotted in the glaucophane-magnesioriebeckite diagram show that eight out of nine analyses (eight new) are grouped under magnesioriebeckite composition range. It may thus be concluded that the juddites generally refer to (manganiferous) magnesioriebeckite compositions. In some cases, however, the composition of juddite shows considerable departure from ideal magnesioriebeckite composition and the juddite and winchite (manganiferous tremolite-richterite) show evidences of compositional transition, indicating partial miscibility. The juddites have been formed by the interaction of pegmatitic fluid on manganese ore, gondite, and other country rocks such as mica schists and diopside-forsterite marble.

JUDDITE, a manganese-bearing amphibole, was first described by Fermor (1909) from metamorphosed manganese silicate rocks (gondite) of Kacharwahi, Nagpur District, Maharashtra, India. Named after Professor J. W. Judd, the mineral has since then been described from different areas of metamorphosed manganese formations of India, though its occurrence outside India is still to be reported.

Juddite has been reported mainly from regionally metamorphosed manganese silicate rocks (gondite) of the Sausar Group of Precambrian age, in the states of Madhya Pradesh and Maharashtra. Bilgrami (1955) and Zwaan and Van der Plas (1958) described it from Chikla, Bhandara District, and different parts of Nagpur District, respectively. The occurrence of juddite has been reported from Tirodi, Balaghat District (Roy, 1966; Roy and Mitra, 1964), and Gowari Wadhona, Chhindwara District, Madhya Pradesh (Roy and Purkait, 1968). Nayak (1961) described juddite from gonditic rocks of Kajlidongri, which form part of the Precambrian Aravalli Group.

Fermor (1909) considered all manganese silicate minerals including juddite to be part of the gondite, formed by metamorphism of manganese-bearing sediments. Bilgrami (1955) pointed out that the manganese-bearing amphiboles at Chikla were not formed as part of the gondites by metamorphism, but crystallized from a pegmatitic fluid during its interaction with surrounding manganese ores and mica schists. Roy (1966) and

Roy and Purkait (1968) also pointed out the role of pegmatites in the formation of manganese silicates at their contact with manganese ores and gondites.

Zwaan and Van der Plas (1958) and Nayak (1961) considered juddite to be related to alkali amphiboles, particularly riebeckite. Roy and Mitra (1964) and Roy (1966) corroborated this and expressed the composition of juddite in terms of glaucophane and magnesioriebeckite. Deer, Howie, and Zussman (1963) and Nayak and Neuvonen (1963) considered juddite to be equivalent to manganarfedsonite and (manganoan)-magnesioarfedsonite respectively.

The *optical properties* of juddite have been compiled in tables I and II. Excluding no. 16,  $\alpha$  ranges from 1.647 to 1.667 and  $\gamma$  from 1.658 to 1.692. The  $2V_{\alpha}$  varies from  $58^{\circ}$  to  $114^{\circ}$  and the extinction angle ( $\alpha$ : [001]) varies from  $12^{\circ}$  to  $35^{\circ}$ . The optic axial plane, in all except nos. 15, 16, and 17, is normal to (010).

The refractive indices of the juddites are too high for eckermannite and glaucophane and too low for arfedsonite. The data, more or less, indicate a magnesioriebeckite composition (lower values of riebeckite range; Deer, Howie, and Zussman, 1963) and also fit in the range for richterites. That the juddites may not refer to richterite is indicated by the orientation of their optic axial plane normal to (010) (comparable to arfedsonite). The refractive indices of synthetic magnesioriebeckite ( $\alpha$  1.633 to 1.656;  $\gamma$  1.651 to 1.674;  $\gamma-\alpha$  0.013 to 0.022) as given by Ernst (1960, table 13) agree fairly well with those of the juddites compiled in tables I and II. The refractive indices of natural magnesioriebeckite described by Miyashiro and Iwasaki (1957;  $\alpha$  1.659,  $\gamma$  1.668, and  $\alpha$  1.660,  $\gamma$  1.670) and De Villiers (1949;  $\alpha$  1.659,  $\gamma$  1.668) also agree with those of the juddites described here. Among the juddites studied, the one from Gowari Wadhona (no. 16) shows rather low refractive indices compared to the general range of the juddites. The remarkable variation in the extinction angle of juddites ( $\alpha$ : [001] =  $12-35^{\circ}$ ) is characteristic as in the case of magnesioriebeckites (Ernst, 1960, p. 34).

*X-ray powder data* for juddite were obtained with Cu- $K_{\alpha}$  radiation (table III), and differ appreciably from those obtained by Zwaan and Van der Plas (1958) for juddite from Nagpur district.

*Chemical analyses* of nine cleaned samples of juddite from different parts of the metamorphosed manganese formations of India are presented in table I. Besides these, four other chemical analyses for juddite from Indian localities have so far been published (from N. Tirodi, Roy and Mitra, 1964; from Gowari Wadhona, Roy and Purkait, 1968; from Chikla, Bilgrami, 1955; from N. Tirodi,<sup>1</sup> Nayak and Neuvonen, 1963).

As the juddites optically resemble magnesioriebeckite, the analyses were plotted in the glaucophane-magnesioriebeckite field of Miyashiro (1957) as modified by Deer, Howie, and Zussman (1963). In view of the fact that  $Fe^{2+}$  is either absent or negligible in juddite, the analyses were expressed as 100  $Mn^{2+}$ :( $Mn^{2+} + Mg + Fe^{2+}$ ), instead of 100  $Fe^{2+}$ :( $Fe^{2+} + Mg + Mn$ ), and 100  $Fe^{3+}$ :( $Fe^{3+} + Al^{VI} + Ti$ ) (fig. 1). Mn in juddite being low, there is no question of modification of the riebeckite or ferroglaucophane

<sup>1</sup> The locality has erroneously been mentioned as Goldongri, India (Nayak, pers. comm.).

TABLE I. *Chemical composition and optical properties*

	1	2	3	4	5
SiO <sub>2</sub>	54.28	55.06	54.40	53.95	54.25
Al <sub>2</sub> O <sub>3</sub>	2.46	1.72	1.16	0.57	2.04
TiO <sub>2</sub>	1.38	1.44	0.98	0.88	1.27
Fe <sub>2</sub> O <sub>3</sub>	12.16	12.04	12.46	9.00	12.64
FeO	tr.	tr.	tr.	2.70	tr.
MgO	12.38	13.51	15.83	15.66	14.57
MnO	2.62	3.79	4.53	4.28	2.14
CaO	4.60	3.60	2.37	3.96	2.75
Na <sub>2</sub> O	8.00	5.74	5.37	5.73	7.15
K <sub>2</sub> O	1.76	1.55	1.47	1.60	1.60
H <sub>2</sub> O <sup>+</sup>	0.32	0.58	0.55	0.90	0.71
H <sub>2</sub> O <sup>-</sup>	0.16	0.25	0.28	0.20	0.26
F	0.16	0.36	0.34	0.12	0.26
	100.28	99.64	99.74	99.55	99.64
O ≡ F	0.07	0.15	0.15	0.05	0.12
Total	100.21	99.49	99.59	99.50	99.52
100 Mg (Mg + Fe <sup>2+</sup> + Fe <sup>3+</sup> + Mn)	62.07	62.14	64.13	64.53	65.69
<i>Atomic ratios to Σ (O, OH, F) = 24:</i>					
Si	7.94	8.01	7.96	7.94	7.85
Al	{ 0.06 0.36	0.30	{ 0.04 0.16	{ 0.06 0.03	{ 0.15 0.20
Ti	0.15	0.16	0.11	0.10	0.14
Fe <sup>3+</sup>	1.33	1.33	1.37	0.99	1.38
Fe <sup>2+</sup>	—	—	—	0.33	—
Mg	2.70	2.95	3.45	3.42	3.14
Mn	0.32	{ 0.26 0.21	0.56	{ 0.13 0.43	{ 0.14 0.12
Ca	0.72	0.56	0.37	0.63	0.43
Na	{ 1.28 0.98	{ 1.23 0.40	{ 1.07 0.45	{ 0.94 0.68	{ 1.45 0.56
K	0.32	0.29	0.27	0.30	0.29
OH	0.32	0.57	0.54	0.88	0.69
F	0.07	0.17	0.16	0.05	0.12
Σ Z	8.00	8.01	8.00	8.00	8.00
Σ Y	4.86	5.00	5.09	5.00	5.00
Σ X	2.00	2.00	2.00	2.00	2.00
Σ A	1.30	0.69	0.72	0.98	0.85
α	1.659	1.657	1.652	1.650	1.650
β	—	—	—	—	—
γ	1.770	1.668	1.664	1.661	1.660
α	Rose pink	Light carmine	Light carmine	Deep pink	Deep carmine
β	Pale violet	Bluish green	Pale greenish yellow	Pale greenish yellow	Lilac
γ	Light pinkish orange	Light pink	Pinkish orange	Light orange	Brownish orange
α: [001]	26°	20°	30°	28°	12°
2V <sub>α</sub>	75°	72°	60°	—	58°
Ax. pl.	⊥ (010)	⊥ (010)	⊥ (010)	⊥ (010)	⊥ (010)

of juddite (anal. B. P. Gupta). For localities see table II

	6	7	8	9
SiO <sub>2</sub>	54.60	54.58	53.78	54.82
Al <sub>2</sub> O <sub>3</sub>	1.52	1.41	4.62	2.59
TiO <sub>2</sub>	1.90	1.38	1.48	1.11
Fe <sub>2</sub> O <sub>3</sub>	12.28	9.59	10.53	10.18
FeO	tr.	tr.	tr.	nil
MgO	14.63	15.67	14.64	16.14
MnO	0.93	2.68	1.55	2.98
CaO	2.05	3.65	2.95	2.66
Na <sub>2</sub> O	8.79	8.88	6.24	7.04
K <sub>2</sub> O	2.43	1.78	1.56	1.82
H <sub>2</sub> O <sup>+</sup>	0.45	0.40	0.10	0.48
H <sub>2</sub> O <sup>-</sup>	0.10	0.08	2.30	0.16
F	0.15	0.13	0.06	0.41
	99.83	100.23	99.81	100.39
O ≡ F	0.06	0.05	0.03	0.17
Total	99.77	100.18	99.78	100.22
100 Mg (Mg + Fe <sup>2+</sup> + Fe <sup>3+</sup> + Mn)	68.53	71.11	70.19	70.26
<i>Atomic ratios to Σ (O, OH, F) = 24:</i>				
Si	7.94	7.93	7.89	7.90
Al	{ 0.06 0.20	{ 0.07 0.17	{ 0.11 0.69	{ 0.10 0.34
Ti	0.21	0.15	0.16	0.12
Fe <sup>3+</sup>	1.34	1.05	1.16	1.10
Fe <sup>2+</sup>	—	—	—	—
Mg	3.17	3.39	3.18	3.47
Mn	{ 0.08 0.04	{ 0.24 0.09	0.19	0.36
Ca	0.32	0.57	0.43	0.41
Na	{ 1.64 0.84	{ 1.34 1.16	{ 1.38 0.39	{ 1.23 0.74
K	0.45	0.33	0.29	0.33
OH	0.44	0.39	0.10	0.46
F	0.07	0.06	0.05	0.19
Σ Z	8.00	8.00	8.00	8.00
Σ Y	5.00	5.00	5.19	5.03
Σ X	2.00	2.00	2.00	2.00
Σ A	1.29	1.49	0.68	1.07
α	1.651	1.648	1.652	1.649
β	—	—	—	—
γ	1.663	1.658	1.662	1.660
α	Carmine	Carmine	Light carmine	Carmine
β	Pale blue-green	Bluish green	Almost colourless with pale purple tint	Bluish green
γ	Pinkish orange	Light pink	Light pink with orange tint	Light pinkish orange
α: [001]	21°	15°	34°	24°
2V <sub>α</sub>	66°	70°	66°	68°
Ax. pl.	⊥ (010)	⊥ (010)	⊥ (010)	⊥ (010)

TABLE II. *Optical properties of juddite*

	10	11	12	13	14	15	16	17
$\alpha$	—	1.659	1.667	1.658	1.650 ± 0.002	1.647 ± 0.006	1.638 ± 0.002	1.658
$\beta$	—	—	1.683	—	—	—	—	—
$\gamma$	—	1.681	1.692	1.668	1.660 ± 0.002	1.658 ± 0.004	1.650 ± 0.002	1.668
$\alpha$	Carmine	Light carmine to deep carmine	Light carmine	Light yellow	Rose pink	Carmine	Carmine	Carmine to violet
$\beta$	Blue with lilac tinge to pale green with lilac tinge	Colourless to pale violet	Carmine with a tinge of violet	Carmine with a tinge of violet	Pale greenish yellow	Bluish green	Pale pink with bluish tinge	—
$\gamma$	Orange or pinkish orange	Light pinkish orange to orange, sometimes with tinge of brown	Pleochroic from carmine to red	Light pinkish orange to orange	Orange with pinkish tint	Light pink	Pale brown	Pinkish orange
$\alpha: [001]$	30°	21-33°	—	20-35°	32°	30°	25°	20-35°
$2V_{\alpha}$	—	108-14°	78°	108-10°	62°	75°	64°	108-10°
Ax. pl.	—	—	—	—	⊥ (010)	∥ (010)	∥ (010)	∥ (010)

Localities of samples in tables I and II; all localities except nos. 10, 12, and 13 are in Madhya Pradesh, India, and nos. 1-9 are all in Balaghat District

1. Garra
2. Miragpur
3. Sitapatore
4. Tirodi South Hill
5. Sitapatore
6. Tirodi West Hill
7. North Tirodi
8. Tirodi West Hill
9. Ponia
10. Kacharwahi, Nagpur District, Maharashtra, India (Fermor, 1909)
11. Kallidongri, Jabua District
12. Chikla, Bhandara District, Maharashtra, India (Bilgrami, 1955)
13. Nagpur District, Maharashtra, India (Zwaan and Van der Plas, 1958)
14. Tirodi, Balaghat District (Roy, 1966)
15. North Tirodi, Balaghat District (Roy, 1966)
16. Gowari Wadhona, Chhindwara District (Roy and Purkait, 1958)
17. North Tirodi, Balaghat District (Nayak and Neuvonen, 1963)

TABLE III. X-ray powder data for juddite

<i>d</i>	<i>I</i>								
8.305 Å	52	3.383 Å	15	2.707 Å	40	1.888 Å	11	1.582 Å	11
4.457	15	3.350	11	2.578	8	1.659	17	1.579	11
4.447	11	3.246	23	2.352	77	1.629	8	1.496	11
4.179	11	3.103	100	2.259	8	1.610	8	1.492	8
3.390	15	2.796	52	2.166	20	1.606	11	1.447	5

compositional fields due to this substitution. All the analyses of juddite in table I, except no. 8, show compositions in magnesioriebeckite field. It is thus evident that the juddites correspond generally to the composition of manganoan magnesioriebeckite. The  $\text{Fe}^{3+}:\text{Al}^{\text{vi}}$  ratio in all analyses in table I is greater than unity. The optic axial plane is normal to (010) and the  $2V$  is fairly large in each case (cf. Deer, Howie, and Zussman, 1963).

Deer, Howie, and Zussman (1963, p. 369) grouped juddite with magnesioarfvedsonite, depending upon the chemical analyses of Bilgrami (1955) where Na (2.55 atoms per formula unit) and Mn (0.956 atoms per formula unit) are considered high enough to be included in the eckermannite–arfvedsonite series. In the juddites under study here,

however, Na attains values above 2.00 only in analyses 1, 6, and 7 and the Mn is low. Moreover, arfvedsonites are generally high in  $\text{Fe}^{2+}$  (Miyashiro, 1957; Deer, Howie, and Zussman, 1963, table 57, anal. nos. 4–12) whereas  $\text{Fe}^{2+}$  is absent or negligible in juddite.

The composition of the Chikla juddite (Bilgrami, 1955), despite its high MnO content (7.7%), falls in the magnesioriebeckite compositional field. The chemical analyses of juddite from North Tirodi (Roy and Mitra, 1964) and Gowari Wadhona (Roy and Purkait, 1968) are at variance with those shown in table I. The North Tirodi juddite shows a composition at the boundary of the glaucophane–crossite composition field and its optic axial plane is parallel to (010). The Gowari Wadhona juddite is abnormally high in CaO (14.56%), high in MgO (19.87%), and low in  $\text{Na}_2\text{O}$  (3.20%). The 100 Mg:(Mg+ $\text{Fe}^{2+}$ + $\text{Fe}^{3+}$ +Mn) ratio is 89.18, which is outside the range of 62.07 to 70.26 in anals. 1–9, table I. Thus the Gowari Wadhona juddite shows a compositional affinity to richterite–tremolite and approaches winchite in composition. The refractive indices of this juddite are low ( $\alpha = 1.638$ ,  $\gamma = 1.650$ ) and approach the normal range for winchites. In pleochroic scheme and  $2V$  value, however, it resembles normal juddite. It is possible that the Gowari Wadhona juddite represents an intermediate member between juddite and winchite. It is interesting to note in this connection that riebeckite–tremolite has been described by Klein (1966) from metamorphosed iron formations of south-western Labrador and Coleman and Papike

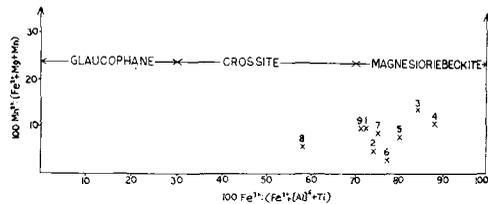


FIG. 1. Composition of juddites expressed as 100  $\text{Mn}/(\text{Mn}+\text{Mg}+\text{Fe}^{2+})$  and 100  $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al}^{\text{vi}}+\text{Ti})$ . Numbers as in key to table II.

(1968) indicated partial miscibility between glaucophane and actinolite. The analysed Gowari Wadhona 'juddite' was separated from the assemblage blanfordite-juddite-manganoan-diopside-hollandite-calcite-piemontite-microcline-cryptomelane. The presence of manganoan diopside and Ca-Mg-rich blanfordite (44.11 % aegirine, 33.17 % diopside; Roy and Purkait, 1968) also indicates a considerable amount of Ca and Mg in the bulk composition. The formation of the Ca-Mg-rich juddite, blanfordite, and manganoan diopside at Gowari Wadhona was facilitated by the juxtaposition of the gondite with the overlying diopside-forsterite marble, with the pegmatite dike cutting across them. The CaO and MgO were derived in abundance from the calc-magnesium metasediments during regional metamorphism in almandine-amphibolite facies (Roy and Purkait, 1968).

*Geologic implications.* Though juddites are reported mainly from those parts of the metamorphosed manganese formations where the regional metamorphism attained almandine-amphibolite facies, it has also been recorded from rocks of greenschist facies at Kajlidongri (Nayak, 1961).

The juddites are invariably associated with blanfordite (Fermor, 1909; Bilgrami, 1955; Nayak, 1961; Nayak and Neuvonen, 1963; Roy, 1966; Roy and Purkait, 1968) so much so that Fermor considered the association of blanfordite as a criteria for recognition of juddite. Blanfordite has been proved to be manganoan aegirine-augite with a large quantum of aegirine molecule (Roy, 1969*a*).

The juddites are always developed in the vicinity of pegmatite veins or dikes cutting across the manganese formation. They either form well within the pegmatite body or at the contact region with gondite.

The range of optical properties and chemical composition of juddite is fairly limited in the case of the occurrences within the pegmatite or at the pegmatite-gondite contact (table I). The composition of juddite occurring in contact with other rocks (e.g. diopside-forsterite marble), however, varies considerably from this range (cf. Gowari Wadhona).

Ernst (1960) has shown experimentally that magnesioriebeckite is stable over a wide range of temperature and pressure in rocks of appropriate bulk composition. The same observation has been made by Chatterjee (1969) who described magnesioriebeckite from both greenschist and almandine-amphibolite facies of the metamorphosed iron formations of Bailadila area, Madhya Pradesh, India. This is in contrast with the limited stability range of glaucophanes, which become unstable at low pressure or high temperature. The development of juddite in both greenschist and almandine-amphibolite facies of rocks is in conformity with the above observations of Ernst (1960) and Chatterjee (1969).

The constant association of blanfordite with juddite is interesting, as such associations of aegirine-augite with riebeckite or crossite-magnesioriebeckite have been reported from Hokkaido, Japan (Suzuki and Suzuki, 1959), Bailadila, Madhya Pradesh, India (metamorphosed iron formation; Chatterjee, 1969), and other places. Ernst (1960) showed that at a low vapour pressure under oxidizing conditions, magnesioriebeckite breaks down to acmite at temperatures above 750 °C. Chatterjee

(1969) suggested that coexistence of these two phases indicates disequilibrium or non-completion of the breakdown reaction and signifies that a temperature close to the breakdown point of magnesioriebeckite at the existing partial pressure had been attained.

Winchite (richterite-tremolite; Roy, 1969*b*) has been described from manganese silicate rocks either in exclusion of juddite or associated with it. Ernst (1960) discussed the physico-chemical conditions directing the formation of magnesioriebeckite or richterite in a rock containing abundant Ca-Mg carbonates reacted upon by a soda-rich fluid. He suggested that magnesioriebeckite should crystallize under conditions of soda metasomatism involving relatively high  $P_{\text{CO}_2}$  or low temperature. The formation of richterite should, on the other hand, be favoured by lower  $P_{\text{CO}_2}$  or higher temperature.

The author concludes that the role played by pegmatites in the formation of juddite is most important. The juddites have formed either within the pegmatite when the latter cut across the manganese formation and assimilated part of it, or in the gondites in which soda metasomatism took place due to the emplacement of the pegmatites. The formation and the chemical composition of juddites are dependent on the nature and field relationships of the pegmatites, the manganese formation, and any other country rock in physical contact. Where the pegmatites cut across manganese formation and mica schist, juddites with high  $\text{Na}_2\text{O}$  and low  $\text{CaO}$  and  $\text{MgO}$  (magnesioriebeckite composition) were formed (e.g. Tirodi), but at the junction of pegmatite, gondite, and diopside-forsterite marble (at Gowari Wadhona), a member intermediate in composition between magnesioriebeckite and richterite-tremolite was formed.

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