THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 51 JULY, 1966 No. 7

ROEDDERITE, A NEW MINERAL FROM THE INDARCH METEORITE[1]

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ABSTRACT

The new mineral roedderite, $(Na_{1.30}K_{0.69})_{1.99}$ $(Mg_{4.86}Fe_{0.27})_{5.13}$ $(Si_{11.88}\ Al_{0.07})_{11.95}$ O_{30} has been found as an accessory in the enstatite chondrite, Indarch. The assemblage in which it occurs consists of enstatite, clinoenstatite, troilite, nickel-iron and small amounts of schreibersite, plagioclase $(Ab_{90}An_{10})$, tridymite, oldhamite, glass, and carbon. *X*-ray studies of the roedderite established it to be isostructural with osumilite and merrihueite as well as synthetic $K_2O \cdot 5MgO \cdot 12SiO_2$ and $Na_2O \cdot 5MgO \cdot 12SiO_2$. Electron probe analyses, an indexed *x*-ray diffraction pattern, unit cell dimensions ($a = 10.139 \pm 0.01$; $c = 14.275 \pm 0.01$ Å) and optical data ($\omega = 1.537$; $\epsilon = 1.542$) for roedderite are presented.

Indarch is a black enstatite chondrite weighing about 27 kg that fell on April 7, 1891, in Transcaucasia (Meunier, 1897). The stone is remarkably firm for a chondrite and is comparable to a terrestrial basalt in this regard. The mineralogical description by Merrill (1915, 1916) and a chemical analysis by Whitfield, cited by Merrill, indicated it to consist of clinoenstatite (and enstatite) 74.42 per cent, nickel-iron 11.50 per cent, troilite 13.296 per cent, oldhamite 0.596 per cent and carbon 0.31 per cent. A re-analysis by Wiik (1956) adds alkali and chromium determinations, gives the carbon content as 0.43 per cent and the nickel-iron as 25.96 per cent.

In thin section and in polished section Indarch is seen to consist of a breccia of more or less fragmented chondrules and crystal fragments of clinoenstatite and enstatite with the interstices occupied by troilite and nickel-iron. The stone is heavily impregnated with carbon or a black carbonaceous material, that renders the fine-grained matrix virtually opaque and penetrates along cracks in the pyroxene.

The present paper represents two investigations carried on independently at Argonne National Laboratory and at Harvard. Separate descriptions of the new mineral here reported chanced to be submitted

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[1] Mineralogical Contribution No. 421, Harvard University.

almost simultaneously to the International Mineralogical Association for approval, and are here unified under joint authorship. Part of a specimen of Indarch preserved in the Harvard Mineralogical Museum was crushed to pass 200 mesh and then was extracted with a mixture of benzene and alcohol. This yielded a small amount of free sulfur and organic material. While being crushed the stone gave off a faint odor resembling coal gas. The leached residue was then fractionated by magnetic and heavy liquid methods and the mineral components identified. Polished sections and hand picked grains also were examined from a specimen of Indarch obtained from the Chicago Natural History Museum.

The major components are enstatite, clinoenstatite, troilite, and nickel-iron, as earlier reported. Schreibersite also is present. Olivine was not found, but a plagioclase feldspar with indices of refraction corresponding to $Ab_{90}An_{10}$ in composition is present in very small amounts. The feldspar probably is high-albite, reported in a number of chondrites by Miyashiro (1962), as is indicated by the large angular separation, 1.85°, measured between the $(1\bar{3}1)$ and (131) powder reflections (Smith and Yoder, 1956). The nonmetallic accessory constituents totaled at least 0.5 per cent, on the basis of a presumably incomplete mechanical separation. They included the new mineral here described, together with carbon, tridymite, oldhamite, glass and several unidentified minerals including a sulfide containing Mg, Fe, Mn and Cr. Apatite has been reported by Merrill (1917) and two unidentified minerals by Ramdohr (1963). We have been unable to verify the occurrence of apatite.

Although Indarch has a total carbon content of 0.43 per cent, the carbon is so intimately interwoven with and adherent to the other constituents that it hardly can be separated mechanically. A very small amount obtained by flotation in a liquid of low density did not give an x-ray diffraction pattern. The substance is not graphite but may be a highly disordered form of carbon or a black hydrocarbon with a high C/H ratio. Crystalline graphite also is present, as anisotropic inclusions in the nickel-iron. Tridymite is the principal accessory mineral and constitutes at least 0.1 per cent of the meteorite. It contains inclusions and is intergrown with or adherent to other constituents, with an accompanying variation in apparent density, so that a complete mechanical separation in heavy liquids cannot be effected. The indices of refraction of the tridymite are α 1.474, β 1.475, γ 1.478.

A compound known as a synthetic phase in the systems K_2O-MgO-SiO_2 and Na_2O-MgO-SiO_2 but hitherto not found as a mineral was identified among the accessory constituents. The name roedderite is proposed for this mineral. It occurs as colorless grains that lack cleavage. A few broken crystals also were observed. These were flat plates partly bounded laterally by faces intersecting at 120°. A precise measure of the abundance of this mineral could not be obtained, but on the basis of the mechanical separation it constitutes about 0.01–0.001 per cent of the meteorite. Scanning of the groundmass in polished thin sections by an electron microprobe, however, indicated that it may be more abundant than this and possibly amounts to as much as 0.1 per cent of the whole.

Table 1. Indexed *X*-Ray Powder Diffraction Data for Roedderite. Copper Radiation, Nickel Filter, in Angstrom Units. Relative Intensities in Arbitrary Chart Units. Indexing for Hexagonal Cell With *a* 10.139, *c* 14.275 Å

I	d (obs.)	d (calc.)	hkil	I	d (obs.)	d (calc.)	hkil
64	7.15	7.14	0002	9	2.375	2.379	0006
36	5.540	5.538	$10\bar{1}2$	7	2.171	2.168	$13\bar{4}3$
22	5.084	5.069	$11\bar{2}0$	11	2.094 b	2.098	$40\bar{4}2$
						2.092	$02\bar{2}6$
32	4.391	4.390	$20\bar{2}0$				
				5	1.936 b	1.934	$12\bar{3}6$
66	3.747	3.740	$20\bar{2}2$				
				5	1.902	1.899	$14\bar{5}1$
100(?)	3.570	3.569	0004				
				8	1.853	1.855	$14\bar{5}2$
13	3.35 b	3.319	$12\bar{3}0$				
				13	1.784	1.784	0008
26	3.309	3.306	$10\bar{1}4$				
				10	1.737 b	1.737	$21\bar{3}7$
77	3.239	3.233	$12\bar{3}1$				
				5	1.621 b	1.616	$42\bar{6}2$
67	2.922	2.927	$30\bar{3}0$				
		2.920	$11\bar{2}4$	5	1.570 b	1.567	$24\bar{6}3$
44	2.772	2.769	$20\bar{2}4$	5	1.335 b	1.333	$16\bar{7}1$
14	2.720	2.722	$12\bar{3}3$			1.335	$23\bar{5}8$
12	2.435	2.433	$12\bar{3}4$				

b = broad.

X-ray powder diffraction data obtained in filtered Cu radiation by the diffractometer method are given in Table 1. The *x*-rayed sample was known to be admixed with tridymite and small amounts of enstatite and plagioclase, whose diffraction lines were readily identified. The roedderite pattern was completely indexed in terms of a hexagonal cell with *a* 10.139±.01, *c* 14.275±.01 Å; the cell dimensions were refined by the computer program of Burnham (1962). An *x*-ray powder pattern obtained on film from a single analyzed grain, using diamond as an internal standard, gave cell dimensions identical with those cited, within the limits of error (±.02 Å). This pattern included lines at 4.126, 2.543, and 2.019 but lacked two lines obtained on the chart sample (1.936 and 1.621); the last two lines may represent admixture although both can be indexed. The strongest line within the film pattern was 3.239. The latter line also is strongest in the powder patterns of the isostructural compounds $K_2O \cdot 5MgO \cdot 12SiO_2$ (Roedder, 1951), $Na_2O \cdot 5MgO \cdot 12SiO_2$ (Schreyer and Schairer, 1962) and osumilite (Miyashiro, 1956). The strongest line obtained from the chart sample was 3.570, possibly because of preferred orientation or through enhancement from an admixed substance. The related line intensities of the isostructural substance merrihueite (Dodd, *et al.* 1965), $(K,Na)_2O \cdot 5(Fe,Mg)O \cdot 12SiO_2$ show further differences. Single-crystal *x*-ray data could not be obtained, and the initial indexing was guided by the isostructural relation with osumilite (Miyashiro, 1956), discussed beyond. The unit cell contains two formula-units. The density calculated from the formula found by chemical analysis is 2.63.

Chemical analyses of roedderite were effected by the electron microprobe technique using carbon-coated polished thin sections (Harvard); analysis no. 1, Table 2. Analyses no. 2 to 6 were made on single polished grains (Argonne). The analytical conditions and correction procedures are given in Table 2. The separate analyses made at the two laboratories are in good agreement (Table 2), and afford the formula $(Na,K)_2(Mg,Fe)_5Si_{12}O_{30}$. The ratio of Na to K is 1.88:1 and of Mg to Fe 18.0:1. Roedderite is the Na and Mg analogue of merrihueite, $(K,Na)_2(Fe,Mg)_5Si_{12}O_{30}$. In the probe analyses it was observed that low values for Na were obtained if the sample was held stationary under the beam, through volatilization. This was obviated by using low beam currents (0.03 microamperes) and short counting times (10 seconds), and by moving the beam over the sample during the counting period.

A complete solid solution series probably exists between roedderite and merrihueite, by mutual substitution of Na and K and of Mg and Fe^{2+} and from both to the Al analogue, osumilite, via the mechanism $2Al = (Mg,Fe)Si$. A complete series doubtlessly exists to $K_2Mg_5Si_{12}O_{30}$. We propose to restrict the name roedderite to that part of this presumed solid solution region with $Mg > Fe$, $Na > K$, and $Si/Al > 7$, in atomic ratio.

Optically, roedderite is uniaxial positive with ω 1.537, ϵ 1.542. The density could not be measured accurately, but is near 2.6. The indices of refraction and also the unit cell dimensions are slighly lower than those of synthetic $K_2Mg_5Si_{12}O_{30}$. A comparison of the optical properties, density, and unit cell dimensions of roedderite, merrihueite, and osumilite is given in Table 3.

In the system K_2O-MgO-SiO_2 (Roedder, 1951), the compound $K_2Mg_5Si_{12}O_{30}$ is stable in contact with clinoenstatite and silica, as found in Indarch for the (Na,K) analogue, as well as with clinoenstatite and forsterite. The content of alkalies in chondrites is in general quite low. The more reliable analyses indicate an average content of approximately 0.92 per cent Na_2O and 0.12 per cent K_2O (Mason, 1962). Roedderite thus can be expected to occur in only very small amounts in chondritic meteorites, as an accessory constituent. The content of Al is an added

TABLE 2. ELECTRON MICRO-PROBE ANALYSES OF ROEDDERITE

	1	2	3	4	5	6	7	Cations per 30 oxygens		Theory
SiO_2	71.4	70.6	71.3	70.8	71.1	70.8	71.0	11.88	11.95	12
Al_2O_3	0.4	0.4	0.6	0.4	0.4	0.4	0.4	0.07		
MgO	19.2	19.1	19.1	19.7	20.1	19.6	19.5	4.86	5.13	5
FeO	3.0				0.6	1.0	2.0	0.27		
K_2O	2.7	3.4	3.4	3.4	3.4	3.4	3.3	0.69	1.99	2
Na_2O	4.0	3.9	4.2	4.0	4.0	4.2	4.0	1.30		
Total	100.7	97.4	98.6	98.3	99.6	99.4				

1. C. Klein, analyst. Ca not detected. FeO average of values in different grains, 2.4 to 3.6 FeO. Carbon present as inclusions in very small but undetermined amount. Analytical conditions: 20KV accelerating voltage, 0.05 to 0.03 microamperes sample current, 2 micron beam size, 10 as well as 30 seconds counting time; analyzed in polished, thin-section. Synthetic $MgSiO_3$ was used for Mg and Si determinations, analyzed hornblende and anorthoclase for K, Na, Fe, and Al determinations. Mass absorption coefficients were taken from Heinrich (1966); absorption corrections were made after Philibert (1963).

2 to 6. C. Knowles and L. Fuchs, analysts. FeO values range from 0.1 to 0.3 weight per cent for most crystals, as much as 2.0 weight per cent for some spots. The analyses were made on carbon-coated, polished sections. The data are averaged results for several selected spots on each crystal. The largest crystals analyzed were about 0.1 mm in diameter. Analyzed feldspar standards were used for Al, Si, K and Na. Analyzed enstatite, olivine and diopside glass were used for Mg and Si. Absorption corrections were applied after Philibert (1963), atomic number corrections after J. V. Smith (unpublished), and fluorescence after Reed and Long (1965).

7. Average of all analyses. FeO of analysis no. 1 is more heavily weighted.

TABLE 3. PROPERTIES OF MINERALS RELATED TO ROEDDERITE

	Roedderite	Synthetic $K_2Mg_5Si_{12}O_{30}$	Merrihueite	Osumilite
a, in Å	10.139 ± .01	10.18[1]	10.16 ± .06	10.17
c, in Å	14.275 ± .01	14.29[1]	14.32 ± .06	14.34
d (meas.)	2.6	2.58	—	2.64
d (calc.)	2.63	2.63	2.87	
ω	1.537	1.543	1.559–1.592	1.545–1.547
ϵ	1.542	1.550		1.549–1.551
	colorless	colorless	greenish blue	black

[1] Calculated values from "d" spacings of Roedder (1951), indexing according to Miyashiro (1956) for osumilite.

factor in the formation of roedderite insofar as it results in the formation of feldspar, the chief Al mineral in chondrites and the chief host mineral for alkalies in this environment.

The name roedderite is proposed for this mineral after Dr. Edwin Woods Roedder of the U. S. Geological Survey, who identified the compound $K_2O \cdot 5MgO \cdot 12SiO_2$ in the system K_2O-MgO-SiO_2 and who expressed the belief that there may be environments for its occurrence in nature. This name has been submitted to and approved by the Commission on New Mineral Names of the International Mineralogical Association.

The work by L. H. Fuchs at Argonne National Laboratory was performed under the auspices of the Atomic Energy Commission, and that at Harvard was supported by NASA grant NsG-282-63.

ACKNOWLEDGMENTS

Grateful acknowledgment is made to Dr. Edward Olsen of the Chicago Natural History Museum for a sample of Indarch and for assistance in correcting the probe data, to Elizabeth Gebert of Argonne National Laboratory for aid in film measurements, and to Mr. Charles Knowles of the Department of Geophysical Sciences, University of Chicago, for operation of the electron probe.

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Manuscript received, December 2, 1965; accepted for publication, December 23, 1965.

NOTE ADDED IN PROOF

The following communication was received by us from Dr. R. A. Binns of the Geology Department of the University of New England, Armidale, N.S.W.: "Dr. Richard Davis, of the British Museum, and I found what proved to be roedderite in heavy liquid separations (D *ca.* 2.6) of both Indarch and Kota Kota (enstatite chondrite). We had obtained powder photographs, contaminated with some high albite, and also single crystal photographs showing it to be hexagonal *a* with about 10 Å, *c* about 14 Å, when the I.M.A. notice of your work arrived. For the sake of comparison, we are continuing to work on the Kota Kota material. . . . "