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RINGWOODITE AND MAJORITE IN THE CATHERWOOD METEORITE

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Abstract

A network of dark veins in the Catherwood olivine-hypersthene chondrite contains ringwoodite and majorite as discrete transparent grains, and as intimate mixtures with minor maskelynite, which form the dark brown matrix of the veins. All of the ringwoodite and majorite is polycrystalline and extremely fine-grained. Minor amounts of olivine, pyroxene, and plagioclase are associated with some transparent grains.

The occurrences and properties of ringwoodite and majorite in Catherwood are similar to those in the Tenham and Coorara meteorites of Australia. The ringwoodite is Fa_{25} in composition, as is the Catherwood olivine, and has a=8.122±0.012Å. The majorite is $Wo_1En_{78}Fs_{21}$ in composition, as is the Catherwood pyroxene, and has a=11.543±0.018Å. Ringwoodite and majorite in Catherwood are considered to be high-pressure products of olivine and pyroxene which were localized along fractures in the meteorite and which were transformed by shock resulting from extraterrestial collision.

Sommaite

Un réseau de filons de couleur sombre recoupent la chondrite à olivine-hypersthène de Catherwood. Ils contiennent de la ringwoodite et de la majorite en grains isolés transparents et, avec un peu de maskelynite, en agrégats qui forment la gangue brun foncé des filons. Tous les spécimens de ringwoodite et de majorite sont polycrystallins et de grain extrêmement fin. De petites quantités d'olivine, de pyroxène et de plagioclase sont associées à quelques grains transparents. Le mode de gisement et les caractères de la ringwoodite et de la majorite sont les mêmes dans la chondrite de Catherwood que dans les météorites de Tenham et Coorara, en Australie: la ringwoodite (a=8.122±0.012Å) y a la composition de l'olivine Fa_{25} et la majorite (a=11.543±0.018Å), celle du pyroxène $Wo_1En_{78}Fe_{21}$; l'olivine et le pyroxène, originellement localisés dans les fractures de la météorite, se transformèrent sous haute pression en ringwoodite et majorite, transformation peut-être déclenchée par le choc d'une collision extraterrestre.

(Traduit par la Rédaction)

Introduction

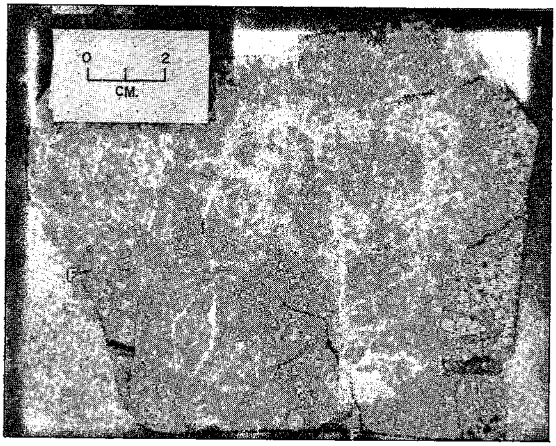
The Catherwood meteorite was discovered in 1964 or 1965 when it became entangled in farming equipment of the Lorne E. Horton farm near Catherwood, about 55 km west of Saskatoon, Saskatchewan. It was first recognized as a meteorite in 1971 and, through the offices of its Meteorite Observation and Recovery Project, was acquired by the National Research Council of Canada. It is now part of the national collection that is housed at the Geological Survey of Canada in Ottawa.

Catherwood is ovoid with a maximum dimension of about 17 cm and a weight of 3,963 gm. Although some of the fusion crust is still present, it has been fairly extensively weathered and much of its interior is rusty brown. A prominent feature of this meteorite that is evident on any sawn surface is a network of dark veins (Fig. 1). Work on Catherwood in the Mineralogy Section of the Geological Survey of Canada during the summer of 1971 established the presence of ringwoodite and majorite in and associated with these veins (Coleman & Fillo 1973).

General Description

In most respects, Catherwood appears to be a typical olivine-hypersthene chondrite of type L6 according to the classification of Van Schmus & Wood (1967). Chondrules, from about 1 to 6 mm in diameter, are readily discernible and comprise about 15% of the meteorite by volume; their boundaries are diffuse with respect to the enclosing matrix. They are composed principally of olivine and pyroxene of similar compositions and in similar proportions to those in the matrix. Most chondrules have a barred appearance; some appear to be granular with individual grains about 0.1 mm in diameter; others have a fan-like lamellar structure, and some appear to be an aggregate of several part-chondrules.

The matrix surrounding the chondrules consists of anhedral to subhedral grains generally ranging from 0.015 to 0.5 mm and most commonly about 0.2 mm in diameter. The matrix and the chondrules seem to have been subjected to extensive brecciation which is considered to have been responsible for the small size of ma-



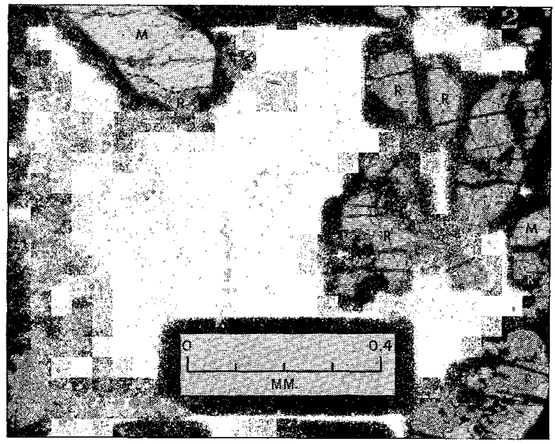


FIG. 1. Surface of sawn slab of Catherwood displaying network of dark veins. The broken specimen was glued together along fracture F-F.

FIG. 2. Part of a dark vein in Catherwood with transparent segregations of ringwoodite (R) and majorite (M) within fine-grained dark brown matrix containing spheroidal opaque inclusions (black).

trix grains at the lower end of the size range.

Catherwood is heterogeneous in terms of the proportions of the minerals present from one part to another. However, an average modal composition is approximately 55% olivine, 25% low-Ca pyroxene, 13% opaque minerals (kamacite-taenite, troilite, chromite), 7% plagioclase (or maskelynite), and accessory diopsidic pyroxene and apatite. The minerals seem to be homogeneous: olivine is about Fa_{25} and the low-Ca pyroxene is about $Wo_1En_{78}Fs_{21}$. The plagioclase, which in most places appears to have been converted to maskelynite and has a composition of about $An_{10}Or_8Ab_{82}$, occurs as irregular grains rarely more than 0.05 mm in diameter and interstitial to olivine, pyroxene and opaque minerals.

Evidence of strain is the wavy extinction common in the larger olivine and pyroxene grains, and abnormally low birefringence in olivine.

OCCURENCE OF RINGWOOD AND MAJORITE

A network of dark veins is a prominent feature on sawn surfaces of Catherwood; these veins range from about 0.1 to about 10.0 mm in apparent width (Fig. 1), but the average true width is estimated to be 0.5 mm. A visual estimate is that the veins make up about 1% of the meteorite by volume. Microscopic examination of the veins reveals that they consist of a very fine-grained translucent dark brown matrix with spheroidal opaque inclusions (Fig. 2) ranging in diameter from more than 0.04 to less than 0.001 mm and averaging about 0.01 mm, and subangular to subrounded aggregates of several transparent minerals (Figs. 2, 3).

Microscopic examination and X-ray diffraction and microprobe investigations indicate that these transparent aggregates are composed principally of ringwoodite, the spinel of olivine composition, and majorite, the garnet of bronzite composition, and that some of the aggregates also contain the minerals which occur in the matrix of the meteorite. The aggregates generally range from 0.2 to 1.0 mm (Fig. 3) but some have maximum dimensions in excess of 2.0 mm. Some aggregates up to 1 mm in diameter are monomineralic and consist of either ringwoodite or majorite (Fig. 2), and others consist of adjoining segregations of these two minerals. Small grains of olivine, orthopyroxene, and plagioclase are included by some of the aggregates. Laue photographs of individual, apparently homogeneous, transparent grains display no spots but only circles concentric about their centers; this indicates the grains are polycrystalline and extremely fine-grained.

Both ringwoodite and majorite are isotropic and, therefore, can be difficult to distinguish from each other in thin section. However, much of the ringwoodite is pale purple to smoky grey whereas much of the majorite is pale yellowish brown. Both are colorless in some occurrences and, in such cases, can only be differentiated readily with a microprobe.

Microprobe and X-ray diffraction examination of the translucent matrix of the veins indicates that it consists principally of majorite

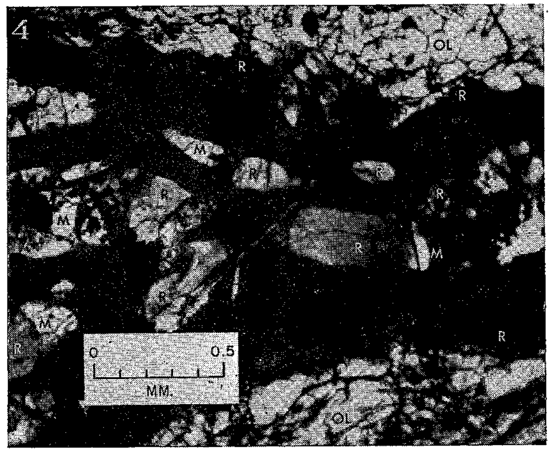


FIG. 3. Photomicrograph displaying the full width of one of the dark veins in Catherwood.

FIG. 4. Photomicrograph of a part of a relatively narrow dark vein in Catherwood. Greyish purple ringwoodite (R) occurs as segregations within the vein matrix (black) and between the vein and the olivine (OL) of the body of the meteorite. Segregations of majorite (M) are also present within the vein.

and somewhat more abundant ringwoodite, and minor amounts of maskelynite. The opaque inclusions appear to consist of an intimate intergrowth of troilite and meteoritic Ni-Fe alloy.

All majorite detected in this study is contained within the dark veins, but some ringwoodite occurs outside of them. Most of this ringwoodite is along the vein margins where it is continuous with, and apparently replaced, grains of olivine (Fig. 4). A few small patches of ringwoodite were observed on the margins of olivine grains near the dark veins. No ringwoodite was observed more than 0.5 mm from the veins and, in general, it is within 0.2 mm of them.

The above aspects of the occurrences of ringwoodite and majorite in Catherwood appear to be identical to those described by Mason *et al.* (1968), Binns *et al.* (1969), Smith & Mason (1970), and Binns (1970) for the same two minerals in the Coorara and Tenham meteorites of Australia. Thin sections of a fragment of Tenham have been examined by the author and appear very similar but not identical to those from Catherwood; the most notable differences are that the purple color of the ringwoodite in Tenham is more vivid than in Catherwood, and the size of the transparent aggregates in the dark veins, and width of the veins, are somewhat greater in Catherwood than in Tenham.

Compositions of Ringwoodite and Majorite

Clear grains of ringwoodite and majorite in the dark veins of Catherwood were first analyzed with a microprobe by A. G. Plant at the Geological Survey of Canada during the initial examination of the meteorite in 1971. These minerals and the olivine and pyroxene in the main body of the meteorite have been analyzed at the University of Saskatchewan and at the University of Manchester as part of the present study (Tables 1, 2). Results of the analyses performed at the Geological Survey of Canada are also reported in these tables as are those of Binns *et al.* (1969) of ringwoodite and olivine in Tenham and of Smith & Mason (1970) of majorite in Coorara.

Analyses at the University of Saskatchewan were carried out with an Acton MS-64 microprobe using wavelength dispersive methods and those at the University of Manchester with a Cambridge Geoscan microprobe using energy dispersive methods. A much larger number of analyses of each of the phases was performed in the latter case and their results are considered to be the more reliable.

Ringwoodite in Catherwood has a composition that is practically identical to that of the olivine in the main body of the meteorite (Table 1). A similar relationship was reported for ringwoodite and olivine in Tenham (Binns *et al.* 1969) and in Coorara (Smith & Mason 1970). Binns (1970) found that purple ringwoodite within the veins in Tenham is not as Fe-rich as that which is grey and outside the veins. He suggested that a diminution of shock pressures away from the veins at the time that olivine was being transformed to ringwoodite could have been responsible for this compositional difference. Minor differences were noted between analyses of different ringwoodite grains during the present study, but no systematic difference of the type noted by Binns was observed.

The analyses of Catherwood majorite (Table 2), except for those performed at the University of Manchester, contain significant amounts of Ti, Al, Cr, and Na. Of the 15 clear majorite grains analyzed at the University of Manchester, minor amounts of Ti were detected in 5 and Cr in 3; Al and Na were detected in none. It is thought that the differences in these analyses are due to the presence of minor impurities in the grains analyzed at the Geological Survey of Canada and the University of Saskatchewan. Similar differences between the pyroxene analyses performed at the University of Saskatchewan and the University of Manchester are considered to be due to the same effect. The composition of majorite in Catherwood (Table 2) is almost the same as that of the pyroxene in the main body of the meteorite. It should be noted that the composition of Coorara majorite, reported by Smith & Mason (1970) and listed in Table 2, is not of a clear grain but of the brownish matrix of one of the veins. The corresponding material in Catherwood is an intimate mixture of majorite and ringwoodite with minor amounts of maskelynite.

Twenty-five analyses were made of the translucent brown matrix of the dark veins (Fig. 2). All areas selected appeared to be remote from opaque inclusions. Despite this, about half the analyses exhibited significant amounts of S or Ni and somewhat excessive amounts of Fe which indicated the presence of some troilite or meteoritic alloy. Of the others, ten yielded results that could be accounted for entirely by mixtures of variable amounts of ringwoodite, majorite, and maskelynite as indicated in Table 3.

X-Ray Diffraction Studies

Laue photographs of ringwoodite grains, majorite grains, and fragments of the ringwoodite-majorite-maskelynite matrix display smooth rings that indicate that these phases are all polycrystalline with an extremely fine grain size. Powder photographs of individual grains of olivine and pyroxene exhibited rings with preferred orientation rather similar to those of olivine from Bruderheim (Heymann 1967, Fig. 2c).

Powder photographs were obtained for each of several clear grains of ringwoodite, from clear grains of majorite, and from brownish matrix (57.3 mm diam. camera, FeKα). The ringwoodite gave patterns virtually identical to those reported by Binns *et al.* (1969) for Tenham ringwoodite, and a similar cell dimension (a= 8.122±0.012Å). The clear majorite grains produced patterns similar to that of pyrope and have a=11.543±0.018Å, similar to that reported

TABLE 1. COMPOSITIONS OF RINGWOODITE AND OLIVINE IN CATHERWOOD AND TENHAM

	Catherwood					Tenham (Binns *et al.* 1969)		
	Ringwoodite			Olivine		Ringwoodite		Olivine
wt.%	US*	UM*	GSC*	US*	UM*	Purple	Grey	
SiO_2	38.0	38.4	38.1	38.3	38.4	38.9	38.7	38.3
MgO	37.2	39.0	37.6	37.4	39.3	37.0	38.8	37.6
MnO	.4	.4	.3	.6	.4	nr'	nr'	nr'
FeO	24.1	22.5	23.6	24.1	22.4	23.4	23.2	23.2
Total	99.7	100.3	99.6	100.4	100.5	99.3	100.7	100.1
	ATOMIC FORMULA ON BASIS OF 24 OXYGENS							
Si	6.01	5.98	6.01	6.03	5.99	6.16	6.01	5.99
Mg	8.79	9.06	8.84	8.78	9.08	8.73	8.98	8.98
Mn	0.05	0.06	0.04	0.07	0.05	nr'	nr'	nr'
Fe	3.19	2.93	3.11	3.17	2.92	3.10	3.01	3.02
$\frac{Fe+Mn}{Mg+Fe+Mn}$	.27	.25	.26	.27	.25	.26	.25	.25

* US: analyses performed in the Department of Geological Sciences of the University of Saskatchewan during the present study; UM: analyses performed in Department of Geology, University of Manchester during the present study; GSC: analysis by A.G. Plant at the Geological Survey of Canada in August 1971.

nr': not reported

TABLE 2. COMPOSITION OF MAJORITE AND PYROXENE IN CATHERWOOD AND OF MAJORITE IN COORARA

	Catherwood					Coorara*
	Marjorite			Pyroxene		Majorite
wt.%	US*	UM*	GSC*	US*	UM*	
SiO_2	54.1	56.7	55.1	54.5	55.9	51.9
MgO	27.7	29.5	28.6	30.1	28.8	27.5
CaO	.4	.6	.8	.6	.8	0
MnO	.6	.5	.6	.6	.5	0
FeO	15.1	13.3	14.4	14.5	13.0	16.9
TiO_2	.2	<.05	.2	.2	0	0
Al_2O_3	.8	0	.1	.3	0	2.7
Cr_2O_3	.1	0	.3	.1	0	.7
Na_2O	.5	0	0	<.05	0	.7
NiO	na'	0	na'	na'	0	.1
Total	99.5	100.6	100.1	100.9	99.0	100.5
	ATOMIC FORMULA ON BASIS OF 24 OXYGENS					
Si	7.86	8.02	7.88	7.80	8.02	7.24
Mg	6.00	6.21	6.12	6.40	6.16	5.96
Ca	.06	.10	.12	.09	.13	0
Mn	.07	.06	.07	.07	.06	0
Fe	1.83	1.60	1.73	1.73	1.56	2.04
Ti	.02	<.01	.02	.02	0	0
Al	.13	0	.02	.04	0	.46
Cr	.01	0	.03	.01	0	.06
Na	.13	0	0	.01	0	.20
NiO	na'	0	na'	na'	0	.01
$\frac{Mn+Fe}{Mg+Fe+Mn}$	.24	.21	.23	.22	.21	.26

* Coorara: composition reported by Smith & Mason (1970); US: analyses performed in the Department of Geological Sciences, University of Saskatchewan during the present study; UM: analyses performed in the Department of Geology, University of Manchester during the present study; GSC: analysis performed by A.G. Plant at the Geological Survey of Canada in October, 1973. na': not analyzed.

TABLE 3. MINERAL PROPORTIONS IN THE VEIN MATRIX OF CATHERWOOD CALCULATED FROM MICROPROBE ANALYSES

	Range of wt.%	Average wt.%
Ringwoodite	39 - 89	60
Majorite	11 - 56	34
Maskelynite	0 - 12	6

by Smith & Mason (1970) for Coorara majorite. The fragments of matrix produced composite patterns in which the majorite pattern is generally more intense than that of ringwoodite.

Discussion

The similarities of their compositions support the idea that ringwoodite in Catherwood has formed from olivine and the majorite from pyroxene. Furthermore, the relative abundances of the ringwoodite and majorite as clear grains and in the matrix of the dark veins (Table 3) are similar to those of olivine and pyroxene in the main body of the meteorite. The fineness of the grain size of the ringwoodite and majorite, the character of the powder patterns of the olivine and pyroxene, and the texture of the meteorite indicate that these two transformations may have been brought about by severe shock such as would accompany extraterrestrial impact. All of this is in agreement with the ideas of Mason *et al.* (1968), Binns *et al.* (1969), Binns (1970), and Smith & Mason (1970) for the origin of ringwoodite and majorite in Coorara and in Tenham.

Mason *et al.* (1968) and Binns (1970) discuss the physical conditions necessary for the olivine-ringwoodite and orthopyroxene-majorite inversions and mention temperatures in the order of 1000°C and shock pressures of as much as 450 kbar. Conditions similar to those attained in Coorara and Tenham would have been necessary for these transformations to take place in Catherwood because of the great similarity of the mineral compositions. These compositional similarities may reflect a common parentage for Catherwood, Coorara, and Tenham. Alternatively, the compositional similarities could indicate only that the physical conditions necessary to produce ringwoodite and majorite are most readily attained if a meteorite's olivine and pyroxene have these compositions.

Acknowledgements

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