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Descriptions of Two Meteorites: Karoonda and Erakot

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THE KAROONDA METEORITE

At 10.53 P.M. on November 25, 1930, an extremely brilliant meteor was seen by many observers in South Australia. A meteorite fell near Karoonda, a small settlement some 75 miles due east of Adelaide. It was found two weeks later in a sandy, fallowed wheat field by a search party from the University of Adelaide and Adelaide Observatory. The meteorite evidently consisted of a single stone which shattered on impact with the ground; some 92 pounds of fragments were collected, the largest weighing 7 pounds. The circumstances of the fall and the discovery were described by Grant and Dodwell (1931).

The mineralogy and petrology of the meteorite were described by Mawson (1934), who published an analysis by A. R. Alderman. Mawson recognized that Karoonda was a chondritic meteorite of an unusual type, containing little or no nickel-iron, and he classified it as a chondritic asiderite.

Wahl (1950) pointed out that Alderman's analysis showed an improbably high amount of Al_2O_3 (5.55%). In view of this and in view of the unusual mineralogy of the meteorite, we decided to re-analyze and redescribe this unusual meteorite. The piece investigated (A.M.N.H. No. 3903) was obtained by exchange from the South Australian Museum.

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Mineralogical Composition

The meteorite consists largely of olivine, with minor amounts of plagioclase, pigeonite, pentlandite, troilite, and magnetite, and trace amounts of pyrite and chalcopyrite; a small amount of a phosphate mineral (apatite or merrillite) is probably present. No nickel-iron was detected on a polished surface, nor was any chromite. Notes on the individual minerals follow.

Olivine: The refractive indices are $\alpha = 1.696$, $\gamma = 1.735$, indicating a content of 32 mol per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). With the use of the X-ray method of Yoder and Sahama (1957), the composition was found to be 34 mol per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp and well defined, indicating olivine of uniform composition.

Pigeonite: A concentrate containing the pigeonite (and plagioclase and pentlandite) was obtained by digesting a sample of the meteorite powder in 1:1 HCl, and boiling the residue in Na_2CO_3 solution to remove the colloidal silica produced by the decomposition of the olivine. The pigeonite was identified by its X-ray powder photograph. Its indices are $\alpha = 1.698$, $\gamma = 1.732$, indicating 46 atom per cent Fe in total Ca+Fe+Mg, according to the determinative curve of Hess (1949). An interference figure on one grain was essentially uniaxial. Occasional grains show polysynthetic twinning of the clinopyroxene type.

Plagioclase: The refractive indices are $\alpha' = 1.543$, $\gamma' = 1.550$, indicating a composition of An_{30}.

Pentlandite: This mineral was first identified in the acid-insoluble residue of the meteorite, by its characteristic X-ray powder photograph. It is the principal sulphide mineral in the meteorite.

Magnetite: A magnetic fraction extracted from the powdered metorite gave the X-ray powder photograph of magnetite; the unit cell dimension is 8.376 A. This is close to that of pure Fe_3O_4; however, since $MgFe_2O_4$ has an almost identical cell edge, the possibility of substitution of some iron by magnesium cannot be eliminated. Chromite was not identified in the meteorite, and the Cr_2O_3 found by chemical analysis is probably in solid solution in the magnetite. Paul Ramdohr has observed that the magnetite occurs in several different forms: as coarse grains, with typical exsolution of ilmenite in very thin plates; in association with troilite; and as minute grains forming a rim around the chondrules of olivine.

Troilite: This mineral is a minor constituent, being present in much smaller amount than pentlandite.

PYRITE: Pyrite is a rare constituent, occurring in myrmekitic intergrowth with some pentlandite grains. Ramdohr suggests that this intergrowth is the disintegration product of linnaeite, $(Fe, Ni)_3S_4$.

CHALCOPYRITE: This mineral occurs as small inclusions in pentlandite.

The quantitative mineralogical composition (in weight per cent) is estimated to be: olivine, 70; plagioclase, 9; pigeonite, 8; magnetite, 8; pentlandite, 4; others, 1.

A thin section of the meteorite shows that it consists largely of chondrules, ranging from 0.5 to 3 mm. in diameter, in a fine-grained groundmass. The chondrules consist of granular olivine. The groundmass, which also consists largely of olivine, is turbid and almost opaque, probably from fine-grained pentlandite, troilite, and magnetite. Some irregular to prismatic grains of plagioclase, up to 0.1 mm. long, were recognized in the groundmass.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride, and was found to be 3.57. Since the meteorite is quite porous, the piece was placed in a beaker under a bell jar, which was evacuated with an oil pump before running in the carbon tetrachloride.

CHEMICAL COMPOSITION

The chemical analysis is given in table 1, in the conventional form expressed as oxides, troilite, and metal; in terms of the individual elements as determined by analysis, with oxygen to bring the total to 100; and recalculated as atom percentages with the elimination of H, O, and S. The conventional form of presenting analyses involves certain assumptions, viz., that all Ni is present in nickel-iron, that all S is present as FeS, and that Fe in excess of free metal and FeS is present as FeO. These assumptions are probably valid for most chondritic meteorites, but are certainly not for Karoonda. As there is no free metal in Karoonda, the nickel must be present in another form, evidently as pentlandite; so S is present as (Fe,Ni)S, as well as FeS. Hence some of the Fe conventionally calculated as FeS is present elsewhere, specifically in the silicate minerals and as magnetite. Some of the Fe reported as FeO in the conventional form is certainly present as ferric iron in the magnetite. Under these circumstances the form of presentation in column B in table 1 is preferable, since it gives the results actually obtained by the analysis. In effect, the chemical analysis determines the amounts of the different elements, except the oxygen, no readily applicable method for this element being available.

TABLE 1
CHEMICAL COMPOSITION OF THE KAROONDA METEORITE

A		B		C	
Fe	0.0	H	0.09	Mg	34.97
Ni	1.40	C	0.00	Si	30.81
Co	0.062	N	0.01	Fe	25.54
Cu	0.0101	Na	0.53	Al	3.03
FeS	4.33	Mg	15.24	Ca	2.09
SiO_2	33.28	Al	1.47	Ni	1.33
TiO_2	0.22	Si	15.548	Na	1.28
Al_2O_3	2.77	P	0.043	Cr	0.45
FeO	29.33	S	1.58	Ti	0.15
MnO	0.19	K	0.024	Mn	0.15
MgO	25.27	Ca	1.500	P	0.08
CaO	2.10	Ti	0.132	Co	0.06
Na_2O	0.716	V	0.016	K	0.03
K_2O	0.03	Cr	0.424	V	0.02
P_2O_5	0.10	Mn	0.147	Cu	0.01
H_2O	0.81	Fe	25.55		
Cr_2O_3	0.62	Co	0.062		100.00
V_2O_5	0.028	Ni	1.40		
C	0.00	Cu	0.0101		
N	0.01	(O	36.22)		
	101.27		100.00		

A Chemical analysis in weight per cent of the oxides of the electropositive elements
B Chemical analysis in weight per cent of the elements, with oxygen to bring the sum to 100
C Atomic per cent of the elements on a volatile (C, H, O, N, S)-free basis

The expression of the analysis as atomic percentages after eliminating H, O, and S was used by one of us (Wiik, 1956) for comparing analyses of the different types of chondrites. Such a procedure in effect distinguishes non-volatile elements from those likely to be lost or gained during heating in extra-terrestrial environments. The figures for the Karoonda meteorite show that its composition is similar to other meteorites in his group of ornansites (Warrenton, Felix, Lance, and Mokoia). Along with these meteorites, Karoonda belongs to the H (high-iron) group of Urey and Craig (1953).

DISCUSSION

In structure and mineralogical and chemical composition the Karoonda meteorite clearly belongs in the large group of chondrites, specifically in the olivine-pigeonite chondrites as defined by Mason (1962). Nevertheless, it has certain peculiarities that confer on it a certain degree of uniqueness. It contains no metallic phase, a feature that links it with many of the carbonaceous chondrites, although it contains no carbon or organic compounds. The principal sulphide phase is not troilite, as in virtually all other chondrites, but is pentlandite. Incidentally, the sulphur content is notably low, 1.58 per cent, the average in chondritic meteorites being 2.09 per cent (Urey and Craig, 1953). The Karoonda meteorite contains a notable amount of magnetite, a mineral normally absent from fresh, unweathered chondrites. All in all, while the elemental composition is closely similar to that of other H-group chondrites, the Karoonda meteorite represents a highly oxidized condition for such meteorites, with no free metal, with nickel as a sulphide phase, and with virtually all the iron as ferrous iron, with some as ferric iron.

THE ERAKOT METEORITE

This meteorite, a carbonaceous chondrite, fell at Erakot (latitude 19° 02′ N., longitude 81° 53′ E.), near Jagdalpur in Bastar State, India, at 5 P.M. on June 22, 1940. One stone weighing 113 grams was recovered and is preserved in the Museum of the Geological Survey of India in Calcutta. The Director of the Geological Survey provided us with a sample to make the chemical and mineralogical examination reported here; we would like to express our appreciation for the opportunity to investigate this rare and interesting meteorite.

Mineralogy and Structure

The sample investigated was a fragment of the original stone. The material is black and compact, and one surface retains part of the fusion crust, which is very thin (about 0.1 mm.) and has a rippled, slag-like surface. An examination of the interior surfaces with a hand lens or binocular microscope shows a number of white or pale yellow chondrules, up to 1 mm. in diameter, in a dense, black, irresolvable groundmass. The material is not especially friable but is readily crushed in an agate mortar, the chondrules being much more resistant than the groundmass. The density was determined by suspending small fragments in acetone-methylene iodide mixtures of the same density, and measuring the density of the liquid; it was found to be 2.66. Notes on the individual minerals follow.

Serpentine: The black groundmass, which makes up about 90 per cent

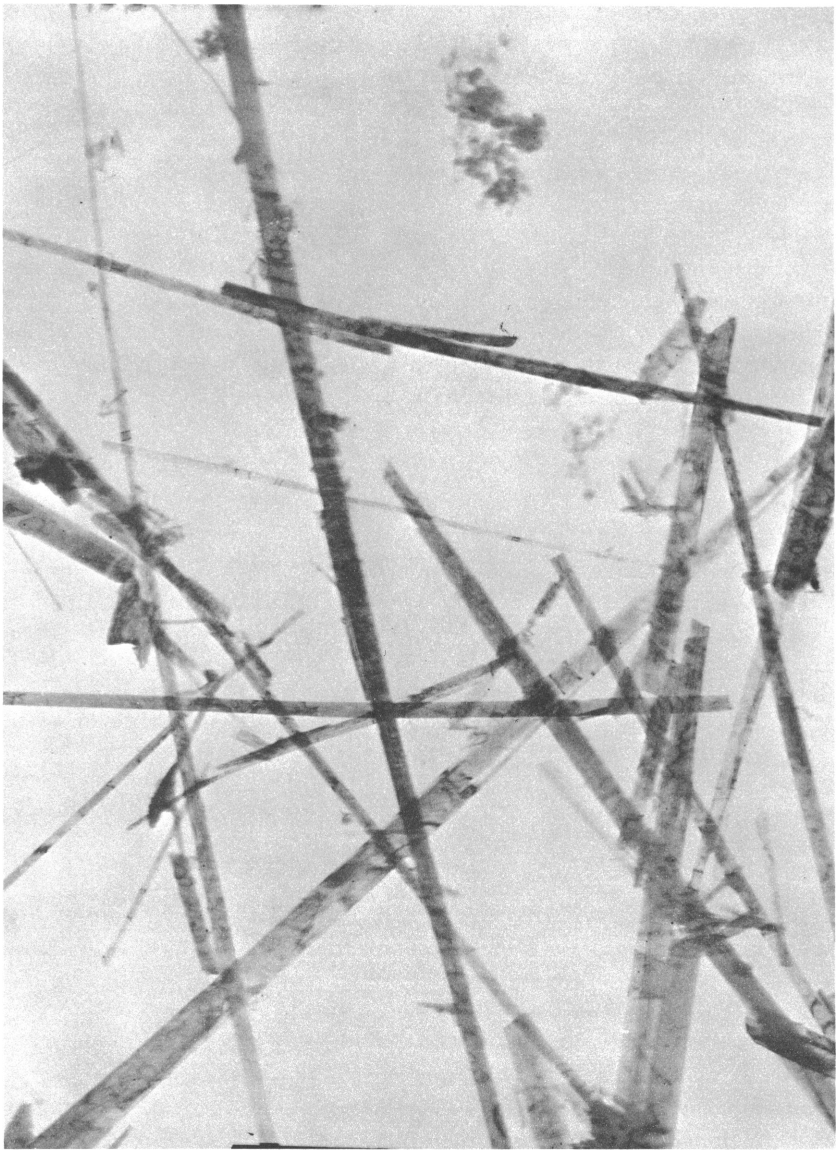

FIG. 1. Electron micrograph of material of the Erakot meteorite, showing the lath-like and tubular crystals characteristic of the chrysotile variety of serpentine. Photograph courtesy of Prof. J. D. Bernal, Birkbeck College, London. × 24,000.

of the meteorite, is completely opaque, even in the smallest grains, because of the all-pervading carbonaceous material. An X-ray powder photograph showed lines with the following d-spacings (estimated intensities in brackets): 7.2 [10]; 3.59 [7]; 2.56 [3]. This pattern agrees with that of serpentine (using this term in a broad sense for the whole group of serpentine minerals), and this identification is confirmed by an electron micrograph (fig. 1), which shows the characteristic tubular form of the chrysotile variety of serpentine.

OLIVINE: The white or pale yellow chondrules mentioned above consist of olivine, and make up approximately 10 per cent by weight of the meteorite. When examined in immersion oils, most grains have a gamma index close to 1.670, indicating a composition near Mg_2SiO_4 (pure forsterite); a few grains have distinctly high indices, thus showing the presence of some Fe_2SiO_4 in solid solution.

ENSTATITE: Along with the olivine grains, a little enstatite was recognized, probably less than 1 per cent of the meteorite as a whole. The refractive indices are $\alpha = 1.660$, $\gamma = 1.670$, corresponding to essentially pure $MgSiO_3$.

MAGNETITE: A hand magnet extracts a very small amount ($< 1\%$) from crushed material of this meteorite. The X-ray powder photograph corresponds to that of magnetite, and the cell edge is 8.38 A, close to that of pure Fe_3O_4; however, in view of the possibility of extensive replacement of Fe by Mg, Cr, Ni, and other elements, it would be venturesome to claim that this magnetic spinel is pure Fe_3O_4.

OTHER MINERALS: Other minerals, not certainly identified, and present in small amounts, include sulphur, extracted from the meteorite by toluene; a water-soluble sulphate, probably magnesium sulphate; and black carbonaceous material which is not graphite, because it is amorphous to X-rays (it is probably a complex polymer of high molecular weight). Toluene also extracts a small amount of crystalline organic material.

ABSENCES: Equally significant is the absence of some minerals otherwise common in stony meteorites. Erakot contains no free nickel-iron, no feldspar, no chromite, and no troilite; the elements normally present in these compounds are present in the above minerals or are possibly contained in an amorphous phase.

CHEMICAL COMPOSITION

The chemical composition is presented in table 2, in three forms: (A) the percentages of the elements as determined by analysis, with

TABLE 2
CHEMICAL COMPOSITION OF THE ERAKOT METEORITE

A		B		C	
Fe	22.42	FeO	28.84	Mg	32.49
Si	12.77	SiO_2	27.35	Si	31.16
Mg	11.53	MgO	19.12	Fe	27.51
S	3.34	Al_2O_3	1.97	Al	2.64
C	2.14	CaO	1.61	Ca	1.97
H	1.29	NiO	1.54	Na	1.64
Ni	1.21	Na_2O	0.74	Ni	1.42
Ca	1.15	Cr_2O_3	0.43	Cr	0.38
Al	1.04	P_2O_5	0.33	P	0.31
Na	0.55	MnO	0.23	Mn	0.23
Cr	0.29	TiO_2	0.09	Ti	0.08
N	0.26	CoO	0.073	Co	0.07
Mn	0.18	V_2O_5	0.023	K	0.05
P	0.14	S	3.34	Cu	0.03
Co	0.057	C	2.14	V	0.02
Ti	0.054	N	0.26		
Cu	0.028	Cu	0.028		100.00
K	0.027	H_2O	11.52		
V	0.013				
(O	41.51)		99.63		
	100.00				

A Chemical analysis in weight per cent of elements, with oxygen to bring the sum to 100
B Chemical analysis in weight per cent of the oxides of the electropositive elements
C Atomic per cent of the elements on a volatile (C, H, O, N, S)-free basis

oxygen added to bring the sum to 100; (B) in the conventional form, reporting the electropositive elements as oxides; (C) recalculated in atom percentages on a volatile (C, H, S, N, O)-free basis.

Column A presents the results actually obtained by the analysis and is in effect the primary data from which columns B and C are calculated. The recalculation into the figures of column B involves certain assumptions, most of which are probably valid, but some of which are not. These assumptions are: (a) the electropositive elements are present in the meteorite in their usual valence states—probably valid for all these elements except iron, which is reported as FeO, whereas the presence of a magnetic spinel (certainly in very small amount) implies the presence of Fe_2O_3, and the serpentine phase may also contain ferric iron; (b) sulphur is reported as free S—some of it is in this form, but some is present as sulphate, and some may be in the form of organic compounds containing sulphur; (c) carbon is reported as free C, but most or all of it is present as complex organic compounds which also contain H, O, and probably N and S; H is reported as H_2O, but some is certainly present in organic compounds, possibly hydrocarbons. At the present state of our knowledge these assumptions cannot be avoided. Their over-all validity in the case of this meteorite may be argued from the close approach of the sum of column B to 100, although possibly this close approach is in part fortuitous, produced by the balancing of deviations in opposite directions.

Column C, which presents atom percentages on a volatile-free basis, enables comparison of this meteorite not only with other carbonaceous chondrites, but also with the common (non-carbonaceous) chondrites, as shown by Wiik (1956). This shows that Erakot is closely comparable in elemental composition to the other carbonaceous chondrites, and to the chondrites of the H (high-iron) group of Urey and Craig (1953). Erakot belongs to the Type II carbonaceous chondrites as defined by Wiik, and is essentially identical with Cold Bokkeveld, Mighei, and other meteorites of this type.

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REFERENCES

GRANT, K., AND G. F. DODWELL
1931. The Karoonda (S.A.) meteorite of November 25, 1930. Nature, vol. 127, pp. 402–403.
HESS, H. H.
1949. Chemical composition and optical properties of common clinopyroxenes. Amer. Min., vol. 34, pp. 621–666.
MASON, B.
1962. The classification of chondritic meteorites. Amer. Mus. Novitates, no. 2085, 20 pp.
MAWSON, D.
1934. The Karoonda meteorite. Trans. Proc. Roy. Soc. South Australia, vol. 58, pp. 2–5.
POLDERVAART, A.
1950. Correlation of physical properties and chemical composition in the plagioclase, olivine, and orthopyroxene series. Amer. Min., vol. 35,

pp. 1067–1079.

UREY, H. C., AND H. CRAIG
1953. The composition of the stone meteorites and the origin of the meteorites. Geochim. et Cosmochim. Acta, vol. 4, pp. 36–82.

WAHL, W.
1950. A check on some previously reported analyses of stony meteorites with exceptionally high salic contents. Geochim. et Cosmochim. Acta, vol. 1, pp. 28–31.

WIIK, H. B.
1956. The chemical composition of some stony meteorites. Geochim. et Cosmochim. Acta, vol. 9, pp. 279–289.

YODER, H. S., AND T. G. SAHAMA
1957. Olivine X-ray determinative curve. Amer. Min., vol. 42, pp. 475–491.