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The Redfields meteorite—A unique iron from Western Australia

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SUMMARY. A metallic mass brought to the Western Australian Museum from the Wongan Hills district N.W. of Perth has been identified as an iron meteorite of unique type. It has graphite inclusions about 1 mm across distributed throughout the metal giving a 'raisin bread' appearance. Its nickel content (6·65 %) is comparable with that of coarse octahedrites but the kamacite grain structure is anomalous. Its gallium, germanium, and nickel contents place it close to, but outside, Wasson's chemical group IIb. Taenite is absent and troilite is rare. Neumann bands in the kamacite are distorted and the kamacite has flowed around large schreibersite inclusions. The latter have an exceptionally low nickel content (7·0 %) and probably formed at an unusually high temperature. The kamacite contains more phosphorus than normal iron meteorites, and small schreibersite grains in the kamacite are relatively nickel-poor (22 %). The unusual structure of this iron is thought to be due to one or more of the factors high carbon, high phosphorus, and relatively rapid cooling.

Details of the find. Mrs. M. Bennett of Wongan Hills, Western Australia, reported a 'football-sized' piece of iron recovered some years ago during stone picking in fields at Redfields Farm, 30° 43′ S. 116° 30′ E., about 11 km E. of Gabalong. Fig. 1 is a sketch map of the area.

In September 1969 Mrs. Bennett took a small piece to the Western Australian Museum in Perth. This was found to contain appreciable nickel, suggesting a meteoritic origin, though no characteristic etch pattern was observed. On request the entire mass was sent to the Museum where its meteoritic nature was confirmed by the presence of typical surface indentations (rhegmaglypts). It was apparent that the sample previously examined came from a corner that had been attacked with a blow-torch and was thermally modified. A cut, polished, and etched face on the main mass showed an unusual etch pattern.

Mrs. Bennett donated the meteorite to the Western Australian Museum, but retained a polished slice weighing 668 g. The main mass weighed 8·740 kg before

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cutting. Pieces of 350 g, 147 g, and 83 g are now in the Western Australian Institute of Technology collection, and pieces originally weighing 120 g are in the Australian National University collection. An end section of 500 g prepared as a display specimen is in the Western Australian Museum, with the remainder of the main mass (catalogue no. 13141). This meteorite was originally listed as Redlands, but its correct name is Redfields.

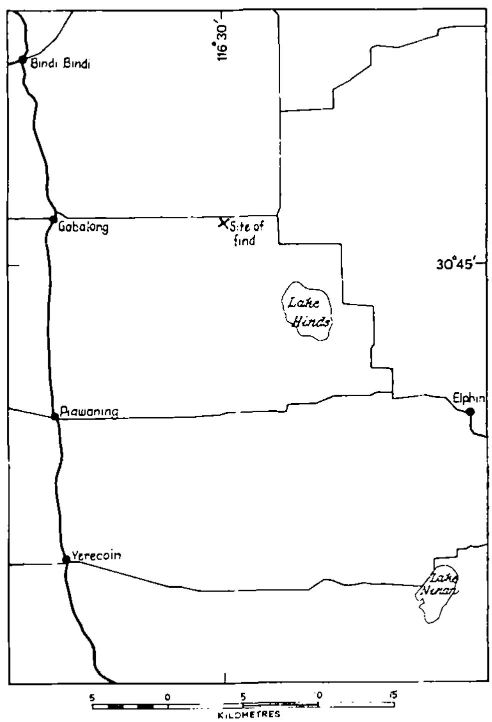


FIG. 1. Sketch map of area of find.

Description. The sole mass recovered was an elongate wedge with a brown oxidized surface showing faceting, and with rather poorly defined rhegmaglypts in a moderately fine network. Its specific gravity is 7·8. The mass is illustrated in fig. 2.

Etching a polished surface with nital reveals the kamacite grain structure (fig. 3), which, though it shows orientation, is not a normal Widmannstätten pattern. The rather irregular kamacite laths that give rise to the oriented appearance are typically 0·2 mm wide. Dark spots of graphite are distributed throughout the metal. A massive schreibersite inclusion can be seen in fig. 3. Irregular cracks traverse the mass.

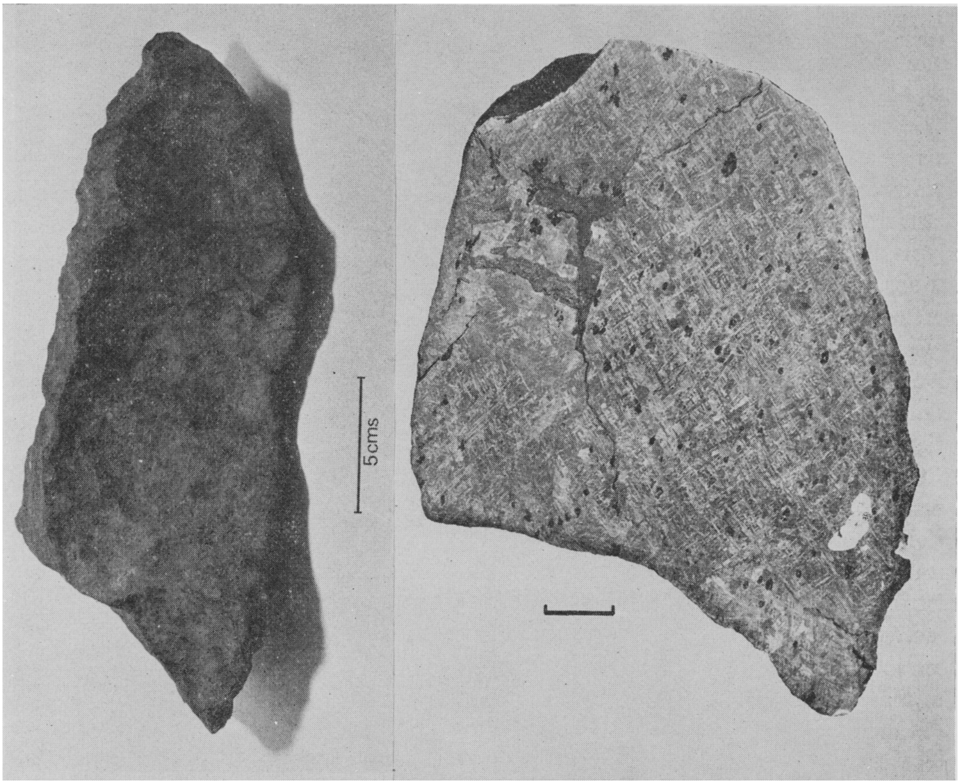
Microscopic examination of the kamacite shows Neumann bands, which are somewhat distorted throughout the mass (fig. 4). Further evidence of deformation is shown in fig. 5, where the relatively ductile kamacite is seen to have flowed around a projecting piece of schreibersite, which is heavily fractured. A similar effect in the La Primitiva iron is illustrated by Axon (1968, fig. 10, p. 222).

The kamacite away from massive schreibersite inclusions contains small schreibersite grains of similar size to the rhabdite commonly found in irons, but lacking its typical rhombic forms (fig. 6). These small grains sometimes occur at kamacite grain boundaries, and in rows down the centre of kamacite laths, but otherwise they appear to be distributed randomly. Precipitation of schreibersite has not occurred on pre-existing Neumann bands, as is sometimes observed in other irons. Small schreibersite grains are not found close to massive schreibersite inclusions, presumably because the kamacite is depleted in phosphorus in these areas.

Under the microscope a typical graphite particle is seen to consist of a core of pure graphite surrounded by a rim of graphite containing finely dispersed metal.

No taenite was found, and troilite was observed only as occasional microscopic grains.

Chemical composition. Analyses of the Redfields meteorite by various methods are given in table I. In addition to the bulk composition, analyses of kamacite and a large grain of schreibersite are included.

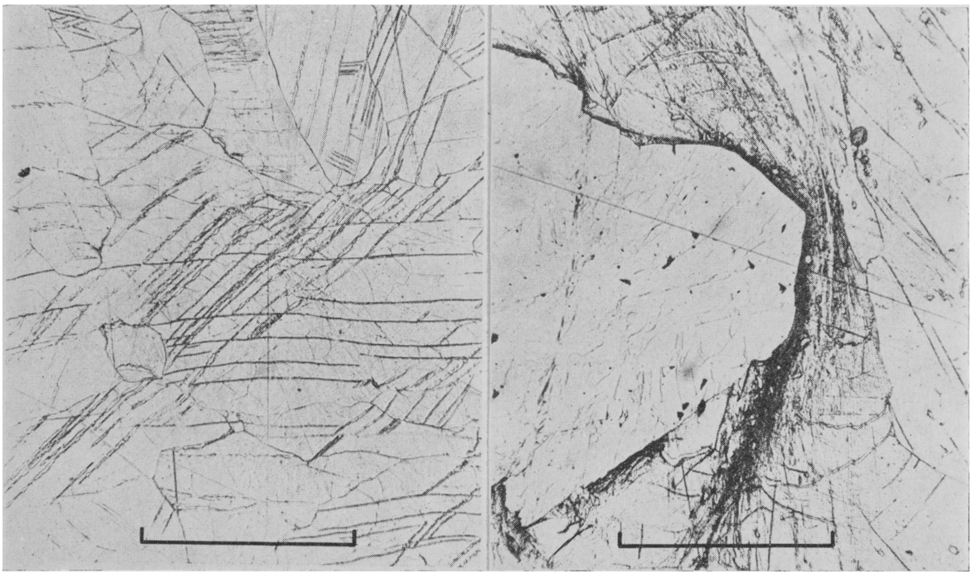


FIGS. 2 and 3: FIG. 2 (left). View of the meteorite. FIG. 3 (right). Polished and etched face showing 'raisin bread' appearance caused by graphite inclusions, also oriented kamacite grain structure and large schreibersite inclusion (scale bar 1 cm).

The X-ray fluorescence analyses were performed at the Western Australian Institute of Technology and the Australian National University, using two different procedures described elsewhere (Thomas and De Laeter, 1972; Reed, 1972). The values given for Ni, Ga, and Ge are the means of two independent determinations, and the Co figure represents a single determination at the W.A.I.T. Flat, polished, inclusion-free surfaces about 1·5 cm in diameter were selected for analysis. Samples of known composition were used as standards.

A 1-g inclusion-free sample was analysed for Ga by an isotope dilution procedure (De Laeter, 1972). A 12-g sample was used to determine Zn by isotope dilution

(Rosman, 1972). The wet chemical method described by Moss *et al.* (1961) was used to determine S. Carbon was estimated from the area of the graphite inclusions in the polished section illustrated in fig. 3, but the true total carbon content may be higher due to carbon in solution in the kamacite.



FIGS. 4 and 5: FIG. 4 (left). Distorted Neumann bands in kamacite (scale bar 0·5 mm). FIG. 5 (right). Deformation of kamacite adjacent to large schreibersite grain (scale bar 0·5 mm).

Electron microprobe analyses were carried out at the Australian National University with an A.R.L. EMX instrument, using an accelerating voltage of 15 kV. Pure element standards were used for Ni, Co, and Fe, and analysed schreibersite for P. The corrections used were those described by Sweatman and Long (1969).

Classification. The Redfields meteorite does not fall readily into any recognized class. An iron containing 6·65 % Ni would normally be a coarse octahedrite, but the structure of Redfields is quite fine and does not resemble that of an ordinary octahedrite.

The gallium and germanium contents do not lie within the limits of any of the four groups defined by Lovering *et al.* (1957). Wasson (1969) subdivided group II into four groups, of which Redfields is close to group IIb, but lies outside its limits. It is nearest to the very coarse octahedrites at the nickel-rich end of Wasson's group IIb (approximately 6·4 % Ni, 46 ppm Ga, 107 ppm Ge), which have kamacite band widths of about 0·5 to 1 cm. They have large schreibersite inclusions, but not so large or nickel-poor as those in Redfields, nor do they have 'raisin bread' graphite inclusions.

Cooling history. Schreibersite in iron meteorites is generally formed by solid-state precipitation due to saturation of the metal with phosphorus during cooling. The largest schreibersite inclusions are the first to form, and the higher the precipitation temperature the lower the nickel content. During cooling the equilibrium nickel content of schreibersite increases, but diffusion in the metal is inadequate to maintain equilibrium and therefore large early schreibersite grains retain their low nickel content. In ordinary octahedrites schreibersite contains a minimum of about 15 % Ni (Reed, 1965), and even in the anomalous phosphorus-rich irons La Primitiva and Zacatecas large grains contain more nickel (11 % and 10 % respectively) than in Redfields. The large schreibersite grains in Redfields with the exceptionally low nickel content of 7 % probably indicate formation at an unusually high temperature. This may be due to a high bulk phosphorus content, which is difficult to estimate because the phosphide phase occurs in such large, widely-spaced grains.

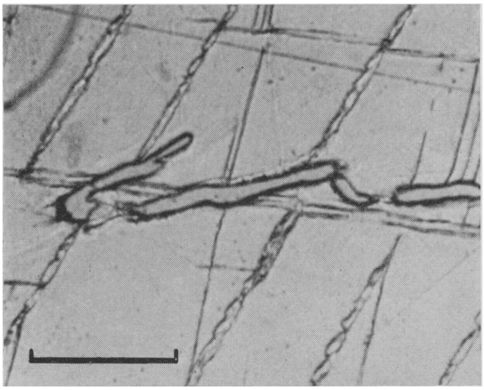


FIG. 6. Small schriebersite grains in kamacite, with Neumann bands (scale bar 100 μm).

The Fe–Ni–P phase diagram (Goldstein and Doan, 1972) shows that a high phosphorus content has a marked effect on metal phase transitions, and hence on Widmannstätten pattern formation. At 6·5 % Ni a phosphorus concentration of 1 % is sufficient to eliminate the $\gamma \rightarrow \gamma + \alpha$ transition, which normally gives rise to the Widmannstätten structure by exsolution of kamacite (α) in large taenite (γ) single crystals. Phosphorus may therefore be the cause of the anomalous structure of Redfields, but the high carbon content could also be a significant factor.

TABLE I. *Analyses of the Redfields meteorite*

	Bulk composition	Kamacite	Large schreibersite
Ni	6·65 % ± 0·1*	6·8 % ± 0·2¶	7·0 % ± 0·2¶
Co	0·48 % ± 0·01*	0·5 % ± 0·1¶	0·6 % ± 0·1¶
Fe	92·3 %†	92·2 % ± 1·0¶	76·8 % ± 0·8¶
P	—	0·23 % ± 0·02¶	15·7 % ± 0·3¶
C	0·5 % ± 0·1‡	—	—
S	0·1 %§	—	—
Zn	0·94 ppm ± 0·02‖	—	—
Ga	41 ppm ± 1‖ 40 ppm ± 4*	—	—
Ge	93 ppm ± 7*	—	—

Methods of analysis: * X-ray fluorescence, † by difference, ‡ area of graphite, § wet chemical, ‖ isotope dilution, ¶ electron microprobe.

Electron microprobe analysis showed small schreibersite grains to contain about 22 % Ni. Similar sized grains in ordinary octahedrites have at least 40 % Ni, and 35 % in hexahedrites (Reed, 1965). A typical normal schreibersite grain with 22 % Ni would have more than ten times the linear dimensions of those in Redfields. This suggests unusually fast cooling, which would allow less time for diffusion to feed the growth of schreibersite.

The phosphorus concentration of 0·23 % in Redfields kamacite is at the upper extreme of the range of concentrations found in kamacite in irons of all types (Reed, 1969). According to the Goldstein and Doan (1972) phase diagram, this amount of phosphorus saturates kamacite at about 550 °C. Ordinary octahedrites and hexahedrites generally continue precipitating phosphide to well below this temperature. The phosphorus content of kamacite cannot be taken as a direct cooling-rate indicator, since supersaturation with phosphorus may occur at low temperatures if phosphide nucleation and growth are inhibited. However, in Redfields, nucleation and growth should be easy because of the abundance of grain boundaries; therefore the phosphorus-rich kamacite may be taken as supporting evidence for fast cooling. The anomalous kamacite grain structure also may be in part the result of unusually rapid cooling.

Shock history. Neumann bands (twin lamellae) are an indication of relatively low-intensity shock found quite commonly in iron meteorites. Those in Redfields were evidently produced after the present kamacite grain structure formed, suggesting that the latter was not produced by a late reheating episode such as is known to have affected some irons. The deformation that caused the Neumann bands to be somewhat distorted throughout the mass presumably postdated both kamacite grain structure and Neumann band formation. The latter probably occurred after the precipitation of the ubiquitous small schreibersite grains, since these are not found 'decorating' Neumann bands as in some irons. The deformation that caused distortion of Neumann bands is accentuated at some points adjacent to large grains of hard and rigid schreibersite, producing flow effects in the kamacite. The cracks visible in fig. 3 are probably due to stress during atmospheric entry or landing.

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