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THE CAROLINE STONY METEORITE.[1]

By F. L. Stillwell, D.Sc.

Plate XI.

The meteorite, which looks like a piece of ironstone, was picked up by Mr. S. McEachern at the site of a blackfellows' camp about four miles north of Caroline, near the half-mile stretch of the Glenelg River which is within the South Australian border not far from the mouth of the river. A fragment of ironstone is an unusual object on extensive Tertiary limestone plain where the meteorite was found. Mr. McEachern gave it to Mr. R. A. Keble, of the National Museum, Melbourne, who recognized that it was probably a stony meteorite.

The weathered condition of the meteorite indicates that it did not fall in recent years, and since it was found at the site of a blackfellows' camp, it may have been carried there by aborigines.

The stone would not attract attention on the basaltic areas in Victoria, and this may be a reason why no stony meteorite has yet been found in Victoria.

The Caroline meteorite (Pl. XI, fig. 5) is rusty in colour, roughly rectangular in shape, and approximately 8 x 8 x 6 cm. in size; after slicing, the specimen, with detached chips, weighed 800 gm.; specific gravity, 3·40. The thin outer skin is the colour of limonite, unlike the black skin of fresh stony meteorites. One surface, where the skin was broken away, has a fractured appearance; the opposing surface, where the skin is partly preserved, displays shallow "thumb-mark" depressions which are characteristic of many meteorites. Other surfaces are relatively smooth. A hand lens reveals small fused and slaggy patches.

A vein of limonite 0·5 cm. wide (Fig. 5, lower left-hand corner) forms a slight ridge on a surface which is otherwise smooth. This vein, together with the even impregnation of iron oxide on both sides of the ridge simulates banded ironstone, but it is probably an oxidized seam of nickel-iron or pyrrhotite. After polishing, surfaces reveal numerous small secondary limonite veins formed during weathering.

In several places, irregular cracks up to 4 cm. long penetrate

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some distance below the surface; they are independent of the secondary limonite veins and were probably developed during the flight of the meteorite through the atmosphere.

Examination was confined to microscopical study of thin sections and polished surfaces, together with some chemical tests. No quantitative chemical analysis was undertaken since oxidation of much of the nickel-iron and pyrrhotite prevents satisfactory separation into magnetic and non-magnetic fractions, which is the initial step in chemical analysis of stony meteorites.

Examination in Transmitted Light.

Thin sections show the Caroline meteorite is a veined bronzite olivine chondrite.

Numerous chondrules, both monosomatic and polysomatic, are distributed through a crystalline matrix of olivine and pyroxene with small amounts of pyrrhotite and nickel-iron, scattered minute grains of chromite and rare interstitial areas of merrillite. Some chondrules are sharply defined and more or less spherical; others more irregular in shape appear to merge into the groundmass or have their outlines obscured by dense iron-staining. One monosomatic chondrule consists of a single grain of olivine 1 mm. in diameter. The polysomatic chondrules are usually aggregates of olivine crystals or of olivine and pyroxene. One of the clearest examples is a spheroid 1·7 mm. in diameter, formed largely of radiating prisms of bronzite which appears granular between crossed nicols, owing in part to intergrown monoclinic pyroxene; others consist of bronzite without the fan structure. One is composed of olivine grains separated by fine granular material including olivine, pyroxene and merrillite. Another, which is finely granular, contains minute specks of chromite and is made conspicuous by a rim of coarsely crystalline olivine and pyroxene.

Both orthorhombic and monoclinic pyroxenes are present. In sections normal to the optic axis, the orthorhombic pyroxene gives an interference figure in which the hyperbola is practically a straight line and the optical sign is indeterminate; the optic axial angle is, therefore, approximately 90° and the mineral is bronzite, not enstatite nor hypersthene. The monoclinic pyroxene has extinction angles up to 27°, indicating clino-bronzite rather than diopside.

The matrix is wholly crystalline; coarse crystals of olivine are in considerable excess over crystals of pyroxene; the grain-size is, however, variable. Many of the olivine crystals are iron-stained and some contain clusters of minute opaque inclusions some of which proved, in reflected light, to be nickel-iron and pyrrhotite.

Occasionally very minute particles of reddish brown isotropic chromite form inclusions in both pyroxene and olivine. Small irregular plates of merrillite (1), a sodium calcium phosphate, occur interstitially between crystals of olivine and pyroxene. These plates are clear and colourless and have very low polarization colours; they are uniaxial and negative, with a refractive index a little lower than that of olivine. Merrillite is attacked by dilute nitric acid, and when a little powdered meteorite, from which the more highly magnetic fraction has been extracted (the bulk of the powder can be lifted by a strong magnet), is treated with dilute nitric acid for five minutes, the solution gives reactions for both calcium and phosphorus. These tests do not distinguish between phosphorus derived from merrillite and phosphorus derived from oxidized nickel-iron. Dr. A. B. Edwards determined the amount of P_2O_5 extracted in this way to be 0·21 per cent., and the total amount of P_2O_5 in the fraction to be 0·48 per cent. Occasional small, clear, interstitial particles of low refraction and birefringence are attributed to felspar; they are biaxial and positive, sometimes show cleavage and one shows traces of lamellar twinning. A green secondary mineral in one of the limonite veins is either a chloritic or serpentinous decomposition product of the silicates. Another vein of limonite has a core of undetermined clear, colourless, secondary mineral with a low refractive index and very low birefringence.

Examination in Reflected Light.

Primary minerals recognizable on polished surfaces of the meteorite include small grains of nickel-iron, pyrrhotite and chromite disseminated among the silicates; in addition, trevorite and limonite, are present as products of weathering.

Nickel-Iron. The largest grain of nickel-iron measures 0·43 x 0·23 mm. and is comparable in grain-size with the olivine. Oxidation of nickel-iron has progressed inwards from the surface and, when incomplete, a core with a corroded outline is surrounded by limonite; grains initially large may be represented by one or more particles of nickel-iron in a large area of limonite (Fig. 1); some small particles of nickel-iron, however, have a mere thin rim of limonite, and a few are free from oxidation. Nickel-iron visible on polished surfaces does not occupy more than 0·3 per cent. of their area, but this figure would be much greater if slices were taken from the core of the meteorite, instead of from the marginal zone as has been done to avoid undue damage to the specimen. The original amount of nickel-iron, however, was probably not greater than that of pyrrhotite.

Nickel-iron, which appears bright white on the polished surface, is readily attacked by nitric acid and the solution so obtained gives microchemical reactions for nickel with dimethylglyoxime. Etching with 2 per cent. picric acid in alcohol reveals the internal structure and composition of the grains; kamacite is more readily attacked than taenite or schreibersite. Occasionally the kamacite grains enclose thin laminae which are less readily attacked and are presumably taenite; some thicker laminae consist of eutectoid mixtures of kamacite and taenite. Kamacite grains are often surrounded by a thin film of more resistant mineral (Fig. 2), probably taenite, but in one instance the proportions are reversed, the taenite rim exceeding the kamacite core in amount. In some grains an unattacked particle is attached to the kamacite (Fig. 4). Several of these chemically resistant particles were large enough to scratch with a needle; all but one were malleable, and may be regarded as taenite; one is brittle and is, therefore, schreibersite. A rare, internal, irregular intergowth with kamacite may also be schreibersite.

In some grains the progress of oxidation has been arrested at a lamina of taenite, other grains coated with a film of taenite have escaped oxidation in many cases. The taenite film may be partially separated from the kamacite by a layer of limonite, and even in completely oxidized grains, there are occasionally traces of marginal taenite.

An attempt was made to verify the presence of schriebersite by determining the phosphorus content of the more highly magnetic fraction of a sample of powdered meteorite. The highly magnetic fraction contained particles of nickel-iron, and limonite, some pyrrhotite and trevorite, and small quantities of transparent minerals; its P_2O_5 content, determined by Dr. A. B. Edwards on a sample weighing 0·15 grain, was 0·47 per cent. This percentage is higher than the average figure for stony meteorites, but is practically the same as that (0·48 per cent. P_2O_5) for the fraction unattracted by the magnet. The close approximation of the two percentages, together with the great impurity of the magnetic fraction, suggests that the oxidized minerals include some phosphate; and since schreibersite, merrillite and possibly apatite are the only likely compounds of phosphorus in the unaltered meteorite and since merrillite is relatively unaltered, it seems likely that such phosphate as is associated with limonite has been derived from phosphide in the nickel-iron. There is thus an indirect suggestion that the residual nickel-iron contains phosphorus in sufficient amount for the presence of the phosphorus-rich constituent schreibersite.

Pyrrhotite. Pyrrhotite appears in the section as small irregular brownish-cream grains of variable size; they are magnetic, strongly anisotropic, and resistant to nitric acid, but tarnish slowly with caustic potash. In appearance and behaviour they are identical with pyrrhotite from other sources. Short's statement (2) that troilite, the iron sulphide in meteorites, is attacked by nitric acid with effervescence, was confirmed by a test on troilite in a polished surface of the Henbury meteoritic iron. Troilite occurs in iron meteorites in a matrix of metallic iron, and has frequently been reported in stony meteorites. Allen, Crenshaw, Johnston and Larsen (3) pointed out that troilite is the end member of a series of solid solutions of iron and sulphur known as pyrrhotite, and that stony meteorites probably contain ordinary pyrrhotite. Examination in reflected light determines that the sulphide in the Caroline meteorite is indistinguishable from pyrrhotite.

Numerous small particles of pyrrhotite occupy about 3 per cent. of the area of the polished surfaces, and are generally isolated in the silicates from the scarcer particles of nickel-iron. In a few instances pyrrhotite is in partial contact with nickel-iron or limonite derived from nickel-iron (Fig. 1). In rare cases minute particles of pyrrhotite are enclosed in nickel-iron.

Pyrrhotite, though much less weathered than nickel-iron, presents all stages of decomposition into limonite; decomposition proceeds, not so much from the external surface as along fractures, where veins of limonite develop; all stages of alteration are represented, from a pyrrhotite grain transversed by a network of limonite veins, to a limonite mesh containing minute particles of pyrrhotite. Traces of this meshwork remain after oxidation is complete and distinguish an area of limonite derived from pyrrhotite from one derived from nickel-iron.

Chromite. Grains of chromite are much fewer than those of pyrrhotite. One of the larger grains measures 0·18 x 0·10 mm. Occasional minute particles not more than 0·006 mm. wide are embedded in the silicates or in interstices between them and correspond to the small particles of chromite recognized in transmitted light. The grains are hard, resistant to weathering, and distinguished on polished surfaces by their colour, greyish white with a tinge of brown; they are isotropic and resistant to all standard etching agents. Their shape is at times suggestive of octahedral outlines. They are free from inclusions except in rare instances when they appear to enclose small particles of pyrrhotite or of a silicate; narrow veins of iron-oxide occasionally extend from surrounding areas into a grain of chromite, sometimes dying out within the limits of the crystal, sometimes cutting through it. Pyrrhotite when in contact with chromite appears to be moulded on it. The edges of small particles excavated from the polished section and examined in transmitted light, are translucent and dark green merging in places into brownish. Normal chromite grains are brownish in transmitted light, and the green tint may indicate an isomorphic mixture of chromite with picotite or hercynite.

The presence of chromium was confirmed by a qualitative "spot" test with diphenylcarbazide. Powdered meteorite was fused on a platinum wire in a bead of potassium carbonate and potassium chlorate; the bead was dissolved in water, the solution concentrated, and then acidified with two drops of 1:1 H_2SO_4. Two drops of a 1 per cent. alcoholic solution of diphenylcarbazide added to this solution gave the violet-blue colouration characteristic of chromium in the absence of mercury and molybdenum, neither of which is present in the meteorite. The same test applied to particles of chromite excavated from the section gave a similar positive result.

Trevorite. Weathering has produced numerous narrow, anastomising veins of limonite in addition to isolated areas of limonite derived from pyrrhotite and nickel-iron. Many of these veins are extremely narrow, others are 0·2 mm. wide, and still wider areas of limonite occur at the intersection of veins and in other localized areas. Colloform banding in many veins is indicated on polished surfaces by different shades of grey assumed by different varieties of limonitic hydroxides, and in places the banding is accentuated by very thin lines of a whiter mineral, possibly hematite. Trevorite, $NiO.Fe_2O_3$, sometimes forms part of the banding (Fig. 3), and small massive areas within the vein; trevorite was also observed as a small crystal attached to a limonitic pseudomorph after nickel-iron.

Trevorite was established as a mineral species by Walker

(4) and shown to be a common product of oxidation of meteoric irons by Shannon (5). Its reflective power is higher than that of limonite or chromite, and on the polished section its colour is greyish-white with a pinkish tint. It is isotropic, slightly harder than limonite, and does not have internal reflections. It resembles magnetite except perhaps for its pinkish tinge and for its obviously secondary character. It is negative to nitric acid and other standard etching agents, but is slowly attacked by concentrated hydrochloric acid. Particles are magnetic and when dissolved in hot hydrochloric acid give reactions for nickel with dimethylglyoxime.

Occasionally the colloform banding including trevorite is cut transversely by newer narrow limonite veins (Fig. 3). In some instances margins of areas of massive trevorite are corroded by limonite, and in places the edges of trevorite bands are separated from limonite by extremely narrow whitish zones which may possibly be hematite. These phenomena suggest that the formation of trevorite is a phase in the oxidation of nickel-iron which will ultimately be converted into limonite with complete removal of nickel. The ratio of trevorite to limonite is small, just as is the ratio of nickel-iron to silicates.

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Plate XI.

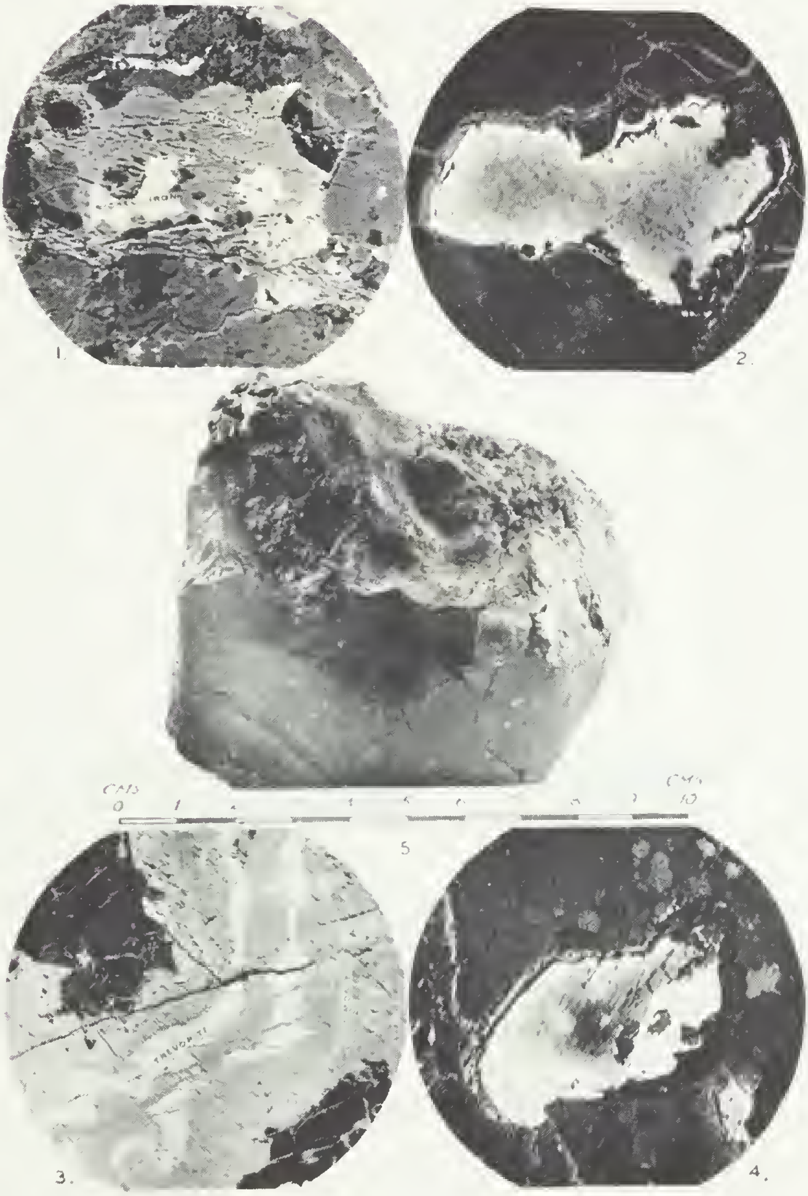
Fig. 1. Two residual cores of nickel-iron in an area of limonite in contact with a particle of pyrrhotite. Mag. 110.

2. Grain of nickel-iron, etched with 2 per cent. picric acid in alcohol; the darkened area of kamacite is surrounded by an unattacked, marginal film of taenite. Mag. 400.

3. Trevorite in a limonite vein showing colloform banding. Trevorite is cut by later narrow veins of limonite. Mag. 110.

4. Grain of nickel-iron, etched with 2 per cent. picric acid in alcohol, composed of a darkened area of kamacite with a partial marginal film of taenite and an unattacked particle of taenite. Mag. 400.

5. The Caroline stony meteorite, showing pitted and fractured surfaces in the upper part and a vein of oxidized nickel-iron in the lower left corner.



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