

MINERALOGICAL MAGAZINE

JOURNAL OF THE MINERALOGICAL SOCIETY

Vol. 33

June 1962

No. 257

The Wairarapa Valley, New Zealand, chondrite.

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[Taken as read 25 January 1962.]

Summary. The Wairarapa Valley hypersthene-olivine chondrite, found about 1863, has been analysed with the following result: SiO_2 35.72, TiO_2 0.11, Al_2O_3 2.91, Cr_2O_3 0.48, FeO 12.42, MnO 0.28, MgO 23.28, CaO 1.73, Na_2O 0.96, K_2O 0.20, P_2O_5 0.31, Fe 12.61, Ni 1.50, Co 0.04, FeS 5.46, Cl 0.07, H_2O^+ 1.05, H_2O^- 0.48, less O for Cl 0.03; total 99.58%. D. 3.65. The phases present are kamacite, taenite, plessite, troilite, magnetite, chromite, olivine Fa_{16} , bronzite Fs_{15} , possibly enstatite, plagioclase An_{25} , and (?) maskelynite An_3 . The structures of the silicate phases and those disclosed by etching the metal phase are illustrated and described.

THE earliest published reference to this meteorite is in an essay written for the New Zealand Exhibition of 1865 by Crawford (1869) who records that it was found in the year 1863, on, or near the surface of, a plain underlain by coarse gravel, in front of the house of a Mr. Donald, at Manaia, near the left bank of the Waingawa River in the Wairarapa district of Wellington Province. On modern maps 'Manaia Road' is shown $3\frac{1}{2}$ miles south of the town of Masterton (Provisional One Mile Sheet N 162, grid reference 140590). Crawford gives the dimensions as 9 in. by 6 in. by 7 in., and quotes a report from the Laboratory of the Geological Survey, Dunedin, as follows:

The fragment submitted for analysis was externally of a rust colour with an exudation of chloride of iron. The freshly fractured surface was of a dull grey colour. Its hardness was between 5 and 6, and its specific gravity 3.254. It is affected by the magnet, but does not exhibit polarity. It consists principally of earthy silicates and sulphide of iron, but also contains nickel and native iron, and possesses the general character of a meteoric stone.

In the Reports and Awards of Jurors of the New Zealand Exhibition, 1865, p. 410, the following additional description is given (some chemical tests are also reported):

The shape of the mass is an irregular pyramid with rounded edges measuring as

follows: height 7 inches; length of base 7 inches; breadth of base 6 inches; contents 49 cubic inches; weight $9\frac{1}{4}$ lbs. The surface is broken by rounded indentations, never exceeding half an inch in depth, evidently produced by weathering.

Flight (1875), quoting Sir James Hector, Director of the New Zealand Geological Survey, gives the date of the find as 1864, and reproduces, with slight paraphrasing, the description given in the Jurors' Reports of the 1865 Exhibition, including the results of the chemical tests mentioned above. He gives the weight of the stone, however, as 480 oz. The meteorite is recorded as being preserved in the Colonial Museum in Wellington.

In the New Zealand Court Catalogue of the Centennial International Exhibition, Melbourne, 1888, p. 13, item 20, appears the following:

Cast of a meteorite found at Manaia near Masterton in 1862 by Mr. W. H. Donald, who gave it to Mr. Richard Collins of Te Ore Ore; Mr. Collins presented it to the Hon. W. B. D. Mantell, M.L.C., F.G.S., F.R.G.S., etc., who deposited it¹ in the Colonial Museum, Wellington, New Zealand, in 1867.

Hector (1898) refers in passing to the meteorite found at Masterton, and repeats its weight as 9 lb. At this time it was apparently still in the Colonial Museum.

Marriner (1910, p. 177) attributes the find to Mr. Richard Collins at Tohirua [? Te Ore Ore] near Masterton. He reproduces Flight's article, recording in a footnote that 'the stone was only deposited in the Museum. It is now in the possession of Mr. W. G. Mantell [? W. B. D. Mantell] to whom it belongs.' After quoting the account in the Jurors' Reports of 1865 he writes (p. 178): 'Mr. Donovan² of Wellington is at present making a more complete analysis of this stone.'

The Accession Register of Auckland War Memorial Museum for 1928 records the presentation by Mrs. Mantell, widow of Mr. W. B. D. Mantell, of 'two pieces of meteorites that have fallen in New Zealand' (Accession no. 55/28). After being mislaid for some years this specimen was recovered, during reorganization of the collections, in 1955. It corresponds, from the descriptions already quoted, with the greater part, at least, of the Wairarapa Valley meteorite.

¹ The late Dr. W. R. B. Oliver, formerly Director of the Dominion Museum (formerly the Colonial Museum), informed me that there is no trace in the Museum register for 1867, or any other year, of the meteorite having been deposited by Mr. Mantell.

² Mr. Donovan was at one time Director of the Dominion Laboratory. Dr. Grigg, Director of the Laboratory, informed me in 1955 that he was unable to discover any details of the analysis Mr. Donovan was stated to have been making. It did not appear in the Index of analyses published in the Annual Reports of the Laboratory.

It will be observed that the volume of the stone given in the early accounts does not correspond with the dimensions quoted. Nor does the weight recorded correspond with the volume and specific gravity. A rough estimate of the volume based on the dimensions given in the early papers, together with the newly determined specific gravity of 3.646, gives, however, a figure in reasonable agreement with the actual weight of the fragments of Accession 55/28, which was 5861 g (nearly 13 lb).

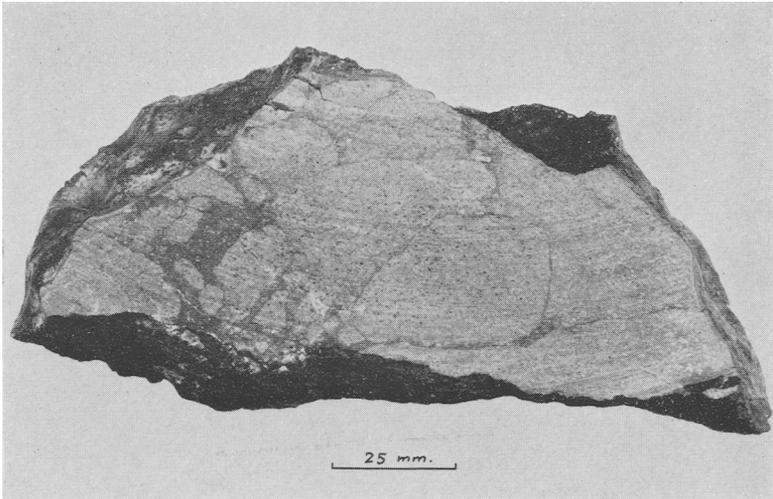


Fig. 1. Sawn surface of Wairarapa Valley chondrite, showing brecciation.

The identity of the Auckland Museum specimen with the Wairarapa Valley chondrite has been confirmed by examination of a thin section from the collection of the late Prof. P. Marshall, now in the Dominion Museum,¹ labelled 'Wairarapa Meteorite'. This corresponds in every respect with sections from the Auckland Museum specimen.

Description. The external appearance of the stone is sufficiently described above. Though it bears thumb-print depressions on its surface, no distinct glassy crust remains. The texture is firm, but the stone breaks with an irregular fracture controlled by fine cracks, not visible on the exterior, the interior surfaces of which bear a rusty stain. A sawn surface shows its brecciated character (fig. 1): the fracture is, however,

¹ This thin section was kindly made available by Mr. Geoffrey Shaw, Geologist at the Dominion Museum. His courtesy and that of the Museum authorities are gratefully acknowledged.

independent of this brecciation and passes through fragments and matrix alike.

The general texture of the stone in thin section is shown in fig. 2. A variety of chondrules occur, including barred olivine chondrules (figs. 5, 7), polysomatic olivine chondrules with acicular enstatite (?) crystallizing between the olivine sub-individuals (fig. 4), excentric radiating

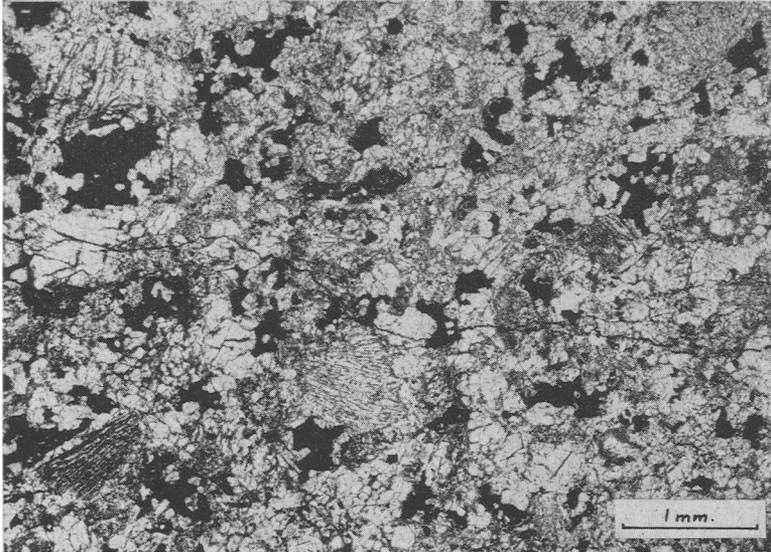
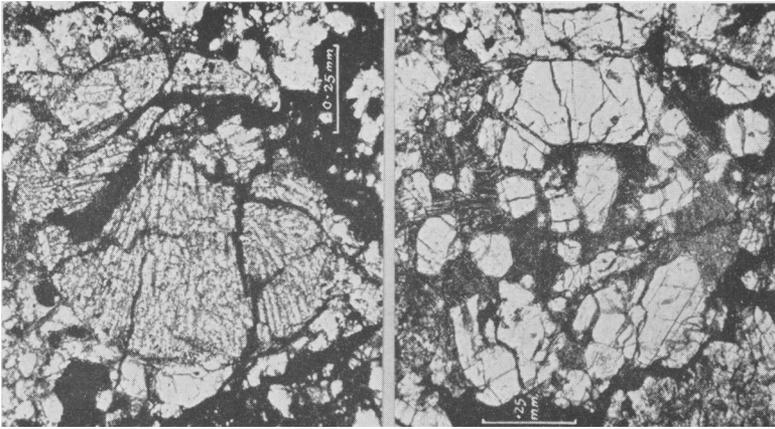


FIG. 2. Thin section of Wairarapa Valley chondrite, showing various types of chondrules.

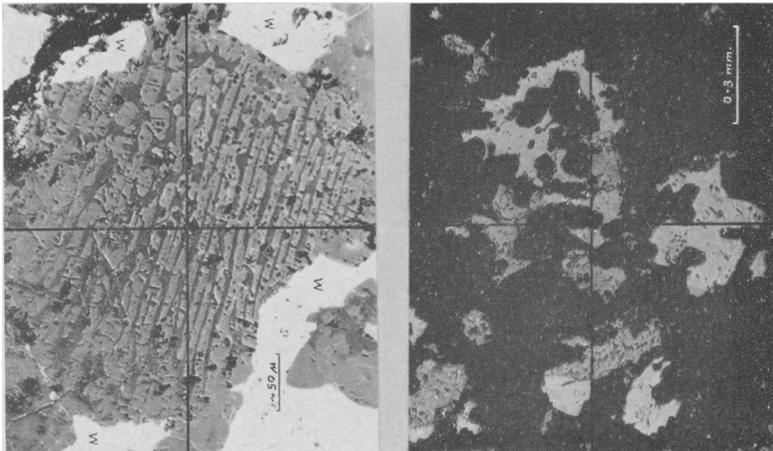
chondrules of probable enstatite or bronzite (fig. 3), others consisting of decussate groups of orthopyroxene rods, and some with a more or less parallel intergrowth of olivine and orthopyroxene.

These structures are set in a groundmass of rounded olivines and rather more elongated bronzite crystals, between which are films and lanes of extremely fine anhedral, rounded (? triturated) crystal fragments, which sometimes show a tendency to recrystallize in elongate habit.

Nickel-iron and troilite are evenly distributed in amoeboid and spongy masses and appear to be moulded on chondritic structures, at least in part (figs. 5, 6, 7). The particles of both metal and sulphide range downwards in size to small dimensions, the sulphide in particular being present as tiny specks in the lanes of fine-grained material.

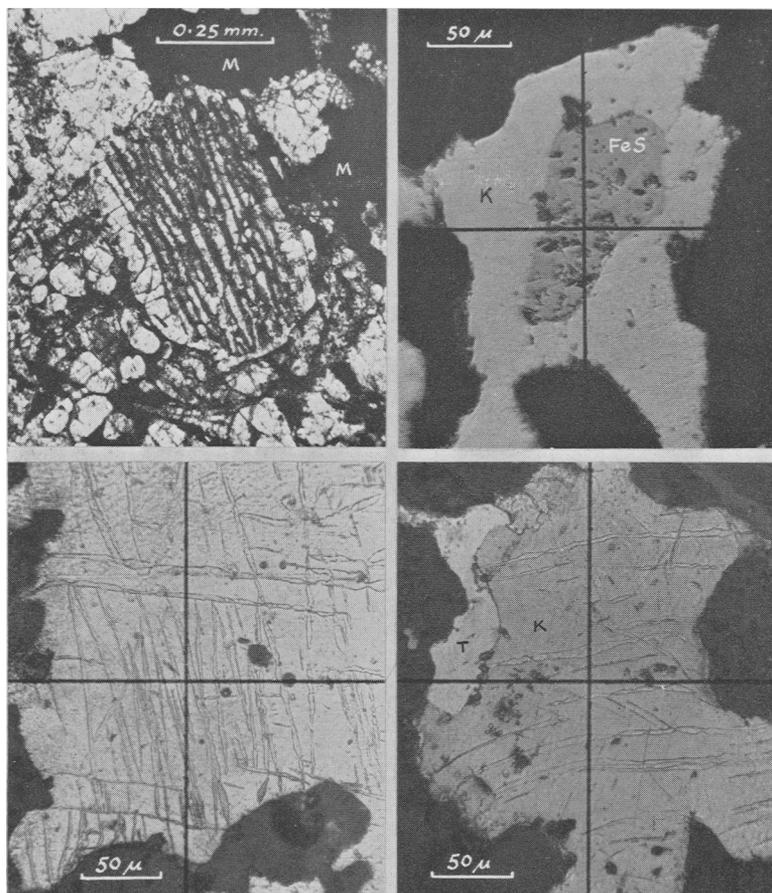


FIGS. 3 and 4: FIG. 3 (left): Excentric radiating chondrules of orthopyroxene. (Transmitted light.) FIG. 4 (right): Polysomatic olivine chondrule with orthopyroxene needles. (Transmitted light.)



FIGS. 5 and 6: FIG. 5 (left): Barred olivine chondrule. (Reflected light.) *M* = metal. FIG. 6 (right): Nickel-iron (white) and troilite (light grey) in silicates (dark grey). (Reflected light.)

Magnetite forms a partial rim to many metal and sulphide areas and is also scattered as independent rounded grains, whilst in places it forms a network in between silicate grains. The whole is traversed by unevenly distributed veinlets and strings of dark-brown iron oxide material and in part of magnetite. The specific gravity of the chondrite is 3.65.



FIGS. 7 to 10: FIG. 7 (top left): Barred olivine chondrule. (Transmitted light.) *M* = metal. FIG. 8 (top right): Troilite (FeS) surrounded by kamacite (K). (Reflected light.) FIG. 9 (bottom left): Kamacite with Neumann's lines. (Reflected light.) FIG. 10 (bottom right): Kamacite (K) and taenite (T). (Reflected light.)

Chemical composition. Table I presents the results of a chemical analysis of the stone. Separation of the metal from the silicates was carried out by Wiik's modification (1950) of Friedheim's procedure (1888), a digestion with mercuric chloride and ammonium chloride. Two extractions were made and duplicate titrations of iron carried out on each, with good agreement of the results. The accepted result for nickel from this extraction (1.45 %) is a little lower than that

found on the main portion used for the silicate analysis (1.50 %). One would expect any difference to be in the other direction since some analysts believe a small amount of nickel comes down with the ammonia precipitate (Groves, 1951, p. 139). It is therefore just possible that some nickel occurs in the silicate phase; but if so the amount is

TABLE I.

	A.	B.	C.
SiO ₂	35.72	45.55	Orthoclase 1.11
TiO ₂	0.11	0.14	Albite 8.38
Al ₂ O ₃	2.91	3.72	Anorthite 3.06
Cr ₂ O ₃	0.48	0.61	Diopside 3.26
FeO	12.42	15.84	Hypersthene 15.33
MnO	0.28	0.36	Olivine 47.40
MgO	23.28	29.69	Chromite 0.67
CaO	1.73	2.21	Apatite 0.67
Na ₂ O	0.96	1.22	Troilite 5.57
K ₂ O	0.20	0.26	Nickel-iron 14.43
P ₂ O ₅	0.31	0.40	
Silicate	78.40	100.00	
Fe	12.61	89.12	
Ni	1.50	10.60	
Co	0.04	0.28	
Metal	14.15	100.00	
Fe	3.47		
S	1.99		
Troilite	5.46		
Cl	0.07		
H ₂ O ⁺	1.05		
H ₂ O ⁻	0.48		
	99.61		
Less O for Cl	0.03		
Total	99.58		
D.	3.65		

A, chemical analysis of Wairarapa Valley chondrite. Analyst: M. H. Battey.
B, silicate and metal portions calculated water-free and to 100 %.
C, normative composition.

small and the higher figure has been returned as metallic nickel, without any adjustment to the iron.

The presence of magnetite in the stone means, of course, that the usual practice, which has been followed here, of reporting all the iron as ferrous is incorrect. But as it is impossible to separate the two oxidation states satisfactorily in the presence of sulphide, and as the micrometric estimation of the magnetite would be very uncertain, this error cannot be corrected.

The water content of the stone is high and this, together with the rusty exudation from the stone, suggests that it is somewhat weathered, as is to be expected from its history as a find. Chlorine was sought, in

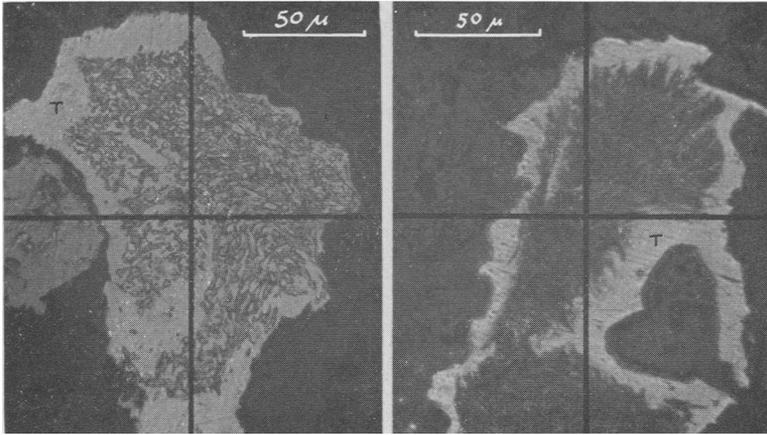
connexion with the brown exudation from fine cracks in the stone, which was thought possibly to be lawrenceite. A definite positive test resulted, but the amount present is very small.

The ratios Fe:Ni and MgO:FeO place the Wairarapa Valley stone as a hypersthene-olivine chondrite (Baroti and Soko-Banja types) in Prior's classification (Prior and Hey, 1953, p. xi). With regard to total iron content and distribution of iron between metal+sulphide and silicate, the analysis plots exactly between the two areas of concentration found by Urey and Craig (1953). The plotted point falls between their two lines of constant total iron and on a line parallel to the 45° line from the origin lying between the two areas of concentration.

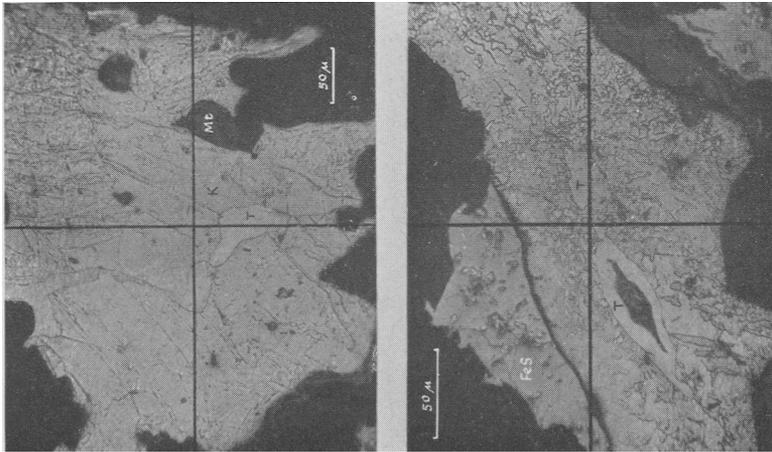
The norm (table I) has been calculated in accordance with the recommendations of Wahl (1950) except that P₂O₅ is allotted to apatite as suggested by Mason and Wiik (1960).

Mineralogy.

The metal phases. On a water-free basis the metal phase constitutes 14.43 % by weight (about 6.8 % by volume) of the chondrite. Its percentage composition by weight is Fe 89.1, Ni 10.6, Co 0.3. Etched with nital (2 %) a variety of structures is shown in different grains, some of which are illustrated in figs. 9 to 14. They mostly fall into the following three groups: Homogeneous grains apparently little affected by etching; some of these are, by their hardness, shown to be taenite, others are apparently kamacite. Grains with Neumann lines are of kamacite, but may enclose areas of taenite, in which case the Neumann lines stop at the taenite boundary. The 'lines' are, in section, narrow lanes bounded on either side by a fine line, and these bounding lines are wavy, so that the lanes pinch and swell, sometimes breaking up into trains of discrete spindle-shaped areas. The bounding lines show anisotropy in reflected light. The lanes are rarely straight, being most commonly gently curving, but sometimes quite sharply bent. They may divide, and frequently taper out. Sets intersecting at angles near 90° occur, while in other cases two trends may intersect at an acute angle. Though the lustre of the etched iron within and without the lanes is sometimes different, there is often no marked distinction of this kind. In the rather rare cases when the lanes are wide enough to be tested, the hardness of the iron within them is the same as that of the field outside. Grains with an intergrowth of two phases (plessite)—these intergrowths vary in fineness, being sometimes very dense and etching a dark grey, so that they are irresolvable under the microscope (fig. 12); in other cases the two



FIGS. 11 and 12: FIG. 11 (left): Plessite with taenite border (T). (Reflected light.)
 FIG. 12 (right): Fine plessite crystallizing in needles, surrounded by taenite (T).
 (Reflected light.)



FIGS. 13 and 14: FIG. 13 (left): Kamacite (K) with Neumann's lines, which show passage to irregular lobed areas. Taenite (T) and magnetite (Mt). (Reflected light.)
 FIG. 14 (right): Fine plessite surrounded by taenite (T) surrounded by polycrystalline kamacite with some irregular taenite areas. Troilite (FeS). (Reflected light.)

phases are distinct (fig. 11). Such intergrowths are commonly surrounded by a clear border shown by its hardness to be taenite. The complete structure of plessite and its taenite envelope may be enclosed in kamacite at the level of the section.

The reflectance¹ of the metal phase in green light, before etching, is 61.4 %. The reflectances of the phases distinguishable after etching were not measured, as these would probably be dependent on the exact

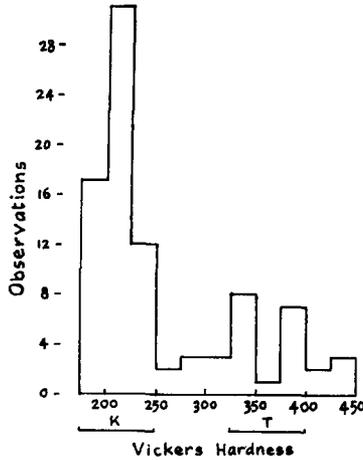


FIG. 15. Hardness of kamacite (K) and taenite (T).

etching technique. The average Vickers hardness of the kamacite is 210 and that of the taenite 352. The range of values found was fairly wide, but, as is indicated in fig. 15, a well-marked distinction exists between the two alloys and the hardness is a useful determinative criterion if sufficient measurements are made.

In the X-ray powder pattern of the strongly magnetic portion of the meteorite, separated by a hand-magnet, nearly all the lines can be accounted for by α -iron, γ -iron-nickel, magnetite, and troilite. The cell-edge of the α -iron is approximately 2.868 Å and that of the γ -phase 3.588 Å. Using the data of Owen and Sully (1941) this suggests that the kamacite contains about 3 % (atomic) Ni and the taenite somewhat over 30 % (atomic) Ni. On the Fe-Ni phase diagram (Owen and Liu, 1949) this would correspond to an equilibrium temperature of about 480° C,

¹ The writer is greatly indebted to Dr. J. M. Jones of King's College, Newcastle, for determining the reflectance on a newly developed electronic photometer (J. M. Jones, *Econ. Geol.*, in press). The standards employed were a glass of reflectivity 10.26 % and pyrrhotine (Krantz-Ramdohr) with a value of 38.28 %.

but little significance can attach to this figure in view of the variable character of the metal particles in the Wairarapa chondrite.

Sulphide phase. Troilite comprises 5.46% by weight of the stone. It is distinctly yellow in reflected light and always contains numerous unidentified inclusions. Its average Vickers hardness is 285, compared with pyrrhotine, 263. It occurs both as separate amoeboid areas and in intimate association with the metal phase. Between crossed polars the anisotropy discloses that the areas are often polycrystalline. Where troilite is in contact with metal the two phases meet in a smooth curving boundary (fig. 6), though sometimes a layer of magnetite intervenes. It is possible to find sections giving the appearance either of enclosure of troilite by metal (fig. 8) or metal by troilite. Larger areas of both troilite and metal appear to be moulded around silicate crystals and especially silicate chondrules. Particles of both sulphide and metal may, however, be very small (down to a few microns across) and these may appear within silicate crystals or chondrules.

Oxide phases: Magnetite. The powder photograph of the strongly magnetic fraction shows the lines of magnetite (fig. 16), the presence of lines at d 2.425 Å, and d 0.988 Å, together with spacings in the middle 2θ region being relied upon to distinguish the pattern from that of chromite. Although Wahl (1950) expresses doubt whether magnetite can occur in a chondrite containing metallic nickel-iron, it certainly seems to be present in the Wairarapa Valley stone.¹

In thin sections examined by oblique reflected light many of the metal particles are seen to have a discontinuous border, from a few microns to 20 μ wide, of black material, which is identified as the magnetite. The same substance in places forms an anastomosis between metal and silicate grains, and also forms part of the filling of fine cracks traversing the stone, which are for the rest filled with goethite. Under vertical reflected light the magnetite is light grey in colour, fairly highly reflecting, and isotropic. It contains numerous small inclusions. Vickers hardness tests gave variable results, averaging 850 and in general higher than standard magnetite tested and higher than the value given by Bowie and Taylor (1957). The areas available for test were, however, very limited, and measurable indentations were achieved with difficulty.

Chromite. The chemical analysis indicates that chromite is probably present. A sample of the meteorite was strongly digested in HCl and the residue centrifuged in heavy liquid to produce a concentrate for powder

¹ It has recently been reported in the interiors of a number of chondrites (e.g. Yudin, 1955, 1958; Sztrókay, 1960; Hey, priv. comm., 1962).

photography. On the resulting photograph the magnetite line at d 2.425 Å is absent, the d 0.988 Å line is not visible (all high angle lines are faint, and the strong absorption of the Fe radiation used may itself indicate chromium), and the spacings of the other lines of the spinellid phase indicate chromite.

Goethite. In thin section the silicates are fairly extensively stained by brown secondary iron hydroxide. Fine cracks in the stone are in part filled by material that is dark reddish-brown by transmitted light. In vertical reflected light it is light grey in colour with a reflectivity less than that of magnetite, which is associated with it in the veinlets. It is anisotropic, the appearance between crossed polars being dominated by reddish internal reflections.

Silicate phases: *Olivine* forms a variety of barred and polysomatic chondrules, as well as rounded granules. It often shows a conspicuous parting parallel to the optic axial plane. In the barred olivine chondrules the dominant direction of the 'bars' of finely recrystallized material is parallel to the c -axis, and the parting parallel to the optic axial plane is well developed in the intervening strips of olivine (figs. 5, 7). The optical properties, $2V_\alpha = 88^\circ$ and $\beta = 1.683$, give a composition Fa_{16} according to the curve of Poldervaart (1950).

Orthopyroxene. Except when it forms excentric radiating chondrules, this mineral is with difficulty distinguished from olivine in thin section. Intersecting sets of cleavage cracks are not well seen. Some crystals have fine, parallel, rod-like inclusions or an excessively fine striping of exsolution lamellae near the extinction position; but the low birefringence remains the only distinguishing feature of most grains. In larger crystals $2V_\alpha$ averages 87° and $\gamma = 1.680$, indicating a bronzite, Fs_{15} (curves of Kuno, 1954). In the bundles of rods forming radiating chondrules, or crystallizing between the olivines of polysomatic chondrules, the refractive index along the length (taken as γ) averages 1.670, suggesting that enstatite may be present as well as bronzite.

Plagioclase. Only one crystal of this was observed in the thin sections, but it was recognized in crushed material briefly treated with HCl. It has a refractive index β of 1.547, indicating a composition An_{25} .

Maskelynite. In crushed material treated with HCl there was also clear colourless isotropic material of refractive index 1.496. The refractive index given for maskelynite is 1.51 (Merrill, 1918), but the value may be expected to vary with composition. Comparison with refractive indices of glasses of plagioclase compositions (Larsen, 1909) suggests that the present substance may be maskelynite of composition An_9 .

Acknowledgements. The author's thanks are extended to Dr. J. M. Jones and Mr. J. Lee, Geology Department, and Dr. R. F. Tylecote and Mr. D. Maxwell, Metallurgy Department, King's College, for their help: and to Dr. G. Archey, Director, Auckland War Memorial Museum, for making the meteorite available for study.

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