

*New material from, and a reconsideration of,
the Dalgaringa meteorite and crater,
Western Australia*

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[Taken as read 23 September 1965]

Summary. Two small fragments of unpromising-looking ferruginous material, recovered from inside the Dalgaringa crater, near Mount Magnet, Western Australia, have been sectioned and, while one is largely composed of iron oxides and adds little to the record of this crater, the second fragment is one of the rare, predominantly stony ones reported by Ninninger and Huss, and is sufficiently fresh for a thin section to be prepared. As far as is known no thin sections have been described of material from this crater. Microscopic study with transmitted light shows the stony material to be achondritic and to have affinities with the mesosiderites, and, in spite of the low nickel-iron content of this fragment, it seems preferable to regard it as representative of an iron-poor area within a mesosiderite than as true stony meteorite material. Although closely related to the howardites it cannot be classified with any known achondrite type because of the prominent olivine phenocrysts and it bears no resemblance at all to chondritic material. Mineralogical and petrographical details are described and illustrated, and the significance of this new evidence discussed. The origin of the crater is reconsidered.

IN December 1964 two small fragments were sent to Mr. W. H. Cleverly of the School of Mines, Kalgoorlie, by Mr. F. W. G. Power of Geraldton. He had obtained them from Mr. J. S. Nevill, who reports that he recovered them from the pit excavated by a Mr. Latham on the southern side of the crater floor, against the granite wall, after the last set of fragments were sent to Dr. H. H. Ninninger (about 1960). The crater has been mentioned by Simpson (1938), described in detail by Ninninger and Huss (1960), and again mentioned by McCall and de Laeter (1965). It has a diameter of 70 ft, a maximum depth to the surface of the fill of 10 ft, and the most accurate co-ordinates so far obtained are 27° 43' S., 117° 15' E.

Previous observations at Dalgaringa crater

Simpson (1938, p. 157) briefly reported the existence of this crater and the association of small, twisted iron fragments of octahedrite

character. Nininger and Huss (1960) published the first appreciation of the evidence: they consider the crater to have been formed about 25 000 years ago by impact of a meteorite weighing 10–20 tons, and predominantly composed of stony material (90 %). They reached this conclusion in spite of the overwhelming predominance of iron and stony-iron fragments among the recovered material, dismissing the apparent proportional anomaly as due to ease of decay of stony material. They mention chondrule-like inclusions but certainly make no firm claim that the stony component was chondritic. They conclude that much of the meteorite was mesosideritic, a conclusion that seems to have been based on polished section studies. The textures illustrated, networks of metal in a highly oxidized state enclosing silicates, do, in the illustrations they provide, closely resemble mesosiderite textures in character and degree of fineness. Silicate grains were extracted and have been reported on as rhombic pyroxene, probably bronzite, by E. R. du Fresne (Nininger and Huss, 1960, p. 634) and more accurately determined by B. H. Mason as hypersthene (p. 483).

McCall and de Laeter (1965) have summarized the evidence, noting a dissentient view expressed by Mason (letter to the writer) that this could represent an iron meteorite with abundant silicate inclusions rather than a mesosiderite. These authors agree with Nininger that this crater must be of considerable antiquity—for the southern pit, deepened since Nininger left the area, has now revealed stratified sedimentary material composed of coarse, angular grains of quartz and feldspar, derived from the nearby granite and underlying the soil and rubble forming the upper part of the crater infill.

Doubts have even been expressed by geologists that this is a meteorite crater at all, but such scepticism discounts the unquestionable, though meagre, association of meteorite fragments.

Nininger's preference for a predominantly stony mass seems to stem from consideration of the meagre total recovery alongside the supposed theoretical requirements of a crater of this size, which lead him to assume that the mass was of 10–20 tons. However, the discrepancy of meagre recovery from a set of craters of comparable dimensions is known from Sikhote-Alin, Siberia, where a group of fragmentation craters was formed within a dispersion ellipse during a fall in 1949 (Krinov, 1961, p. 142). Dalgara shows no evidence of being anything but a fragmentation crater (though no detailed search for coesite or traces of fusion indicative of explosion has yet been carried out). The Sikhote-Alin meteorite was entirely composed of nickel-iron, and so no recourse to an

explanation such as is offered by Nininger and Huss could apply in this case. This suggests that some quite different resolution is needed for the anomaly of small recovery from large fragmentation craters, and the invocation of dominantly stony composition for Dalgara is probably unnecessary. Sikhote-Alin was a mass estimated at 70 tons before disintegration late in atmospheric flight, and this produced several craters of equivalent size to Dalgara (Krinov, 1963): in contrast Dalgara is a lone crater and it seems likely that the entire mass hit the crater without any atmospheric fragmentation. Thus it seems obvious that a crater of this size could be produced by impact fragmentation of a mass of only a ton or two—and it is significant that the Sikhote-Alin craters of comparable dimensions show comparable evidence of fine fragmentation (Krinov, 1963*b*). The initial velocity of Sikhote-Alin is estimated as 14.5 Km/sec (Krinov, 1963*b*, p. 219), and so there seems, on the face of it, no need to invoke high velocity impact such as could ensue from head on collision with the Earth (a situation that, from consideration of inclinations to the plane of the ecliptic and direction of movement of asteroidal orbits together with statistics of meteor brightness (Fedynsky, 1959, p. 77), seems extremely improbable). Yet there is a difference between the case of a single mass of 1–2 tons plunging unfragmented to Earth and that of a 70-ton mass coming in fast through the atmosphere to fragment only a few thousand feet up and able to propel larger crater-forming fragments to Earth with some residual cosmic velocity (though it is uncertain that they did, in fact, retain any cosmic velocity). And the same difference exists between Dalgara and Kaalijarv, Estonia (Krinov, 1963*a*), where a 110-foot diameter crater is grouped with many smaller ones, and was apparently produced by a small mass, which burst into minute fragments on impact. However, it is significant that Krinov considered that this mass had lost all cosmic velocity, and it seems likely that masses of a ton or so impacting at free fall velocity can fragment on impact to form craters provided conditions are favourable—probably hardness of the ground (a reality at Dalgara) and internal strain differentials (due to inhomogeneity of the mass) are contributing factors to such striking impact fragmentation effects. Either way, whether one accepts unusually high initial velocity or not, the estimate of 10–20 tons by Nininger and Huss (1960) now seems excessive from the evidence more recently summarized by Krinov (1963*a*, 1963*b*).

The meteoric iron from Dalgara is atypical, being medium octahedrite (nickel—8.63 %) divided into fields, often rounded in shape

and swathed in kamacite bands about as wide as the lamellae within the Widmanstätten figures. These irons do not resemble any common structure in octahedrites and this fact alone suggests that we are dealing with a most unusual meteorite. It might be profitable to search for such an etch pattern within large nickel-iron nodules in mesosiderites.

The new material

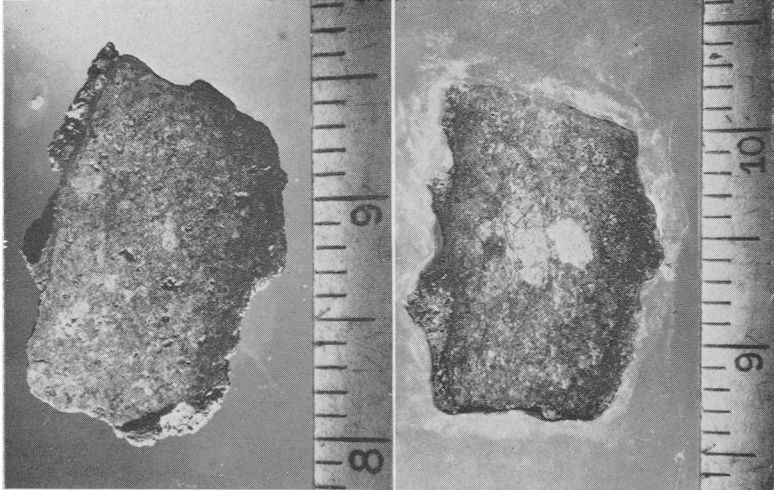
The two fragments are small: the oxidized, iron-rich fragment has dimensions 1.75×1.0 in. on the cut face, and the stony fragment 1.5×1.0 in. on the cut face (fig. 1). Specific gravity measurements are of little significance in the case of such weathered material but values of 2.71 and 2.67 respectively were obtained. Both fragments gave strongly positive nickel reactions to testing with dimethylglyoxime.

The iron rich fragment (wt. 22.5 gm after cutting, No. 9803 School of Mines, Kalgoorlie, collection) was studied only in cut face using a binocular microscope and oblique, reflected light. There is one rounded field including Widmanstätten lamellae, preserved in palimpsest in limonite-goethite: the remainder of the mass seems to have been an iron-rich aggregate enclosing some silicate—a trace of olivine could be seen. No more could be determined than this.

The stony fragment (wt. 26.2 gm after cutting, No. 9804, School of Mines, Kalgoorlie, collection), was first studied in cut face, using a binocular microscope and oblique, reflected light. It is apparent that no more than 20 % of nickel-iron has been present, now partly converted to ferruginous oxides; the nickel-iron and its derivatives are aggregated in irregular veinlets or stringers traversing a base of grey silicates (fig. 1). The texture has been one of discontinuous metal stringers within a continuous silicate host, not unlike that of a veined chondrite but including more nickel-iron. The ferruginous oxides are mostly hematite, limonite, and goethite, and they also fill hairline fractures, which produce a brecciated structure. Troilite grains could be recognized but seem to have a finer grain size than the nickel-iron (which ranges up to 0.5 mm grain diameter) and also to have been disseminated within the silicate fraction rather than being aggregated with the native metal fraction.

The silicate has the appearance of some very weathered chondrites—a fact noted by Nininger and Huss (1960, p. 632): speckled grey under low magnification, it shows no trace of rounded chondrules. It is very carious, the irregular cavities being either empty or infilled with iron oxide (figs. 1 and 2). A number of pale brown, vitreous phenocrysts can be seen, inset into this grey silicate matrix, and they are traversed by

white serpentine veinlets, suggestive that they are olivines, an identification compatible with their shape (fig. 2). The resemblance between the host material and the silicate fraction of Frenchman Bay, a newly discovered bronzite chondrite showing a high degree of weathering (McCall, unpublished manuscript) led the writer to attempt thin sectioning—the weathered chondrite had yielded excellent thin sections.

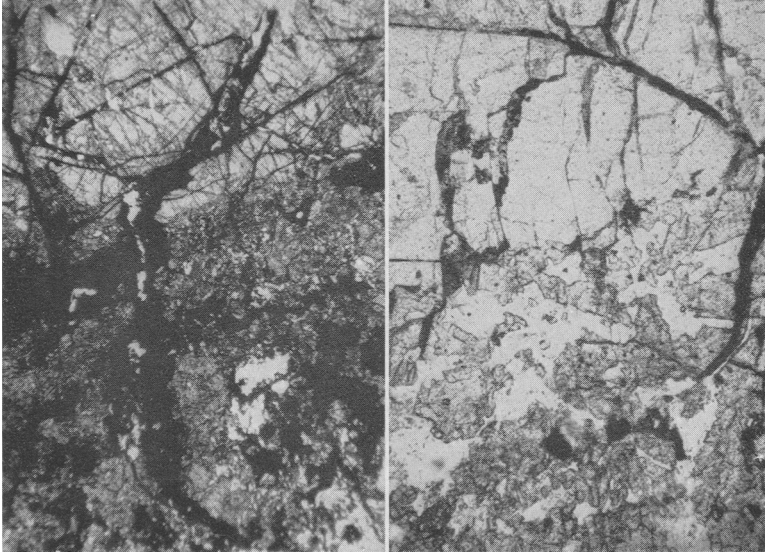


FIGS. 1 and 2: FIG. 1. Stony fragment from Dalgara crater, showing irregular mottlings due to stringers of nickel-iron (dark grey) in a lighter, carious silicate matrix (School of Mines Kalgoorlie, Specimen No. 9803). Scale in inches. FIG. 2. Stony fragment from Dalgara crater, cut off slice showing an olivine phenocryst (or more probably a xenocryst) within the stony base and a white patch of iron oxide to the right of it (as above). Scale in inches.

Mr. W. Smeed, geological technician at the University of Western Australia, who had earlier this year prepared some dozen excellent slides of mesosiderite material from Mount Padbury and thus knew the difficulty involved, prepared with great care a thin section that surpassed all expectations. It reveals the original minerals and texture, allowing the nature of the Dalgara meteorite to be established without any remaining doubt.

It showed that the large, brown vitreous phenocrysts are, indeed, olivine, quite fresh but veined by chrysotile (figs. 3, 4). Slight brecciation is visible near this vein. The chrysotile is probably a product of terrestrial decomposition. The phenocryst lies within a matrix that is not

significantly brecciated close to the phenocryst: this could be a pressure-shadow effect since this fringing zone of ophitic texture passes outwards into a metal-rich area, including broken fragments of the same minerals (fig. 3). In one area the metal network encloses separate rounded



FIGS. 3 and 4: FIG. 3. Photomicrograph (West Australian Museum Specimen No. 12365) of the fragment illustrated above, showing the olivine crystal (top), traversed by ferruginous cracks and fringed by fine, ophitic howardite material (top, centre), and set in an aggregate of silicate fragments (grey) within a network of altered nickel-iron (black) (bottom); $\times 10$, plane polarized light. FIG. 4. Photomicrograph of the same, higher magnification, showing the ophitic howardite, composed of hypersthene (grey) and interdigitating bytownite (white), fringing the large crystal of olivine (top, grey). $\times 100$, plane polarized light.

silicate grains in the manner of some pallasites. The outer material presumably represents the bulk of the meteorite, the mesosiderite host.

The ophitic area consists of hypersthene and calcic plagioclase, the latter forming laths interdigitating the base of irregular pyroxene granules (fig. 4), and these are the minerals found in the metal-rich, brecciated area (fig. 5). The hypersthene is a non-pleochroic variety, showing straight extinction and a biaxial negative interference figure ($2V_{\alpha}$ *c.* 60° – 70°). The feldspars show clear-cut twin lamellae in many grains and are approximately determined as labradorite, $An_{64}Ab_{36}$, on

the basis of extinction angles of albite twins in sections nearly normal to *a*. A trace of droplet inclusions was noted in some feldspar grains. The olivine also contains many and varied inclusions. A little pigeonite showing augite exsolution lamellae is also present.

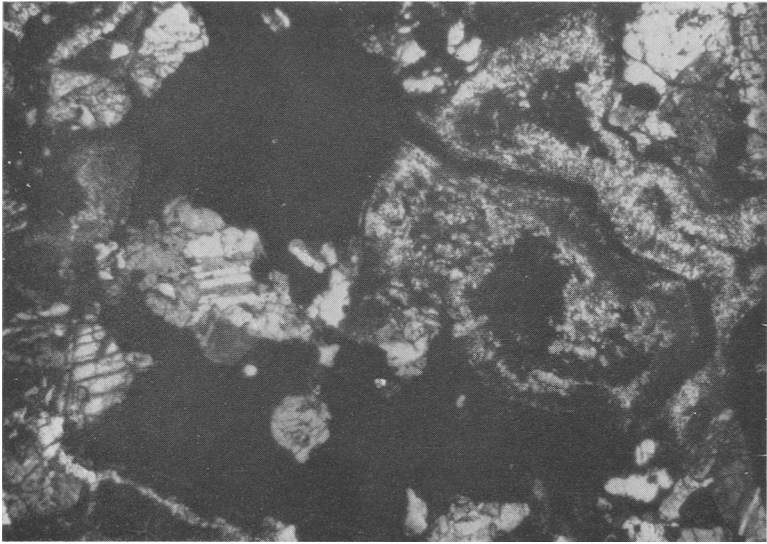


FIG. 5. Photomicrograph of the ferruginous area surrounding the olivine and howardite enclave. Fragments of bytownite (showing albite twin lamellae) and hypersthene (grey) (left) are enclosed in altered nickel-iron (black), while a colloform growth of iron oxide occupies the right-hand side of the photograph. $\times 63$, crossed nicols.

Texturally four points are of significance. The presence of olivine phenocrysts within a howardite base (Mason's usage, 1962, p. 113) excludes classification as a howardite (nickel-iron with octahedrite character is in any case not characteristic of howardites). The presence of increased nickel-iron content in areas of brecciated silicate is typical of mesosiderites, which frequently include eucritic or howarditic material (Prior, 1918; Lovering, 1962; McCall and Cleverly, in press). The interdigitation of feldspar into pyroxene provides an unequivocal magmatic texture—this meteorite has had some history of crystallization from a molten state. And finally the olivine phenocryst does not appear exotic—it appears to be a phenocryst or xenocryst in the howardite, not a later addition.

The likely paragenesis suggested by this texture is that howardite crystallized around earlier formed phenocrysts (or possibly xenocrysts) and was later invaded by nickel-iron during a phase of brecciation, some unbrecciated patches being preserved around the olivine crystals.

Confirmation of the mineralogy. Dr. B. H. Mason has identified the olivine as Fa_{13} by X-ray diffraction (using the method of Yoder and Sahama, 1957), and the hypersthene has γ 1.704, indicating Fs 34, in agreement with the earlier result. The feldspar has γ 1.575, equivalent to a composition of $An_{72} Ab_{28}$ —labradoritic bytownite.

Discussion. This material represents an enclave of howardite containing olivine phenocrysts or xenocrysts, a subordinate patch in a dominantly stony-iron meteorite, and the outer part of the fragment has the character of the bulk of most mesosiderites though rather lower in iron than some. In view of the proportion of iron, mesosiderite, and stony fragments recovered this cannot be considered representative of the meteorite as a whole, but of a localized iron-poor patch. Two periods of brecciation are reflected, the earlier associated with the phase of nickel-iron invasion of the silicate and certainly occurred deep within the parent planetary body before fragmentation; the later reflected in hairline fractures and possibly reflecting shock in atmospheric flight or on impact.

Mason (written communication) remarks that this is the typical olivine of pallasites, but whether the hypothesis that mesosiderites are composed of eucritic or howarditic achondrite material invaded by pallasitic material (Prior, 1918; Lovering, 1962; McCall and Cleverly, in press) can be retained is questionable. It seems more likely that the large olivines were caught up in the howardite melt before that in turn crystallized: because of the dissimilarity in Fe/Mg ratio to the pyroxene the olivine does not seem to be easily dismissed as an early crystallization from the howardite melt, even though textural evidence rather favours this interpretation. Certainly the alternative chronological sequence recognized by Lovering (1962) in Pinnaroo is quite inapplicable here, for very few stony fragments were recovered and the stony material clearly has the character of enclaves. We can follow Prior with the reservation that olivine did not accompany nickel-iron, but olivine and howardite were together invaded by it.

There is now a record of the following relationships in mesosiderites: eucrite invaded by nickel-iron and olivine (pallasitic melt) (Prior, 1918, studies of Vaca Muerta, &c.); eucrite invading nickel-iron and olivine (pallasitic material) (Lovering, 1962, discussion of Pinnaroo, initially

described by Alderman (1940)); howardite including olivine xenocrysts invaded by nickel-iron (this paper); and eucrite, diogenite, and olivine invaded by nickel-iron (or alternatively eucrite and diogenite invaded by nickel-iron and olivine (pallasitic melt) (Mount Padbury: McCall and Cleverly, in press).

Now it is noted that Lovering (*op. cit.*) recognized that olivine has been invaded by eucrite in Pinnaroo—thin section evidence of intrusion and

TABLE I. Composition of some constituents of mesosiderites

	Olivine	Ortho- pyroxene	Nickel, % in metal
Bencubbin	Fa ₇	≈Fs ₀	6.6
Crab Orchard	Fa ₉	Fs ₃₃	7.1
Dalgaranga	Fa ₁₃	Fs ₃₄	8.6
Estherville	Fa ₁₄	Fs ₃₃	7.1
Hainholz	Fa ₁₂	Fs ₃₃	8.8
Łowicz	Fa ₁₉	Fs ₂₃	—
Mincy	Fa ₁₄	Fs ₂₉	10.0
Morristown	—	Fs ₃₃	7.5
Mount Padbury	Fa ₉	Fs ₂₅	n.d.
Patwar	Fa ₂₁₋₂₅	Fs ₀ (?)	—
Pinnaroo	—	—	8.9
Simondium	—	Fs ₃₃	—
Udei Station	Fa ₉	Fs ₃₃	9.7
Vaca Muerta	Fa ₉	Fs ₃₃	7.5
Veramin	—	—	7.5
Weatherford	—	—	6.1

disruption is illustrated. No such positive indication is present in the Dalgaranga slide, but the contact of olivine and howardite suggests that the olivine did not crystallize later. The probable explanation for these anomalies is that the pallasitic invasion concept is incorrect.

Records of mesosiderites show the mineralogical determinations summarized in table I (Bencubbin, Patwar, and Weatherford do not appear to be typical mesosiderites, and should perhaps be classed separately). These values have been mainly obtained from Prior and Hey (1953): values may well be recorded in literature not in the writer's possession and more accurate values for those given may also be so recorded.

Now turning to pallasites we find that nickel percentages range from 8 to 14 %, and all but a very few have nickel percentages exceeding 10 (Mason, 1963, p. 7). Olivine composition ranges from Fa₁₁ to Fa₂₀, there being two distinct groups (11–13) and (17–20), the latter having nickel contents of 13–14 %, quite outside those of the mesosiderites (Mason,

1963, pp. 7-10). It seems apparent that mesosiderites show generally lower nickel percentages than pallasites, though some of the higher mesosiderite percentages correspond to those of the lowest pallasites. The fayalite content of the olivine, again, is not far off that of the lower group of pallasite values (11-13), but shows a wider range, including values of Fa_9 and Fa_{14} . It is significant that Fa_9 is represented more than once. The conclusion is reached that the mesosiderites are not simply invasions of achondrite by pallasite melts since the 'pallasitic component' is not strictly typical of the pallasite mineralogy; they seem to represent, rather, a less nickeliferous group bordering on the pallasites. Taking this evidence alongside the evidence that the olivine in some mesosiderites does not crystallize contemporaneously with the nickel-iron (Pinnaroo, Dalgara), and the size of some olivine inclusions (crystals inches long within the fine-textured Mount Padbury meteorite), one may feel justified in doubting the validity of the concept of pallasitic invasion.

Yet the olivine is almost certainly foreign to the achondrite: in chondrites the fayalite and ferrosilite contents of olivine and orthopyroxene respectively are very close to one another, the latter being consistently slightly lower (Mason, 1962, pp. 89-92). It is very difficult to imagine olivine of so magnesian a composition as Fa_9 crystallizing early within an eucrite or howardite melt that later crystallized hypersthene (Fs_{34}), and the suggestion of a consistent shift of about 20% downwards in the iron silicate index of the olivine seems irreconcilable with such a process.

Yet the very consistency of the hiatal relationship does seem to indicate that the chemistry of olivine and orthopyroxene is not entirely unrelated—they are not simply randomly accreted. Beyond this we cannot at present go.

The exact role of the troilite—that is the stage at which it enters mesosiderites—does not seem to have been considered by Prior (1918): it certainly does not always show close association with nickel-iron as might be expected, rather tending to disseminate the silicate fraction included in the nickel-iron as much finer grains. What evidence there is suggests that this was the case with Dalgara—it may well represent the last introduction of all. Further work on mesosiderite polished sections is called for to determine troilite distribution.

Conclusions

It is concluded, then, that Dalgara was a stony-iron meteorite, characterized by uneven distribution of nickel-iron, solid lumps within

the meteorite showing Widmanstätten patterns and composite 'field' structure—probably due to brecciation or shock. This metal fraction is now only found in twisted iron fragments of no great size. The silicate fraction was made up of howardite and olivine xenocrysts, being left as patchy iron-free residual enclaves, and represented by fragmental enclosures in a nickel-iron network in the bulk of the meteorite. Ninninger's analogy with Estherville (1960, pp. 637–8) is apt, but petrologically there is a strong resemblance to Mincy (Prior, 1918). The conclusion of Ninninger that this is one of the few craters of any size known not to have been formed by an iron meteorite is endorsed (Haviland is the only other case), but the deduction of an original mass of 10–20 tons before fragmentation seems ill-founded. It was probably a mass of only one or two tons, and came in without residual cosmic velocity.

Future work. This crater should be systematically trenched under scientific supervision when funds are available for such a project. This material came from near the crater wall in the deepest part so far excavated and it seems likely that more material must be revealed by further excavation. The area adjacent to the crater should also be searched again. Meanwhile the crater is fortunately protected by law from unschooled exploration.

Acknowledgements. To Messrs. F. W. G. Power, J. Nevill, and W. H. Cleverly the author is indebted for supplying the information and the material on which this report is based, and the last has had many discussions with the writer on this crater and material. Messrs. W. Smeed and K. C. Hughes assisted him with technical work, the latter preparing the photographic illustrations. To Dr. B. H. Mason he is especially indebted for the precise determination of composition of the olivine and other silicate grains.

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[*Manuscript received 26 April 1965*]

Note added in proof. Metallic nodules from the Mount Padbury mesosiderite have yielded Widmanstätten figures similar to those of the Dalgaranga fragment (pp. 478–9, above); see McCall and de Laeter (1965).
