New stony meteorite finds including two ureilites from the Nullarbor Plain, Western Australia

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Summary. Two groups of meteorite finds in separate areas of the Nullarbor Plain are reported. It is suggested that the grouping is due to the fact that these are areas in which a family of rabbit trappers operates: these people have made most of the finds. There is, however, one shower of 71 small meteorites represented. Several arrivals on earth are represented by each group. The meteorites are described and it is shown that several distinct types are represented. Two quite different ureilites have been identified—only the fourth and fifth ever discovered in the world. Analyses are given for these rare carbonaceous achondrite meteorites. The remainder of the stones are olivine-hypersthene and olivine-bronzite chondrites. The whole question of the reason for the profusion of meteorite recoveries now being made on the Nullarbor Plain is briefly discussed.

SINCE the publication of the catalogue of Western Australian Meteorite Collections (McCall and de Laeter, 1965), several more finds have been made on the Nullarbor Plain. In this account, the recoveries of stones from two separate areas of the plain—the first north of Haig Station on the Trans-Australian Railway and the second near Cocklebiddy Tank on the Eyre Highway—are described. The new discoveries are described in some detail, and results of a re-examination of two meteorites previously briefly recorded are given (Sleeper Camp; North Haig). Brief mention is made, purely to complete the picture, of the Billygoat Donga, Rawlinna, and Cocklebiddy stones, which have been previously described in some detail.

This account does not take in the stony-irons and irons of the Nullarbor Plain: sufficient to say here that the recovery of a small stony-iron from south of Rawlinna Station about 1959 (Rawlinna (pallasite)) has been confirmed: and that more than twenty tons of octahedrite material has come to light near Mundrabilla Siding to the east of Haig (Wilson and Cooney, 1967).

The localities considered here are shown in fig. 1.

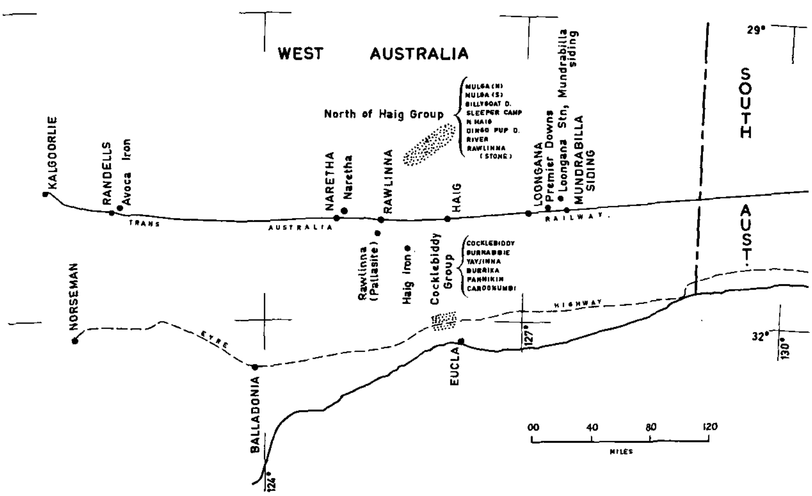


FIG. 1. Map of the Nullarbor Plain area, Western Australia, showing the localities of the meteorite discoveries discussed here.

The second named author has provided the details of the field recoveries, while the first named author has carried out the petrographic description. Analyses using the classic wet gravimetric methods have been carried out by E. Jaresowich of the Smithsonian Institution as part of an exchange agreement: earlier, analyses of the silicate fraction using X-ray fluorescent spectroscopy were carried out by W. R. O'Beirne on the same ureilite material and, both because of the fact that these analyses first revealed the abnormal character of these meteorites and for reasons of comparison between the methods, O'Beirne's values are inserted alongside the values finally obtained.

Stony meteorites from the area north of Haig Station

The discovery of several stony meteorites in this area was first reported by McCall and de Laeter (1965). Separate stones recovered were named Billygoat Donga, North Haig, and Sleeper Camp. All were found to be olivine-hypersthene chondrites though, in the case of the latter two stones, the material was not examined by the authors, being at that time on loan to Dr. Lovering at Canberra. The Naretha stone, long known and of similar composition (*op. cit.*, p. 46), was proposed as a possible fourth member of a group representing a single arrival event. At the time of writing some doubt was felt about the validity of the extremely long ellipse of dispersion depicted (*op. cit.*, p. 26); dispersion ellipses seldom exceed 10 miles in length.

TABLE I. Meteorites from the Rawlinna–Haig area

Found	*Name*	*Type and Fa %*	*Weight*	*Preserved at*	*Finder*
1951	Haig	Om–Og	480 Kg*	K., W.A.M.	A. J. C.
Pre-1959	Rawlinna (pallasite)	P	c. 50 g	H.H.N.	A. J. C.
Pre-1959	Rawlinna (stone)	CBr (R) 20	243 g	W.A.M., Ariz.	A. J. C.
1961	North Haig	U 0 to 30	973 g	K., W.A.M.	R. F. K.
1962	Billygoat Donga	CHy (R) 25	142 g	K., W.A.M.	T. & P. D.
1962	Sleeper Camp	CHy (R) 25	1·25 Kg	K., W.A.M.	H. E. C.
1964–65	Mulga (south)	CBr (S) 18	298 g†	K., W.A.M.	W. H. C.
1965	Mulga (north)	CBr (R) 18	2787 g‡	K., W.A.M.	W. H. C.
1965	River	CHy (R) 25	190·5 g	K., W.A.M.	D. C.
1965	Dingo Pup Donga	U 10	122·7 g	K., W.A.M.	A. J. C.

S, spherical, not recrystallized; R, recrystallized.
K., School of Mines, Kalgoorlie; W.A.M., Western Australian Museum; H.H.N., H. H. Nininger's collection; Ariz., Arizona State University.
A.J.C., A. J. Carlisle; D.C., D. Carlisle; H.E.C., H. E. Carlisle; W.H.C., W. H. Cleverly; T. & P. D., T. and P. Dimer; R.F.K., R. F. Kilgallon.

* A second mass, of 23 Kg, was found by A.J.C. in 1965.
† 8 fragments. ‡ 71 individuals.

It is now believed that this ellipse is a human artifact, its long axis following the line of an access track through an area of the plain that is frequently visited by rabbit trappers. The new finds and necessary reassessment consequent on them have led the writers to the view, already expressed by McCall (1965) 'that the Nullarbor Plain, with limestone only lightly veneered by superficial material and enjoying a climate of extreme aridity, is probably littered with meteorites of all types'. At least five quite distinct varieties of meteorites have now been recognized in this elliptical area: meteorites do not arrive in groups of contrasting types in observed falls. Nothing but *finds* are known from this area (indeed only a single fall is well established for the whole extent of this immense, but sparsely populated, State).

The entire recovery from this area is listed in table I and the localities of recovery are shown in fig. 2.

Billygoat Donga. The details of this olivine-hypersthene chondrite are given by McCall and de Laeter (1965, p. 25). The site of the find is more accurately defined in fig. 2 than in that description, on account

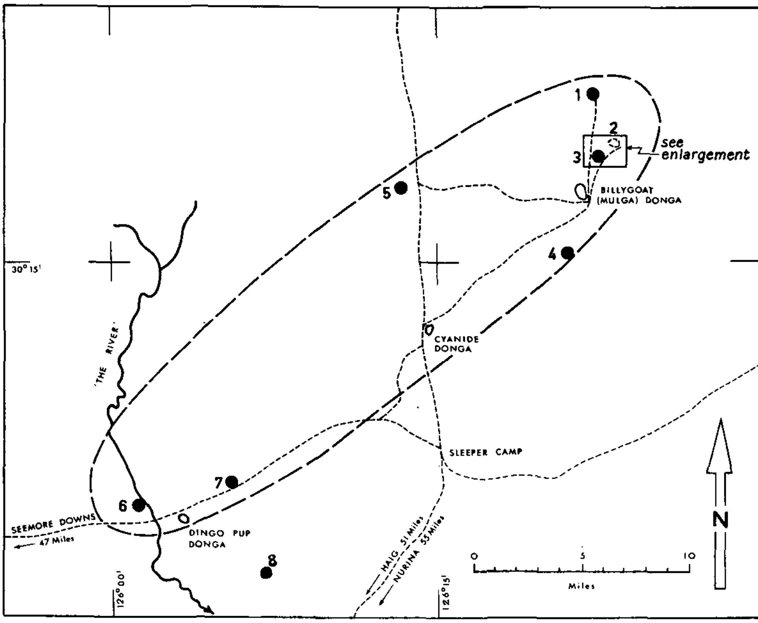


FIG. 2. Sketch map of the area north of Haig Station, showing the sites of the various meteorite recoveries: 1, Billygoat Donga; 2, Mulga (north) ellipse; 3, Mulga (south); 4, Sleeper Camp; 5, North Haig; 6, River; 7, Rawlinna (stone); 8, Dingo Pup Donga.

of new information: the small stone known as Billygoat Donga No. 2 has been lost, and that referred to as Billygoat Donga No. 3 is now known to be material from a quite different type of meteorite (see Mulga (south) below). The first and largest mass recovered is thus all that is considered here: it is a faceted, weathered olivine-hypersthene chondrite, recrystallized, and with large chondrules evident. The olivine is Fa_{25} (determined by Mason).

Mulga (north) (71 individual stones). Cleverly (1965) has briefly recorded the original find by himself of these stones. Fifty-nine, of similar character and dispersed in a small elliptical area situated just north of the site of the Billygoat Donga No. 2 recovery (which was the cause of his searching the area in the first place), were then recovered. In December 1966 he and M. K. Quartermaine found twelve similar stones, extending the area of recovery slightly westwards towards the site of the Mulga (south) recovery (see below), and slightly elongating the ellipse of dispersion.

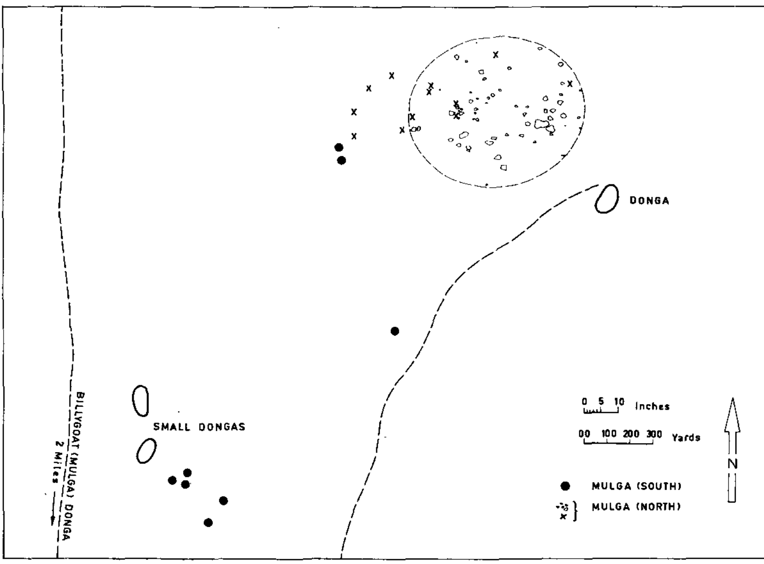


FIG. 3. Diagram showing the distribution of the Mulga (north) and Mulga (south) meteorite recoveries; the new finds made late in 1966 are marked by crosses.

The meteorites have now been examined petrographically, and are found to be olivine-bronzite chondrites, and so must be regarded as quite distinct from the meteorites previously described from the 'elliptical area'. The name Mulga has been adopted ('Mulga Donga' is an alternative name used for 'Billygoat Donga').[1]

The small dispersion ellipse, already figured by Cleverly (1965), is shown in fig. 3 together with the positions of the Mulga (south) recoveries. It is 800 yards long, elongated approximately east–west, and not significantly attenuated. An approach on an east–west path at

[1] The term donga is used in this area to denote a shallow depression, due to sink-holing; such depressions are commonly used as camp sites by the itinerant population, and are given names: the only reference points in a plain almost devoid of other named features.

a steep angle is indicated, but the actual direction of approach is not known, since the distribution of the masses reveals no predominance of large masses at one end of the ellipse. The pattern of distribution of masses within the ellipse is irregular, though larger masses are grouped towards the centre (fig. 3).

The fresh state of the stones and their position, resting on the land surface like pebbles, suggests no great age on earth. They are probably the latest arrivals of the group considered here. A word of caution is, however, called for because on the Nullarbor Plain we are clearly dealing with exceptionally beneficial conditions for meteorite preservation and their age on earth might still be in the order of several hundred years. The position of this find is close to the sites of recovery of eight very weathered olivine bronzite chondrite fragments, also by Cleverly, now referred to as the Mulga (south) meteorite. The reasons for distinguishing between the two groups of stones are given below (p. 699).

The weights of individual members of the group range from a complete individual of 2·0 g to one of 631·1 g, and the total weight recovered amounted to 2787 g. The masses recovered are mostly entire, fusion-crust coated individual meteorites, though many show broken faces. The fusion crust is dark brown, and mottled; light brown surfaces are revealed on fresh-cut faces. There is little sign of oriented form. A representative selection of these stones is shown in fig. 4.

Spherical texture is not easily detected, even using a binocular microscope under reflected light; the chondrules are merged with the finer groundmass (as microscopic study using transmitted light confirms), a granoblastic aggregate of grains averaging 0·2 mm grain diameter. The chondrules also show some distortion (fig. 5). Opaque minerals account for about 25 % by volume, and include troilite (about 5 %), the balance being nickel-iron and oxides derived from it. The metal is aggregated in irregular specks and patches: some troilite fills narrow veinlets but most of these are filled with secondary oxides. Orthopyroxene is rather more abundant than olivine, and the only other silicate mineral is plagioclase feldspar, very sparsely present in the interstices between ferromagnesian grains of the fine groundmass, and showing low relief and birefringence. Most is untwinned but, here and there, very faint twin lamellae can be detected. Chondrules are not uncommon, but are of small size and tend to merge with the base.

The olivine was determined by Mason as Fa_{18}, using the X-ray diffractometer method of Yoder and Sahama (1957) (all determinations by Mason referred to in this text are by this method). The value confirms a tentative petrographic identification of the material as olivine-bronzite chondrite, based on the amount of metal fraction present (Mason, 1962, p. 80). It also shows that this material is quite distinct from the Rawlinna (stone), which gave Fa_{20} (p. 704), and also from any other meteorite in the group north of Haig Station considered here, except Mulga (south), which gives the same value (see below).

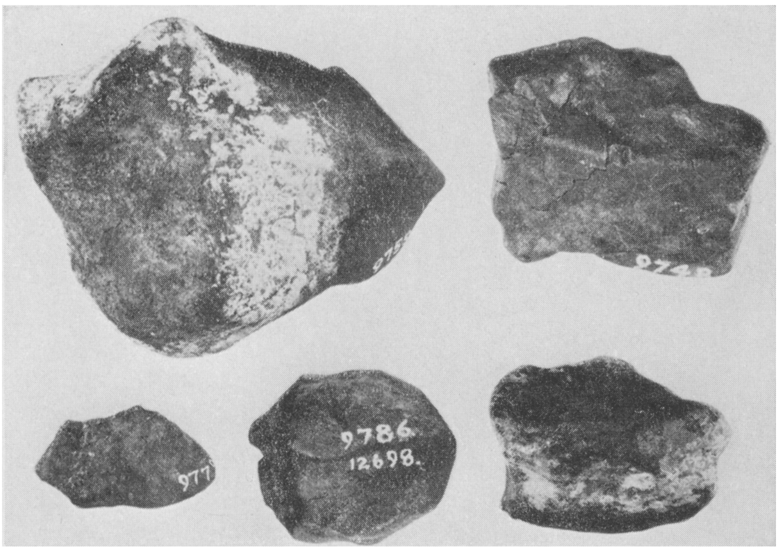
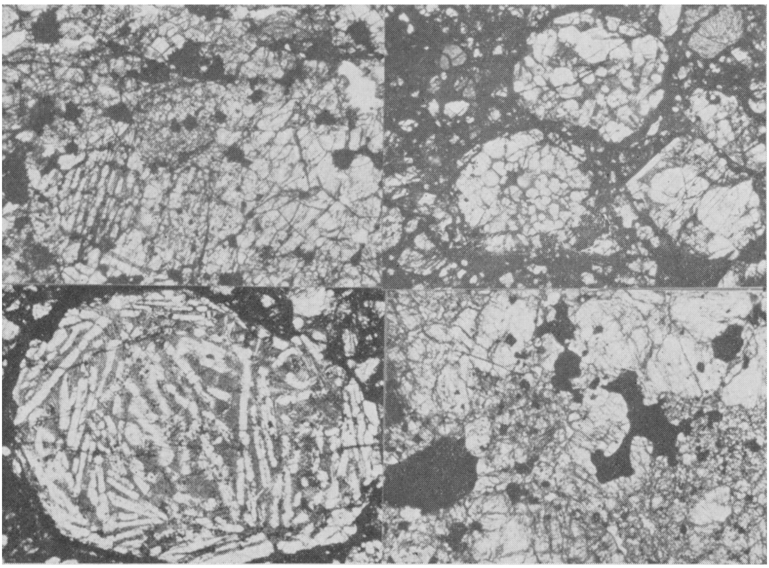


FIG. 4. Five typical members of the Mulga (north) shower group. The fusion-crust-enveloped meteorites show white on the surfaces buried in the sand, and the crust remains dark on surfaces left exposed to air. W.A.M. nos. 12579, 12698.

Mulga (*south*) (8 fragments). Cleverly (1965) has recorded the find by himself in 1963 and 1964 of eight small fragments of meteoritic material, pieces of one or more masses and not individual meteorites. The material, eight fragments in all (three of which were previously listed as Billygoat Donga No. 3 (McCall and de Laeter, 1965), a name that should now lapse), is unlike the material described under Mulga (north) above. The fragments totalled 298·1 g.

The meteorite is a spherical chondrite, and the fragments show a pale chocolate-brown coloration on fresh-cut surfaces, on which the chondrules appear small, spherical, bluish-white, and clearly defined. In thin section the chondrules are seen to be set in a fine base, which is in part crystalline and in part amorphous, composed of iron oxides. The material is much more decomposed by terrestrial weathering than the Mulga (north) material, and may well have a greater age on earth. Nickel-iron is only sparingly evident in the form of scattered specks,



FIGS. 5–8: FIG. 5 (top left). Photomicrograph of the largest member of the Mulga (north) shower, showing pronounced recrystallization and small, ill-defined chondrules (×63, plane-polarized light; W.A.M. no. 12584.) FIG. 6 (top right). Photomicrograph of a Mulga (south) fragment, showing the spherical texture, comprising clear-cut orbicular chondrules set in a dark, almost opaque cryptocrystalline or glassy base (×63, plane-polarized light; W.A.M. no. 12798). FIG. 7 (bottom left). Photomicrograph of another Mulga (south) fragment, showing an unusual chondrule structure. Laths of olivine within the chondrule are set in an isotropic base (? devitrified glass ?) and 'swirl around' the chondrule, following the margins; the texture is not unlike the trachytic texture common in volcanic rocks. One lath on the right-hand side of the photograph has a continuation in optical continuity outside the limits of the chondrule. (×63, plane-polarized light; W.A.M. no. 12798). FIG. 8 (bottom right). Photomicrograph of the Sleeper Camp meteorite, showing the strong recrystallization (×63, plane-polarized light; S.M.K. no 9248).

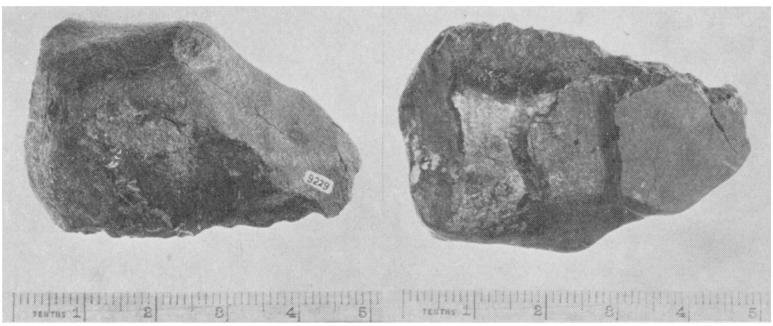
being mostly altered to oxide. Troilite is aggregated with it, and fills fine veinlets. It is difficult to estimate the metal fraction by volume, but it seems to have been rather low for an olivine-bronzite chondrite (Mason, 1962, p. 80).

Olivine is less abundant than orthopyroxene; lamellated clinopyroxene (Tschermak, 1885, fig. 58), probably pigeonite (McCall, 1966*a*, p. 49) is evident, in the form of very small grains. The chondrules include monosomatic, barred types, but most are polysomatic, including fan, grated, and porphyritic types. The spherical outlines are very clearly defined (fig. 6). A feature of this meteorite is the abundance of bi-mineralic chondrules, in which olivine and pyroxene occupy areas of contrasting texture within the same chondrule. One chondrule (fig. 7) shows elongated olivine crystals aligned in a manner that reflects the chondrule boundaries, suggesting the trachytic flow texture of volcanic rocks. Another remarkable feature is the optical continuity of one lath with an extension outside the boundary of the chondrule within the base: a relationship that suggests some degree of resorption of the chondrule by the base encroaching on it.

X-ray diffractometric determination of the olivine gave a value of Fa_{18} (determination by Mason), indicating an olivine-bronzite chondrite. In spite of this agreement with Mulga (north), both authors regard the textural differences and the contrasting weathering state as indicative of a separate arrival event. The classification is different—olivine-bronzite chondrite, spheroidal, not recrystallized—and this requires an extraordinary degree of inhomogeneity within a single meteorite in space for one to attribute Mulga (north) and Mulga (south) to a single arrival event. The contrast of weathering state seems to remove all further doubt. However, a nomenclature has been adopted that allows for the remote possibility of simultaneous arrival: and the coincidence of fayalite indices is indeed strange, even though this is a quite common value (see further discussion, p. 714).

Sleeper Camp. Brief information has already been given (McCall and de Laeter, 1965, p. 50). The site of the find by H. E. Carlisle in 1962 is shown in fig. 2. The mass is flattened and rounded, weighs 1·25 kg, and is coated by a black and dark-brown mottled fusion crust. Broken surfaces show the stone to be a light grey chondrite, very similar to Woolgorong (McCall and Jeffery, 1964); the external form is illustrated by McCall and de Laeter (1965, p. 121). A cut section studied under reflected light showed a content of about 15 % by volume nickel-iron and troilite, aggregated together in disseminated grains of irregular shape: the troilite makes up about 5 %, and may enclose the metal in a sheath. In thin section (fig. 8) considerable recrystallization is apparent: there is no fine, cryptocrystalline or glassy interstitial material at all, the large chondrules, present as irregular remnants with hazy outlines, being partly merged with a granoblastic base composed of grains averaging 0·05 mm diameter. Olivine is the most abundant silicate mineral, orthopyroxene being also abundant. The other silicate present is in the form of material of low relief, almost isotropic, which seems to be maskelynite after plagioclase. It is only sparingly evident. Secondary iron oxides fill cracks that traverse the mass.

The olivine has been determined by Mason as Fa_{25}, a value also obtained for Billygoat Donga. The two finds were made $7\frac{1}{2}$ miles apart (fig. 2), within the likely limits of dispersion from a single arrival event.



FIGS. 9 and 10: FIG. 9. The North Haig meteorite, showing rounded, faceted and dimpled fusion crust surfaces (S.M.K. no. 9229). FIG. 10. The North Haig meteorite showing a cut face (S.M.K. no. 9229).

Certainly there is a great degree of similarity between the microscope slides. These could well, therefore, represent a single arrival event, but these are the only two members of the group of eight north of Haig Station that are likely to have arrived together on earth (though the two ureilites could also have come in simultaneously, p. 715).

North Haig. Like the Sleeper Camp stone, this only became available for petrographic study subsequent to the publication of the catalogue (McCall and de Laeter, 1965, p. 47). Though, in the case of Sleeper Camp, petrographic examination has supported the classification given there, the same cannot be said of North Haig, which is a most unusual meteorite, a ureilite, and only the fourth of its class of achondrite ever found. The site of the find by R. F. Kilgallon in 1961 is shown in fig. 2. The stone (figs. 9 and 10) is a mass weighing 0·973 Kg, and covered by a thin, even, brownish fusion-crust. It has a broken surface on one side, but about $\frac{2}{3}$ of the original mass is preserved. The fresh-cut face appears greenish-grey mottled, and fine-textured: it shows no sign of metal or of rounded chondrules. The mass was found to be abnormally hard and difficult to cut with the diamond saw. The specific gravity is 3·27, which would be low for a chondrite with such a moderate degree of weathering.

Thin section and polished section study, using transmitted and reflected light reveals: An aggregate of large grains (average diameter 1 to 2 mm) of olivine and clinopyroxene, many of which are broken to angular fragments forming a breccia; the meteorite has the character of a crystal breccia formed from an initially coarsely crystalline aggregate,

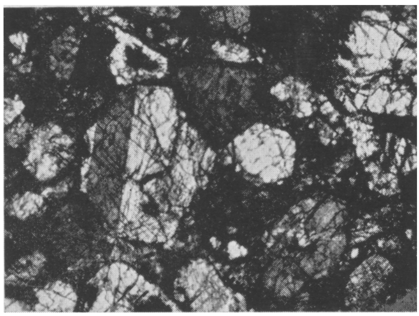


FIG. 11. Photomicrograph of the North Haig ureilite, showing euhedral and subhedral grains (centre, half-left; bottom, half-right), which display broad twin lamellae in contrast to the olivine grains around them (× 25, crossed nicols; W.A.M. no. 12779).

probably of granoblastic texture; the crystals show, here and there, quite good crystal form. There are also areas of very fine, granular crystallization, some rounded in outline, but showing no other feature characteristic of chondrules, and not considered to be such. Finally, there is a cement between the crystals that seems to be mainly composed of iron oxide. Some very dark, non-reflectant patches could be carbonaceous considering the analytical results. Specks of nickel-iron and troilite could be detected in this cement under reflected light. The cement seems to be a primary feature of the meteorite, though modified by terrestrial weathering: it could be a cryptocrystalline crush matrix to the crystal breccia or a primary matrix of ferruginous and carbonaceous glass.

The olivine and clinopyroxene, the former predominant and occurring as rather poorly formed grains and the latter as rather better-formed grains displaying broad twin lamellae or a very fine strip twinning, gave one of the authors (G. J. H. McCall) the first indication that this could not be a chondrite, a view strengthened when the pyroxene was found to have a negligible optic angle ($2V$), only consistent with pigeonite, a mineral that never forms large euhedral grains in chondrites. The only clinopyroxenes known from chondrites are in the form of Tschermak's lamellar pyroxene (1885, fig. 58), now recognized as pigeonite (McCall, 1966*a*, p. 49) and these grains are never of any size, being found in the very fine fraction, in small quantities. The doubts concerning this meteorite were expressed to Dr. Mason in correspondence and though an initial determination had given the value Fa_{23} for the olivine, a careful

TABLE II. Analyses of two new ureilites, by E. Jaresowich, together with partial analyses by W. R. O'Beirne by X-ray fluorescence and flame photometry

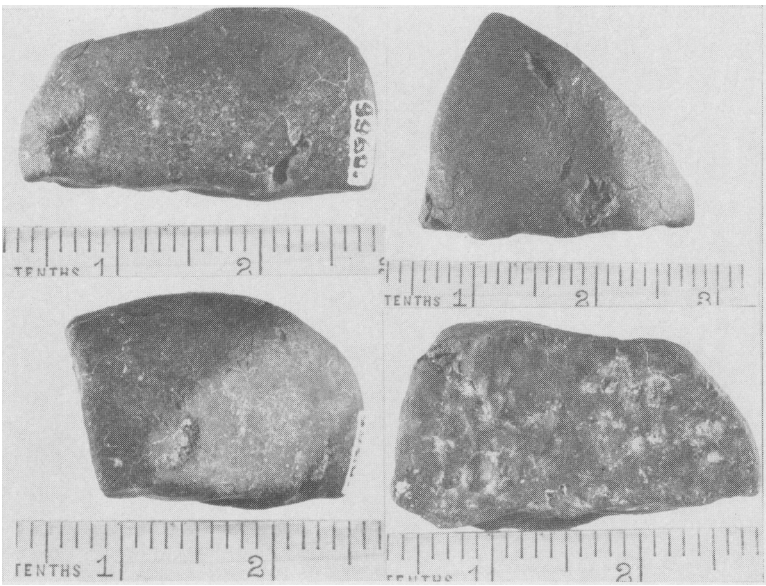
	North Haig		*Dingo Pup Donga*	
Fe	0·34	—	0·36	—
Ni	0·11	0·20	0·23	0·33
FeS	0·99	—	0·93	—
C	4·10	—	3·10	—
SiO_2	36·87	38·73	38·26	43·87
TiO_2	0·08	0·02	0·08	0·03
Al_2O_3	0·18	0·70	0·34	—
Cr_2O_3	0·66	—	0·74	—
Fe_2O_3	9·25		11·52	
FeO	8·07	19·03	8·51	16·20
MnO	0·40	0·46	0·33	0·43
MgO	34·68	31·40	30·36	29·69
CaO	1·26	1·72	1·41	2·00
Na_2O	0·08	0·01	0·06	0·20
K_2O	0·03	0·04	0·03	0·05
P_2O_5	0·21	—	0·19	—
H_2O^+	2·76	—	3·16	—
H_2O^-	0·36	—	0·53	—
Sum	100·44		100·14	

	North Haig	*Dingo Pup Donga*
Ni in metal	23 %	39 %
MgO/(MgO+FeO)	88 %	86 %
Mg/Si	1·17	1·02
Fe in silicates	12·8	14·68
Fe in metal and sulphides	0·97	0·95

check using X-ray diffractometry, showed the olivine to be variable between Fa_0 and Fa_{30}: the clinopyroxene was found to vary between smaller limits, the ratio 100 Fe/(Fe+Mg) ranging from 5 to 20. At the same time this meteorite was analysed by Mr. O'Beirne using X-ray fluorescent spectroscopy and flame photometry. While it was realized that the method could only give a partial analysis of the silicate fraction, it would show if the chemistry was anything like that of any known chondrite. The results obtained resembled no values ever obtained for a chondrite, and it was then suggested that this meteorite was a ureilite. Analysis by wet methods, using the classic gravimetric techniques, has shown that this is indeed the case: it is a brecciated ureilite, (otherwise a carbonaceous olivine-pigeonite achondrite). The results of the analyses are given in table II.

River. The recovery of this stone by D. Carlisle in 1965 was made about eighteen miles south-west of that of the North Haig meteorite, the nearest of the stones so far described (fig. 2). The mass, weighing

190·5 g before cutting, is wedge-shaped, having two very distinctly flattened, pitted faces, and several rounded facets covered by a smoother fusion crust. The meteorite appears to be oriented, the pitted, flattened surfaces being the rearward facing surfaces in atmospheric ablating flight, while the smooth, rounded facets are the anterior surfaces (figs. 12–15). The former are dark, almost black, while the latter are of a



FIGS. 12 to 15: The River meteorite (S.M.K. no. 9960). FIG. 12. Anterior surface (side view of ridged cone) showing the smooth fusion-crust-coated anterior surface and thumb-print regmaglypts. FIG. 13. The same smooth anterior surface (end-on view of the ridged cone). FIG. 14. Other end of the ridged cone. FIG. 15. The rough, pitted, flat posterior surface of this oriented meteorite (the base of the ridged cone).

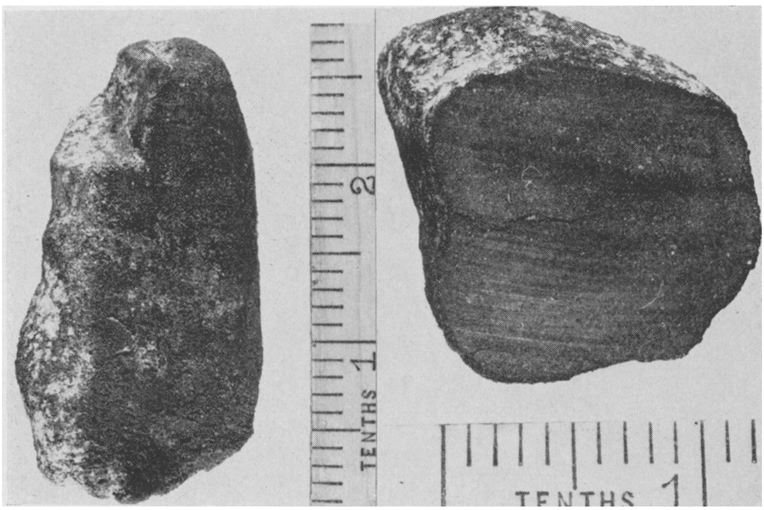
chocolate brown colour. The specific gravity was found to be unusally low, 3·24. The fresh-cut surface has an orange coloration quite unlike any other meteorite from this area: with the binocular microscope, under reflected light, coarse irregular specks of nickel-iron, aggregated with troilite, are visible. The total opaque content is about 15 % by volume, troilite being subordinate (about 5 %). In thin section (fig. 18), a considerable degree of recrystallization is apparent. The chondrules, mostly large with ill-defined merging boundaries, are set in a quite coarse granoblastic base. There is no glass or cryptocrystalline material present and little trace of a spherical texture. Plagioclase is rather more abundant than usual, a not uncommon feature of recrystallized chondrites: it is estimated that it makes up 5 % by volume. It tends, with opaque minerals, to swathe the margins of chondrules. Olivine predominates over orthopyroxene, and both occur in chondrules and also in the granoblastic base.

The olivine was determined by Mason as Fa_{25}: in spite of the agreement between this value and that of two other olivine-hypersthene chondrites in this group, Billygoat Donga and Sleeper Camp, distance of separation between the finds and marked physical disparity suggest that River represents quite a distinct arrival even from these meteorites.

Rawlinna (*stone*). Two meteorites named Rawlinna are listed in the supplement to the catalogue of Western Australian Meteorites (McCall, 1966: held in manuscript form at the Western Australian Museum prior to duplication). A pallasite (Rawlinna (pallasite)) and an olivine-bronzite chondrite were given by A. J. Carlisle to H. H. Nininger in 1959. While the former is held in his private collection, the stone is represented at the Arizona State University, the olivine being determined by Mason as Fa_{20}. The locality of the find of this stone is known: it was found in the elliptical area shown in fig. 2, about 4½ miles east of the site of the River find. It is clearly representative of a quite different arrival event to any other meteorite of this group. Another stone in the Western Australian Museum collection is also called Rawlinna, is identical with that in the Arizona collection in its fayalite index (olivine, Fa_{20}), and appears physically similar. It was erroneously referred to as an olivine-hypersthene chondrite in the catalogue (McCall and de Laeter, 1965, p. 49). It is not a complete meteorite, but has only lost a small fraction of its mass, and it seems doubtful if the Arizona specimen could have come from it: there still remains some doubt about the Rawlinna (stone), but it seems clear that similar material is represented in Perth and in Arizona, and both are therefore referred to by the same name. The probability is that more than one mass was picked up.

Dingo Pup Donga. The last of the group north of Haig, the Dingo Pup Donga stone, was found by A. J. Carlisle late in 1965. The location of the find was initially given as close to the River find, but the site was visited in 1966, and found to be some miles to the south-east, as shown in fig. 2. It must be appreciated that this is quite featureless country without any points of easy reference, and laced by tracks that all look alike: even the names used for the meteorites are taken from informal names used by the trappers. In this case the name refers to a skeleton in the donga.

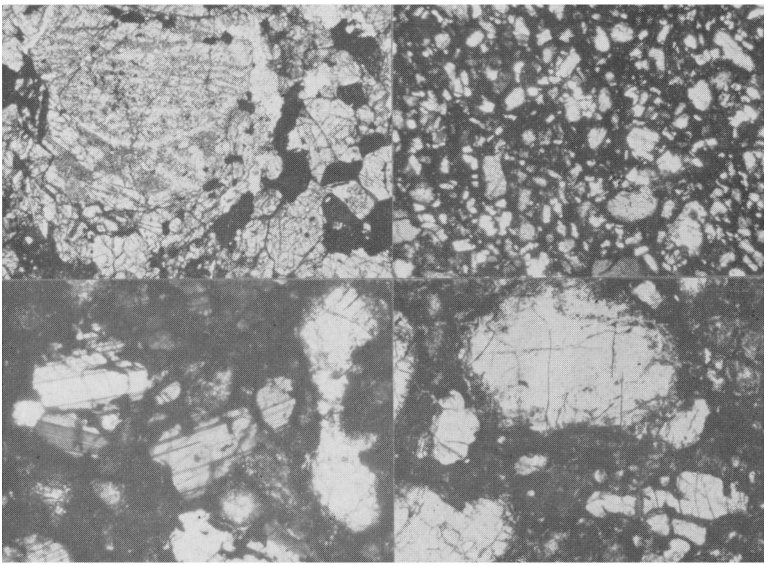
There was never any doubt that this stone is an achondrite. It is an elongated, wedge-shaped mass (fig. 16), covered on one side by very thin, brownish-black fusion crust—the side not buried in the soil. The fusion crust is seen to be finely mamillated under the binocular microscope.



FIGS. 16 and 17: FIG. 16. The Dingo Pup Donga meteorite, showing the finely mamillated fusion crust and white caliche-stained surface formerly in the soil. FIG. 17. The same, showing the fine-textured, dark, fresh-cut face (S.M.K. no. 9959).

The mass weighed 122·7 g before cutting, and the specific gravity is 3·05. Though the stone appeared weathered, cutting revealed a surprisingly fresh interior, fresh-cut surfaces having a dark greenish-grey core of exceedingly fine texture, and quite free from secondary oxide staining (fig. 17). The lack of iron in this meteorite has probably militated against rapid decomposition. Dark green, cracked, vitreous 'phenocrysts' of olivine, of subhedral form and up to 5 mm long, sparingly punctuate the fine base.

Thin sections (figs. 19, 20, and 21) reveal a fine breccia, composed of olivine and subordinate lamellar clinopyroxene, which has the appearance of plagioclase. The olivine 'phenocrysts' are not represented in the thin sections, because they tear out on grinding. The olivine of the base is in the form of anhedral grains, quite fresh and showing good cleavage. The refractive index (γ) was determined as 1·702, which agrees quite well with the value of Fa_{10} obtained by Mason, using X-ray diffractometry. The acid-cleaned pyroxene separated from this meteorite is reported by Mason to have refractive index (γ) of 1·678. This pyroxene



FIGS. 18–21: FIG. 18. Photomicrograph of the River meteorite, showing a large chondrule with ill-defined boundaries owing to recrystallization, and a rim of opaque minerals, kamacite and troilite, aggregated with maskelynite (white) ($\times 63$, plane-polarized light; W.A.M. no. 12780). FIG. 19. The Dingo Pup Donga ureilite, showing a general view of the brecciated texture. Olivine, grey, and pigeonite, showing polysynthetic twin lamellae. The base is a black cryptocrystalline aggregate, punctuated by a few reflectant metal and troilite specks ($\times 25$, crossed nicols; W.A.M. no. 12778). FIG. 20. Photograph of the Dingo Pup Donga ureilite, showing clinopyroxene (pigeonite) displaying twin lamellae extraordinarily like those of calcic plagioclase and olivine grains (white, untwinned) ($\times 100$, crossed nicols). FIG. 21. Photomicrograph of the Dingo Pup Donga meteorite showing an area virtually free from clinopyroxene—only olivine grains are visible ($\times 100$, plane-polarized light).

is a pigeonite, and has an extinction angle for the lamellae of about 38°. It was originally mistaken for bytownite and indeed in these small subhedral grains only a high relief distinguishes it, for the birefringence is low (first order greys, yellows) and the lamellar twinning cannot be distinguished from albite twinning without sophisticated measurements on the universal stage, or separation of the very fine and sparse grains.

Modal analysis using a point-counter showed the composition to be very variable: some areas are almost free from pigeonite: the over-all composition is $\sim 10\ \%$ by volume, the only other silicate mineral, olivine, making up $\sim 80\ \%$, and the remainder being a fine, opaque, black intercrystalline base, which shows highly reflectant specks along some grain boundaries (nickel-iron?): no other opaque mineral can be recognized with the equipment available, though the analysis suggests that troilite and chromite are present, and also carbon, which may give this base its dark colour. This base, like that of the North Haig meteorite (p. 700) may be a fine crush matrix—the crystal grains are certainly broken, suggesting brecciation. If so, it reflects a primary brecciation. A few patches of crystalline material appear to be lithic fragments in the breccia, consisting of intergrown grains of anhedral to subhedral and almost equidimensional form: possibly this is the material from which the breccia was derived. The possibility that the fine, dark base was originally a glass cannot be discounted, but in this case the attribution to the breccia process seems more likely.

The meteorite was first thought to be an abnormal howardite. It was however analysed by Mr. O'Beirne, using X-ray fluorescent spectroscopy, and the results, though of course only giving a partial analysis, clearly showed that this is a calcium-poor achondrite. They also showed that the lamellar-twinned mineral could not be plagioclase. The meteorite was later analysed by Mr. E. Jaresowich, of the Smithsonian Institution, using the classic wet gravimetric methods. The results of both analyses are included in table II. The significance of this second ureilite find is further considered below (see discussion).

Meteorites from the area near Cocklebiddy Tank, Eyre Highway

The *Cocklebiddy* stone was described by McCall and de Laeter (1965, p. 27) as a dark coloured, very fresh olivine-bronzite chondrite (Fa_{18}). Since this discovery was made another olivine-bronzite chondrite and four olivine-hypersthene chondrites have come to light in this area, which is covered by the Miocene Nullarbor Limestone, thinly veneered by patches of sandy soil. All the recoveries made, the distribution of which is shown in fig. 22, are of meteoritic material lying loose on this surface. They are listed in table III.

Burnabbie is a purplish-grey, weathered chondrite, quite unlike Cocklebiddy, which was recovered only 7 miles away. It probably is of much greater age on earth (Cocklebiddy is unusually fresh). The main

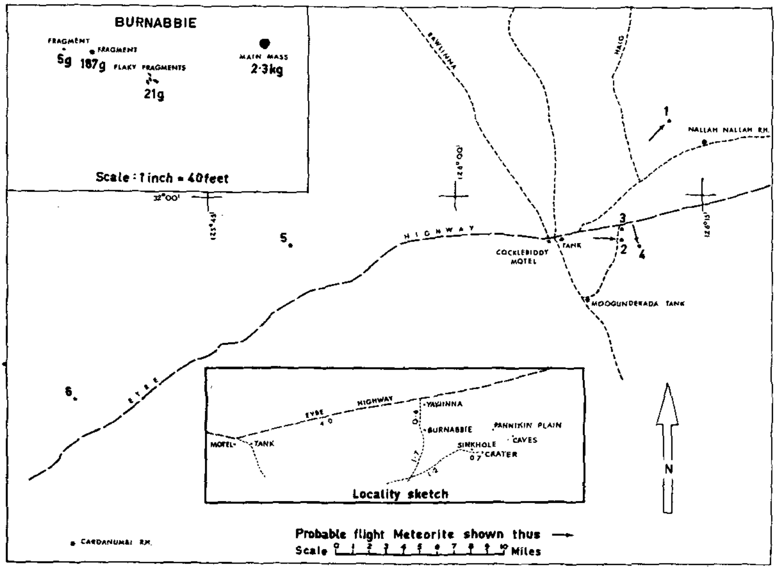


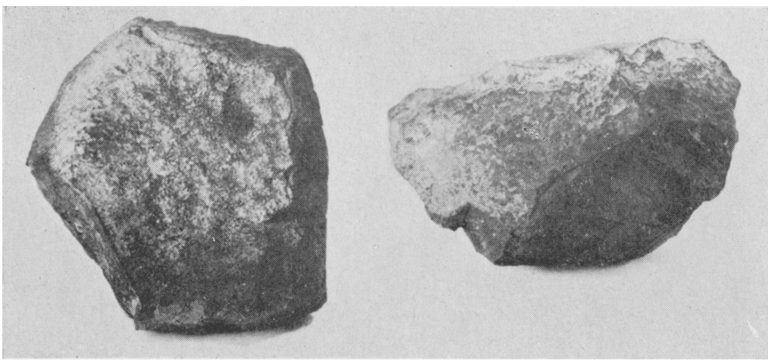
FIG. 22. Sketch-map of the area around Cocklebiddy Tank, Eyre Highway, showing the sites of meteorite recoveries.

TABLE III. Meteorites from the Cocklebiddy Tank area, Eyre Highway

Found	*Name*	*Type and Fa %*		*Weight*	*Preserved at*	*Finder*
1949	Cocklebiddy	CBr	18	19·5 Kg*	W.A.M., K.	A. J. C.
1965	Burnabbie	CBr	18	2·5 Kg†	K., W.A.M.	A. J. C. Jr., W. H. C.
1965	Yayjinna	CHy (RR)	25	262·4 g	K., W.A.M.	A. J. C. Jr.
1965	Pannikin	CHy (R)	24	13·6 g‡	K., W.A.M.	A. J. C.
1966	Burrika	CHy (RR)	24	20·4 g	K., W.A.M.	A. J. C.
1966	Cardanumbi	CHy (R)	24	6·4 g	K., W.A.M.	D. C.

Notes as in table I, also: RR, extremely recrystallized. A. J. C. Jr., A. J. Carlisle Jr.
* Fresh, black.
† One mass of 2·3 Kg found by A. J. C. Jr., three fragments, 0·2 Kg, found by W. H. C.; a weathered grey spherical chondrite.
‡ Two masses.

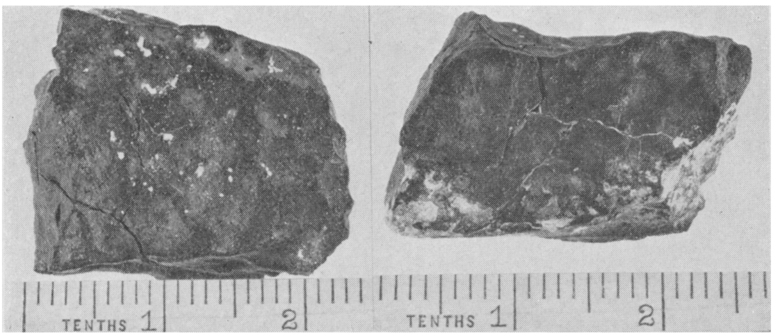
mass is a fusion-crust covered stone weighing 2·3 Kg. The finder, Mr. A. J. Carlisle Jr., showed the second-named author (W. H. C.), the site in January 1965 and he was able to pick up three more chips of similar material. The distribution of the material is shown in fig. 22 (inset A). The main mass shown in figs. 23 and 24 is an incomplete meteorite, and these chips may well have broken off from it on impact. The fusion crust has the character of a whitish film, and a zone 0·5 cm thick underlying it shows a tendency to peel away from the rest of the mass. Striations and regmaglypts mark the surface. There is no glassy material evident, the crust having been decomposed to a caliche by groundwater action (cf. Dalgety Downs, McCall, 1966*b*). On the purplish-grey fresh-cut surface spherical chondrules are prominent, but the metal and sulphide are decomposed and no longer detectable.



FIGS. 23 and 24: FIG. 23. The Burnabbie meteorite, showing the whitish, altered fusion crust and regmaglypts indenting it; the mass is 6 in. long (S.M.K. no. 9846). FIG. 24. The Burnabbie meteorite showing the weathered, grey broken surface and white, 'fibrous' dermal zone beneath the fusion crust, a zone nearly a centimetre deep; same scale as fig. 23.

In thin section (fig. 27) the meteorite is seen to be a spherical chondrite, with numerous rather small chondrules crammed together in a matrix of fine, iron-stained, amorphous or cryptocrystalline material, probably an altered glassy base. Chemical analysis is of no value in the case of such weathered material. The olivine was however determined by Mason and gave a value of Fa_{18} (the same as Cocklebiddy). The meteorite is thus classified as a spherical olivine-bronzite chondrite, quite devoid of recrystallization.

Yayjinna. Another small stone was found close to the site of the Burnabbie find by Mr. A. J. Carlisle Jr. in May 1965. The mass is almost cuboidal and shows very sharp corners between the surfaces. It was, before cutting, entirely coated with a blackish-brown fusion crust (figs. 25 and 26); there is no trace of oriented form. The specific gravity is 3·27, rather low, but the mass is very weathered. A prominent vein of troilite cuts right across the mass forming a ridge in the fusion crust. A peculiar orange-brown coloration is displayed by the fresh-cut surface, quite unlike either Cocklebiddy or Burnabbie. That this meteorite comes from a quite different arrival event was confirmed by X-ray diffractometer determination of the olivine by Mason which gave a figure of Fa_{25}, indicating an olivine-hypersthene chondrite. Metal and associated troilite occurs only as rather sparse scattered specks of reflectant material. Chondrules cannot readily be detected though there



FIGS. 25 and 26: FIG. 25. The Yayjinna meteorite, showing the cuboidal form and dark, wavy fusion crust (S.M.K. no. 9961). FIG. 26. The Yayjinna meteorite, showing the flattened form of the cube and a white caliche formed on the part that lay in the soil.

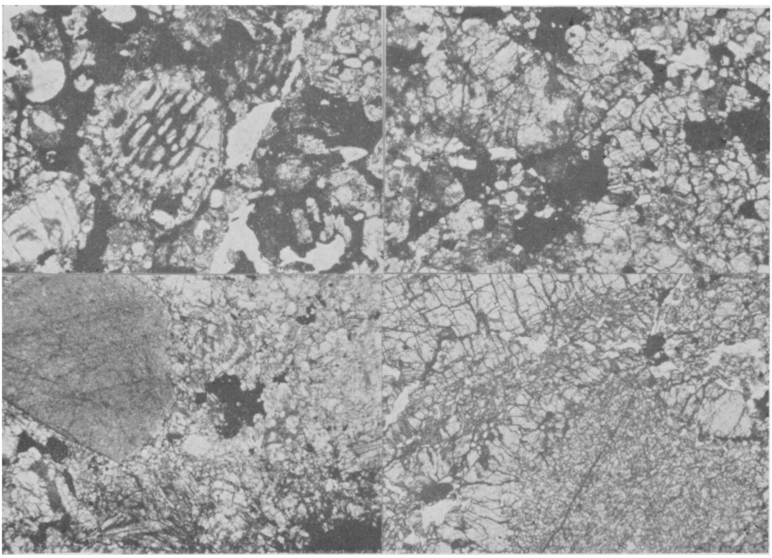
are a few irregular remnants visible. In thin section (fig. 28), the meteorite is seen to be extremely recrystallized. The chondrules, few and large, show ragged, merging outlines with the coarsely granoblastic aggregate that forms the bulk of the mass. Olivine is the predominant silicate mineral, aggregated with subordinate orthopyroxene. Maskelynite after plagioclase, isotropic or almost so, of low relief and birefringence, n 1·504, is an abundant accessory.

The recrystallization texture is one of large, anhedral skeletal grains aggregated together: it is interesting to contrast this texture with that of the achondrite North Haig (p. 701), in which the grains are not irregular or skeletal, and show distinct crystal faces. The meteorite is classified as an extremely recrystallized, veined olivine-hypersthene chondrite.

Pannikin. The fourth of this group is very poorly represented in the material sense. Only two very small chips of meteoritic material were collected by Mr. A. J. Carlisle from within a distinct impact pit[1] (fig. 31).

[1] An australite was found within this pit; one of us (W. H. C.) regards this as evidence of considerable age on earth (? some thousands of years), since there is nothing to suggest that it was not *in situ*. Others were recovered nearby.

The site is very close to that of the Yayjinna and Burnabbie finds (fig. 22). The ground surface evidence is recorded in fig. 22 (inset B). The chips are purplish-grey coloured, like Burnabbie. Under the microscope (fig. 29) olivine is seen to be the predominant mineral present, being



FIGS. 27–30: FIG. 27. Photomicrograph of the Burnabbie meteorite, showing the spherical texture, sharply defined orbicular chondrules being set in a dark glassy or cryptocrystalline base (×63, plane-polarized light; W.A.M. no. 12580). FIG. 28. Photomicrograph of the Yayjinna meteorite, showing the recrystallized aggregate of orthopyroxene and olivine granules (both grey), maskelynite (white, low relief), and nickel-iron–troilite aggregates (dark, opaque) (×63, plane-polarized light; W.A.M. no. 12785). FIG. 29. Photomicrograph of the Pannikin meteorite, showing a large, well-defined chondrule set in a fine, recrystallized base, in which elongate pyroxene grains are prominent (×25 plane-polarized light; W.A.M. no. 12799). FIG. 30. Photomicrograph of the Burrika meteorite; the outlines of chondrules can be seen, but the mass is extremely recrystallized. Large irregular masses of cracked olivine extinguish simultaneously. Maskelynite is evident (white, low relief), also nickel-iron–troilite aggregates (black, opaque) (×63, plane-polarized light; W.A.M. no. 12786).

aggregated with orthopyroxene and lamellar pigeonite. There are rare, minute grains of untwinned plagioclase present. Nickel-iron and troilite make up about 15 % of the meteorite by volume. The chondrules are clearly defined and set in an uneven, granoblastic base, which consists of grains mostly of two diameters, 0·4 and 0·02 mm. The olivine has been determined by Mason as Fa_{24}, and this meteorite is therefore classified as a recrystallized olivine-hypersthene chondrite.

Burrika. Again this is but meagrely represented in terms of material. Mr. A. J. Carlisle picked up a single, very small stone in the same

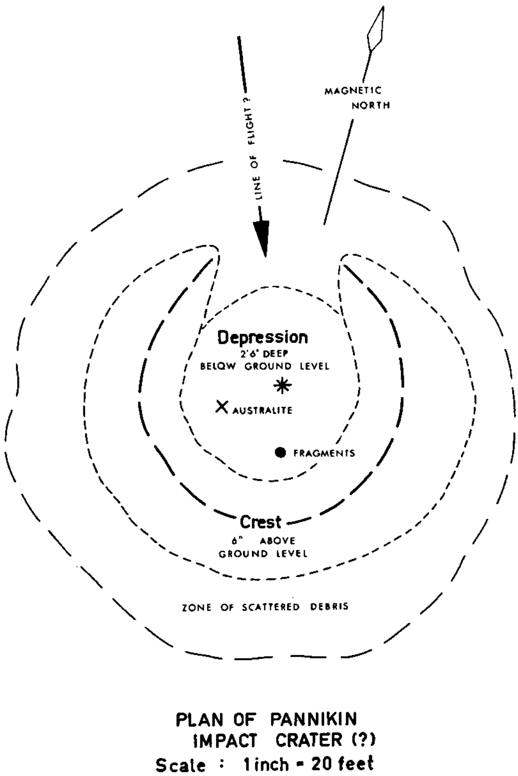


FIG. 31. Sketch plan of the Pannikin impact crater.

general area (fig. 22) in February 1966. The total weight is only 20·4 g. The stone consists of a convex, fusion-crust coated surface, black in colour, and backed by irregular, dark, iron-stained fresh-cut surfaces (fig. 32). It has the form of a flake. The specific gravity is 3·32, low, but consistent with the weathered character. A thin section (fig. 30) shows it to be a recrystallized chondrite of the same rather unusual character as Yayjinna, and the olivine determination by Mason gave nearly the same figure (Fa_{24}). Like Yayjinna, too, maskelynite is in evidence.

Cardanumbi. Another meagre recovery of material was made by

Mr. D. Carlisle in January 1966 in the same general area. This is a complete meteorite, in the form of a pellet, coated on all sides by a black fusion crust (fig. 33). It is an olivine-hypersthene chondrite, very recrystallized. The fayalite index of the olivine determined by Mason

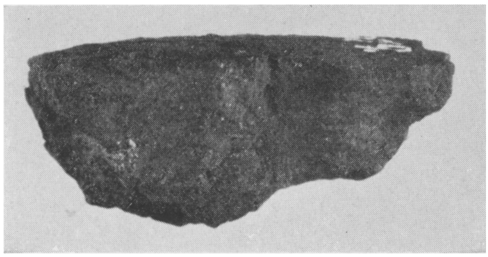
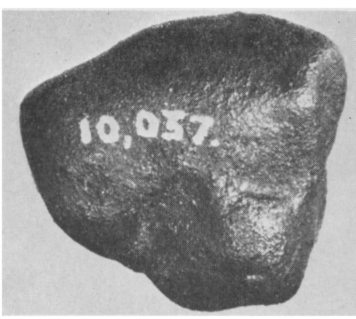
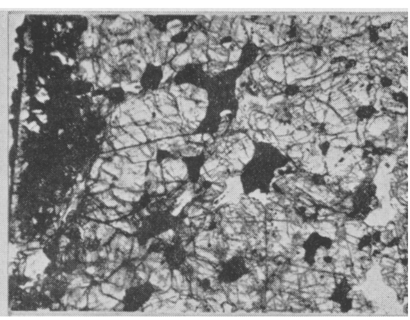


FIG. 32. The Burrika meteorite, showing a curved fusion crust surface and black coloration of both crust and fresh-cut surface (S.M.K. no. 9979).





FIGS. 33 and 34: FIG. 33. The Cardanumbi meteorite, a minute, fusion-crust-enveloped pellet (diameter $\frac{3}{4}$ in.; S.M.K. no. 10037). FIG. 34. Photomicrograph of the Cardanumbi meteorite, showing recrystallization: olivine and pyroxene (both grey), plagioclase or maskelynite (white, low relief), and nickel-iron-troilite aggregates (black, opaque). The three-layered fusion zone shows on the left of the photograph (×63, plane-polarized light; W.A.M. no. 12794).

is Fa_{24}, the same as Burrika, though this meteorite does not resemble either Burrika or Yayjinna physically. The fresh-cut surface is creamy-grey coloured. The thin section shows it to be reasonably like Burrika in texture (fig. 34) and it contains plagioclase that is almost isotropic, having been converted to maskelynite. There is too little of this material for it to be of any importance except in terms of statistics and distribution, and the only feature of interest is the very good section across the fusion crust zones revealed by the slide.

Discussion

Most of the meteorites described here were found by members of the Carlisle family (Mr. A. J. Carlisle, his brother H. E. Carlisle, and his two sons A. J. Carlisle *Jr.* and D. Carlisle). It is of interest to record this fact, for perhaps no single family has such a record of meteorite recoveries throughout the world. Their generosity must be acknowledged here, for meteorites found by them are represented in collections all over Australia. The family is mainly occupied with rabbit trapping, and they are familiar with the Nullarbor Plain in a manner that few other people can be. The two areas described here are those which they mostly frequent for the purpose of trapping.

It is now apparent that the groupings are due to the fact that these are areas visited by people who cover the limestone desert closely, moving on foot or by motor-bicycle, and with an eye to the ground. Any hypothesis suggesting synchronous arrival of the meteorites of either group must fall down. It would have to allow for contrasting types to arrive together, and this is never observed in the case of recorded falls of meteorites. Though the evidence that we have from the Mount Padbury meteorite (McCall, 1966*c*) and the Dalgaranga Meteorite (McCall, 1965) does indicate that octahedrite, mesosiderite, eucrite or howardite, diogenite, and olivine achondrite material could so arrive, and other evidence from Bencubbin indicates that olivine-enstatite stony-iron and chondrite material could so arrive (McCall and de Laeter, 1965, p. 108): but the evidence of contrasting weathering states, distribution, morphology, and chemical variation of olivines of the chondrites recorded here leave little doubt that in each group several falls are represented. Five for certain, and possibly up to eight in the case of the first group, are established: and at least four in the case of the second group.

Can primitive (in the sense of not being at all recrystallized) chondritic material occur in the same meteorite as highly recrystallized chondritic material? The work of Wahl (1952) suggests that such a type of textural inhomogeneity is not observed. There is, further, little or no evidence from observed falls, or from material obtained from finds, that the four classes of chondrites are found mixed up in polymict breccia masses: indeed there is little or no evidence that olivine of differing fayalite indices even may be found in such masses (except for the carbonaceous chondrites which show variable olivine). And so, in the case of the chondrites, it is only the juxtaposition of finds with identical fayalite indices that cause some doubt. Such a juxtaposition in the case of the two Mulga finds is, the authors still believe, quite fortuitous, even though the dispersion areas almost overlap. Both authors have quite independently noted the physical disparity of texture and of weathering state. The coincidence in the case of Cocklebiddy and Burnabbie (strangely also both Fa_{18}) is certainly fortuitous, and these are but 7 miles apart.

By far the oddest feature is the find of *two* ureilites only 19 miles apart. All the dictates of reason suggest that there must be a connexion. The analyses are remarkably similar; the lower magnesia content in Dingo Pup Donga correlates with an observed, slightly higher clinopyroxene content, and other slight variations may be similarly attributed. The acid soluble and insoluble percentages are interesting:

Acid soluble: Dingo Pup Donga 65·9, North Haig 81·1
Acid insoluble: Dingo Pup Donga 34·1, North Haig 18·9

The acid insoluble component is essentially the pyroxene component. The cause for the difference may be related to sampling problems, and could depend on the much greater proportion of fine base material in Dingo Pup Donga. The most significant differences are the much coarser texture of North Haig, and the nature of the pyroxene twinning. The twinning of the clino-pyroxene in North Haig is either just like that seen in many igneous rock augites and pigeonites (a few broad, repeated bands) or in very fine lamellae, resembling striations. In the case of Dingo Pup Donga the lamellae are not like striations, being of uneven width, like calcic plagioclase. Such textural differences could, of course, come about in different parts of an inhomogeneous mass. The distance apart is great for meteorites from a single arrival event, but by no means rules out synchronous arrival. Finally it must be noted that there is a record of two meteorites of a similar extremely rare type falling in the same part of India a few years apart, and so we must at least leave the matter open: North Haig and Dingo Pup Donga could well come from a single arrival event, but there is some evidence to the contrary.

The fourteen meteorites described here come from two very small areas of the Nullarbor Plain. How many more meteorites must lie out in these vast limestone desert expanses, both in Western Australia and in South Australia—in parts not visited by the Carlisle family and their associates? In this age of sophisticated instrumental techniques it is easy to assume that we have gathered in virtually the total amount of material available for scientific study. This, perhaps, tends to be assumed because the most favourable source known, the great plains of North America, are either largely worked out or lost to science on account of the adverse influence of trading in meteorites. Unpopulated stony deserts such as the Nullarbor Plain must provide similar favourable areas, and a full-scale programme of collection from this area, utilizing, if possible, the skills of people already familiar with the area should, perhaps, be set in motion before it is too late—and without undue publicity.

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