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The Dunbogan L6 Chondrite: A New Meteorite Fall from New South Wales, Australia

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ABSTRACT. A meteorite crashed through the roof and ceiling of a house at Dunbogan on the north coast of New South Wales, Australia, on 14 December 1999, and 30 g of fragments were recovered. The fall was observed by a girl at Tinonee, 50 km to the SSW. The meteor was observed in the mid northern sky at about 22h00 East Australian DST (GMT + 11 hrs), moving in a SSE direction. In mid-flight the meteor broke into at least 3 fragments. Detailed mineralogical and petrological examination of the meteorite have revealed that it is comparable to an L6 ordinary chondrite with mean olivine composition Fa_{25} and pyroxene Fs_{21}.

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At 22h05 East Australian DST (GMT + 11 hrs) on Tuesday, 14 December 1999, an object crashed at Dunbogan (c. 152°50'E, 31°40'S), leaving a 30 × 50 cm hole in the roofing tiles and timber-clad ceiling, coming to rest on the living-room floor of the home of Mr Paul Hancox (Fig. 1). The object, with calculated volume of 9 cm^3 and weighing a minimum of about 30 grams, broke into several fragments on impact with the roof. The Australian Museum and the University of New England were each provided with one small fragment for study. The aerial fragmentation and later impact were not observed by the same person. No other persons reported rumbles or explosions. No other fragments have been located on the house roof or nearby. The name *Dunbogan* has been approved by the Meteorite Nomenclature Committee of the Meteoritical Society (Grossman & Zipfel, 2001).

Recoveries from observed meteorite falls are not common, and this is only the fourteenth such recovery from Australia. Meteorite falls which cause structural damage to buildings are even more significant, because their rarity generates considerable scientific and popular interest. For these reasons it is important to document the meteorite involved.

The Fall

An eyewitness account by Elyse Smith, a girl residing at Tinonee, 50 km south of the impact site, reported observing a bright object “like a huge flamy ball crossing in a direction from the middle northern sky. After a few seconds it broke into one large fragment and two middle-sized bits with a lot of rubble fragments flying off”. It was observed falling over a period of several seconds. There were no other reports of sound effects or light trails, except when it hit the house. This account suggests that more fragments of the meteorite may have fallen to Earth than were recovered.

The Meteorite

The fragment provided to researchers at the University of New England was approximately 7 mm in diameter and about 2 mm thick. The specimen was catalogued as R77552 in the University of New England Earth Sciences Rock Collection and has since been transferred to the Australian Museum petrology collection and catalogued as a polished block mount DR16659. Another specimen, approximately 8 mm in diameter, 5 mm thick and 0.48 g in weight, loaned to the Australian Museum by Mr Hancox for specific gravity measurement, has been returned. A group of fragments totalling approximately 5 g, registered as DR16713 has been presented to the Australian Museum by Mr Hancox to satisfy requirements of the International Meteoritical Society.

A freshly-broken surface of the meteorite is pale grey-brown with scattered opaque grains and veinlets, but appears much darker in polished section. The UNE specimen is a dark brown colour in polished section, displaying a 1 mm thick, black glassy fusion crust on one side and dispersed metallic blobs throughout a brecciated groundmass (see Petrography and Chemistry). Individual pyroxene and olivine crystals which constitute the bulk of the grains rarely exceed 0.4 mm in diameter. The metallic blobs are up to 0.5 mm in diameter. The SG of the fragment examined by the Australian Museum was 3.48±0.03. Scanning Electron Microscopic examination of the UNE specimen clearly displayed the brecciated nature of the sample and the black glassy rim overlying an earlier melting surface which now displays quench textures.

Petrography and Mineral Chemistry

A polished block (approximately 30 mm^2 surface area) was prepared from the fragment mounted in resin. Petrographic observations of the main textural characteristics of the fragment in reflected light showed that it is probably chondritic. Abundant aggregates are irregular, angular to sub-rounded in outline and up to 2.5 mm across, in places with through-going fractures. No well-defined chondrules are apparent, but many apparent breccia clasts are sub-rounded (Fig. 2) and may represent variably recrystallised and broken chondrules. Certain clasts contain variably recrystallised chondrule material (e.g., relicts of "barred olivine"). The breccia is typically clast-supported and the amount of matrix interstitial to the clasts does not exceed 20 vol. % (Fig. 2). In general, clasts are composed of inequigranular aggregates of interlocking silicate grains (typically up to 0.8 mm across), with a few grains of a spinel phase, rare grains of a phosphate phase, and heterogeneously distributed metal and sulphide masses, commonly in composites. In-between the fragments, and locally forming apparent injection masses up to 0.2 mm wide into clasts, is a fine grained matrix, commonly showing a fine "emulsion" texture. The matrix appears to be composed of a mixture of finely comminuted silicate material, possible glass and tiny "droplets" of metal ± sulphide (Fig. 3). This looks like eutectic melting in the heat affected zone of the meteorite. The amount of "emulsion-textured" material in the sample is 10 vol. %.

On one side of the meteorite fragment, there are relicts of a possible former glassy margin (fusion crust) (Figs. 4, 5). Adjacent to crystalline clast material, there is an inner zone up to 0.2 mm thick of quench-textured former glass which appears to grade into microbreccia matrix. This has been subsequently bordered by an apparently homogeneous but vesicular glassy phase up to 0.1 mm thick. Similar fusion crust components were described by Genge & Grady (1999).

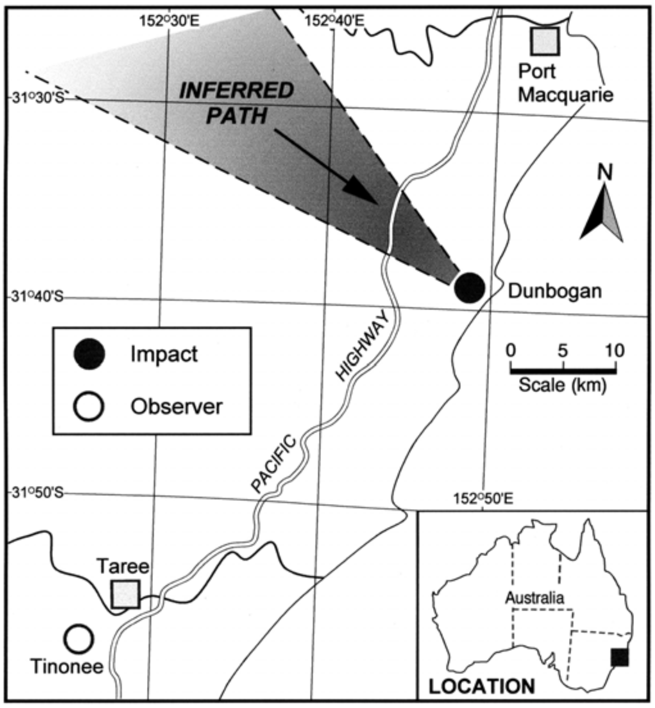

Figure 1. Estimated flight path of the fireball which resulted in the Dunbogan meteorite.

Examination under reflected light and using back-scattered electron (BSE) and secondary electron imagery (SEI) showed that the approximate mineral mode of the meteorite fragment was as follows: olivine and pyroxene each 40 vol. %, plagioclase 10 vol. %, sulphide phase 5 vol. %, metal phase(s) 3 vol. %, chromite and glass each about 1 vol. % and a tiny trace of a phosphate phase. These minerals were subsequently subjected to electron probe micro-analyses, with several grains of each phase being analysed and results listed in Table 1. Olivine and pyroxene are clear to pale brownish in colour from their internal reflections and have relatively constant compositions. Olivine averages Fa_{25} (with minor Mn, and locally detectable trace amounts of Al, Cr, Ni and Ca). The pyroxene is a Ca-poor type with an average composition of Fs_{21} (containing minor Ca and Mn, and trace amounts of Ti, Al, Cr, Ni and Na). Plagioclase appears to be largely interstitial to olivine and orthopyroxene (Figs. 5, 6) and has a rather consistent composition ranging between $An_{10–11}Ab_{84–85}Or_{4–5}$. The chromite forms individual anhedral grains up to 0.2 mm across, as well as local aggregates up to 0.3 mm across, in places attached to metal grains (Fig. 6). Chromite also occurs as scattered small inclusions in olivine and orthopyroxene; in the latter it may form oriented exsolution blebs. Compositionally, the spinel is a rather Fe-rich chromite, with minor Al, Ti, Mg, Mn, Zn and Ni (Table 1). Assuming stoichiometry, it has an approximate composition of $(Fe^{2+}_{0.89}Mg_{0.12}Mn_{0.02}Zn_{0.01})(Cr_{1.64}Al_{0.20}Fe^{3+}_{0.07}Ti_{0.05})O_4$.

The sulphide phase is slightly more abundant than the metal phase, and although the two are commonly closely associated, they can occur discretely. Both are found as isolated anhedral grains up to 0.5 mm across interstitial to silicates, as inclusions in silicates, as a fracture-fill component, and as a fine emulsion-like phase in the matrix

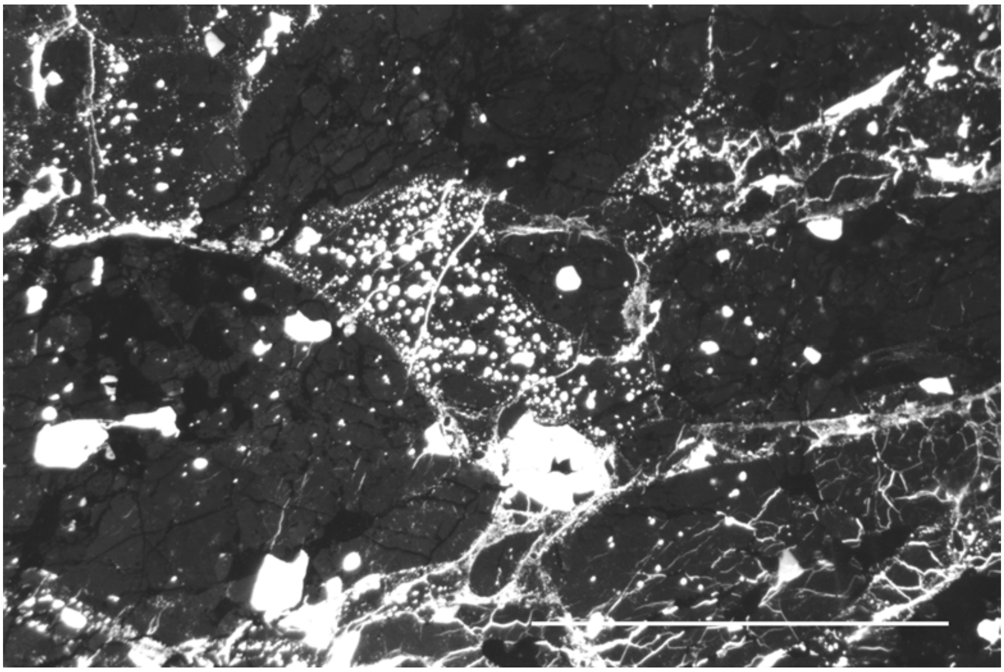

Figure 2. Photomicrograph showing chondrule texture (dark silicates, white sulphide and metal phases) and interstitial fine grained matrix with "emulsion" texture of metal/sulphide globules in silicate groundmass (?shock-melt vein). Note that the possible chondrules are locally strongly fractured. Scale bar 1 mm., plane polarised reflected light, oil immersion.

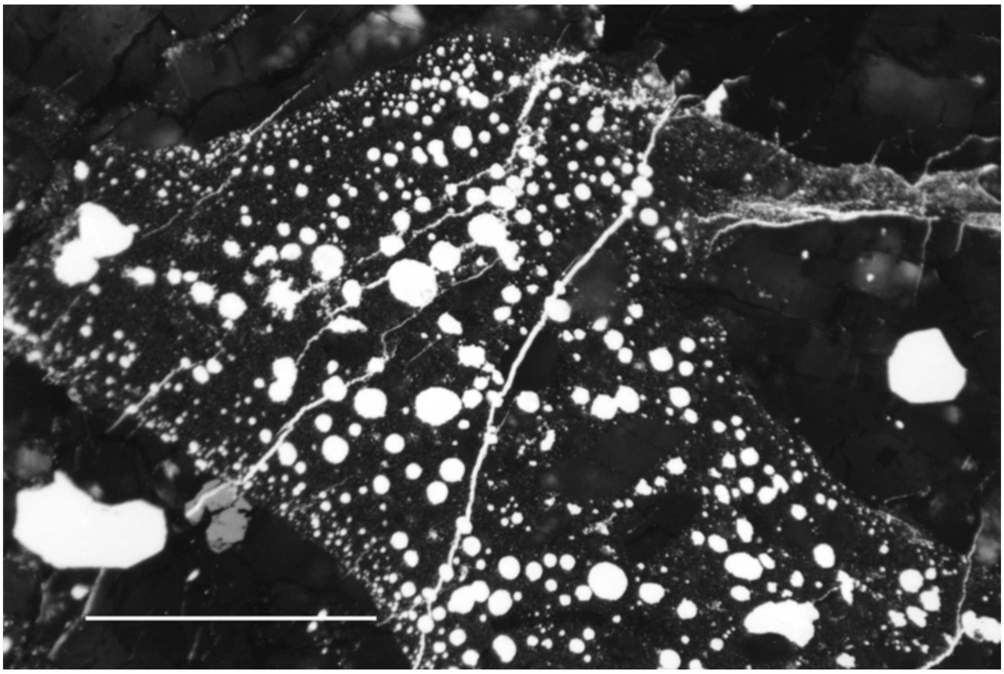

Figure 3. Photomicrograph showing enlarged detail from Fig. 2. Matrix interstitial to possible chondrule fragments contains abundant small white metal/sulphide droplets in a dark silicate groundmass, forming "emulsion" texture. Scale bar 0.25 mm. Plane polarised reflected light, oil immersion.

between the breccia clasts (Figs. 2, 3). Many composite masses of sulphide and metal phases show finely developed eutectoid textures (Fig. 7) indicative of having crystallised from a melt. Compositionally, the sulphide is a non-stoichiometric FeS-like phase, resembling pyrrhotite. It is strongly anisotropic under crossed polars and may contain minor to trace amounts of Ni, Co and Cu (Table 1). Under high-power examination and using X-ray mapping on the electron microprobe, it was observed that the metal phase is heterogeneous, with two constituents of slightly varying reflectivity and varying Fe and Ni contents. There is a range from Fe-rich to a phase approaching Fe_3Ni. Minor Co is present, with its content being highest in the most Fe-rich phase (Table 1). The metallic material, consists of both kamacite and taenite. Rare anhedral grains of a phosphate phase up to 0.05 mm across, enclosed in silicates, were noted during BSE scanning. A single analysis of this phase (Table 1) demonstrated that it was a Ca-rich orthophosphate, with minor Fe and Mg. No F or Cl was detected and the stoichiometry was inconsistent for apatite; the phase is merrillite (cf. Dowty, 1977) and has a composition similar to that reported by Bevan *et al*. (1988) and Cooney *et al*. (1999).

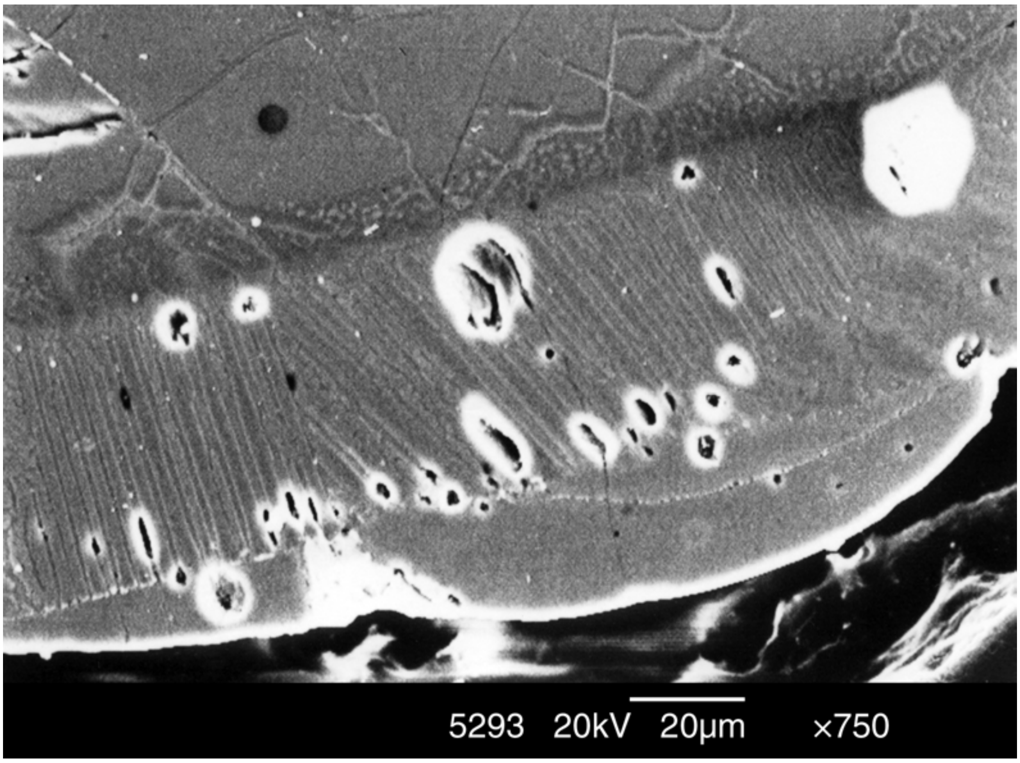

Figure 4. Secondary electron image of fusion crust of meteorite (lower right-hand area of Fig. 5) showing crystalline silicate material at top, bordered by a zone of crystallised glass (now containing bladed crystallites) plus one grain of metal phase (white), and with a thin rim of homogeneous glass at bottom of image. Scale bar 20 µm.

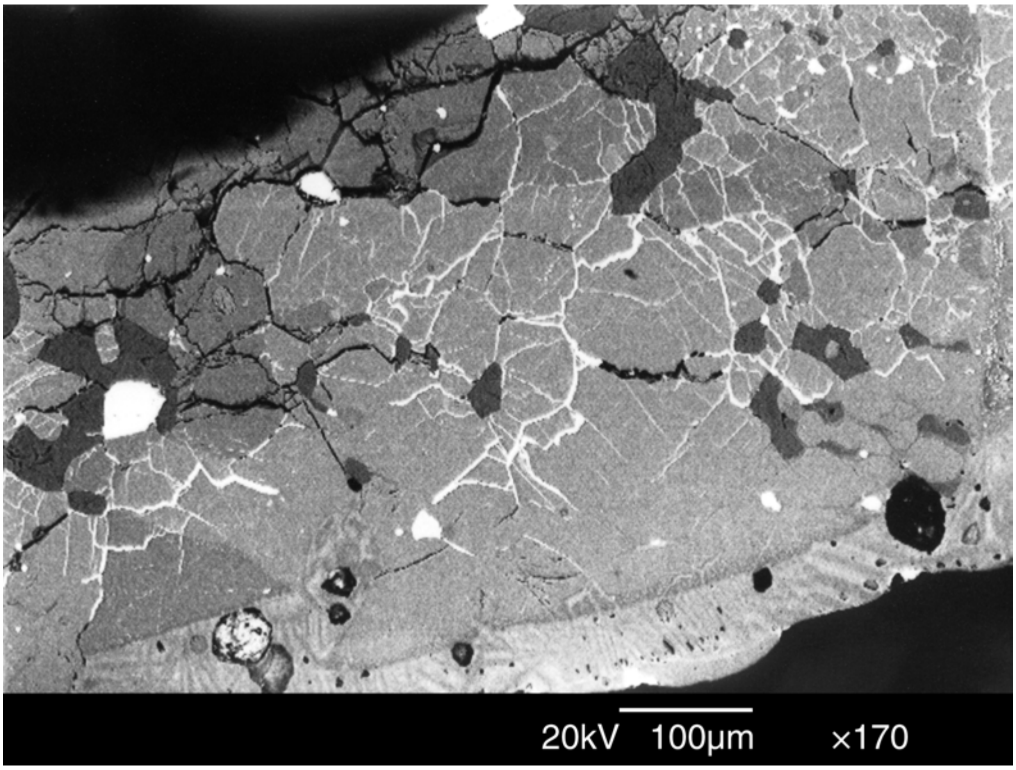

Figure 5. Back-scattered electron image of portion of the meteorite showing a granular crystalline aggregate of olivine (medium grey), pyroxene (slightly darker grey), plagioclase (black) and metal phase (white). There is a compound rim (fusion crust) of crystallised glass, partly bordered by a thin zone of homogeneous glass towards the bottom of the image. Note how the metal phase has invaded along silicate grain boundaries. Scale bar 100 µm.

In the quench-textured zone (fusion crust) rimming part of the meteorite fragment, two bladed phases are evident on SEI scans (Fig. 4). Analyses of these phases indicated that they do not conform to stoichiometric minerals perhaps because of electron beam overlap onto adjacent phases. One phase is olivine-like, but contains higher Si, Al, Cr, Ca and

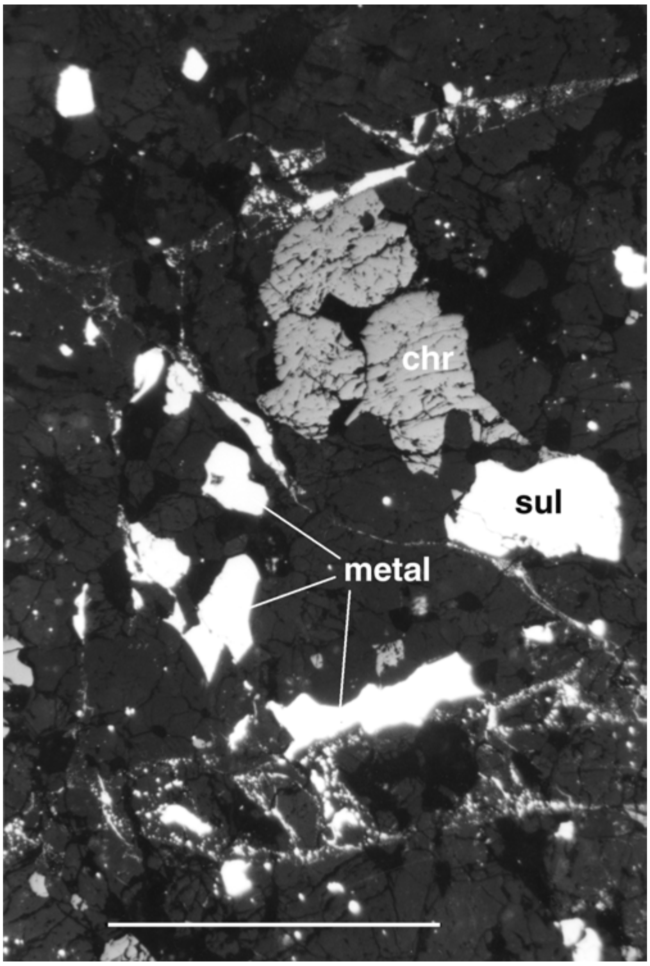

Figure 6. Portion of chondrule showing intergrowth of olivine and pyroxene (dark grey), with plagioclase (black), chromite (chr), troilite (sul) and metal phase. Scale bar 1 mm. Plane polarised reflected light, oil immersion.

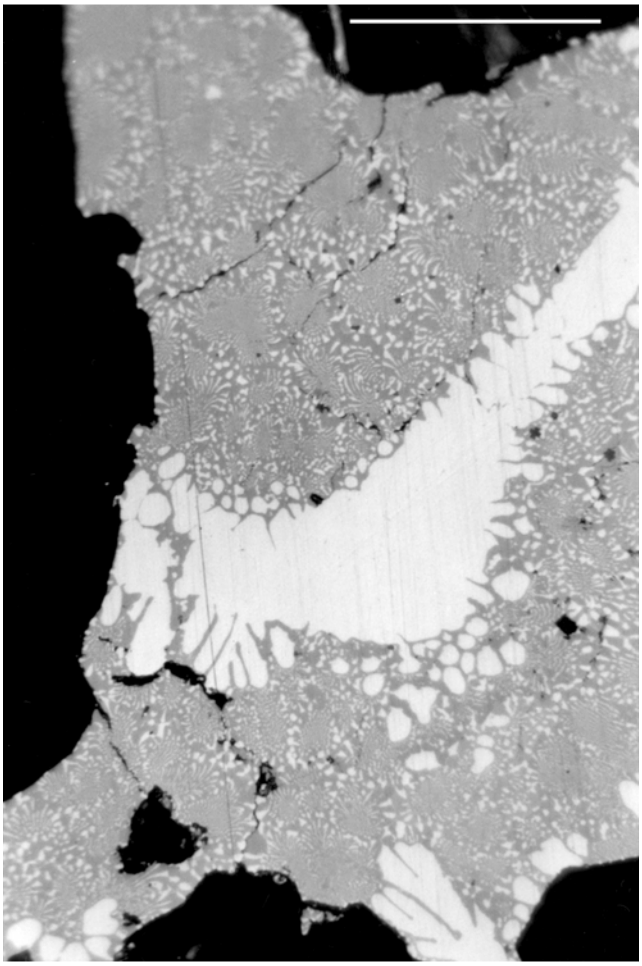

Figure 7. Detail of composite sulphide-metal grain showing eutectoid textures (indicative of crystallisation from a melt) between metal phase (white) and troilite (grey). Scale bar 0.1 mm. Plane polarised reflected light, oil immersion.

lower Fe and Mg than analysed olivines. The other phase is more heterogeneous and may contain the components of olivine, orthopyroxene, plagioclase and sulphide. Analyses of the thin rim of apparently homogeneous glass could give an indication of the bulk composition of the meteorite. However, it is clear that the amount of Fe, Ni and S in this glass is insufficient to balance what is obviously present in the bulk of the meteorite. It is possible that when melting during atmospheric passage formed the fusion crust, the sulphide-metal phase became mobile and infiltrated into fractures and along grain boundaries in adjacent crystalline material (e.g., Fig. 5).

Discussion

Classification of the meteorite. From the observed textures in the meteorite, the sample represents a chondritic type, based on the preservation of chondrule outlines (e.g., Fig. 2). However, the chondrules have been strongly recrystallised, as well as being subject to fracturing and brecciation. The presence of planar fractures in olivine and interconnected melt veins suggest an S4 shock stage (moderately shocked) of Stoffler *et al*. (1991). The compositions of olivine (average Fa_{25}) and Ca-poor pyroxene (average Fs_{21}) are consistent with the meteorite belonging to the L-group of ordinary chondrites of Van Schmus & Wood (1967) and Dodd (1981). Forty EDS analyses of olivine grains showed a narrow variation within ± $Fa_{1.8}$ of the mean for 90% of the analyses, indicating an equilibrated chondrite. Sodic plagioclase is common in equilibrated ordinary chondrites of moderate to extensive recrystallisation, especially for petrologic type 6 (Nakamuta & Motomura, 1999). The Wo content of Ca-poor pyroxene is a key quantitative parameter for distinguishing petrologic types, and determined values (Wo 1.5–1.6), indicate an L6 classification (Scott *et al*., 1986).

The recrystallised textural characteristics, the olivine and pyroxene compositions, presence of sodic plagioclase and metal phases including Fe-rich and significantly Ni-rich types, are most consistent with the meteorite being of petrologic type 6 (Van Schmus & Wood, 1967). The L6 group is the most common type of chondritic meteorite seen to fall and the Dunbogan sample displays strong textural and mineralogical similarities to other L6 examples (e.g., Bevan *et al*., 1992). Up to 1992, 55 L6 chondrites from Australia had been documented, representing 19.9% of known Australian meteorites and four out of 13 observed falls (Bevan, 1992).

Table 1. Mineral chemistry of phases in the Dunbogan L6 chondrite. Analyses by P. Garlick and P. Ashley, University of New England, using a JEOL JSM5800LV SEM/Oxford Link Isis EDS, at 20kV and 34 nA, with a 100 second count time; *n.d.* = not detected; *In chromite, Fe_2O_3 and FeO are calculated assuming stoichiometry. In other analyses total Fe is expressed as ΣFeO.

	Olivine mean n=4 (range)	**Pyroxene** mean n=4 (range)	**Plagioclase** mean n=3 (range)	**Chromite** mean n=3 (range)
SiO_2	38.0 (37.8–38.3)	54.7 (54.4–55.0)	66.8 (66.2–67.3)	*n.d.*
TiO_2	*n.d.*	0.12 (0.11–0.12)	*n.d.*	1.80 (1.08–2.46)
Al_2O_3	0.06 (0.03–0.12)	0.12 (0.08–0.15)	20.1 (19.9–20.3)	4.70 (3.64–6.47)
Cr_2O_3	0.03 (0.03–0.07)	0.19 (0.13–0.24)	*n.d.*	57.7 (56.0–58.8)
Fe_2O_3*				2.53 (0.61–4.25)
FeO*				29.7 (28.4–31.4)
ΣFeO	22.7 (22.2–23.2)	13.8 (13.4–13.7)	0.42 (0.30–0.53)	
MnO	0.44 (0.40–0.47)	0.60 (0.57–0.65)	*n.d.*	0.76 (0.64–0.87)
MgO	38.6 (38.3–38.7)	29.3 (28.9–29.5)	0.25 (0.24–0.28)	2.24 (1.77–2.60)
NiO	0.04 (0.03–0.15)	0.08 (0.03–0.16)	*n.d.*	0.12 (0.03–0.31)
ZnO	*n.d.*	*n.d.*	*n.d.*	0.50 (0.34–0.59)
CaO	0.05 (0.03–0.09)	0.78 (0.71–0.90)	2.07 (2.03–2.14)	*n.d.*
Na_2O	*n.d.*	0.16 (0.16)	9.41 (8.83–10.2)	*n.d.*
K_2O	*n.d.*	*n.d.*	0.79 (0.70–0.94)	*n.d.*
BaO	*n.d.*	*n.d.*	0.06 (0.05–0.13)	*n.d.*
total	99.9	99.8	99.8	100.0
	$Fa_{25.1}$ (24.5–25.6)	$Fs_{20.9}$ (20.2–21.2)	$An_{10.6}Ab_{84.9}Or_{4.5}$	

	metal range n=4	**sulphide** range n=2		**phosphate**
Fe	72.3–93.4	59.6–60.5	FeO	1.01
Co	0.21–1.63	0.06–0.07	MgO	3.15
Ni	4.32–25.9	0.03–2.24	CaO	49.0
Mn	0.03–0.03	*n.d.*	P_2O_5	46.8
Cu	0.03–0.17	0.03–0.11	Total	99.9
Cr	0.03–0.05	*n.d.*		
S	0.05–0.12	37.9–39.8		

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