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Report

Nullarbor 018: A new L6 chondrite from Australia

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Abstract–A new meteorite find from the Nullarbor Plain in Australia was studied using optical, SEM, and electron microprobe techniques. The meteorite, Nullarbor 018, is an orthodox L6 chondrite that experienced minor-to-moderate alteration of metal during terrestrial weathering (grade A-B to B). During weathering, troilite was preferentially altered, and roughly 20% of the original complement of S in the meteorite was removed. Shock metamorphic effects corresponding to shock stage S4 (or shock facies d) are found, including the presence of some diaplectic feldspar (maskelynite). The meteorite is not obviously paired with other finds from the Nullarbor region, but the possibility that it is paired cannot be excluded.

INTRODUCTION

This report describes a new chondrite from the Nullarbor Plain in Australia, of which we obtained a portion from Mr. Ronald Farrell in 1991 February. The chondrite was found by an anonymous member of a meteorite collecting expedition at the beginning of 1990 September, as a single, largely buried stone "just under one kilogram" in total mass, north of the Trans-Australia railway and between the Mundrabilla and Forrest stations (R. Haag, pers. comm., 1994). This appears to place the find within either the eastern "Mundrabilla" or the western "Forrest" named areas of Bevan and Binns (1989a), but the precise find location is unclear. The meteorite is designated as Nullarbor 018, in accordance with the approved naming scheme of meteorites that have uncertain find locations in the Nullarbor region (Bevan and Binns, 1989a; Bevan and Pring, 1993).

SAMPLES AND METHODS

The fragment (4.01 g) given to us by Mr. Farrell contained a partial fusion crust and showed patchy red staining caused by terrestrial weathering. Polished thin and thick sections were made and were used for optical, scanning-electron-microscope (SEM) and wavelength-dispersive electron microprobe studies. The microprobe was operated at an accelerating voltage of 15 kV and a beam current of 10 nA, with a stationary beam focussed to a 1-μm-diameter fluorescing spot. The analysis routines involved 30-s counts on the peak of each element, and Na was counted at the beginning of analyses. Analyses were accepted as "olivine" and "pyroxene" if totals ranged between 98–102 wt% and if the calculated number of total cations was 3.00 ± 0.01/4 oxygens (for olivine) and 4.00 ± 0.01/6 oxygens (for pyroxene). Analyses were initially accepted as "feldspar" for phases consisting primarily of Si, Al, Ca, Na, and K, but subsequent investigation showed that not all of these analyses had a stoichiometry entirely consistent with crystalline feldspar (see below). The mode of the meteorite was determined from image-processed, backscattered-electron micrographs covering an area of ≈73 mm^2, and has an estimated precision ≈0.1–0.5 vol% for most phases. Samples of Nullarbor 018 available at the Department of Planetary Sciences, University of Arizona, include a polished thin section, a polished thick section, and 1.46 g (in five pieces) of the original fragment that was given to us (UA# 145,1; 145,2; and 145,3 respectively).

RESULTS

The mineralogy and modal composition of Nullarbor 018 is that of an ordinary chondrite and includes olivine, orthopyroxene, feldspar, clinopyroxene, phosphate (both merrillite and chlorapatite), ilmenite, chromite, troilite, kamacite (3.25–7.17 wt% Ni, 0.50–1.08 wt% Co), taenite (25.5–35.1 wt% Ni, 0.07–0.44 wt% Co), tetrataenite (≈51 wt% Ni, ≈0.15 wt% Co), martensite (≈10–17 wt% Ni, ≈0.6 wt% Co), and various Fe-oxides that constitute weathering products primarily of troilite and metal, and possibly of olivine (Table 1). Tetrataenite and martensite are both rare; the former appears to be confined to the edges of zoned taenite grains, while the latter occurs as individual grains. The overall abundance of metal (≈6.5 wt%) and the kamacite/taenite mass ratio (≈1.6) in Nullarbor 018 are similar to, or slightly lower, than that typically found in L-group chondrites (Table 1; Ikeda and Kojima, 1991), although the metal abundance was lowered somewhat as a result of weathering (see below). The composition of olivine (mean and standard deviation of $Fa_{25.2 \pm 0.5}$, based on 28 analyses), kamacite (Co 0.81 ± 0.12 wt%, 16 analyses), and orthopyroxene ($Fs_{21.3 \pm 0.4}$, $Wo_{1.5 \pm 0.3}$, 22 analyses) confirm that Nullarbor 018 belongs to the L-group (Figs. 1, 2).

TABLE 1. Modal composition of Nullarbor 018 (this work) compared to average L-chondrites (Mason, 1965).

	Nullarbor 018		average L
	vol%[1]	wt%[2]	wt%[3]
olivine	40.5	39.9	47.0 (40 - 53)
pyroxene	30.9	28.3	27.3
feldspar	15.5	11.5	10.7
phosphate	0.7	0.6	0.6
ilmenite	0.2	0.3	0.2
chromite	1.0	1.4	0.6
troilite	1.7	2.3	6.1 (4.3 - 7.9)
kamacite	1.8	4.0 } 6.5	7.5 (5.0 - 10.1)
taenite	1.1	2.5 }	
Fe-oxides	6.6	9.3	----
	100.0	100.1	100.0

1 Determined from BSE micrographs. Pyroxene includes both ortho- and clinopyroxene; feldspar includes both crystalline and amorphous varieties; phosphate includes both merrillite and chlorapatite; taenite includes taenite and tetrataenite; and Fe-oxides are various weathering products of troilite, metal, and possibly olivine.

2 Calculated from the volume mode by assuming the following densities (g/cm^3): olivine = 3.50, pyroxene = 3.25, feldspar = 2.63, phosphate = 3.14, ilmenite = 4.74, chromite = 4.97, troilite = 4.74, kamacite = 7.88, taenite = 8.13, Fe-oxides = 5.0.

3 Range for olivine from Mason (1965), and ranges for L-chondrite troilite and metal from Fredriksson and Fredriksson (1990).

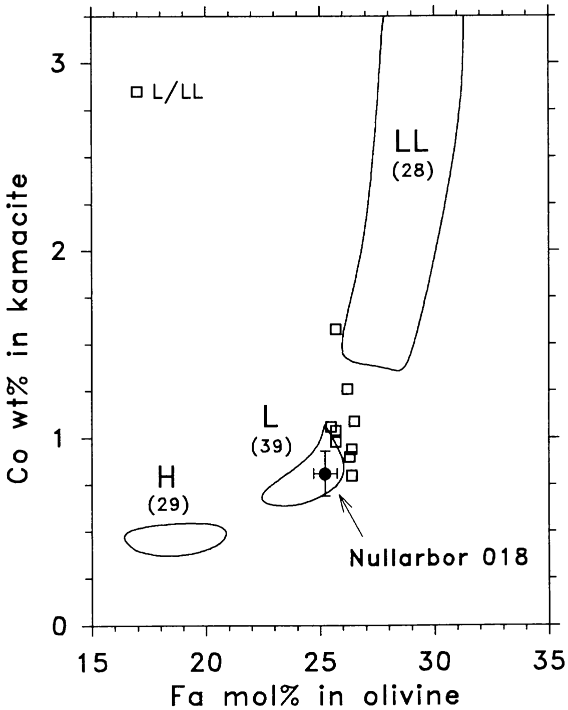

FIG. 1. Mean Fa (mol% Fe/[Fe + Mg]) in olivine and Co content in kamacite from Nullarbor 018 compared to 29 H4-6, 39 L4-6, and 28 LL4-6 chondrites (Rubin, 1990). Error bars represent the standard deviation from the mean. Squares indicate chondrites designated as "L/LL" type 4-6 by Rubin (1990). Of these "L/LL" chondrites, the one closest to the LL field is Qidong; the others were classified as L-chondrites by Graham *et al.* (1985). Olivine and kamacite compositions in Nullarbor 018 are typical of L-group chondrites.

The meteorite has a granular texture overall, although a few relict chondrules are evident. The relict chondrules are visible as ill-defined, sub-millimeter regions with textures of barred olivine/feldspar, olivine microporphyry, and radial pyroxene. This suggests that Nullarbor 018 is a highly metamorphosed chondrite, corresponding to Type 6 of the Van Schmus and Wood (1967) classification. Also consistent with a Type 6 designation are the coarse size of feldspar (mean diameter and standard deviation of 88 ± 39 μm, based on 21 grains), which is near the high end of that typically found in Type 6 chondrites ($\approx$50–100 μm; Van Schmus and Wood, 1967), and the average Wo content of orthopyroxene ($Wo_{1.5 \pm 0.3}$), which is near the low end of that typically found in Type 6 chondrites ($Wo_{1.4–2.4}$; Scott *et al.*, 1986).

Weathering resulted in the formation of Fe-oxide veins in olivine, rinds of Fe-oxide on metal, and pseudomorphs of Fe-oxide after troilite. While some Fe-oxide clearly formed by the weathering of metal and troilite, it is uncertain whether the Fe-oxide veins in olivine formed at the expense of this mineral or merely served as conduits of material transported from elsewhere. Calcite, a common weathering product in chondrites from the Nullarbor region (Bevan and Binns, 1989a), has not been found. Some metal grains are unaltered, although most have been altered at their margins only. Based on the hand specimen appearance of the meteorite and an estimate of the amount of metal that was oxidized during weathering ($\approx$10–15%), the weathering grade of the meteorite is best described as light-to-moderate, corresponding to weathering grades A-B or B of Cassidy (1980) and Ikeda and Kojima (1991).

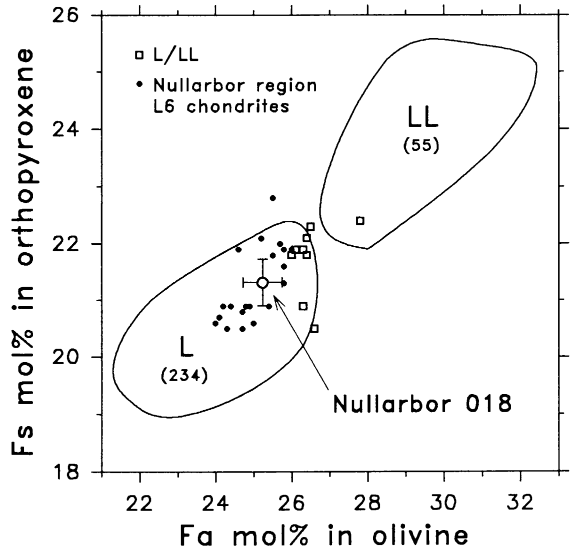

FIG. 2. Mean Fa (mol% Fe/[Fe + Mg]) in olivine and Fs (mol% Fe/[Fe + Mg + Ca]) in orthopyroxene from Nullarbor 018 compared to 234 Type 4-7 L-chondrites and 55 Type 4-7 LL-chondrites. Error bars represent the standard deviation from the mean, squares Type 4-7 "L/LL" chondrites, and solid dots additional L6 chondrites from the Nullarbor region (Western and Southern Australia). Olivine and pyroxene compositions in Nullarbor 018 fall within the L-chondrite field but appear to be distinct from other Nullarbor L6 chondrites at the 1-σ confidence level. Data sources: Keil and Fredriksson (1964); Fredriksson *et al.* (1968); Graham (1987, 1988); Bevan and Binns (1989a,b); Wlotzka (1990, 1991a,b, 1992a,b, 1993a,b); Grossman (1994).

Despite the modest degree of metal oxidation, most of the troilite in the meteorite is altered, and over half of the Fe-oxide in Nullarbor 018 (Table 1) is an alteration product of troilite. This indicates that troilite was preferentially weathered. Altered troilite is depleted in sulfur compared to stoichiometric troilite ($\approx$23–29 *vs.* 36.5 wt% S) and yields low microprobe totals ($\approx$86–88 wt%), suggesting that during weathering of troilite, S was removed, and light elements (O, H?) were added. As there is no other significant sink for S in Nullarbor 018, it appears that a significant amount of S was leached from the meteorite. The modal abundances and compositions of troilite and altered troilite can be used to calculate the amount of S that was lost. Each altered troilite grain is depleted in S on average by $\approx$30%, and $\approx$70% of the troilite initially present was altered. This suggests that $\approx$20% of the initial complement of S was leached from the meteorite during weathering.

Metal is often more susceptible to terrestrial weathering than sulfide (Ikeda and Kojima, 1991; K. Keil, pers. comm., 1994), so the preferential weathering of troilite in Nullarbor 018 is notable. Similarly, troilite appears to have been selectively removed, possibly by weathering, from the outer portions of the Mundrabilla iron meteorite, which also fell in the Nullarbor Plain (Buchwald, 1975). The weathering environment of the Nullarbor Plain may therefore have been conducive to troilite alteration. The plain is arid to semi-arid and is underlain by limestone (Bevan and Binns, 1989a). Possibly some combination of aridity, carbonate-rich soils, and high temperatures promoted the breakdown of troilite before metal.

Whatever the reason for the preferential alteration of troilite, S probably was removed from Nullarbor 018 in the form of an aqueous solution. Weathering reactions for troilite that are especially favorable thermodynamically include

$$\underset{\text{troilite}}{FeS} + \underset{\text{liquid}}{H_2O} + \underset{\text{gas}}{5O_2} \rightarrow \underset{\text{hematite}}{Fe_2O_3} + \underset{\text{aqueous}}{2HSO_4^{-1}} \quad , \quad \text{Rxn. (1)}$$

which has $\Delta G^\circ_{(1)} = -434.1$ kcal, and

$$\underset{\text{troilite}}{2FeS} + \underset{\text{calcite}}{CaCO_3} + \underset{\text{liquid}}{H_2O} + \underset{\text{gas}}{9O_2}$$

$$\rightarrow \underset{\text{hematite}}{Fe_2O_3} + \underset{\text{gas}}{CO_2} + \underset{\text{aqueous}}{2HSO_4^{-1}} + \underset{\text{aqueous}}{Ca^{+2}}, \quad \text{Rxn. (2)}$$

which has $\Delta G^\circ_{(2)} = -390.9$ kcal (data from CRC Handbook, 1990). In the carbonate-rich soils surrounding the meteorite, the aqueous species produced by reactions (1) and (2) could form either anhydrite ($CaSO_4$) or gypsum ($CaSO_4 \cdot 2H_2O$) as precipitates. Reactions (1), (2), and other plausible oxidation and hydration reactions for troilite produce S-bearing weathering products that are relatively soluble in water, whereas Fe-bearing weathering products such as hematite are relatively insoluble (CRC Handbook, 1990). This may explain why S was selectively leached from troilite.

Nullarbor 018 shows petrographic and other evidence of having been affected by a shock event of weak-to-moderate intensity. Olivine grains exhibit planar fractures and undulose-to-mosaic extinction, characteristic of shock deformation, and the presence of some martensite in the chondrite is consistent with relatively rapid cooling following a transient shock heating event. Plagioclase grains typically show undulatory extinction, and some of the plagioclase appears to be isotropic. These possible isotropic areas are small, however, and thus the identification of isotropic feldspar is uncertain. Fifteen out of 22 analyses of feldspathic material in Nullarbor 018 have a stoichiometry consistent with crystalline feldspar and form a tight compositional cluster with a mean and standard deviation of $An_{11.4 \pm 0.2}Or_{5.9 \pm 0.9}Ab_{82.8 \pm 0.8}$ (Fig. 3). This cluster probably represents analyses of crystalline feldspar. Other analyses deviate significantly from feldspar stoichiometry and define a chemical trend suggestive of Na loss (Fig. 3). This trend does not reflect substitutions of the type primarily involving Fe and Mg described by Miúra (1984) and Miúra and Tomisaka (1984). Instead, as explained below, it is considered to be indirect evidence for the presence of diaplectic or shock-produced glass (maskelynite).

Van Schmus and Ribbe (1968) found that a microprobe beam with a 10 nA current focussed to a 1-μm stationary spot (the same conditions as used in this study) gave steady Na intensity readings on crystalline feldspar in Type 6 ordinary chondrites, but that a similar beam on maskelynite in these chondrites resulted in Na volatization. Similarly, Ribbe and Smith (1966) noted that microprobe analyses of sodic ($An_{<40}$) glasses resulted in rapid loss of Na unless a low beam current (5 nA) or an expanded beam size (>5 μm) were used. This suggests that in our analyses of feldspathic material, Na should have been volatilized from feldspathic glass but not from crystalline feldspar. Thus, it seems likely that some of the "feldspar" in Nullarbor 018 is indeed crystalline and that some, probably about a third, is at least partially amorphous.

Relict (pre-metamorphic) glass is unlikely to be present in Type 6 chondrites, and so the feldspathic glass inferred to be present in Nullarbor 018 presumably formed by shock metamorphism. This conclusion is consistent with the observed deformation of olivine and feldspar. The data suggest that Nullarbor 018 was shocked to an intensity at which maskelynite just begins to form, corresponding to a "low" shock stage S4 (Stöffler *et al.*, 1991) and a "low" shock facies d (Dodd and Jarosewich, 1979; Dodd, 1981). This entailed a shock pressure slightly above ≈15–20 GPa (Stöffler *et al.*, 1991).

PAIRING

The Nullarbor Plain in the Australian states of Western Australia and Southern Australia is one of the most productive meteorite recovery areas on Earth (Bevan and Binns, 1989a,b; Bevan and Pring, 1993). Because of the relatively high density of meteorites found in this region, many of the specimens are probably paired (part of the same fall). In this section, the possibility that

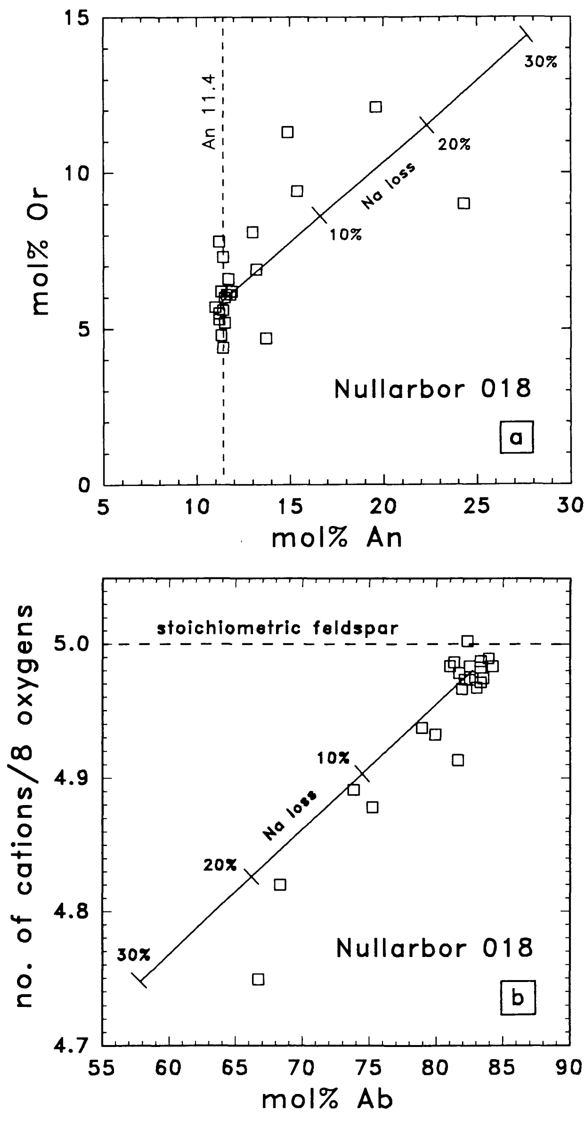

FIG. 3. Composition of feldspathic phases in Nullarbor 018. **(a)** An *vs.* Or, where An = mol% Ca/(Ca + Na + K) and Or = mol% K/(Ca + Na + K). **(b)** Ab *vs.* total number of cations/ 8 oxygens, where Ab = mol% Na/(Ca + Na + K) and the number of oxygens was calculated by assuming standard valencies for cation species (including a valence of +2 for Fe). The solid line with tick marks indicates the removal of 10, 20 and 30 atom% Na from the mean of the main cluster of analyses, which is defined by $An_{11.4 \pm 0.2}Or_{5.9 \pm 0.9}Ab_{82.8 \pm 0.8}$ and 4.98 ± 0.01 cations/8 oxygens. The cluster is believed to represent crystalline feldspar, while other analyses are thought to represent amorphous feldspar (maskelynite) that experienced variable degrees of Na volatization during microprobe analysis.

Nullarbor 018 may be paired with previously described L6 chondrites from the Nullarbor Plain is evaluated.

Besides find locations, potentially useful discriminants between different L6 chondrites are the composition of olivine and orthopyroxene, shock effects, and to a lesser extent, the weathering grade. The issue of pairing among Nullarbor meteorites is complicated by the uncertain find locations of some Nullarbor meteorites (including Nullarbor 018) and by the incomplete characterization of some of these meteorites.

Several L6 chondrites for which only olivine (but not orthopyroxene) compositions have been reported have been collected from the Nullarbor region. While some of these may be paired with Nullarbor 018, this seems unlikely, as none were found in the two areas (Mundrabilla or Forrest) in which Nullarbor 018 was probably found.

Among other L6 chondrites from Nullarbor for which both olivine and pyroxene compositions have been reported, Nullarbor 018 has a somewhat distinctive combination of mean olivine ($Fa_{25.2 \pm 0.5}$) and orthopyroxene ($Fs_{21.3 \pm 0.4}$) compositions (Fig. 2). This suggests that Nullarbor 018 is a distinct (non-paired) fall. However, because these compositions are distinct only at a 1-σ ($\pm$ one standard deviation) level (Fig. 2), pairing cannot be ruled out completely. The L6 chondrites that are most similar to Nullarbor 018 in both mean olivine and orthopyroxene compositions include: Nullarbor 004 ($Fa_{25.8}$; $Fs_{21.3}$), Forrest 006 ($Fa_{24.8}$; $Fs_{20.9}$), Forrest 009 ($Fa_{25.4}$; $Fs_{20.9}$), Reid 002 ($Fa_{24.9}$; $Fs_{20.9}$), and Reid 007 ($Fa_{25.8}$; $Fs_{21.6}$) (Bevan and Binns, 1989b; Wlotzka, 1992a). Of these, only Forrest 009 is reported to contain maskelynite (Bevan and Binns, 1989b). Forrest 009 was also found within one of the two areas (Mundrabilla or Forrest) in which Nullarbor 018 was probably found, and it even has a similar weathering grade (B) as Nullarbor 018. Thus, it appears that the best candidate for pairing with Nullarbor 018 is Forrest 009.

CONCLUSION

A new meteorite from the Nullarbor Plain in Australia is classified as an L6 (S4) ordinary chondrite that experienced light-to-moderate terrestrial weathering (grade A-B to B). About 20% of the S in the meteorite was removed during weathering. Maskelynite is inferred to be present based mainly on microprobe evidence for feldspar that experienced Na loss during analysis. The meteorite does not appear to be paired with other L6 chondrites from the Nullarbor Plain, but the possibility that it is paired (especially with Forrest 009) cannot be excluded.

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