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Maralinga, a metamorphosed carbonaceous chondrite found in Australia

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Abstract—The Maralinga meteorite was found near the village of Maralinga, South Australia (30°18′S, 131°16′E) in 1974, but was not recognized as a meteorite until 1989. One weathered individual was recovered with a total mass of 3.38 kg. The bulk composition and petrography of Maralinga indicate that it is a metamorphosed (petrographic type 4) carbonaceous chondrite with major similarities to the Vigarano-subtype. However, recent trace element data from the literature suggest that Maralinga should be included with the CK (Karoonda-type) carbonaceous chondrites. We classify Maralinga as an *anomalous* CK4 chondrite because of its abundant chondrules and refractory inclusions relative to other known members of the CK group. Maralinga contains homogeneous silicates, including Ni-bearing olivines (Fa_{34}), high-Ca clinopyroxene, and rare orthopyroxene. Plagioclase is chemically heterogeneous and falls into two distinct compositional groups one of $\sim An_{20}$ and an $\sim An_{80}$ group. Highly oxidizing conditions during metamorphism of Maralinga are indicated by the abundance of magnetite and the paucity of Fe-Ni metal.

INTRODUCTION

LARGE NUMBERS OF METEORITES have been recovered from the Nullarbor Plain region of western and southern Australia (Bevan and Binns, 1989a,b). We report here a description and classification of a stony meteorite that was found approximately 35 km west-south-west of Maralinga, South Australia (30°18′S, 131°16′E) in 1974. Only one weathered specimen was recovered, and it was not recognized as a meteorite until 1989. The total mass of the stone is 3.38 kg (not 33.8 kg as reported in the *Meteoritical Bulletin* by Wlotzka, 1991 and by Kallemeyn *et al.*, 1991). The bulk of the specimen is in the possession of David New, Box 278, Anacortes, WA 98221 USA. The petrographic thin section used for classification purposes is curated by the Center for Meteorite Studies at Arizona State University. Our study indicates that Maralinga is an anomalous CK4 carbonaceous chondrite with strong affinities to the CV type. Preliminary analytical data for Maralinga were reported by Geiger and Spettel (1991) and by Kallemeyn *et al.* (1991).

ANALYTICAL PROCEDURES

Quantitative wavelength-dispersive X-ray analyses were obtained from two thin sections of Maralinga using a JEOL 8600 Superprobe equipped with Tracor-Northern automation and analysis systems. A 15 kV accelerating voltage and a beam current of 10 nA were employed for all analyses and imaging. Analyses of silicates were reduced using the Bence-Albee procedure, while ZAF corrections were applied to analyses of metals, sulfides, and oxides. For the magnetite analyses, we analyzed directly for oxygen. Bulk and matrix compositions were determined using a 100-μm diameter defocussed beam and reduced using a ZAF correction. The estimated bulk composition was obtained from 240 random analyses from one thin section. The estimated matrix composition was derived from 20 analyses of regions between chondrules free of large fragments. Bulk C was determined from three random 100-mg samples using a Leco IR-12 Carbon Analyzer following the procedure of Moore *et al.* (1973). The VISTA software package from Tracor-Northern was used for SEM image analysis.

RESULTS

Petrography

Maralinga contains well-defined chondrules, chondrule fragments, and inclusions set in a semi-transparent matrix (Fig. 1). We estimate that the ratio of chondrules to matrix is ~50:50. Chondrules are variable in size, with diameters of 100 μm up to 5 mm in thin section. Optical microscope observations from 172 objects in two polished thin sections show that porphyritic olivine chondrules are the most abundant (47%), followed by granular olivine (20%), porphyritic olivine-pyroxene (15%), barred-olivine (9%), and radial pyroxene chondrules (2%), and Ca- and Al-rich objects (3%). Compound chondrules such as a barred texture enclosed within a porphyritic type also occur. In some of the larger porphyritic-olivine chondrules, mesostasis is turbid and partly devitrified, while in the majority of barred-olivine chondrules, mesostasis is optically isotropic and fresh-looking. Typically, chondrules contain aggregates of magnetite up to 100 μm in diameter. This magnetite is intergrown with pentlandite blebs (typically ~10 μm in dia., but up to 60 μm), and occupies the regions where metal/sulfide aggregates would normally be expected. Coarse-grained magnetite also occurs as partial rims surrounding chondrule (Fig. 2). Metal is exceedingly rare in Maralinga, only 1 kamacite grain was observed in two thin sections. High-Ca pyroxene is more abundant than Ca-poor pyroxene.

Ca- and Al-rich inclusions (CAIs) are also present in Maralinga but are not homogeneously distributed. Of the four thin sections we studied three contained CAIs, and one thin section contained three of the six CAIs that were identified. We identified two varieties of CAIs, amoeboid inclusions and coarse-grained CAIs (up to 2 mm in length in thin section). The latter are more common (4 of 6) in our thin sections, their mineralogy is dominated by plagioclase and lesser clinopyroxene (Fig. 3). A characteristic feature of Maralinga CAIs is the presence of emerald green euhedral spinels that occur as inclusions in plagioclase and a lack of melilite. Maralinga CAIs show similarities to type C CAIs from the CV chondrites.

Bulk and Matrix Compositions

Analytical data for the estimated bulk and matrix composition of Maralinga are given in Table 1 and compared with the instrumental neutron activation analyses (INAA) of Kallemeyn *et al.* (1991) and Geiger and Spettel (1991). Our defocussed electron microprobe analyses compare favorably with the INAA data except for Al which is higher than the INAA results. Our Ca and Al values have larger standard deviations which suggests that these elements are heterogeneously distributed in the thin

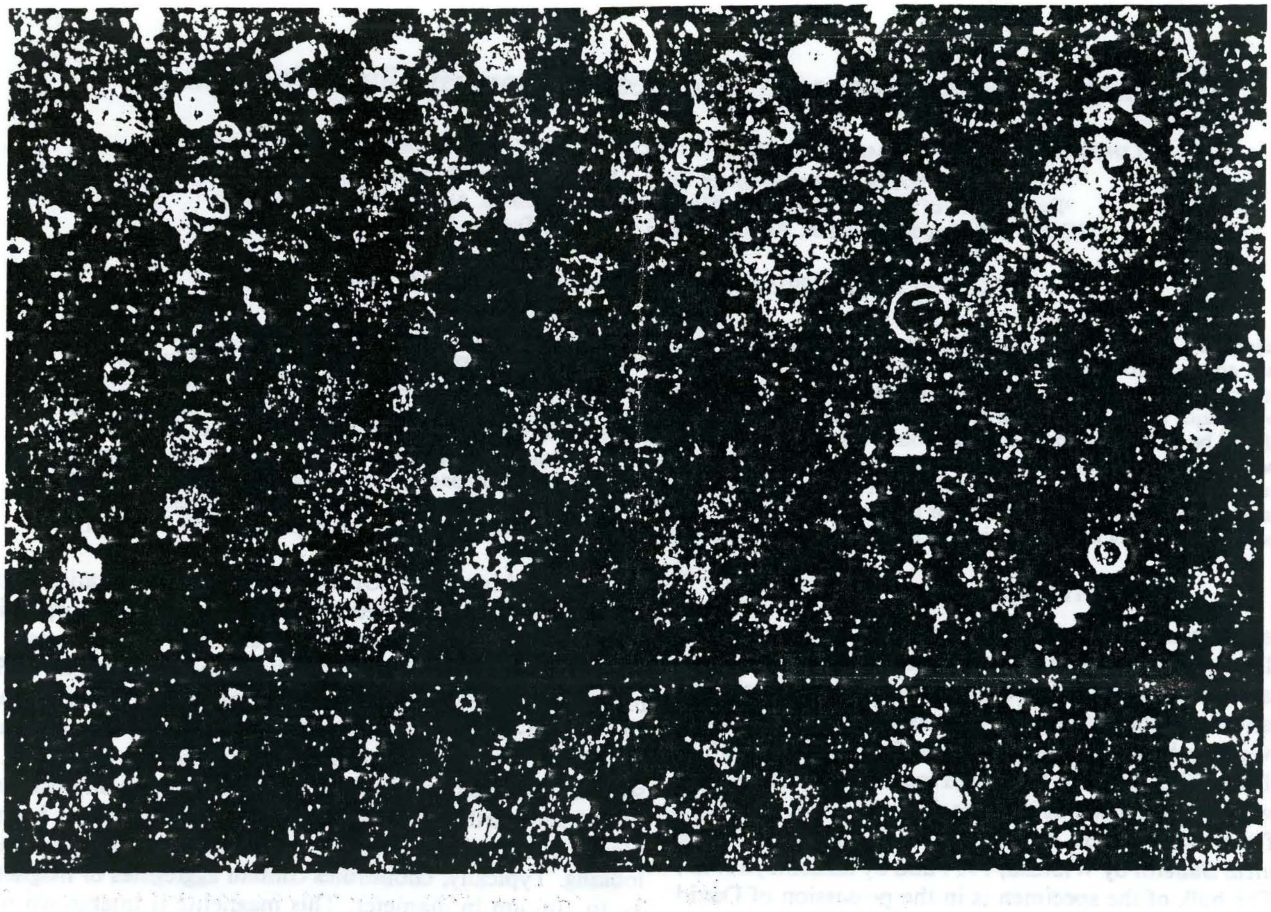

FIG. 1. Low magnification transmitted light image of a Maralinga thin section. The field of view is ~21 mm wide.

sections, probably as terrestrial weathering products (*i.e.*, calcite, clays) and/or refractory inclusions. We note that veins of fine-grained carbonate are present in the thin sections, and patches of caliche are observed on the meteorite surface. Our thin sections also contain CAIs that were not observed by other workers (*e.g.*, Kallemeyn *et al.*, 1991; Geiger and Spettel, 1991).

A comparison of our major element data to that for other meteorite groups shows that Maralinga is most similar to the Vigarano-type carbonaceous chondrites, although slight differences exist (Table 2). The bulk S/Si ratio of Maralinga is mark-

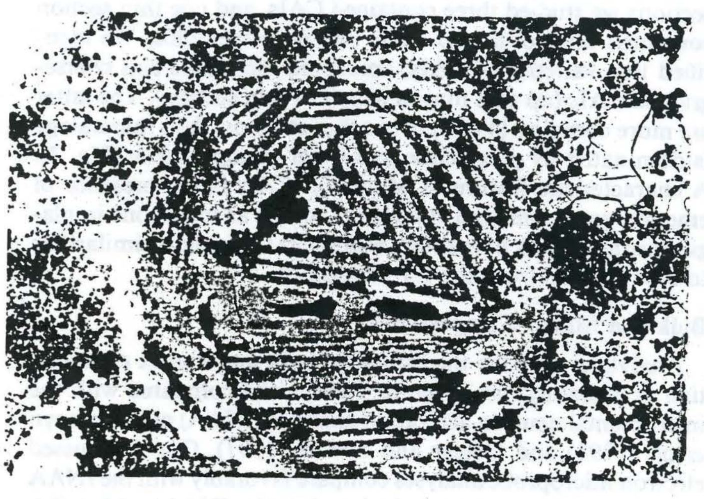

FIG. 2. Backscattered electron image of a barred-olivine chondrule (~800 μm in diameter) showing a partial rim of coarse-grained magnetite (white band).

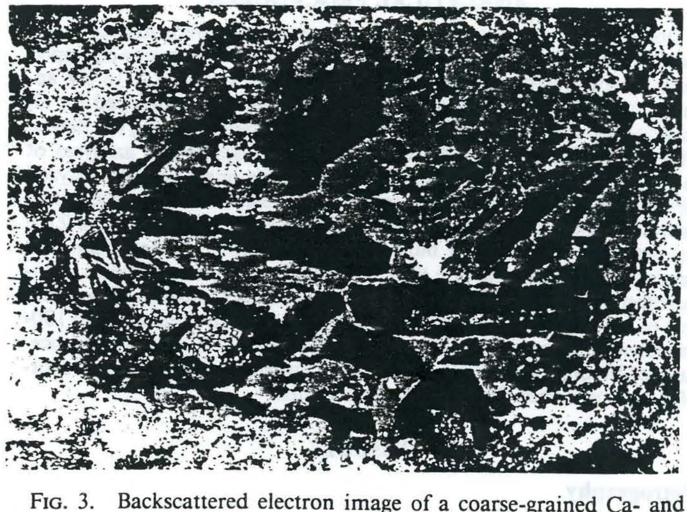

FIG. 3. Backscattered electron image of a coarse-grained Ca- and Al-rich inclusion (~1.6 mm in diameter) that contains lath-shaped plagioclase (dark) and zoned fassaitic pyroxene (light). Hercynitic spinels occur as inclusions in the plagioclase and along grain boundaries. Bright specks are magnetite.

TABLE 1. Bulk and matrix composition of Maralinga from defocussed electron microprobe analyses. The "bulk" composition was normalized to 100% (Column 1) for comparison with INAA data from Kallemeyn *et al.* (1991, Column 2) and Geiger and Spettel (1991, Column 3).

	Bulk	1	2	3	Matrix
Na_2O	0.46 (±0.05)[a]	0.54	0.37	0.37	0.63 (±0.05)
MgO	21.5 (±0.1)	25.2	24.4	22.7	21.0 (±0.1)
Al_2O_3	4.04 (±0.05)	4.72	2.95	2.34	4.86 (±0.05)
SiO_2	29.7 (±0.4)	34.8	n.a.	n.a.	30.3 (±0.2)
P	0.08 (±0.01)	0.09	n.a.	n.a.	0.04 (±0.01)
S	0.05 (±0.01)	0.06	n.a.	n.a.	0.05 (±0.01)
CaO	3.25 (±0.05)	3.80	3.30	2.70	2.54 (±0.04)
TiO_2	0.11 (±0.02)	0.13	n.a.	n.a.	0.05 (±0.01)
Cr_2O_3	0.42 (±0.04)	0.49	0.53	0.52	0.26 (±0.03)
MnO	0.14 (±0.02)	0.16	0.17	0.17	0.14 (±0.02)
FeO	25.2 (±0.3)	29.5	29.9	30.4	22.4 (±0.3)
CoO	0.07 (±0.02)	0.08	0.05	0.04	0.06 (±0.02)
NiO	0.43 (±0.03)	0.50	0.45	0.51	0.47 (±0.03)
Totals:	85.5	100.00			82.8

[a] Numbers in ( ) are relative errors based on counting statistics.

edly depleted relative to that in other carbonaceous chondrites including Karoonda. The bulk C content of Maralinga is 0.26 wt.% (±0.01) and may contain a component of terrestrial carbonate.

Mineralogy and Mineral Chemistry

Silicates

Olivine is the most abundant mineral in chondrules and comprises the bulk of the fine-grained matrix of Maralinga. Analyses of olivine (Table 3) show them to be remarkably constant in composition with an average fayalite content of 34.4 mol% (1 sigma = 0.34). Olivine in Maralinga contains significant quantities of Ni (0.6 wt.% NiO) and Mn (0.22 wt.% MnO), but only trace amounts of Ca (<0.03 wt.% CaO). Olivines in chondrules typically contain inclusions of micrometer-sized magnetite grains as do matrix olivines.

High-Ca clinopyroxene (cpx) is more abundant than orthopyroxene in Maralinga and is Fe-poor (Table 3). The clinopyroxene grains in matrix are ~30 μm in size. Coarse-grained, euhedral, titanium-bearing cpx (fassaite) occurs with plagioclase, olivine, and hercynite in one of the CAIs (Fig. 3).

Orthopyroxene occurs in the outer parts of porphyritic-olivine-pyroxene chondrules and as rare grains in matrix. The most notable feature of the low-Ca pyroxene is a lack of twinning. Like the olivine, orthopyroxene is compositionally homogeneous with an average ferrosilite component of 28 mol% (Table 3).

Polysynthetically twinned plagioclase occurs in chondrules and inclusions. Lath-shaped plagioclase in CAIs is coarse-grained and is nearly pure anorthite (Fig. 3). Plagioclase in chondrules and in matrix is generally of fine-grain size (<30 μm) and falls into two distinct compositional groups (Table 3); an anorthite-rich (~An_{80}) and an anorthite-poor plagioclase (~An_{20}). Geiger and Spettel (1991) report analyses for intermediate anorthite compositions, but we believe that these represent small scale intergrowths of the two compositions we observed. The anorthite-rich plagioclase is typically surrounded by the anorthite-poor variety. Some of the plagioclase in chondrules is intergrown with mesostasis.

Oxides and Sulfides

A striking feature of Maralinga is the abundance and distribution of magnetite. Analyses of backscattered scanning electron microscope images from two thin sections indicate that magnetite comprises ~4% of the cross-sectional area of the sections. The magnetite is stoichiometric and contains appreciable Cr (Table 3). Several of our magnetite analyses showed high Ti contents. Closer examination of these grains revealed thin lamellae of ilmenite. Ilmenite lamellae in magnetites are apparently common in CK chondrites (Geiger and Bischoff, 1990). The magnetites exhibit a bimodal size distribution with coarse-grained aggregates in chondrules, fine-grained <10 μm magnetites present in veins in olivine and pyroxene, and as particles concentrated along grain boundaries. In CAIs, magnetite also occurs as isolated lamellae in and as overgrowths on hercynitic-spinel.

Hercynite occurs as distinctive, emerald-green euhedral crystals up to 200 μm in diameter. Their occurrence is restricted to Ca- and Al-rich inclusions, where they occur as clusters of crystals included within anorthite. Unlike the magnetites in Maralinga, the hercynites contain appreciable NiO (between 1 and 2 wt.%, Table 3). Maralinga hercynites resemble those reported from Karoonda (MacPherson and Delaney, 1985) in major element composition but contain higher contents of transition metals (Cr and Ni).

Pentlandite and troilite are the only sulfides present in Maralinga. Troilite is present in minor amounts with a typical grain size of 5 μm. Pentlandite is the dominant sulfide. Grains are variable in size from 5 to 60 μm, but typically ~10 μm. The pentlandite is highly variable with respect to the metal : sulfur ratio suggesting an intergrowth of pentlandite and monosulfide on a very fine scale (Fig. 4). We were unable to quantify the varying compositions within a given grain, thus the analysis in Table 4 should be considered as an average composition.

TABLE 2. Element/Si ratios for Maralinga (bulk) defocussed microprobe analyses.

	Na/Si	Mg/Si	Al/Si	S/Si	Ca/Si	Ti/Si	Cr/Si	Mn/Si	Fe/Si	Ni/Si
Maralinga	0.026	0.931	0.173	0.009	0.175	0.004	0.021	0.008	1.408	0.024
Karoonda[1]	0.034	0.980	0.095	0.102	0.096	0.008	0.027	0.010	1.643	0.090
Coolidge[1]	0.013	0.954	0.107	n.r.[2]	0.106	0.006	n.r.	0.008	1.535	n.r.
Avg. CV3[1]	0.017	0.936	0.110	0.137	0.120	0.006	0.022	0.009	1.481	0.085

[1] Data from McSween and Richardson (1977).
[2] n.r. = not reported.

for Maralinga is most appropriate. The other major uncertainty is whether Maralinga is more closely related to the CV chondrites or to the recently defined Karoonda (CK) subtype (Kallemeyn *et al.*, 1991). A CK4 classification (rather than a CV4) for Maralinga was suggested by Kallemeyn *et al.* (1991) based mainly upon the abundances of refractory lithophile and refractory siderophile elements, which for CK chondrites are intermediate between those in CO and CV chondrites. We agree that the trace element data for Maralinga indicates a CK affinity; however, the high abundance of chondrules and presence of several CAIs in Maralinga is very atypical for the CK group as defined by Kallemeyn *et al.*, and so we believe that Maralinga should be classified as an *anomalous* CK4 carbonaceous chondrite.

It is widely known (*e.g.*, Scott and Taylor, 1985; Geiger and Bischoff, 1989a, 1990) that the metamorphosed carbonaceous chondrites (CK group) have a number of features in common including: 1) homogeneous Fe-Mg silicates, 2) abundant magnetite and a lack of Fe-Ni metal, and 3) heterogeneous plagioclase compositions. In addition, there are a number of small scale features that are also common such as: 1) the presence of ilmenite lamellae in coarse-grained magnetites (Geiger and Bischoff, 1990), 2) the composition and abundance of refractory metal-rich particles (Geiger and Bischoff, 1989b), and 3) the low Ca content of olivines (Scott and Taylor, 1985) combined with significant Ni (Geiger and Bischoff, 1990). All of these features are observed in Maralinga. However, we emphasize that despite these similarities, Maralinga also has significant differences from the majority of the members of the CK group. Maralinga contains abundant chondrules and refractory inclusions unlike any other member of the CK group, thus we propose that Maralinga be classified as an anomalous member of the CK group.

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