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Report

Campo del Cielo iron meteorite: Sample shielding and meteoroid's preatmospheric size

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Abstract–Long-lived cosmogenic radioisotopes, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca and ^{59}Ni, have been measured in five samples from the Campo del Cielo iron meteorite by accelerator mass spectrometry (AMS). The ^{36}Cl activities were significantly above the background. For the concentrations of the other four radioisotopes, only upper limits were obtained that were, however, consistent with the ^{36}Cl result. The measured ^{36}Cl activity allowed an estimate of the meteoroid's preatmospheric size: a radius larger than 300 cm and a mass of at least 840 000 kg. We conclude that this meteorite might be one of the largest meteorites to have been recovered.

INTRODUCTION

Meteoroids are ejected from their parent bodies as a result of collisions. During their subsequent journey in space, they are subjected to bombardment by cosmic radiation, which produces cosmogenic nuclides as a result of the interaction between the energetic cosmic-ray particles and the nuclei of the meteoritic matter. Analysis of the concentrations of these cosmogenic products in meteorites allows some of the meteorite's most recent history to be reconstructed. For example, it is possible to deduce the length of time a meteoroid has been traveling in space, the size of the meteoroid, or how long ago it fell on Earth.

In Chaco Province, Argentina, there is a region between 27°30' S and 27°40' S and 61°30' W and 61°50' W that is known as Campo del Cielo crater field (Romaña and Cassidy, 1972). There are more than 20 craters formed as a result of impact of fragments of a large meteorite, which broke during its passage through the atmosphere. The bulk composition of the Campo del Cielo meteorite is principally iron (92.7%), nickel (6.15%), cobalt (0.42%), carbon (0.37%) and phosphorus (0.28%). Silicon, titanium, vanadium, gallium, copper, and sulfur are present at trace levels (Buchwald, 1975; Talleres Metalúrgicos Gral. San Martín, 1989). Campo del Cielo is a IA iron octahedrite, with abundant coarse silicate inclusions.

The crater field was extensively studied by Cassidy and collaborators between 1962 and 1972 (Cassidy *et al.*, 1965, Romaña and Cassidy, 1972), and Cassidy and Renard (1996). Romaña and Cassidy (1972) determined the time of fall to be ~4000 years B.P. by radiocarbon dating of charcoal samples extracted from the bottom of one of the craters. Even if this terrestrial age is incorrect by a factor of 10, and the state of preservation of the craters would argue against this, the effect on the conclusions of this work would be trivial. Excavation of two medium-sized craters (crater 9 and 10, following mentioned references) revealed two pieces of ~5000 kg each buried in one and another piece of ~36 000 kg in the other. Assuming a minimum mass of 5000 kg in each of the other 18 craters implies a recovered mass of at least 140 000 kg (Cassidy, pers. comm.). This value corresponds to an original meteoroid radius of at least 160 cm.

Nyquist and collaborators (Nyquist *et al.*, 1967) measured the concentration of noble gases in three samples of the El Taco fragment of the Campo del Cielo meteorite and estimated a cosmic-ray exposure age of (14 ± 8) × 10^6 years. This exposure age is enough to guarantee that the studied radionuclides are in equilibrium.

In this work, concentration of long-lived radioisotopes have been measured in five samples of Campo del Cielo iron meteorite using accelerator mass spectrometry (AMS). By comparing experimental results with theoretical predictions from production rate models and the previous estimation of the meteorite's terrestrial age, the preatmospheric size of the parent meteoroid has been estimated.

EXPERIMENTS AND RESULTS

Concentrations of ^{10}Be ($t_{1/2}$ = 1.51 × 10^6 years), ^{26}Al ($t_{1/2}$ = 7.2 × 10^5 years), ^{36}Cl ($t_{1/2}$ = 3.0 × 10^5 years), ^{41}Ca ($t_{1/2}$ = 1.0 × 10^5 years) and ^{59}Ni ($t_{1/2}$ = 7.5 × 10^4 years) were measured in five samples that came from two small fragments. One of them, JFN1 (~25 g), was part of the previously studied (*e.g.*, Chang and Wänke, 1969; Nyquist *et al.*, 1967) El Taco fragment. It was a highly weathered sample consisting principally of oxides, with little metal remaining.

The other four samples came from an unnamed fragment that was picked up from one of the craters (the crater number is unfortunately unknown). This fragment, ~2 kg, was clearly metallic, with very little oxidation. Samples ANU-I and ANU-B came from the inside and the border of this fragment, respectively, while TPC and TPB were part of the crust of the fragment. Figure 1 shows a picture of the fragment from which these samples were taken and a schematic of the particular slice

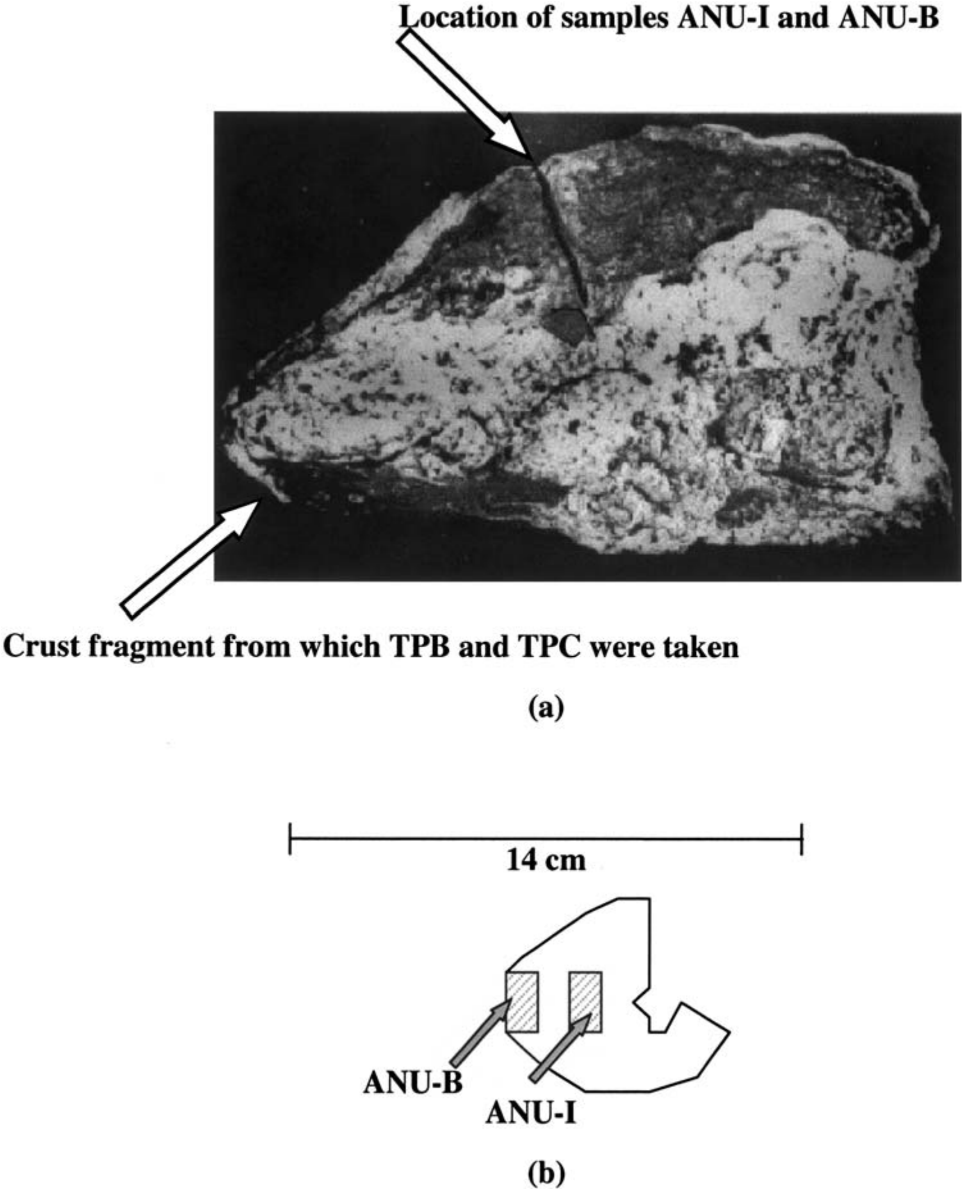

FIG. 1. (a) Photograph of the fragment for samples TPB, TPC, ANU-I and ANU-B. Location where slice for samples ANU-I and ANU-B was taken and crust fragment from which TPB and TPC were taken. (b) Sketch of the slice and samples ANU-I and ANU-B.

from which ANU-I and ANU-B were cut. ANU-B included a small amount of crust.

The chemical procedures used to prepare the samples for AMS measurements were adopted from Vogt and Herpers (1988), Nagai *et al.* (1993) and Stone and di Tada (1997; pers. comm.). Carrier, at concentrations of ~1 mg/g for Be, Al and Cl, and 4 mg/g for Ca, were added to the samples before the chemical preparation. Each sample was subdivided in two: one subsample to obtain Be, Al, Ca and Ni fractions and the other subsample to obtain the Cl fraction. Sample masses ranged between 0.87 and 2.83 g for Be-Al-Ca-Ni analyses and between 1.42 and 2.85 g for Cl analyses. These sample masses are slightly higher than those typically used in this kind of measurements, such as for Canyon Diablo by Michlovich *et al.* (1994). Unfortunately, it was not possible to measure ^{36}Cl on sample JFN1 because it could not be dissolved in HNO_3.

Measurements were performed with the 14 UD tandem accelerator at the Department of Nuclear Physics, Australian National University (ANU). Blanks were prepared with each batch of the unknown meteoritic samples, and measurements of these gave ratios of the order of 10^{-14} for ^{10}Be/Be, ^{26}Al/Al and ^{41}Ca/Ca, of 10^{-15} for ^{59}Ni/Ni and of 10^{-16} for ^{36}Cl/Cl, which are in fact sensitivity limits. The ^{10}Be, ^{26}Al, and ^{41}Ca measurements were normalized to standards of well-known isotopic ratios (the Be standard ratio was $^{10}\mathrm{Be}/^{9}\mathrm{Be} = 3 \times 10^{-11}$, the Al standard ratio $^{26}\mathrm{Al}/\mathrm{Al} = 2.78 \times 10^{-10}$ and the Ca standard ratio $^{41}\mathrm{Ca}/\mathrm{Ca} = 1.13 \times 10^{-11}$). The ^{36}Cl/Cl and ^{59}Ni/Ni ratios were measured absolutely from the integrated currents of the stable isotope beams and the counting rates of the radioisotopes.

Table 1 shows the AMS results for the isotopic ratios and the derived concentrations of each radionuclide expressed as disintegration per minute per kilogram of meteorite (dpm kg^{-1}). It is clear that the concentrations of cosmogenic nuclides in these samples were so low that only for ^{36}Cl was it possible to measure a value that was significantly above the blank. For the other four isotopes, to establish only upper limits on their concentrations could be determined.

PREATMOSPHERIC SIZE OF THE CAMPO DEL CIELO METEORITE

In order to deduce the preatmospheric size of the Campo del Cielo meteorite from our experimental results, theoretical calculations of the radionuclide production rate as a function of depth are required. These were calculated for each measured isotope using the LAHET Code System (LCS) (Prael and Lichtenstein, 1989), assuming spheres with radii of 3, 5 and 15 m and the composition of the Campo del Cielo meteorite. In each case the sphere was divided into concentric shells of 4 cm thickness.

The main production channels for radionuclides are reactions between protons and neutrons and the iron and nickel nuclei in the meteorite, but production from minor components of the meteorite, such as ^{26}Al from phosphorus and ^{10}Be from carbon, have also been included. Calculations for the production of ^{10}Be, ^{26}Al, and ^{36}Cl by spallation reactions were performed using the same data and codes as employed for Canyon Diablo by Michlovich *et al.* (1994). Production rates for ^{41}Ca were calculated in the same way using the cross sections in Fink *et al.* (1998). Production of ^{59}Ni by neutron-capture on ^{58}Ni was calculated according to the prescription applied to Canyon Diablo by Schnabel *et al.* (1999). Figure 2a shows the theoretical production rates of ^{10}Be, ^{26}Al, ^{41}Ca and ^{59}Ni for a 3 m radius meteoroid, while Fig. 2b shows the theoretical production rate of ^{36}Cl for each of the three different radii. There are no good measurements with which to test calculated production rates for very deep in iron meteorites, but we estimate that our calculated production rates have uncertainties of about 20–30%.

Of the isotopes measured in the present work, as we have already mentioned, only ^{36}Cl yielded results that were significantly different from the blank. All four measured samples came from the same small fragment of meteorite, and would be expected, *a priori*, to have similar shielding depths and therefore similar activities. This is clearly not the case. The lowest value, which is considered the most reliable, was

TABLE 1. Isotope ratios for the five radioisotopes.*

Sample	AMS results ($\times 10^{-15}$) [Activities (dpm kg^{-1})]				
	^{10}Be/Be	^{26}Al/Al	^{36}Cl/Cl	^{41}Ca/Ca	^{59}Ni/Ni
TPB	<25 [$<8 \times 10^{-4}$]	<24 [$<6 \times 10^{-4}$]	17(2) [18 (2) $\times 10^{-4}$]	<54 [<0.03]	<356 [<3.8]
TPC	<65 [$<22 \times 10^{-4}$]	<38 [$<10 \times 10^{-4}$]	52(4) [53 (4) $\times 10^{-4}$]	<62 [<0.04]	<102 [<1.1]
ANU-I	<10 [$<2 \times 10^{-4}$]	<52 [$<8 \times 10^{-4}$]	6.0(1.3) [6 (3) $\times 10^{-4}$]	<44 [<0.02]	<157 [<2.8]
ANU-B	<3 [$<0.6 \times 10^{-4}$]	<117 [$<20 \times 10^{-4}$]	9(1) [9 (1) $\times 10^{-4}$]	<46 [<0.02]	<286 [<3.1]
JFN1	<330 [$<85 \times 10^{-4}$]	<81 [$<40 \times 10^{-4}$]	–	<110 [< 0.4]	<374 [<4.0]
Blank	21	52(30)	0.3	<110	7

*The numbers between brackets are the corresponding activities for each ratio. For ^{36}Cl the number between parenthesis are the experimental uncertainties.

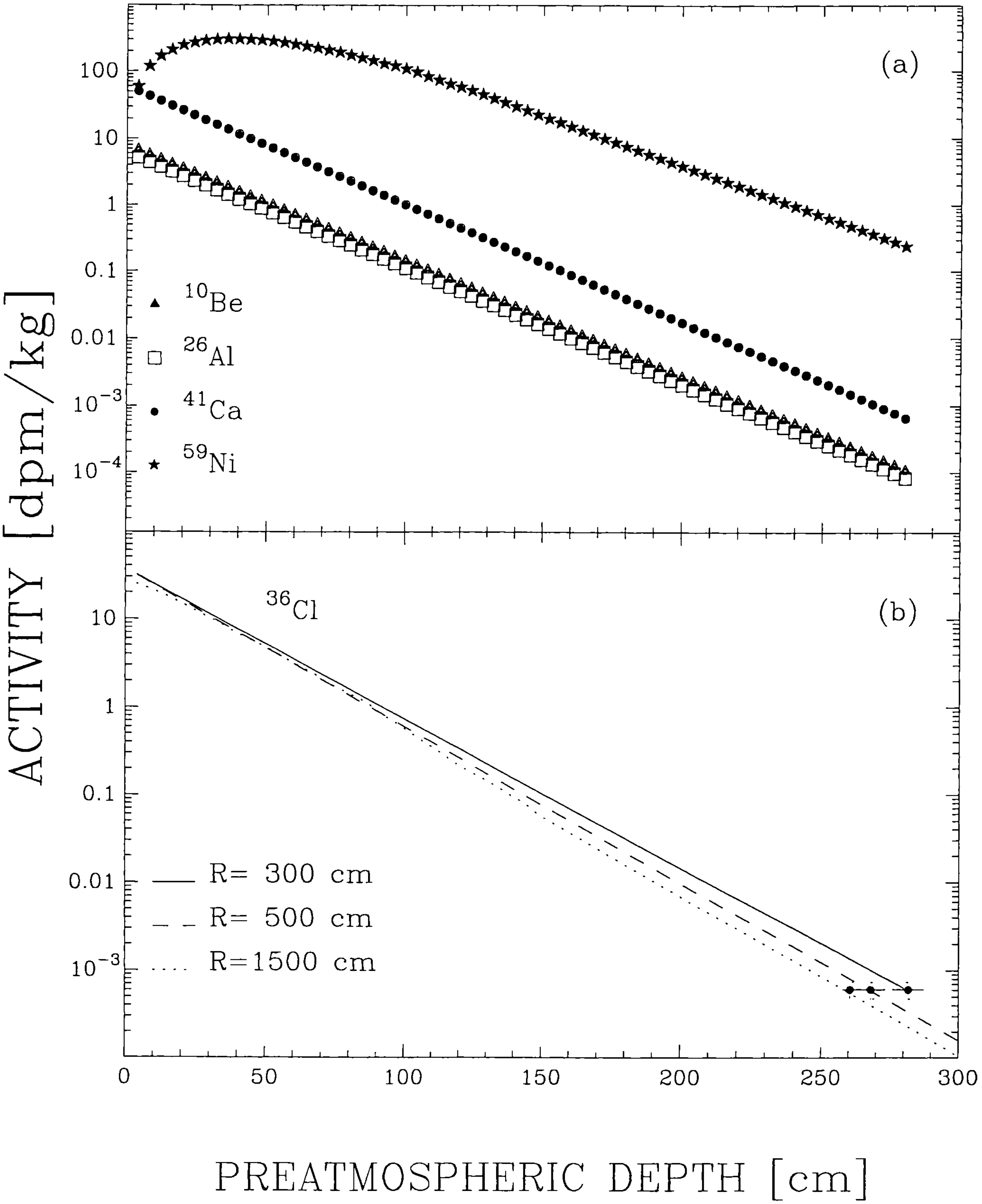

FIG. 2. Theoretical production rates as a function of sample preatmospheric depth at time of fall for (a) ^{10}Be, ^{26}Al, ^{41}Ca and ^{59}Ni in a meteoroid with a preatmospheric radius $R = 3$ m and (b) ^{36}Cl in meteoroids with $R = 3$, 5 and 15 m, respectively. The experimental points represent the ANU-I preatmospheric depth in each case: (260 ± 3) cm if $R = 3$ m, (268 ± 5) cm if $R = 5$ m and (282 ± 6) cm if $R = 15$ m.

TABLE 2. Preatmospheric depth of different samples for the ^{36}Cl measurements and upper limits from other radioisotopes, assuming a meteoroid radius of 3 m.

Sample	d(^{36}Cl) (cm)	d(^{26}Al) (cm)	d(^{10}Be) (cm)	d(^{41}Ca) (cm)	d(^{59}Ni) (cm)
ANU-I	282 ± 6	>206	>247	>187	>181
ANU-B	270 ± 4	>188	>275	>185	>178
TPB	242 ± 3	>213	>215	>171	>173
TPC	225 ± 2	>201	>190	>166	>204
JFN1	–	>170	>149	>167	>172

obtained for ANU-I, which came from a region of pure metal ~2 cm inside the fragment and well away from the pronounced crust on the surface of the fragment. Of the remaining three samples, TPB and TPC came from this crust and ANU-B may also have incorporated a small amount of crust. The higher ^{36}Cl concentrations measured for these three samples suggest that the crust incorporates additional ^{36}Cl relative to the unmodified metallic component of this fragment.

A terrestrial age of 4000 years has a negligible effect on the ^{36}Cl activity. It follows that the preatmospheric depth of the fragment studied can simply be read off the ^{36}Cl curve of Fig. 2b: (282 ± 6), (268 ± 5) and (260 ± 3) cm if the preatmospheric radius was 3, 5 and 15 m, respectively. Note that in the first case our sample would have been almost at the center of the meteoroid. Therefore, our best estimate of the preatmospheric size of the parent meteoroid of the Campo del Cielo meteorite is that it had a radius of at least 300 cm and a mass of at least 840 000 kg.

In Table 2, the minimum preatmospheric depth calculated from the activity limits (in a meteoroid with a radius of 3 m) for ^{10}Be, ^{26}Al, ^{41}Ca and ^{59}Ni are compared with those obtained from the ^{36}Cl measured activities. In each case, the minimum depth is significantly less than the depth deduced from ^{36}Cl (*i.e.*, all the data are consistent).

There are only a few other radionuclide measurements in samples of Campo del Cielo. Chang and Wänke (1969) obtained (0.31 ± 0.19) dpm kg^{-1} of ^{10}Be in a sample from El Taco, which is probably an upper limit. This sample and our JFN1 sample came from the same fragment of the parent meteoroid (*i.e.*, El Taco), but it was a big fragment of ~2000 kg, therefore it is not necessary that results of the measurements on these samples were exactly the same. Chang and Wänke (1969) also measured ^{10}Be and ^{36}Cl in another sample from Campo del Cielo and obtained (0.21 ± 0.45) and (0.59 ± 0.69) dpm kg^{-1}, respectively.

Nagai *et al.* (1993) measured ^{10}Be in samples of the El Taco fragment of Campo del Cielo. They inferred ^{10}Be production rates in pure silicate of (0.13 ± 0.03) dpm kg^{-1} and in pure carbon of (0.77 ± 0.09) dpm kg^{-1} and reported ^{10}Be activities in metallic fractions that ranged between 0.015 and (0.001 ± 0.001) dpm kg^{-1}, with the higher values from samples that had some silicates in them. In addition, metallic ^{26}Al values of ~0.01 dpm kg^{-1} were obtained in the metallic fraction. Our ^{10}Be and ^{26}Al limits for JFN1, which also came from the El Taco fragment, are comparable to the activities of Nagai *et al.* (1993). Further, the literature values for the El Taco fragment are higher than our results for the TPB, TPC, ANU-I and ANU-B samples. It follows that the fragment from which these four samples were taken was originally deeper in the parent body than the El Taco fragment.

SUMMARY AND CONCLUSIONS

A suite of five long-lived cosmogenic isotopes has been measured in a fragment of the Campo del Cielo meteorite. Of these, only ^{36}Cl yielded a finite value to determine that the particular fragment came from a depth between 260 and 281 cm in the parent meteoroid, depending on its radius. This places a lower limit of 3 m on the preatmospheric radius of Campo del Cielo, which implies that the parent meteoroid must have had a mass of at least 840 000 kg. This minimum size of the Campo del Cielo parent body is substantially larger than was possible to estimate previously. This has implications for the masses contained in the known craters that have not yet been studied and it also suggests the presence of more—perhaps many more—impact craters that have not been discovered.

The fragment of Campo del Cielo studied in the present work is among the most heavily shielded samples known. Fragments from similar depths have been reported for only two other meteorites, Brenham and Nantan. Nagai and coworkers (1993) reported that a fragment from the Brenham pallasite had a slightly larger shielding parameter than the El Taco fragment (but smaller than the fragment measured here). Support for their conclusion came from measurements of the concentrations of ^{10}Be and ^{26}Al by Honda *et al.* (1996): between (0.004 ± 0.001) and (0.93 ± 0.03) dpm kg^{-1} for ^{10}Be and between (0.0006 ± 0.0002) and (0.80 ± 0.07) dpm kg^{-1} for ^{26}Al, in metallic fractions. For the Nantan iron meteorite, Nishiizumi and coworkers (1995) estimated that their samples were from depths between 150 and 175 cm.

The present measurements are right at the limit of even the AMS technique. There are, however, many other fragments of Campo del Cielo in collections around the world and it would be of interest to make a more systematic study of a number of these in order to complement the results of the present work.

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