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Exposure age, terrestrial age and pre-atmospheric radius of the Chinguetti mesosiderite: Not part of a much larger mass

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Abstract–We measured the concentrations of the cosmogenic radionuclides ^{14}C (half-life = 5.73 × 10^3 years) in the bulk and of ^{10}Be (1.5 × 10^6 years), ^{26}Al (7.05 × 10^5 years), ^{36}Cl (3.01 × 10^5 years) and the light noble gases in metal and stone fractions of the Chinguetti meteorite to investigate the controversial claim that the 4.5 kg mesosiderite is part of a much larger mass in the Mauritanian desert. Based on the ^{36}Cl-^{36}Ar, ^{10}Be-^{21}Ne and ^{26}Al-^{21}Ne pairs in the metal fraction, we derive an average cosmic-ray exposure age of 66 ± 7 Ma. Chinguetti is now the third out of 20 mesosiderites with an exposure age between 60 and 70 Ma. This may be the first hint of a major impact on the parent body of the mesosiderites, which show ages ranging from 10 to 300 Ma (Terribilini *et al*., 2000). From the ^{14}C-^{10}Be pair we derive a terrestrial age of 18 ± 1 ka, which seems too recent to be consistent with the original description of the main mass having a heavily wind-eroded base, overhung by the upper part of the meteorite. Finally, from the radionuclide concentrations in combination with Monte-Carlo based calculations, we conclude that our sample of Chinguetti was irradiated at a depth of ~15 cm in an object not larger than 80 cm in radius. This is the most compelling evidence against the reports that the Chinguetti mesosiderite is a small fragment of a mass 100 m long and 40 m high.

INTRODUCTION

Chinguetti is a 4.5 kg mesosiderite find recovered from the Adrar region of Mauritania, some 45 km from the oasis town of Chinguetti, in 1916. Several years after its discovery it was confirmed as a meteorite (Lacroix, 1924). After the description of the find was released in 1924, it generated considerable excitement, especially with astronomers. Gaston Ripert, the French officer who found the meteorite, maintained that it was a representative sample of a much larger mass. His description, as transcribed by Lacroix (1924), states: "It was lying on top of an enormous metallic mass measuring about 100 m on one side and about 40 m in height, which stands up in the middle of the dunes…". Ripert's position as a French officer convinced many that his story was true. In addition, his comparative lack of interest in the find, and the fact that he had returned a sample of a new meteorite, appeared incompatible with his account being a simple hoax. After recovering the 4.5 kg sample, he turned the specimen over to M. H. Hubert, a friend and a Doctor of Science in Dakar. In the intervening years between the find and the announcement in 1924, Ripert made no effort to follow up on any progress made in its analysis, and in fact never reclaimed his meteorite.

Following the announcement in 1924, questions were asked in the French parliament, and numerous expeditions were mounted to find the larger mass, most notably those of Theodore Monod (*e.g.*, Monod, 1955). In later years, Monod (elaborating on a suggestion made to him by M. Malavoy, Chief of the Department of Mines, in 1934) became convinced that Ripert had mistaken desert varnished sandstone for an iron mass, and suggested that the guelb (a spur of rock) at Aouinet N'Cher matched the size and approximate location of Ripert's rock. The complete history of the search for the Chinguetti meteorite has been described in more detail in Monod and Zanda (1992). Most recently, following a sighting from the air by Jacques Gallouedec (a freelance pilot) in 1980 of a large black rock standing alone in the desert 45 km southeast of Chinguetti, an expedition, which included two of the authors (P. A. B and S. S. R.), returned to the area. All these searches have proved fruitless. Several explanations have been offered to explain their failure: the find location being somewhat uncertain; possibly dunes had partially or completely covered the mass; Ripert may have mistaken desert varnished sandstone for a large metallic mass, and just happened by chance to stumble on the smaller sample; or, for his own reasons, he simply lied. In order to throw a little more light on this problem, we chose to analyse a portion of the recovered sample for cosmogenic noble gases and radionuclides, to determine its exposure age, terrestrial age, and most importantly its pre-atmospheric radius. Preliminary results were presented at the 31st Lunar and Planetary Science Conference in Houston (Welten *et al*., 2000a).

EXPERIMENTAL PROCEDURES

Noble Gases

An olivine and a metal separate from specimen Nr. 1586 of the National Museum of Natural History, Paris (France) were analyzed for noble gases using methods described by Schultz and Weber (1996). In addition, a stone fraction was measured from a sample of the Natural History Museum in London, that was also used for radionuclide studies. The concentration and isotopic composition of He, Ne and Ar determined in the metal separate (118 mg), an olivine separate (75.3 mg) and a stone fraction (80 mg) are given in Table 1.

Radionuclides

For the measurement of radionuclides a fragment of 3.8 g from the Natural History Museum in London (BM 1980, M25) was taken ~5 cm from the fusion crust. We removed a chip of 0.24 g and by gently crushing we separated 136 mg of metal and 96 mg of stone fraction. We obtained a clean metal sample of 106.5 mg by treating the metal phase several times in an ultrasonic bath with 0.2 N HCl and then with concentrated HF to remove attached troilite and silicates, respectively. After adding carrier solutions, containing several milligrams of Be, Al, Cl and Ca, the metal and stone fractions were dissolved in 1.5 N HNO_3 and concentrated HF/HNO_3, respectively. After dissolution, aliquots of the dissolved samples were taken for chemical analysis by atomic absorption spectroscopy (AAS). The Be, Al and Cl fractions of the metal and stone samples were separated, purified and converted to BeO, Al_2O_3 and AgCl as described in Welten *et al*. (1999a). The ^{10}Be, ^{26}Al and ^{36}Cl concentrations are determined using the Lawrence Livermore National Laboratory tandem accelerator (Davis *et al*., 1990). The measured ^{10}Be/^{9}Be, ^{26}Al/^{27}Al and ^{36}Cl/Cl ratios were normalized to an ICN ^{10}Be standard and NBS (National Bureau of Standards, now National Institute of Standards and Technology) ^{26}Al and ^{36}Cl standards, all prepared by K. Nishiizumi (see references in Welten *et al*., 1999a). From the remaining 3.5 g of our sample a bulk fragment of ~1.8 g was used for ^{14}C analysis. The ^{14}C measurements were performed at the University of Arizona NSF-AMS facility (Jull *et al*., 1998).

Model Calculations

We used the Los Alamos High Energy Transport (LAHET) Code System (LCS) to calculate primary and secondary particle fluxes in cosmic-ray irradiated H chondrites with radii ranging from 4 to 200 cm (Masarik and Reedy, 1994; Welten *et al*., 2001). Using the fluxes of high-energy particles we calculated the production rates of ^{36}Cl and ^{26}Al in the metal phase and of ^{10}Be in both the metal and stone fractions. In order to convert the calculations for H chondrites to mesosiderites, we assumed a density of 5 g/cm^3 for Chinguetti. This is on the high end of typical values for stony-iron meteorites (Consolmagno and Britt, 1998), but consistent with the relatively high metal content of Chinguetti as reported by Lacroix (1924).

RESULTS

Noble Gases

The ^{36}Ar/^{38}Ar ratio of 0.63 in the metal phase indicates that these Ar isotopes are entirely of cosmogenic origin. The ^{21}Ne/^{38}Ar ratio of ~0.29 in the metal phase is somewhat higher than typical values of 0.17–0.26 found in iron meteorites (Voshage and Feldman, 1978; Lavielle *et al*., 1999). The main cause of the high ^{21}Ne/^{38}Ar in the metal is the presence of a minor amount of silicates, which have 30–70× higher ^{21}Ne concentrations (Table 1). Figure 1 shows the cosmogenic ^{38}Ar/^{21}Ne ratio in the metal phase of Chinguetti as a function of the ^{4}He/^{21}Ne shielding indicator, compared with results for iron meteorites. From Fig. 1 we derive that ~32% of the measured ^{21}Ne and ~7% of the measured ^{4}He originates from silicates, which corresponds to a silicate contamination of ~1.5%. This small contamination does not affect the cosmogenic Ar concentrations in the metal phase, since their production rates are similar to those in the silicate fraction. The corrected ^{4}He/^{21}Ne ratio of 320 ± 15 indicates moderate, but not extremely high-shielding conditions for the Chinguetti sample. The ^{3}He/^{38}Ar ratio of 16.0 in the metal phase corresponds very well to the expected value of 16.2 ± 0.8 (see Schultz and Hintenberger, 1967; Lavielle *et al*., 1999) and thus indicates that no ^{3}He (nor ^{3}H) was lost from the Chinguetti meteoroid due to solar heating.

The ^{22}Ne/^{21}Ne ratios of 0.96 in the olivine and 1.01 in the stone fraction are much lower than typical ratios of 1.05–1.30 in chondrites. It was shown previously that these low ratios in mesosiderites are due to the enhanced fluxes of low-energy secondary particles in metal-rich meteorites which produce especially ^{21}Ne from Mg in the silicate phase (Begemann and

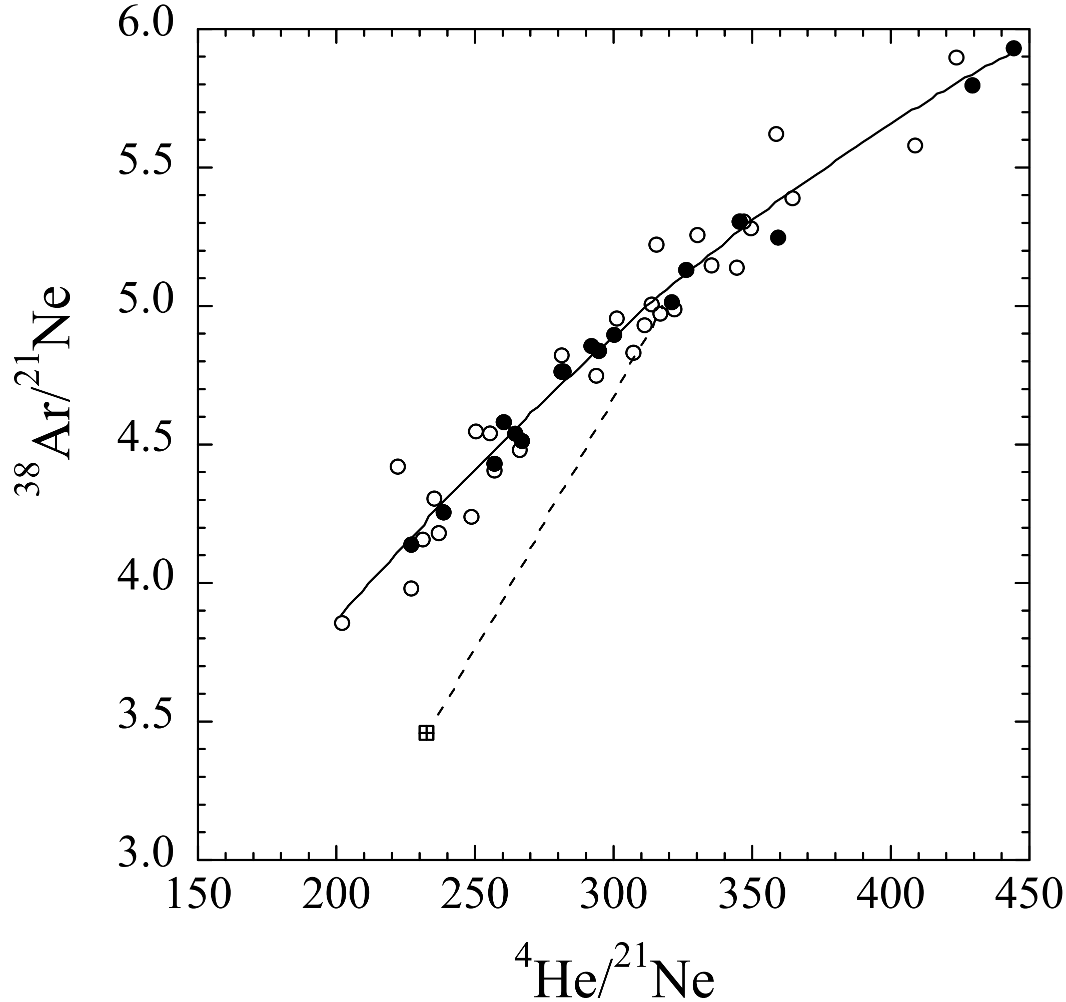

FIG. 1. Estimation of the silicate contamination in the metal phase from measured $^{38}Ar/^{21}Ne$ *vs.* $^{4}He/^{21}Ne$ ratios in Chinguetti, represented by a square, compared with ratios in clean metal fractions of iron meteorites. Closed circles represent data from Voshage and Feldmann (1978), open symbols data from Lavielle *et al*. (1999). The dashed line represents extrapolation of the measured noble gas record in the metal phase towards the noble gas record of clean metal, assuming that the Chinguetti metal was contaminated with bulk silicates (Table 1, col. 3). By extrapolation, Chinguetti's metal phase has a $^{4}He/^{21}Ne$ ratio of 320 ± 15, a $^{38}Ar/^{21}Ne$ ratio of 5.04 ± 0.27 and a ^{21}Ne concentration of 0.856 ± 0.050 cm^3 STP/g.

TABLE 1. Noble gas concentrations in the olivine, stone and metal fractions of the Chinguetti mesosiderite.

	Olivine	Stone	Metal	Silicate-corrected
^{3}He	137.0	102.3	69.0	68.5
^{4}He	958	1418	291	274
^{20}Ne	47.3	24.4	1.21	0.859
^{21}Ne	55.9	27.3	1.25	0.856
^{22}Ne	53.8	27.5	1.42	1.025
$^{22}Ne/^{21}Ne$	0.96	1.01	1.14	1.20
^{36}Ar	0.58	3.82	2.72	2.71
^{38}Ar	0.61	4.51	4.32	4.32
^{40}Ar	76.4	490	25.5	18.4

Noble gas concentrations are given in 10^{-8} cm^3 STP/g.

Schultz, 1988; Jentsch and Schultz, 1996). The enhanced production of ^{21}Ne from Mg also explains the lower $^{22}Ne/^{21}Ne$ ratio in the olivine fraction, which has a much higher Mg content than the bulk silicate fraction (Table 2). Therefore, the cosmogenic $^{22}Ne/^{21}Ne$ ratio cannot be used as shielding indicator.

Radionuclides

The ^{14}C, ^{10}Be, ^{26}Al and ^{36}Cl results are shown in Table 3. The extremely low Mg concentration of the purified metal phase (Table 2) shows that the metal used for radionuclide analysis contains no significant silicate contamination, so corrections for ^{10}Be and ^{26}Al from silicates are negligible. The radionuclide concentrations will be used to derive the terrestrial

TABLE 2. Chemical composition of the olivine, stone and metal fractions of the Chinguetti mesosiderite.

	Olivine*	Stone†	Metal†
Mg	30.0 ± 0.2	13.5 ± 0.2	<0.001
Al	–	1.90 ± 0.03	–
Si	19.5 ± 0.3	–	–
K	–	100 ± 10	–
Ca	0.03 ± 0.02	2.23 ± 0.03	–
Fe	6.9 ± 0.2	14.8 ± 0.2	87.0 ± 0.8
Ni	–	–	12.6 ± 0.2

*Average of two analyses of bulk samples by XRF.
†Measured by AAS on aliquots from dissolved sample used for radionuclide analyses. Concentrations are in wt%, except for K, which is

TABLE 3. Cosmogenic radionuclide concentrations in the stone and metal fractions of the Chinguetti mesosiderite.

	Stone	Metal
^{14}C	4.35 ± 0.06*	
^{10}Be	21.2 ± 0.3	3.35 ± 0.05
^{26}Al	77.8 ± 1.3	2.39 ± 0.06
^{36}Cl	–	17.4 ± 0.20

Radionuclide concentrations are given in dpm/kg, 1σ errors include all known AMS errors, but not the uncertainties in the AMS standards.
*^{14}C was measured in a bulk sample.

age of Chinguetti as well as to determine its cosmic-ray exposure age.

DISCUSSION

Terrestrial Age

Reliable terrestrial ages can be obtained with the ^{36}Cl-^{10}Be, ^{36}Cl-^{26}Al and the ^{14}C-^{10}Be methods, which are all independent of shielding conditions (Lavielle *et al*., 1999; Welten *et al*., 2000b; Jull *et al*., 2000). The ^{36}Cl-^{10}Be and ^{36}Cl-^{26}Al methods yield a terrestrial age <30 ka. For the ^{14}C-^{10}Be method we adopt a ^{14}C/^{10}Be production ratio of 2.65 and used a bulk ^{10}Be content of 14.4 dpm/kg, derived from the measured ^{10}Be concentrations in the metal and stone fraction of Chinguetti and an estimated silicate/metal ratio of 60/40. The measured ^{14}C-^{10}Be ratio then gives a terrestrial age of 18 ± 1 ka. This terrestrial age implies a ^{36}Cl saturation value of 18.1 ± 0.2 dpm/kg, slightly below average saturation values of 19–25 dpm/kg. All terrestrial age methods assume that ^{10}Be and ^{26}Al were saturated at the time of fall, which requires an exposure age >10 Ma, an assumption that will be tested below.

Cosmic-Ray Exposure Age

A reliable exposure age method is the ^{36}Cl-^{36}Ar method in the metal phase (Begemann *et al*., 1976). After correction for a terrestrial age of 18 ka, the ^{36}Cl-^{36}Ar age is calculated using $P(^{36}\text{Cl})/P(^{36}\text{Ar}) = 0.835 \pm 0.040$ (Lavielle *et al*., 1999). This method gives an exposure age of 64 ± 3 Ma. We also calculated the ^{10}Be-^{21}Ne and ^{26}Al-^{21}Ne ages from the metal phase, assuming production rate ratios of $P(^{10}\text{Be})/P(^{21}\text{Ne}) = 0.55$ and $P(^{26}\text{Al})/P(^{21}\text{Ne}) = 0.38$ (Lavielle *et al*., 1999) and a cosmogenic ^{21}Ne concentration of $(0.855 \pm 0.05) \times 10^{-8}$ cm^3 STP/g. After correcting the ^{10}Be and ^{26}Al concentrations for decay during terrestrial residence, the ^{10}Be-^{21}Ne and ^{26}Al-^{21}Ne methods give exposure ages of 72 ± 6 and 69 ± 5 Ma, respectively, both consistent with the ^{36}Cl-^{36}Ar age, but with higher uncertainties due to the correction for ^{21}Ne from silicates. We adopt an average exposure age of 66 ± 7 Ma. We added an uncertainty of ~10%, since the noble gases and radionuclides were measured in different samples that were 5 ± 5 cm apart and thus may have been from slightly different depths. The exposure age of 66 Ma is typical for mesosiderites, which show ages in the range of 10–300 Ma (Terribilini *et al*., 2000; Albrecht *et al*., 2000).

Matrix Effects

Given the exposure age of 66 ± 7 Ma, the ^{21}Ne concentrations in the olivine and stone fraction correspond to ^{21}Ne production rates of (0.84 ± 0.08) and $(0.41 \pm 0.04) \times 10^{-8}$ cm^3 STP/g Ma, respectively. The production rate in the olivine fraction is a factor of 2 higher than the maximum values for ordinary chondrites and is on the high end of the range observed in mesosiderites (Albrecht *et al*., 2000). The high ^{21}Ne production rate can partly be explained by the high Mg concentration (30 wt%). However, according to equations given in Eugster (1988), the chemical composition of the olivine corresponds to a maximum ^{21}Ne production rate of $(0.65–0.75) \times 10^{-8}$ cm^3 STP/g Ma for high shielding conditions (corresponding to a chondritic ^{22}Ne/^{21}Ne ratio of 1.05–1.07). The additional 10–30% in the ^{21}Ne production rate indicates enhanced secondary particle fluxes due to the high Fe and Ni contents of Chinguetti as was also shown by the extremely low ^{22}Ne/^{21}Ne ratio of 0.96.

Matrix effects are also evident from the $P^{38}(\text{Ca})/P^{38}(\text{Fe})$ production rate ratio, which is up to a factor of 2.5 higher in mesosiderites than in ordinary chondrites (Begemann and Schultz, 1988). The almost eight-fold difference in the ^{38}Ar concentration between the olivine and the stone fraction clearly illustrates the large contribution from Ca, which is almost absent from the olivine fraction. Assuming an average Ca concentration of 2.2% in the stone fraction, we find a production rate ratio $P^{38}(\text{Ca})/P^{38}(\text{Fe}) = 38$, well in the range of typical values of 20–50 for mesosiderites (Begemann and Schultz, 1988).

Pre-atmospheric Size

The moderate shielding conditions in Chinguetti, as suggested by the $^{4}He/^{21}Ne$ ratio of 320 ± 15 in the metal phase, are confirmed by the somewhat low ^{10}Be, ^{26}Al and ^{36}Cl activities in the metal phase. However, although the ^{36}Cl saturation value of 18.1 dpm/kg may be lower than for "average" shielding conditions (19–25 dpm/kg), it is significantly higher than the maximum expected concentration of ~12 dpm/kg under 2π irradiation. Therefore, the radionuclides do not support a very large size for Chinguetti, as reported by Ripert.

In order to constrain the pre-atmospheric size of Chinguetti, we applied Monte-Carlo based calculations for H chondrites (Welten *et al.*, 2001) to the case of Chinguetti by simply correcting for the difference in target element concentrations. The higher fluxes of low-energy secondary particles in mesosiderites do not affect the production rates of ^{10}Be in metal and stone fractions nor of ^{26}Al and ^{36}Cl in the metal phase, as was shown by calculations (Masarik and Reedy, 1994) as well as empirical data (Albrecht *et al.*, 2000). Figure 2 shows that the range of measured ^{10}Be, ^{26}Al and ^{36}Cl concentrations, corrected for terrestrial age, only occur in meteoroids with a radius >200 g/cm^2, whereas the ^{36}Cl value constrains the radius to a maximum of 400 g/cm^2. Assuming a density of 5.0 g/cm^3, this corresponds to a pre-atmospheric radius of 40–80 cm for Chinguetti.

In addition, the ^{10}Be(stone)/^{10}Be(metal) ratio can be used to constrain the depth of our sample in the pre-atmospheric object (Welten *et al.*, 1999b, 2001). The concentration of oxygen, the main target element for the production of ^{10}Be, in the silicate fraction of most mesosiderites is between 40 and 45 wt% (Albrecht *et al.*, 2000), that is, very similar to the average value of 43.5 wt% in the silicate fraction of H chondrites (derived from a bulk H-chondrite value of 357 mg/g; Wasson and Kallemeyn, 1988). Therefore, no corrections for differences in target element composition were made. Figure 3 shows that the measured ^{10}Be(stone)/^{10}Be(metal) ratio of 6.3 ± 0.2 is typical for shielding depths of 60–100 g/cm^2. The combined radionuclide data indicate that our sample of Chinguetti was irradiated at a depth of ~15 cm in an object of 40–80 cm in radius. Such a radius is also in agreement with the noble gas results. According to the model of Signer and Nier (1960) the measured $^{4}He/^{21}Ne$ and $^{3}He/^{21}Ne$ ratios of 320 and 80, respectively, only occur in iron meteorites with a radius larger than 30 cm, which corresponds to a minimum radius of ~45 cm for Chinguetti.

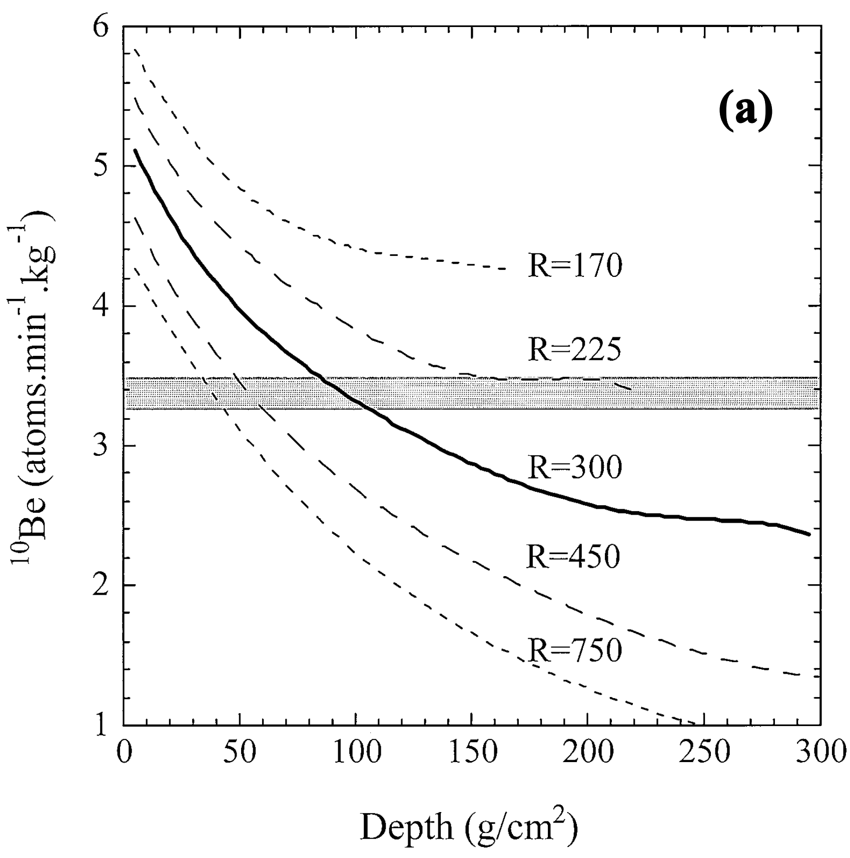

FIG. 2. Monte-Carlo based calculations of ^{10}Be (a), ^{26}Al (b) and ^{36}Cl (c) production rates as a function of depth in the metal phase of H chondrites with pre-atmospheric radii (*R*) ranging from 170–750 g/cm^2 (45–200 cm), compared with measured production rates in Chinguetti, as represented by the grey bars. Based on the calculations, the measured activities in the metal phase of Chinguetti constrain its pre-atmospheric radius to 200–400 g/cm^2. *Figure 2 is continued on the next page.*

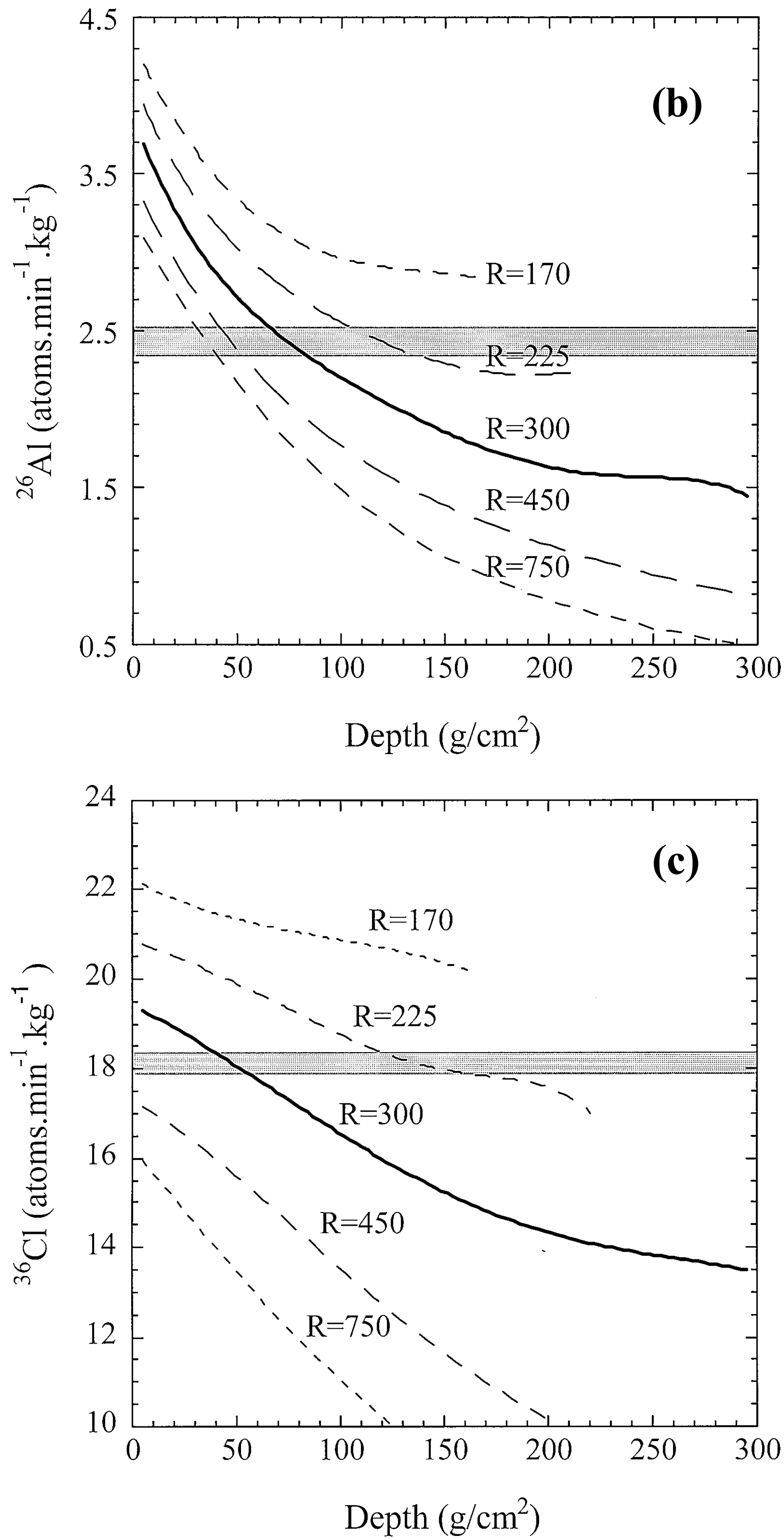

FIG. 2. *Continued*. Monte-Carlo based calculations of ^{26}Al (b) and ^{36}Cl (c) production rates.

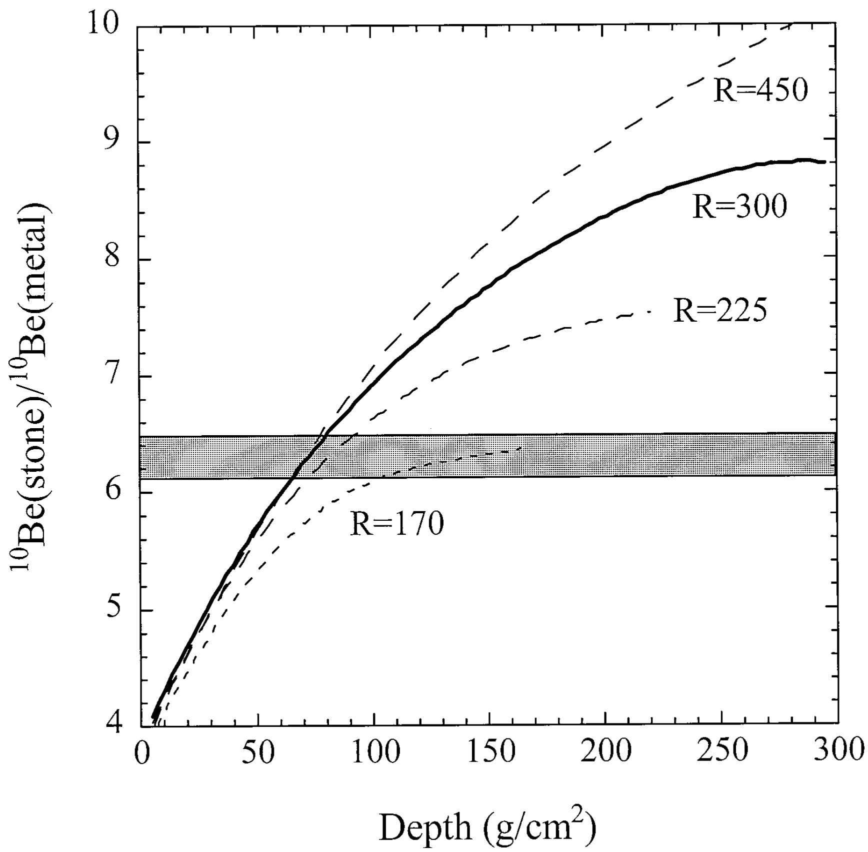

FIG. 3. Measured ^{10}Be(stone)/^{10}Be(metal) ratio of the Chinguetti sample compared with Monte-Carlo based calculations for H chondrites with pre-atmospheric radii (R) ranging from 170–450 g/cm^2. Based on the calculations, the measured ^{10}Be activities in the stone and metal fraction of Chinguetti constrain the pre-atmospheric depth to 60–100 g/cm^2 in an object with a radius of ~300 g/cm^2.

CONCLUSIONS

The combined radionuclide data indicate that our sample of Chinguetti was irradiated at a depth of ~15 cm in an object of ~60 cm in radius, and landed on Earth ~18 ka ago. This comparatively recent terrestrial age seems too recent to be consistent with Ripert's original description of the main mass having a heavily wind eroded base, which is overhung by the upper portion of the meteorite. Even more compelling is our evidence of a pre-atmospheric radius of <80 cm, which implies that Chinguetti originated from a relatively small object. Although we cannot completely exclude that another large meteorite—not related to the Chinguetti mesosiderite—is buried somewhere in the Mauritanian desert, it seems more likely that Ripert's description of the find was incorrect. Whether he was simply mistaken, he lied or whether his original story was changed in the four years it took to transfer the meteorite from Ripert to Hubert in Dakar to Lacroix in Paris will probably always remain a mystery.

Based on the measured ratios of ^{36}Cl-^{36}Ar, ^{10}Be-^{21}Ne and ^{26}Al-^{21}Ne in the metal fraction, we derive an average cosmic-ray exposure age of 66 ± 7 Ma. With this age, Chinguetti is now with Estherville and Crab Orchard the third out of 20 mesosiderites with an exposure age in the 60–70 Ma range. Although this peak is statistically not significant in a distribution which shows ages ranging from 10–300 Ma, it may be the first hint of a major impact on the parent body of the mesosiderites. It must be noted that Chinguetti represents a different compositional group than the other two mesosiderites with similar exposure ages. This suggests that the two main types of mesosiderites reside close enough on the parent body to be ejected in one single impact event.

Acknowledgments–This paper is dedicated to the memory of Prof. Theodore Monod, who spent many years in the Mauritanian desert searching for the missing large mass of the Chinguetti meteorite, and died on 2000 November 22 at the age of 98. The authors would like to thank B. Zanda, I. Leya and the associate editor, R. Wieler, for useful reviews of this manuscript. This work was supported by NASA grants NAG5-4832 and NAG5-4992, and was performed under the auspices of the U.S. DOE by LLNL under contract W-7405-ENG-48. We thank the Natural History Museum in London as well as the Museum of Natural History in Paris for providing samples of Chinguetti.

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