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Exposure history of the Peekskill (H6) meteorite

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Abstract–The Peekskill H6 meteorite fell on 1992 October 9. We report extensive measurements of cosmic-ray produced stable nuclides of He, Ne, and Ar, of the radionuclides ^{22}Na, ^{60}Co, ^{14}C, ^{36}Cl, ^{26}Al, and ^{10}Be, and of cosmic-ray track densities. After correction for shielding *via* the ^{22}Ne/^{21}Ne ratio, the concentrations of cosmic-ray produced ^{3}He, ^{21}Ne and ^{38}Ar give an average exposure age of 25 Ma, which is considered to be a lower limit on the true value. The ^{10}Be/^{21}Ne age is 32 Ma and falls onto a peak in the H-chondrite exposure age distribution. The activities of ^{26}Al, ^{14}C, ^{36}Cl, and ^{10}Be are all close to the maximum values expected for H-chondrites. Together with cosmic-ray track densities and the ^{22}Ne/^{21}Ne ratio, these radionuclide data place the samples at a depth >20 cm in a meteoroid with a radius >40 cm. In contrast, the ^{60}Co activity requires a near-surface location and/or a much smaller body. Calculations show that a flattened geometry for the Peekskill meteoroid does not explain the observations in the context of a one-stage irradiation. A two-stage model can account for the data. We estimate an upper bound of 70 cm on the radius of the earlier stage of irradiation and conclude that Peekskill's radius was <70 cm when it entered the Earth's atmosphere. This size limit is somewhat smaller than the dynamic determinations (Brown *et al.,* 1994).

INTRODUCTION

The cosmic-ray exposure history of a meteorite fall is of special interest when the orbit is known. On the evening of 1992 October 9, a spectacular fireball traced a shallow trajectory some 700 km long over a northeastern portion of the United States (Brown *et al.*, 1994). Numerous observers recorded the event on videotape and photographically. The images show the object fragmenting into over 70 pieces. By analyzing the tapes and films, Brown *et al.* (1994) and Ceplecha *et al.* (1994, 1996) were able to determine the original orbit of the object and to estimate dynamically its original mass. According to Ceplecha *et al.* (1996), Peekskill is best represented by a meteoroid with a mass of ~10^4 kg and a flattened shape with dimensions of 1.7 × 1.7 × 1 m. Near the end of the fireball's observed path, a meteorite fell and struck a parked car in Peekskill, New York; a mass of ~12.4 kg was recovered. The Peekskill H6 chondrite presents an unusual opportunity to compare a dynamic estimate of pre-atmospheric size with one inferred from cosmic-ray-produced nuclide concentrations. A consortium was organized to measure the stable and radioactive nuclides as well as track densities in order to study Peekskill's history of exposure to cosmic rays. Here we report the results and assess the evidence for a multi-stage exposure history, the limits on size of the meteoroid, and the shielding conditions of the recovered samples. The currently available records of H-chondrite exposure histories were recently discussed by Graf and Marti (1995).

EXPERIMENTAL METHODS

Samples–Measurements were made in three different samples of Peekskill. Martin Prinz (American Museum of Natural History) supplied one sample (AMNH 4382) with a mass of 50 mg that had been recovered from the driveway where the meteorite fell. A 7 g slab sketched in Fig. 1 was sawed from the main, 12.9 kg fragment. The slab had a location adjacent to the third sample BNW 930420, which was taken for low level counting. The horizontal and vertical dimensions of this slab are 3.4 cm and 2.1 cm, respectively. The heavy solid lines in Fig. 1 represent fractures that existed in the sample when received. The heavy dashed line depicts a ribbon of Fe Ni metal (II-3/4) that was removed and analyzed separately. The light dotted lines indicate where the slab was broken to provide samples for the various measurements. To the right of the longer dashed line that bisects the sample from top to bottom, the meteorite appeared to have a shocked texture.

Measurements–The stable isotopes of He, Ne, and Ar were analyzed by static mass spectrometry in sample I-4b from the 7 g slab; the analytical approach is discussed by Graf *et al.* (1990a). Gamma decays of the long-lived radionuclide ^{26}Al and the shorter-lived ^{22}Na and ^{60}Co were counted nondestructively in sample BNW 930420 at Battelle Pacific Northwest Laboratories using multiparameter gamma ray spectrometry (Simon *et al.*, 1995). Samples of the 7 g slab and AMNH 4382 were taken for destructive analysis of the cosmogenic radionuclides ^{36}Cl, ^{14}C, and/or ^{26}Al and ^{10}Be. The radionuclides ^{26}Al, ^{10}Be, and ^{36}Cl were isolated in chemical forms suitable for accelerator mass spectrometry (AMS) following procedures described by Vogt and Herpers (1988). Jull *et al.* (1994) sketch the methods for releasing meteoritic C as CO and CO_2 and reducing it to graphite for the determination of ^{14}C. Silicate- and metal-rich portions of samples III-2 and II-2 were prepared by first crushing bulk meteorite in an agate mortar and pestle and then separating the metal-rich material with a hand magnet. Etching of the metal-rich material with concentrated hydrogen fluoride removed much of the adhering silicate. An aliquot of each silicate-rich

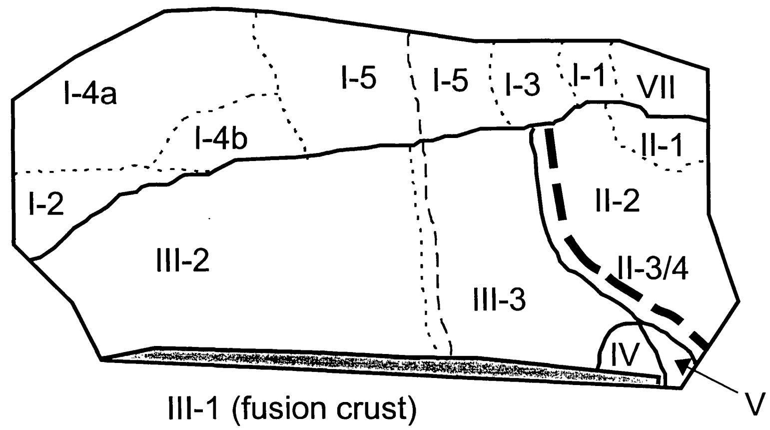

FIG. 1. Sketch of the 7g slab which was sawed from the main, 12.9 kg fragment. The horizontal and vertical dimensions of the slab are 3.4 cm and 2.1 cm, respectively, and the thickness is ~0.5 cm. The heavy solid lines represent fractures that existed in the sample when received. The heavy dashed line depicts a ribbon of Fe Ni metal (II-3/4) that was removed and analyzed separately. The light dotted lines indicate where the slab was broken to provide samples for the various measurements. To the right of the light dashed line that bisects the sample from top to bottom, the meteorite appeared to have a shocked texture.

sample was set aside for elemental analysis by atomic emission spectroscopy with a directly coupled Ar plasma source (Feigenson and Carr, 1985).

Radionuclide measurements were carried out using AMS facilities at the University of Pennsylvania for ^{26}Al and ^{10}Be (Middleton and Klein, 1986, 1987), the NSF Accelerator Facility (Jull *et al.*, 1993) for ^{14}C, and at Chalk River Laboratories (Andrews *et al.*, 1994) for ^{36}Cl. For nuclear track revelation, polished thin sections of samples I-4a and VII + I-1 were etched in WN solution (Krishnaswami *et al.*, 1971) for ~4 h. Track counting was performed with a polarizing microscope in transmitted light at a magnification of 1600.

RESULTS

Noble Gases–The results of the noble gas measurements appear in Table 1. Aliquots have been measured at UCSD, La Jolla, and ETH Zürich. All concentrations agree within 3% and isotopic ratios agree within 1%. The concentrations of radiogenic ^{4}He and ^{40}Ar imply that shock heating caused little loss of these components, despite the fact that the slab appears to show a shocked texture just ~1 cm away from the sample. Assuming average K concentrations for H-chondrites of 800 ppm (Wasson and Kallemeyn, 1988), we obtain a nominal K-Ar crystallization age of 4.3 Ga. The ratios of ^{20}Ne/^{22}Ne are consistent with pure spallation gases and yield no evidence of exposure close to any preatmospheric surface. The average ^{22}Ne/^{21}Ne ratio of 1.075 lies close to, but not at the low end, of the chondritic distribution, which is consistent with a preatmospheric radius >40 cm and a depth >20 cm (Graf *et al.*, 1990b).

We use standard production rates of ^{3}He, ^{21}Ne, and ^{38}Ar (*e.g.*, Graf and Marti, 1995) to obtain exposure ages. Shielding corrections are based on the cosmic-ray produced ^{22}Ne/^{21}Ne ratio. Assuming a single-stage irradiation, these production rates yield exposure ages (in Ma) of $T_3 = 25$, $T_{21} = 28.1$, and $T_{38} = 23$, respectively, with an average of 25 Ma. This exposure time reveals that the activities of all radionuclides measured have reached their steady-state or saturation values in a one-stage exposure.

Compositional Analysis–Direct coupled plasma spectrometry gave the following results in weight percent for Mg, Al, Ca, Ti, and Fe respectively: Sample II-2, 16.68, 1.46, 1.39, 0.07, and 14.6; Sample III-2, 17.28, 1.61, 1.39, 0.07, and 14.82. Assuming that Fe was present as FeO in these samples and that all oxides sum to 100%, we obtain for O and Si: Sample III-2, 42.6, and 21.9; Sample II-2, 42.8, and 22.6.

Long-lived Cosmogenic Radionuclides–Peekskill's ^{14}C activity is 51.1 ± 0.4 dpm/kg (Table 2). According to Jull *et al.* (1994), L-chondrites contain on average 51 dpm/kg of ^{14}C. In Knyahinya, an L/LL5 chondrite with a preatmospheric radius of ~45 cm, ^{14}C activities increase from 37.3 dpm/kg near the surface to 55.9 dpm/kg close to the center. The central value in a body of Knyahinya's size is important because it seems to represent the maximum chondritic production rate reached by spallogenic nuclides in the absence of solar energetic particles (Graf *et al.*, 1990a). Because of compositional differences between H- and L-chondrites, we expect a maximum production rate some 5–8% lower in the former (*i.e.*, ~53 dpm/kg). We conclude that the ^{14}C activity of Peekskill is close to or a little lower than the chondritic spallogenic maximum.

The metal-rich samples of Peekskill contain 23 ± 1 dpm/kg of ^{36}Cl. Up to a size that includes Knyahinya (radius ~45 cm), ^{36}Cl production rates in the metal phases of chondrites depend only weakly on shielding conditions, scarcely budging from the value of 22 dpm/kg (Nishiizumi *et al.*, 1989; Reedy *et al.*, 1993). Eventually, as radius continues to increase, the surface and interior production rates both decrease. In a sphere of Jilin's size, $R \sim 85$ cm, $P(^{36}Cl_{metal})$ decreases from a surface value of ~16 dpm/kg to lower values in the interior. We infer that ^{36}Cl production rates in the metal phase set an upper limit of 60–70 cm on Peekskill's radius. The ^{36}Cl activities of the silicate-rich phases are more difficult to interpret for they change in response to small variations in composition (K and Ca in particular) and may include a component produced by ^{35}Cl's capture of thermal neutrons. The measured values of 7.4 and 7.8 dpm/kg are in agreement with the few literature values for bulk chondrites (Nishiizumi, 1987).

The ^{26}Al activity determinations for the bulk BNW 930420 and slab samples agree well (<1 σ). The average value is 72 ± 3 dpm/kg. From the composition data given above and standard production rate equations (see Vogt *et al.*, 1990), we estimate the ^{26}Al production rate in sample III-2 to be 24% higher compared to production rates for average H-chondrite composition. Applying this normalization to the ^{26}Al activity from the silicate-rich separate of sample III-2 yields 72 ± 7 dpm/kg, which is again in good agreement with the results for the bulk samples. We have no elemental analysis of the silicate from AMNH 4382. If we assume the same factor used for III-2, then we obtain an H-chondrite normalized ^{26}Al activity of

TABLE 1. Noble gas concentrations (10^{-8} cm^3 STP/g) of Peekskill samples.

	^{3}He	^{4}He	^{21}Ne	^{22}Ne/^{21}Ne	^{20}Ne/^{22}Ne	^{38}Ar	^{40}Ar	^{36}Ar/^{38}Ar	^{38}Ar$_c$
La Jolla	38.9	1290	9.76	1.079	0.832	1.62	5050	1.892	1.19
Zürich	39.2	1350	9.80	1.070	0.833	1.58	5900	1.877	1.16
Mean	39.1	1320	9.78	1.075	0.832		5480		1.18

TABLE 2. Cosmogenic radionuclide activities (dpm/kg) of Peekskill samples.

	^{22}Na	^{60}Co	^{14}C	^{36}Cl	^{26}Al	^{10}Be
Half-life	2.6 a	5.3 a	5.72 ka	0.3 Ma	0.71 Ma	1.5 Ma
Sample						
BNW 930420	117 ± 13	11 ± 2			77 ± 5	
I-2			51.1 ± 0.4			
II-2						
Bulk						23.8 ± 1.2
Silicate				7.4 ± 0.4		26.4 ± 1.3
Metal				23.4 ± 0.5		5.3 ± 0.2
II-3/4 metal				22.1 ± 0.9	3.35 ± 0.16	5.0 ± 0.2
III-2						
Bulk					71 ± 4 69 ± 6	21.5 ± 1.0
Silicate				7.8 ± 0.4	93 ± 7 85 ± 4	27.3 ± 1.4
Metal				22.7 ± 0.5	4.4 ± 0.3	5.3 ± 0.3
AMNH 4382						
Silicate					74.4 ± 6.0	20.0 ± 1.6

60 ± 6 dpm/kg, which is ~15% lower than that of the slab and BNW 930420 samples. Evidently AMNH 4382 was separated from the slab by a radial distance of ~10 cm (away from the center) while it was in the meteoroid.

Calculations show that galactic cosmic-ray-induced ^{26}Al activities peak at ~70 dpm/kg toward the centers of bodies with radii of 45 to 65 cm (Michel *et al.*, 1991; Reedy, 1987). Thus, the size and shielding estimates based on ^{14}C and ^{26}Al are at least qualitatively similar. The ^{26}Al found in the metal ribbon II-4, 3.35 ± 0.16 dpm/kg, agrees well with the values reported for small iron meteorites by Aylmer *et al.* (1988) and for the metal phases of chondrites (Nagai *et al.*, 1993). The higher activity measured in metal separated from III-2 probably reflects a small degree of silicate contamination.

The ^{10}Be activities of bulk samples II-2 and III-2, 23.8 ± 1.2 and 21.5 ± 1.0 dpm/kg, approach the maximum galactic cosmic-ray (GCR) production rates seen in ordinary chondrites, namely, those in the center of Knyahinya (Graf *et al.*, 1990a). We normalize the ^{10}Be results for silicate samples just as we did those for ^{26}Al. The calculated ^{10}Be production rate for samples II-2 and III-2 is ~16% larger compared to production rates for average H-chondrite composition. Applying this normalization factor yields 22.8, 23.6, and 17.3 dpm/kg for silicate-rich samples from II-2, III-2, and AMNH 4382, respectively. The uncertainties are 5–10% depending on the size of the error assigned to the composition correction. On averaging the normalized ^{10}Be data for the slab, we obtain 22.4 ± 1.2 dpm/kg, which is ~30% larger than for AMNH 4382. The ^{10}Be/^{21}Ne age (Graf *et al.*, 1990b) of Peekskill is 32 Ma. For a preatmospheric radius of Peekskill ≥50 cm, the ^{10}Be/^{21}Ne age is probably more accurate than the ages calculated from the light noble gases alone because the ^{22}Ne/^{21}Ne shielding corrections tend to overestimate production rates for such large meteoroids. The ^{10}Be/^{21}Ne age of 32 Ma places Peekskill in a 33 Ma peak of the H-chondrite exposure age histogram. We infer that Peekskill is a likely fragment from a major collision 33 Ma ago (Graf and Marti, 1995).

Cosmic-Ray Tracks–Despite Peekskill's long exposure age, the separated olivines registered few cosmic-ray tracks (Table 3). We estimate track production rates using the ^{10}Be/^{21}Ne exposure age. The value inferred for VII + I-1, ~ 5 × 10^2 tracks cm^{-2} Ma^{-1}, occurs only in bodies with radii >31 cm (Bhattacharya *et al.*, 1973). The track densities for the two samples correspond to depths of 20 and 23 cm in a meteoroid of radius 50 cm. These depths are not very sensitive to the radius or the exposure age; a 15% increase in the assumed exposure age would increase these depths by ~1 cm.

Short-lived Cosmogenic Radionuclides–Over the course of the solar cycle, solar modulation of the GCR flux changes the production rates of spallogenic short-lived radionuclides (Evans *et al.*, 1982; Vogt *et al.*, 1990). Peekskill fell at a time when solar activity was nearing a maximum and the GCR flux a minimum. Accordingly, Peekskill's ^{22}Na ($t_{1/2}$ = 2.6 a) and ^{60}Co contents ($t_{1/2}$ = 5.27 a), are estimated to be ~15% lower than those expected in a body exposed to the average, long-term GCR flux. With a 15% correction, the measured activities of ^{22}Na and ^{60}Co (Table 2) become 133 ± 15 dpm/kg and 13 ± 3 dpm/kg, respectively. Finally, we note that decay of ^{56}Co ($t_{1/2}$ = 77.7 d) was not detected (<25 dpm/kg at the time of fall). As solar cosmic rays (SCR) can produce ^{56}Co, its absence suggests that the sample depth before impact was at least 1 cm, assuming the meteoroid intercepted an "average" number of solar flare particles. However, we cannot rule out the possibility that the lack of ^{56}Co is simply a consequence of no large solar particle

TABLE 3. Track densities, track production rates P_{Tracks} in pyroxene, and sample depths for various preatmospheric radii assuming an exposure age of 32 Ma.

	I-4a	VII+ I-1
# olivine grains	150	220
# analyzable olivine grains	45	43
Surface area counted (mm2)	0.1113	0.1117
# tracks	13	6.5
Track density (10^3 cm^{-2} olivine)	11.7	5.82
Track density (10^3 cm^{-2} pyroxene)	28.1	14.0
P_{Tracks} (10^3 cm^{-2} Ma^{-1})	0.88	0.44
Sample depth (cm) for		
radius = 35 cm	24	27
radius = 50 cm	20	23
radius = 1000 cm	18	21

Where track like features cannot be identified unambiguously, the feature is counted as 0.5 tracks.

events occurring in the months before Peekskill's fall. Indeed, Shea and Smart (1995) indicate that no big solar particle events occurred in the period from June until 1991 October.

If saturated, the ^{60}Co and ^{22}Na activities help constrain the geometric conditions of irradiation during the last few years. To interpret the ^{60}Co result, we assume an average bulk Co content of 800 ± 100 ppm (Wasson and Kallemeyn, 1988) and scale published production calculations for Torino (Co = 690 ppm; Wieler *et al.*, 1996). The scaled calculations match the measured ^{60}Co activity in meteoroids with radii R (cm) and depths d (cm), bounded by the values R = 25, d = 25 and R = 50, d = 1. With radii <25 cm, thermal neutron fluxes are too low to produce a ^{60}Co activity of 13 dpm/kg at any depth. With radii >50 cm, samples must lie within 1 cm of the surface to avoid ^{60}Co overproduction; and at such shallow depths, a shortage of cosmic-ray secondary particles reduces ^{22}Na production below 80 dpm/kg. Indeed, even with a 1 σ allowance, the adjusted ^{22}Na activity of 133 dpm/kg is reached only for d > 35 cm with 35 < R < 50 cm. As the ^{22}Na and ^{60}Co activities are barely mutually consistent with model calculations, we suspect that the measured ^{22}Na activity may be too high.

DISCUSSION

To summarize, all stable and long-lived cosmogenic nuclides—^{3}He, ^{21}Ne, ^{38}Ar, ^{10}Be, ^{26}Al, ^{36}Cl, and ^{14}C—and the ^{22}Ne/^{21}Ne ratio occur at levels consistent with a long (>5 Ma) irradiation at depths >20 cm in a meteoroid with a radius of 45–65 cm. For a nominal, one-stage exposure, the track densities are reproduced well by an irradiation at a depth of ~20–25 cm in a body of radius >40 cm. On the other hand, the ^{60}Co activity places the samples within 10 cm of the preatmospheric surface for R > 40 cm. We conclude that a single-stage irradiation of a spheroidal body cannot explain all the data. Either Peekskill had a complex exposure, in which case the task is to devise a plausible two-stage history, or Peekskill had an unusual geometry, in which case the problem is to construct a shape with the right properties. We consider the two-stage scenario first.

Two-stage Exposure History–The key constraint for any plausible history is that the activities of the nuclides ^{14}C, ^{26}Al, and ^{10}Be are close to the chondrite maximum for the inner solar system. It follows that Peekskill (1) had to be in a body with a radius of 40–60 cm at depths >20 cm for at least 3–4 Ma (long enough to saturate ^{10}Be); and (2) the conditions of the most recent irradiation stage did not allow the ^{14}C activity to fall much below the chondrite maximum. A simple hypothesis accounts well for most of the observations: The long-lived cosmogenic nuclides and tracks accumulated at depth of ~20–25 cm in a body with a radius of 40–60 cm until recently when a collision occurred. The collision reduced the radius to a value between 25 and perhaps 40 cm; the depth of proto-Peekskill could have remained the same or decreased, but only to a minimum of ~5 cm. The concentrations of the noble gases and of the long-lived cosmogenic radionuclides changed little during the second stage while ^{22}Na and ^{60}Co activities quickly adjusted to the new irradiation conditions. Solar cosmic rays present a possible complication for the second stage. We discount SCR effects for two reasons: first, as noted above, no ^{56}Co was observed; second, careful searching has turned up only a few meteorites with clear-cut evidence for SCR effects (Nishiizumi *et al.*, 1995). Figure 2 shows the range of possibilities discussed.

Oblate Meteoroid–As an alternative to a complex history, we considered the possibility that a one-stage irradiation of a flat object might explain the low ^{60}Co activity. A flattened geometry for the Peekskill meteoroid has also been suggested by Ceplecha *et al.* (1996) based on dynamic data. We speculate that such a shape would allow a significant fraction of thermal neutrons to escape and depress ^{60}Co production rates but would support the development of a large enough flux of cosmic-ray secondaries to maintain spallation production rates close to the levels attained in spheres. Figure 3 shows production rate profiles calculated for a sphere with a radius of 43 cm (1250 kg for a density of 3.7 g/cm^{3}) and for the central axes of two cylinders, one with a height of 30 cm and a radius of 60 cm (1250 kg) and the other with a height of 30 cm and a radius of 120 cm (5000 kg). Though depressed as expected, the ^{60}Co production rates calculated for the axis of the larger cylinder exceed the measured activity. This observation suggests that even in a large flat body, a sample with Peekskill's ^{60}Co content could only have occupied a near-surface, off-axis location. From ^{26}Al and track concentrations, on the other hand, we infer a depth >10 cm. Therefore, the oblate object hypothesis does not explain the low ^{60}Co activity in the context of a one-stage irradiation.

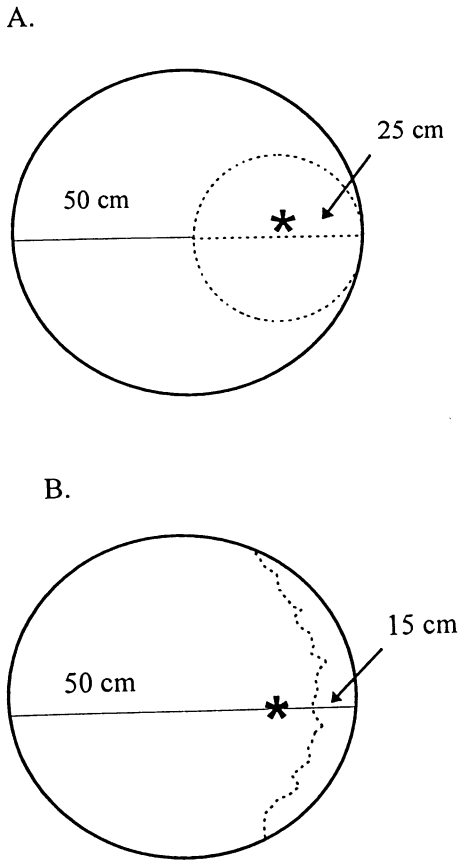

FIG. 2. Range of exposure histories that are discussed in the text: (A) A spherical meteoroid with a radius of ~50 cm undergoes a collision yielding a spherical meteoroid with a radius of ~25 cm. Proto-Peekskill (asterisk) remains at a depth of ~25 cm throughout. (B) A spherical meteoroid with a radius of ~50 cm undergoes a collision that chips off a substantial part of the surface of one hemisphere. Proto-Peekskill rises from a depth of ~25 cm to a depth of ~10 cm.

CONCLUSIONS

The Peekskill meteoroid had a complex irradiation history but the second stage was quite short. Calculations based on a two stage model satisfactorily explain most of the data. During the first stage

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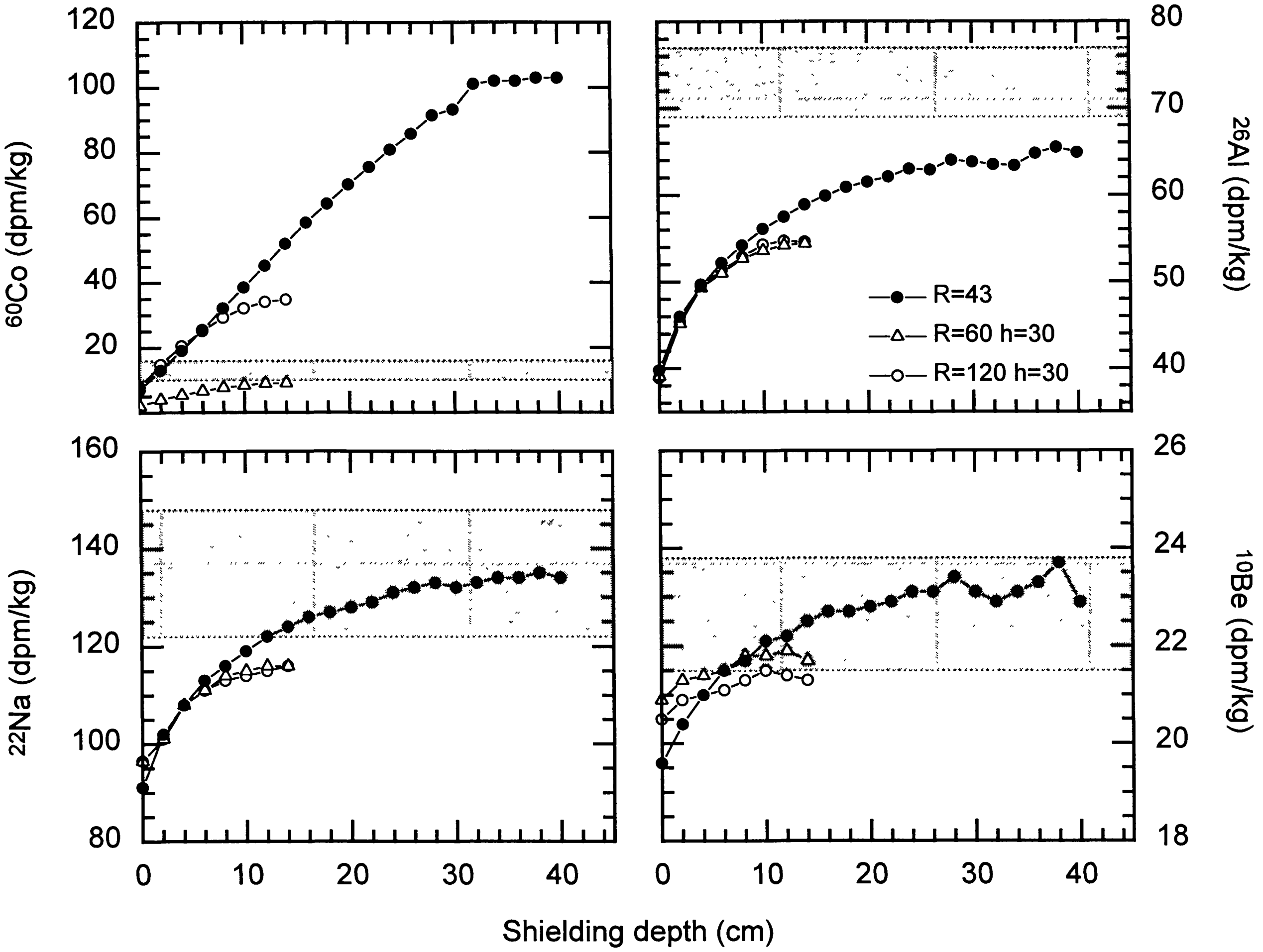

FIG. 3. Production rate depth profiles calculated for a sphere with a radius of 43 cm (1250 kg for a density of 3.7 g/cm^3) and for the central axes of two cylinders, one with a height of 30 cm and a radius of 60 cm (1250 kg) and the other with a height of 30 cm and a radius of 120 cm (5000 kg). The calculations assume average H-chondrite composition. Shaded areas indicate the range of measurements.

the radius and sample depth were 40–60 cm and 20–25 cm, respectively; during the second stage, the radius and sample depth were between 25–40 cm and >7 cm, respectively. The data constrain only weakly the duration of the second stage, which did not last long enough to raise either the ^{22}Ne/^{21}Ne ratio or the number of tracks much above the values established during the first stage. An upper limit of 0.2 Ma is estimated. Therefore, the single stage exposure age of 32 Ma is also applicable in the two-stage scenario. We infer 70 cm as a strong upper limit on the preatmospheric radius of Peekskill. This limit is somewhat smaller than the size estimated from the dynamic determinations (Brown *et al.*, 1994) but confirms the rather large size of the Peekskill meteoroid.

Peekskill's exposure age of 32 Ma falls in a peak of the H-exposure age histogram (Graf and Marti, 1995). Peekskill's two-stage history suggests that no correlation with the orbital elements of other H6 chondrites, even those produced in the same asteroidal event 32 Ma ago, should be anticipated.

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