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Cosmogenic ^{53}Mn in the main fragment of the Norton County aubrite

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Abstract—Cosmogenic ^{53}Mn was determined for the first time in an aubrite, a very Fe-poor achondrite. Six samples of the main fragment of Norton County were selected near locations where preatmospheric depths of 11–21 cm had been determined from cosmic ray tracks. The measured ^{53}Mn activities ranged from 414 to 552 dpm/kg-Fe and increased rapidly with depth. Production rates of ^{53}Mn calculated with the LAHET Code System agree with the measured activities and show that the radius of Norton County (65 cm) was near that for maximum production rates. No special irradiation conditions are needed to explain cosmogenic nuclides in Norton County.

INTRODUCTION

The Norton County aubrite, which fell on February 18, 1948, is a peculiar meteorite in several aspects. With an estimated preatmospheric mass of about 3600 kg (Bhandari et al., 1980) (the main fragment has a mass of 1070 kg), it was the largest stony meteorite known, until the fall of the Jilin chondrite in 1976. Additionally, the cosmic ray exposure age of Norton County is one of the highest observed in stony meteorites so far, although the ^{3}He/^{3}H age of 220 Ma by Begemann et al. (1957), which was the very first exposure age determined for such a meteorite, has been revised downward several times to 80–100 Ma by Herzog and Anders (1971) and Herzog et al. (1977). The ^{21}Ne production rates established by Nishiizumi et al. (1980) and Eugster (1988) lead to an age of 115 Ma, based on the noble gas measurements of Herzog et al. (1977). This age is still at the high end of the range of exposure ages for stony meteorites.

Herzog et al. (1977) investigated the ^{26}Al production rates in aubrites and found that, after correction for chemical composition, the aubrites show ^{26}Al activities that are 5–10% higher than expected at that time. As an explanation, Herzog et al. (1977) discussed unusual orbits for the aubrites where those achondrites were exposed to a higher cosmic ray flux than ordinary chondrites. That would be in accord with Eberhardt et al. (1965), who demanded such orbits to account for the very long collisional lifetimes of aubrites. Such an explanation is especially acceptable for the friable Norton County.

Until now no evidence of a multistage exposure, as in the case of Jilin (Heusser et al., 1985), has been found for Norton County, and thus, the aubrite still constitutes an ideal object to study the depth dependence of cosmic ray effects inside a large meteorite body. Here, we report the first measurements of cosmogenic ^{53}Mn ($T_{1/2}$ = 3.7 Ma) in an aubrite. Measurements were made in six documented samples from the main fragment of Norton County in order to study shielding effects and to understand cosmic ray induced spallation processes in extraterrestrial material.

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EXPERIMENTAL

Extensive studies on cosmic ray tracks (CRTs) had been performed on surface samples of the Norton County main fragment by Bhandari et al. (1980) and have established preatmospheric depths at many surface locations. The best way of investigating the depth dependence of galactic cosmic ray induced effects would be by analyzing samples from an appropriate core through the preatmospheric center of the meteorite. Because of the friable nature of the achondrite, however, such drilling might result in severely damaging the main mass, which is carefully preserved at the Institute of Meteoritics of the University of New Mexico. Therefore, only samples from the postatmospheric surface of Norton County were available for this work. Most of the samples analyzed here (Fig. 1) came from locations that are adjacent to those previously studied by CRT analysis (Bhandari et al., 1980).

A difficulty for ^{53}Mn determinations in Norton County via the neutron activation method is caused by the chemical composition of the aubrite. The abundance of Fe, which is the main target element for ^{53}Mn production by cosmic ray primary and secondary particles in space, is lower than 1%, whereas the average Mn content is 1700 ppm (Nichiporuk et al., 1967). Starting with bulk samples, the neutron activation of ^{53}Mn would be accompanied by an extremely large contribution from the interfering reaction ^{55}Mn(n, 2n)^{54}Mn, which could easily exceed 90% of the total ^{54}Mn activity induced during the thermal-neutron irradiation.

Fortunately, the occurrence of Fe in aubrites is almost entirely limited to the elemental state sometimes occurring as sizable metal flakes. It is, therefore, possible to obtain samples enriched in Fe and depleted in Mn through magnetic separation. Material containing metal flakes was handpicked from five main fragment locations. After grinding in an agate mortar, the metal-bearing phases were separated with a hand magnet. This procedure was repeated several times in order to remove most silicates. Starting with 150–550 mg of bulk material, separates of 10–85 mg enriched material (45–68% Fe) were obtained. Details on the mass and the chemical composition of the separates are given in Table 1. Furthermore, a 44 mg chip from a large metallic inclusion (K) was investigated. In this case, Mn carrier had to be added to allow for the chemical separation of ^{53}Mn from the Fe and for the determination of chemical yield.

The ^{53}Mn analysis was performed by radiochemical neutron activation. Chemical separations were basically the same as described by Englert and Herr (1978) and Englert et al. (1987); changes in preirradiation chemistry were necessary to account for the small sample amounts available. The isolated Mn samples were irradiated at a highly thermalized position of the reactor FRJ-2 at Jülich (thermal neutron flux of 4×10^{12} n cm^{-2} s^{-1}) for two months. Nevertheless, the low ^{54}Mn activity induced required counting times of up to eleven days per sample. A preliminary report on these results was made by Englert and Sarafin (1984).

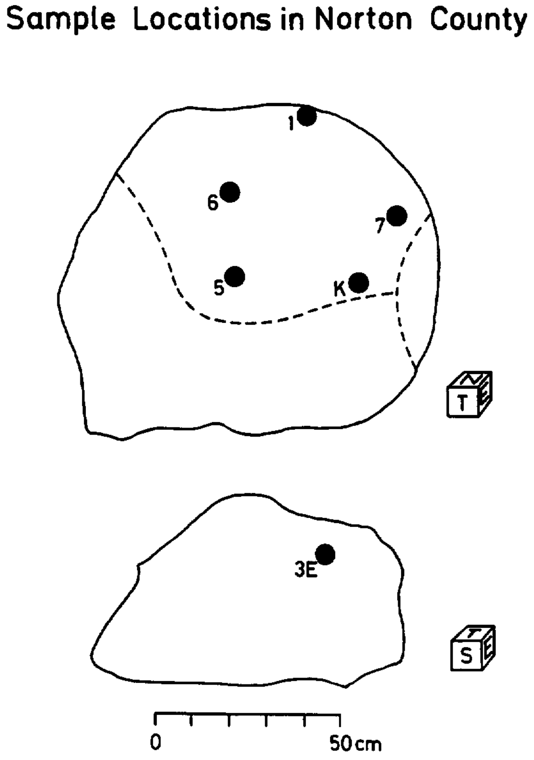

FIG. 1. Locations of the six samples from the postatmospheric surface of the Norton County main fragment that were available for this work.

RESULTS

The results of the ^{53}Mn determinations are summarized in Table 2, and represent the first such measurements in aubrites. It is obvious from the (n, $2n$)-corrections applied, which ranged from 9–37% of the total induced ^{54}Mn-activity, that the metal-phase separation was effective enough to provide samples suitable for the activation method (Englert et al., 1987). The errors given include counting statistics and (n, $2n$) corrections as well as uncertainties in determinations of chemical yields and target element concentrations. Except for sample 1, the (n, $2n$) corrections are typical of ^{53}Mn analyses in most bulk meteorite samples. The (n, $2n$) correction for sample 1 is about twice as much, and the errors reported for it, calculated with standard procedures, might be too small. Where possible, the track-density results of the CRT analyses in adjacent samples (Bhandari et al., 1980) are also given in Table 2.

In Fig. 2, our measured ^{53}Mn activities are plotted vs. the observed track density as a shielding depth indicator. As Norton County suffered irregular ablation and fragmentation, sampling of the surface of the main fragment resulted in a depth profile that extends only about a third of the way to the center. With increasing depth the ^{53}Mn activities, which represent the production rates, increase rapidly from about 410 dpm/kg Fe to more than 550 dpm/kg Fe over a distance of 10 cm. The profile seems to flatten towards the center. The Norton County ^{53}Mn production rates are high when compared to average chondritic production rates, which are about 414 dpm/kg Fe (Nishiizumi et al., 1980) or 434 dpm/kg Fe (Englert, 1979). Such high-^{53}Mn activities are unusual, but also observed for a few ordinary chondrites (Nishiizumi, 1987).

DISCUSSION

The data on preatmospheric shielding depths deserve a closer look. A crucial parameter in such studies is the expo-

Table 1. Masses and Chemical Composition of Norton County Main Fragment Samples.

Sample	Initial Mass (mg)	Magnetic Separates					
		Mass (mg)	Fe (%)	Ni (%)	Co (ppm)	Mn (ppm)	Cr (ppm)
1	392.55	9.61	53.0	4.38	2180	5300	14200
3E	339.00	85.35	67.6	6.21	2790	2740	2970
5	151.15	9.74	45.2	4.73	1580	1940	1620
6	553.85	18.43	55.9	3.90	2080	783	810
7	319.65	9.60	59.2	4.01	2260	992	1420
K	44.15		80.6	4.97	3120	3720*	10400
Av.†			0.96	0.03	5.8	1700	390

* Includes Mn carrier added to facilitate separation of ^{53}Mn.

† Average values for bulk material as given by Nichiporuk et al. (1967). The concentration ranges given are: Fe 0.43–1.36%, Ni 0.01–0.05%, Co 2.8–7.9 ppm, Mn 800–2600 ppm, and Cr 140–580 ppm.

Table 2. Activities of ^{53}Mn in Samples of the Norton County Aubrite.

Sample	^{53}Mn (dpm/kg-Fe)	$^{55}Mn(n,2n)$ Correction (%)	CR-Track Density* (cm^{-2})	Pre-Atmospheric Depth* (cm)
1	552 ± 48	37	5×10^5	16
3E	538 ± 41	20	1.02×10^5	21
5	507 ± 41	19	5×10^5	16
6	428 ± 32	9	1.78×10^6	12
7	414 ± 31	11	2.35×10^6	11
K	503 ± 22	22		

* Cosmic-ray track densities and pre-atmospheric depths are from Bhandari et al. (1980).

sure age, which is needed to derive the observed cosmic ray track production rates. As already mentioned, the exposure age determinations vary between 220 Ma and 76 Ma. Our adopted exposure age of 115 Ma is 15% higher than the one estimated by Bhandari et al. (1980). However, assuming a preatmospheric radius of 65 cm and applying the track production curves of Bhattacharya et al. (1973), the shielding depths of our samples remain unchanged.

In view of the very high exposure age, the influence of space erosion also becomes important for the discussion of CRT-derived shielding depths. Assuming erosion rates between 0.3 and 3 mm/Ma, as derived from studies of lunar rocks by Crozaz et al. (1972) and Wahlen et al. (1972), the pre-atmospheric depth of a given sample may have changed by 3.5–35 cm during the exposure time. Because of the integrating nature of CRTs, the apparent depth found today only represents a "mean" value. If the lower value for the erosion rate is correct, the difference between the track-derived depth and the shielding during the last 15 Ma of irradiation (the ^{53}Mn activity observed today has been produced during this interval) is negligible for the following discussion. On the other hand, if the higher estimate holds, large discrepancies can arise. Laboratory simulations by Schaeffer et al. (1981) indicate that stony meteorites had space erosion rates of 0.65 mm/Ma. In discussing the ^{53}Mn depth profile, it must be kept in mind that, depending on the actual rate of space erosion, the profile given may be shifted by up to 10 cm away from the center of Norton County. Note, however, that the relative distances between individual samples (positions relative to each other) are nevertheless described correctly.

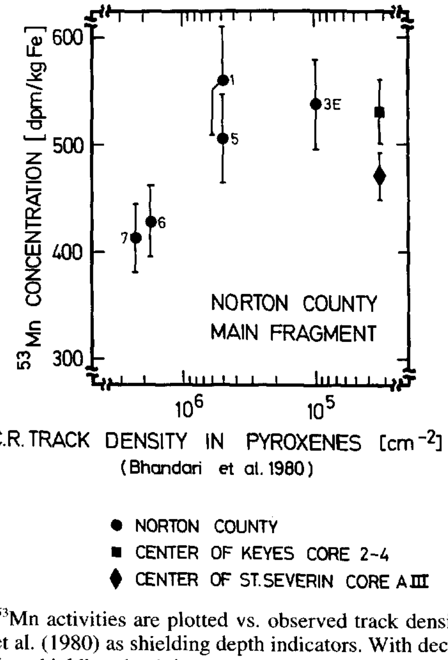

FIG. 2. ^{53}Mn activities are plotted vs. observed track densities by Bhandari et al. (1980) as shielding depth indicators. With decreasing track density, shielding depth increases. As the Norton County main fragment did not suffer uniform ablation and fragmentation, sampling of the surface resulted in a depth profile that only covers a range from 11 to 21 cm; the estimated shielding depths in (cm) are given in Table 2. The ^{53}Mn center activities of Keyes Core 2-4 and St. Severin Core AIII also are given for comparison.

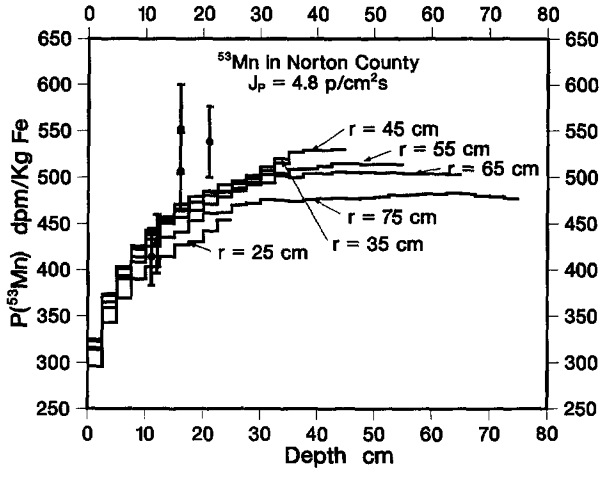

FIG. 3. For ^{53}Mn, the total LCS-calculated production rates are shown for several preatmospheric radii from 25 to 75 cm, and the measured ^{53}Mn activities are also shown.

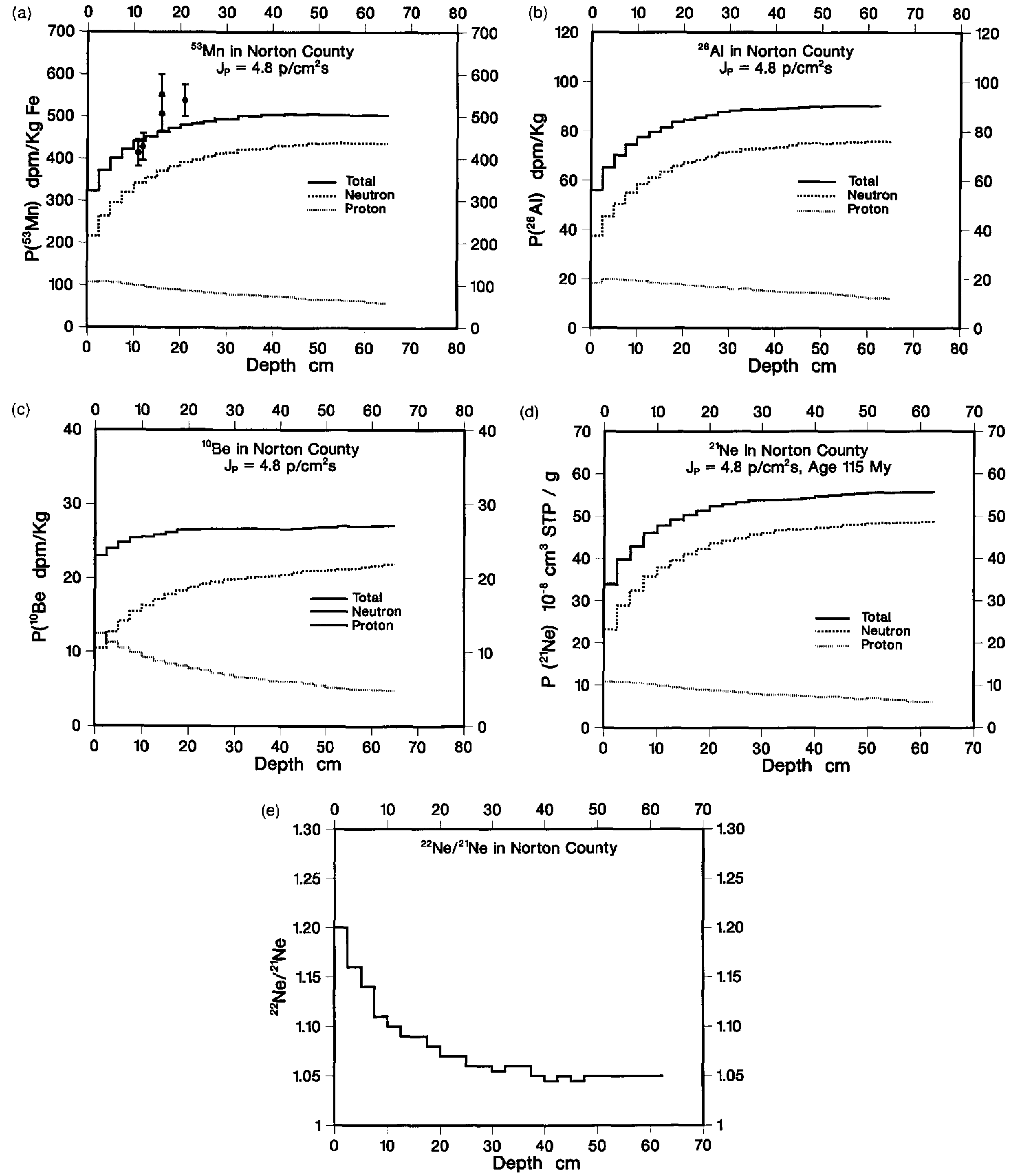

FIG. 4. (a–e) The LCS-calculated production rates of ^{53}Mn, ^{26}Al, and ^{10}Be; concentrations of ^{21}Ne for an age of 115 Ma; and the ^{22}Ne/^{21}Ne ratio are shown as a function of shielding depth for a radius of 65 cm. Production contributions by neutrons and protons are also shown for production rates and ^{21}Ne concentrations. The calculated production rates of ^{53}Mn go from 320 dpm/kg Fe near the surface and level out at 500 dpm/kg Fe at depths exceeding 40 cm and, within the limits of uncertainty, agree with most of the measured ^{53}Mn activities. Similarly good agreements are obtained for the calculated production rates and measured activities of ^{26}Al and ^{10}Be (see text).

A possible explanation for the elevated ^{26}Al reported by Herzog et al. (1977) and our relatively high ^{53}Mn activities could be the different composition of aubrites compared to other meteorite classes. Due to the depletion in Fe in aubrites, both the mean atomic number $\langle Z \rangle$ and the mean mass number $\langle A \rangle$ are considerably lower than in the case of iron meteorites or ordinary chondrites. According to Fraser and Bartholomew (1983), the multiplicity of secondary particles in spallation reactions increases with higher atomic number of target elements. On the other hand, matter having a lower $\langle A \rangle$ should better moderate secondary particles into the low-energy region effective for ^{53}Mn production from Fe nuclei. If the moderating effect of $\langle A \rangle$ dominates, the corresponding increase of low-energy nuclear active particles could lead here to a steeper rise of ^{53}Mn production with depth than expected based on studies of other meteorite types.

The bulk composition of meteorites has been shown by Masarik and Reedy (1994a) to affect production rates of cosmogenic nuclides. They calculated that ^{53}Mn production rates in objects with radii of 100 g/cm^2 are highest for Fe meteorites and the lowest for aubrites. We used the same set of Monte Carlo simulation codes, the LAHET Code System (LCS), to numerically simulate the production of ^{10}Be, ^{21}Ne, ^{22}Ne, ^{26}Al, and ^{53}Mn in spherical meteoroids with the composition of Norton County, a density of 3.2 g/cm^3, and radii of 25–75 cm. Norton County was probably fairly spherical in space based on its recovered shape and that only 69% of it was removed by ablation (Bhandari et al., 1980). Even an ellipsoidal meteoroid with one axis twice as long as the other two axes has production rates only ~5% or less different than those for a sphere (Masarik and Reedy, 1994b). The effective galactic cosmic ray flux for meteorites, 4.8 protons cm^{-2} s^{-1}, from Reedy et al. (1993) was used. The calculated production rates for ^{53}Mn are shown in Fig. 3 for these radii along with the measured ^{53}Mn activities. Details on LCS are in Masarik and Reedy (1994a). LCS has successfully calculated ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl in the 45 cm L5-chondrite Knyahinya (Reedy et al., 1993); ^{10}Be, ^{21}Ne, and ^{53}Mn in St. Severin (Masarik and Reedy, 1994b); ^{10}Be, ^{26}Al, ^{36}Cl, and ^{53}Mn in the Moon (Reedy and Masarik, 1994); and ^{53}Mn in Keyes and ALHA78084 (unpublished calculations). We estimate that the uncertainties in our calculated production rates are ~10%. A similar set of codes were used by Michel et al. (1991) and Bhandari et al. (1993) to calculated production rates of ^{53}Mn in chondrites as a function of radius and depth.

Figure 4 a–e shows the LCS calculations in a aubrite with a preatmospheric radius of 65 cm (208 g/cm^2) of the production rates for ^{10}Be, ^{26}Al, and ^{53}Mn, concentrations of ^{21}Ne for an age of 115 Ma, and the ^{22}Ne/^{21}Ne ratio as a function of shielding depth. Production contributions by neutrons and protons and measured experimental data points are also given. Production rates of ^{53}Mn go from 320 dpm/kg Fe near the surface and level out at 500 dpm/kg Fe at depths exceeding 40 cm. Within the limits of uncertainty the high production rates of ^{53}Mn in Norton County, ranging from 414 dpm/kg Fe to 552 dpm/kg Fe, are confirmed. The match is good for four out of the five ^{53}Mn data points measured at various depths, with the sample farthest from the calculations being the one with the large $(n, 2n)$ correction. Production rates calculated for ^{53}Mn in a spherical L-chondrite of the same mass were 10% higher, indicating that the production of secondary neutrons in the L chondrite with its higher $\langle Z \rangle$ relative to an aubrite dominates transport effects. A similar result for ^{53}Mn (14% higher in L-chondrites than aubrites) was reported by Masarik and Reedy (1994a,b) for meteoroids with radii of 106.5 g/cm^2.

A similar match with our calculated production rates is obtained for the range of ^{26}Al activities measured by Herzog et al. (1977), Matsuda et al. (1969), Rowe and Clark (1971), and Herpers and Englert (1983). The depths of these samples are not as well known as those for the ^{53}Mn samples. The measured ^{26}Al activities range from 72–97.6 dpm/kg, whereas the calculated values range from 56–90 dpm/kg at depths exceeding 40 cm. The only ^{10}Be measurement by Matsuda et al. (1969) of 25 dpm/kg is well within the range of calculated variation from 23 dpm/kg at the surface and 28 dpm/kg at greater depths. The calculated ^{21}Ne concentrations agree fairly well with the measured concentrations using an exposure age of 115 Ma. The LCS-calculated ^{22}Ne/^{21}Ne ratio range well covers that measured by Herzog et al. (1977), 1.086 and 1.107. It seems unlikely that Norton County had been exposed at higher than usual cosmic ray fluxes, although, within the uncertainties of the calculations, an increase in the cosmic ray flux of up to 10% may be possible. Effects of size, sample location, and chemical composition can explain the high cosmogenic nuclide production rates in Norton County.

To conclude, the observed ^{53}Mn depth profile in Norton County need not be explained by an unusual cosmic ray flux. Monte Carlo simulation calculations that well reflect the chemical composition and its effects on cosmogenic nuclide production have provided an explanation for the unusually high ^{53}Mn and ^{26}Al production rates in the Norton County aubrite, which is mainly because of its preatmospheric radius of 65 cm being near that for peak production rates. Additional depth profiles of cosmogenic products, such as ^{14}C, ^{10}Be, ^{26}Al, and ^{36}Cl, in aubrites, especially at greater preatmospheric depths, would help to strengthen the observations made on Norton County samples.

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