^{53}Mn AND COSMIC RAY TRACK PRODUCTION RATES: CONTRIBUTIONS TO EXPOSURE HISTORIES OF DJERMAIA AND LOST CITY.

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Introduction: Research on understanding effects of shielding on production of cosmogenic nuclides has come to an accepted closure for regular meteorites with the completion of multi-dimensional cosmogenic nuclide studies on meteorites such as St. Severin and Knyahinya etc. [1]. Extensive cross section measurements [2,3] and simulation experiments [4,5] accompanied by model calculations of increasing sophistication [6], have contributed to understanding factors that influence cosmogenic nuclide production in meteorites. Empirical, semi-empirical, and physical model correction relations for cosmogenic nuclides are converging and are applied successfully [7,8,9,10].

This study proposes to use two cosmic ray products, ^{53}Mn ($t_{1/2}$ = 3.7 Ma) and Cosmic Ray Tracks (CRTs), to evaluate additional aspects of depth and size studies for meteorites. Different cosmic ray interaction processes exhibiting strong depth and size sensitivity generate both products [11,12,13]. It evaluates the usefulness of a CRT vs. ^{53}Mn relation in shielding depth and size prediction and as tool for interpretation of meteorite histories.

Cosmic ray tracks, produced directly by the heavy ion component of the GCR in meteorite silicate minerals are one of the most sensitive shielding indicators [14,15]. CRT production rates [# of CRTs per cm^2 and million years] is very high at the surface and can decline by several orders of magnitude between surface and center of objects with pre-atmospheric radii exceeding a few centimeters. CRT measurements have been used to reconstruct pre-atmospheric sizes and shapes of larger meteorites [15] and in combination with other cosmic ray products, such as noble gases, have been extensively used to estimate ablation [12]. ^{53}Mn ($t_{1/2}$ = 3.7 Ma) is produced by low energy cosmic ray secondary particles from iron and nickel. Its saturation activities vary from about 250 dpm/kg at surfaces of small meteorites to about 600 dpm/kg at centers of large meteorites (about 40 cm diameter). This is supported by models [10] and by measurements in. e.g. Allan Hills A78084 and Knyahinya. A factor of about 2 between minimum and maximum ^{53}Mn production rate is suitable for comparison with CRTs.

Framework: Alexeev (2004) [16] has provided a summary discussion of cosmic ray track production rates as a function of meteorite size and depth. A comparison to ^{53}Mn production rates of Leya and Mazarik (2009) [10] is explored via the ^{53}Mn/log CRT Production Rate Ratio (^{53}Mn/log CRT PRR) as a function of meteorite depth and size. For ^{53}Mn production the whole range of data is considered. CRT production rates of less than 1 track cm^{-2} Ma^{-1} are not considered. Figure 1 shows the ^{53}Mn/log CRT PRR for shielding depths of up to 50 cm.

For meteorites with radii of up to 20 cm the ^{53}Mn/log CRT PRR provides information on depth and size. This is also valid for meteorites with radii between 20 to 40 cm and a shielding depth exceeding 10 cm and meteorites with radii up to 50 cm and a shielding depth exceeding 15 cm. For radii exceeding 50 cm the depth and size information of the ratio is dominated by the cosmic ray track production rate.

For the majority of practical applications, meteorite radii from ~5 cm to ~60 cm are of interest, the upper limit set by Knyahinya [17] and Norton County [18], not including the unique Almahata Sitta fall [19]. Data of model meteorite drill cores and surface samples with different shielding depths are available for ALH 78084, St. Severin, Keyes, Knyahinya, and Norton County. These data establish a practical framework of ^{53}Mn and CRT production rates for applications. Meteorite data of Lost City and Djermaia are interpreted in this framework.

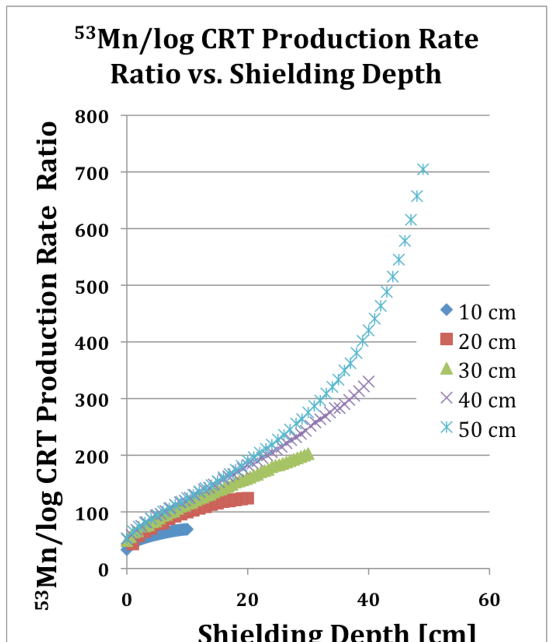


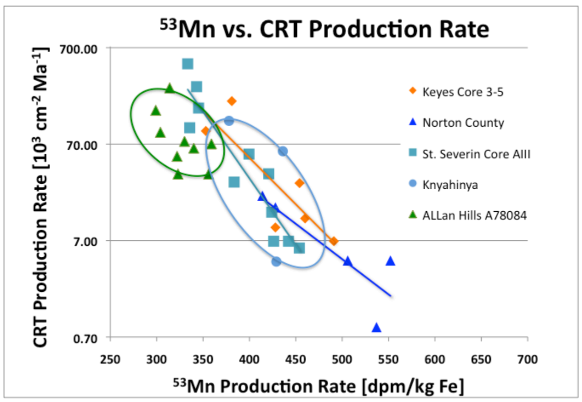
Figure 1: Comparison of ^{53}Mn and Cosmic Ray Track production rates to shielding depth [10,16].

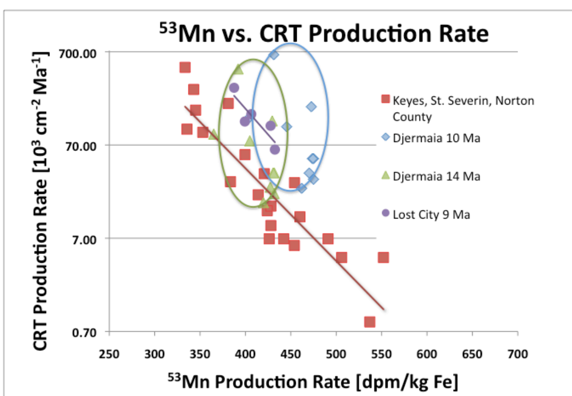
Exposure Ages: Reliable production rates particularly of CRTs depend on evaluated cosmic ray exposure (CRE) ages. CRE ages for model meteorites St. Severin, Keyes, Knyahinya, Norton County, and Allan Hills A78084 are 14.9±0.9 Ma, 26.1±0.7 Ma, 35.4±1.3 Ma, 115±6 Ma), and 32.1±1.0 Ma, respectively [e.g.10]. ^{21}Ne derived CRE ages are preferred. The exposure history of the H-chondritic breccia Djermaia is complex as described by Lorin and Pellas (1977) [20], Schultz and Signer (1977) [21], and Lorin and Pellas (1979) [22]. Schultz and Signer (1977) report a last stage CRE age of 14.2±0.3 Ma based on ^{3}He of the matrix and the spallogenic component of ^{3}He, ^{21}Ne, and ^{38}Ar of four light clasts. Lorin and Pellas (1979) [22] derive a probable CRE age of 10±2 Ma. Many exposure ages have been derived for Lost City. Although CRE age variation is very high, shielding corrected ^{21}Ne exposure ages cluster well around 9 million years. Radionuclide derived CRE ages range from 6.1 to 10.1 million years. For this study an exposure age of 9.1±1.1 Ma will be used.

Discussion: ^{53}Mn and CRT production rates for model meteorites show a unique relationship over a wide range of shielding depths; see Figure 2a.

Figure 2a

Figure 2b





Exponential trend lines are given for St. Severin (R^2=0.88), Keyes (R^2=0.72), and Norton County (R^2=0.72). For Knyahinya and Allan Hills A78084 (exponential trend line $R^2 \leq 0.32$) visually fit ellipsoids describe the data area. Data for St. Severin Core AIII and Keyes Core 3-5 overlap, yet the center of Keyes is more shielded. Allan Hills A78084 shows the behavior of a pre-atmospherically small body. Knyahinya and Norton County show the largest shielding depths. The model meteorites define an empirical ^{53}Mn- CRT production rate relation; see Figure 2b. An exponential trend line is constructed from Keyes, St. Severin, and Norton County (R^2=0.81). Including Knyahinya and Allan Hills A78084 results in a lower correlation coefficient. For the assumed exposure age of 9.0±1.1 Ma, the Lost City exponential trend line (R^2=0.78) is close to St. Severin and Keyes exhibiting almost the same slope. The data spread may indicate a small pre-atmospheric body, but is not in agreement with the Allan Hills A78084 data set. Inversely, the data indicate that a CRE age of 9.0±1.1 Ma is a plausible estimate. This is important for the Djermaia data set. Based on an exposure age of 10 Ma [21] almost all Djermaia data points fall outside of the model meteorite range (Fig. 2b). Applying the exposure age of Schultz and Signer (1977) [20] the majority of the data points (exceptions: NMNH 2424, L2-L4; NMNH 2433, L2-D2) fall within the model meteorite range. A 14.2±0.3 Ma first stage exposure age [21] of the complex irradiation history of Djermaia is therefore supported by this study. Other meteorites will be included in this study. Statistical analysis of the data including uncertainties is underway. Uncertainties of NAA determined ^{53}Mn data influence the information content of ^{53}Mn-CRT relationships. Application of Accelerator Mass Spectrometry (AMS) to ^{53}Mn may make the ^{53}Mn-CRT relationship a very useful tool for depth and size analysis of meteorites.

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