A REGOLITH PRE-EXPOSURE SIGNATURE IN FOSSIL MICROMETEORITES FROM AN ASTEROID COLLISION 470 MILLION YEARS AGO

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Introduction: More than 80 fossil meteorites have been found in a ~4 m quarry layer of mid-Ordovician limestone in Sweden [1, 2]. Their cosmic-ray exposure (CRE) ages correlate inversely with sediment deposition age and indicate very rapid (<1.2 Myrs) transport from the asteroid belt [3]. The same layer contains up to 3 sediment-dispersed, extraterrestrial chromite (SEC) grains (>63 μm) per kg of sediment, around two orders of magnitude more than sediments immediately below the meteorite-rich strata [2]. Both fossil meteorite chromite and SEC have L chondritic composition in major elements [2] and oxygen isotope ratios [4, 5]. They have both been linked to the L chondrite parent body break-up event ~470 Myr ago [6]. Since the highly resistant SEC kept their extraterrestrial noble gas inventory, and since SEC are much more abundant than fossil meteorites (which are mere chance finds), SEC offer the potential to study the Ordovician asteroid collision and its terrestrial effects on a broader basis. SEC could become a tracer for as yet unknown showers of meteoritic material, even when no fossil meteorites are found. Batches of SEC [7] and individual grains [8] all contained He and Ne of solar composition. As only 3% of the L chondrites falling to Earth today are solar-wind bearing regolith breccias [9], finding solar wind in almost every SEC grain analyzed implies that they are fossil micrometeorites. While the fossil meteorites are delivered by orbital resonances in the asteroid belt [3], the SEC micrometeorites are additionally affected by Poynting-Robertson drag, limiting the maximum transfer time to Earth to about 1.2 Myrs for a 200 μm particle.

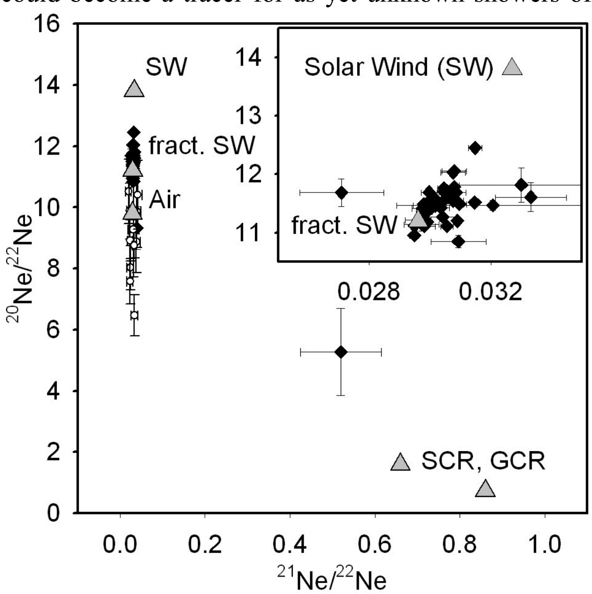

Figure 1: Ne three isotope plot: Measured values (diamonds for SEC, open circles for terrestrial chromite) and Ne components (triangles). One grain shows a very large ^{21}Ne excess relative to solar composition. Many other grains show a resolvable excess, while only one grains plots to the left of the line connecting the solar components, which can be explained by analytical uncertainty. Errors are 1-σ and include analytical uncertainities. The extremely gas-poor terrestrial grains show neither solar gases nor any significant excesses of ^{21}Ne. The large scatter of the data points for terrestrial grains indicates that we may underestimate the error for very small (< 2 * 10^{-16} cm^3 STP) gas amounts.

Samples and Methods: Here we extend our earlier investigation by 21 new SEC grains (five from the lowermost "Arkeologen" bed containing the oldest fossil meteorites with CRE ages of ~0.05 to 0.20 Myrs [7]; one from "Golvsten" (~0.30 Myrs) and 15 from lower "Sextummen". We also include earlier data from 16 grains from the upper and middle "Sextummen" beds [8]. The fossil meteorites from "Sextummen" have CRE ages of ~0.4 Myrs [7]. In addition to the SEC grains, 11 terrestrial chromite grains from "Sextummen" and "Arkeologen" where analyzed, to control for a possible contribution of nucleogenic ^{21}Ne, induced by α-particles either produced in the grains themselves or recoiled from the surrounding sediment. The grains (63 to ~180 μm diameter, 0.3 – 13.7 μg) were analyzed in a low-blank extraction line and an ultra-high-sensitivity mass spectrometer [10]. Ne was frozen at 12.7 K, and then measured separately from He. Detection limit for ^{21}Ne was ~4 x 10^{-16} cm^3 STP, and ~2 x 10^{-16} for ^3He. Grain mass is accurate to ~10-20% in most cases. Cosmic-ray production rates for ^{21}Ne are based on [7].

Results and Discussion: At least 35 of the 37 grains contained Ne and He of solar wind composition. In Fig. 1, almost all data points fall near a line connecting the unfractionated SW component ($^{20}Ne/^{22}Ne$ = 13.8, $^{21}Ne/^{22}Ne$ = 0.0327) with the "fractionated SW" (former "SEP" component, $^{20}Ne/^{22}Ne$ = 11.2, $^{21}Ne/^{22}Ne$ = 0.0296). Essentially all grains show a solar $^3He/^4He$ ratio of ~(2-3) * 10^{-4}. As discussed in [8], this demonstrates that the SEC are fossil micrometeorites. The one grain from "Golvsten" is solar-gas free and thus may be the only SEC grain found so far from a larger, dissolved fossil meteorite. However, assuming GCR irradiation only (see below), its age of 1.04 ± 0.25 Myrs would not agree with the age of "Golvsten" fossil meteorites [3, 7]. Considering 1-σ (2-σ) errors, 21 (12) of the grains plot significantly to the right of the tie-line defining solar composition, indicating a cosmogenic ^{21}Ne excess (Fig. 1). A CRE age (Fig. 2) can be calculated for these grains. In the 11 terrestrial grains analyzed, no comparable ^{21}Ne-excesses are observed, demonstrating negligible nucleogenic or terrestrially acquired cosmogenic ^{21}Ne. As micrometeorites, the extraterrestrial grains have been exposed to two different kinds of high-energy radiation: galactic cosmic rays (GCR) with a penetration depth of 1-2 m and comparatively low production rates, and solar cosmic rays (SCR) with a penetration depth of a few mm and high production rates. Radial dependance of SCR production is ill constrained. We adopted SCR production rates from [11], adjusted for a R^{-2} dependence and an average heliocentric distance of 1.5 AU. Ne-21 ages of SEC have higher uncertainities than those of fossil meteorites, because cosmogenic Ne amounts are very small, compared to the solar component. Solar He prohibits the derivation of ^{3}He ages. For 75% of the SEC grains, the ^{21}Ne ages, within error, roughly agree with the ages of the fossil meteorites from the same sediment bed, suggesting that these grains have been exposed to cosmic radiation only during their relatively short (0.4 - 0.6 Myrs) transfer from the asteroid belt. 25% of the SEC grains, on the other hand, show CRE ages of 10 to 50 Myrs. These ages can not be due to a severely underestimated SCR production rate, because we would then expect high ages in all of the grains. We therefore propose that this grain population has been pre-exposed to cosmic radiation in the thick regolith of the pre-breakup L chondrite parent body. From the number of SEC grains with large exposure ages found in the Ordovician sediment layer, the total mass of the precursor regolith can be calculated. Assuming a parent body diameter of ~200 km [12], this mass can be contained in a regolith layer of 600 m thickness, contributing 7% to the total mass of the asteroid. This is in reasonable agreement with 25% of the grains having long exposure ages. If a regolith of this size is well mixed, typical residence time of a grain in the topmost 2 m exposed to cosmic radiation is a few 10 Myrs over 4.1 Gyrs, again in agreement with the observations.

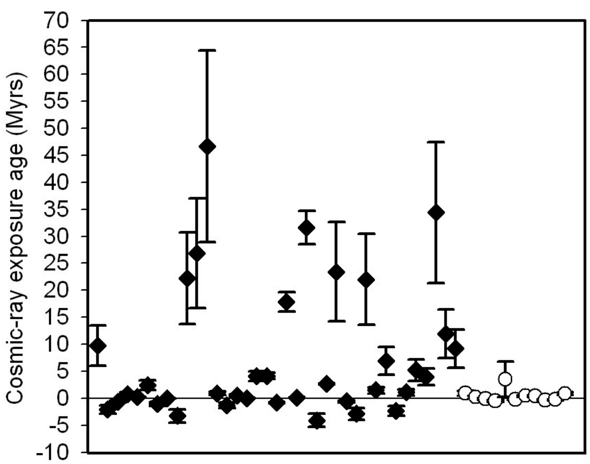

Figure 2: CRE ages for all 37 SEC grains (diamond symbols; based on GCR production rates plus SCR production rates added for a typical PR transfer time of 0.4 Myrs) and the 11 terrestrial grains (open circles; age based on GCR production rates). The age range of fossil meteorites from the "Sextummen" and "Arkeologen" sediment beds is 0.05 to 0.42 Myrs [7]. Grains with negative ages in this figure are probably overcorrected, i.e. were exposed to SCR radiation for less than 0.4 Myrs (e.g., were produced in secondary collisions and then delivered by the faster way of orbital resonances rather than by PR drag). Errors are 1–σ and include analytical and mass errors.

A similar pattern (25% of grains having high exposure ages) has been observed in recent micrometeorites from Greenland [13] and Antarctica [14], as well as in IDPs [15]. A cometary origin has been proposed in these cases, as Poynting-Robertson-drag requires a few 10 Myrs to deliver particles from the Kuiper belt to Earth. But in our case, this explanation is not viable, since the SEC grains and the fossil meteorites unequivocally have an asteroidal origin. This strongly suggests that also the purported cometary origin of recent IDPs and micrometeorites needs to be revisited.

Conclusion: At least 35 of 37 sediment-dispersed chromite grains from the L-chondrite parent-asteroid break-up event found in Ordovician limestone contain He and Ne from the SW, implying that these grains were once micrometeorites. Neon-21-derived cosmic-ray exposure ages of 10-50 Myrs observed in ~25% of the grains indicate that about a quarter of the grains had been pre-exposed in the regolith of the parent body prior to the break-up. A similar data pattern observed by others in recent micrometeorites and IDPs thus suggests that these particles may as well have been pre-exposed, requiring to revisit their putative cometary origin.

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