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Quantifying the Nugget Effect: Reproducibility of Extraterrestrial ^{3}He as a Function of Area–Time Product

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Extraterrestrial ^{3}He ($^{3}He_{ET}$) in marine sediments is a powerful proxy for interplanetary dust flux and has been widely used to reconstruct sediment mass accumulation rates (MARs) and paleoenvironmental change. However, replicate analyses of the same sediment sample exhibit large variability, far exceeding analytical uncertainty, due to the stochastic distribution of rare, high-^{3}He interplanetary dust particles (IDPs), the so-called "nugget effect." The dominant control on this variability is the Area–Time Product (ATP), defined as the sediment mass analyzed divided by the local mass accumulation rate. ATP controls the effective accumulation window sampled and thus the expected number of IDPs per measured aliquot. Here, we evaluate $^{3}He_{ET}$ reproducibility across a controlled range of ATPs using extensive replicate analyses of homogenized marine sediments from two contrasting equatorial Pacific settings: (1) a high-carbonate, high-MAR site at 1°N and (2) a low-MAR red clay site at 11°N. To assess long-term preservation effects, we also perform replicate analyses on an ~80 Ma marine sediment from Apiro, Italy. By measuring identical material repeatedly at varying ATPs, we isolate the statistical behavior of IDP sampling and test how sedimentological parameters (carbonate content, MAR, and age) influence replicate variability at constant ATP. Preliminary results indicate that replicate variability at low ATPs is substantial. The mean fractional difference (FD) is 36% and the median FD is 27%, reflecting a strongly heavy-tailed distribution. Approximately 12% of measured aliquots exceed the mean by ~40%, and 6% exceed it by more than 80%. In contrast, terrigenous ^{4}He shows lower variability, with a mean FD of ~20% and a median FD of ~15%. These results provide the first empirical constraints on the magnitude and frequency of the nugget effect as a function of ATP. By improving the statistical rigor of ^{3}He measurements, this work strengthens the interpretative framework for the $^{3}He_{ET}$ proxy.