Angrite Lu-Hf whole rock data provide no direct support to accelerated decay of ^{176}Lu by supernova irradiation.

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Introduction: Radioactive decay of ^{176}Lu to ^{176}Hf with a half-life of 37 Ga is a powerful isotopic tracer for studying the evolution of the Earth and other planets. The decay rate of ^{176}Lu is well known from the studies of terrestrial rocks and minerals [1, 2], and meteorites that formed more than 10 million years after the beginning of the Solar System accretion [3]. However, the excess of ^{176}Hf correlated with Lu/Hf ratios, observed in older meteorites, was interpreted as evidence for a gamma-ray [4] or neutrino or cosmic ray [5] irradiation event of enormous magnitude that occurred during or shortly after accretion and caused accelerated decay of ^{176}Lu by converting a fraction of nuclei to the faster decaying nuclear isomer ^{176m}Lu. Since potential sources of radiation within the Solar System are not powerful enough, it was suggested that a supernova event took place in close proximity to the nascent accreting Solar System. Such an event would have had a profound impact on the composition and structure of the Solar System. Considering the possibility that previously determined meteorite ^{176}Lu-^{176}Hf isochrons could have been affected by disturbance of the isotopic systems, we have sought a more reliable confirmation for accelerated decay of ^{176}Lu using the ^{176}Lu-^{176}Hf isotope systematics of angrites – the oldest and best preserved igneous meteorites.

Methods: Whole rock samples of two quenched angrites (D'Orbigny and Sahara 99555), three plutonic angrites (NWA 2999, NWA 4590 and NWA 4801), two eucrites (Camel Donga and Ibitira) and Allende CAI SJ101 were dissolved without acid leaching and processed for ^{238}U/^{235}U, Lu-Hf and Sm-Nd isotopes (Sm-Nd work is in progress). The U-isotopic data are reported by [6]. The Lu/Hf ratios were measured in 10-15% aliquots of dissolved samples using a ^{176}Lu-^{180}Hf mixed tracer calibrated against the mixed Lu-Hf reference solutions prepared in Toronto [7], Copenhagen [8], Davis [9] and Ottawa (unpublished data of the first author) of high purity Ames metals dissolved together. All four reference solutions yielded coherent spike calibrations, providing analytical consistency with the published data. Chemical separation procedure is modified from [10]. Isotope analyses of spiked aliquots were performed at the ANU using MC-ICPMS for Hf and TIMS for Lu. Hf isotope compositions were measured on unspiked aliquots at UC Davis using a *Neptune Plus* MC-ICP-MS with the high sensitivity Jet interface. The ^{176}Hf/^{177}Hf values are reported relative to 0.282160 for the JMC-475 standard. The average values of the ^{178}Hf/^{177}Hf ratio, used for analysis quality monitoring, were 1.467235 ± 0.000031 for meteorites and 1.467218 ± 0.000025 for terrestrial standard rocks (errors are 2 SD).

Results: Lu-Hf isochron regression for all five angrites yields a slope of 0.08918 ± 0.0010, MSWD = 0.83, which corresponds to an age of 4576 ± 49 Ma using the decay constant of ^{176}Lu of 1.867×10^{-11} a^{-1} [2]. Substantial spread in ^{176}Lu/^{177}Hf ratios between 0.015 and 0.052 among angrites helps to precisely constrain the isochron slope.

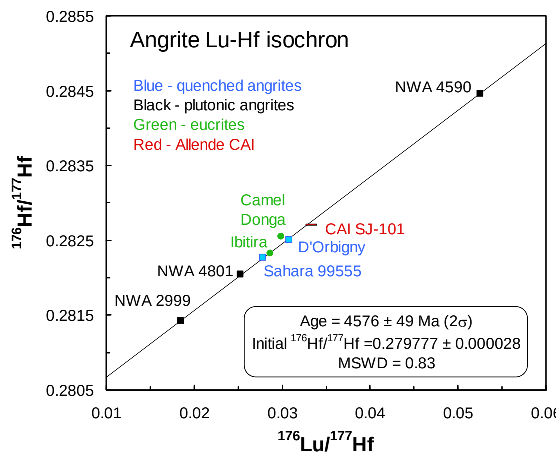

Fig. 1. Lu-Hf isochron for angrites and selected other meteoritic materials. Error bar for the CAI SJ-101 is 2σ, error bars of other data points are smaller than the plotting symbols. The data for the eucrites and the CAI are not included in the regression.

The data points of the eucrite Ibitira of non-HED origin [11] and Allende CAI SJ-101 also plot on the angrite isochron, but the point of Camel Donga, a basaltic eucrite belonging to the HED group of achondrites, plots distinctly above the isochron.

Discussion: The angrite Lu-Hf isochron yields an age very close to the range of Pb-isotopic ages between 4567 and 4557 Ma for the angrites, Ibitira, and CAI SJ-101. In other words, it does not show an excess slope that can be attributed to accelerated decay of ^{176}Lu. Significance of this isochron, however, depends on the nature of the event(s) that caused variations in Lu/Hf among the angrites. If these variations were produced by early magmatic differentiation in the angrite parent body, then it pre-dated crystallization of all angrites, including the two quenched angrites that formed 3-4 million years after the beginning of accretion [12, 13]. In this case, the absence of the excess slope can be taken as an evidence that there was no massive irradiation event in the nascent Solar System. It is also possible that the Lu/Hf fractionation is caused mainly by crystal fractionation during formation of plutonic angrites, in which case it could have post-dated the irradiation event. Much greater spread of the Lu/Hf ratio in the plutonic angrites compared to quenched angrites (similar to the greater spread of Lu/Hf in cumulate eucrites compared to basaltic eucrites [14]) is consistent with the latter possibility, but does not rule out early fractionation.

Assuming that the data presented here and in [5] are both analytically consistent and represent undisturbed geochemical systems (as can be expected from generally good preservation of other isotopic systems in angrites), we can seek interpretation that would explain both of these data sets as shown in Fig. 2:

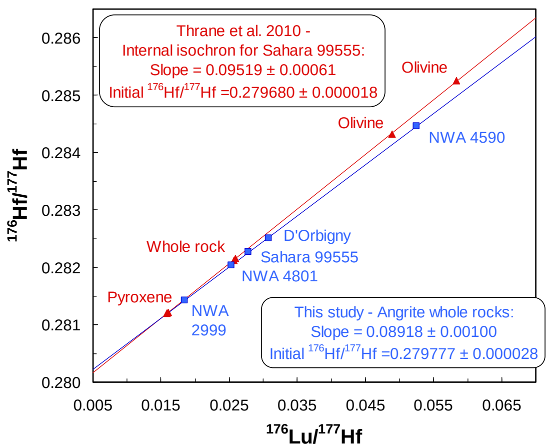

Fig. 2. Lu-Hf isochrons for angrite whole rocks (this study, blue symbols) and internal isochron for the quenched angrite Sahara 99555 ([5], red symbols).

Irradiation with gamma-rays [4] or cosmic rays [5] can indeed explain the difference in the isochron slopes, if irradiation took place after accretion of the angrite parent body and crystallization of quenched angrites, but before crystallization of plutonic angrites that have widely variable Lu/Hf ratios and largely control the slope of our isochron. Considering that mineralogy of plutonic angrites requires crystallization within the parent body at a considerable depth [15, 16] sufficient to shield the rocks from penetration of cosmic rays up to 10-20 m [5], or much shallower penetration of gamma-rays [4], we can expect that plutonic angrites have escaped irradiation that accelerated decay of ^{176}Lu. In this case, the isochrons with and without excess slope are expected to yield identical y-intercepts, i.e. initial ^{176}Hf/^{177}Hf ratios, as shown in Fig.1 of [5]. This is not the case with the data shown in our Fig. 2. The intersecting isochrons with different y-intercepts would be observed if irradiation was pervasive and uniform irrespective of the depth, as would be the case if accelerated decay was induced by neutrinos. The possibility of ^{176}Lu decay acceleration by neutrino irradiation was ruled out by [5] on the basis of insufficient (by several orders of magnitude) neutrino fluence, but the required fluence estimate may change if other mechanisms of producing excited ^{176}Lu nuclei by neutrinos are considered, such as the Gamow-Teller transition $\nu_e + {}^{176}\mathrm{Yb} \rightarrow e^- + {}^{176m}\mathrm{Lu}^*$ [17] that was proposed for use in detectors for low-energy neutrinos. Alternatively, our starting assumptions of analytical consistency between the two laboratories and closed geochemical systems may be invalid.

An unambiguous answer about the existence of the accelerated ^{176}Lu decay event and the nature of radiation can be obtained if reliable internal isochrons for both a quenched angrite and a plutonic angrite are constructed and compared, and the Lu isotopic composition in these materials is measured. In the case of accelerated decay of ^{176}Lu by cosmic ray or gamma-ray irradiation, the isochrons would have different slopes but identical y-intercepts, and quenched angrites would have ^{176}Lu deficit matching ^{176}Hf excess, compared to the plutonic angrites. In the case of accelerated decay of ^{176}Lu by neutrino irradiation, the isochrons would have different slopes and different intercepts, and the ^{176}Lu/^{175}Lu ratio would be uniform. Other patterns would be suggesting an open geochemical system behavior, such as leakage of radiogenic ^{176}Hf from Lu-rich phosphate minerals.

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