INTERNAL Lu-Hf ISOCHRONS FOR THE QUENCHED AND PLUTONIC ANGRITES AND THEIR CHRONOLOGICAL IMPLICATIONS.

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Introduction: Numerous long- and short-lived radiogenic isotope systems (e.g., Pb-Pb, Sm-Nd, Rb-Sr, Al-Mg, Mn-Cr, and Hf-W) have thus far been investigated in the angrites to better understand the chronology and differentiation history of the angrite parent body (APB). However, there have been only limited studies of the Lu-Hf systematics in this unique group of ancient achondrites. A recently reported internal ^{176}Lu-^{176}Hf isochron for the fine-grained (quenched) angrite Sahara 99555 yielded an age of 4874±48 Ma [1]. Subsequently, to account for this implausibly old age, a model was proposed for producing excess ^{176}Hf via the formation a short-lived ^{176}Lu isomer by cosmic ray irradiation [2]. Another recent study, however, reported a whole-rock ^{176}Lu-^{176}Hf age of 4576±49 Ma for the angrites [3]. To address the question of whether there was excess ^{176}Hf produced in crustal rocks on the APB due to intense irradiation in the early Solar System, internal Lu-Hf isochrons were determined for additional fine- (quenched) and coarse-grained (plutonic) angrites. Here we report the initial results of our investigation of the ^{176}Lu-^{176}Hf systematics in whole-rock fractions and mineral separates of the D'Orbigny quenched angrite, and the NWA 4590 and NWA 4801 plutonic angrites.

Analytical Methods: Interior chips of D'Orbigny, NWA 4590, and NWA 4801 (~1 g each) were processed under clean laboratory conditions in the Isotope Cosmochemistry and Geochronology Laboratory at Arizona State University to obtain whole-rock fractions and mineral separates. A small fragment (~60 mg; WR) was broken from each interior chip and was processed as a whole-rock sample for each meteorite. The remaining material from each interior chip was then crushed and sieved. The finest-grain fraction (<53 μm; F) was reserved for analysis. Pyroxene (PX), olivine (OL), and plagioclase (PL) separates were then prepared from the 75-150 μm size fraction using a Frantz magnetic separator. These separates were then further purified by handpicking. In the case of D'Orbigny, we similarly processed another interior chip (~300 mg) to obtain an additional whole-rock fraction (~50 mg; WR2) and a pyroxene (PX2) mineral separate.

Sample dissolution and column chemistry were performed at the Carnegie Institution of Washington (CIW). The mineral separates (pyroxene, plagioclase, olivine), finest-grain fraction, and whole-rock sample for each meteorite were digested using a 2:1 HF-HNO$_3$ mixture in a Parr digestion vessel at 150°C in an oven overnight (with the exception of the D'Orbigny WR2 and PX2 fractions that were digested by heating at 95°C on a hotplate overnight). Each sample was spiked before dissolution for Lu and Hf concentration measurements. All isotopic analyses were made on the Nu Instruments multicollector inductively coupled plasma mass spectrometer at CIW. The ^{176}Hf/^{177}Hf isotopic ratios of each sample are reported relative to the JMC 475 standard (^{176}Hf/^{177}Hf = 0.282160).

Results and Discussion: In the case of the D'Orbigny quenched angrite, the pyroxene and olivine mineral separates, the finest-grained fraction, and the two whole-rock fractions fall along a single ^{176}Lu-^{176}Hf isochron (Fig. 1); the plagioclase separate does not fall on this isochron. A regression through all of the D'Orbigny data with the exception of plagioclase yields a slope of 0.08810±0.0020, with an initial ^{176}Hf/^{177}Hf ratio of 0.279775±0.000043 (2SD). The slope of this regression line corresponds to an age of 4520±97 Ma (using the ^{176}Lu decay constant of 1.867x10^{-11}yr^{-1} [4,5]).

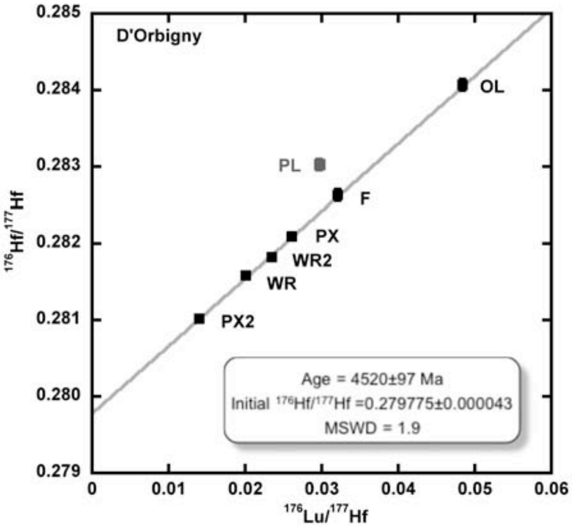

Figure 1. Lu-Hf internal isochron for D'Orbigny; the regression line is drawn through all the data points except plagioclase (gray symbol). Error bars in this and following figures are 2SD (with some error bars being smaller than the data points).

For the NWA 4590 plutonic angrite, the pyroxene and olivine separates, the finest-grained fraction and the whole-rock fraction define a ^{176}Lu-^{176}Hf isochron (Fig. 2); the plagioclase separate falls off this isochron. These data points span an exceptionally wide range of ^{176}Lu/^{177}Hf ratios (from 0.012 to 0.483). The regression line through all the data points with the exception of plagioclase yields a slope of 0.08704±0.00048 corresponding to an age of 4470±23 Ma, and an initial ^{176}Hf/^{177}Hf ratio of 0.279939±0.000036 (2SD).

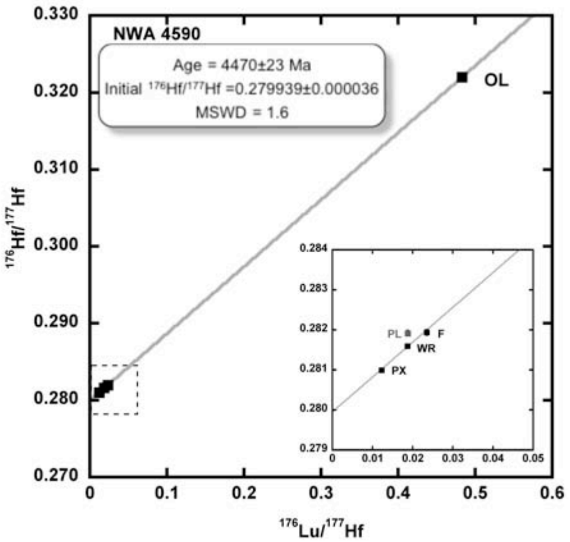

Figure 2. Lu-Hf internal isochron for NWA 4590. The regression line is drawn through all the data points except plagioclase (gray symbol).

Just as for NWA 4590, the pyroxene and olivine separates, the finest-grained fraction and the whole-rock fraction of the plutonic angrite NWA 4801 also define a ^{176}Lu-^{176}Hf isochron, while the plagioclase separate falls off this isochron (Fig. 3). The slope of the regression line through all the data except plagioclase is 0.08916±0.0010, corresponding to an age of 4575±50 Ma, and an initial ^{176}Hf/^{177}Hf ratio of 0.279768±0.000046 (2SD).

The Lu-Hf ages obtained here for D'Orbigny and NWA 4801 are concordant with their previously reported Pb-Pb [6,7] and ^{147}Sm-^{143}Nd [8] ages. Furthermore, the Lu-Hf internal isochrons for these two angrites yield initial ^{176}Hf/^{177}Hf ratios that agree, within the errors; the average value currently provides the best estimate of the initial ^{176}Hf/^{177}Hf ratio for the APB (i.e., 0.279772±0.000045).

Cooling rate estimates suggest the crystallization of D'Orbigny at shallow depth on the APB (i.e., <0.5 m burial depth) [9]. Furthermore, Pb-Pb ages of D'Orbigny and Sahara 99555 indicate that these quenched angrites crystallized contemporaneously [6,7]. If the accelerated decay of ^{176}Lu due to cosmic ray irradiation caused excess ^{176}Hf in Sahara 99555, this would also be expected for D'Orbigny. However, the Lu-Hf data reported here for D'Orbigny do not yield an implausibly old age as for Sahara 99555 [1] and, therefore, do not require such a scenario. The similar initial ^{176}Hf/^{177}Hf ratios of the D'Orbigny and NWA 4801 isochrons also do not support an enhanced production through irradiation of ^{176}Hf in the quenched angrites (i.e., near-surface crustal rocks on the APB) compared to the plutonic angrites (i.e., deeper crustal rocks on the APB).

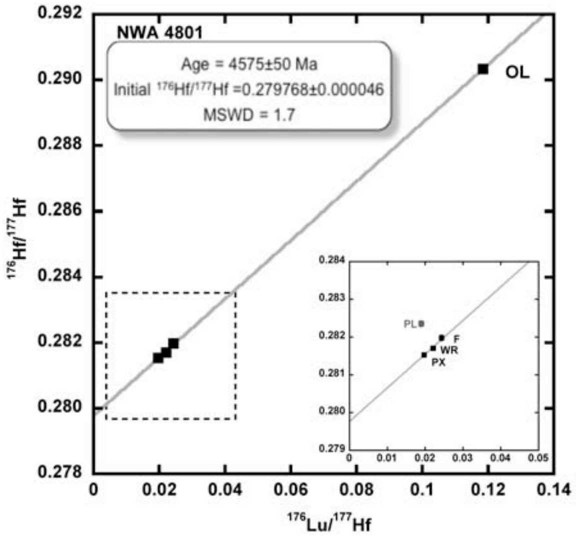

Figure 3. Lu-Hf internal isochron of NWA 4801. Sample labels are identical those in Fig. 1.

The Lu-Hf internal isochron for the NWA 4590 plutonic angrite yields an age that is somewhat younger than its Pb-Pb [7] or ^{147}Sm-^{143}Nd [8] age, with a higher initial ^{176}Hf/^{177}Hf ratio than that determined for D'Orbigny and NWA 4801. Furthermore, none of the fractions analyzed in NWA 4590 (PX, WR, F, and OL) fall on the isochrons defined by D'Orbigny and NWA 4801 (which are essentially coincident within the errors). These observations suggest a significant disturbance of the Lu-Hf systematics among all the phases in NWA 4590 after the initial closure of the isotopic system.

References: [1] Thrane K. et al. (2006) *69th Meteoritical Society Meeting*, Abstract #5340. [2] Thrane K. et al. (2010) *The Astrophysical Journal, 717*, 861-867. [3] Amelin Y. et al. (2011) *Workshop on Formation of First Solids in the Solar System*, Abstract #9014. [4] Söderlund et al. (2004) *EPSL, 219*, 311-324. [5] Amelin Y. (2005) *Science*, *310*, 839-841. [6] Amelin Y. (2008), *GCA, 72,* 221-232. [7] Amelin Y. and Irving A. J. (2007) *Workshop on Chronology of Meteorites*, Abstract #4061. [8] Sanborn et al. (2011), *LPS XLII*, Abstract #2369. [9] Mikouchi et al. (2001) *MAPS, 36*, A134-A135.