THE CHRONOLOGY OF EARLY ASTEROID PROCESSES. L. E. Nyquist[1], T. Kleine[2], C.-Y. Shih[3], N. Kita[4], A. Yamaguchi[5], Y. D. Reese[6], [1]Mail Code KR, NASA Johnson Space Center, Houston, TX 77058-3696, USA, laurence.e.nyquist@nasa. gov, [2]Inst. Isotope Geochemistry and Mineral Resources, ETH Zurich, Switzerland, [3]Mail Code JE-23, ESCG/Jacobs Sverdrup, P.O. Box 58477, Houston, TX 77258-8477, USA, [4]Dept. Geology and Geophysics, UW-Madison. [5]Antarctic Meteorite Research Center, National Institute of Polar Research, 1-9-10 Kaga, Tokyo 173-8515, Japan. [6]Mail Code JE-23, ESCG/Muniz Engineering, Houston, TX 77058, USA.

Introduction: We examine the chronology of differentiated asteroids as obtained by applying the ^{26}Al-^{26}Mg ($t_{1/2}$ = 0.73±0.03 Ma), ^{53}Mn-^{53}Cr ($t_{1/2}$ = 3.7±0.4 Ma), ^{182}Hf-^{182}W ($t_{1/2}$ = 8.90±0.09 Ma), and ^{146}Sm-^{142}Nd ($t_{1/2}$ = 103 Ma) chronometers in combination with ^{207}Pb-^{206}Pb ages.

Planetary Differentiation: Fig.1 shows ^{26}Al/^{27}Al ratios (Log$_{10}$) vs ^{207}Pb/^{206}Pb (Pb-Pb) ages. Pb-Pb ages from [1] and mineral separate isochron values of ^{26}Al/^{27}Al for angrites and the oldest eucrite, Asuka 881394 [2,3,4] (red squares and blue hexagons, resp.)

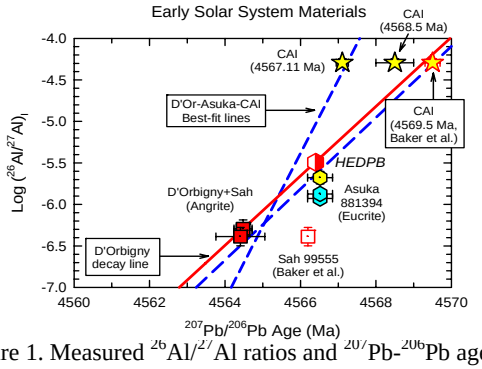


Figure 1. Measured ^{26}Al/^{27}Al ratios and ^{207}Pb-^{206}Pb ages in D'Orbigny, Sah99555, A881394, and CAI.

imply some heterogenity in ^{26}Al/^{27}Al between the Angrite Parent Body (APB), the HED Parent Body (HEDPB, i.e., Asteroid 4 Vesta?), and the Efremovka E60 CAI dated at ~4567.11 Ma [1]. This problem is relieved for the SIMS ^{26}Al/^{27}Al data for A881394 [5] (yellow hexagon), and more for the highest "model ^{26}Al/^{27}Al" calculated for eucrites by [6] (HEDPB, half-filled hexagaon). These data imply an age of ~4569.5 Ma [7] for the solar system.

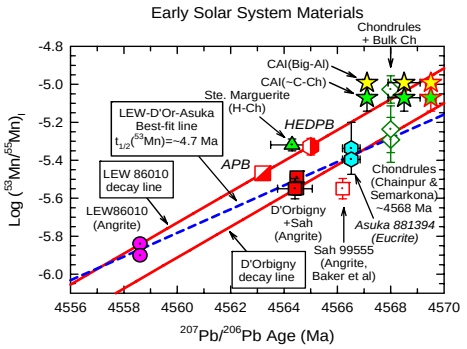


Figure 2. Measured ^{53}Mn/^{55}Mn ratios and ^{207}Pb/^{206}Pb ages in some early solar system materials. The Pb-Pb age for Ste. Marguerite are for ol and px residues [18].

Because of the longer halflife of ^{53}Mn, the "young" LEW86010 angrite can be included in Fig. 2. A curious feature of Fig. 2 is that the mineral isochron data for the two angrite groups and A881394 are collinear along a line corresponding to an apparent ^{53}Mn decay halflife of ~4.7 Ma.

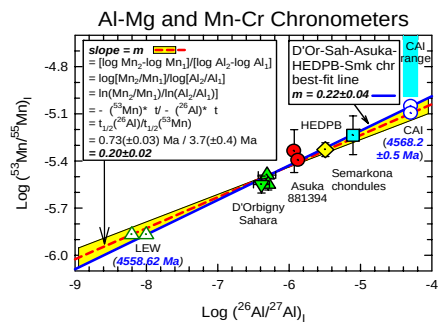


Figure 3. Al-Mg and Mn-Cr data for two angrites, the HEDPB, and Semarkkona chondrules.

Alternatively, a relative chronology from the short-lived chronometers can be anchored to the Pb-Pb age of a single reference. Fig. 3 shows Mn-Cr and Al-Mg data for D'Orbigny and Sah 99555, A881394, HEDPB, and Semarkona chronrules. The good linear correlation of these data allows an "absolute" age to be calculated for the time when the solar system had the canonical ^{26}Al/^{27}Al ratio relative to the initial ^{53}Mn/^{55}Mn and revised Pb-Pb age of LEW86010 [1]. The result obtained from the ^{53}Mn/^{55}Mn intercept of the best fit (blue line; slope = 0.22±0.04) averaged with that from a line of slope 0.20±0.02 calculated from the relative decay constatnts (red line) gives a "best estimate" of 4568.2±0.5 Ma for the solar system.

As shown in Fig. 4, the T_{LEW} Mn-Cr model ages

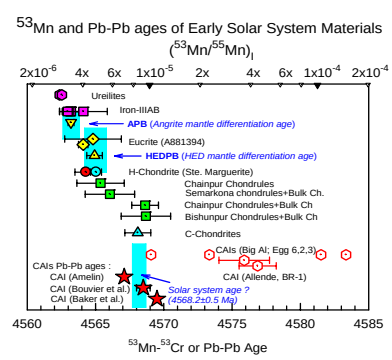


Figure 4. T_{LEW} ^{53}Mn/^{55}Mn ages and measured Pb-Pb ages (red symbols) in early solar system objects and materials.

for mantle differentiation of the APB and HEDPB are, respectively, ~4563 and ~4565 Ma. Mn-Cr model ages for other differentiated meteorites suggest similar time scales for differentiation of other asteroidal bodies (Fig. 4). Magmatic iron meteorites have unradiogenic $^{182}W/^{184}W$ ratios that are identical to or slightly below the initial $^{182}W/^{184}W$ of Allende CAIs [8]. $^{182}W/^{184}W$ of iron meteorites having short exposure times indicate that core formation in their parent bodies occurred < ~1 Ma after formation of CAIs [8].

Magmatism on the HEDPB: T_{LEW} Mn-Cr ages and zircon Pb-Pb ages (red circles, [9]) show that several eucrites crystallized as basaltic rocks within a few million years of differentiation of the HEDPB (Fig. 5). The Hf-W zircon age of A881388 [10] and the Hf-W mantle differentiaton age (Fig. 5) also suggest very early initiation of magmatism on the HEDPB.

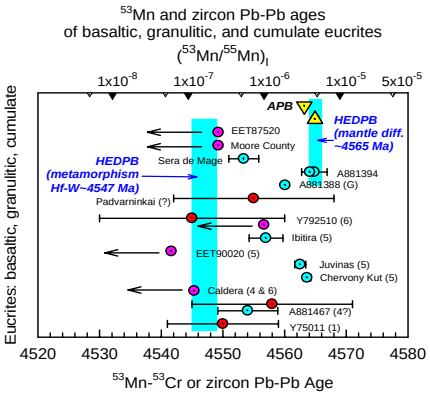


Figure 5. $^{53}Mn/^{55}Mn$ ages (rel. LEW86010) and zircon Pb-Pb ages [9] (red symbols).

Thermal Metamorphism on the HEDPB: Metamorphic grades based on the pyroxene equilibration criteria of [11] are shown in parentheses in Fig. 5. $^{53}Mn/^{55}Mn$ appears to have been completely equilibrated in the Type-6 eucrite, Y792510, for example. The zircon Pb-Pb age of this eucrite also hints at an age slightly lower than for the other eucrites. The time of thermal metamorphism inferred from Hf-W chonometry for 5 of 6 eucrites was 4547±2 Ma [12]. Upper limits to the Mn-Cr ages of most of the eucrites shown in Fig. 5 are consistent with reequilibration at that time. However, both the Mn-Cr and Hf-W zircon ages of EET90020 indicate later isotopic equilibration. Fig. 7 shows T_{LEW} model ages for ^{146}Sm-^{142}Nd data for some of the same eucrites included in Figs. 5 and 6. The longer halflife of ^{146}Sm allows the ^{146}Sm-^{142}Nd model age of 4484±26 Ma of EET90020 to be well-defined. The EET90020 age may be attributable to formation of a single large crater on the surface of 4

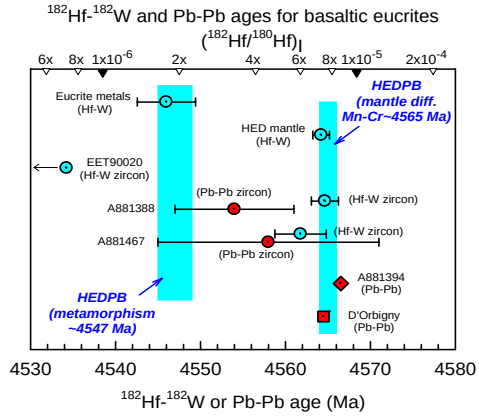
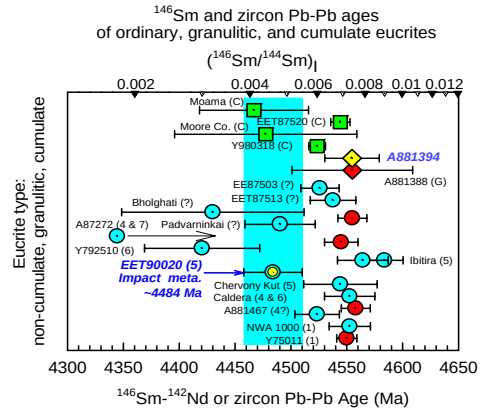


Figure 6. ^{182}Hf-^{182}W and Pb-Pb ages.

Vesta [13]. Other eucrites. may have been involved in the same event [14] (*cf.* Fig. 7).

Conclusions: Short-lived chronometers define a mostly-consistent chronology for events in the early solar system. An age of the solar system near 4569 Ma seems to be implied by combining Al-Mg and Mn-Cr data with available Pb-Pb data, but an age of 4568.2±0.5 Ma relative to 4558.62 Ma for LEW86010 [1] also can be derived from Al-Mg and Mn-Cr data. Space limitations preclude consideration here of the effect of additional asteroidal processes.



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