COMPARISON OF SHORT-LIVED AND LONG-LIVED CHRONOMETERS: TOWARDS A CONSISTENT CHRONOLOGY OF THE EARLY SOLAR SYSTEM. M. Wadhwa[1], Y. Amelin[2], M. Bizzarro[3], N. Kita[4], T. Kleine[5], G. W. Lugmair[6], and Q. Yin[7], [1]Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA, [2]Geological Survey of Canada, Ottawa, Ontario K1A 0E8, Canada, [3]Geological Institute, University of Copenhagen, Copenahgen, Denmark, [4]Dept. Geology and Geophysics, University of Wisconsin, Madison, WI, USA, [5]Inst. Isotope Geochemistry and Mineral Resources, ETH Zurich, Switzerland, [6]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA, [7]Department of Geology, University of California at Davis, One Shields Avenue, Davis, CA 95616, USA.

In the last few decades, chronometers based on both long- and short-lived radionuclides have been applied extensively to a variety of meteoritic materials with the goal of determining the timing of events that occurred in the early solar system, including the formation of the first solids in the solar nebula, as well as the accretion and differentiation of asteroidal and planetary bodies. Long-lived chronometers typically do not have the time resolution required to resolve events occurring within the first tens of millions of years of solar system history. In contrast, short-lived chronometers can provide high time resolution (i.e., a million years or less); however, an isochron from such a chronometer provides not an age but a measure of the abundance of the radionuclide at the time of last isotopic closure, and comparison of the isochron slopes for two separate events can provide only a relative time difference (ΔT) between these events. Therefore, for the high-resolution relative ages obtained from short-lived chronometers to be mapped on to an absolute time scale, they need to be "anchored" to an absolute age. This absolute age is usually provided by the U-Pb chronometer which is capable of providing ages with the sub-My precision comparable to that of short-lived chronometers. Furthermore, application of a high resolution chronometer based on a short-lived radionuclide requires that the initial abundance of this radionuclide be uniform in the region of the solar system where rocky bodies were forming, a condition that may not necessarily have been met.

Analytical advances over the last several decades have allowed dramatic improvements in the precision and accuracy of isotope ratio measurements for a wide range of elements in meteoritic and planetary materials. As a result, since the first evidence for the former presence of a short-lived radioncuclide, i.e., ^{129}I (t1/2 ~15.7 My) in the Richardton chondrite [1], there have been numerous other such radionuclides with half lives <100 My whose former presence in the early solar system has been unambiguously established (primarily through detection of small variations in the abundance of the daughter isotope that correlate with parent/daughter element ratios) [2-4]. Furthermore, these analytical advances have also made it increasingly feasible to analyze multiple isotope systematics in the same meteoritic objects, thereby making it possible to compare ages from several short-lived chronometers. Here we provide a review of ages obtained primarily from three short-lived chronometers (i.e., ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W; Table 1) that have thus far been most extensively applied towards obtaining chronological constraints on a variety of meteorites and their components and evaluate whether these chronometers provide time scales consistent with each other and with the absolute Pb-Pb chronometer. For all three of these chronometers, the D'Orbigny angrite is chosen as the time anchor since this is a rapidly cooled, relatively unmetamorphosed basaltic sample [5] in which the Pb-Pb, Al-Mg, Mn-Cr and Hf-W systems are likely to have closed contemporaneously.

Table 2 provides a comparison of ^{207}Pb-^{206}Pb absolute ages with the ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W ages (calculated relative to the D'Orbigny angrite time anchor; Table 1) for several types of meteorites and their components. With a few exceptions, the three short-lived chronometers appear to yield ages that are generally consistent with each other and with the absolute Pb-Pb ages, implying that the initial distributions of ^{26}Al, ^{53}Mn and ^{182}Hf were uniform in the meteorite-forming region of the protoplanetary disk.

Calcium-aluminum-rich inclusions (CAIs) in chondritic meteorites have the oldest absolute (Pb-Pb [6-9]) and relative (Al-Mg [10]; Hf-W [11,12]) ages. The most precise absolute age of 4567.11±0.16 Ma is defined by the Efremovka E60 CAI [7,8]. Chondrules from unequilibrated chondrites have Pb-Pb [7], Al-Mg [10] and Mn-Cr [13] ages that are typically ~1-3 My younger than CAIs. Silicate differentiation on the parent body of the Howardites-Eucrites-Diogenites (HED) group, as dated by ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W systematics in whole rock samples of these meteorites, occurred essentially contemporaneously with chondrule formation [14-16]. Igneous activity and basalt formation on early-accreted planetesimals also began within a few My after CAI formation [17-19].

In the cases where there is discordancy between chronometers (indicated in red in Table 2), there are several possibilities that may explain the lack of concordance. For example, the discordant ages may be a reflection of the different closure temperatures of the different isotope systems in a slowly-cooled sample. This may be the case for the Asuka 881394 eucrite, which shows textural evidence for slow cooling at near-solidus temperatures, and in which the Pb-Pb system may have closed earlier than the Al-Mg and Mn-Cr systems. Differences in closure temperatures may also account for discordant ages obtained for some H chondrites. While the Pb-Pb, Mn-Cr and Hf-W systems closed simultaneously in silicates in the Ste Marguerite (H4) chondrite at relatively high (near-solidus) temperatures, the Al-Mg system probably reflects slow cooling below 400-500°C [20] (Table 2). This is supported by the fact that the Pb-Pb age of phosphates in Ste Marguerite [21] (which also dates cooling below ~480°C) is identical within errors to this Al-Mg age. Secondary alteration processes, such as shock and thermal metamorphism, may also have affected different isotope systems to different degrees in a given sample.

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Table 1. Short-lived radioisotopes applied extensively towards refining the chronology of the early solar system events.

Radioisotope (R*)	$T_{1/2}$ (My)	Daughter Isotope (D*)	Reference Isotope (R)	Solar System Initial Ratio $(R^*/R)_0$	Time Anchor
^{26}Al	0.72	^{26}Mg	^{27}Al	~5 × 10^{-5}	D'Orbigny Angrite $(R^*/R)_T$ = 5.06 × 10^{-7} [22] at 4564.5±0.2 Ma [19]
^{53}Mn	3.7	^{53}Cr	^{55}Mn	~10^{-5}	D'Orbigny Angrite $(R^*/R)_T$ = 3.23 × 10^{-6} [23] at 4564.5±0.2 Ma [19]
^{182}Hf	8.9	^{182}W	^{180}Hf	~10^{-4}	D'Orbigny Angrite $(R^*/R)_T$ = 7.4 × 10^{-5} [24] at 4564.5±0.2 Ma [19]

Table 2. Comparison of ^{207}Pb-^{206}Pb absolute ages with those based on the ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, and ^{182}Hf-^{182}W chronometers.

Sample	^{207}Pb-^{206}Pb age (Ma)	^{53}Mn-^{53}Cr age (Ma)	^{26}Al-^{26}Mg age (Ma)	^{182}Hf-^{182}W age (Ma)
E60 CAI	4567.11±0.16 [7,8]		4569.2±0.2 [7]	
Allende CAI	4566±2 [6]			4568.4±0.7 [11,12]
	4568.1±9.4 [9]			
Chondrules	4564.7±0.6 [7]	4566.9±2.0 [13]	~4566-4568 [10]	
Ste Marguerite (H4) silicates	4566.7±1.6 [21]	4566.6±0.5 [25]	4563.9±0.3 [26]	4566.2±0.7 [27]
Richardton (H5) silicates	4562.7±1.7 [28]	4557.8±1.6 [25]		4562.8±1.0 [29]
HED silicate differentiation		4566.5±0.7 [14]	4565.1-4566.6 [16]	4564.2±1.0 [15]
Acapulco (acapulcoite)	4556.5±0.8 [30]	4556.6±1.1 [31]		
Ureilite feldspathic clasts		4563.9±0.4 [32]	4564.2±0.3 [33]	
Sahara 99555 (angrite)	4564.4±0.7 [19]	4563.8±0.8 [35]	4564.5±0.2 [22]	4564.1±0.6 [24]
	4564.6±0.2 [34]		4564.4±0.3 [17]	
D'Orbigny (angrite)	**4564.5±0.2 [19]**	**≡4564.5±0.2**	**≡4564.5±0.2**	**≡4564.5±0.2**
LEW 86010 (angrite)	4557.8±0.5 [36]	4559.4±0.4 [14]		
	4558.6±0.2 [19]			
Asuka 881394 (eucrite)	4566.5±0.3 [8]	4565.4±0.4 [18]	4565.5±0.2 [18]	
Ibitira (eucrite)	4557.4±0.6 [8]	4558.6+2/-3 [14]	<4562.8 [37]	

For a given sample, ages indicated in red are discordant with the ages determined from other chronometers for the same sample (within ±3σ). The ^{207}Pb-^{206}Pb age for the D'Orbigny serves as the anchor for the ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr snd ^{182}Hf-^{182}W systems (indicated in black bolded letters). Errors in the ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W ages include the errors in the ^{26}Al/^{27}Al, ^{53}Mn/^{55}Mn and ^{182}Hf/^{180}Hf ratios, respectively, and the uncertainty in the absolute age of the anchor; all errors shown in the table are ±2σ.