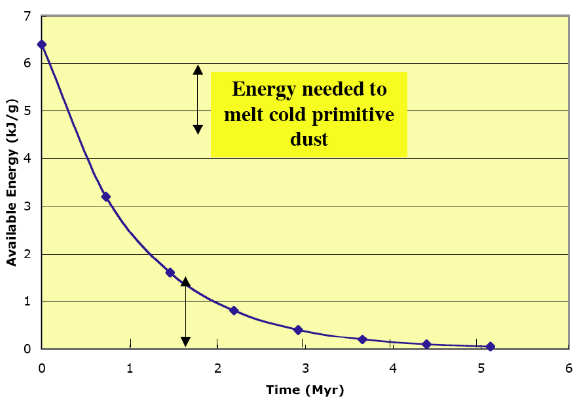
METEORITE CONSTRAINTS ON THE FIRST 5 MYR OF PLANETARY GROWTH IN THE INNER SOLAR SYSTEM.
Edward R. D. Scott[1], Ian S. Sanders[2], Joseph I. Goldstein[3], and Alexander N. Krot[1]. [1]HIGP, University of Hawaii at Manoa, Honolulu, HI 96822, USA; [2]Dept of Geology, Trinity College, Dublin 2, Ireland; [3]Dept. of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA. Email: escott@hawaii.edu.

Introduction: Growing evidence indicates that CAIs are the oldest objects with Pb-Pb ages that date solar system formation 4567 Myr ago and provide the best reference point (t_0) for early solar system chronologies [1, 2]. The overall consistency between chronometers based on long-lived ^{235}U and ^{238}U isotopes and the short-lived isotopes, ^{26}Al, ^{53}Mn, ^{182}Hf and ^{129}I, coupled with improved understanding of secondary geological processes such as alteration and impact heating have provided a coherent geological history of early high temperature events [e.g., 3, 4]. This geological history is strengthened by its consistency with thermal models for asteroidal bodies based on the inferred initial concentration of ^{26}Al in CAIs being uniformly distributed throughout the solar system and the assumption that meteorite parent bodies were large enough (>40 km in radius) so that surface zones that lost heat by conduction during ^{26}Al decay were relatively small [5-8].



This plot shows how the available energy for heating dry asteroids decreases according to the half-life of ^{26}Al of 0.73 Myr [see 6]. Bodies that were melted would have accreted <1-1.5 Myr after CAI formation; metamorphosed bodies accreted ~1-3 Myr, and unmetamorphosed bodies accreted after 3 Myr. Below we summarize the meteorite constraints on planetesimal and protoplanetary accretion at these three stages during the first 5 Myr of solar system evolution. Parent body sizes are inferred from cooling rate measurements and thermal modeling.

0-0.1 Myr: CAIs probably formed close to the protosun in <0.1 Myr [7, 8, 17] and were dispersed throughout the solar disk so that they accreted over the next 5 Myr with other nebular materials.

0.1-1 Myr: Evidence for accretion in this period comes from magmatic iron meteorites. After correction for cosmic-ray effects, these irons have $^{182}W/^{184}W$ ratios that are indistinguishable from the initial ratio derived from the CAI isochron [9, 10]. This implies that magmatic irons come from differentiated bodies in which the metallic cores formed <0.5-1 Myr after CAI formation. The parent bodies of irons were traditionally inferred from metallographic cooling rates to be 10-200 km in size, assuming that the cores cooled inside insulating silicate mantles [11]. However, 50-fold variations in the cooling rates in group IVA iron meteorites and smaller ranges in other groups can only be explained by cooling in metallic bodies with little or no silicate mantle [12]. The cooling rates of IVA irons are compatible with a hot metallic body 300±100 km in diameter that developed significant thermal gradients on cooling [12]. Because impacts cannot efficiently strip mantle material from cores, the original differentiated body from which IVA metal was derived was probably much larger than 600 km in size.

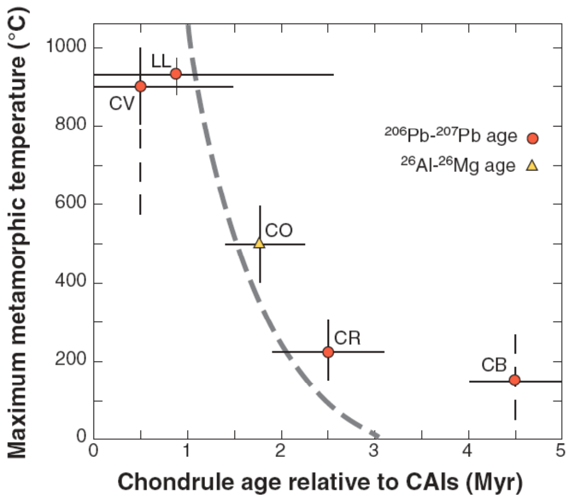
Protoplanetary collisions provide a plausible mechanism for generating metal-rich asteroidal bodies. Asphaug et al. [13] found that Moon-to-Mars sized protoplanets are eviscerated by hit-and-run collisions which generate strings of metal-rich bodies from the smaller body. Thus the 150 km radius metallic IVA body was plausibly derived from a protoplanet that accreted <1 Myr after CAI formation. These studies imply that protoplanets ~1000 km in size accreted and differentiated 0.1-1 Myr after CAI formation [12].

According to Bottke et al. [14], differentiated meteorites come from bodies that accreted inside 2 AU and broke up early generating debris that was perturbed by protoplanets into the asteroid belt.

We do not know when the IVA protoplanetary impact occurred, but collisional disruption of protoplanets probably started in the first few Myr, as IIIAB irons record Mn-Cr isotopic closure only 4±1 Myr after CAIs [15]. Protoplanetary collisions may also be responsible for the extremely low volatile concentrations in IVA irons [16], eucrites [24], and angrites.

1-3 Myr: Most chondrite groups (~90%) have chondrule ages of 1-3 Myr after CAIs. The range of chondrule ages within a group could be <1 Myr [27]. During this period chondrules formed episodically and were accreted into diverse asteroidal bodies along with CAIs, stardust, planetary debris, and solar nebula dust.

The earlier bodies to accrete at 1-3 Myr were strongly metamorphosed, e.g., CV and O chondrites. Bodies accreting 2-3 Myr after CAIs, like CR chondrites, were only mildy metamorphosed (<300°C) consistent with thermal models (Fig. 1).



This figure (reprinted with permission from the Annual Review of Earth and Planetary Sciences, Volume 35 ©2007 [4]) shows how maximum metamorphic temperatures decline with increasing chondrule formation age, consistent with theoretical calculations assuming immediate accretion after chondrule formation [7]. For data see refs [4, 17].

Assuming that H chondrites have typical thermal histories, the chondritic parent bodies that formed at 1-3 Myr were ≈200 km in size [18]. Since protoplanets prevented adjacent planetesimals from accreting [28], chondritic planetesimal growth may have been confined to a region between ~2 AU and the snowline.

3-5 Myr: The few chondrites with chondrules that formed at 3-5 Myr accreted into bodies that show the lowest degrees of metamorphism, as ^{26}Al heating was minimal after 3 Myr. Thus parent body sizes have not been inferred from meteorite thermal histories. CB chondrules, may have formed from a protoplanetary collision that created an impact plume of vapor and droplets that was mixed with CAIs and carbonaceous clasts, presumably in a still dusty disk [19]. CH chondrites, which have some CB-like features and clasts that probably come from other asteroids, probably also formed in this period.

Basalts from Vesta and several other disrupted, presumably Vesta-sized asteroids record two kinds of igneous processes at 3-5 Myr. Whole-rock ages for eucrites, angrites, mesosiderites, and ungrouped basalts (Ibitira, Asuka 881394, and NWA 011) of ~3-4 Myr after CAIs record global igneous processes that created chemical heterogeneous but isotopically homogeneous reservoirs [20-22]. At least for Vesta, this process was probably crystallization of a magma ocean, rather than partial melting, as Hf-W data show that core formation preceded eucrite whole-rock ages by 1 Myr [22, 23]. Rare Vestan basalts and several basalts from other sources have crystallization ages of 4-5 Myr; most Vestan basalts were probably reheated later by impact burial [29].

It is commonly inferred that Vesta accreted at ~1.5 Myr after CAIs so that basaltic reservoirs formed at 3-5 Myr by partial melting, e.g. [7], but magma oceans could have formed in bodies that accreted earlier and cooled rapidly by convection until crystal lock-up [22]. Low concentrations of volatiles like Na and K in all asteroidal basalts suggest that volatile loss by protoplanetary impacts may have been prevalent prior to 3 Myr [22, 24)]. Thus even Vesta may be a "second-generation" body.

Implications: Meteorites show that planetesimals did not accrete simultaneously throughout the inner solar system. Instead planetesimals appear to have been accreting in the asteroid belt long after protoplanets had formed and collided in the terrestrial region. This 5 Myr record of planetesimal and protoplanet accretion recorded in meteorites is not consistent with planetary accretion and disk evolution models and appears to require that planetesimal formation spread across the nebula from regions where the differentiated bodies formed [25]. Numerical modeling is needed to understand the meteorite constraints [26].

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