The accretion and impact history of the ordinary chondrite parent bodies

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Abstract: A working timeline for the history of ordinary chondrites includes chondrule formation as early as 0-2 Ma after our Solar System's earliest forming solids (CAIs), followed by rapid accretion into undifferentiated planetesimals that were heated internally by ^{26}Al decay and cooled over a period of tens of millions of years. There remains conflict, however, between metallographic cooling rate (Ni-metal) and radioisotopic thermochronometric data over the sizes and lifetimes of the chondrite parent bodies, as well as the timing of impact related disruptions. The importance of establishing the timing of parent body disruption is heightened by the use of meteorites as recorders of asteroid belt wide disruption events and their use to interpret Solar System dynamical models. Here we attempt to resolve these records by contributing new ^{207}Pb - ^{206}Pb data obtained on phosphates isolated from nine previously unstudied ordinary chondrites. These new results, along with previously published Pb-phosphate, Ni-metal and thermometry data, are interpreted with a series of numerical models designed to simulate the thermal evolution for a chondrite parent body that either remains intact or is disrupted by impact prior to forming smaller unsorted "rubble piles".

Our thermal model and previously published thermometry data limit accretion time to 2.05-2.25 Ma after CAIs. Measured Pb-phosphate data place minimum estimates on parent body diameters of ~260-280 km for both the L and H chondrite parent bodies. They also consistently show that petrologic Type 6 (highest thermal metamorphism) chondrites from both the H and L bodies have younger ages and, therefore, cooled more slowly than Type 5 (lesser metamorphism) chondrites. This is interpreted as evidence for Type 5 chondrite origination from shallower depths than Type 6 chondrites within initially concentrically zoned bodies. This contrasts metallographic cooling rate data that are inconsistent with such a simple onion shell scenario. One model that can reconcile these two data sets takes into account subtle differences in temperature to which each system responds. This working model requires that disruption occur early enough such that the Ni-metal system can record the cooling rate associated with a rubble pile (<70 Ma), yet late enough that the Pb-phosphate system can record an onion shell structure (>30 Ma). For this 30-70 Ma timeline, reaccumulation into smaller rubble piles will ensure that the originally deeply buried and hot Type 6 samples will always cool faster as a result of disruption, yielding nearly uniform ages that record the time of parent body disruption. This is consistent with the available Pb-phosphate data, where all but one Type 6 chondrite (H, n=3; L, n=4) yields a cooling age within a narrow 4505 ± 5 Ma timeframe. These data collectively imply that both the H and L chondrite parent bodies were catastrophically disrupted at ~60 Ma. In addition, combined Ni-metal and Pb-phosphate models confirm that a subset of Type 4 chondrites record early rapid cooling likely associated with erosional impacting of the H and L parent bodies on ~5 Ma timescales.

1. Introduction: Ordinary chondrites (OCs) provide a record of planetesimal formation in the asteroid belt through the accretion of some of the Solar System's earliest formed solids, including silicate chondrules, metallic Fe, Ni grains and fine-grained matrix. They preserve an early stage of planetesimal assembly that can guide our understanding of early Solar System

processes, including how planetesimal accretion times and parent body sizes varied within the protoplanetary disk. Numerical simulations of planetesimal growth in the terrestrial planet region predict rapid early growth of bodies that were large enough to melt within 10^5 - 10^6 years (Chambers, 2004). This rapid, early timeline for terrestrial region planetesimal formation is supported by radioisotopic studies of igneous achondrite meteorites, e.g., eucrites (Kleine et al., 2002), angrites (Amelin, 2008), and irons (Kruijer et al., 2014), whose documented early differentiation likely occurred as a result of melting induced by the decay of short-lived radioactive nuclides (^{26}Al , ^{60}Fe). The unmelted OCs, however, preserve accretion textures, primitive geochemistries and a range of chondrule ages (e.g., 0-3 Ma after CAIs; Connelly et al., 2008; Gounelle and Russell, 2005; Kleine et al., 2008; Mostefaoui et al., 2002) that reflect a younger timeline for planetesimal accretion relative to achondrites. Thermal modeling studies have attempted to define an OC parent body accretion time by constraining the conditions under which a chondrite parent body would remain undifferentiated (Hevey and Sanders, 2006; Miyamoto et al., 1982; Sugiura and Fujiya, 2014). The main criteria used to constrain these models include: 1) remaining below the onset of melting, defined by either the Fe-FeS eutectic at 980 °C (Dodd, 1981), or a silicate solidus at 1050-1100 °C (Johnson et al., 2016), 2) reaching the central temperatures estimated by thermometry of Type 6 chondrites ($\sim 900 \pm 50$ °C) (e.g., Olsen and Bunch, 1984; Slater-Reynolds and McSween, 2005), and 3) a mechanism for generating the ranges in thermal metamorphism observed in chondrite suites, classified as petrologic Types 3-6 (Van Schmus and Wood, 1967). The latter is most easily produced by a thermal gradient across the radius of a body resulting from internal radiogenic heating and variable degrees of insulation. While strongly dependent upon the thermal modeling constants chosen, the above criteria limit undifferentiated OC parent bodies to those accreting (instantaneously) after ~ 2.0 Ma (Hevey and Sanders, 2006; Miyamoto et al., 1982; Sugiura and Fujiya, 2014).

Reconstruction of chondrite parent body size may be provided by chondrite cooling rate estimates from a number of temperature-sensitive systems, including major element distributions within silicate minerals (Ganguly et al., 2013), metallographic cooling rates (Ni distribution in metal) (Scott et al., 2014; Taylor et al., 1987; Willis and Goldstein, 1982) and temperature sensitive radioisotopic dates or thermochronology. The thermochronologic data alone yield a compelling case for the concentrically zoned “onion shell model” for the OC parent bodies. Multiple systems, including Hf-W (Kleine et al., 2008), phosphate ^{207}Pb - ^{206}Pb (Amelin et al., 2005; Blinova et al., 2007; Gopel et al., 1994) and phosphate fission track (Pellas and Storzer, 1981; Trierloff et al., 2003), yield dates that are inversely correlated with metamorphic Type. This has been interpreted by a number of studies (Henke et al., 2012; Kleine et al., 2008; Trierloff et al., 2003) as evidence that the H-chondrite parent body had a long-lived (>100 Ma) layered structure - with Type 4 representing the shallowest and most quickly cooled of the equilibrated samples, and Type 6 representing the deeper more slowly cooled planetesimal centers. Prior estimates of parent body size are consistently 200 km in diameter (e.g., Trierloff et al., 2003; Henke et al., 2012; Kleine et al., 2008).

Despite this seemingly concordant result, the onion shell model appears to be inconsistent with metallographic cooling rates estimated from Ni diffusion profiles in Fe-metal (Bennett and McSween Jr, 1993; Scott et al., 2014; Taylor et al., 1987; Tomiyama et al., 2003). The metallographic cooling rate data (Ni-metal) have been interpreted as a record of chondrite parent body disruption (Taylor et al., 1987) or impact driven mixing (Scott et al., 2014) prior to cooling below the temperature (500 °C) at which Ni diffusion in Fe-metal is negligible. Parent body disruption would have had to have been followed by rapid reaccumulation of material into unsorted rubble

piles while the fragments were still hot (Taylor et al., 1987). This last step is consistent with both the lack of correlation between Ni-metal cooling rates and petrologic Type, as well as the existence of chondrite regolith breccias. Both petrologic (e.g., Ruzicka et al., 2015), and modeling (e.g., Davison et al., 2013) studies have stressed the inescapable importance that impact processing has for the thermal and mechanical mixing histories of chondrite parent bodies.

The importance of impacts in the evolution of the chondrite parent bodies is supported by dynamical simulations of Solar System evolution that predict that the asteroid belt's first several hundred million years will have been punctuated by episodes of planetesimal disruption. Possible drivers for increases in high velocity impact events are numerous and include the injection of material into the inner Solar System or clearing of the asteroid belt due to: 1) Dissipation of the gas disk, gas giant planet formation and/or early migration (1-10 Ma) (Chambers and Wetherill, 2001; Kaib and Chambers, 2016; Turrini et al., 2012; Walsh et al., 2011); 2) terrestrial planet formation (30-100 Ma) (Bottke et al., 2006; Bottke et al., 2015); 3) or through dynamical events responsible for the late heavy bombardment (~700-800 Ma) (Bottke et al., 2012; Gomes et al., 2005; Levison et al., 2009). One method for testing dynamical simulations has been to utilize meteorites as time recorders for these impact events (Bottke et al., 2015).

Our study has three goals. First, to produce new Pb-phosphate data for the OC meteorites, focusing primarily for the lesser-studied L-chondrites. Second, to explore whether primary information about the structure and accretion time of chondrite parent bodies is reliably recorded in the moderate-to-high temperature cooling histories of some equilibrated OCs and. Finally, we aim to understand why the two temperature sensitive systems, ^{207}Pb - ^{206}Pb phosphate thermochronology and metallographic cooling rates disagree. While these two systems are typically reported with the same nominal closure temperature (~500 °C), our numerical simulations will show that Pb-retention begins at higher temperatures (~800 °C) and earlier timescales than the Ni-metal system (<600 °C). Here we propose that the timing of disruption of both the H and L chondrite parent bodies can be measured through reconciliation of these two temperature sensitive systems. This event, in short, must occur early enough such that the Ni-metal system can record the cooling rate associated with rubble piles, yet late enough so that the Pb-phosphate system can record the initial onion shell structures.

2. Methods

2.1 Overview of Phosphate $^{207}\text{Pb}/^{206}\text{Pb}$ dating methods: The thermal history of chondritic meteorites can be reconstructed through the use of temperature-sensitive ^{207}Pb - ^{206}Pb thermochronologic dates. Here we assume that temperature-sensitive ^{207}Pb - ^{206}Pb dates are the result of thermally activated volume diffusion of radiogenic Pb produced by the *in situ* decay of U (Schmitz and Bowring, 2003; Schoene and Bowring, 2007). Common accessory phases in equilibrated OCs, apatite and merrillite, preferentially incorporated U into their crystal structure when they formed during thermal metamorphism as P was exsolved from Fe-Ni metal grains (Perron et al., 1992). Type 3 samples, or unequilibrated OCs, do not contain sufficiently large phosphate grains for this study, consequently we do not consider the thermal histories of these presumably shallowest samples here.

At high temperatures, Pb produced by the radioactive decay of U is lost from phosphates through diffusion. Only as the host meteorite cools does the mineral begin to retain Pb. A thermal gradient within an internally heated chondrite parent body due to radiative cooling from its surface (the so-called onion shell model) would have resulted in variable rates and timescales

of cooling of the parent body's interior through the 300-800 °C apatite Pb partial retention zone—a temperature range defined by the gradation between total diffusive loss and complete retention of Pb within a phosphate crystal (modeled here using kinetics from Cherniak and others, (1991)). In such a scenario, the shallow Type 4 samples would have cooled first and fastest through this thermal window, while the deeper Type 6 samples would have cooled more slowly and passed through this thermal window last. The U-Pb system has a dual decay scheme, where the parent isotopes ^{238}U and ^{235}U decay at different rates to the daughter isotopes ^{206}Pb and ^{207}Pb , respectively. The dual isotopic system results in distinctive isotopic ratios for both parents ($^{238}\text{U}/^{235}\text{U}$) and instantaneously produced daughters ($^{207}\text{Pb}/^{206}\text{Pb}$) at each point in the Solar System's history. In slowly cooled systems, this isotopic evolution will also result in a relationship between the burial depth within a planetary body and the timescales of cooling implied by the $^{207}\text{Pb}/^{206}\text{Pb}$ compositions, where the shallowest samples should yield the highest $^{207}\text{Pb}/^{206}\text{Pb}$ ratios and deeper samples that closed to Pb diffusion at later times will have lower values. We have developed a system of numerical models that permits forward simulation of both the parent body thermal histories and the resulting Pb-phosphate data. These thermal histories can be that of an unperturbed concentrically zoned body, or a body that undergoes total disruption at a given time followed by reaccrction into smaller rubble piles. It is through comparison between the models and measured Pb-phosphate data that we draw conclusions on the thermal history of a chondrite parent body.

2.2 Sample description and preparation for Pb analysis: Nine OCs were provided for our study from the Smithsonian and Antarctic meteorite collections (Table 1). The samples included representatives of almost all equilibrated petrologic Types (Types 4-6) from the three OC parent bodies (H, L, and LL) (we did not date a H5 or LL5). While we present new data for 2 LL chondrites, our interpretation will focus on the better-sampled H and L chondrites. The samples were chosen on the basis of sample mass (to allow for sample sizes of 20-40 g), low shock level and minimal degree of weathering. Estimates of the shock levels for the previously unstudied Antarctic meteorites were made during this study using the optically observed deformation of olivine in thin sections of the meteorites (Stöffler et al., 1991). All Antarctic samples contained olivine grains that were found to exhibit undulatory extinction and planar fractures, and are thus estimated at the S2-S3 shock stage. Bruderheim (L6) records a higher shock level (S4) (Ruzicka et al., 2015) and is used to evaluate the effects of shock heating on the Pb-phosphate system.

Sample preparation included crushing by hand using an agate mortar and pestle, sieving (<50, 100, 200 μm), and magnetic separations. Phosphates were found purified in non-magnetic at 1.4 amps, 20° slope. Heavy liquids (bromoform) was used on a portion of ALHA 78115, Ladder Creek and found to have no effect in separate purity relative to samples not processed this way. The phosphate separates were sorted by grain size and rinsed 3x and sonicated within, 18 MOhm deionized water. The samples were then spiked with and mixed with the EARTHTIME ET535 ^{233}U - ^{235}U - ^{205}Pb tracer (Condon et al., 2015), dissolved in 6N HCl and converted to 1.1N HBr for column introduction. The Pb was separated from the other elements using a HBr based anion exchange recipe following (Schmitz and Bowring, 2003) which use a 50ul micro-column, eluting Pb in 6N HCl and 18 MOhm deionized water. Best results were achieved using 2 passes to separate Pb. The Pb isotopic compositions were measured by peak jumping on the single detector ion counting systems of both the ThermoFinnigan Triton at the Department of Terrestrial Magnetism and the IsotopX X62 at the Massachusetts Institute of Technology. Model ^{207}Pb - ^{206}Pb dates were calculated using U-Pb Redux (McLean et al., 2011)

and by assuming that the initial Pb isotopic composition was that of Canyon Diablo troilite (Table A2) (Tatsumoto et al., 1973), and an initial $^{238}\text{U}/^{235}\text{U}$ ratio of 137.786 ± 0.0065 (1σ) (Connelly et al., 2012). Uncertainties propagated into these model dates are reported in table A2 and include uncertainties associated with: measured Pb isotopic composition, corrections for spike (Condon et al., 2015), blank and isotopic mass fractionation, initial Pb isotopic composition and present day U isotopic composition. The Pb isotopic mass fractionations in the mass spectrometers were externally determined using NBS 981. Laboratory blank amounts (~ 0.5 -2 pg) and isotopic compositions were measured throughout the data acquisition time period.

2.3 Thermal model: A thermal model was developed to define the thermal histories of OC meteorites within a primary “onion shell” structure. This model assumes that a body accreted instantaneously, was heated internally by the homogeneously distributed short-lived radionuclide ^{26}Al ($^{26}\text{Al}/^{27}\text{Al} = 5\text{e-}5$, MacPherson et al., 1995) and then cooled without experiencing disruption. Lacking evidence for achondrites associated with the H or L chondrite suites, we consider only scenarios in which the OC parent body remains unmelted. This model calculation uses an analytical solution to the heat equation following that of previous studies (Elkins-Tanton et al., 2011; Hevey and Sanders, 2006; Miyamoto et al., 1982) and uses the constants and initial values reported in Table A1. The key variables to be explored with this model are the parent body diameter and time of accretion after Solar System formation. For our purposes, the important results from the thermal models are the predicted time-temperature histories, from deep samples in the planetary center to the shallowest sample that reached a peak temperature of 700 °C (our definition for the shallowest depth for Type 4 chondrites). These time-temperature histories can be used: 1) as an input to numerical models simulating the Pb-phosphate and Ni-metal systems; 2) to allow us to examine the relationship between parent body temperatures and the timing of accretion (^{26}Al activity); 3) to allow us to predict cooling rates for any depth within the body with which to compare to Ni-metal data.

2.4 Pb-diffusion model: We developed a numerical model to forward calculate the Pb isotopic composition ($^{204}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$) of chondritic phosphates for some assumed time-temperature history. This model replaces the assignment of Pb-phosphate closure temperatures to the measured Pb-phosphate ages. Here instead, we calculate the Pb isotopic and corresponding ^{207}Pb - ^{206}Pb model ages that result from possible accretion and disruption scenarios. We determine the viability of these scenarios based on a comparison between the measured and modeled Pb-phosphate results. With this model, any time-temperature path may be tested, including those generated by our simple onion shell thermal model or histories that include planetesimal disruption. This Pb-diffusion model uses a numerical solution to solve the production-diffusion equation at each node across the radius of a modeled phosphate crystal (Blackburn et al., 2011; Blackburn et al., 2012). Output from this model includes the predicted Pb profiles for the radiogenic ^{207}Pb and ^{206}Pb isotopes (Fig. A1). An initial component, having the Pb isotopic composition of Canyon Diablo Troilite (CDT), is seeded into these profiles. Integrals of these profiles permit determination of the whole-crystal isotopic composition and model ^{207}Pb - ^{206}Pb dates for a given thermal history. Full model details are provided in the supplementary material section A.2. The compositions of analyzed phosphate separates include both apatite and merrillite. Unlike apatite, the diffusion kinetics for Pb in merrillite have not been measured directly. We can, however, make an estimate for the closure temperature following the

methods of Dahl (1997), where the ionic porosity of minerals with unknown diffusion kinetics are compared to the closure temperature and ionic porosity of studied minerals (e.g., apatite and titanite). Here we report a calculated ionic porosity (Z) for merrillite of 36 %. Given an observed correlation between ionic porosity and closure temperature (Dahl, 1997), we calculate a Pb-closure temperature for merrillite of: $T_C \text{ merrillite} = 540 \text{ }^\circ\text{C}$ ($T_C \text{ apatite} = 500 \pm 27^\circ\text{C}$). The similarity of the closure temperatures suggest that the diffusion kinetics for each mineral are also likely to be similar. Figure A2 in the supplementary section presents forward model simulations for possible chondrite thermal histories showing less than 5 Ma variations in predicted Pb-phosphate ages resulting from the uncertainties in apatite diffusion kinetics. The knowledge that merrillite Pb-closure is similar to, though higher than, apatite will permit interpretation of measured data (supplementary material A.2)

2.5 Model for Ni diffusion in taenite and kamacite: We use here a reformulated model following Willis and Goldstein (1982) for Ni diffusion in a cooling taenite-kamacite grain. Following the “model 2” described in Willis and Goldstein (1982), we track the taenite field alone, using a fixed spatial mesh, with changing scale to track kamacite growth (Fig. A3). Nickel is supplied to the surface of the taenite grain and diffuses inward. We use the phase diagram of Romig and Goldstein (1981) and diffusion kinetics from Goldstein et al. (1965). Following Willis and Goldstein, we assume a 10 wt.% initial Ni content for the bulk metal (H chondrites), recognizing that higher Ni content in L chondrites (12 wt.%) results in a small difference in results. Chondrite Ni-metal data are well-known to not record cooling rates consistent with an onion shell model (Bennett and McSween Jr, 1993; Scott et al., 2014; Taylor et al., 1987; Tomiyama et al., 2003). Our goal is to use the Ni-metal model to explore how this temperature sensitive system responds to changes in cooling rate as would occur during planetesimal disruption and reassembly, and to compare this response to that of the Pb-phosphate system. During histories in which samples experience reheating, we assume that equilibrium between taenite-kamacite is maintained.

3. Results:

3.1 New ^{207}Pb - ^{206}Pb Phosphate data: The Pb isotopic compositions of phosphate separates from the 9 OCs are given in Table 1. These data are corrected for isotopic mass fractionation, and blank and spike contributions. After these corrections, the remaining Pb is a mixture of initial, or common Pb (Pb_c) and Pb resulting from radiogenic ingrowth (Pb^*). All our data form linear arrays where $^{207}\text{Pb}/^{206}\text{Pb}$ is correlated with $^{204}\text{Pb}/^{206}\text{Pb}$ (Fig. A5). Model Pb dates are calculated assuming that the initial Pb (Pb_c) within each aliquot of phosphate is primordial in its isotopic composition (Fig. 1) (i.e., like that of CDT), Table A2). New model Pb-phosphate dates are plotted in Figure 1 (marked with black central dots), along with previously published OC data (no central dots) (Amelin et al., 2005; Blinova et al., 2007; Gopel et al., 1994). The sensitivity of model Pb dates (and the propagated age uncertainties) to the assumed initial Pb isotopic composition scales with the Pb^*/Pb_c (Table 1). For example, the high Pb^*/Pb_c of the H6 Alan Hills (ALH) 78115 results in minimal (<1 Ma) sensitivity to the assumed initial Pb isotopic composition. The low Pb^*/Pb_c of most Type 4 analyses, including Bjurbole (L/LL4) makes these model dates very dependent on the initial Pb composition. Any model dates from these weakly radiogenic samples should be treated with caution, and as such are not included in Figure 1. These unradiogenic Type 4 data do lie along statistically significant lines with previously published and more radiogenic analyses from Forest Vale and Ste. Marguerite (Gopel et al., 1994). The age calculated from such regressions is within uncertainty of values using CDT (as

reported by Gopel et al. 1994), supporting the hypothesis that the initial Pb incorporated into phosphates upon crystallization has an isotopic composition similar to CDT. One radiogenic analysis from the slightly shocked (S1-S2) H4 Avanhandava is a seemingly reliable young date and is consistent with the slow Ni-Metal cooling rates estimate for this sample: 20 °C/Ma (Scott et al., 2014).

Model Pb-dates for the different size fractions from ALH 81023 (L5) agree within their ~1 Ma uncertainties at 4534 Ma. Multiple L6 samples, including ALH 85025, Bruderheim and Ladder Creek yield dates for size fractions between 50-200 µm that are limited to 4509-4511 Ma and consistent with a singular L6 measurement from Marion (4510.7 ± 0.5 Ma) (Gopel et al., 1994). Data from a H6 (ALH 78115) yield a range of ages between ~4504.5-4507.9 Ma, with agreement within uncertainties between analyses of different size fractions. These new H6 dates cluster with previous results from Guarena, Kernouve (Gopel et al., 1994) and Estacado (Blinova et al., 2007) to within ~10 Ma (Fig. 1). Assuming Kernouve with its older 4520 Ma is derived from a shallower depth, the reported ages from the remaining Type 6 data (n=7) define a narrow 10 Ma window from ~4500-4510 Ma (grey bar in Fig. 1). For all data sets, we observe no consistent relationship between grain size and Pb composition, an observation that may reflect relatively fast cooling. Uncertainties on individual aliquot analyses are reported in Table 1 and are typically 1-2 Ma.

3.2 Model predictions for a concentrically zoned body: The thermal model described in sections 2.3 and A.1 provides the means to predict the thermal history of a chondritic parent body for an assumed accretion time and parent body diameter. An example thermal history is shown in Figure 2, where both the temperature as a function of depth (Fig. 2A) and temperature as a function of time (Fig. 2B) are shown for a 300 km diameter body that accreted at 2.15 Ma (after CAIs). We assume cold accretion (Fig. 2A, dashed line), but the body warms rapidly from ^{26}Al decay on timescales < 5 Ma. The maximum temperatures attained within the body are correlated with depth and are presumed to have produced the different petrologic Types observed in the OCs (e.g., Type 3-6). After this early heating phase, the parent body begins to cool with shallow depths (e.g., 20 km, blue curve, Fig. 2B) cooling to 500 °C (nominal apatite Pb-closure temperature) over 50 Ma prior to the parent body center (red curve, Fig. 2). This conductive gradient will result in a continuous age-depth relationship in the Pb-phosphate system. To quantify this, we use the Pb-diffusion model for phosphates described in sections 2.4 and A.2 to calculate the Pb isotopic compositions (Fig. A.1) and corresponding ^{207}Pb - ^{206}Pb model ages (Fig. 3) for chondritic phosphates that experienced the time-temperature paths shown in Figure 2B. As expected, the shallowest layers yield the oldest Pb-phosphate dates, while the deeper, hotter samples yield far younger dates. From this single scenario alone we can conclude that a concentrically zoned body will result in: 1) Older phosphate dates in samples that are both shallow and attained lower maximum temperatures; 2) Youngest phosphate dates are anticipated to be found in the most deeply buried samples with the highest recorded peak temperatures; 3) That an undisturbed body will have a continuous relationship between depth and age; 4) For the 900±50 °C maximum temperatures estimated for Type 6 samples (Clayton, 1993; McSween and Patchen, 1989; Slater-Reynolds and McSween, 2005), model results predict a >60 Ma range in Pb-phosphate cooling dates.

3.2.1 Accretion time: For a given set of chondrite heat transfer properties (Table A1), the thermal models presented in section 2.3 and A.1 can be used to show that the temperatures reached

within the center of a planetesimal is dependent upon the accretion time (^{26}Al activity). The linear relationship between accretion time and central temperature (Fig. 4) has a demonstrable lack of sensitivity to planetesimal size, particularly at planetary diameters above 150 km. Measurements for peak metamorphic temperatures for H6 and L6 chondrites are 900 ± 50 °C (Clayton, 1993; McSween and Patchen, 1989; Slater-Reynolds and McSween, 2005) and provide one way to limit the conditions in the planetesimal center. We assume that Type 6 chondrites are derived from the parent body center based on the lack of evidence for higher-grade samples that share an O isotopic composition with the H and L chondrites. For planetesimal diameters between 75-300 km, this would place the accretion times at ~ 2.05 - 2.25 Ma (Fig. 4). At diameters smaller than what is shown in figure 4 (< 75 km), central temperatures do not reach those recorded by Type 6s and are thus not viable scenarios. This result and modeling methods are similar to the accretion time (2.14 ± 0.1 Ma) concluded by Sugiura and Fujiya (2014) for a single parent body size. The result presented here considers multiple parent body sizes. This conclusion is not influenced by planetesimal disruption and is sensitive only to the assumed thermal constants, thermal modeling methods, boundary conditions and Type 6 thermometry data.

3.2.2 Parent body size: While accretion time controls the temperatures within the center of a body, planetesimal diameter directly controls the timescales of cooling within that same body. A measure of the timescales of cooling is provided by the Pb-phosphate system. Figure 5 shows the predicted Pb-phosphate dates for the center of a body over a wide range of planetesimal sizes. This calculation is made using the thermal model presented in sections 2.3 and A.1, and combining the time-temperature results for the center of a parent body (variable diameters) with the Pb-diffusion model presented in sections 2.4 and A.2 to determine the Pb-phosphate age. A small body will cool relatively fast, yielding older dates in comparison to large, slower cooling bodies, which are predicted to have young dates. The age–parent body size curves are produced for the end-members of acceptable accretion times (2.05 and 2.25 Ma; Sect. 3.2.1), and for two phosphate crystal sizes (20 μm and 200 μm diameter). As expected, the model predicts an increased offset between small and large crystals with the slower cooling that accompanies increased body size.

Model results for the timescales of cooling within a body center are compared with phosphate Pb data for Type 6 chondrites (Fig. 5). We recognize that not all Type 6 meteorites studied (or perhaps none) were derived from the planetesimal center, yet these data do set a minimum limit on planetesimal size. This is a minimum limit given that any deeper unstudied sample would yield younger dates. Given that both H and L chondrite data share a minimum age of ~ 4500 Ma, these data are consistent with *minimum* estimates for the L and H parent body diameters of ~ 260 - 280 km (depending on accretion time) (Fig. 5).

Though not as sensitive to variations in parent body size, the Pb-phosphate dates predicted for Type 4 chondrites (defined as the shallowest depth to which the maximum temperature is 700 °C; appendix section A.5 for review) are also controlled by parent body size (Fig. 6A). Assuming a higher temperature (e.g. deeper origin) will yield model Pb-phosphate dates that are far younger than the 4560-4562 Ma dates that are observed (Forest Vale and Ste. Marguerite (Gopel et al., 1994)). The timescales of cooling at these shallower depths are more sensitive to the time of accretion than for the centers of the body (Fig. 6A). Also unlike deeper samples, there is no difference between the model Pb-phosphate dates for crystals of different sizes because of the faster cooling rates. These curves are compared with Pb-phosphate dates for the *only* Type 4 chondrites with dates approximating 4560-4562 Ma, (Forest Vale and Ste.

Marguerite (Gopel et al., 1994)). Ste. Marguerite is consistent with 2.05 Ma accretion of all considered parent body sizes but for later accretion is consistent with parent body sizes of ~125 km diameter. Forest Vale is only consistent with 2.25 Ma accretion with a parent body diameter less than ~225 km. Either constrains are inconsistent with the parent body determinations made using the Type 6 data (Fig. 5). We will address this inconsistency in section 4.3.

3.3 Comparing metallographic and Pb-phosphate system closure: Here we present the results of numerical modeling designed to test how each temperature sensitive system responds to changes in cooling rate—as would occur after planetesimal disruption and reassembly in rubble piles. Figure 7 presents the forward modeled Pb-phosphate and metallographic data projected for thermal histories in which a change in cooling rate occurs. This numerical experiment was designed to simulate initial cooling within an onion shell body, followed by disruption of the body and reburial at different depths in a rubble pile. To minimize the potentially large parameter space, we only evaluated two scenarios. In one the cooling rate was initially fast (50 °C/Ma) and then slowed (10 °C/Ma). This would reflect a relatively shallow burial depth in the initial onion-shell body followed by reburial at greater depth after a collision (Fig. 7A inset). In the second scenario, a slow cooling rate (10 °C/Ma) was followed by a faster one (50 °C/Ma). This is what would happen if a sample was initially buried deep in the onion-shell body and then reburied at shallower depths (Fig. 7B inset) in a rubble pile. The cooling rates of 50 °C/Ma and 10 °C/Ma were chosen as estimates for the cooling rates through 500 °C experienced by Type 5 and Type 6 samples, respectively.

Beginning with the metallographic system, if the cooling rate of the sample changed when the ambient temperature was above 600 °C (Fig. 7A/B, light green), the system will record the subsequent cooling rate and will have no record of the initial cooling rate. If the change in cooling rate occurred below 500 °C (Fig. 7A/B, green), the system will record the initial cooling rate and will be unaffected by the change in cooling rate. Changes in cooling rate between 500-600 °C yields results that cut across our modeled taenite width vs. Ni concentration curves, reflecting a smaller crystal's propensity to record the post-disruption history, while a larger crystal may retain information about the earlier high-temperature history. All of this is interpreted to indicate that the effective closure temperature of this system, for the 10-50 °C/Ma cooling rates explored here, should be modified upwards to 600 °C (previously reported to be 500 °C).

The Pb-phosphate system responds to changes in cooling rates over a wider temperature range than the Ni-metal system (Fig. 7 C-D). A disruption when the temperature was 800 °C would result in a near perfect recording of the cooling rate after disruption. At 700 °C, the data are strongly influenced by the pre-disruption cooling history. Full system closure for Pb-phosphate is below 500 °C, i.e., similar to the Ni-metal system. Nevertheless, the phosphate system begins to retain Pb, and thus records information about the samples cooling history, at a higher temperature than the Ni-metal system. While the Ni-metal system retains no information about a thermal history above 600 °C, the Pb-phosphate data is strongly controlled by the thermal history at 600-800 °C. This is a key piece of information needed to understand how the pre-disruption history of the chondrite parent body can be recorded by the Pb-phosphate system, while evidence for only the post-disruption rubble pile is seen in the Ni-metal data.

3.4 The effect of shock heating on Pb in phosphate: Here we summarize the numerical results and observations that are designed to place limits on the duration of heating that is required to perturb or reset the Pb-phosphate system. The purpose of this calculation is to determine whether impacts on the OC parent bodies could have reset or partially reset the phosphate dates. Forward model simulations of Pb-phosphate data show that short-lived (hours-days), high temperature heating events have negligible effects on the U-Pb systematics within accessory phases (Table A3), and that maintaining temperatures of 800 °C for greater than 100 years are required to partially reset the Pb-phosphate system. Peak shock temperatures of ~800 °C are estimated for shock stage S5 (Stöffler et al., 1991), which is much stronger than the meteorites studied here experienced (<S4, Table 1). The Pb-phosphate data for Bruderheim support these modeling results, confirming that the duration of heating needed to reset the Pb-phosphate system has not been exceeded for shock stages of S4 or less. Evidence for high shock induced temperatures include small melt pockets within mechanically deformed meteorites (Dodd and Jarosewich, 1979). Bruderheim (L6, S4) is one meteorite dated in our study that has experienced intense shock and has been noted to contain up to 0.3 vol.% shock melt (Dodd and Jarosewich, 1979). Despite the high shock temperatures experienced by this sample, the Pb-phosphate cooling ages for Bruderheim are in good agreement with the lesser-shocked (S3) and unmelted (0% melt) Ladder Creek (L6). These two L6 meteorites yield Pb-phosphate dates of multiple aliquots that all cluster within 3-4 Ma and are consistent with the cooling ages for Marion (Gopel et al., 1994) and ALH 85026, both L6 samples, with estimates of shock stages of S2-S3. The agreement in phosphate ages for these L6 samples likely indicates that they all experienced shock heating after cooling through Pb-phosphate closure, and that it had no measurable effect on the phosphate $^{207}\text{Pb}/^{206}\text{Pb}$ dates. Thus, we suggest that any record of impact processing that would be recorded by the Pb-phosphate system would be heavily biased towards early impacts prior to cooling fully through the Pb-phosphate system closure temperature.

4. Discussion:

4.1 Chondrite parent body disruption at ~60 Ma: Our new and previously produced Pb-phosphate data consistently shows that H6/L6s cooled more slowly than the H5/L5s, evidence that points to concentric zoning within both parent bodies. Further, assuming that H6/L6 dates reflect cooling within the center of their respective cooling bodies, these data imply that both the H and L parent bodies were either 1) the same approximate size (Fig. 5), or 2) they may have differed in size but were disrupted at roughly the same time. In either case, Ni-metal data still require disruption and random reassembly of both parent bodies to produce the lack of correlation between petrologic type and Ni-metal cooling rate.

In the first model we consider, the H and L-chondrites are derived from originally concentrically zoned bodies that just happened to be nearly the same size (~275 km diameter), and both remained undisturbed until after Pb-phosphate system closure. Multiple aliquots of variable phosphate crystal sizes from four different L6s give Pb-phosphate ages that all cluster within a ~5 Ma window, overlapping with the data for three H6s that agree within a 10 Ma window (Fig. 1). This narrow range is in contrast to the >60 Ma range that would be predicted for meteorites that experienced temperatures consistent with thermometry of Type 6s (900±50 °C, Fig. 3). In this model, the near uniformity of Type 6 dates would have to be explained by the happenstance that all the studied samples once resided at the same approximate depths in their parent bodies. By volume, this would represent a very small amount of material. For instance, less than 5% of the volume of a body would have Pb-phosphate dates that are within 10 Ma of

the center date (Fig. 8). This compares with the observation that >50% of a body would have experienced temperatures consistent with Type 6 thermometry (e.g. 50% of body has dates within 60 Ma of central age). Such a biased sampling in the Type 6s seems unlikely given that we seem to have samples from a wide range of depths (i.e., Types 3-6). In addition, a successful model still requires that disruption and reassembly occur in order to satisfy the lack of correlation between Ni-metal cooling rate and petrologic type.

Alternatively, both the H and L parent bodies could have had different sizes (260-280 km are lower limits, Fig. 5) but both experienced early catastrophic disruptions at about the same time followed by reassembly in rubble piles. Predictions for the size of reaccumulated rubble piles forming after large scale impacts are just a fraction (up to 23%) of the original mass of a body (Michel et al., 2015). Reaccumulation into such significantly smaller rubble piles will ensure that deeply buried and hot Type 6 samples will *always* cool faster than in undisrupted objects. This faster cooling would yield uniform dates within the deeper samples that had yet to cool through the Pb-phosphate closure temperature. As a result, the timing of disruption would be directly dated by the youngest Type 6 Pb-phosphate dates in a chondrite group. This scenario is consistent with a near uniform age distribution for Type 6 Pb-phosphate dates, as well as the lack of correlation between dates and phosphate grain size (Table 1) that implies faster cooling than an onion shell model predicts (Fig. 3, note age spread in phosphate grain sizes at depth). In this scenario, the youngest dates for H and L chondrites (~4505 Ma) would most closely approximate the timing of disruption, ~60 Ma after CAI formation. Older Type 6 dates such as Kernouve (H6, ~4520 Ma) (Gopel et al., 1994) are entirely consistent with derivation from shallower depths within the original parent body and Pb-retention prior to disruption. The narrow Type 6 age range for most Type 6s is supported by I-Xe measurements, where the L6 chondrites Modoc, Walters and Bruderheim have I-Xe dates between 4501-4512 Ma (Brazzle et al., 1999).

While all Type 6 samples will have cooled faster in this scenario, some Type 4 samples could have been reheated for a short duration within the subsequent rubble piles through contact with fragments of hotter Type 6 chondrites. These same Type 4 samples could also have become more deeply buried within a rubble pile than they were in the primary body, resulting in slower apparent cooling rates than the onion shell model predicts for Type 4s. This latter possibility is consistent with Ni-metal and Pb-phosphate data for H4 Avanhandava. Additional Type 4s with Ni-metal cooling rates less than 20 °C/Ma include: ALH 87029, U70036, Bjurbole, LEW 86024, Wellman, Quenggouk, Conquista, Kesen, Sena, Sete Lagoas (Bennett and McSween Jr, 1993; Taylor et al., 1982; Tomiyama et al., 2003; Willis and Goldstein, 1982). Any viable chondrite disruption model must be able to explain the slow cooling rates observed for these Type 4 chondrites.

Central to the determination of the timing of disruption is the thermal budget of a chondrite parent body. If disruption occurred too late or the parent body was too small, the result will be a cold rubble pile(s) and Ni-metal cooling rates that correlate with petrologic type. If disruption occurred too early, the random arrangement within a rubble pile will prevent the correlation between petrologic type and Pb-phosphate data. While the importance of disruption timing is a simple concept, explicitly modeling the thermal evolution of a rubble pile is not, with additional factors including the fragmentation size, the depth and proportion of material accreted from the original body and the size of the subsequent rubble pile(s).

Because of this complexity, we instead attempt to simulate end member scenarios. Impact disruption is assumed to have occurred 10-100 Ma after CAI formation. We assume that no heat is imparted from the external impactor onto the body. Following disruption, samples are heated

to central temperatures at the time of disruption and then cool at rates of 10-100 °C/Ma (consistent with Ni-metal data, Fig. A4). This range of post-disruption cooling rates indirectly simulates rubble piles formed over a range of sizes. Heating samples to central temperatures upon disruption is designed to simulate the possible occurrence of reheating originally shallow samples through contact with fragments of hotter, originally deeper material. This occurrence maybe implied by the observation that some Type 4 and Type 5 samples record Ni-metal cooling rates slower than those predicted for an onion shell scenario (Fig. A.4). Also of importance is the observation that Type 5 samples yield older Pb-phosphate dates than Type 6 samples and thus these samples have not been heated to the point of destroying this early onion shell signature.

Figures 9A-C show model Pb-phosphate dates for a range of disruption times, plotted as a function of depth within the original body. We find that model predictions for early disruptions (10-50 Ma) produce a uniform age distribution as a function of depth (Fig. 9). While fast post disruption cooling will result in a uniform age-distribution that marks the timing of the disruption event (Fig. 9 A, B), slower post disruption cooling (Fig. 9 C) results in young dates reflecting the prescribed post-disruption cooling history (10 °C/Ma). All 10-50 Ma scenarios are consistent with there being sufficient heat in the debris to prevent recording an onion shell, instead recording the subsequent rubble pile. A disruption time of 60 Ma preserves evidence for an onion shell structure, where shallow samples have older dates that reflect cooling prior to disruption, but leave a portion of deeply buried samples with a uniform age-distribution similar to the age range observed for H6/L6 (4505 ± 5 Ma) (Fig. 9A,B). For *all* post-disruption cooling rates, disruptions later than 70 Ma will not be “recorded” as the body will have cooled to the point that the Pb-phosphate system yields ages that are indistinguishable from an onion shell-scenario (Fig. 9 A-C). Further, for a 60 Ma event, the volume of the body with Pb-phosphate dates within 10 Ma of the central age will exceed 50% of the total volume of the parent body, increased from ~5% for an undisturbed 300 km diameter body. This may perhaps explain the ubiquity of ~4505 Type 6 cooling dates (Fig. 8).

The complementary disruption tests for the Ni-metal system are relatively insensitive to the rate of post disruptive cooling (e.g. 10, 50, 100 °C/Ma). The results presented in figure 10 assume 100 °C/Ma. If for a particular disruption time (10-100 Ma) the Ni-metal data yield cooling rate information consistent with this prescribed post disruption cooling rate, we conclude that a rubble pile setting is recorded. Disruptions prior to 60 Ma yield central Ni-contents that are consistent with the Ni-metal contents predicted by the prescribed post disruption cooling history (Fig. 10A). This is because at the time of disruption there is enough thermal energy stored in the fragments to allow the Ni-metal system to record the cooling rates of a rubble pile rather than the original onion shell. Disruptions occurring at 70 Ma and after yield results that are indistinguishable from an onion shell structure because temperatures in the original bodies would have fallen below the closure temperature of the Ni-metal system (Fig. 10B).

Based on the above, we conclude that disruptions of both the H and L parent bodies at 60 ± 10 Ma is most consistent with the measured Pb-phosphate age and Ni-metal cooling rate data. Our reasons for reaching this conclusion include the observations that:

- 1) Early disruptions (< 50 Ma), independent of post-disruption cooling history, are ruled out because they would result in Pb-phosphate dates that are inconsistent with the observation that Type 5 dates are always older than Type 6 dates (Fig. 9);
- 2) Later disruptions (> 70 Ma), while consistent with an onion shell model and Pb-phosphate results (Fig. 9), would yield Ni-metal data that incorrectly records an onion shells structure (Fig. 10B);

3) Finally, the typical ~4505 Ma ages (60 Ma after CAIs) for Type 6 chondrites are most simply explained by disruption and rapid cooling at this time.

4.2 Implications of chondrite parent body disruption at ~60 Ma: Here we observe that *both* the L and H chondrite parent bodies experience disruption at 60 ± 10 Ma, a conclusion that very likely makes this event applicable to the asteroid belt as a whole except in the unlikely event that they collided with each other. Currently, dynamical simulations of Solar System evolution predict several semi-discrete events during which the terrestrial planets may have experienced increased orbital excitation and a correlated spike in high velocity (>5 km/s) impact events (Bottke et al., 2015; Bottke et al., 2012; Chambers and Wetherill, 2001; Gomes et al., 2005; Levison et al., 2009; Turrini et al., 2012). An event at ~60 Ma could be recording a cataclysmic stage of planet formation in the terrestrial region and perhaps linked to the Moon-forming giant impact. Bottke et al. (2015) suggested that the Moon-forming impact would have showered the asteroid belt with $\sim 10^{10} < 20$ km-sized fragments traveling at velocities in excess of 10 km/s. At these velocities, a ~275 km diameter chondrite parent body would have experienced large-scale disruption by impactors as small as 10 km (Taylor et al., 1987). Bottke et al. (2015) suggested that Moon-formation was responsible for a ~100 Ma after Solar System formation peak in $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock dates for 34 highly shocked ordinary and enstatite chondrites (Bottke et al., 2015). Interestingly, the data for these 34 highly shocked ordinary and enstatite chondrites contain a *more predominant* ~50 Ma age peak that may have been interpreted as recording cooling within a parent body and unrelated to impacts by Bottke et al. (2015). If this larger peak were instead linked to disruption of the ordinary and enstatite parent bodies, the ~100 Ma peak may record cooling within a rubble pile, a conclusion that is consistent with the correlation between H-chondrite $^{40}\text{Ar}/^{39}\text{Ar}$ dates and cloudy taenite particle size, data previously interpreted to reflect ~100 Ma post-disruption cooling at ~300 °C within an already mixed rubble pile (Scott et al., 2014). A possible link in time between a 60 ± 10 Ma chondrite disruption and Earth-Moon formation is barely consistent with >60 Ma constraints provided by ^{182}W - ^{182}Hf data (Kleine et al., 2009) and is just within uncertainty of model predictions that utilize the bulk silicate Earth siderophile content and N-body simulations (Jacobson et al., 2014). However, it is outside the >100 Ma age estimates placed by Pb (Allège et al., 2008; Tera, 1980) and Nd data for lunar rocks (Borg et al., 2011; Carlson et al., 2014). Alternatively, this ~60 Ma event could reflect the timing of inner Solar System excitation due to migration of the gas giants (Kaib and Chambers, 2016)

4.3 Early, <6 Ma, erosional impacting: Some Type 4 chondrites provide evidence for thermal histories that differ from Type 5-6 samples and an onion shell model. Nickel-metal cooling rates for the H4 Beaver Creek, Ste. Marguerite, Forest Vale (Scott et al., 2014) and L4 Yamato (Y)-86753 (Tomiya et al., 2003) (incorrectly described in reference as L5) are estimated to have been 10^3 - 10^4 °C/Ma (Fig. 6B). Only Type 4 chondrites record cooling rates of this magnitude. Within this subset of samples, Pb-phosphate data for Ste. Marguerite and Forest Vale (Gopel et al., 1994) reflect early closure (~4560-4562 Ma). These dates have been interpreted (Henke et al., 2012; Trieloff et al., 2003) to reflect the timing of Pb-closure for the more shallow layers within the H-chondrite parent body. Assuming that Type 4 chondrites represent samples heated to a maximum of 700 °C (Kessel et al., 2007; Wlotzka, 2005), then, taken together, these dates are only consistent with an onion shell scenario with a parent body diameter less than ~225 km, (Fig. 6A). This diameter is 50km less than the minimum estimate arrived at here from modeling

of the Type 6 Pb-phosphate data (Fig. 5). As pointed out by Scott et al. (2014), the Ni-metal cooling rates of 10^3 - 10^4 °C/Ma far exceed the predictions for an onion shell model (≤ 100 °C/Ma) and likely reflect early impact related excavation and rapid cooling prior to Ni-metal closure. Constraining the timing of rapid cooling using the Ni-metal data alone is complicated by the fact that rapid cooling through Ni-metal closure could occur at any time depending on the depth at which the samples resided. For example, deeper samples whose maximum temperatures were 900 °C could still maintain uniform 10 wt.% Ni profiles consistent with $>10^4$ °C/Ma impact-induced rapid cooling as late as 8 Ma after CAIs. Yet, identical uniform 10 wt.% Ni profiles are found for rapid cooling of a shallower-formed sample that reached a maximum temperature of only 700 °C if ejection were to occur immediately after chondrite accretion (~2.2 Ma). Combining Pb-phosphate and Ni-metal data can limit when this rapid cooling event occurred.

In Figure 6, we present forward model Pb-phosphate (A) and Ni-metal (B) results for scenarios in which the sample is quenched at 5-7 Ma following Solar System formation. This time frame is guided by the Pb-phosphate data for Forest Vale and Ste. Marguerite (Fig. 6A). Model Pb-phosphate results for quenched samples at 5-7 Ma (color lines, Fig. 6A) will directly date the time of quenching if samples were originally buried deeply enough to be heated to at least 850 °C (~27.5 km in 300 km body). Derivation at shallower depths will yield data that reflect minor pre-disruption cooling within a concentrically zoned body. Measured phosphate dates for Ste. Marguerite (4561.7 ± 0.7 Ma) and Forest Vale (4559.9 ± 0.7 Ma) (Gopel et al., 1994) (adjusted using revised $^{238}\text{U}/^{235}\text{U}$ (Connelly et al., 2012), Table A2) are consistent with quenching at ~5 Ma and 7 Ma, respectively (Fig. 6A). Assuming a 5 Ma quench time, the extremely low central Ni content for taenite in Ste. Marguerite can only be replicated by quenching a sample that formed at ~27.5 km depth (max T = 850 °C) within a 275 km diameter body (Fig. 6B). This 27.5 km depth (max T = 850 °C) is the shallowest sample that could replicate the Ste. Marguerite Ni-metal data with an impact time as indicated by the Pb phosphate data. While deeper samples are permissible by the Ni metal data, shallower samples will have experienced pre-disruption cooling and would require earlier disruptions to meet such low central Ni-contents. These earlier disruption scenarios would be inconsistent with the Pb-phosphate results. The Ni-metal data from Forest Vale reflects slower cooling rates than Ste. Marguerite. The slower cooling could mean that either (1) Forest Vale formed at shallower depth than Ste. Marguerite and was excavated at the same time, or (2) Forest Vale resided at the same or similar depth within the parent body but was excavated at a later time (7 Ma). Pb-phosphate results show that Forest Vale yields a younger date than Ste Marguerite and are thus consistent with the latter scenario (Fig. 6A). This implies that these rapid cooling events are discrete, separated by ~2 Ma. Nickel-metal data for two other Type 4s, Beaver Creek and (Y)-86753, reflect rapid cooling on the same 5-7 Ma timescales if we assume the same 27.5 km formation depth, yet until Pb-phosphate data are available, later exhumation of deeper samples cannot be ruled out.

Evidence for very early (~5-7 Ma after Solar System formation) events on both the H and L-chondrite parent bodies suggests that this may have been a disturbance that affected the entire asteroid belt. The fact that only Type 4s seem to be affected may characterize this event as involving smaller impactors and/or modest velocities. The ~5 Ma timescale for this event is comparable with predictions for enhanced collisions after the clearing of the protoplanetary disk (Chambers and Wetherill, 2001) and/or gas giant migration (Turrini et al., 2012; Walsh et al., 2011).

5. Conclusions: Thermal modeling results, combined with thermometry estimates on chondrite equilibrium temperatures, phosphate thermochronologic data and improved estimates on material and thermal properties all work to limit chondrite accretion times to ~2.05-2.25 Ma after CAIs and limit parent body diameters to greater than ~275 km. Ni-metal cooling rate studies resolve no apparent relationship between cooling rates for Type 5 and Type 6 petrologic Types, suggestive of large-scale impact disruption prior to recreation of unsorted rubble piles and cooling through Ni-metal system closure. This is in contrast to Pb-phosphate cooling dates, which yield older dates for Type 5s than for Type 6s for both H and L parent bodies, consistent with a concentrically zoned body. Numerical tests presented here for both Pb-phosphate and Ni-metal systems suggest that the conflicting records for these systems can remain consistent with one another if a large-scale planetesimal disruption were to occur at 60 ± 10 Ma. A smaller scale and earlier impact event is resolved by Ni-metal and Pb-phosphate data for a sub-set of H4 and L4 chondrites which record rapid cooling prior to 6 Ma after Solar System formation.

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Figure Captions:

Figure 1. Summary of model ^{207}Pb - ^{206}Pb dates. The symbols correspond to the different ordinary chondrite chemical groups (parent bodies). Model Pb-ages are calculated assuming that the phosphates incorporated primordial Pb (Canyon Diablo troilite) upon crystallization. The colors correspond to petrologic Type (4-6). Black central dots indicate the data presented in this study (Table 1). The previously published data sets are from: (Amelin et al., 2005; Blinova et al., 2007; Gopel et al., 1994) are corrected using a revised $^{238}\text{U}/^{235}\text{U}$ (Table A2)(Connelly et al., 2012). Both L5 and H5 chondrites yield older cooling dates than L6/H6 samples, consistent with a concentrically zoned “onion shell” structure. All Type 6 samples, with the exception of Kernove (H6 at ~4520 Ma) yield cooling ages within a ~10 Ma range (grey horizontal bar).

Figure 2. The results of a thermal model showing the warming and cooling within an internally heated 300 km diameter body that accreted 2.2 Ma after CAIs. (A) Temperature-depth profiles at different times. The dashed line marks the initial temperature of the body at the time of accretion. Early, rapid warming is followed by slower cooling on timescales of tens of millions of years. (B) Time-temperature histories at different depths in the body.

Figure 3. Forward calculated ^{207}Pb - ^{206}Pb model Pb dates. Colors correspond to the sample depths as in Figure 2B. The Pb-phosphate ages will be slightly dependent on grain size, with the difference increasing with depth (decreasing cooling rate). Model Pb-ages are calculated assuming that phosphates incorporate primordial Pb (Canyon Diablo troilite) upon

crystallization. An onion shell model predicts correlations between Pb-phosphate age, the maximum temperature reached (black lines), and formation depth within the body (grey lines). We predict a large (>60 Ma) age range associated with the maximum temperatures predicted for Type 6 chondrites (900 ± 50 °C).

Figure 4. The model maximum central temperatures for parent bodies accreting between 2.05 Ma and 2.3 Ma after Solar System formation. The vertical black lines mark the Fe-FeS eutectic and the silicate solidus. The central temperatures are relatively insensitive to planetesimal size above ~ 150 km in diameter. Equilibrium temperatures for Type 6 chondrites are marked by the shaded region and provide minimum estimates for the peak temperatures at the centers of the OC parent bodies and thus limit accretion times to 2.05-2.25 Ma after CAIs.

Figure 5. Predicted Pb-phosphate dates for the centers of parent bodies as a function of parent body sizes. Model central Pb-phosphate dates are relatively insensitive to accretion time. However, they are highly sensitive to parent body size, and to a lesser extent phosphate grain size. A minimum estimate of parent body diameter is provided by comparison to measured Pb-phosphate dates for H6 and L6 chondrites, yielding a lower limit on the parent body diameter of ~ 260 -280 km.

Figure 6. Model (A) Pb-phosphate and (B) Ni-metal data projections for undisrupted and disrupted Type 4 chondrites. (A) Solid black rectangles mark the phosphate Pb dates for Forest Vale (FV) and Ste Marguerite (SM) (Gopel et al., 1994). Black curves mark the Pb-phosphate ages as a function of parent body diameter and accretion time for samples that reached peak of 700 °C and then cooled without impact disruption (onion shell scenario). Colored lines mark Pb-phosphate dates for samples disrupted and quenched at the indicated times. (B) Plotted measured Ni-metal results are restricted to a subset of Type 4 chondrites characterized by low, uniform Ni concentrations that are consistent with fast cooling rates. Model results (colored curves) are generated assuming an onion shell scenario followed by quenching of samples at different times. The Ni-content vs. grain size curves indicate that the apparent slower cooling of Forest Vale relative to the very low central contents of Ste. Marguerite can be produced by rapid cooling at a slightly later timeframe.

Figure 7. Model results from the (A-B) Ni-metal and (C-D) Pb-phosphate systems for scenarios in which the cooling rate changes from fast to slow (A&C) or slow to fast (B&D). The colors correspond to the temperature at which this change in cooling rate occurs. These two temperature sensitive systems are often noted to have the same closure temperature. Ni-metal data indicate that this system does not retain information about a sample's thermal history above 600 °C, while Pb-phosphate data are influenced by the thermal history between 600-800 °C.

Figure 8. Volume percent within an undisturbed spherical body (200 km diameter dashed, 300 km diameter solid) plotted as a function of the model Pb-phosphate date (for that volume). Assuming an undisturbed parent body, the uniformity of Type 6 data ($n=3$, H6; $n=4$, L6; all in ~ 10 Ma age range) implies that all samples happened to have derived from $<5\%$ of the parent body volume. This is compared to $>50\%$ of the body having cooling ages within 50 Ma of center—the age range expected for Type 6 samples, see figure 3. The dotted line shows a

scenario in which a body is disrupted at 60 Ma resulting in a significant increase in the percent by volume of a body recording a narrow age range.

Figure 9. Simulations of the Pb-phosphate ages for a 275 km diameter parent body that was disrupted at 10 Ma intervals after CAIs and reassembled into rubble piles of unknown sizes. Here we explore a range of potential rubble pile sizes, assuming that post-disruption cooling occurs at 100 °C/Ma (A), 50 °C/Ma (B) and 10 °C/Ma (C). (A-C) Pb dates are colored by the timing of the disruption event (colors: 10-70 Ma). If the Pb-phosphate system records data consistent with this post-disruption cooling rate, we can then conclude that a disruption at that time would result in a rubble pile being recorded. An undisturbed onion shell scenario (OS) is plotted in black. Horizontal gray bar marks the range of Type 5 Pb-phosphate dates, while the vertical gray bar marks the average Type 6 date. Preferred model scenarios will have: 1) older cooling dates for shallow samples, similar to the range of dates observed for Type 5 samples; 2) central dates consistent with observed Type 6 cooling dates. These data are interpreted to indicate that disruptions prior to 50 Ma following CAIs will result in a Pb-phosphate record with a uniform age distribution and rubble pile conditions, failing to match old dates in shallow samples and young dates at depth, while disruptions after 70 Ma will match these criteria.

Figure 10. Simulations of the Ni-metal system for a 275 km parent body undergoing disruption, and reassembly in rubble piles. Ni-metal data are plotted as the difference between the apparent central nickel content of an originally 200 µm grain and that of (A) the post-disruption central nickel content and (B) an undisturbed onion shell scenario. Ni-metal data are relatively insensitive to post disruption-cooling rate (shown here: 100 °C/Ma). These data are interpreted to indicate that disruptions occurring after 50 Ma record our model's post disruption history and are thus consistent with a rubble pile.

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Table 1

Table 1. Pb phosphate data										
	207Pb- 206Pb (Ma) a	±2σ abs	Pb* (pg) c	Pbc (pg) d	Pb*/ Pbc e	204Pb/ 206Pb f	±2σ abs	207Pb/ 206Pb f	±2σ abs	grain size (um)
Avanhandava, H4, S1										
p1	4513.12	0.81	7230.8	664.4	10.9	0.003392	0.000642	0.618421	0.000721	100-200
p2	4518.57	3.66	849.3	419.9	2.0	0.017460	0.008778	0.686901	0.002374	<50
ALHA-78115, H6, S1-S2										
p1	4507.88	0.66	1150.3	40.5	28.4	0.001268	0.000245	0.606309	0.000502	100-200
p2	4505.27	2.24	206.5	39.0	5.3	0.006595	0.001160	0.630475	0.000533	100-200
p3	4506.06	1.98	1868.5	25.2	74.1	0.000447	0.000351	0.601575	0.001340	<50
p4	4504.55	1.91	18225.8	835.9	21.8	0.001893	0.000371	0.607788	0.000669	<50
Bjurbole, L4/LL4, S1										
p1	4516.09	1.71	1114.9	1105.0	1.0	0.032040	0.005213	0.753523	0.000624	<50-200
ALHA-81023, L5, S2-S3										
p1	4534.84	2.46	549.2	387.9	1.4	0.022684	0.004652	0.716032	0.000741	<50
p2	4534.91	2.26	782.8	17.4	45.0	0.000548	0.001141	0.614194	0.001587	50-100
ALH-85026, L6, S2-S3										
p1	4506.43	0.67	1219.3	45.9	26.6	0.001298	0.000236	0.605791	0.000510	50-100
p2	4504.99	1.36	10723.6	622.8	17.2	0.002356	0.000434	0.610454	0.000590	<50
Bruderheim, L6, S4										
p1	4510.19	0.81	15546.1	354.4	43.9	0.000885	0.000487	0.605460	0.001861	50-200
p2	4509.53	1.42	3032.5	1724.4	1.8	0.019705	0.005697	0.693646	0.001451	<50
p3	4509.29	1.34	17181.0	934.9	18.4	0.002026	0.000380	0.610645	0.000601	<50
p4	4509.19	1.72	42397.9	11618.3	3.6	0.010183	0.002902	0.648988	0.001578	50-100
Ladder Creek, L6, S2										
p1	4511.26	0.84	2932.9	314.3	9.3	0.004136	0.000008	0.621156	0.000732	50-100
p2	4511.49	1.09	187.2	28.3	6.6	0.004682	0.000011	0.623700	0.000580	<50
p4	4511.16	0.82	3271.8	122.1	26.8	0.001436	0.000004	0.608079	0.000603	<50
p5	4509.46	1.06	3307.9	225.7	14.7	0.002608	0.000044	0.612937	0.004469	100-200
EET-87544, LL4, S2-S3										
p1	4499.09	6.20	302.9	243.6	1.2	0.027069	0.004410	0.724996	0.000593	<50-200
Cherokee Springs, LL6, S3										
p1	4517.40	3.80	72.0	37.1	2.0	0.024089	0.003791	0.716000	0.000600	100-200

a Isotopic dates calculated using the decay constants $\lambda^{238} = 1.55125\text{E-}10$ and $\lambda^{235} = 9.8485\text{E-}10$ (Jaffey et al. 1971).
b Th contents calculated from radiogenic 208Pb and the 207Pb/206Pb date of the sample, assuming concordance between U-Th and Pb systems.
c Total mass of radiogenic Pb.
d Total mass of common Pb.
e Ratio of radiogenic Pb (including 208Pb) to common Pb.
f Measured ratio corrected for fractionation and spike contribution only.

Figure 1

Figure 2

Figure 2

Figure 3

Figure 4

Figure 4

Figure 5

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Figure 7

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Figure 10

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Figure 6

Figure 6