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Thermal constraints on the early history of the H-chondrite parent body reconsidered

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Abstract

Reconstructions of the early thermal history of the H-chondrite parent body have focused on two competing hypotheses. The first posits an undisturbed thermal evolution in which the degree of metamorphism increases with depth, yielding an "onion-shell" structure. The second posits an early fragmentation–reassembly event that interrupted this orderly cooling process. Here, we test these hypotheses by collecting a large number of previously published closure age and cooling rate data and comparing them to a suite of numerical models of thermal evolution in an idealized parent body. We find that the onion-shell hypothesis, when applied to a parent body of radius 75–130 km with a thermally insulating regolith, is able to explain 20 of the 21 closure age data and 62 of the 71 cooling rates. Furthermore, six of the eight meteorites for which multiple data (at different temperatures) are available, can be accounted for by onion-shell thermal histories. We therefore conclude that no catastrophic disruption of the H-chondrite parent body occurred during its early thermal history. The relatively small number of data not explained by the onion-shell hypothesis may indicate the formation of impact craters on the parent body which, while large enough to excavate all petrologic types, were small enough to leave the parent body largely intact. Impact events fulfilling these requirements would likely have produced transient crater diameters at least 30% of the parent body diameter.

1. INTRODUCTION

The H-chondrite meteorites are thought to have originated in a single, undifferentiated parent body (e.g., Wasson, 1972). The parent body underwent varying degrees of metamorphism as a result of heat released internally, probably by the radioactive decay of ^{26}Al (Minster and Allégre, 1979). The degree of metamorphism is inferred from petrologic type, which ranges from type 3 (least metamorphosed) to 6 (most metamorphosed; Van Schmus and Wood, 1967). Petrologic type has thus been used as a proxy for peak metamorphic temperatures (Dodd, 1969, 1981). The peak temperatures of Dodd (1981) were derived for types 3 and 6 only (the respective ranges are 400–600 and 750–950 °C), with peak temperatures for types 4 and 5 calculated by interpolation. Newer thermometric techniques have yielded temperature ranges of 865–926 °C for type 6 meteorites (Slater-Reynolds and McSween, 2005), 675–750 °C for the lower bound on peak temperatures for types 4–6 (Wlotzka, 2005; Kessel et al., 2007), and temperatures anywhere from 260 to 600 °C for the different subclasses of type 3 (Huss et al., 2006, and references therein).

The relationship between peak temperature and petrologic type has allowed broad constraints to be placed on the early thermal history of the H-chondrite parent body. The most straightforward approach, arising from a simple thermal model of internal heating in a sphere, is the "onion-shell" model. Peak temperatures decrease monotonically away from the center of the body, producing layers of progressively lower petrologic type (Wood, 1967; Minster and Allégre, 1979; Pellas and Storzer, 1981). The lower the peak temperature, the shorter the cooling time, and a range of methods (described in further detail below) have been employed in recent years to infer such times (Trieloff et al., 2003; Amelin et al., 2005; Bouvier et al., 2007).

Additional constraints are available in the form of cooling rates: samples that originated near the center of the

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parent body, where temperature gradients were low, likely cooled slowly, while samples from shallow depths, where temperature gradients were steeper, likely cooled rapidly. The onion-shell model might thus be confirmed if petrologic type (i.e., peak temperature) were observed to correlate inversely with cooling rate.

Some of the first cooling rate measurements made on H-chondrites (Pellas and Storzer, 1981; Lipschutz et al., 1989) seemed to confirm the onion-shell hypothesis, while others did not (Scott and Rajan, 1981). The analysis of a large number of samples by Taylor et al. (1987) again appeared to contradict the onion-shell model, leading these workers to invoke the hypothesis, first suggested by Grimm (1985), that the early hot parent body was shattered by a large impact, followed by the haphazard reassembly of fragments of various temperatures. Subsequent cooling of such a body would be expected to record no correlation between petrologic type and cooling rate.

There are, however, problems with some of the cooling rate data collected by Scott and Rajan (1981) and Taylor et al. (1987). The highest H-chondrite cooling rates recorded by these workers are for metals in the fine-grained matrices of regolith breccias. These matrices appear to have formed by the comminution of larger clasts as a result of shallow regolith development on the surface of the parent body (Bischoff et al., 1983). If this process occurred during the early metamorphic heating of the parent body, the comminution of hot clasts into finer grains would have accelerated cooling rates in the material, explaining the very wide range of values up to a few thousand °C/Ma (Scott and Rajan, 1981; Taylor et al., 1987; Williams et al., 2000). Alternatively, these materials may have been reheated following early metamorphism (e.g., Kessel et al., 2007). These cooling rates may therefore have little relevance to global-scale parent body thermal history. While this does not necessarily put to rest the fragmentation–reassembly hypothesis, there are additional concerns about the Taylor et al. (1987) data that raise significant doubts, and these are addressed later.

Some cooling rate data published after those of Taylor et al. (1987) appear to support an onion-shell model once again (Göpel et al., 1994; Trieloff et al., 2003), leaving a somewhat conflicting picture of the early H-chondrite parent body thermal history. We attempt to address this problem here by bringing together a large sample of the available data and comparing them to numerical models of onion-shell thermal development in an idealized parent body.

2. METHODOLOGY

Our methodology, which is similar to that of Bennett and McSween (1996), consists of the following steps: (1) Initialize a numerical model of parent body thermal history with thermal parameter values drawn from a plausible range (Section 2.2). (2) Run the model iteratively, each time adjusting the heat source (via the initial $^{26}Al/^{27}Al$ ratio) until the peak temperature attained at the center of the body is approximately 1000 °C (Section 2.2). (3) Rerun the model with different parent body radii until an optimal fit is found to closure time and cooling rate data from the literature (Section 2.1).

We proceed first with a detailed description of the literature data used, followed by a full characterization of our thermal model.

2.1. Data analysis

Our study integrates two types of data from the literature that are often reported separately. The first is the closure time corresponding to a particular radiometric dating technique, namely the time elapsed before a meteorite passes through a given temperature during metamorphic cooling of the parent body. The second type of data gives the rate at which the sample is thought to have cooled through a particular closure temperature. Critical to the comparison between these data and numerical results is the choice of peak temperatures used to distinguish each petrologic type: data from the literature are also used to motivate this choice. We discuss our various data sources below.

2.1.1. Closure times

Closure time is defined as the difference between calcium–aluminum-rich inclusion (CAI) age and the closure age of the sample under consideration. We use a recently calculated CAI age of 4568.5 ± 0.5 Ma (Bouvier et al., 2007) for all data except those of Kleine et al. (2008), whose closure times use the statistically indistinguishable CAI age of 4568.3 ± 0.7 Ma (Lugmair and Shukolyukov, 1998).

(1) *^{40}Ar–^{39}Ar closure times:* ^{40}Ar produced by the radiogenic decay of K is retained in oligoclase feldspar below about 280 °C (Turner et al., 1978). The amount of ^{40}Ar and, therefore, the time taken for the sample to reach the closure temperature, is measured relative to artificially produced ^{39}Ar. Trieloff et al. (2003) performed Ar–Ar measurements on several samples (Table 1), and we include their results in our analysis. We have followed the recommendation of Trieloff et al. (2003) and subtracted 30 Ma from their closure times to account for recent recalibrations of the Ar–Ar age scale (Renne, 2000; Begemann et al., 2001; Trieloff et al., 2001).

(2) *Pb–Pb closure times:* Production of ^{207}Pb by the decay of ^{235}U early in the solar system allows age measurements of very old samples to be made through measurements of the lead ratio $^{207}Pb/^{206}Pb$. The reliability of this method for a particular sample can be gauged by comparing its results against those of the ^{238}U–^{206}Pb system. Pb–Pb closure times, which have a closure temperature in the range 430–530 °C, were used by Göpel et al. (1994) to date phosphates in ordinary chondrites. Their results are widely cited (e.g., Ganguly and Tirone, 2001; Trieloff et al., 2003; Bouvier et al., 2007), and we include them in our analysis. We also include related Pb–Pb measurements, made by Bouvier et al. (2007) and Amelin et al. (2005), that have closure temperatures of 680–880 °C. (A 480 °C Pb–Pb closure age of 77 ± 16 Ma for the Estacado meteorite is also available; Blinova et al., 2007. We acquired knowledge of this datum too late for it to be fully integrated into our analysis,