METEORITIC CONSTRAINTS ON THE 500 MA DISRUPTION OF THE L CHONDRITE PARENT BODY

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Abstract The high abundance of heavily shocked L chondrites (50%) with Ar-Ar ages of ≈ 500 My [1] suggests that the parent asteroid of these meteorites was catastrophically disrupted at that time [2]. The L chondrite Chico is a 105 kg meteorite containing approximately 60 % impact melt and 40 % host chondritic material [3]. The texture of Chico and other heavily shocked L chondrites indicates an origin close to the impact site and does thus provide clues to catastrophic fragmentation of asteroids. We have used data on the texture, post-impact thermal history, and exposure age of these meteorites to constrain their evolution. We suggest that after the 500 My event, the majority of these meteorites cooled relatively slowly (0.01-1°C/y) inside kilometer-sized fragments or rubble piles.

Introduction The study of cratering on asteroids and, in particular, catastrophic fragmentation suffers from a serious lack of physical data which can be used to constrain numerical models of the process. Some groups of meteorites which show evidence of catastrophic fragmentation may provide useful constraints [2]. The L chondrites are the most heavily shocked group of chondrites, with more than 50% of the samples having been shocked to more than 15 GPa [1] and all having Ar-Ar ages of ≈ 500 My. This is a higher fraction of shocked material than observed even within terrestrial impact craters [4] which suggests that the parent body was disrupted in the 500 My event [2,5]. The large proportion of impact melt observed in the L chondrite, Chico, and the occurrence of the melt as dikes intruded into the host chondrite, suggests that this meteorite was derived from a location close to the impact site. The thickness of kamacite rims in metal from the impact melt indicate post-impact cooling rates of 0.1°C/s at high temperatures (above 1150°C) and 0.01-1°C/y at low temperatures (700-500°C) [3]. The high temperature cooling rates are consistent with thermal equilibration of mixtures of melt and cold rocks with dimensions of decimeters. The slow low temperature cooling rates found in several heavily shocked L chondrites including Chico require a burial depth of at least several hundred meters if the rock was solid and less if it was fractured. Models of catastrophic fragmentation of asteroids suggest that the fragment size approaches zero near the impact site [6] which would suggest that these meteorites were derived from small fragments. On the other hand, studies of secondary craters on the Moon and Mars [7] and "megablocks" from the Ries crater suggest that kilometer-sized fragments can be ejected intact from impact craters.
We will discuss three scenarios that we considered to explain the formation of the features observed in L chondrites:
1. The L chondrite parent body was not catastrophically fragmented and Chico cooled at some depth under the crater floor.
If the high abundance of shocked L chondrites is a result of selective sampling of a crater floor on the parent body, then the thermal history of Chico could be the result of slow cooling at some depth under the crater floor. This would require a heated layer (≈ 1000°C) which was at least 1000 meters thick. Also, Chico must have cooled several hundred meters below the crater floor within the heated layer. In order to explain the high abundance of heavily shocked L chondrites, this scenario would require a later impact into the crater that delivered meter-sized fragments into Earth-crossing orbit. Exposure ages of L chondrites are diverse and all are younger than 500 Ma, indicating that such fragments experienced later impact stripping. Since the fraction of shocked material is very high, even if we assume that all of the L-chondrites were derived from the crater, this scenario also

implies that impacts outside the crater were unable to produce a significant amount of Earth-crossing fragments of unshocked L chondrite material.

2. The target material was broken into m-sized pieces and parts of it reaccreted into one or more rubble piles of kilometer size.

Experiments suggest that catastrophic fragmentation can produce "jets" of debris with small internal velocity differences [8], possibly resulting in loosely bound rubble pile bodies. This view is also supported by the relatively high abundance of terrestrial "doublet" craters [9] and of contact or nearly contact binary Earth-approaching asteroids (such as 4769 Castalia and 4179 Toutatis) which suggests that large fragments from asteroidal collisions can remain gravitationally bound. The fast low-temperature cooling rate of the heavily shocked L chondrite Ramsdorf (100°C/day) indicates a burial depth of $\approx$ 1m [10]. The fact that Ramsdorf survived to the present suggests that it was protected from space erosion by later accretion/rubble pile formation. A rubble pile scenario is thus consistent with the thermal histories of heavily shocked L chondrites and allows for small sizes of the fragments from which they were later derived. The lower thermal diffusivity of rubble would also allow for a smaller size of the rubble pile relative to a solid fragment. The slow post-impact cooling rate of Chico (0.01-1°C/y) is consistent with cooling in a rubble pile with a diameter of 100-1000 m or more, depending on the depth of burial.

3. A large fragment of the crater floor was dislodged from the parent body.

Although models of catastrophic fragmentation suggest that the material near the impact site is broken down to very small pieces, the intrinsic uncertainties are large, and evidence from large craters suggests that kilometer-sized fragments may be ejected from locations near the impact site. Studies of kilometer-sized "megablocks" from the Ries Crater [4] show abundant dikes with sizes similar to the ones observed in Chico. By assuming that Chico cooled in the center of a spherical fragment, a lower limit on the diameter of the fragment of 400-4000 m is obtained, which is similar to the size of the "megablocks". However, unlike the impact melt dikes in Chico, the "megablock" dikes are filled with brecciated material and the "megablocks" are also much less shocked than Chico.

Discussion We suggest that scenarios 2 and 3 are the most likely. Both of these would also be consistent with the survival of a large fraction of the parent body (i.e., a non-catastrophic impact), but for reasons discussed in [2] this may not have been the case. The only model which is consistent with the numerical models of catastrophic break-up and the cooling rate data from Chico is the second scenario. Unfortunately, very little is known about the formation of rubble piles. Therefore, although crater models predict too small a fragment size, we conclude that the abundant evidence for large fragments from large lunar and terrestrial impact craters makes an origin for Chico inside a kilometer-sized fragment the most likely scenario. The "megablocks" from the Ries crater could be analogs to these fragments (e.g. they have similar dike patterns and similar overall dimensions). Finally, the evidence for re-accretion from Ramsdorf suggests that some of the fragments from the catastrophic disruption of the L chondrite parent body 500 My ago may have re-accreted to form rubble piles.

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