COLLISIONAL HISTORIES OF ORDINARY CHONDRITE PARENT BODIES: INFORMATION FROM SHOCK-INDUCED HIGH-PRESSURE MINERALS.

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Introduction: Asteroid collision is one of the major processes that accounts for the main belt dynamic evolution and the delivery of meteorites to the Earth. A critical question for the main belt study is whether the meteorite flux is dominated by several of the largest asteroid collisions or by collisions of the small sized bodies. While N-bodies simulation method improves our understanding of main belt dynamic, the answer, however, is still debatable because the physics of asteroid collision and meteorite transportation is not completely understood. Besides the dynamics, meteoritical study can also be useful for addressing this question.

High-pressure minerals in shocked chondrite are a robust product of asteroid collision. Shock pressure-temperature condition (P-T-t) can be extracted from high-P minerals to reflect the nature of their corresponding collision [1]. However, they are not extensively used to constrain the collision scenario in the main belt because of the vague linkage between chondrites and their potential source bodies. In this study, we investigated several representative, highly shocked, L and LL chondrites to suggest the possible size of their parent body collision. We also introduce a method for systematically linking the shock metamorphic features in meteorites to their impact origin.

Sample and method: Thin sections of S5-6 L chondrite Acfer 040, RC 106 and Mbale and S4-6 LL chondrite NWA 757 are investigated with optical, scanning electron and transmission electron microscope in LeRoy Eyring Center for Solid State Science (LE-CSSS) at Arizona State University, to characterize high-pressure minerals. Finite Element Heat Transfer (FEHT) code is used to model quenching shock melt to constrain shock duration.

P-T-t of shocked ordinary chondrites:

High-pressure minerals. Crystallization assemblages of shock melt record the pressure during solidification [2]. Therefore shock-melt crystallization through time can record the evolution of pressure condition. The quench time of a shock melt vein is primarily dependent on the volume and geometry of the melt. Other factors such as the thermal conductivity of the material and the temperature difference between the melt and host-rock do not seem to vary significantly between thin and thick melt veins. The high-pressure assemblage versus melt-vein thickness is summarized in Table 1. The crystallization pressure is estimated using the liquidus phase diagram from high-pressure experiment [2, 3]. Here we do not suggest the crystallization during shock reaches thermal-dynamic equilibrium and occurs under exactly the same pressure range as static experiments. However, the chondritic melt crystallizes fast enough to produce the liquidus-solidus phases that are consistent with experiments.

Sample	Melt vein	Assemblage	Pressure
Acfer 040 (L)	separated 0.1mm vein	bgm + rwd	>26 GPa
	network of 0.1 to 1.5mm veins	rwd + aki	~23 GPa
RC 106 (L)	separated 2mm vein	rwd + maj + mw	22-25 GPa
Mbale (L)	separated 1mm vein	wads + maj + mag	15-17 GPa
NWA 757 (LL)	network of 0.3 to 1mm veins	rwd + maj + mw	22-25 GPa

Table 1. The high pressure crystallization assemblage in the samples. Abbreviation: rwd-ringwoodite, maj-majoritic garnet, aki-akimotoite, bgm-bridgmanite, mw-magnesiowüstite, mag-magnetite

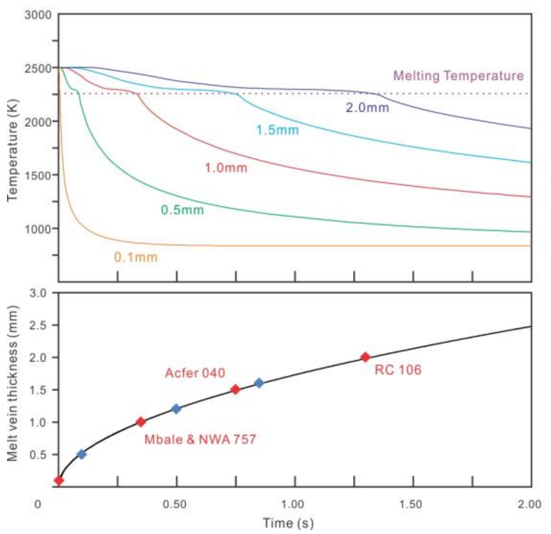

Figure 1. The cooling history of the center of melt veins with different thickness (upper). The red diamonds on the melt-vein thickness vs. quench time diagram (lower) are conditions from the real samples.

Thermal modeling. We employ FEHT code to calculate the cooling history of the investigated melt veins. The model is by one-dimensional heat transfer from melt to host-rock. The correlation between vein center quench time and vein thickness follows approximately a power law (Fig. 1). The result is useful because the quench time of the melt vein center provides a lower bound for the shock pulse. The shock pressure has to be above the crystallization pressure through the quench time if the high-P mineral assemblage is constant throughout the vein. It is noteworthy that the cooling of a network of veins is significantly slower than separated veins of the same thickness, which is not considered in our 1D model.

From the HP assemblage and thermal modeling, Acfer 040 is likely shocked to above 26 GPa for approximate 50 ms. The pressure drops to ~23 GPa at 0.75 s with the thick melt vein solidifying. RC 106 indicates a 1.3s shock pulse at 22-25 GPa. Mbale experienced 15-17 GPa shock pulse for at least 0.35 s. The shock pressure of LL chondrite NWA 757 is similar to that of RC 106 with possibly shorter shock pulse.

Asteroid collision: Shock pressure and pulse duration in the meteorite constrains the velocity and size of the colliding asteroids. The planar impact approximation technique can be used to simplify the calculation of pressure and compression duration with a given projectile [4]. The mean pressure P is expressed with $P = \rho_o U u_p$, where ρ_o is the initial density of the material, U is shock velocity and u_p is particle velocity. The empirical equation for shock velocity and particle velocity is $U = C + Su_p$. For a known material, C and S can be considered as constants. We add up the mineral constituents of ordinary chondrite to get the hugoniot of the bulk material [2]. The parameters are C=5.55 km/s, S=0.806 and ρ_o=3.30 g/cm^3. Assuming the projectile and target are both chondritic asteroids, the common particle velocity at contact is $u_p=v_i/2$ for an impact velocity v_i.

Shock pulse t is estimated by adding the time t_c for shock wave to reach the rear surface of the projectile with the time t_r for the rarefaction wave to traverse the compressed projectile. Thus $t = t_c + t_r = L/U + (\rho/\rho_o)L/c_r$, where c_r is the rarefaction wave speed, estimated by $c_r = [(K_o + nP/\rho)]^{1/2}$. K_o is bulk modulus and constant $n = 4S-1$.

A mean shock pressure versus shock pulse diagram is shown in Fig. 2. The three solid lines represent the shock pressure-duration correlation for 1 km, 3 km and 5 km diameter projectiles. The P-t condition of all the four samples fall in the area between the 1 km and 5 km curves, suggesting the diameter of their corresponding projectiles are likely between 1 and 5 km. The impact velocities for all the samples are close to 2 km/s.

Discussion: The calculations indicate the three L and one LL highly shocked chondrites experienced similar condition from asteroid collisions. Although the samples do not fall on a P-t correlation curve for a single parent body with certain diameter, their comparable conditions suggest collisions of kilometer-sized bodies might be capable of producing the shock conditions for all the samples. It is noteworthy that we likely underestimate the projectile size because the shock pulse constrained by quench time can be longer with the reheating between adjacent veins in more realistic 3D model. The planar impact approximation is a simplified model for calculating the mean shock pressure during contact and compression. In realistic asteroid collisions, the pressure distribution of the target is more complex. Also the shock from jetting or excavation flow, instead of compression, could also produce the local melting under pressure. Further hydrocode simulation is needed for more precisely constraining the asteroid collision.

Within the uncertainties of the method, highly shocked ordinary chondrites, including H chondrites from other studies, all seem to be produced by moderately large asteroid collisions. This is in support of the hypotheses that large collision makes meteorite flux, if majority of weakly shocked samples experience the same events and have consistent cosmic ray exposure ages. However, the exposure age of L chondrites are scattered, although L impact melt Ar-Ar dating indicates a catastrophic disruption of their source body [5, 6]. In contrast, the exposure age of LL chondrites are well concentrated while LL rarely have large impact signature. It is possible that the original chondrite parent bodies were catastrophically disrupted leaving fragments as source bodies with distinct shock level and cosmic exposure histories.

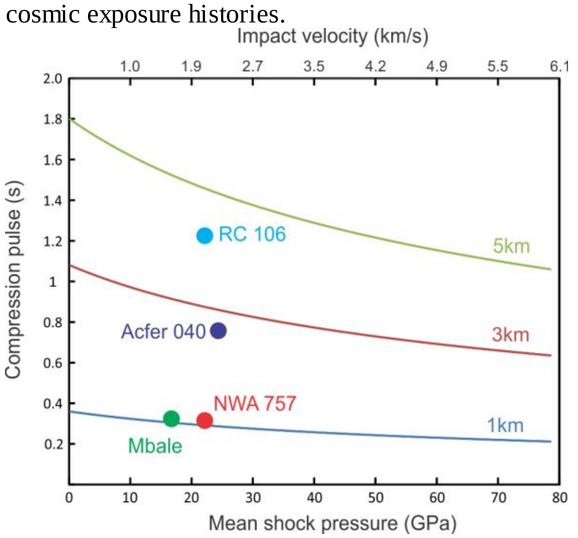

Figure 2. The shock pressure-pulse correlation for 1 km, 3 km and 5 km projectiles (solid lines). The solid circles are the pressure-pulse condition of the samples. Note the impact velocity (upper axis) that corresponds to the pressure (lower axis) is not linear.

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