Deciphering the Impact Dynamics of Ordinary Chondrites

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Introduction: Retracing the collisional history of asteroids is the key to understand the early dynamics of the Solar System. This can be attempted through the investigation of meteorites presenting shock melt veins, traces of the asteroidal impacts on parent bodies. Several studies designed to uncover the timescales of the asteroidal collisions based on high pressure polymorph assemblages, their crystal growth kinetics and associated chemical redistribution (of Mn, Ca and Fe) between resulting assemblages have been undertaken [1-6]. Somewhat contradictory timescales ranging from microseconds to minutes were obtained. This discrepancy led to the need for a robust method to study high pressure polymorphs. Here, we carried out nanoSIMS analyses to characterize high pressure polymorphs assemblages. We first verified the validity of this approach by comparing nanoSIMS and TEM chemical profiles of the exact same assemblages. We demonstrate that the NanoSIMS equipped with the new RF plasma source can adequately characterize chemical gradients in shocked meteorites. Then, optical, structural and chemical measurements were performed on seven different meteorites, on ringwoodite ($(Mg,Fe)_2SiO_4$), as well as akimotoite ($MgSiO_3$) when possible. Based on this revised method we initiate a database of meteoritic shock timescales and discuss the implications on the shocked meteorites parent body.

Methods: Thin sections of Sixiangkou (L5-6), Acfer 040 (L5-6), NWA 757 (LL5), and Tenham, NWA 2478, Coorara, Dhofar 649 (all L6) were first observed with optical microscopy. A Renishaw InVia Reflex Raman microspectrometer (IMPMC) was then used to determine the structure of selected minerals. A laser beam ($\lambda=532nm$) was focused onto the sample for 5 seconds and with 5 to 20 stacked measurements. Polymorph textures were investigated by SEM with a Zeiss Ultra55 SEM-FEG (IMPMC). Chemical maps of ^{44}Ca, ^{25}Mg, ^{28}Si, ^{23}Na, ^{55}Mn, and ^{56}Fe were acquired with a NanoSIMS 50 (MNHN) over selected $20x20\mu m$ areas in order to derive chemical profiles. In order to validate the nanoSIMS approach, FIB sections were prepared, studied via TEM, and then deposited onto aluminum plots to be carbon coated and observed via nanoSIMS. The resulting profiles were then compared.

Results: As for the TEM-nanoSIMS comparisons, overall, the profiles are very similar. Slight differences in the widths of Mn profiles in ringwoodites were observed when comparing the NanoSIMS to TEM profiles. However, these differences do not significantly change the resulting timescales. Furthermore, akimotoite presents even more TEM-consistent profiles. This mineral is thus a precious resource when calculating shock timescales.

While various microstructures were found in the samples [7], all contained ringwoodite in their shock melt veins. These could be found as lamellae inside olivine crystals in all samples but Coorara and Acfer 040. In those, the ringwoodite formed rims around olivine crystals and was also present in interwoven assemblages (Fig 1.C). These textures were also described in Peace River [6]. In the other meteorites, different types of lamellae were observed. In NWA 757 and Tenham, dendrites contain an iron poor, thinner center and coarser, iron enriched edges (Fig 1.A) whereas in NWA 2478 they appear homogenous and aligned (Fig 1.B.). In Dhofar 649, both textures were found (Fig 1.D.) In Sixiangkou, the lamellae appear to be successions of discontinued, oriented crystals.
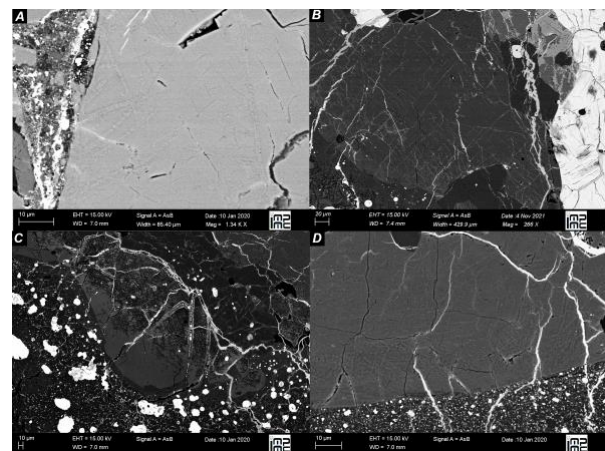

*Fig 1: Example of ringwoodite assemblages:
A: NWA 757, B: NWA2478 C: Coorara, D: Dhofar 649.*

Akimotoite was found in Tenham and Sixiangkou as crystallites. Lamellae were also found in Tenham. In Acfer 040, however, akimotoite appears as patches in $MgSiO_3$ glass. All these polymorph textures allowed us to estimate shock timescales.

Discussion: Using the newly measured ringwoodite lamellae width and diffusion profiles, it is possible to deduce shock timescales for the meteorites (see Fig 2.). We note that the results obtained via akimotoite appear to be consistent with the values derived from ringwoodite, supporting the idea that akimotoite is a viable shock marker.
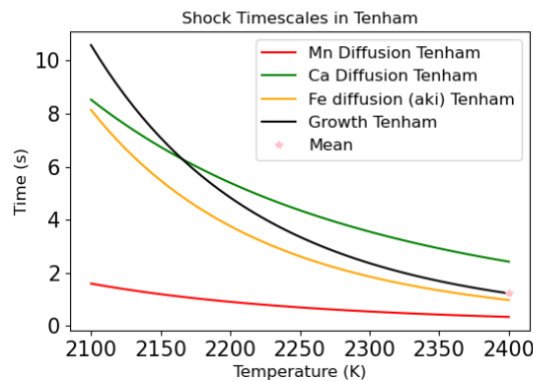

Fig 2: Example of shock timescales determined by diffusion and growth rate profiles. The values are presented in function of the temperature as it is difficult to evaluate for shock melt veins.

Assuming a temperature of 2400K in the veins, which is the melting temperature of a silicate composition such as the Allende CV3 chondrite [8], the resulting timescales are provided in table 1. Following the empirical laws correlating shock timescale, impactor velocity and impactor diameter detailed in [9], the impactor diameters can be deduced. Assuming that the parent body was big enough not be volatilized by a collision with the impactor [7], it is possible to deduce a minimal diameter for the parent body.

Meteorite	Timescale (s)	Impactor (km)	Parent Body Radius (km)
Tenham	1.2	6	56
Dhofar 649	1.4	7	62
NWA 757	0.9	4.5	47
NWA 2478	1.4	7	62
Sixiangkou	6.9	14	93
Acfer 040	16.4	82	270
Coorara	11.3	34	159

Table 1: Calculated shock timescales, impactor and parent body radii

Three hypotheses could explain the differences in textures between chondrites such as Acfer 040 or Coorara and the other mentioned L6: (i) They come from a different parent body explaining the difference

in shock timescale and derived parent body size; (ii) they result from a different P-T-t path within the same impact or (iii) they originate from very different zones in the parent bodies. We currently favor hypothesis (i), as a dichotomy is observed among many samples with some presenting abundant fractional crystallization textures (Fig. 2 and 3).
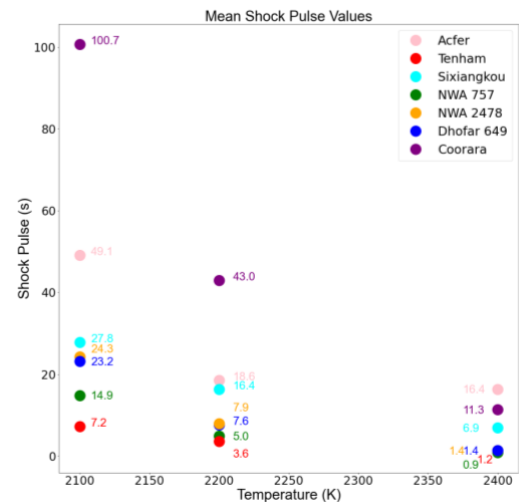

Figure 3 : Shock timescales obtained for an array of meteorites – two separate groups are clearly visible.

These values and conclusions, however, could be refined by determining diffusion coefficients for the relevant phases as well as growth rates, notably for akimotoite, to get another constrain on the shock pulse duration. Furthermore, dating of the impacts could allow us to assess the validity of the several parent body hypothesis.

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