

Introduction

- Impact cratering alters the texture and mineralogy of rocks via shock metamorphism. The amount of shock metamorphism can be quantitatively evaluated using X-ray diffraction (XRD) methods.
- Uchizono et al. [1] use the lattice strain (ϵ) of olivine to determine the peak shock pressure experienced by a meteorite.
- McCausland et al. [2], use the strain-related mosaicity (SRM) of olivine to sort meteorites into various shock stages.
- Both methods are useful for evaluating shock metamorphism, however, these methods are only applicable to olivine-bearing rocks.
- This work aims to expand on these XRD-related methods by creating calibration curves to relate ϵ and SRM in clinopyroxene (Cpx) to the peak shock pressures they have experienced using artificially shocked samples.

Samples and Tools

- Both ϵ and SRM were determined using XRD methods. Data was collected with a Bruker D8 Discover *in situ* micro X-Ray Diffractometer (μ XRD) (Fig. 1) [3] with Co $K\alpha$ radiation ($\lambda = 1.79026 \text{ \AA}$) with nominal 300 μm beam diameter, and a Vantec-500 Area Detector.
- Samples A1-A7 (Fig. 2A) were sent to the University of Kent to be shocked with the two-stage light gas gun (LGG) there [4]. Sample A0 is an unshocked augite sample of identical composition.
- Samples EXP2 and HEXP6 (Fig. 2B) were shocked at the Experimental Impact Laboratory of NASA-JSC. EXP2 was shocked with a vertical gun (VG) and HEXP6 was shocked with a flat plate accelerator (FPA).
- Samples B1-B3 (Fig. 2C) were shocked by a FPA by Meyer et al. [5].
- The created calibration curves were applied to the martian meteorites Nakhla and Zagami to evaluate effectiveness.
- Nakhla is a clinopyroxenite. Cpx in Nakhla shows exsolution features (Fig. 2D), while both Cpx and olivine show undulatory to mosaic extinction. This places it in the shock stage U-S4 (14-28 GPa) [6]. Using Uchizono et al.'s [1] calibration curve, Jenkins et al. [7] have determined that it had experienced 18.0 ± 0.6 GPa of peak shock pressure.
- Zagami is a gabbro composed of Cpx and plagioclase. The Cpx shows exsolution features and mosaic extinction, while the plagioclase has been completely converted into feldspathic glass (Fig. 2E). This puts it in the shock stage U-S5 (28-50 GPa) [6]. Using the refractive index of feldspathic glass, Fritz et al. [8] have determined that it experienced 29.2 ± 0.6 GPa of shock pressure.

Methods: Strain-Related Mosaicity

- General Area Detector Diffraction System (GADDS) images depict XRD data in a manner similar to Debye-Scherrer films.
- Unshocked coarse-grained samples (large individual crystals) yield single diffraction spots (Fig. 3A) [3]
- Shocked samples will show strain-related mosaicity (SRM) [3,7,9,10] and sometimes asterism (Fig. 3B and Fig. 3C, respectively) [3, 9].
- SRM is the misorientation of subgrains smaller than $\sim 5 \mu\text{m}$, while asterism is the misorientation of subgrains larger than $\sim 15 \mu\text{m}$ [9]. SRM can be determined by measuring the peak Full-Width-Half-Maximum (FWHM_χ) of an intensity versus chi (χ) plot (Fig. 3D) [10].

Methods: Lattice Strain

- The peak width of diffraction peaks in an intensity versus 2θ plot increases linearly with $\tan\theta$. The rate of this increase is greater with higher lattice strain, ϵ [11].
- This can be described with a Williamson-Hall (WH) plot (Fig. 4), which has the equation $\beta = 4\epsilon \tan\theta + \beta_0$, where β is a measurement of peak width known as integral breadth, and β_0 is a constant [1].
- The lattice strain experienced by the crystal grain can be determined from the slope of the trend line of the WH plot (slope = 4ϵ).



Fig. 1. The Bruker D8 Discover μ XRD with sample A2 on XYZ stage. Co source on top left, microscope/laser top centre, Vantec-500 to right.

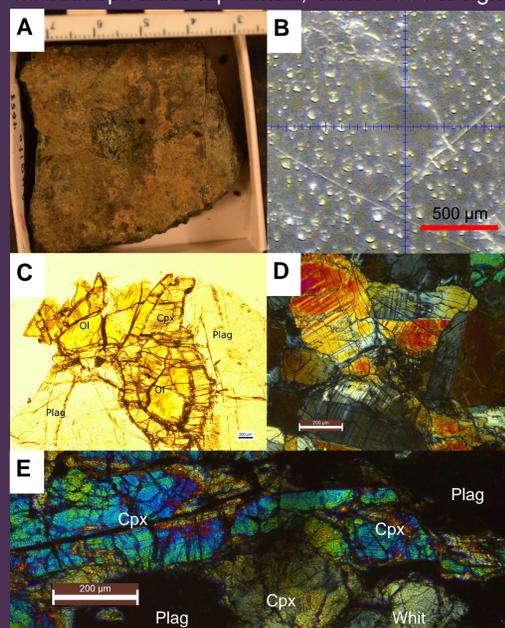


Fig. 2. Analyzed samples. A) Sample A2. Image taken by Kathryn Harriss. B) Sample HEXP6 target 1 on the μ XRD. Photomicrographs: C) Sample B3 in plain polarized light, showing olivine (Ol), Cpx, and feldspathic glass (Plag) are labelled. D) Nakhla in cross polarized light (xpl) showing exsolution features and undulatory extinction in Cpx. Cpx is the dominant mineral shown in this image. E) Photograph of Zagami taken in xpl, showing exsolution and undulatory extinction in Cpx, and isotropic feldspathic glass (Plag). Whitlockite (Whit) is also shown.

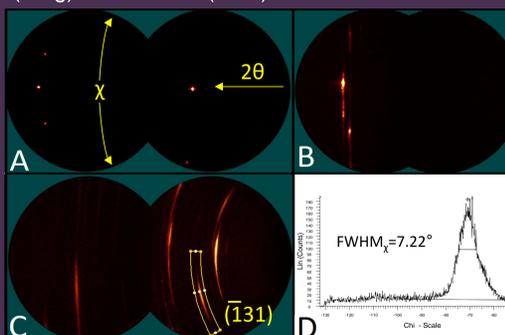


Fig. 3. GADDS images of samples. A) GADDS image from an unshocked piece of spall from the 101 GPa sample (A7). B) GADDS image from the bottom of the crater of A2 showing asterism. C) GADDS image from HEXP6 showing SRM. D) SRM measurement of peak (-131) in HEXP6 corresponding to a FWHM_χ of 7.22°

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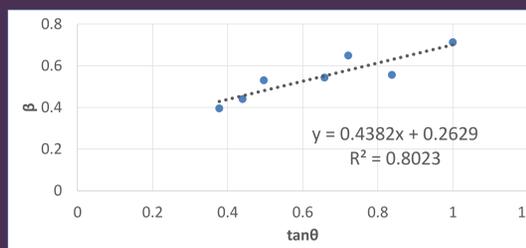


Fig. 4. Williamson-Hall plot for the centre of the crater of sample A1. Sample A1 was shocked to 8 GPa with a LGG.

Results and Conclusions

- Both ϵ and SRM values from samples A1-A7 were at their highest at the centre of the "impact craters" of the samples. Other locations showed ϵ and SRM values similar to A0 (unshocked) (Fig. 5 and 6). Only data from the centre of the craters were used for the calibration curves.
- Error for ϵ value was calculated using the standard error of regression, while the error for peak SRM value was determined using standard error. Any ϵ value with an error greater than $\pm 0.120^\circ$ was discarded from the calibration curve.
- Because of the variability of SRM, the peak SRM of each shock pressure was used for the SRM calibration curve (Fig. 5).
- When applying Nakhla and Zagami to these calibration curves, only the top 25% of ϵ and SRM values were used to determine peak shock pressures, to account for the heterogeneity of shock metamorphism. To ensure that no single grain dominated the sample set, the top 25% of measured SRM values for each grain were used.
- Applying our SRM calibration curve to Nakhla gave a peak shock pressure of 14 ± 11 GPa, which is in error with both its shock stage and Jenkins et al.'s [7] results. When applied to the ϵ calibration curve, Nakhla gave a peak shock pressure of only 3 ± 6 GPa. This is in disagreement with its shock stage and Jenkins et al.'s [7] results.
- Applying our SRM calibration curve to Zagami gave a peak shock pressure of 56 ± 11 GPa. This is within error of its shock stage, however is in disagreement with Fritz et al.'s [8] results. When applied to the ϵ calibration curve, Zagami gave a peak shock pressure of 25 ± 6 GPa. This is within error of both its shock stage and Fritz et al.'s [8] results.
- Cpx appears to be more sensitive to changes in SRM than ϵ . The SRM calibration curve lacks accuracy at higher shock pressures, likely due to a lack of data, causing higher SRM values to be inadequately represented. The ϵ calibration curve should not be applied to rocks that have experienced low shock, however, it shows potential for rocks that have experienced moderate to high shock.

Table 1. Lattice strain (ϵ) and SRM (top 25%) for samples.

Sample	Peak Shock Pressure (GPa)	Location	$\epsilon \pm$ Standard Error of Regression ($^\circ$)	Top 25% SRM \pm Standard Error ($^\circ$)				
A0	0	N/A	0.086 \pm 0.055 0.087 \pm 0.068	0.91 \pm 0.05				
A1	8	Crater Centre	0.110 \pm 0.097 0.134 \pm 0.070	2.16				
		Crater Wall	0.094 \pm 0.111					
A2	22	Crater Centre	N/A	0.97 \pm 0.06				
		Crater Wall	0.118 \pm 0.074	0.87 \pm 0.07				
A3	31	Spall	0.092 \pm 0.064 0.057 \pm 0.203 0.090 \pm 0.026 0.100 \pm 0.049 0.089 \pm 0.005	1.72 \pm 0.38				
			HEXP6		0.250 \pm 0.017	9.01 \pm 0.90		
			A4		N/A	3.97		
			B3		50	N/A	0.243 \pm 0.106 0.317 \pm 0.120	7.35 \pm 0.72
							A7	
Nakhla	18.0 \pm 0.6 ^a	Top 25% Most Shocked Grains	0.184 \pm 0.538 0.189 \pm 0.430	2.55 \pm 0.22				
Zagami	29.2 \pm 0.6 ^b	Top 25% Most Shocked Grains	0.184 \pm 0.538 0.189 \pm 0.430	9.14 \pm 0.46				

^aValue from Jenkins et al. [7]

^bValue from Fritz et al. [8]

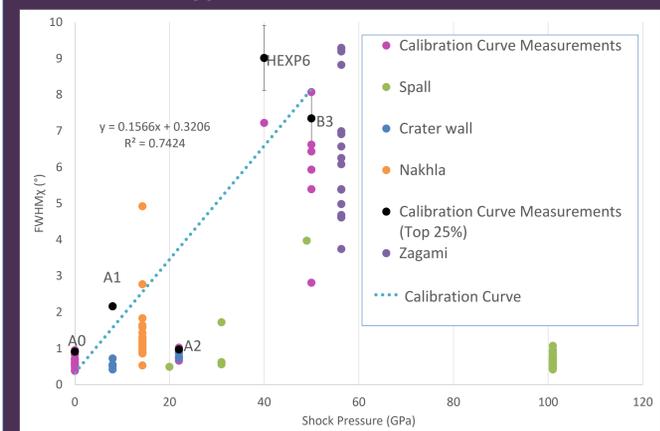


Fig. 5. SRM calibration curve. Calibration curve points are labelled with the corresponding sample. Shock pressures calculated with this curve have a standard error of the estimate of ± 11 GPa.

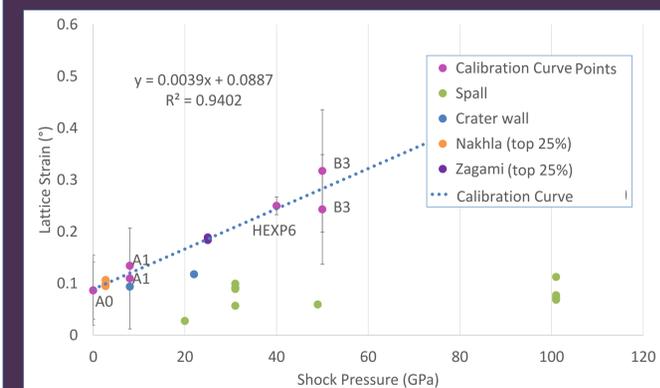


Fig. 6. ϵ calibration curve. Calibration curve points are labelled with the corresponding sample. Shock pressures calculated with this curve have a standard error of the estimate of ± 6 GPa.

References: [1] Uchizono, A. et al. (1999) *Mineral. J.*, 21, 15-23. [2] McCausland, P. J. A. et al. (2010) *AGU Fall Meeting*, Abs. # P14C-031. [3] Flemming, R. L. (2007) *CJES*, 44, 1333-1346. [4] Hibbert, R. et al. (2017) *Procedia Engineering*, 204, 208-214. [5] Meyer, C. et al. (2011) *MAPS*, 46, 701-718. [6] Stöffler, D. et al. (2018) *MAPS*, 53, 5-49. [7] Jenkins, L. E. et al. (2019) *MAPS*, 1-17. [8] Fritz, J. et al. (2003) *LPSC XXXIV*, Abs. # 1336. [9] Vinet, N. et al. (2011) *Amer. Mineral.*, 96, 486-497. [10] Izawa, M. R. M. et al. (2011) *MAPS*, 46, 638-651. [11] Williamson G. K. and Hall W. H. (1953) *Acta Metallurgica*, 1, 22-31.