SHOCK (S4 – S5) HETEROGENEITY IN PULSORA CHONDRITE (H5) – A SEMI-QUANTITATIVE APPROACH.

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Introduction: Pulsora (H5) was a meteorite fall documented in NE Rutham, Malwa, Madhya Pradesh, India on 16th March 1863. In situ trace elements and REE analyses of silicate mineral phases (particularly olivine and enstatite chondrules) from Pulsora (H5) have been carried out using LA-ICP-MS (Quadrapole) [1]. Detailed petrography of shock metamorphic features, shock calibration from Laser Raman Spectroscopy (LRS) and distribution of full width at half maximum (FWHM) values in particular of orthopyroxene and olivine have been attempted in Pulsora (H5) chondrite for the first time for semi-quantitative approximation of shock metamorphic grade.

Methodology: Raman spectra were obtained using a Renishaw In-Via Reflex Micro-Raman instrument at GSI, NCEGR Kolkata. The data were obtained using a 514 nm edge Ar^+ laser (gratings: 2400 lines/mm) and a 785 nm edge diode laser (gratings: 1200 lines/mm), having ~ 0.84 – 1.2 µm spot beam diameter and focus energy varies from 12 – 15 mW to acquire the Raman signal. Accumulations time of Raman spectra lasted for 10 – 100 s. A charge coupled device (CCD) detector is attached with an automated confocal microscope (Leica made) having objective lenses of 5X (N.A = 0.12), 20X (N.A = 0.40), 50X (N.A = 0.75) and 100X (N.A = 0.85; N.A – Numerical Aperture). The room temperature was maintained at 22 ± 1^0C. The peak positions of Raman spectra were determined by the Wire program (Version 3.4). The spectral resolution for each Raman vibrational mode is on the order of ± 1-2 cm^{-1}. The Full Width at Half Maximum (FWHM) is the difference between the two peak values of the independent variable at which the dependent variable is equal to half of its maximum value. Mineral chemical data were acquired using a CAMECA SX-100 electron microprobe (EDS + WDS) analyser at the EPMA Laboratory, GSI, NCEGR Kolkata. An accelerating voltage of 15 - 20 kV and beam current of 12-15 nA with ~ 1 µm beam diameter were used for all samples of this study. These data were corrected internally (PAP) and a set of natural standards were used to control analysis results, with synthetic standards being used for Mn and Ti.

Results: Pulsora (H5) chondrite comprises olivine + orthopyroxene + clinopyroxene (Opx > Cpx) + Na-plagioclase glass + Fe-Ni metals (kamacite and taenite) + magnetite ± troilite ± merrillite. The chondrules are exclusively made of olivine and orthopyroxene ± clinopyroxene, whereas the interstitial spaces are occupied by plagioclase glass. Orthopyroxene chondrules, fragments and clasts are more abundant than olivine chondrules and clasts. The size of chondrules varies from 300 µm – 1 mm (diameter), with chondrule : matrix ratio is approximated by 60 : 40. Individual chondrule's margins are moderately to well defined. Matrix is relatively finer grained (grain size < 100 µm), and partially recrystallized. Petrographic and combined BSE – SEM studies reveal that matrix is dominantly clastic in nature and mainly composed of tiny olivine and orthopyroxene, feldspathic glass, Fe - Ni metal components (both kamacite and taenite) and magnetite. Most of the Fe – Ni metals occur outside these chondrules, either forming partial or complete rims on chondrules, and also form equant or drop-shaped grains in the matrix. The mineral chemical data of different textural variants of olivine, orthopyroxene (mostly clinoenstatite), clinopyroxene (augite - diopside) and plagioclase glass (oligoclase to albite) are given in Table-1. Kamacite (α-Ni, Fe) contains Fe ~ 93 - 94% and Ni ~ 6 - 7% whereas Fe ~ 84% and Ni ~ 16% vary in taenite (γ-Ni, Fe). Different textural variants of olivine and orthopyroxene exhibit near consistent mineral chemical compositional range (X_{Mg}) suggesting Pulsora (H5) is an equilibrated ordinary chondrite (after Meteoritical Bulletin Database) having equilibration temperatures ~ 780 - 960ºC [2].

Table – 1: Mineral chemical data of Pulsora (H5) chondrite (PO: Porphyritic Olivine, PP: Porphyritic Pyroxene, GO: Granular Olivine, GP: Granular Pyroxene, RP: Radial Pyroxene after [3])

Mineral	Textures	X_{Mg}/Formulae
Olivine (Ol)	PO and GO chondrules with matrix component and within metals and shock veins	0.80 – 0.81 (X_{Mg})
Orthopyroxene (Opx)	PP and RP chondrules with matrix component and within metals and shock veins	0.797 – 0.833 (X_{Mg})
Clinopyroxene (Cpx)	Present as matrix component and chondrule (RP)	Augite to diopside composition ~ Wo_{35-48}

		En_{48-57} Fs_{4-8}
Plagioclase glass	Mostly associated with chondrules (PP and PO), also present in the partially recrystallized matrix	Plagioclase glass composition ~ Ab $_{73.4 - 82.3}$ An $_{12.7 - 18.4}$ Or $_{5 - 8.2}$

Granular or near equant shaped olivine crystals (GO chondrule) occur in aggregates within the matrix and show partial mosaicism. This chondrite is characterized by presence of several shocked opaque melt veins (MVs) and melts pockets (MPs) with interconnecting criss-cross shocked melt veinlets. Occurrence of Fe-Ni metals and magnetite along these fractures or melt veins has been observed. These anastomosing opaque melt veins surround/cut across shocked relict and/or recrystallized olivine and orthopyroxene grains. Small fragments of olivine and orthopyroxene are observed close to these shock melt veins (Figure 1). Some of these shock veins also contain fragments of the host meteorite. Raman peaks at 713 cm^{-1}, 736 cm^{-1}, 745 cm^{-1}, 767 cm^{-1}, 791 cm^{-1}, 917 cm^{-1} and 918 cm^{-1} exclusively represent presence of thin wadsleyite lamellae (a few µm) within host olivine (Figure 2; after [4]). In Pulsora (H5) chondrite, the calculated FWHM values of several orthopyroxene clasts and fragments (close to opaque melt veins, within melt veins and away from melt veins) show significant variation (11.88 – 49.92; Median = 17.67 and Avg.= 23.08) against Raman peak shifts of 232.52 – 1020 cm^{-1}, suggesting heterogeneous shock gradient across the melt veins. Orthopyroxene chondrules (PP, GP and RP) show variation of FWHM values 10.73- 51.93 (Median = 17.36 and Avg.= 19.11) against Raman peak shifts of 126-1021 cm^{-1} as shown in Figure 3. Olivine fragments within melt veins and pockets show considerable variation of FWHM values (12.89 - 40.02; Median = 19.86 and Avg.= 23.96) against Raman peak shifts of 821.02 - 855.84 cm^{-1}.

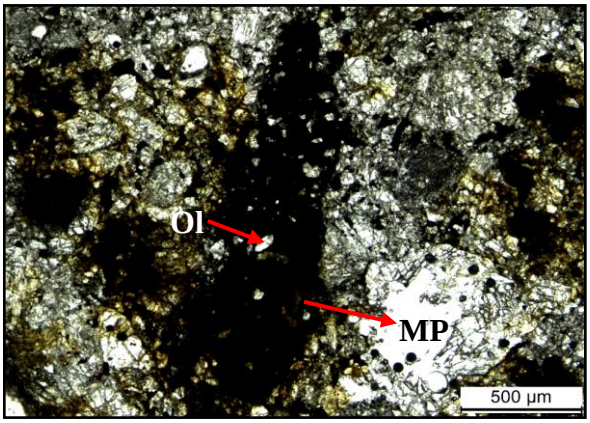

Figure 1: Melt pocket (MP) containing tiny Ol fragments in Pulsora (H5) chondrite (in PPL)

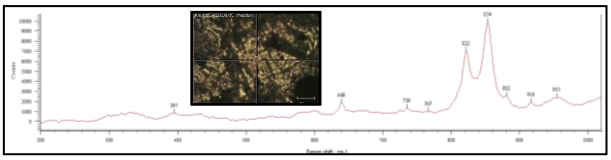

Figure 2: Raman spectra of wadsleyite (736 cm^{-1}, 767 cm^{-1} and 918 cm^{-1}) lamellae in Pulsora (H5) chondrite. Characteristic strong Raman bands at 822 cm^{-1}, 854 cm^{-1} and 955 cm^{-1} represent host olivine structure

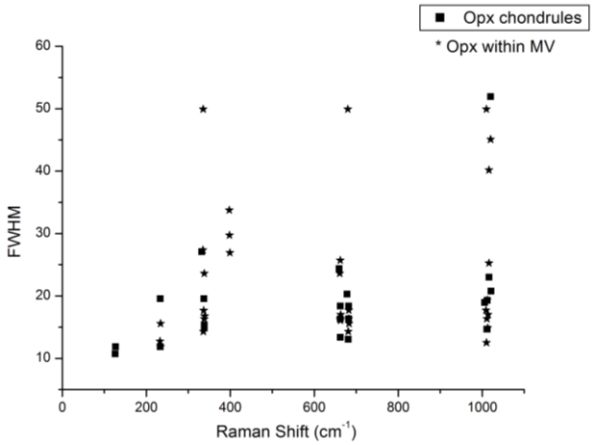

Figure 3: Full Width at Half Maximum (FWHM) values of orthopyroxene chondrules and fragments/clasts within shock melt veins (MVs) in Pulsora (H5) chondrite

Discussion: Presence of isotropic melt pockets and melt veins with fragments of olivine, orthopyroxene and opaque droplets, having wadsleyite lamellae within host olivine and Na-plagioclase glass veins and melt mosaic with Fe – Ni metal (kamacite and taenite) droplets suggest escalation of shock pressures ~ 40 GPa in Pulsora (H5) chondrite (moderately to strongly shocked; S4 – S5 after [5, 6]). Lower the FWHM values indicate more ordered structure for pyroxene and olivine. Thus petrographic and Raman spectroscopic studies suggest extreme shock heterogeneity in Pulsora (H5) chondrite even at microdomain level.

References: [1] Dutta A. et al. (2017) *80th Annual Meeting of the Meteoritical Society 2017 (LPI Contrib. No. 1987), Abstract # 6088* [2] Brey G. P and Köhler T (1990) *Journal of Petrolology 31*, 1353–1378. [3] Hutchison R. (2006) *Meteorites – A Petrologic, Chemical and Isotopic synthesis, Cambridge University Press.* [4] *RRUFF database (http://rruff.info/)* for identification of different mineral phases from the Raman spectrum data. [5] Rubin A. E. (1997) *Meteoritics & Planetary Science 32*, 231–247. [6] Stöffler D. et al. (1991) *Geochimica et Cosmochimica Acta 55*, 3845 – 3867.