HIGH POWER LASER-SHOCK EXPERIMENT OF CHONDRITES: CONTRIBUTION OF IMPACTS TO THE EARLY EARTH ATMOSPHERE

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Introduction: It has been hypothesized that extraterrestrial organic compounds were delivered to the early Earth by meteorites and comets during the Late Heavy Bombardment (LHB) [1]. There have been several exeriments that simulated the shock synthesis of organic compounds during the LHB [2, 3, 4, 5]. However, in the past studies using gas guns, it is difficult to perform an open system experiment at higher impact velocities than Earth's escape velocity (> 11 km/s). In order to simulate more realistic condition of the impact events, a high power laser compression experiment of natural meteorites up to 400 GPa have been carried out in this study. The produced volatile components, which might have been involved to prebiotic chemistry in the early Earth's atmosphere, are identified.

Experimental: Carbonaceous CM2 (Murchison) and ordinary LL3.6 (Parnallee) chondrites were used as impact-target samples. Pellets of the meteorites were prepared by diamond anvil cell, respectively. The thickness of the pellets was about 100 µm. The alminum (Al) or tantalum (Ta) foil was located in front of the sample as the ablator for the laser and for preventing the sample from blowing out. The laser-shock experiment was carried using GEKKO XII/HIPER laser system, Institute of Laser Engineering, Osaka University [6]. The laser wavelength, pulse width, and spot diameter were 1053 nm, ~20 ns, and ~0.4 mm, respectively. The shock pressures were 50-400 GPa for Murchison and 100-300 GPa for Parnallee. The shock-induced volatile components were in-situ analyzed by quadrupole mass spectrometry (QMS). Selected ions are summarized in Table 2. As controlled experiments, the same procedures were conducted without meteorite samples. Relative abundances of the released volatiles were estimated by integrating the time profiles of the individual m/z. Experiments were repeated to verify the results.

Results and discussion: At the pressure of 400 GPa, relative abundances of peaks for H_2 (m/z 2), CH_3^+ (m/z 15), CH_4 (m/z 16), C_2H_2 (m/z 26), $C_2H_3^+$ (m/z 27), $CHO^+/C_2H_5^+$ (m/z 29), CH_2O^+/C_2H_6 (m/z 30), C_2HO^+/C_3H_5 (m/z 41), $C_2H_2O^+/C_3H_6^+$ (m/z 42), $C_2H_3O^+/C_3H_7^+$ (m/z 43) and C_6H_6 (m/z 78) from Murchison meteorite were significanty higher than those from the controlled experiment (Fig. 1). H_2 is the most abundant, and C_1-C_2 components (CH_3^+, CH_4, C_2H_2, $CHO^+/C_2H_5^+$) are one order of magnitude lower than H_2. C_3-C_6 components ($C_6H_6C_2HO^+/C_3H_5$, $C_2H_2O^+/C_3H_6^+$, $C_2H_3O^+/C_3H_7^+$ and C_6H_6) are two order of magnitude lower than H_2 (Fig. 2).

Table 1. Selected ions for QMS analyses of the shock-induced volatiles

m/z	Ions and molecules	m/z	Ions and molecules
2	H2	34	H2S
14	$CH2^+$, NH^+	39	C3H3
15	$CH3^+$	40	C3H4
16	CH4, $NH2^+$	41	$C2HO^+$, $C3H5^+$
17	OH, NH3	42	$C2H2O^+$, $C3H6^+$
18	H2O	43	$C2H3O^+$, $C3H7^+$
			CO2, $C2H4O^+$,
26	C2H2	44	$C3H8^+$
27	$C2H3^+$	48	SO
28	CO, C2H4, N2	64	SO2
29	CHO^+, $C2H5^+$	78	C6H6
30	$CH2O^+$, C2H6	92	C7H8

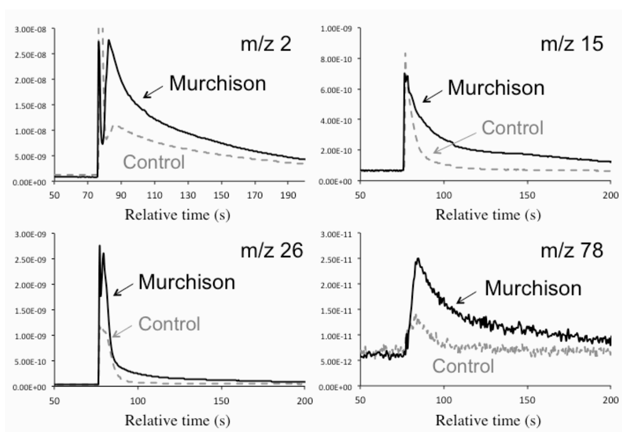

Fig. 1. Time profiles of H_2 (m/z 2), CH_3^+ (m/z 15), C_2H_2 (m/z 26), and C_6H_6 (m/z 78) from Murchison meteorite (black solid line) and controlled experiment (gray dashed line) at 400 GPa.

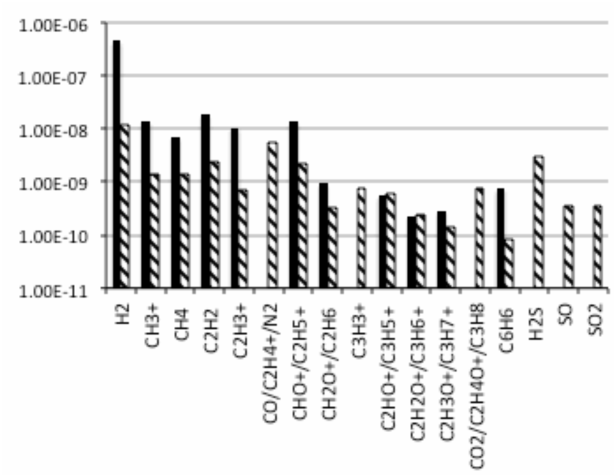

Fig. 2. Relative abundances of the released volatiles from Murchison meteorite at 400 GPa (black) and 50 GPa (diagonal line).

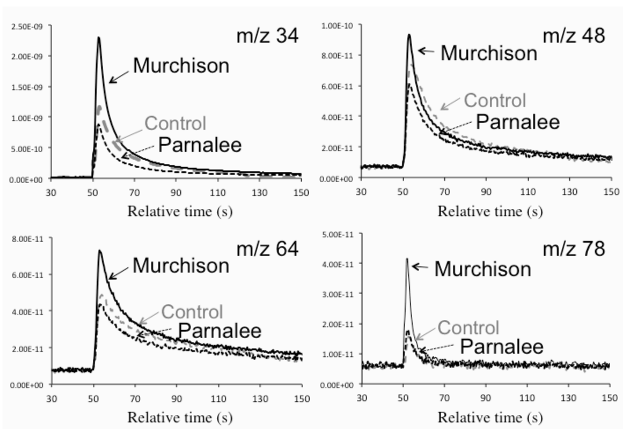

Fig. 3. Time profiles of H_2S (m/z 34), SO (m/z 48), SO_2 (m/z 64), and C_6H_6 (m/z 78) from Murchison meteorite (black solid line), Parnalee meteorite (black dotted line) and controlled experiment (gray dashed line) at 300 GPa.

These volatile components were unlikely "original" components of Murchison meteorite, but rather secondary products of the syntheses of the ions and radical species yielded through shock-induced decomposition of organic molecules in the meteorite. At the pressure of 50-200 GPa, sulfur-bearing compounds, such as H_2S (m/z 34), SO (m/z 48), COS (m/z 60), and SO_2 (m/z 64) were additionally identified from Murchison meteorite (Fig. 3), as well as the similar series of ions and molecules identified at 400 GPa. Similar observation has been reported by [7]. Relative abundance of H_2S is as high as C_2H_2 and CHO^+ (Fig. 2). We could not identify indigenous water from the meteorites, since they were also produced in high abundances from the controlled experiments.

On the other hand, relative abundances of the volatiles from Parnalee meteorite were mostly as low as those from control experiments at any pressure (Fig. 3), thus degassing of the meteorite rarely occurred.

It was previously reported that reduced volatiles are produced by shock reactions of nitrogen atmosphere, water, and metallic iron and inorganic carbon solid, which are constituents of ordinary chondrites [3, 4]. However, our results demonstrate that, even from an oxidized carbonaceous chondrite, the impact-induced volatiles contain high abundances of the reduced molecules such as hydrogen, a variety of hydrocarbons, CHO species, and sulfur-bearing compounds. They are clearly distinct from the major components (CO_2, H_2O, SO_2) yielded by pyrolysis of meteoritic organics (e.g., 250-1000°C, 15s) [8, 9]. Thus, shock process is a trigger of high-temperature reduction of organic C and S in carbonaceous chondrites. This study supports the hypotheses that impact degassing leads to a reductive chemical composition to Earth's early atmosphere (CO_2-N_2-H_2O) [10, 11]. The released reduced volatiles might have led to subsequent prebiotic chemistry in the early earth, e.g., Miller-Urey experiment, as well as HCN synthesized by interaction of impacting material with the ambient nitrogen atmosphere [12].

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