AN EQUATIONS OF STATE MODEL FOR RYUGU BASED ON THERMO-ELASTIC PROPERTIES OF THE RETURNED SAMPLES. K. Kurosawa[1], H. Genda[2], R. Hyodo[3], T. Nakamura[4], S. Tanaka[3], K. Sugiura[2], H. Yurimoto[5], T. Noguchi[6], R. Okazaki[7], H. Yabuta[8], H. Naraoka[7], K. Sakamoto[3], S. Tachibana[9], S. Watanabe[10], and Y. Tsuda[3], [1]Planetary Exploration Research Center, Chiba Institute of Technology (2-17-1, Narashino, Chiba 275-0016, Japan, kosuke.kurosawa@perc.it-chiba.ac.jp), [2]Tokyo Institute of Technology, [3]JAXA, [4]Tohoku Univ., [5]Hokkaido Univ., [6]Kyoto Univ., [7]Kyushu Univ., [8]Hiroshima Univ., [9]The Univ. of Tokyo, [10]Nagoya Univ.

Introduction: Carbonaceous asteroids have been thought to be a carrier of water and organics to the inner solar system [e.g., 1]. Thus, the origin and evolution of C-type asteroids has been one of major problems in planetary sciences. We now have the samples of the asteroid Ryugu, which is one of carbonaceous asteroids, collected by JAXA's Hayabusa2 spacecraft. Ryugu is expected to be a rubble pile of impact fragments of a 100 km-sized parent body [e.g., 2]. The initial location of the constituent materials of Ryugu in the parent body is required to be explored for decoding the origin and history of the carbonaceous asteroid from the samples.

According to a shock physics modelling by [3], the current Ryugu may consist of materials that originated from the vicinity of impact point of the parent body during a catastrophic disruption. We revisit this scenario based on the nature of returned samples [4, 5]. The sample analyses [4, 5] revealed that the Ryugu samples do not exhibit any shock-related features, including strong compression and intense heating, although a number of cracks are observed. The aqueously-altered nature of the samples indicates that the constituent materials of Ryugu is unlikely to have experienced >1 GPa and 90 °C after the formation. We newly constructed a numerical suite pertaining to the catastrophic disruption of a hypothesized Ryugu's parent body with two– (this study) and three-dimensional [6] hydrocodes. In this abstract, we address the peak pressure and temperature distributions in the parent body during the collision as a function of the initial locations in the parent body, and compare with the characteristics of the samples.

Methods:

EOS construction. Equations of state (EOS) should be modeled to conduct shock physics modelling [e.g., 7]. We used physical properties obtained from the third largest grain (C0002) among all returned samples [4]. C0002 was collected at the second touchdown site, and its large size made it possible to measure thermo-elastic properties, including bulk density, P- and S-wave speeds, thermal expansibility, and specific heat, with conventional methods with appropriate modifications [4, 8]. Based on the measured properties, the bulk modulus and the Grüneisen constant under the reference state Γ_0 were calculated.

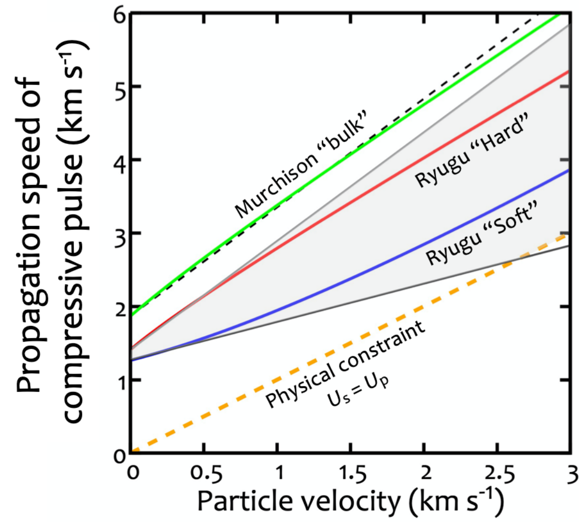

Figure 1. Hugoniot curves calculated by the Tillotson EOS with the parameters determined in this study. The grey shaded region corresponds to the allowable range determined by two target values of the slope s. The physical constraint ($U_S = U_P$) is also shown.

We chose the Tillotson EOS model [9] as a format of the EOS model for Ryugu because it has been widely used in the field of planetary sciences [e.g., 10]. We do not have any constraints on the compressibility against rapid compressions about the Ryugu grain because of the limited amount of the sample and the destructive nature of shock experiments. The compressibility is equivalent to the slope s of a Hugoniot curve on a particle velocity U_p and longitudinal wave speed U_s plane. By setting the "target value" of the slope s on a U_p-U_s plane, we constructed two types of the Tillotson EOS models with different compressibility, which are referred to as "soft" and "hard". The one value of s was derived from an empirical law $\Gamma_0 = 2s - 1$ [e.g., 7, 11], which has been conventionally used to predict the s value of unknown materials. The accuracy of the empirical law, however, is rather low especially at the materials with low densities, such as polymers, water, and a hydrated carbonaceous chondrite (Murchison). Thus, we also employed another value of s = 1.48, which is the same as Murchison meteorite [12], as an upper bound. Figure 1 shows Hugoniot curves on a U_p-U_s plane. We also constructed the Tillotson EOS pertaining to Murchison meteorite as a reference.

Despite the requirement of temperature *T* to compare with the petrological and chemical features of the samples, the Tillotson EOS does not explicitly provide temperature *T*. Thus, we approximately estimated *T* from density and internal energy with the method proposed by [13]. The Tillotson parameters determined in this study will be summarized in [4].

Pressure & Temperature estimation. We conducted a series of two-dimensional simulations, but with a high spatial resolution using the iSALE [e.g., 14–16]. The impactor radius was set to 6 km (Ryugu EOS) and 5.5 km (Murchison EOS). These impactor sizes were estimated by a series of three-dimensional hydrocode simulations [4, 6] with the EOS models constructed in this study to re-produce the largest fragment of Eulalia and/or Polana families, from which Ryugu may have come [2]. The impactor was divided into 50 cells per projectile radius. The impact velocity was fixed at 5 km s^{-1}, which is a typical impact velocity in the main asteroid belt [17]. The initial temperature was set to 220 K, which is close to the equilibrium temperature at the current orbits of Eulalia and Polana families [18].

Results: Figure 2 shows the peak pressure and temperature distributions after the collision as a function of initial locations in the case only without strength and porosity compaction. However, we confirmed that the isobaric line of 1 GPa is located far from the isotherm of 90 ℃ regardless of the EOS model and strength/porosity conditions. Further details will be discussed at the presentation and in [4].

Discussion & Conclusions: We conducted the shock physics modelling based on the actual asteroid sample for the first time. We showed that the shocked region experienced above 1 GPa is likely to be widespread in the hemisphere where impact occurs. The Ryugu would come from the locations far from the impact point as opposed to the prediction by the precede work [3].

Acknowledgments: We appreciate the developers of iSALE, including G. Collins, K. Wünnemann, B. Ivanov, J. Melosh, and D. Elbeshausen. We also thank Tom Davison for the development of the pySALEPlot.

References: [1] Hayatsu, R. & Anders, E. (1981) *Top Curr. Chem*, **99**, 1. [2] Sugita S. et al. (2019) *Science*, **364**, eaaw0442. [3] Michel, P. et al. (2020) *Nature Comm.*, **11**:2655. [4] Nakamura, T. et al., submitted. [5] Yokoyama, T. et al., submitted. [6] Genda, H. et al., This volume. [7] Melosh, H. J. (1989) *Impact cratering: A geologic process*, Oxford Univ. Press, New York. [8] Tanaka, S. et al., This volume. [9] Tillotson, J. H. (1962) *Technical Report GA-3216*, General Atomic Report. [10] Benz, W. & Asphaug, E. (1999) *Icarus*, **142**, 5. [11] Meyers, M. A. (1994) *Dynamic behavior of materials*. John Wiley & Sons, New York. [12] Anderson, W. W. & Ahrens, T. J. (1998) *AIP Conf. Proc.*, **429**, 115. [13] Ivanov, B. A. et al. (2002) *GSA special paper,* **356**, 587-594. [14] Amsden, A. A., et al. (1980) *LANL Report* LA-8095. 101 p. [15] Ivanov, B. A., et al. (1997), *IJIE*, **20**, 411. [16] Wünnemann, K., et al. (2006) *Icarus*, 180, 514. [17] Bottke, W. F. et al. (1994) *Icarus*, **107**, 255. [18] Walsh, K. J. et al. (2006) *Icarus*, **225**, 283.

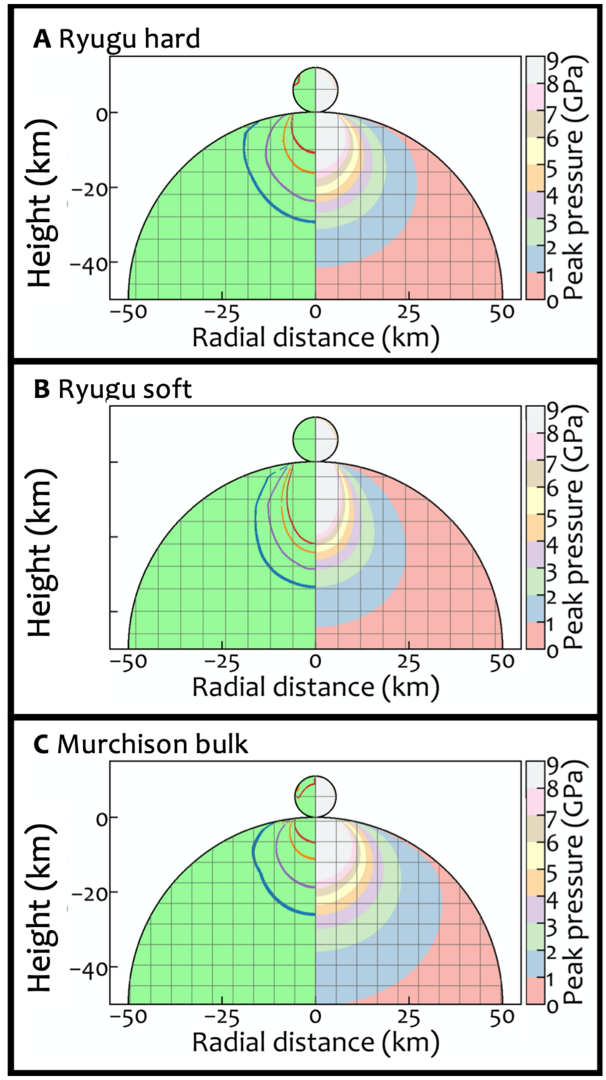

Figure 2. Provenance plots of peak pressure (right) and temperature (left) distributions. In the left panel, the isotherms of peak temperatures are shown as colored curves. The isotherms correspond to 500 ºC (red), 300 ºC (orange), 100 ºC (purple), and 0 ºC (blue), respectively, from the vicinity of the impact point toward the far side. The color scale indicates tracer peak pressures in the right panel.