ANOMALOUSLY POROUS AND DARK ROCKS ON ASTEROID (162173) RYUGU. N. Sakatani[1], S. Tanaka[2], T. Okada[2], T. Fukuhara[1], L. Riu[2], S. Sugita[3], R. Honda[4], T. Morota[3], S. Kameda[1], Y. Yokota[2], E. Tatsumi[5,2], K. Yumoto[2], N. Hirata[6], A. Miura[2], T. Kouyama[7], H. Senshu[8], Y. Shimaki[2], T. Arai[9], J. Takita[10], H. Demura[6], T. Sekiguchi[11], T. G. Müller[12], A. Hagermann[13], J. Biele[14], M. Grott[14], M. Hamm[14,15], M. Delbo[16], W. Neumann[13,17], M. Yamada[8], H. Suzuki[18], C. Honda[6], K. Ogawa[19], M. Hayakawa[2], K. Yoshioka[3], M. Matsuoka[2], Y. Cho[3], H. Sawada[2], K. Kitazato[6], T. Saiki[2], H. Imamura[2], Y. Takagi[20], H. Yano[2], K. Shirai[21], S. Nakazawa[2], M. Arakawa[21], K. Wada[8], T. Kadono[22], K. Ishibashi[8], [1]Rikkyo University, Japan. (sakatani@rikkyo.ac.jp) [2]Institute of Space and Astronautical Sciences, Japan Aerospace Exploration Agency, Japan. [3]University of Tokyo, Japan. [4]Kochi University, Japan. [5]Instituto de Astrofisica de Canarias, University of La Laguna, Spain. [6]University of Aizu, Japan. [7]National Institute of Advanced Industrial Science and Technology, Japan. [8]Chiba Institute of Technology, Japan. [9]Ashikaga University, Japan. [10]Hokkaido Kitami Hokuto High School, Japan. [11]Hokkaido University of Education, Japan. [12]Max-Planck Institute for Extraterrestrial Physics, Germany. [13]University of Stirling, UK. [14]German Aerospace Center (DLR), Germany. [15]University of Potsdam, Germany. [16]Observatoire de la Côte d'Azur, CNRS, France. [17]Universität Heidelberg, Germany. [18]Meiji University, Japan. [19]JAXA Space Exploration Center, Japan Aerospace Exploration Agency, Japan. [20]Aichi Toho University, Japan. [21]Kobe University, Japan. [22]University of Occupational and Environmental Health, Japan.

Introduction: Thermal inertia is key information on physical properties, such as grain size and porosity, of planetary surface materials. In general, porous materials have thermally insulation properties and thus low thermal inertia. Thermal infrared imager (TIR) onboard Hayabusa2 spacecraft revealed the global averaged thermal inertia of 200-400 J m^{-2} K^{-1} $s^{-0.5}$ (hereafter, tiu), and globally-distributed porous boulders (30-50%), whose porosity is much higher than carbonaceous chondrites, globally distributed on Ryugu [1,2,3]. In-situ radiometric observations by MARA onboard MASCOT lander also showed similar high porosity signature for a specific boulder [4]. Furthermore, the high porosity nature of the surface boulders is also suggested on the carbonaceous asteroid (101955) Bennu [5]. Such porous boulders on these asteroids would reflect low degree of compaction but some degree of consolidation in their parent bodies [2], from which the surface boulders originated. Planetary formation theory predicts dust aggregation in the early solar nebula resulting in the fluffy planetesimals [e.g. ref.6]. Thermal evolution and compaction (hot pressing) modeling of such fluffy planetesimals predicts dense materials in the core and porous and consolidated materials near the surface [e.g. ref.7]. Therefore, the porosity of rocks could be a measure of the primitiveness.

In this study, we performed systematic search of the very low thermal inertia and extremely high porosity boulders on Ryugu using high resolution imaging data by TIR during the descent operations. Such high porosity boulders are expected to come from the surface layer of the parent body, in which the peak temperature is comparatively lower and compaction is less effective.

Observations: During the rendezvous phase of the spacecraft, we carried out several descent operations, including MASCOT lander release and touch-down rehearsals. During these sequences, TIR acquired daytime high-resolution images below 500-m altitude, resulting in spatial resolutions better than 45 cm/pixel. In order to find the low thermal inertia and thus high temperature materials, we investigated the average temperatures and their standard deviations for each descent sequence and searched for regions where the brightness temperature differed by more than 2 standard deviations from the average. As expected, the hot regions are generally located at solar-directed boundaries between the boulders and ground, where self-heating by solar reflection and radiation from the boulder's side wall is strong. Moreover, two isolated hot spots were found, which cannot be explained by the self-heating effect and is attributed to the low thermal inertia.

Hot spots thermal inertia and porosity: The two hot spots, we call these as HS1 and HS2, are located near the center of small craters (ID128 and ID69 [8,9], respectively). Both hot spots have high temperatures compared with the surroundings by 10 K or larger. High resolution optical imaging by ONC-T revealed that HS1 consists of a few boulders with tens of centimeters in size. On the other hand, such a high resolution optical image could not be acquired for HS2, so that it is unknown whether HS2 consist of the boulders or fine-grained regolith. To estimate the thermal inertia, we compared the observed temperature and simulated temperature at the observation epoch using the global shape model. The resulting thermal inertia values of HS1 and HS2 are 60 ± 20 tiu and 54 ± 51 tiu, respectively. According to the models of the thermal conductivity in term of the porosity (Model 2 of Grott et al. [4] and Krause et al. [10]), we estimate the highly porous materials with the corresponding porosities of 76-92% and >71% for HS1 and HS2, respectively. The estimated porosity is as high as those of the cometary nuclei.

Discussions: The appearance of the hot spots only in the crater indicates the presence of the highly porous material in the subsurface; otherwise, the high porosity nature could be created by the cratering process. The other craters, which was imaged by TIR with the high resolutions, do not have the central hot spot. Furthermore, an artificial impact crater formed by the small carry-on impactor (SCI) showed homogeneous thermal inertia [11]. The absence of a hot spot in the SCI crater also indicates that high porosity nature of the hot spots is unlikely to be due to single impact comminution and shock-induced cracks. The near-infrared spectrometer NIRS3 revealed relatively deeper OH-related absorption feature at 2.72 μm in the SCI crater than the surroundings, interpreted as that the subsurface materials have avoided the solar radiative heating when Ryugu was in orbit closer to the Sun so that they are less dehydrated than the top-surface materials [12]. The ID69 crater including HS2 also showed the similar deep absorption feature, while the craters without the hot spot do not. This NIRS3 observation data indicates the craters with the hot spots (at least the ID69 crater) are relatively fresher than others.

We also investigated the relation between the thermal and optical properties of the boulders including the hot spots. The data used in this analysis are those acquired during the touch-down rehearsal (TD1-T3) on 25 October 2018. The thermal inertia of individual boulders is estimated by the same method as the hot spots above. We found positive correlation between the thermal inertia and v-band (550 nm in wavelength) reflectance (Fig. 1), with the hot spots being the end-member. This correlation implies the hot spot materials are unlikely to be the exogeneous, but likely to be the inherent in origin. Approximately 70% of the boulders has thermal inertia consistent with the global average (200-400 tiu). Furthermore, the gap between the hot spots and normal boulders consistent with the Ryugu average indicates rapid and selective fragmentation and dissipation of the hot spots after the exposure on the surface due to their comparatively low mechanical strength. The dissipation of the fragmented materials might occur by dust levitation processes, whereas a small part of the fragments of the hot spots is mixed into the regolith, which is supported by the fact that the data of regolith (regions with unresolved grains) lie on the mixing line between the boulders and the hot spots (Fig. 1).

The highly porous materials, we found in this study, are thought to be derived from the uppermost part of a partially consolidated layer on a planetesimal. They would be the least processed in the parent body without a high degree of thermal alteration and compaction. In Hayabusa2's first touch-down and sampling operation, dark and red dust particles consistent with HS1 optical properties were excavated from the surface or subsurface [13]. Such dark dusts could be the fragments of highly porous materials like HS1, and they could be included in the sample, returned onto the Earth on December 2020. The sample analysis will help to reveal the nature of planetesimals as a starting point of the planetary formation process.

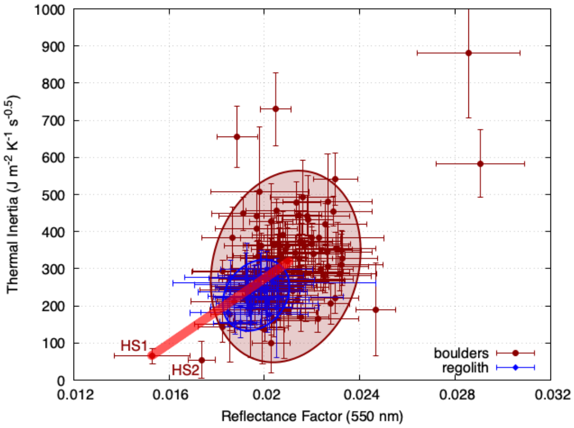

Figure 1: Thermal inertia of boulders and regolith in terms of the v-band reflectance factor. The red and blue elliptic clouds show 95% probability regions assuming 2D Gaussian distributions, except for the two brightest and two darkest (HS1 and HS2) boulders. The red line shows the mixing line between the HS1 and boulders, along which the regolith data are distributed.

Acknowledgments: The authors thank all of the members of the Hayabusa2 project. This research is supported by Japan Society for the Promotion of Science (JSPS) KAKENHI (grant nos. JP20K14547 and JP17H06459) and Core-to-Core program 'International Network of Planetary Sciences.' W.N. acknowledges support by Klaus Tschira foundation. M.H. was financially supported by Geo.X, grant number: SO_087_GeoX. M.D. would like to acknowledge the French space agency CNES and support from the ANR 'ORIGINS' (ANR-18-CE31-0014).

References: [1] Sugita et al. (2019), Science 364, 252. [2] Okada et al. (2020), Nature 579, 518-522. [3] Shimaki et al. (2020), Icarus 348, 113835. [4] Grott et al. (2019), Nature Astron. 3, 971-976. [5] Rozitis et al. (2020), Sci. Adv. 6, eabc3699. [6] Okuzumi et al. (2012), Astrophys. J. 752, 106. [7] Neumann et al. (2021), Icarus in press. [8] Noguchi et al. (2021), Icarus 354, 114016. [9] Cho et al. (submitted). [10] Krause et al. (2011), LPSC #2696. [11] Sakatani et al. (2020), LPSC #1358. [12] Kitazato et al. (2021), Nature Astron., https://doi.org/10.1038/s41550-020-01271-2. [13] Morota et al. (2020), Science 368, 654-659.