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Thermally altered subsurface material of asteroid (162173) Ryugu

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Analyses of meteorites and theoretical models indicate that some carbonaceous near-Earth asteroids may have been thermally altered due to radiative heating during close approaches to the Sun[1-3]. However, the lack of direct measurements on the subsurface doesn't allow us to distinguish it from parent-body processes. In April 2019, the Hayabusa2 mission successfully completed an artificial impact experiment on the carbonaceous near-Earth asteroid (162173) Ryugu[4,5], which provided an opportunity to investigate exposed subsurface material and test potential effects of radiative heating. Here we report observations of Ryugu's subsurface material by the Near-Infrared Spectrometer (NIRS3) on the Hayabusa2 spacecraft. Reflectance spectra of excavated material exhibit a hydroxyl (OH) absorption feature that is slightly stronger and peak-shifted compared with that observed for the surface, indicating that space weathering and/or radiative heating have caused subtle spectral changes in the uppermost surface. The strength and shape of the OH feature suggests that the subsurface material experienced heating above 300 °C, similar to the surface. In contrast, thermophysical modelling indicates that radiative heating cannot increase the temperature above 200 °C at the estimated excavation depth of 1 m, even at the smallest heliocentric distance possible for Ryugu. This supports the hypothesis that primary thermal alteration occurred on Ryugu's parent body.

On 5 April 2019, the Japan Aerospace Exploration Agency's (JAXA) Hayabusa2 spacecraft carried out an artificial impact experiment on the surface of Ryugu using the Small Carry-on Impactor (SCI)[4,5]. The SCI module was separated from the spacecraft at 0.5 km altitude and fired a 2 kg copper projectile at a velocity of

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~2 km s^{-1} toward the target site on the equatorial region of Ryugu. On 25 April, Hayabusa2 approached the target site and acquired images using the Optical Navigation Camera Telescope (ONC-T), which showed that a semi-circular shaped crater of 17 m in diameter (hereafter referred to as the SCI crater) had been formed at 7.9° N, 301.3° E (ref. [4]). A heterogeneous expansion of ejecta was observed by the Deployable Camera (DCAM3) during the SCI experiment, and the analysis of the ONC-T images revealed that the excavated subsurface material was mainly distributed to the north side of the SCI crater[4]. The maximum depth of the SCI crater is ~2.7 m and it has been estimated that much of the subsurface material distributed on and around the crater would have been ejected from ~1 m depth[4]. The SCI experiment thus provides a unique opportunity to test the effects of surface modification by radiative heating[1–3] and/or space weathering[6].

Before successfully acquiring a sample from ~20 m to the northeast of the SCI crater on 11 July 2019, the Hayabusa2 spacecraft performed three descent operations on different days to conduct a detailed survey of the impact site. During those descent operations, the NIRS3 acquired continuous spectra over a wavelength range of 1.8 to 3.2 μm with a 0.1° field of view[7]. Two sites from each of the three descent observations were chosen to search for spectral differences between typical surface and excavated materials (see Methods). Figure 1 shows the location of the NIRS3 footprints and associated reflectance spectra for the six observations of the SCI crater region. The NIRS3 footprints of 16 May (sites 1 and 2) pass through the region south of the crater, whereas those of 30 May (sites 3 and 4) and 13 June (sites 5 and 6) span the region to the north and the crater interior. The distribution of crater ejecta as determined from the ONC-T and DCAM3 images reveals that sites 1 and 2 and sites 3–6 correspond to ejecta-free and ejecta-rich areas, respectively[4]. All the spectra, including those over ejecta-rich areas, exhibit a weak and narrow OH feature with a reflectance minimum at 2.72 μm. This is similar to the spectral feature observed across the entire surface of Ryugu[8] and indicates that the subsurface material in this region has been thermally altered to the same degree as the surface material.

Spectral differences between surface and subsurface were further evaluated by comparing the spectra observed for the SCI crater region with those from regions far from the impact site. Figure 1c shows the ratio of normalized reflectance spectra between the SCI crater region and a surface ‘standard’ (a region chosen to represent typical spectral properties of Ryugu; see Methods). The ratio spectra of sites 1 and 2 are almost flat, whereas those of sites 3 to 6 exhibit a subtle but clear feature at 2.7 μm. The presence of this feature in the ratio spectra indicates that the OH feature is slightly stronger and that the absorption peak is shifted toward a shorter wavelength within the spectral resolution of NIRS3 for the ejecta-rich sites compared with typical surface materials. Similar spectral differences have not previously been confirmed in any other surface materials on Ryugu, suggesting that these are intrinsic properties of the subsurface material. Because the ejecta deposits have been found to span the sampling site[9], the samples to be returned by Hayabusa2 are expected to contain both surface and subsurface materials for comparison in laboratory.

Previous laboratory studies have shown that the peak wavelength of the OH absorption band varies with the Mg/Fe ratio of phyllo-

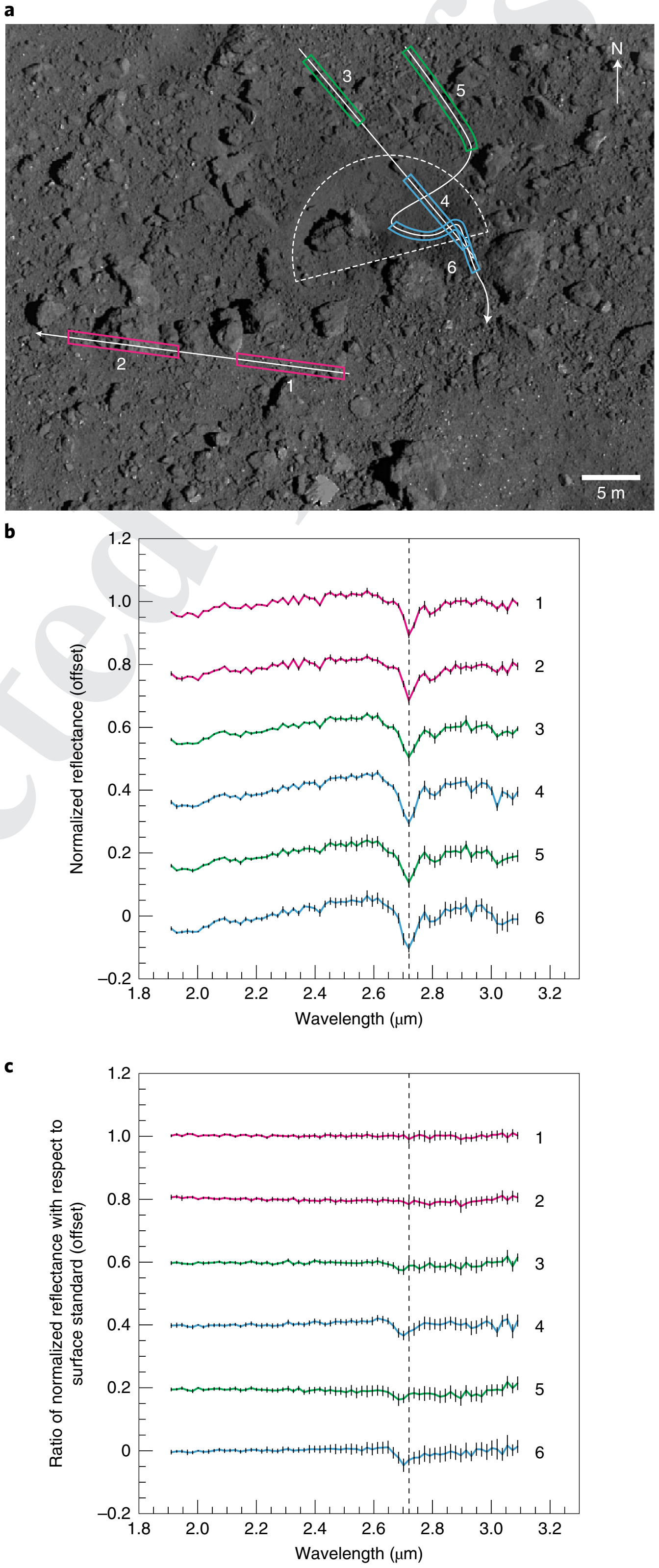

Fig. 1 | NIRS3 observations of the SCI crater region. a, Context image taken by the ONC-T camera. The dashed semi-circle represents the rim of the SCI crater[4]. The arrows indicate the motion of NIRS3 footprints during three descent operations. **b**, NIRS3 spectra averaged over regions corresponding to the coloured boxes shown in **a**. The colour of each site represents its surface characteristics: magenta, green and cyan are the ejecta-free region, ejecta-rich region outside the crater and ejecta-rich region inside the crater, respectively. Error bars are 1σ within the boxes. Individual spectra of each site are shown in Extended Data Fig. 1. **c**, Ratios of the normalized spectra shown in **b** to the ones of the surface standard observed on the day before. The spectra are normalized and vertically shifted for clarity. The dashed vertical lines at 2.72 μm denote the peak wavelength of the OH absorption of the spectra in **b**.

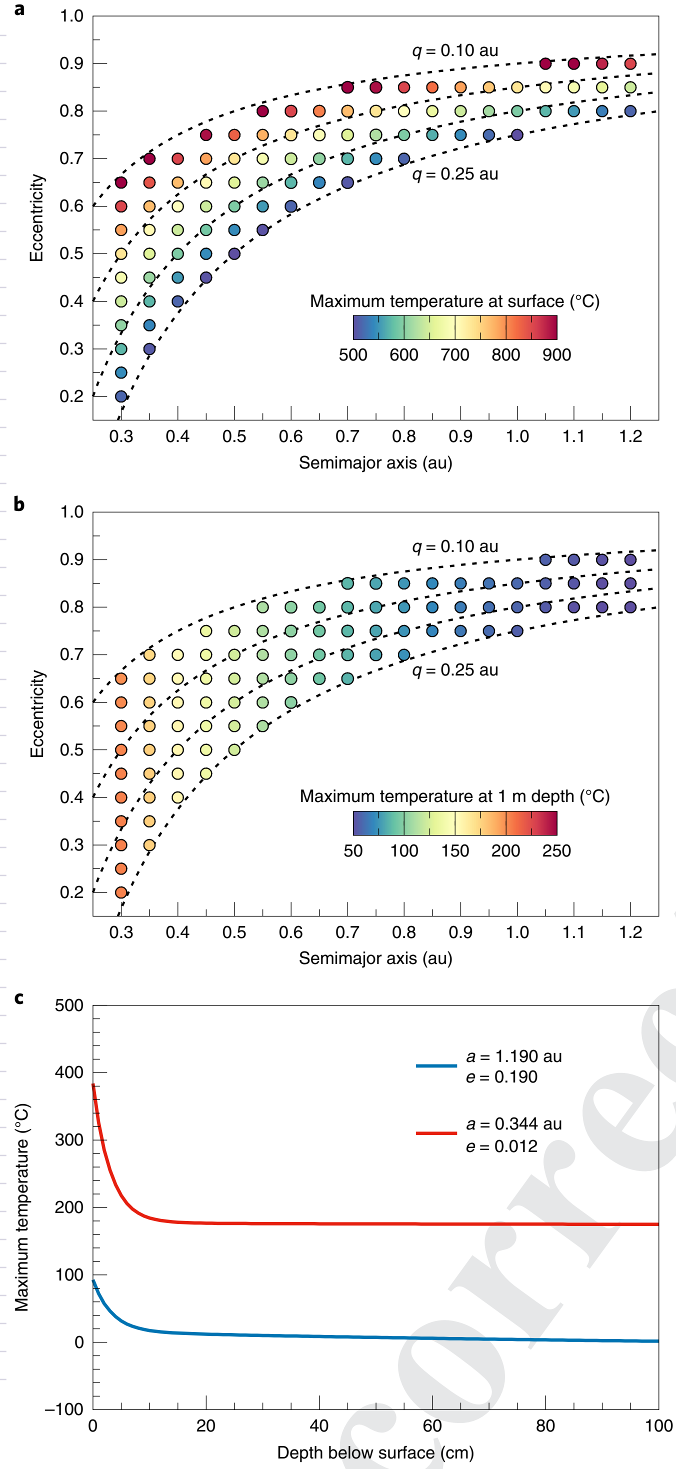

Fig. 2 | Maximum surface and subsurface temperatures at the SCI crater region. a, Maximum surface temperature for one revolution at a given Sun-approaching orbit. A grain density of 2,420 kg m^{-3}, a porosity of 41%, a thermal conductivity of 0.16 W m^{-1} K^{-1}, and a temperature-dependent heat capacity[37] have been assumed. The dashed curves denote the perihelion distance *q* of 0.10, 0.15, 0.20 and 0.25 au. **b**, Same as **a** but for a depth of 1 m. **c**, Maximum temperature profile at the current orbit (blue) and the closest orbit to the Sun (red).

silicates in carbonaceous chondrites[10,11]. This would suggest that the subsurface material on Ryugu is more enriched in Mg–OH phyllosilicates relative to surface materials. Laboratory spectra also indicate that the OH band position does not closely correlate with grain size and/or porosity[12], thus it is unlikely that intrinsic physical attributes can explain the spectral differences between surface and subsurface materials on Ryugu. Indeed, there is currently no evidence in the Thermal Infrared Imager (TIR) data to indicate differences in grain size and/or porosity for the SCI crater region[13]. Alternatively, space weathering can be considered as a likely cause of the observed spectral differences. Solar wind ion irradiation, a primary source of space weathering, affects the surface at depths of tens to hundreds of nanometres and preferentially sputters the volatile and lighter Mg compared with Fe[14,15]. Recent laboratory experiments show that near-infrared spectra of irradiated phyllosilicates measured under vacuum conditions exhibit a similar shift in the OH band position as observed on Ryugu[16]. It is also possible that radiative heating may induce a change in the Mg/Fe ratio of phyllosilicates, but there is currently no available experimental data under relevant conditions to evaluate this possibility.

In spite of some differences from the surface, the overall spectral properties of the subsurface material on Ryugu still support a close similarity with thermally and/or shock metamorphosed carbonaceous chondrites. As previously discussed in ref. [8], the material on Ryugu was likely aqueously altered to a greater extent than indicated by the current weak OH feature, and the aqueously altered material was then heated to high enough temperatures to induce loss of H_2O but only partial dehydroxylation. This process seems to have affected materials that are currently within the upper 1 m of Ryugu. This raises questions as to the source of the heating: thermal alteration due to radiogenic and/or impact heating on the original parent body[17–19], or radiative heating during previous close encounters with the Sun[20,21]? The orbits of near-Earth asteroids evolve chaotically due to a combination of close encounters with the terrestrial planets and resonances with the giant planets[22]. A theoretical study shows the possibility that Ryugu's perihelion distance may have been as small as 0.1 au in the course of its history, resulting in surface temperatures as high as ~1,200 °C (ref. [20]). This suggests that radiative heating might be able to easily explain the thermal alteration of Ryugu's surface, and a recent study suggests this form of heating has likely influenced the spectral properties of Ryugu at visible wavelengths[21]. However, these studies do not consider thermal effects at the excavation depth of the SCI crater, thus we examine the range of temperatures that the subsurface material could have experienced by using a thermophysical model (see Methods).

Figure 2a and b show the maximum temperatures achieved at the surface and at 1 m depth, respectively, for one orbital revolution. We find that the maximum temperature of the surface increases with decreasing perihelion distance, whereas temperatures at 1 m depth increase with decreasing semimajor axis. The surface temperature reaches values of 700 °C at a perihelion distance of 0.15 au, and laboratory spectra of the heated Ivuna CI chondrite sample exhibit the complete loss of OH features above this temperature (Fig. 3). The persistence of an OH feature on Ryugu suggests that it never approached the Sun at a distance less than 0.15 au. In addition, dynamical models of near-Earth asteroids indicate that there is no object having an orbit entirely inside that of Mercury's orbit[23–25], and that their semimajor axis is never less than 0.344 au (ref. [24]). For that semimajor axis, the maximum temperature experienced at a depth of 1 m is estimated to be less than 200 °C (Fig. 2c). If impact gardening and mixing occur simultaneously with radiative heating, then materials that have experienced more heating might be able to exist in the subsurface. However, such mixing would act to homogenize the materials vertically and cannot explain the observed spectral differences between surface and subsurface materials. Thus, we can constrain the radiative heating of the material at the excavation depth of the SCI crater to below 200 °C.

Although it is difficult to estimate the exact temperature to which materials on Ryugu have been heated, the presence of a weak and

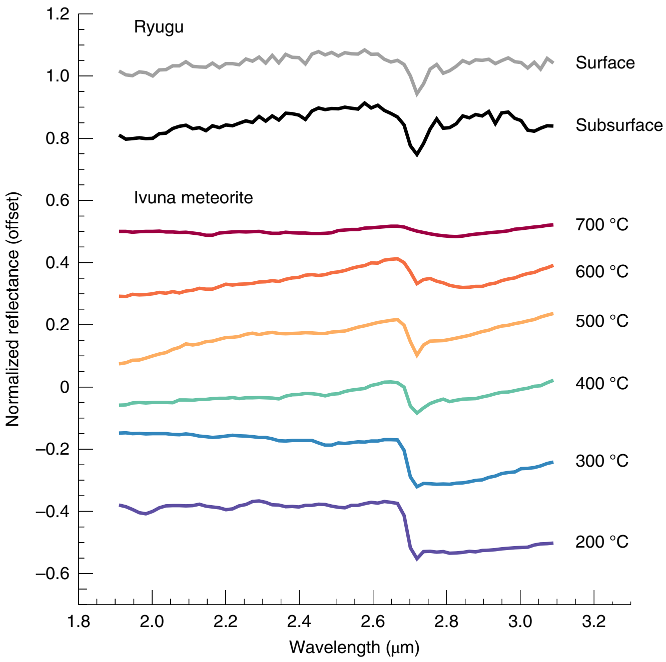

Fig. 3 | Ryugu's surface and subsurface spectra compared with laboratory spectra of heated Ivuna meteorite sample. The spectra of Ivuna meteorite taken from the Reflectance Experiment Laboratory (RELAB) database[38] are resampled with the same resolution as the Ryugu spectra. The spectra are normalized and vertically shifted for clarity.

narrow OH feature in Ryugu's spectra supports temperatures above 300 °C but below 700 °C, as demonstrated by the dehydration and partial dehydroxylation of Mg-rich phyllosilicates within this temperature range[26]. It is also possible that a weak OH feature occurs due to incomplete hydration reactions on the parent body, but the OH band position of 2.72 µm is more indicative of Ryugu's material having experienced a high degree of aqueous alteration[27]. We thus consider that the primary process of thermal alteration for material on Ryugu is more consistent with radiogenic and impact heating on the parent body from which it formed rather than radiative heating after re-accretion and formation. Extended Data Figs. 1–4.

Methods

Location of the NIRS3 footprints. The spacecraft trajectories for observations of the SCI crater region have not been well determined due to frequent delta-v manoeuvres. Therefore, we identified the location of NIRS3 footprints using the continuous series of images acquired by the ONC-T camera during the SCI crater characterization activities. The boresight of NIRS3 is co-registered with the ONCT-T field of view and the pixels of the ONC-T image corresponding to the NIRS3 footprint have been precisely determined[28]. To derive the footprints shown in Fig. 1a, we used 18 images taken from 02:36:15 to 02:40:39 on 16 May, 18 images taken from 02:35:44 to 02:40:07 on 30 May, and 12 images taken from 02:00:18 to 02:16:59 on 13 June.

Analysis of the NIRS3 spectra. Extended Data Fig. 2 shows the details of the NIRS3 spectra that we used for the analysis of the SCI crater region. The spectra of sites 3 and 4 and sites 5 and 6 were obtained under 9 °C and 10 °C higher detector temperatures, respectively, than the nominal value due to thermal flux from the surface of Ryugu. Because the responsivity of the detector changes with its temperature, we corrected that effect using additional calibration data obtained under the same temperature conditions. With the exception of this temperature correction the data processing is the same as previously published[8].

To evaluate spectral differences between the surface and subsurface materials, we compared the spectra of the SCI crater region with those of regions not contaminated by the crater ejecta. Extended Data Fig. 3 shows the details of the NIRS3 spectra of regions that we chose as the surface standard. As shown in Extended Data Fig. 4, it has been found that a small residual of thermal correction appears between spectra of regions with different surface temperatures. To avoid such an artefact, we chose a region having a similar surface temperature to the SCI crater region for the surface standard. Small variations in spectral slope among the spectra shown in Fig. 1c may be due to the thermal residual.

Thermophysical modelling. To investigate the effects of radiative heating on the SCI crater region, we set up a thermophysical model[29] that computes surface and subsurface temperatures on Ryugu with a Sun-approaching orbit. Taking into account the location of the SCI crater[4] and Ryugu's obliquity[30], we assume a single facet on the equator of a spherical object having the spin axis perpendicular to its orbital plane. Because the SCI crater is located at the equatorial region, even if Ryugu's past obliquity was different, the maximum temperature would not exceed that of the current perpendicular spin case considered here. The facet temperature T as a function of time t and depth z is determined by numerically solving the one-dimensional heat conduction equation:

$$\rho(1-\phi)c\frac{\partial T}{\partial t}=\kappa\frac{\partial^2 T}{\partial z^2} \qquad (1)$$

where ρ is the grain density, ϕ is the porosity, c is the specific heat capacity and κ is the thermal conductivity. Because Ryugu's surface is covered by decimetre- to metre-sized rocks without a fine-grained component[31], we used the parameter values derived for a boulder on Ryugu from in situ measurements by the MASCOT lander[32]; $\rho = 2{,}420\,\mathrm{kg\,m^{-3}}$, $\phi = 41\%$, $\kappa = 0.16\,\mathrm{W\,m^{-1}\,K^{-1}}$ and a temperature-dependent heat capacity[27]. These are consistent with remote sensing measurements[33,34].

The boundary condition at the surface is given by

$$\kappa\left(\frac{\partial T}{\partial z}\right)_{z=0}=\varepsilon\sigma T^4_{z=0}-\frac{(1-A)S_\odot}{r^2}\max(0,\cos\theta) \qquad (2)$$

where ε is the emissivity, σ is the Stefan–Boltzmann constant, A is the bond albedo, $S_\odot$ is the solar constant at 1 au, r is the heliocentric distance in au, and θ is the angle between the surface normal and the solar vector. The position of Ryugu with respect to the Sun at a given time is computed using the Kepler's equation solution[35]. We used a bond albedo of 0.0146 and an emissivity of 1.0 (ref. [32]), and assumed a constant rotational period of 7.6326 h (ref. [30]).

To ensure a sufficient depth for the seasonal temperature variations, we assumed an adiabatic boundary condition at 5 m depth:

$$\left(\frac{\mathrm{d}T}{\mathrm{d}z}\right)_{z=5\,\mathrm{m}}=0 \qquad (3)$$

The current seasonal thermal skin depth of Ryugu is $l_s=\sqrt{\kappa P_{\mathrm{orb}}/2\pi\rho(1-\phi)c}\approx 1.1$ m, where P_{orb} is the orbital period, and it decreases with decreasing semimajor axis. We ran the model with a time step of 15 s and a depth step of 0.01 m. After 10 years integration, the results converged to temperature deviations of less than 1 K.

In the model, we used an emissivity of 1.0 as the nominal value considering the results of MASCOT[32], but even in case of an emissivity of 0.9, the maximum temperatures of the surface and subsurface increase by only 15 K. In addition, we have also confirmed that the variation of maximum temperatures by the bond albedo uncertainty[36] is within 1 K.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. The raw and calibrated NIRS3 data will be made available through the JAXA Data Archives and Transmission System (DARTS) website (https://darts.isas.jaxa.jp/planet/project/hayabusa2/).

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Author contributions

K.K. led the study, performed the data analysis and thermophysical modeling and wrote the manuscript. R.E.M. contributed to the interpretation of the results and assisted in the writing. T.I. led the development of NIRS3. M.A., M.O., S.M., M.M., L.R., Y.N., T.K. and T.A. contributed to the development and operation of NIRS3. L.R., C.P., D.L.D., E.P. and A.G. contributed to the data analysis. Y.T., T.N., T.H., M.M., L.R., M.A.B., R.B., C.P., F.P., D.L.D., F.V., D.T., E.P. and A.G. participated in the interpretation of the results. All authors participated in science data acquisition, mission planning, mission operations, or project management, and/or contributed to discussion of the results. The entire Hayabusa2 project team made this mission possible.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41550-020-01271-2.

Correspondence and requests for materials should be addressed to K.K.

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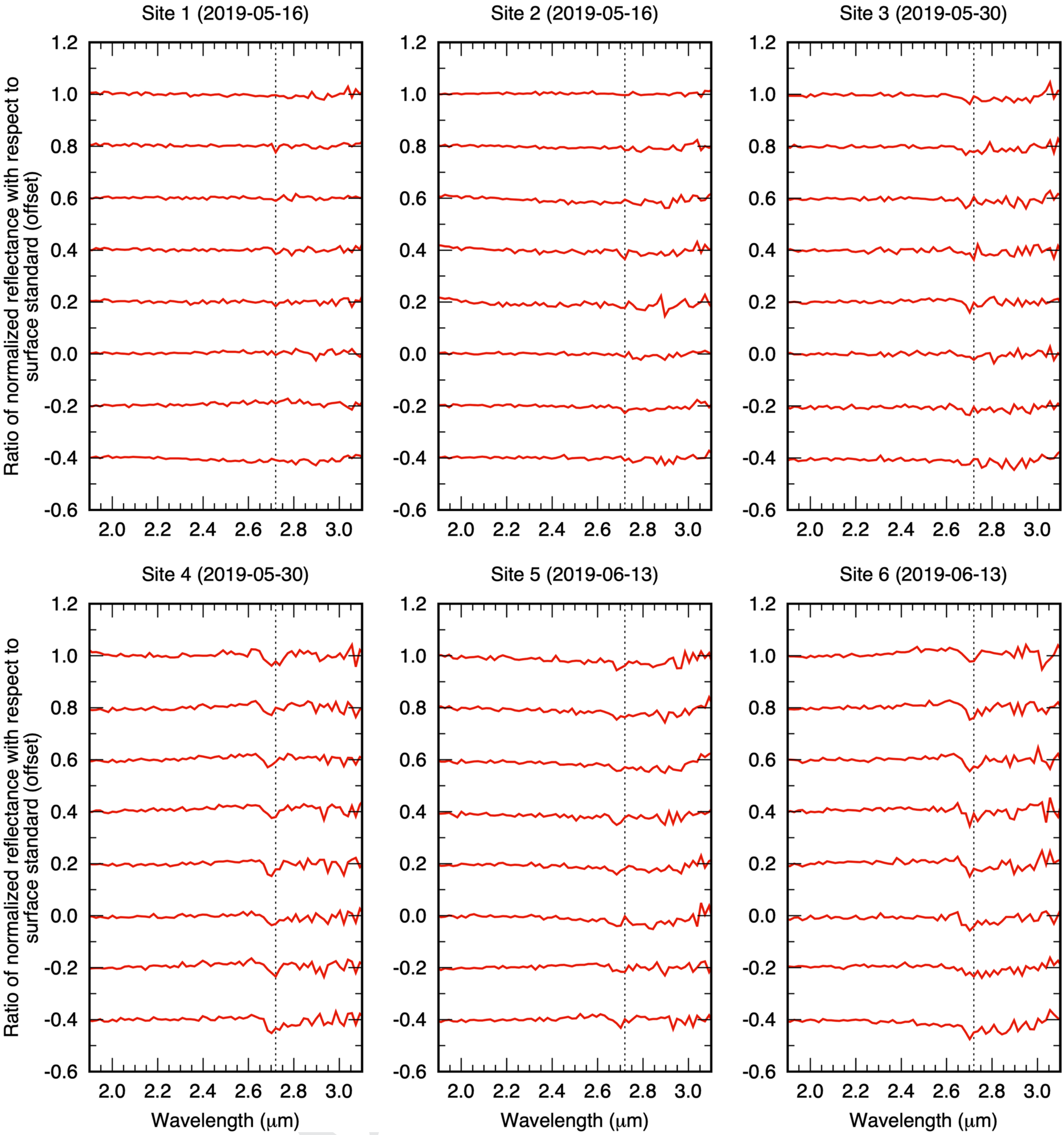


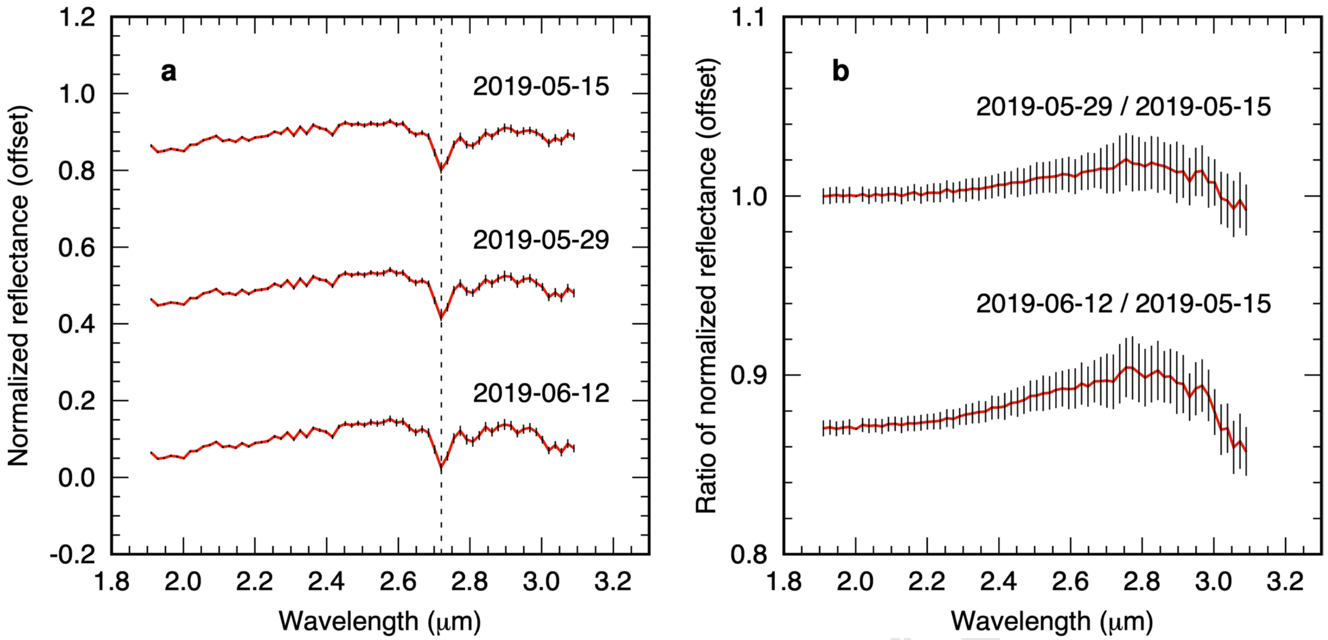
Extended Data Fig. 1 | Individual spectra from each site used to derive the average spectra of the SCI crater region. The spectra are divided by the surface standard spectrum of the day before and vertically shifted for clarity.

Site #	Observation date and time (UTC)		# of spectra	Solar distance (au)	Phase angle (°)	LIDAR range (m)	Surface temp. (°C)
1	2019-05-16	02:36:21 – 02:37:46	8	1.25	31.1	–	35^{+9}_{-9}
2		02:38:50 – 02:40:16	8	1.25	31.1	–	23^{+16}_{-15}
3	2019-05-30	02:35:50 – 02:37:16	8	1.21	33.7	252 – 277	41^{+7}_{-8}
4		02:38:30 – 02:39:56	8	1.21	33.7	298 – 325	50^{+7}_{-9}
5	2019-06-13	02:00:17 – 02:01:43	8	1.17	35.7	82 – 107	41^{+17}_{-12}
6		02:02:26 – 02:03:51	8	1.17	35.7	119 – 145	42^{+20}_{-13}

Extended Data Fig. 2 | Details of observations of the SCI crater region. Add caption.

Observation date and time (UTC)		# of spectra	Longitude (˚)	Latitude (˚)	LIDAR range (km)	Surface temp. (˚C)
2019-05-15	10:22:09 – 10:44:56	128	321 – 340	4 – 7	8.5 – 9.0	32^{+7}_{-11}
2019-05-29	06:58:34 – 07:21:21	128	112 – 136	-33 – -30	13.1 – 13.7	40^{+5}_{-9}
2019-06-12	02:46:54 – 03:09:41	128	314 – 327	-44 – -29	18.5 – 19.1	44^{+2}_{-1}

Extended Data Fig. 3 | Details of observations of the surface standard. Add caption.



Extended Data Fig. 4 | NIRS3 spectra of the surface standard. a, Spectra averaged over regions having the similar surface temperature to the SCI crater region. The details of these spectra are listed in Extended Data Fig. 3. **b**, Ratios between the normalized spectra shown in **a**. The non-flat shape of the ratio-spectra indicates the residual of thermal correction. The spectra are normalized and vertically shifted for clarity. Note that the vertical scale of **b** is much larger than that of **a** to show the curvature and uncertainties of the ratio-spectra.

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