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TECHNICAL REPORT

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Environmental assessment in the prelaunch phase of Hayabusa2 for safety declaration of returned samples from the asteroid (162173) Ryugu: background monitoring and risk management during development of the sampler system

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Abstract

We report ground-based environmental assessments performed during development of the sampler system until the launch of the Hayabusa2 spacecraft. We conducted static monitoring of potential contaminants to assess the environmental cleanliness during (1) laboratory work performed throughout the development and manufacturing processes of the sampler devices, (2) installation of the sampler system on the spacecraft, and (3) transportation to the launch site at the Japan Aerospace Exploration Agency's (JAXA's) Tanegashima Space Center. Major elements and ions detected in our inorganic analyses were sodium (Na), potassium (K), and ionized chloride (Cl^-); those elements and ions were positively correlated with the total organic content and with exposure duration in the range from 10^1 to 10^3 nanograms per monitor coupon within an ~ 30-mm diameter scale. We confirmed that total deposits on the coupon were below the microgram-scale order during manufacturing, installation, and transportation in the prelaunch phase. The present assessment yields a nominal safety declaration for analysis of the pristine sample (> 5.4 g) returned from asteroid (162173) Ryugu combined with a highly clean environmental background level. We expect that the sample returned from Ryugu by Hayabusa2 will be free of severe and/or unknown contamination and will allow us to provide native profiles recorded for the carbonaceous asteroid history.

Keywords: Hayabusa2 spacecraft, Carbonaceous-type asteroid Ryugu, Environmental assessment, Static monitor coupon, Inorganic and organic background, Safety declaration

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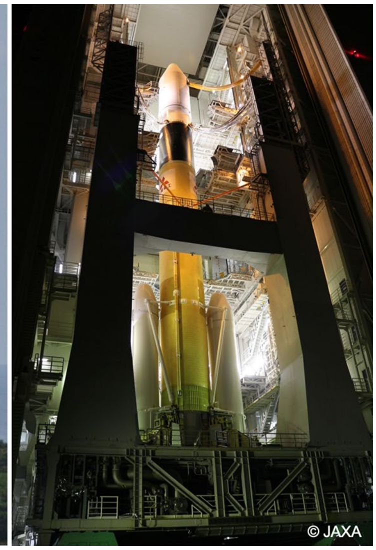
Graphical Abstract



Introduction

The re-entry capsule of the Hayabusa2 spacecraft was successfully retrieved from Woomera, South Australia, on December 6, 2020 (Tachibana et al. 2021; Yada et al. 2021a). Hayabusa2 made comprehensive surveys of C-type near-Earth asteroid (162173) Ryugu (e.g., Watanabe et al. 2019; Sugita et al. 2019; Kitazato et al. 2019, 2021; Grott et al. 2019; Jaumann et al. 2019; Arakawa et al. 2020; Morota et al. 2020; Okada et al. 2020; Tatsumi et al. 2021a, 2021b; Sakatani et al. 2021) with two touchdown operations for sampling. The Hayabusa2 sampler system worked as expected in the two landing operations (e.g., Tachibana et al. 2014, 2021, 2022; Sawada et al. 2017; Okazaki et al. 2017; Appendix). The sample container, which contained the Ryugu sample, was sealed using the metal-seal system developed to maximize the scientific value of the sample, especially with regard to retention of volatile gases from samples and prevention of terrestrial air contamination (e.g., Sawada et al. 2017; Okazaki et al. 2017). If there is no severe and/or unknown contamination on samples, detailed sample analyses will provide us with crucial information on the primordial native condition of organics, water, and mineral interactions regarding key issues in the molecular evolution of the asteroid.

To assess the entire sampling process aimed at safeguarding the scientific value and preventing unknown contamination, the Hayabusa2 sampler team conducted (i) off-nominal operational assessments (e.g., projector operation: Takano et al. 2020; small carry-on impactor: Ito et al. 2021) and (ii) a laboratory-based environmental assessment aimed at monitoring the background cleanliness at each stage of the development of the Hayabusa2 spacecraft (e.g., see the assessment policy by Sawada et al. 2017). Focusing on the latter issues, this technical report describes the assessment results during the pre-launch phase (Table 1). Based on both quantitative and qualitative assessments, we can evaluate potential contaminants that could have been artificially introduced, and this can be performed seamlessly during implementation, engineering development, launch, or capsule re-entry into the Earth's atmosphere. We can thus provide a robust final safety declaration for analyses of samples from the pristine C-type asteroid Ryugu.

Overview of the Hayabusa2 sampler status for quality assurance

We designed a seamless monitoring procedure with an efficient workflow up to the time of initial sample processing (Tachibana et al. 2014; Okazaki et al. 2017; Sawada et al. 2017) to formulate a safety-declaration protocol for the Ryugu sample (i.e., Tachibana et al. 2021, 2022; Yada et al. 2021a, 2021b; Pilorget et al. 2021). Table 1 provides an overview of sample processes through initial implementation, engineering development, and assessment on the Hayabusa2 sampler team axis. To date, we have a range of knowledge from lessons learned during

Table 1 Overview and compilation of the entire sample processes from implementation to engineering development and assessment for quality control for the safety declaration of the Ryugu sample

The assessment status	Location	Date	Profile	Refs.
Implementation plan and practical preparation	ISAS	2010 ~ Nov-2013	New framework of the sampler with lessons and feedback from Hayabusa mission	Tachibana et al. (2014)
			Insight for future curation process	Uesugi et al. (2014), Karouji et al. (2014)
Development of volatile gas sampling system	ISAS	2010 ~ Nov-2013	Metal-seal system for vacuum encapsulation	Okazaki et al. (2017)
Environmental assessment during the sampler development	ISAS/TSC/TNSC	Nov-2013–Dec-2014 (vacuum test in July-2014)	The sampler development, the spacecraft assembly rooms, the vehicle assemble building (STA, SFA, VAB)	This study
Thermal vacuum tests of the spacecraft			Thermal vacuum test with the vibration test	Sawada et al. (2017), This study
Environmental assessment before the launch	TNSC	~3-December-2014		This study
Touchdown sampling (TD1)	The asteroid Ryugu	22-February-2018	Projector operation (1) during TD1	Sawada et al. (2017), Morota et al. (2020)
				Takano et al. (2020)
Small-carry on impactor (SCI)	The asteroid Ryugu	3-April-2019	SCI operation	Saiki et al. (2017), Arakawa et al. (2020)
				Ito et al. (2021)
Touchdown sampling (TD2)	The asteroid Ryugu	11-July-2019	Projector operation (2) during TD2 near the SCI-made creator	Sawada et al. (2017)
				Takano et al. (2020)
Reentry capsule retrieval operation	Woomera, Australia	6-December-2020	Sample recovery and onsite gas extraction	Okazaki et al. (2017), Sawada et al. (2017)
Gas sampling and analysis by GAEA	Woomera, Australia	~8-December-2020	Onsite analysis by GAEA	Tachibana et al. (2021)
			Safety declaration of Ryugu sample	Tachibana et al. (2021), This study
Curation procedure	ISAS	Dec-2020 ~ present	Sample curation	Yada et al. (2021a, 2021b), Yoshitake et al. (2021)
				Tachibana et al. (2021), Sugahara et al. (2018)
	ISAS to designated place	Jun-2021 ~ present	Sample distribution	e.g., Ito et al. (2020)
				Shirai et al. (2020), Uesugi et al. (2020)

More details are provided in the following key references: Tachibana et al. (2014), Uesugi et al. (2014), Okamoto et al. (2015), Okazaki et al. (2017), Saiki et al. (2017), Sawada et al. (2017), Sugahara et al. (2018), Uesugi et al. (2019), Arakawa et al. (2020), Ito et al. (2020), Morota et al. (2020), Shirai et al. (2020), Takano et al. (2020), Uesugi et al. (2020), Ito et al. (2021), Tachibana et al. (2021), Yada et al. (2021a), Yoshitake et al. (2021). For the general protocol adopted for the spacecraft's thermal vacuum test, see JAXA (2021) JERG-2–130-HB005B and Sawada et al. (2017). A process blank was obtained during gas sampling and analysis by the GAEA (GAs Extraction and Analyses system) at Woomera (Miura et al. 2022)

assessments of contaminants in the previous Hayabusa mission (e.g., category-3 particles; Uesugi et al. 2019 and references therein), potential contaminants from off-nominal operations of the Hayabusa2 (e.g., Takano et al. 2020; Ito et al. 2021), the curation procedure and cleanliness level at the Japan Aerospace Exploration Agency (JAXA) Extraterrestrial Sample Curation Center (e.g., Sugahara et al. 2018; Yoshitake et al. 2021; Yoshikawa et al. 2021), and sample transportation containers for Hayabusa2 samples (e.g., Ito et al. 2020; Shirai et al. 2020; Uesugi et al. 2020). We also highlight literature sources for quality control and assurance for other sample-return projects (e.g., Dworkin et al. 2018; McCubbin et al. 2019; Chan et al. 2020; and references therein). As a practical assessment based on that of Sawada et al. (2017), we deployed a contamination monitor coupon set near the sampler flight model to assess how much Earth-derived terrestrial material was present until the launch of the Hayabusa2 spacecraft (Fig. 1a).

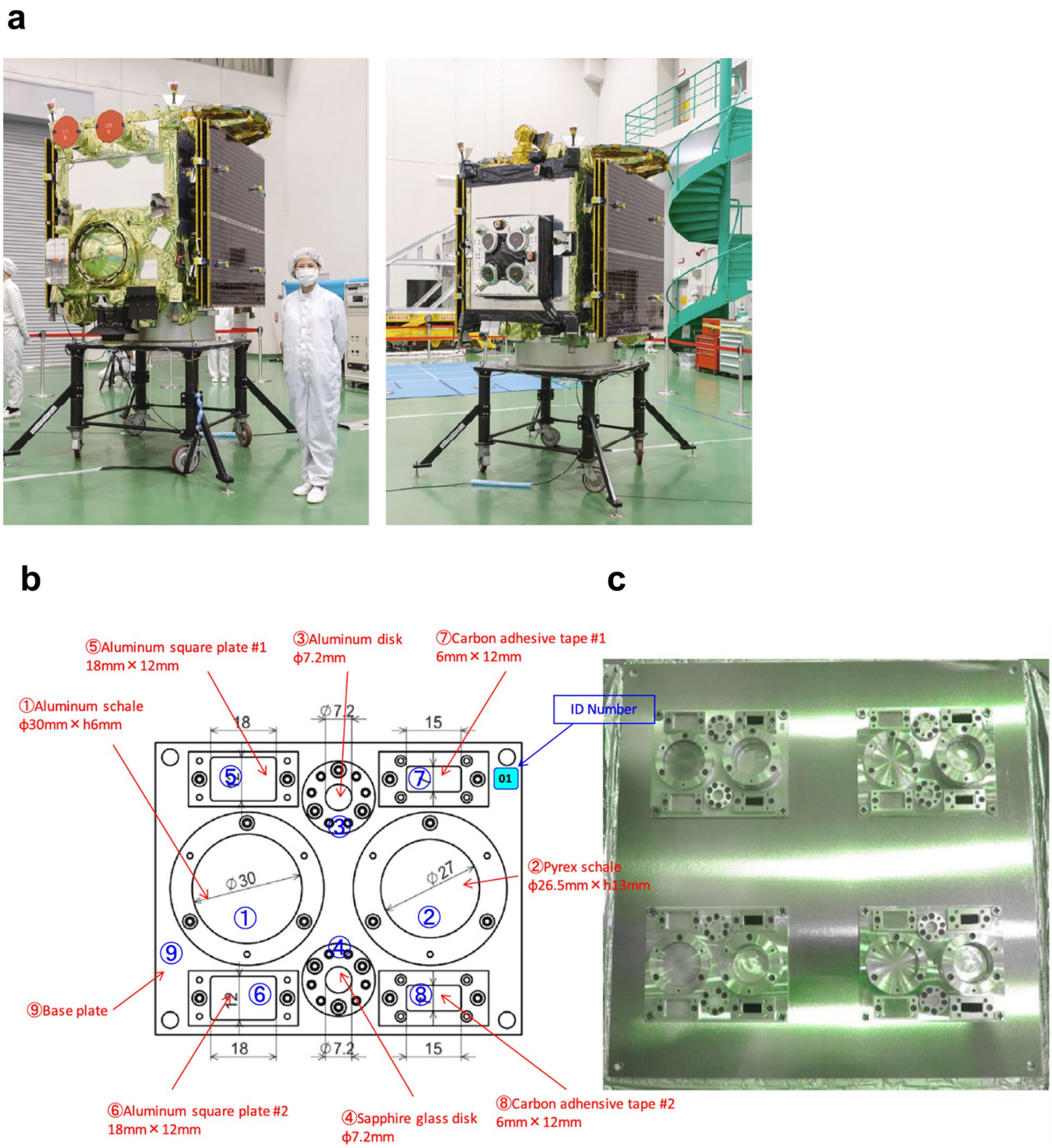


Fig. 1 **a** Photographs of the Hayabusa2 spacecraft in the clean room at ISAS/JAXA (after Tachibana et al. 2014). Please note that hairdressing, perfumes, skincare, cosmetics, hand sanitizer, lotions, and hair spray are prohibited for any visitors to JAXA's clean room facilities. **b**, **c** Schematic design and appearance of the monitor coupon equipped with an aluminium schale, Pyrex schale, aluminium disk, sapphire glass disk, aluminium square plate (#1, #2), and carbon adhesive tape (#1, #2) for the Hayabusa2 witness coupon (after Sawada et al. 2017). **d** Environmental assessment procedures for timelines, locations, and operational profiles from static monitoring. Blue and green bars represent the installation time of the coupon and the nitrogen gas purge time into the sampler system, respectively. Abbreviations for locations are defined at the end of the main text

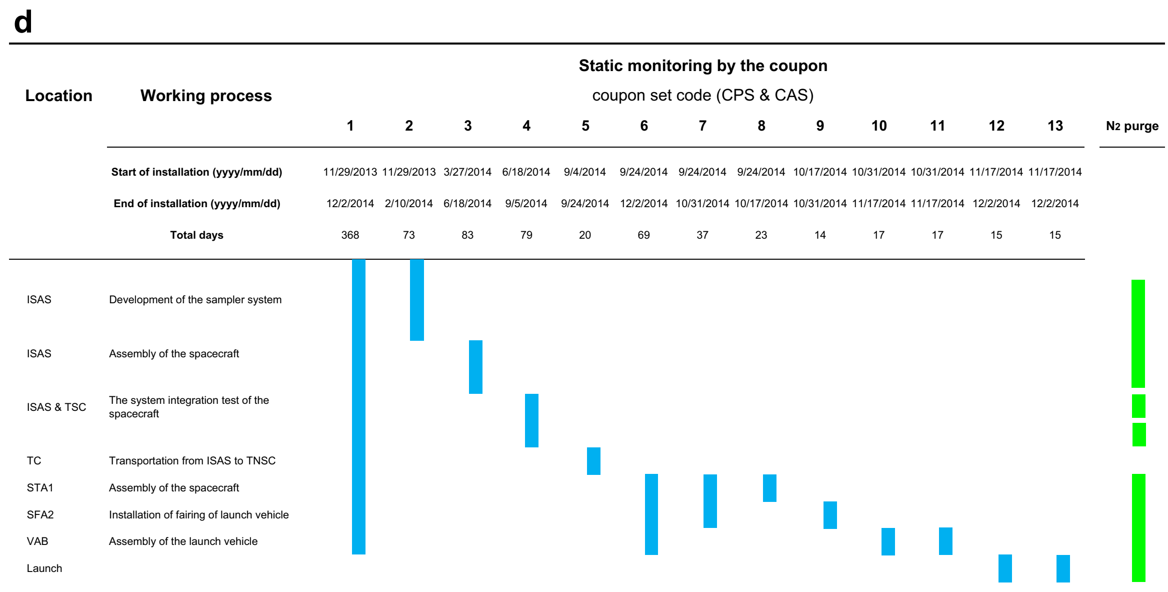


Fig. 1 continued

Environmental assessment based on static monitoring

Figure 1b, c presents the schematic design and appearance of the monitor coupon, which contains a Pyrex container, an aluminium container, and carbon adhesive tapes for inorganic and organic assessments and microscopic observations, respectively (see Sawada et al. 2017 for more details). The timeline and assessment plans for quality control, monitoring, collection, and storage during development of the Hayabusa2 sampler are summarized in Fig. 1d. To evaluate both the inorganic and organic background levels of the ambient environment, we deployed the monitor coupon during assembly of the sampler system (Figs. 2 and 3). For comparison with the static cleanliness test described above, we also performed air-filter sampling (Multistage Andersen Cascade Impactor, Tokyo Dylec Corp.) and swab sampling using reference sources involving a quartz filter (8 cm diameter × 4 mm thickness) and glass wool (~0.3 g), respectively. The artefacts precipitated during the thermal vacuum test of the spacecraft (Sawada et al. 2017) were also analysed for identification of volatile compounds (Additional file 1).

The analytical methods used for inorganic and organic assessments and quantitative and qualitative evaluations have been reported previously (e.g., Takano et al. 2020; Ito et al. 2021). All glassware and aluminium materials were washed with organic solvent and flushed with ultrapure water, as described by Karouji et al. (2014). All glassware and aluminium parts used in the assessment were cleaned by heating (450 °C for 5 h) in air to remove any artefacts of organic contaminants (e.g., Takano et al. 2020).

Results and summary

Inorganic and organic assessments

The concentrations of total organics, major elements, and major ions monitored by the coupons at different locations, occasions, and/or durations (coupon set code; CPS-1 to CPS-12) are summarized in Fig. 4. Concentrations of elements, ions, and total organics were less than or on the order of 10^3 nanograms (i.e., 1 µg or less) for all coupons (~30 mm in diameter). The raw concentrations of the elements (Fe, Cu, Ni, Cr, Zn, Na, K, Ca, Mn, Al, Ti, Mg, Co, Sn, Pb, V, and P), ions (including Cl^-, NO_2^-, Br^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, and F^-), and organics are shown in Tables 2, 3, and 4, respectively. The concentrations normalized to surface area (i.e., ng cm^{-2}) were obtained from the monitor coupon size (Fig. 1b). The quantitative values for static monitoring per unit time are shown in Fig. 4b and Table 4. Although there were some difficulties

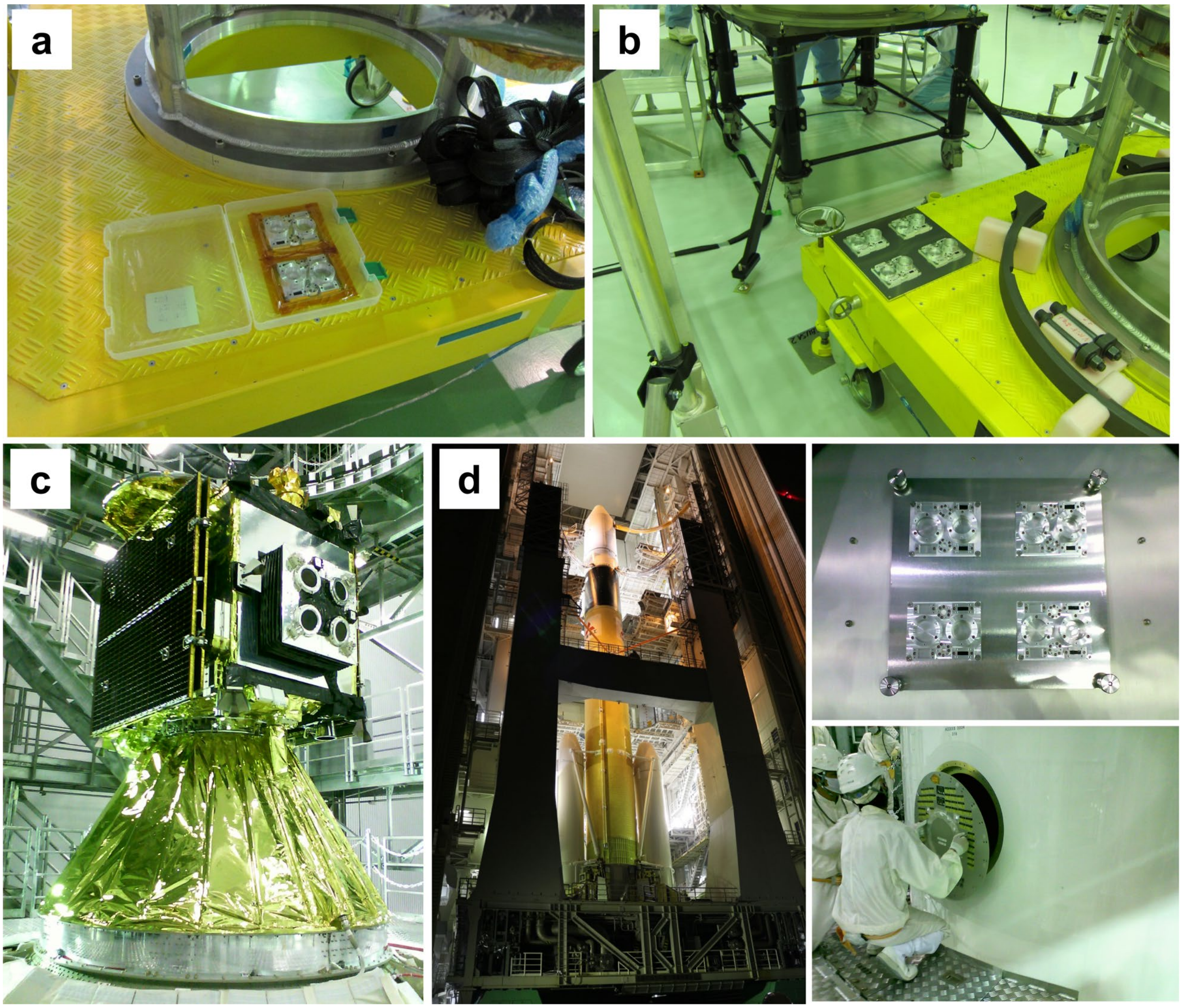


Fig. 2 Representative snapshots of the environmental assessment. **a** Practical deployment of the monitor coupon in the processes of ISAS (ISAS-C building clean room) and TSC (JAXA Tsukuba Space Center), **b** STA1 building clean room at TNSC (JAXA Tanegashima Space Center), **c** SFA2 building clean room, **d** VAB building clean room at TNSC, and **e**, **f** the final launch site at TNSC. When moving to the TNSC monitored with coupon set #5, the continuous flow of nitrogen was temporarily stopped due to logistical reasons, and then the nitrogen purge state (i.e., without exposure time of ambient atmosphere) was maintained by sealing the chamber

in specifying the exact compound source within the ultrasmall-scale analyses, this coupon was stored at JAXA for future secondary analysis (detailed analysis) if necessary.

The major inorganic elements and ions detected were sodium (Na), calcium (Ca), potassium (K), chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-). Their profiles were positively correlated with the total organic content in the range 10^1–10^3 ng per monitor coupon. This result indicates a profile different from the chemical compositions of oceanic salt and anthropogenic biological fluids (e.g., a seawater and sweat composition; Terasawa et al. 2001). Figure 5 shows time-dependent static accumulation of ambient aerial deposits onto the monitor coupons throughout the procedure (CPS-1–12, including

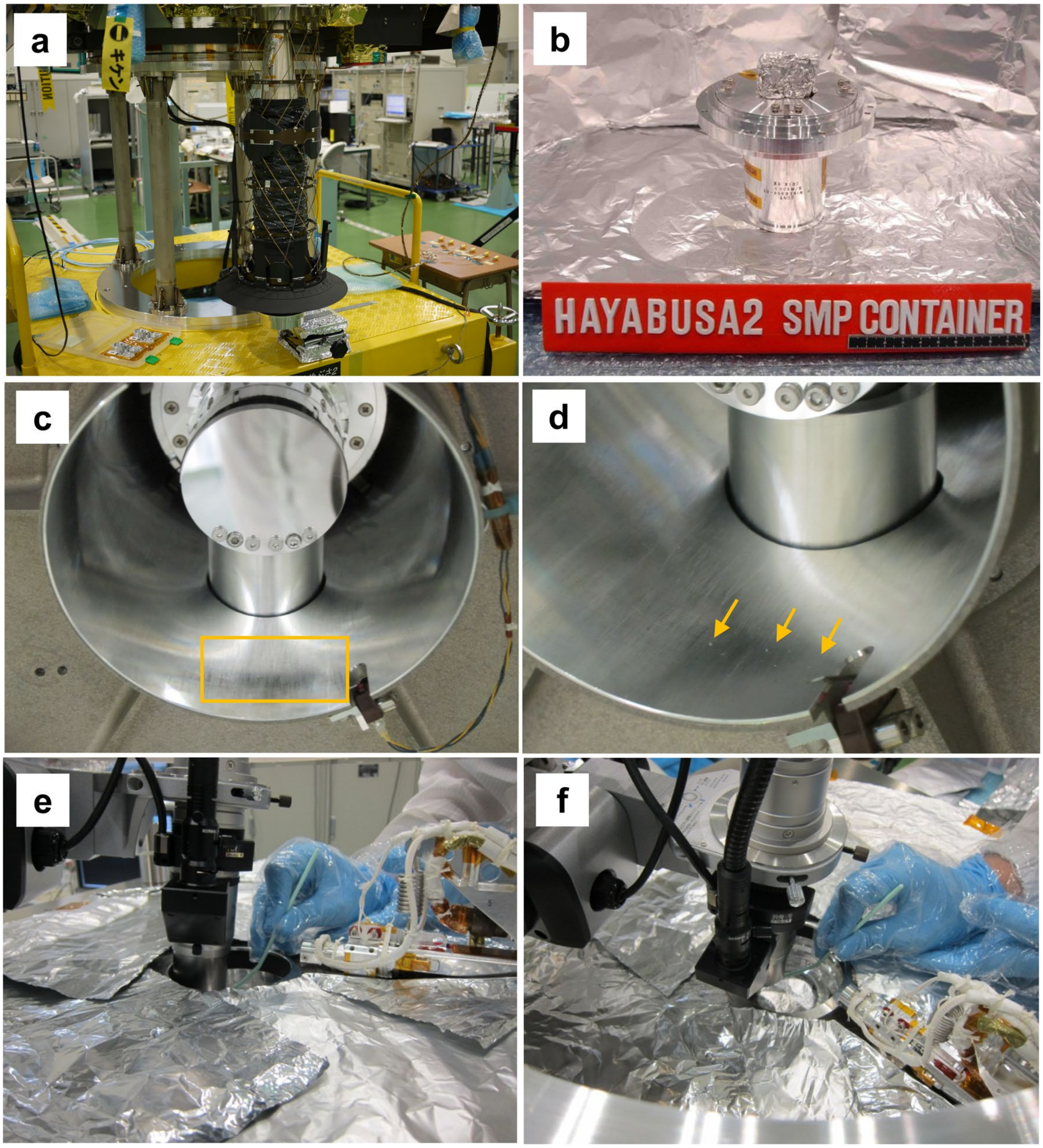


Fig. 3 Environmental monitoring near the Hayabusa2 spacecraft. **a** Sampler horn. **b** Sample container with witness coupon inside (Sawada et al. 2017). **c**, **d** Inside the sample catcher before elimination of surface dust. **e**, **f** Microscopic observation using a wipe stick to see if any artefacts were present

STA1, SFA2, and VAB). There were clear positive correlations between total sodium, potassium, and chloride and total organic contents, which closely approximated the 1:1 line. Both major inorganic ions and total organic fluxes converged in the range 10^1–10^3 ng per monitor coupon, resulting in static deposition of < 1 μg overall within ~ 7.0 and ~ 5.3 cm^2 for aluminium schale and Pyrex schale, respectively. Representative compositions of organic deposits were obtained by the gas chromatography (Fig. 6). This result is a static monitoring method

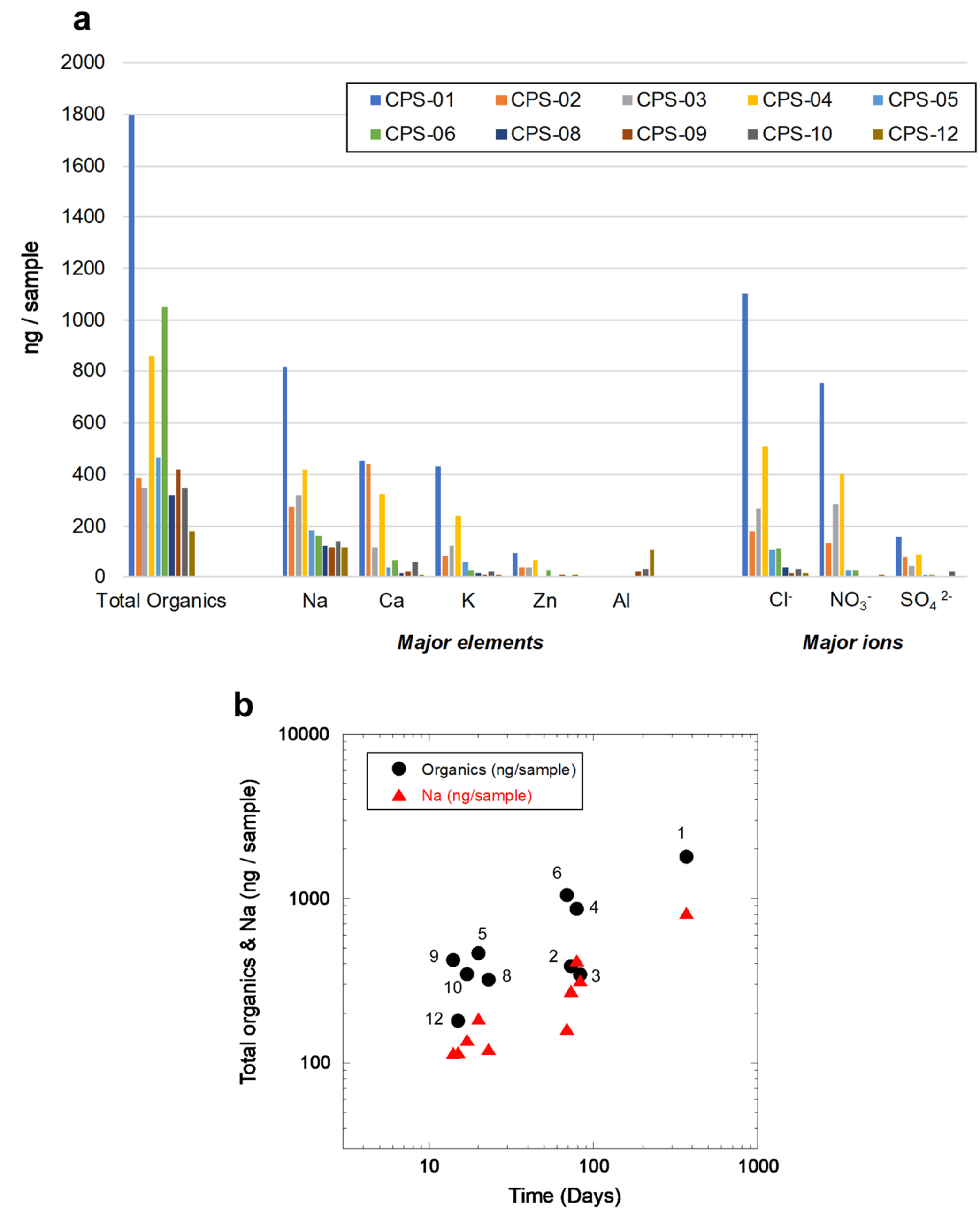


Fig. 4 **a** Concentrations of total organics, major elements, and major ions monitored by the monitor coupon (Nos. 1–12, including STA1, SFA2, and VAB). The sample codes were listed in Tables 2 and 3. Each static, quantitative assessment was normalized in units of nanograms per sample (ng/sample). **b** Quantitative comparison between static monitoring and unit time (days) with regard to total organics and Na concentration

Table 2 Concentrations of main elements (Fe, Cu, Ni, Cr, Zn, Na, K, Ca, Mn, Al, Ti, Mg, Co, Sn, Pb, V, and P) from static sampling, air-filter sampling, and swab sampling during sampler-system development up to the launch of the Hayabusa2 spacecraft

Sample code	Profile	Concentration (ng/sample)																	Remarks
		Fe	Cu	Ni	Cr	Zn	Na	K	Ca	Mn	Al	Ti	Mg	Co	Sn	Pb	V	P	
Static sampling																			
CPS-01	CC1-Py_Schale	2.4	3.6	1.3	–	92	819	428	455	1.4	3.6	4.3	33	< 0.1	0.4	0.3	< 0.1	19	
CPS-02	CC2-Py_Schale	0.3	1.0	0.6	–	36	274	86	441	0.4	5.5	2.4	15	< 0.1	0.1	0.1	< 0.1	6.5	
CPS-03	CC3-Py_Schale	0.9	1.4	1.0	–	39	318	120	118	0.5	4.9	0.6	12	< 0.1	0.1	0.3	< 0.1	4.1	
CPS-04	CC4-Py_Schale	0.5	1.8	0.7	–	66	420	240	325	1.3	3.9	1.8	30	0.2	0.2	0.1	< 0.1	7.6	
CPS-05	CC5-Py_Schale	0.2	0.9	0.3	–	7.7	186	59	39	0.3	4.1	0.2	3.2	< 0.1	< 0.1	< 0.1	< 0.1	1.7	
CPS-06	CC6-Py_Schale	< 0.1	1.3	0.2	–	30	161	30	65	0.4	4.3	0.9	8.1	< 0.1	< 0.1	< 0.1	< 0.1	4.5	
CPS-08	CC8-Py_Schale	< 0.1	0.6	< 0.1	–	6.5	121	19	18	0.1	7.6	0.1	2.2	< 0.1	< 0.1	< 0.1	< 0.1	1.7	
CPS-09	CC9-Py_Schale	0.4	0.9	0.4	–	7.9	115	13	19	0.3	21	0.1	5.7	< 0.1	< 0.1	< 0.1	< 0.1	1.2	
CPS-10	CC10-Py_Schale	0.2	3.8	0.2	–	7.1	138	22	62	0.2	31	0.4	4.3	< 0.1	< 0.1	< 0.1	< 0.1	0.4	
CPS-12	CC12-Py_Schale	2.1	1.1	0.2	–	13	116	9.7	10	0.4	105	0.1	3.7	< 0.1	0.1	0.5	< 0.1	5.4	
CPS-15	CC15-Py_Schale	< 0.1	< 0.1	< 0.1	–	3.4	96	5.3	8.0	0.1	1.2	< 0.1	1.1	< 0.1	< 0.1	< 0.1	< 0.1	< 1.8	Process blank for experimental background
Air filter sampling																			
QFT-01	BLANK-#2	0.8	0.8	1.6	6.4	< 4	< 160	45	< 80	0.8	< 0.4	< 0.4	2.4	< 3.2	–	–	< 0.4	5.6	Quartz filter of process blank
QFT-02	141024-QF-#2	3.9	2.1	3.3	–	37	549	35	375	2.4	23	4.5	29	0.9	< 0.3	< 0.3	< 0.3	< 6	Quartz filter at SFA2
QFT-03	VAB-12F	2.0	39	3.6	4.0	54	1110	42	174	2.0	1.2	< 0.4	15	3.6	–	–	< 0.4	6.8	Quartz filter at VAB-12F
QFT-04	STA1-CR	3.2	0.8	4.0	15	29	876	42	776	2.8	4.4	< 0.4	48	16	–	–	< 0.4	5.2	Quartz filter at STAR1-CR
Swab sampling																			
GWT-01	141024-00B	0.6	< 0.3	< 0.3	–	2.1	22	3.3	7.8	0.3	12	0.3	0.9	< 0.3	0.3	< 0.3	< 0.3	< 6	Glass wool of process blank
GWT-02	141024-01A-#2	0.6	4.2	2.7	–	201	2000	251	245	5.4	23	0.9	54	< 0.3	0.9	1.5	< 0.3	< 6	Glass wool at SFA2 payload room
GWT-03	141024-02A-#2	17	21	3.6	–	5190	1170	489	5310	11	24	11	293	0.6	0.3	8.7	< 0.3	390	Glass wool at SFA2 fairing room elevator
GWT-04	141024-03A-#2	3.0	6.6	1.5	–	336	507	106	252	2.1	19	0.6	44	< 0.3	0.6	2.7	< 0.3	12	Glass wool at SFA2 fairing room
GWT-05	141024-04A-#2	16	17	29	–	4380	9600	257	1830	27	33	3.9	1060	3.6	0.3	21	< 0.3	21	Glass wool at VAB-12F floor
GWT-06	141024-05A-#2	25	21	20	–	2050	9810	345	1730	16	106	4.5	1120	1.2	1.2	22	0.3	12	Glass wool at VAB-12F support rod
FM container																			
Swab sampling	FM launch status	< 0.1	< 0.1	< 0.1	–					0.2	0.7	0.3	0.8	< 0.1	< 0.1	< 0.1	< 0.1		

Static concentrations were normalized in units of nanograms per sample (ng/sample) following Takano et al. (2020) using an inductively coupled plasma–mass spectrometry (ICP-MS; 7500 s, Agilent Technologies Inc.). The concentrations of area-based conversions (i.e., ng cm^{-2}) can be obtained by reference to the size scale (Fig. 1)

Table 3 Concentrations of major ions (Cl^-, NO_2^-, Br^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, F^-, acetic acid, formic acid, NH_4^+, 2A2M (2-amino-2-methyl-1-propanol), and DMA (dimethylamine), from static sampling, air-filter sampling, and swab sampling during sampler-system development up to the launch of the Hayabusa2 spacecraft

Sample code	Profile	Concentration (ng/sample)												Remarks
		Anion									Cation			
		Cl^-	NO_2^-	Br^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	F^-	Acetic acid	Formic acid	NH_4^+	2A2M	DMA	
Static sampling														
CPS-01	CC1-Py_Schale	1100	9.0	< 3.6	754	156	< 6.5	19	16	10	32	< 9.9	< 4.2	
CPS-02	CC2-Py_Schale	181	5.6	< 3.7	136	80	< 6.4	4.0	107	181	< 2.1	< 9.3	< 3.9	
CPS-03	CC3-Py_Schale	269	4.5	< 3.7	287	47	< 6.4	3.8	57	4.2	< 2.1	< 9.3	< 3.9	
CPS-04	CC4-Py_Schale	509	8.5	< 3.7	401	88	< 6.4	11	135	7.6	< 2.1	< 9.3	< 3.9	
CPS-05	CC5-Py_Schale	108	7.1	< 3.7	26	8.8	< 6.4	2.2	27	6.4	< 2.1	< 9.3	< 3.9	
CPS-06	CC6-Py_Schale	110	5.6	< 3.6	29	13	< 6.5	1.5	< 3.7	< 1.9	< 2.1	< 9.9	< 4.2	
CPS-08	CC8-Py_Schale	36	4.0	< 3.7	3.7	6.5	< 6.4	< 0.8	68	4.1	< 2.1	< 9.3	< 3.9	
CPS-09	CC9-Py_Schale	17	< 2.2	< 3.7	< 2.5	5.5	< 6.4	1.9	296	3.7	< 2.1	< 9.3	< 3.9	
CPS-10	CC10-Py_Schale	35	3.1	< 3.7	7.6	20	< 6.4	1.1	107	2.5	< 2.1	< 9.3	< 3.9	
CPS-12	CC12-Py_Schale	17	3.1	< 3.7	9.2	4.4	< 6.4	1.5	64	5.7	< 2.1	< 9.3	< 3.9	
CPS-15	CC15-Py_Schale	< 1.4	3.6	< 3.6	< 2.5	2.2	< 6.5	< 0.8	4.3	5.8	< 2.1	< 9.9	< 4.2	Process blank for experimental background
Air filter sampling														
QFT-01	BLANK-#2	< 80	< 4	< 24	< 80	< 80	20	8	< 80	< 12	180	< 12	< 4	Quartz filter of process blank
QFT-02	141024-QF-#2	213	< 15	< 27	< 18	630	< 78	129	< 30	< 12	< 15	< 66	< 33	Quartz filter at SFA2
QFT-03	VAB-12F	188	< 4	< 24	< 80	132	20	48	< 80	< 12	156	< 12	< 4	Quartz filter at VAB-12F
QFT-04	STA1-CR	156	< 4	< 24	< 80	192	12	160	< 80	< 12	80	< 12	32	Quartz filter at STA1-CR
Swab sampling														
GWT-01	141024-00B	< 12	< 15	< 27	< 18	< 15	< 78	15	< 30	< 12	< 15	< 66	< 33	Glass wool of process blank
GWT-02	141024-01A-#2	2880	42	< 27	159	216	< 78	276	< 30	< 12	< 15	< 66	< 33	Glass wool at SFA2 payload room
GWT-03	141024-02A-#2	1170	63	< 27	330	1980	< 78	1290	150	114	< 15	< 66	< 33	Glass wool at SFA2 fairing room elevator
GWT-04	141024-03A-#2	630	18	< 27	150	540	< 78	12	< 30	< 12	< 15	< 66	< 33	Glass wool at SFA2 fairing room
GWT-05	141024-04A-#2	23,800	120	< 27	5220	2160	< 78	51	48	36	< 15	< 66	< 33	Glass wool at VAB-12F floor
GWT-06	141024-05A-#2	23,000	87	< 27	1860	3930	< 78	51	< 30	< 12	< 15	< 66	< 33	Glass wool at VAB-12F support rod

Static concentrations were normalized in units of nanograms per sample (ng/sample) following Takano et al. (2020) using the system of ion chromatography (IC; DX-120 for cations; DX-500 for anions; Dionex Inc.) with Ion Pac CS10 and Ion Pac AS17 columns for cations and anions, respectively (Dionex Inc.). The concentrations of area-based conversions (i.e., ng cm^{-2}) can be obtained by reference to the size scale (Fig. 1). 2A2M and DMA were analyzed in the same way and are shown as the maximum value for the sample

Table 4 Concentration of total organics from static and air-filter sampling during sampler-system development up to the launch of the Hayabusa2 spacecraft

Sample code	Profile	Days	Concentration total organics			Remarks
			ng/sample	ng/cm^2	ng/cm^2/day	
Static sampling						
CAS-01	CC1-Al	368	1796	254	0.69	Please see, Fig. 1b, c and Sawada et al. (2017)
CAS-02	CC2-Al	73	388	55	0.75	
CAS-03	CC3-Al	83	345	49	0.59	
CAS-04	CC4-Al	79	864	122	1.55	
CAS-05	CC5-Al	20	464	66	3.29	
CAS-06	CC6-Al	69	1049	149	2.15	
CAS-08	CC8-Al	23	320	45	1.97	
CAS-09	CC9-Al	14	422	60	4.27	
CAS-10	CC10-Al	17	346	49	2.88	
CAS-12	CC12-Al	15	180	25	1.70	
Air filter sampling						
QFT-01	20141024-QF-01-#1		588	83		Quartz filter at STA1
QFT-02	20141024-QF-06-#1		425	60		Quartz filter at SFA2
QFT-03	20141024-QF-11-#1		978	139		Quartz filter at VAB
Swab sampling						
Jet deposit	After jet experiment		–	12		

Static concentrations were normalized in units of nanograms per sample (ng/sample) following Takano et al. (2020). The concentrations of area-based conversions (i.e., ng cm^{-2}) can be obtained by reference to the size scale (Fig. 1). The swab sampling during the jet deposit (i.e., thruster test of the aircraft; Tsuda et al. 2013) was assessed by subtracting the value between the experimental deposit and the background (i.e., ng cm^{-2})

and may depend on the environmental gradient to determine whether the dust flux had reached equilibrium or not, especially for volatile components. A wide range of aliphatic hydrocarbons comprising straight-chain alkanes ($< n$-$C_{19}H_{40}$) was detected (e.g., $m/z = 57$ for the extracted ion chromatogram). The total amounts of other miscellaneous organics were quantified based on the corresponding responses with the internal standard method (e.g., Takano et al. 2020). The exposure time-dependent accumulation profiles were similar to the results for cleanliness tests run in the clean-room chamber at the Institute of Space and Aeronautical Science (ISAS)/JAXA (i.e., the nitrogen-circulation clean chamber; Sugahara et al. 2018).

Tables 5 and 6 summarize the basic statistics and the correlation matrix for the concentrations of major components in the static samples (i.e., CPS1–12 and CAS1–12; $n = 10$). Most profiles of the major components (e.g., Na, K, Cl^-, F^-, NO_3^-, Zn, SO_4^{2-}, Mg, and P) were positively correlated with each other, except for the profile of aluminium (Fig. 5e and Additional file 1: Figure S2). We note that we used clean room-type aluminium foil to store and carry the monitor coupons, which could potentially introduce a certain amount of aluminium onto the coupon. We also conducted microscopic observations of the solid contaminants to evaluate their morphological characteristics (Fig. 7) and found that globular particles were more common (70%) than fibrous particles (13%).

(See figure on next page.)

Fig. 5 Representative profiles of the static accumulation of ambient aerial deposits onto the monitor coupons (Nos. 1–12, including STA1, SFA2, and VAB): **a** sodium (Na) and total organics, **b** potassium (K) and ionized chloride (Cl^-), **c** zinc (Zn) and sulfate (SO_4^{2-}), and **d** calcium (Ca) and ionized nitrate (NO_3^-). **e** Principal component loading using the correlation matrix (Table 5) of the major components in the static monitoring data of CPS1-12 ($n = 10$) and CAS1-12 ($n = 10$), as shown in Table 6. Aluminium was used for storage and packaging of the samples, which may have resulted in higher background values

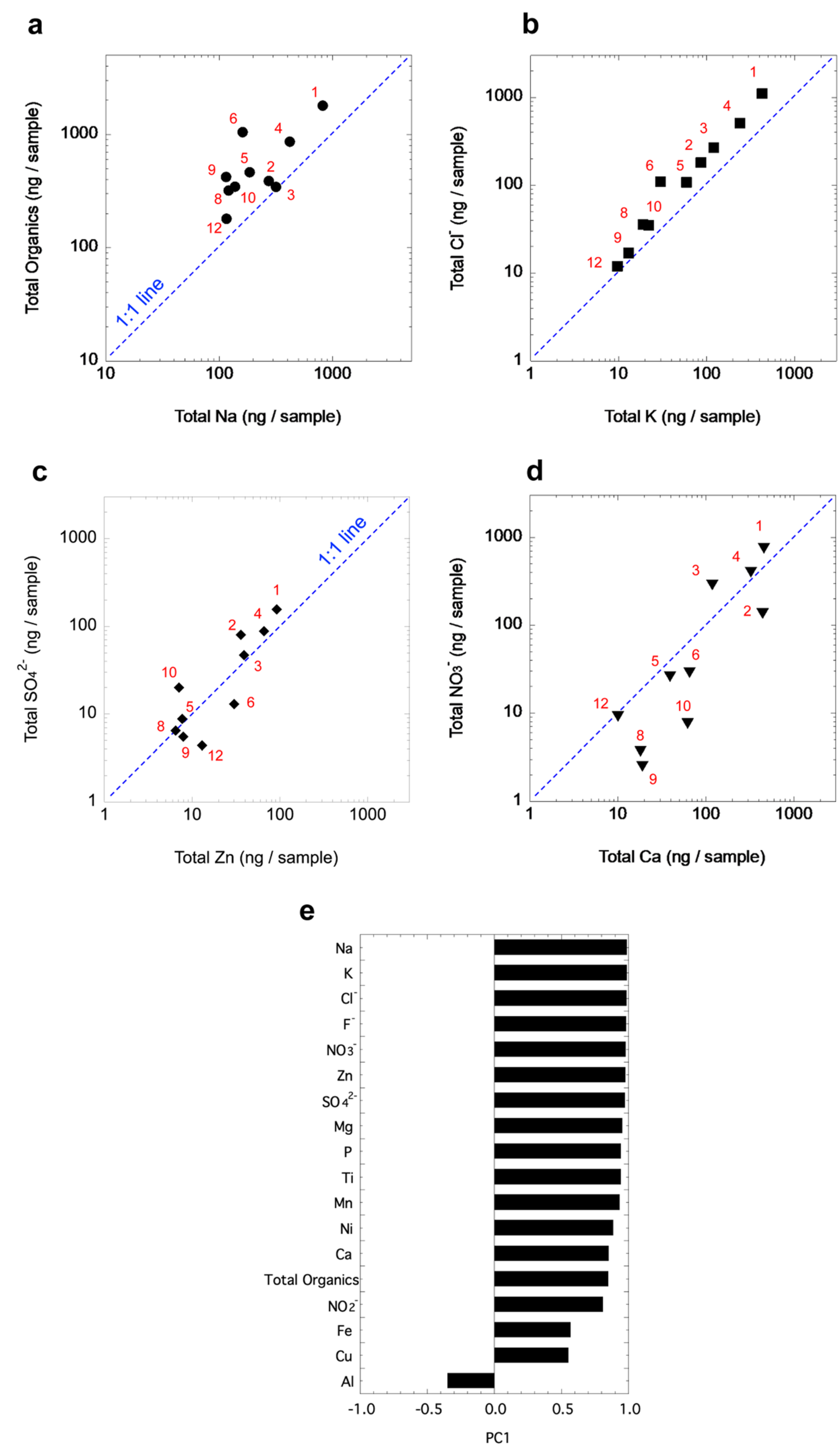


Fig. 5 (See legend on previous page.)

Table 5 Basic principal component statistics in the static samples (i.e., CPS1–12 and CAS1–12; $n = 10$)

Concentration (ng/sample)	Average ($n = 10$)	Standard deviation (1σ)
Total organics	617.4	492.0
Major elements		
Na	266.8	219.2
Ca	155.4	179.5
K	102.7	134.4
Zn	30.5	29.0
Al	19.1	31.7
Mg	11.8	11.2
P	5.2	5.4
Cu	1.6	1.1
Ti	1.1	1.4
Fe	0.7	0.8
Ni	0.5	0.4
Mn	0.5	0.4
Major ions		
Cl^-	238.1	338.9
NO_3^-	165.5	248.9
SO_4^{2-}	43.0	50.6
NO_2^-	5.3	2.3
F^-	4.7	5.9

Further non-destructive analyses using microRaman and infrared spectroscopy (e.g., Kitajima et al. 2015) can be performed at ISAS/JAXA upon request.

We stored the potential Earth-derived artefacts obtained from each procedure (Table 1) (i.e., the category-3 particles; Uesugi et al. 2019). Therefore, if necessary, we can provide a careful description, upon request, as suggested by the lessons learned from the previous Hayabusa mission (the asteroid Itokawa) with regard to high-resolution small-scale mass spectrometry (e.g., NanoSIMS: Ito et al. 2014; ToF–SIMS: Naraoka et al. 2015) and spectroscopy (e.g., X-ray absorption: Yabuta et al. 2014). Interestingly, Chan et al. (2021) and Parker et al. (2022) reported a detailed description of exogenous carbonaceous organic matter derived from the Itokawa sample.

Safety declaration of the Ryugu sample processes

The Hayabusa2 mission succeeded in delivering its re-entry capsule to Earth in December 2020, and the total sample amount was confirmed to exceed 5 g (Tachibana et al. 2021, 2022; Yada et al. 2021a, 2021b; Pilorget et al. 2021), including millimeter-sized grains to centimeter-sized pebbles. This study reports the prelaunch phase environmental assessment performed during manufacturing of the sampler devices, their installation onto the spacecraft, and their transportation. We conclude that the exposure-time-dependent deposition profiles of potential contaminants were firmly underscored and similar to the profiles obtained from the clean-room facility assessment (Sugahara et al. 2018). All potential contaminants have been stored at the JAXA Extraterrestrial Sample Curation Center in a nitrogen-purged storage area and are available for future analysis upon request.

The total amount of potential contaminants in the sampler system is estimated to be less than 100 ng cm^{-2}, which is much smaller than the total amount of returned samples. Along with the fact that there was no off-nominal situation from spacecraft launch to the capsule's re-entry to Earth, we conclude that ambient background artefacts have been characterized and will not affect detailed sample analyses.

We expect that the lessons learned in the process from implementation to practical knowledge during the last 8 years will also provide a valuable baseline for future sample-return missions (e.g., Dworkin et al. 2018; Usui et al. 2020; Anand et al. 2020; Chan et al. 2020; Neveu et al. 2020; Farley et al. 2020; Fujiya et al. 2021) and micro-spacecraft missions with a launch vehicle secondary payload (e.g., Ito et al. 2018; Hernando-Ayuso et al. 2019; Campagnola et al. 2019).

(See figure on next page.)

Fig. 6 Representative extracted ion chromatograms (EICs) of the aliphatic hydrocarbon compounds (*n*-alkanes; $m/z = 57$ on EIC) obtained from online thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) with a quantitative internal standard method (Takano et al. 2020) using an online thermal desorption (TD)-GC/MS using a multipurpose sampling and thermal desorption system (MSTD-258M; GL Science Inc.) and a purge and trap device (P&T; Gestel TDS A2, Gestel Inc.) coupled to a GC/MS system (Agilent 6890 N and 5973 MSD; Agilent Technologies Inc.). **a** Typical terrestrial reference (humic acid as standard reference; from FUJIFILM Wako Pure Chemical Corporation), **b** STA1 (code: 20141024-QF-01-#1), **c** SFA2 (code: 20141024-QF-06-#1). The two signals (*) between 13 and 14 min appear to be compounds that possess the characteristic $-C_4H_9$ fragment. **d** Mass spectra of the gas chromatographic retention time (13.13 min; scan 2252) and the candidate of 2-ethylhexyl acrylate by the NIST database library were shown

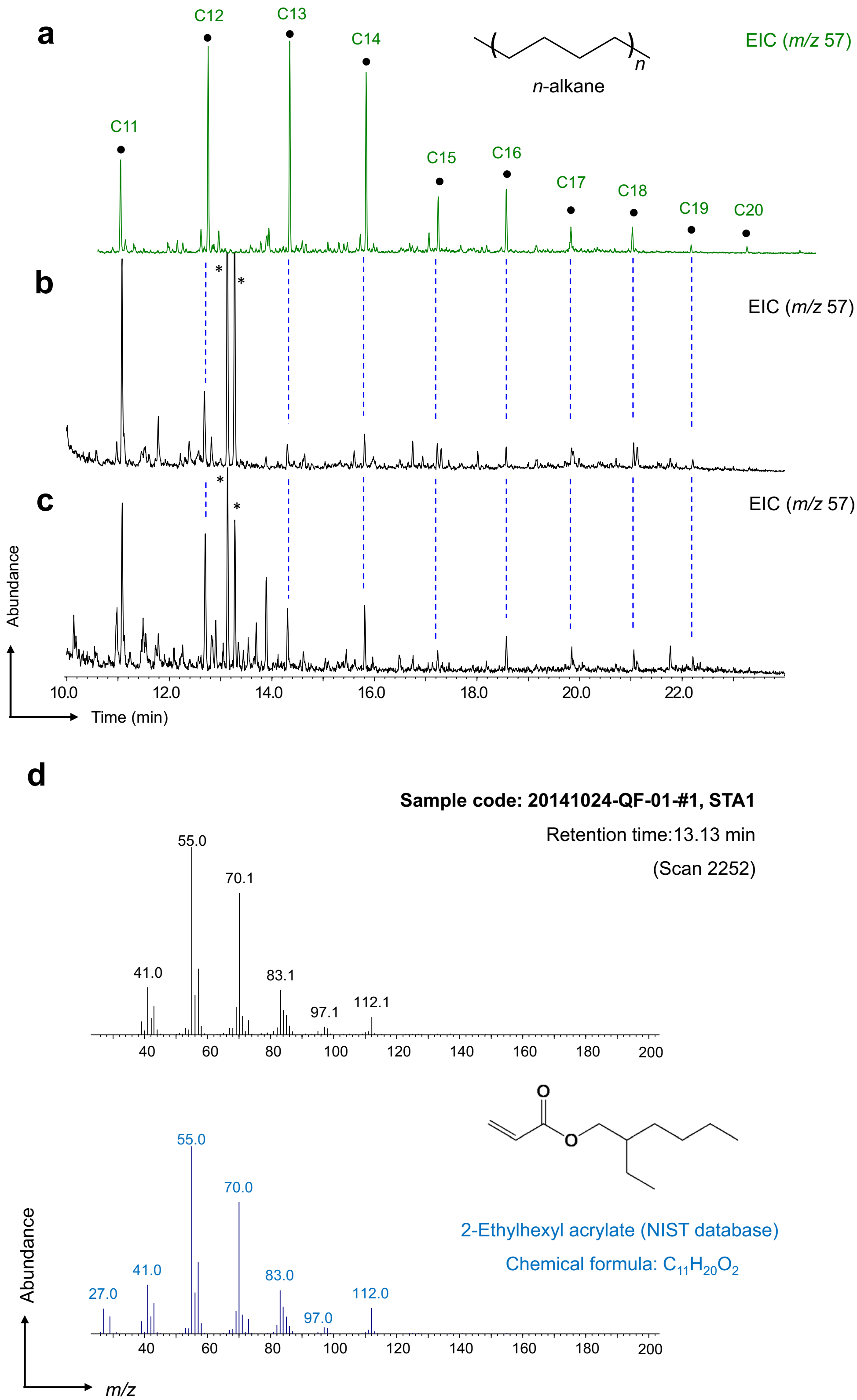
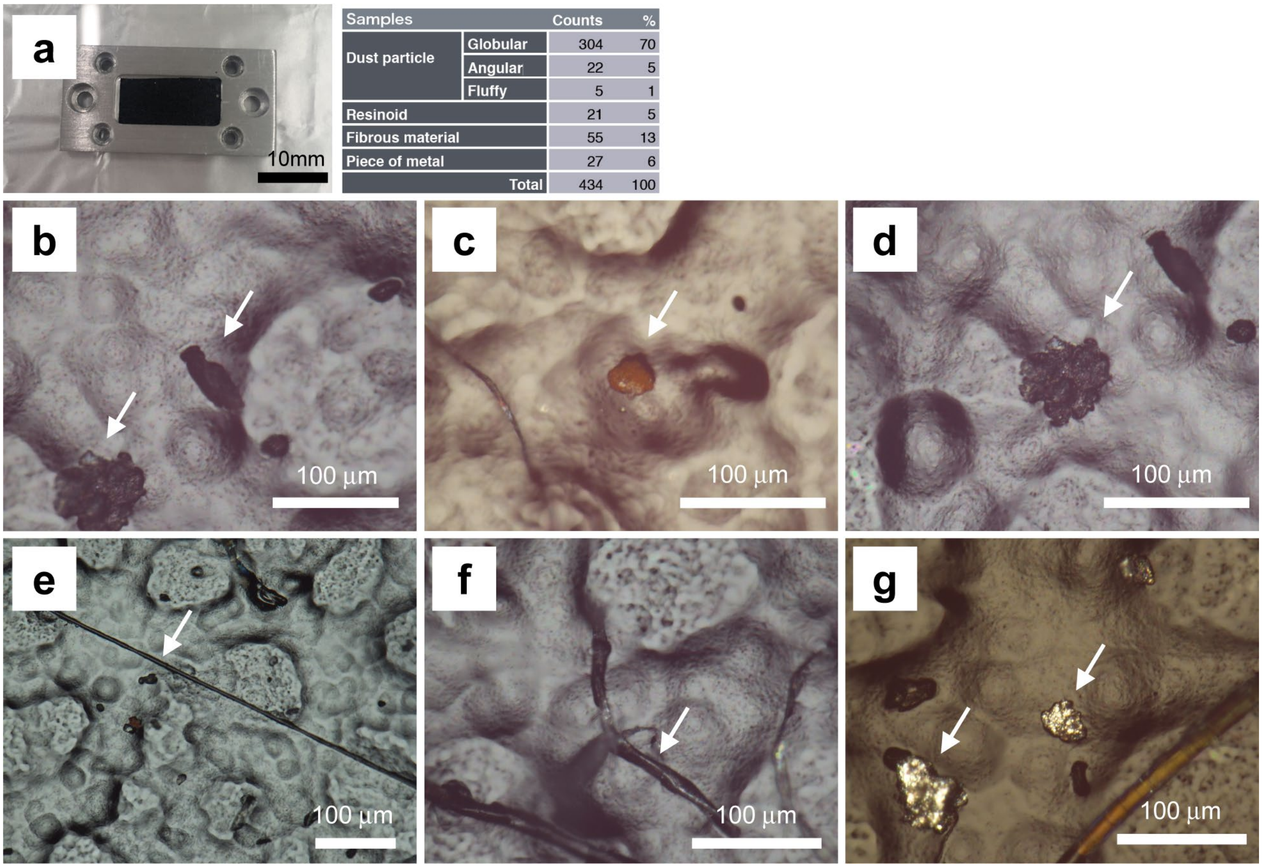


Fig. 6 (See legend on previous page.)

Table 6 Correlation matrix of the major components in the static samples using the CPS1–12 ($n = 10$) and CAS1–12 ($n = 10$) data sets

	Total organics	**Fe**	**Cu**	**Ni**	**Zn**	**Na**	**K**	**Ca**	**Mn**	**Al**	**Ti**	**Mg**	**P**	**Cl^-**	**NO_2^-**	**NO_3^-**	**SO_4^{2-}**	**F^-**
Total Organics	1	0.418	0.531	0.624	0.828	0.839	0.835	0.597	0.789	− 0.406	0.812	0.765	0.840	0.871	0.749	0.798	0.751	0.841
Fe	0.418	1	0.346	0.560	0.532	0.605	0.574	0.321	0.556	0.483	0.490	0.435	0.743	0.605	0.227	0.606	0.507	0.593
Cu	0.531	0.346	1	0.444	0.475	0.566	0.554	0.387	0.458	− 0.058	0.518	0.469	0.476	0.571	0.283	0.542	0.549	0.548
Ni	0.624	0.560	0.444	1	0.876	0.908	0.882	0.772	0.779	− 0.353	0.810	0.839	0.802	0.873	0.598	0.927	0.894	0.846
Zn	0.828	0.532	0.475	0.876	1	0.947	0.953	0.842	0.946	− 0.345	0.907	0.973	0.916	0.948	0.801	0.962	0.946	0.947
Na	0.839	0.605	0.566	0.908	0.947	1	0.991	0.805	0.895	− 0.353	0.918	0.910	0.937	0.995	0.784	0.988	0.956	0.974
K	0.835	0.574	0.554	0.882	0.953	0.991	1	0.790	0.934	− 0.355	0.892	0.935	0.916	0.994	0.815	0.989	0.946	0.991
Ca	0.597	0.321	0.387	0.772	0.842	0.805	0.790	1	0.754	− 0.387	0.935	0.874	0.786	0.771	0.706	0.780	0.936	0.790
Mn	0.789	0.556	0.458	0.779	0.946	0.895	0.934	0.754	1	− 0.210	0.817	0.966	0.869	0.915	0.791	0.919	0.876	0.961
Al	− 0.406	0.483	− 0.058	− 0.353	− 0.345	− 0.353	− 0.355	− 0.387	− 0.210	1	− 0.358	− 0.364	− 0.124	− 0.340	− 0.509	− 0.334	− 0.367	− 0.293
Ti	0.812	0.490	0.518	0.810	0.907	0.918	0.892	0.935	0.817	− 0.358	1	0.886	0.927	0.902	0.743	0.875	0.967	0.892
Mg	0.765	0.435	0.469	0.839	0.973	0.910	0.935	0.874	0.966	− 0.364	0.886	1	0.852	0.912	0.798	0.930	0.944	0.946
P	0.840	0.743	0.476	0.802	0.916	0.937	0.916	0.786	0.869	− 0.124	0.927	0.852	1	0.939	0.709	0.910	0.906	0.924
Cl^-	0.871	0.605	0.571	0.873	0.948	0.995	0.994	0.771	0.915	− 0.340	0.902	0.912	0.939	1	0.793	0.985	0.938	0.984
NO_2^-	0.749	0.227	0.283	0.598	0.801	0.784	0.815	0.706	0.791	− 0.509	0.743	0.798	0.709	0.793	1	0.757	0.755	0.795
NO_3^-	0.798	0.606	0.542	0.927	0.962	0.988	0.989	0.780	0.919	− 0.334	0.875	0.930	0.910	0.985	0.757	1	0.944	0.972
SO_4^{2-}	0.751	0.507	0.549	0.894	0.946	0.956	0.946	0.936	0.876	− 0.367	0.967	0.944	0.906	0.938	0.755	0.944	1	0.938
F^-	0.841	0.593	0.548	0.846	0.947	0.974	0.991	0.790	0.961	− 0.293	0.892	0.946	0.924	0.984	0.795	0.972	0.938	1

Principal component load statistics are included in the Additional file 1



Samples		Counts	%
Dust particle	Globular	304	70
	Angular	22	5
	Fluffy	5	1
Resinoid		21	5
Fibrous material		55	13
Piece of metal		27	6
	Total	434	100

Fig. 7 **a** Carbon adhesive tape used for the environmental assessment. **b**–**g** Representative microscopic observations of the morphologies of artefact materials on the coupon

Appendix

See Fig. 8.

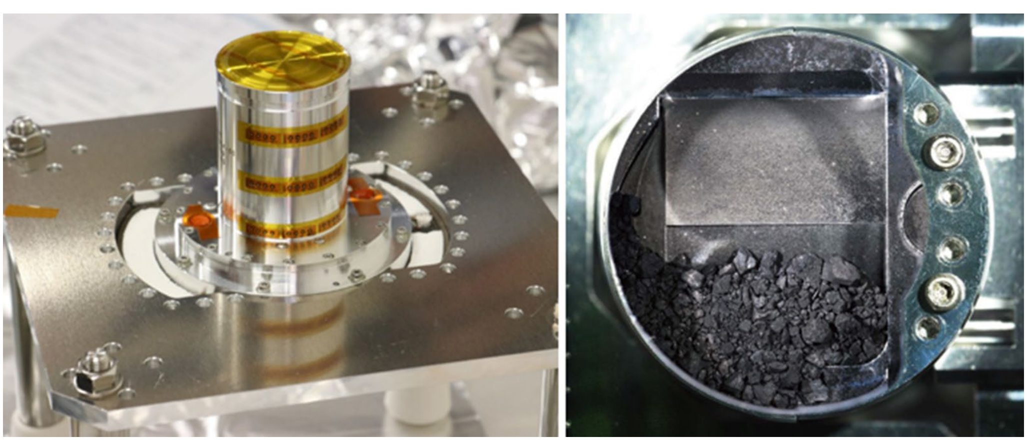


Fig. 8 **a** Hayabusa2 sample box from the asteroid Ryugu. **b** Photos taken immediately after opening the sample box. The sample catcher diameter is 48 mm (credit: JAXA). The fireball movie captures taken near Coober Pedy, Australia, are provided in the Additional file 3: Movie S2, Additional file 4: Movie S3, Additional file 5: Movie S4 (credit: JAXA)

Abbreviations
C-type: Carbonaceous-type; JAXA: Japan Aerospace Exploration Agency; ISAS/JAXA: Institute of Space and Astronautical Sciences/JAXA; ESCuC: Extraterrestrial Sample Curation Center; TNSC: Tanegashima Space Center; TSC: Tsukuba Space Center; STA: Spacecraft Test and Assembly Building; VAB: Vehicle Assembly Building; SFA: Spacecraft and Fairing Assembly Building; NASA: National Aeronautics and Space Administration; TDS: Thermal desorption system; GC: Gas chromatography; GC/MS: GC coupled with mass spectrometry; EIC: Extracted ion chromatogram; FTIR: Fourier transform infrared (spectroscopy); NanoSIMS: Nanoscale secondary ion mass spectrometry; GAEA: GAs extraction and analyses system; NIST: National Institute of Standards and Technology.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-022-01628-z.

Additional file 1: Figure S1. Sample assessment of the potential risk between the worst-assumption lines versus the actual native sample weight. 'Worst case (off-nominal adverse case ~ 100%)' plot of the potential assumption line (e.g., unrealistic artifacts in the range of 0.1 and 1.0 µg up to the launch of the spacecraft; e.g., Fig. 4) versus the native sample weight (5.4 g; actual sample achievement: Tachibana et al. 2021, 2022; Yada et al. 2021a, 2021b). See the minimum mission requirement (100 mg) in a nominal situation (Tachibana et al. 2014). **Figure S2. a** Scheme of the screening and cleanliness test for air-filter sampling (Multi-stage Andersen Cascade Impactor, Tokyo Dylec Corp.) using a quartz filter (8 cm diameter × 4 mm thickness). **b** Screening and cleanliness test for swab sampling using 0.3 g of glass wool and a 20 × 20 cm square. Photos were taken at Tanegashima Space Center before the launch of the Hayabusa2 spacecraft. **Figure S3.** Identification of volatile compounds in the precipitate material during the spacecraft's thermal vacuum test. For the general protocol adopted for a thermal vacuum test of a spacecraft, see JAXA document JERG-2-130-HB005B and Sawada et al. (2017). Small amounts of phenol (C_6H_6O; molecular weight: 94.1), triethylphosphate ($C_6H_{15}O_4P$; molecular weight: 182.1) and benzoic acid ($C_7H_6O_2$; molecular weight: 122.1) were confirmed based on the TD–GC/MS method and a standard library database (method after Takano et al. 2020). **Figure S4. a**–**d** Other locations for collections of potential contaminants before and after launch of the Hayabusa2 spacecraft. Collected samples are in storage at ISAS/JAXA, but the data are not shown in this report. Please see also the Additional file 2: Movies S1 for the launch. **Figure S5.** Hayabusa2 sample capsule entering the Earth's atmosphere (photo taken in Australia). Please see also the fireball movie captures taken near Coober Pedy, Australia, in the Additional file 3: Movie S2, Additional file 4: Movie S3, Additional file 5: Movie S4 (credit: JAXA). **Figure S6.** Hayabusa2 spacecraft just before launch in 2014 at Tanegashima Space Center (TNSC) with the Hayabusa2 sampler team members (credit: JAXA).

Additional file 2: Movie S1. HY2 launch.

Additional file 3: Movie S2. FireBall 1.

Additional file 4: Movie S3. FireBall 2.

Additional file 5: Movie S4. FireBall 3.

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Author contributions
SK and YT led this work, conducted the assessment, deployed the coupon set, monitored the environment, interpreted the data, and finalized the manuscript. TN and RO supported the assessment process as witness scientists up to launch of the spacecraft. HS and ST led the Hayabusa2 sampling system with feedback from KS, YT, YM and RO. HS and SN performed the thermal vacuum test on the spacecraft and collected the precipitate sample. HY, TY, MU and MA supervised the assessment scheme based on feedback from the previous Hayabusa mission. Hayabusa2 project team members confirmed the present assessment with regard to quality control and assurance for future sample processes. YT, HS, and ST designed the implementation of the fundamental scheme. All authors read and approved the final manuscript.

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Availability of data and materials
The Hayabusa2 project is releasing raw data on the properties of the asteroid Ryugu from the following database in the Hayabusa2 Science Data Archives (DARTS, https://www.darts.isas.jaxa.jp/planet/project/hayabusa2/) with regard to the ONC (Optical Navigation Camera), TIR (Thermal InfraRed Imager), NIRS3 (Near InfraRed Spectrometer), LIDAR (LIght Detection And Ranging), SPICE (SPICE kernels) and PDS4 (PDS4 bundles). In addition, the catalogue of the Ryugu samples is also available in the database titled "Hayabusa2, Ryugu Sample Curatorial Dataset, (https://doi.org/10.17597/ISAS. DARTS/CUR-Ryugu-description) after Yamamoto et al. (2016) and Abe (2021)". All of these database publications are compliant with ISAS data policies (https://www.isas.jaxa.jp/en/researchers/data-policy/). Please see also the Additional file 1.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests regarding the data reported in this document.

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