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Supplementary information

Impact remnants rich in carbonaceous chondrites detected on the Moon by the Chang'e-4 rover

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Supplementary Information for

Impact Remnants Rich in Carboncaous Chondrites Detected on the Moon by the Chang'E-4 Rover

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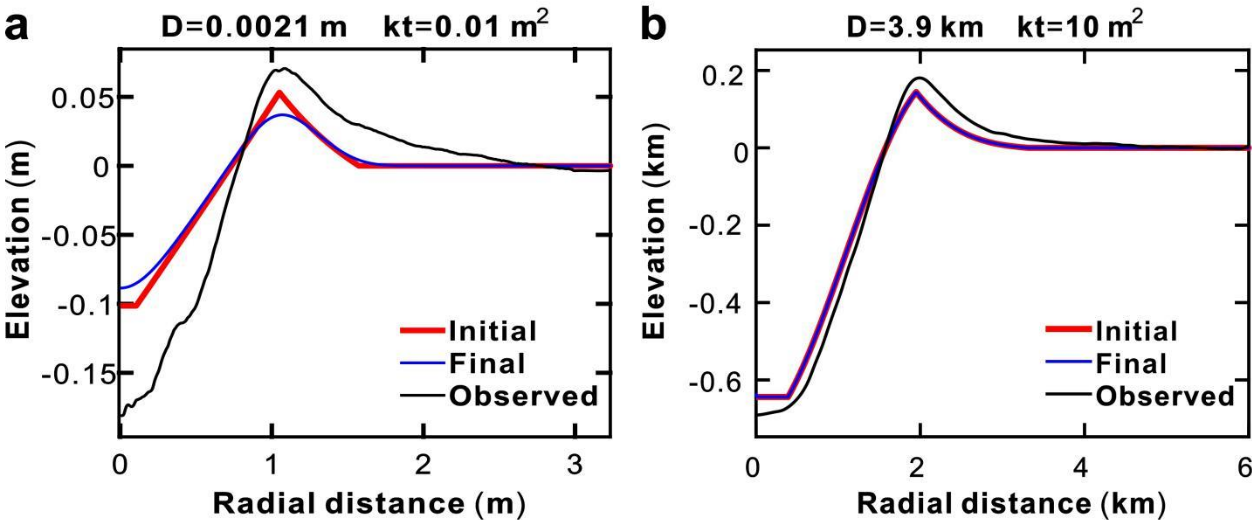
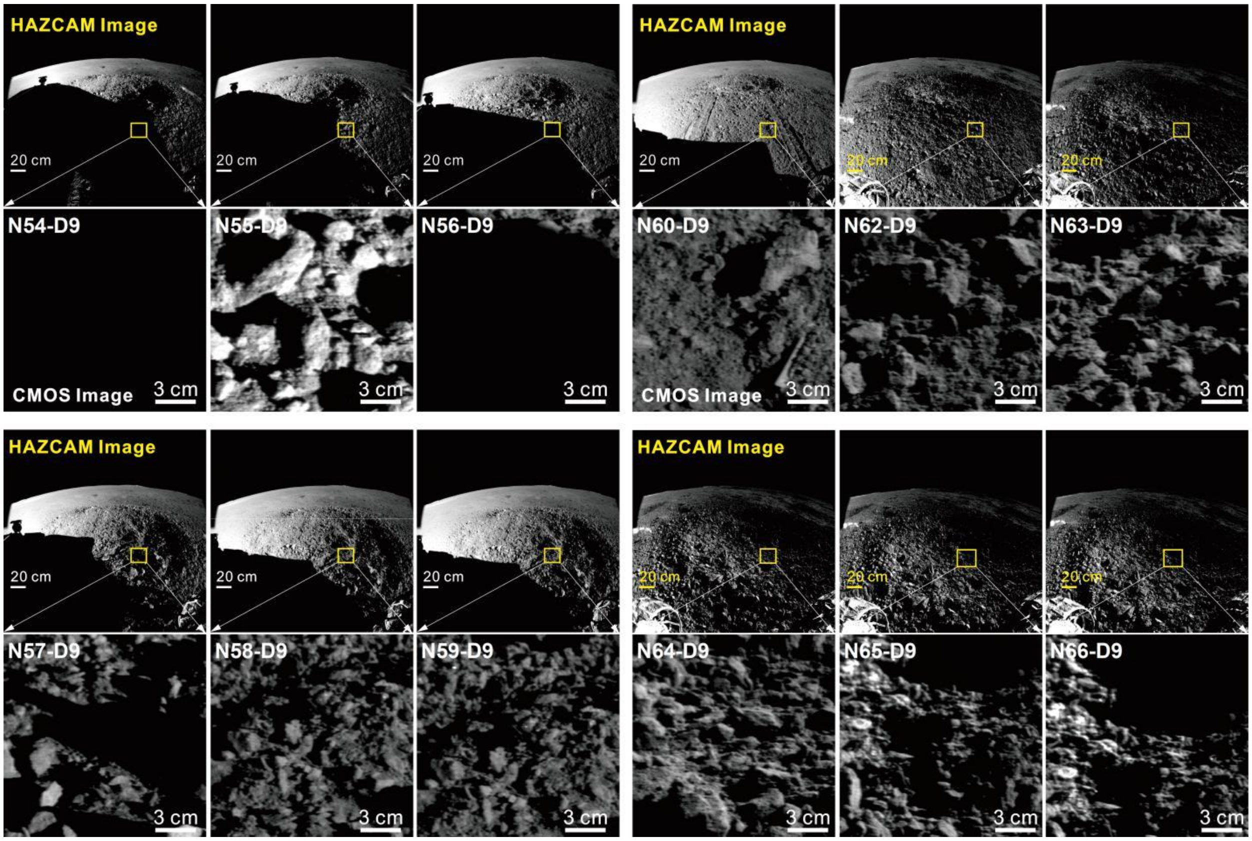


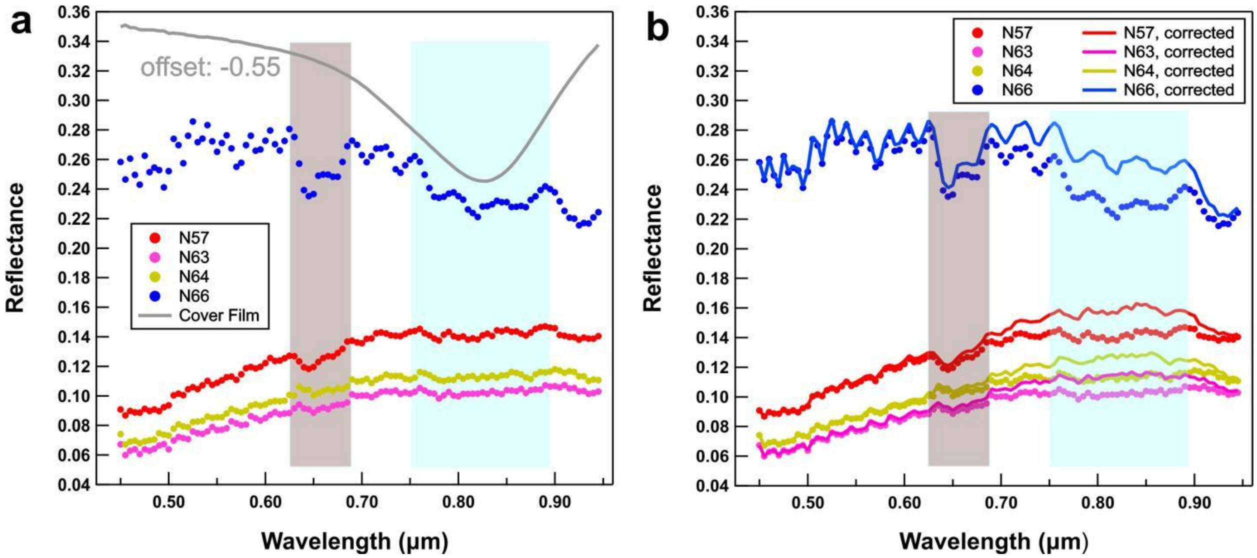
Supplementary Fig. 1.

The measured and modeled radial elevation profiles for (a) the small fresh crater observed on Day 9 and (b) the Zhinyu crater (right). Black lines are the observed profiles obtained from the DEM (Fig. 4a) data and https://quickmap.lroc.asu.edu/, respectively. The red lines are the initial profiles set for the degradation model, and blue lines represent the best-fit results. The observed profiles are not well fitted, because these two craters are younger than those fresh craters (~1 Ma) we used to build the crater degradation-age model *(ref. 22, 23)*. Therefore, the age of the small crater and Zhinyu crater might be less than 1 Ma.



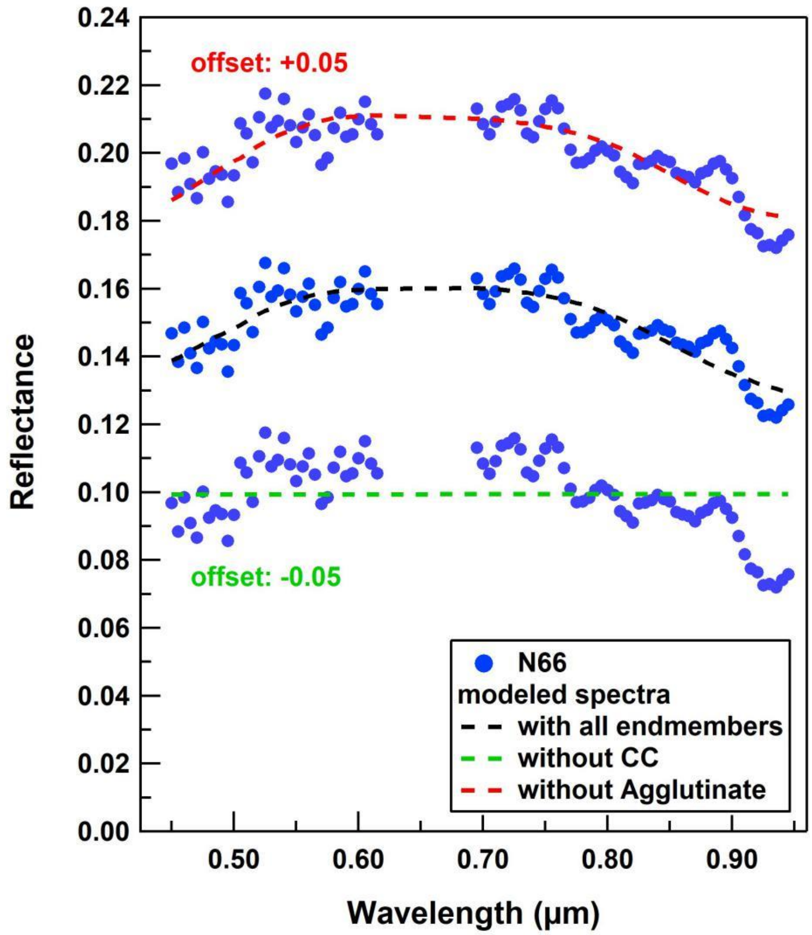
Supplementary Fig. 2.

HAZCAM image and enlarged CMOS image for each VNIS measurement site around the small crater. The yellow boxes in HAZCAM images indicate the areas imaged by the CMOS camera.



Supplementary Fig. 3

(a) Original CMOS spectra of the four ROIs in N66, N64, N63, and N57, and the reflectance spectra of a film material which is the same as the cover material of the Yutu-2 rover. (b) The CMOS spectra of the four ROIs before and after correction.



Supplementary Fig. 4.

Reflectance spectra of N66 ROI (corrected to standard angles, see Methods) and unmixing results of three tests: (1) with all endmembers used; (2) only excluding the CC endmember; (3) only excluding the agglutinate endmember. The model fails to reproduce the Chang'E-4 spectra without the CC endmember (the green dashed line).

Supplementary Table 1.
Sample information for selected endmember spectra.

Endmember	RELAB Spectral File ID	Composition in solid solution (%)*	Particle size (µm)	Refractive index (*n*)	Origin	References
Olivine	c1lr212	Fo34.8	<45	1.83	Apollo 15555, 965	
OPX	c1lr209	En51.3; Fs40.9; Wo7.8	<45	1.77	Apollo 15058, 276, green pyroxene	*(16, 48, 69)*
CPX1	c1lr208	En23.0; Fs54.9; Wo22.2	<45	1.73	Apollo 15058, 276, brown pyroxene	*(16, 48, 69)*
CPX2	c1lr213	En40.3; Fs44.7; Wo15.0	<45		Apollo 15555, 965, light-brown pyroxene	*(16, 48, 69)*
CPX3	c1lr215	En33.3; Fs32.6; Wo34.2	<45		Apollo 70017, 535, deep-brown pyroxene	*(16, 48, 69)*
CPX4	c1lr219	En37.1; Fs31.0; Wo31.9	<45		Apollo 70035, 188, dark-brown pyroxene	*(16, 48, 69)*
Plagioclase	c1lr223	An94.2	<45	1.56	Apollo 62241, 21	*(16, 48, 69)*
Ilmenite	c1lr222	--	<45	2.13	Apollo 70035, 188	*(16, 48)*
Agglutinate	c1lu07	--	100-1000	1.49	Separate from LUNA 20	*(16)*
Glass1	c1lr51	Fo40.1; An:92.1	15#	1.64	Apollo 74220, 806, orange glass	*(16, 69, 70, 71)*
Glass2	c1lr52	Fo47.1; An98.3	15#	1.64	Apollo 15401, 136, green glass	*(16, 69, 70, 71)*
Glass3	c1lr50	--	15#	1.64	Apollo 74001, 439, black spherules	*(16, 69, 70, 71)*
CC	c1mb77		<125	1.93**	Y-693, CK	*(30)*

*Fo: Mg number defined as molar Mg/(Mg+Fe); En, Fs, and Wo represent the three typical pyroxene end-members of enstatite ($Mg_2Si_2O_6$), ferrosilite($Fe_2Si_2O_6$), and wollastonite($Ca_2Si_2O_6$), respectively; An represents the typical end-member of anorthite ($CaAl_2Si_2O_8$).

#: No particle size is recorded in the RELAB database. A mean particle size 15 µm is assumed based on the fact that the optical property lunar surface is dominated by particles at the 10-20 µm group *(ref. 69, 70)*.

**: Estimated by weighting the n of the individual mineral (n_i) by their relative abundance (F_i): $\bar{n} = \sum n_i F_i$ *(ref. 72)*. The modal abundances of Y693 are 2.1 vol.% pyroxene, 63.5 vol.% olivine, 11.5 vol.% plagioclase, and 22.9 vol.% opaque minerals *(ref. 30)*. The opaque phases mainly composed of magnetite with n=2.42 *(ref. 73)*.

Supplementary Table 2.
Similarities between spectra of N66 and selected end-members.

End-member	Spectral Angle (°)	
CC_c1mb77	**2.82894**	
GreenGlass_c1lr52	**3.83309**	**High**
PLG_c1lr223	4.47412	
Agg_c1lu07	6.92018	
OLV_c1lr212	8.83722	
CPX_c1lr215	10.3345	**Similarity**
OPX_c1lr209	11.0578	
CPX_c1lr208	12.5044	
CPX_c1lr219	12.6118	
CPX_c1lr213	12.8784	
OrangeGlass_c1lr51	16.8984	**Low**
ILM_c1lr222	17.2281	
BlackSpherules_c1lr50	23.679	

Supplementary Table 3.
Modeled mineral abundances for ROIs of N66, N64, N63, and N57 which are marked out in Fig. 1d.

End-member*	**Modeled Abundance (wt. %)** (particle size: 0-75 μm)			
	N57	**N63**	**N64**	**N66**
Olivine	0	9	3	8
Pyroxene**	**47**	**40**	**43**	**0**
OPX	0	6	0	0
CPX1	0	9	1	0
CPX2	0	6	0	0
CPX3	40	10	30	0
CPX4	7	10	12	0
Plagioclase	**0**	**5**	**2**	**0**
Ilmenite	**0**	**0**	**0**	**0**
Glasses***	**50**	**34**	**45**	**45**
Glass1	3	8	0	0
Glass2	14	12	12	0
Glass3	33	11	31	44
Agglutinate	0	4	3	0
CC (Y-693)	**2**	**11**	**6**	**47**
npFe^0 (vol.%)	0.20	0.35	0.25	0.00

*See Supplementary Table 1 for detail information about these spectral endmembers.
**Pyroxene: including OPX and four CPX.
***Glasses: including green glass, orange glass, black spherules, and agglutinate.

Supplementary Table 4.
Modeled mineral abundances for ROIs of N60, N55, N16, and N15 which are marked out in Extended Data Fig. 10.

End-member*	**Modeled Abundance (wt. %)** (particle size: 0-75 μm)			
	N65	**N60**	**N55**	**N15**
Olivine	14	5	7	8
Pyroxene**	**0**	**61**	**56**	**41**
OPX	0	6	7	6
CPX1	0	10	11	7
CPX2	0	10	9	4
CPX3	0	16	14	12
CPX4	0	19	15	12
Plagioclase	**0**	**7**	**8**	**8**
Ilmenite	**0**	**1**	**0**	**0**
Glasses***	**71**	**19**	**22**	**34**
Glass1	4	7	7	8
Glass2	47	0	3	7
Glass3	20	9	6	11
Agglutinate	0	3	7	7
CC (Y-693)	**15**	**6**	**6**	**8**
$npFe^0$ (vol.%)	0.00	0.40	0.16	0.11

*See Supplementary Table 1 for detailed information about these spectral end-members.
**Pyroxene: including OPX and all CPX.
***Glasses: including orange glass, green glass, black spherules, and agglutinate.

Supplementary Table 5.

Topography profiles along four different directions.

Profile	Crater depth (m)	Crater diameter (m)	Ratio: depth/diameter
A-A'	0.343	2.129	0.16
B-B'	0.385	1.883	0.20
C-C'	0.347	1.997	0.17
D-D'	0.371	2.110	0.18

Supplementary Table 6.

The ten CC spectra that have the highest similarities with the spectra of the observed “glassy” material at N66.

No.	**RELAB File ID**	**Spectral angle (°)**	**Type**	**Meteorite name**	**Grain size (µm)**	**Viewing geometry (i°, e°)**	**Weathering Index**
1	c1lm17	2.27305	CK6	LEW87009,4	powder, unsorted?	30/0	1
2	c1mp05	2.32317	CK6	LEW87009,4	<63 (?)	30/0	1
3	c1mb88	2.45121	CK6	LEW87009,28	<125	30/0	1
4	c1mp04	2.70066	CK5-6	EET87860,5	<63 (?)	30/0	1
5	c2mb81	2.70499	CK4	ALH85002,25	<125	30/0	1
6	c1mp55	2.80362	CM or CV	A-881655	<125	30/0	unknown
7	cdmb81	2.81142	CK4	ALH85002,25	75-125	30/0	1
8	**c1mb77**	**2.82894**	**CK4/5**	**Y-693**	**<125**	**30/0**	0
9	c1lm19	2.85155	CK5-6	EET87860,5	powder; unsorted?	30/0	1
10	cbmh58	2.88285	CK4	ALH85002,34	<180	30/0	1

Note: Here only the ten most similar CC spectra are listed, the comparison results of all 183 CC spectra are saved as a separate Excel file titled “*Supplementary_Tables_7_10_11.xlsx*” in the supporting material. The weathering index represents the degree of terrestrial alteration, a value of 0 means the meteorite is pristine *(ref. 30)*.

Supplementary Table 7.
Similarities between spectra of N66 and different carbonceous chondrite samples

This table is provided in a separate excel file, see additional supplementary files.

Supplementary Table 8.

Incidence, emission, and phase angles of the ROIs shown in Figure 1c and Extended Data Fig. 10.

Site No.	Incidence Angle (deg.)	Emission Angle (deg.)	Phase Angle (deg.)
N66	71.0	50.0	98.9
N64	68.8	45.7	93.4
N63	67.8	45.8	92.3
N57	65.4	46.7	43.1
N65	70.0	51.8	98.5
N60	58.4	48.4	47.9
N55	73.4	48.2	44.6
N15	63.4	43.8	63.4

Supplementary Table 9.
The IDs for the Chang'E-4 spectral and image data used in this work. These data are archived at http://moon.bao.ac.cn/searchOrder_pdsData.search

Data	**Data ID**
Spectra data	CE4_GRAS_VNIS-VD_SCI_N_20190825003001_20190825053000_0054_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190825053001_20190825080000_0055_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190826010001_20190826060000_0056_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190826070001_20190826083000_0057_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190827000001_20190827020000_0058_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190827030001_20190827053000_0059_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190827060001_20190827100000_0060_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190903143001_20190903150000_0062_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190904010001_20190904040000_0063_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190904053001_20190904073000_0064_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190904093001_20190904113000_0065_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190904130001_20190904140000_0066_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190302060001_20190302131100_0015_A.2B
Fig.1a PCAM data	CE4_GRAS_PCAML-C-008_SCI_N_20190925032918_20190925032918_0076_B.2B CE4_GRAS_PCAML-C-009_SCI_N_20190925033038_20190925033038_0076_B.2B CE4_GRAS_PCAML-C-010_SCI_N_20190925033158_20190925033158_0076_B.2B CE4_GRAS_PCAML-C-011_SCI_N_20190925033318_20190925033318_0076_B.2B CE4_GRAS_PCAML-C-012_SCI_N_20190925033438_20190925033438_0076_B.2B CE4_GRAS_PCAML-C-013_SCI_N_20190925033558_20190925033558_0076_B.2B CE4_GRAS_PCAML-C-020_SCI_N_20190925035057_20190925035057_0076_B.2B CE4_GRAS_PCAML-C-021_SCI_N_20190925035217_20190925035217_0076_B.2B CE4_GRAS_PCAML-C-022_SCI_N_20190925035337_20190925035337_0076_B.2B CE4_GRAS_PCAML-C-023_SCI_N_20190925035457_20190925035457_0076_B.2B CE4_GRAS_PCAML-C-024_SCI_N_20190925035617_20190925035617_0076_B.2B CE4_GRAS_PCAML-C-025_SCI_N_20190925035737_20190925035737_0076_B.2B CE4_GRAS_PCAML-C-026_SCI_N_20190925035857_20190925035857_0076_B.2B CE4_GRAS_PCAML-C-027_SCI_N_20190925040017_20190925040017_0076_B.2B CE4_GRAS_PCAML-C-036_SCI_N_20190925042323_20190925042323_0076_B.2B CE4_GRAS_PCAML-C-037_SCI_N_20190925042443_20190925042443_0076_B.2B CE4_GRAS_PCAML-C-038_SCI_N_20190925042603_20190925042603_0076_B.2B CE4_GRAS_PCAML-C-

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Fig. 4a PCAM data	CE4_GRAS_PCAML-C-000_SCI_N_20190925031838_20190925031838_0076_B.2B CE4_GRAS_PCAML-C-001_SCI_N_20190925031958_20190925031958_0076_B.2B CE4_GRAS_PCAML-C-002_SCI_N_20190925032118_20190925032118_0076_B.2B CE4_GRAS_PCAML-C-003_SCI_N_20190925032238_20190925032238_0076_B.2B CE4_GRAS_PCAML-C-004_SCI_N_20190925032358_20190925032358_0076_B.2B CE4_GRAS_PCAML-C-005_SCI_N_20190925032518_20190925032518_0076_B.2B CE4_GRAS_PCAML-C-006_SCI_N_20190925032638_20190925032638_0076_B.2B CE4_GRAS_PCAML-C-007_SCI_N_20190925032758_20190925032758_0076_B.2B CE4_GRAS_PCAML-C-008_SCI_N_20190925032918_20190925032918_0076_B.2B CE4_GRAS_PCAML-C-

	009_SCI_N_20190925033038_20190925033038_0076_B.2B CE4_GRAS_PCAML-C-010_SCI_N_20190925033158_20190925033158_0076_B.2B CE4_GRAS_PCAML-C-011_SCI_N_20190925033318_20190925033318_0076_B.2B CE4_GRAS_PCAML-C-012_SCI_N_20190925033438_20190925033438_0076_B.2B CE4_GRAS_PCAML-C-013_SCI_N_20190925033558_20190925033558_0076_B.2B CE4_GRAS_PCAML-C-014_SCI_N_20190925034257_20190925034257_0076_B.2B CE4_GRAS_PCAML-C-015_SCI_N_20190925034417_20190925034417_0076_B.2B CE4_GRAS_PCAML-C-016_SCI_N_20190925034537_20190925034537_0076_B.2B CE4_GRAS_PCAML-C-017_SCI_N_20190925034657_20190925034657_0076_B.2B CE4_GRAS_PCAML-C-018_SCI_N_20190925034817_20190925034817_0076_B.2B CE4_GRAS_PCAML-C-019_SCI_N_20190925034937_20190925034937_0076_B.2B CE4_GRAS_PCAML-C-020_SCI_N_20190925035057_20190925035057_0076_B.2B CE4_GRAS_PCAML-C-021_SCI_N_20190925035217_20190925035217_0076_B.2B CE4_GRAS_PCAML-C-022_SCI_N_20190925035337_20190925035337_0076_B.2B CE4_GRAS_PCAML-C-023_SCI_N_20190925035457_20190925035457_0076_B.2B CE4_GRAS_PCAML-C-024_SCI_N_20190925035617_20190925035617_0076_B.2B CE4_GRAS_PCAML-C-025_SCI_N_20190925035737_20190925035737_0076_B.2B CE4_GRAS_PCAML-C-026_SCI_N_20190925035857_20190925035857_0076_B.2B CE4_GRAS_PCAML-C-027_SCI_N_20190925040017_20190925040017_0076_B.2B CE4_GRAS_PCAML-C-028_SCI_N_20190925040933_20190925040933_0076_B.2B CE4_GRAS_PCAML-C-029_SCI_N_20190925041403_20190925041403_0076_B.2B CE4_GRAS_PCAML-C-030_SCI_N_20190925041523_20190925041523_0076_B.2B CE4_GRAS_PCAML-C-031_SCI_N_20190925041643_20190925041643_0076_B.2B CE4_GRAS_PCAML-C-032_SCI_N_20190925041803_20190925041803_0076_B.2B CE4_GRAS_PCAML-C-033_SCI_N_20190925041923_20190925041923_0076_B.2B CE4_GRAS_PCAML-C-034_SCI_N_20190925042043_20190925042043_0076_B.2B CE4_GRAS_PCAML-C-035_SCI_N_20190925042203_20190925042203_0076_B.2B

	CE4_GRAS_PCAML-C-036_SCI_N_20190925042323_20190925042323_0076_B.2B CE4_GRAS_PCAML-C-037_SCI_N_20190925042443_20190925042443_0076_B.2B CE4_GRAS_PCAML-C-038_SCI_N_20190925042603_20190925042603_0076_B.2B CE4_GRAS_PCAML-C-039_SCI_N_20190925042723_20190925042723_0076_B.2B CE4_GRAS_PCAML-C-040_SCI_N_20190925042843_20190925042843_0076_B.2B CE4_GRAS_PCAML-C-041_SCI_N_20190925043003_20190925043003_0076_B.2B CE4_GRAS_PCAML-C-042_SCI_N_20190925044057_20190925044057_0076_B.2B CE4_GRAS_PCAML-C-043_SCI_N_20190925044217_20190925044217_0076_B.2B CE4_GRAS_PCAML-C-044_SCI_N_20190925044337_20190925044337_0076_B.2B CE4_GRAS_PCAML-C-045_SCI_N_20190925044457_20190925044457_0076_B.2B CE4_GRAS_PCAML-C-046_SCI_N_20190925044617_20190925044617_0076_B.2B CE4_GRAS_PCAML-C-047_SCI_N_20190925044737_20190925044737_0076_B.2B CE4_GRAS_PCAML-C-048_SCI_N_20190925044857_20190925044857_0076_B.2B CE4_GRAS_PCAML-C-049_SCI_N_20190925045017_20190925045017_0076_B.2B CE4_GRAS_PCAML-C-050_SCI_N_20190925045137_20190925045137_0076_B.2B CE4_GRAS_PCAML-C-051_SCI_N_20190925045257_20190925045257_0076_B.2B CE4_GRAS_PCAML-C-052_SCI_N_20190925045417_20190925045417_0076_B.2B CE4_GRAS_PCAML-C-053_SCI_N_20190925045537_20190925045537_0076_B.2B CE4_GRAS_PCAML-C-054_SCI_N_20190925045657_20190925045657_0076_B.2B CE4_GRAS_PCAML-C-055_SCI_N_20190925045817_20190925045817_0076_B.2B CE4_GRAS_PCAMR-C-000_SCI_N_20190925031823_20190925031823_0076_B.2B CE4_GRAS_PCAMR-C-001_SCI_N_20190925031943_20190925031943_0076_B.2B CE4_GRAS_PCAMR-C-002_SCI_N_20190925032103_20190925032103_0076_B.2B CE4_GRAS_PCAMR-C-003_SCI_N_20190925032223_20190925032223_0076_B.2B CE4_GRAS_PCAMR-C-004_SCI_N_20190925032343_20190925032343_0076_B.2B CE4_GRAS_PCAMR-C-005_SCI_N_20190925032503_20190925032503_0076_B.2B CE4_GRAS_PCAMR-C-

	006_SCI_N_20190925032623_20190925032623_0076_B.2B CE4_GRAS_PCAMR-C- 007_SCI_N_20190925032743_20190925032743_0076_B.2B CE4_GRAS_PCAMR-C- 008_SCI_N_20190925032903_20190925032903_0076_B.2B CE4_GRAS_PCAMR-C- 009_SCI_N_20190925033023_20190925033023_0076_B.2B CE4_GRAS_PCAMR-C- 010_SCI_N_20190925033143_20190925033143_0076_B.2B CE4_GRAS_PCAMR-C- 011_SCI_N_20190925033303_20190925033303_0076_B.2B CE4_GRAS_PCAMR-C- 012_SCI_N_20190925033423_20190925033423_0076_B.2B CE4_GRAS_PCAMR-C- 013_SCI_N_20190925033543_20190925033543_0076_B.2B CE4_GRAS_PCAMR-C- 014_SCI_N_20190925034241_20190925034241_0076_B.2B CE4_GRAS_PCAMR-C- 015_SCI_N_20190925034401_20190925034401_0076_B.2B CE4_GRAS_PCAMR-C- 016_SCI_N_20190925034521_20190925034521_0076_B.2B CE4_GRAS_PCAMR-C- 017_SCI_N_20190925034641_20190925034641_0076_B.2B CE4_GRAS_PCAMR-C- 018_SCI_N_20190925034801_20190925034801_0076_B.2B CE4_GRAS_PCAMR-C- 019_SCI_N_20190925034921_20190925034921_0076_B.2B CE4_GRAS_PCAMR-C- 020_SCI_N_20190925035041_20190925035041_0076_B.2B CE4_GRAS_PCAMR-C- 021_SCI_N_20190925035201_20190925035201_0076_B.2B CE4_GRAS_PCAMR-C- 022_SCI_N_20190925035321_20190925035321_0076_B.2B CE4_GRAS_PCAMR-C- 023_SCI_N_20190925035441_20190925035441_0076_B.2B CE4_GRAS_PCAMR-C- 024_SCI_N_20190925035601_20190925035601_0076_B.2B CE4_GRAS_PCAMR-C- 025_SCI_N_20190925035721_20190925035721_0076_B.2B CE4_GRAS_PCAMR-C- 026_SCI_N_20190925035841_20190925035841_0076_B.2B CE4_GRAS_PCAMR-C- 027_SCI_N_20190925040001_20190925040001_0076_B.2B CE4_GRAS_PCAMR-C- 028_SCI_N_20190925040917_20190925040917_0076_B.2B CE4_GRAS_PCAMR-C- 029_SCI_N_20190925041347_20190925041347_0076_B.2B CE4_GRAS_PCAMR-C- 030_SCI_N_20190925041507_20190925041507_0076_B.2B CE4_GRAS_PCAMR-C- 031_SCI_N_20190925041627_20190925041627_0076_B.2B CE4_GRAS_PCAMR-C- 032_SCI_N_20190925041747_20190925041747_0076_B.2B

	CE4_GRAS_PCAMR-C- 033_SCI_N_20190925041907_20190925041907_0076_B.2B CE4_GRAS_PCAMR-C- 034_SCI_N_20190925042027_20190925042027_0076_B.2B CE4_GRAS_PCAMR-C- 035_SCI_N_20190925042147_20190925042147_0076_B.2B CE4_GRAS_PCAMR-C- 036_SCI_N_20190925042307_20190925042307_0076_B.2B CE4_GRAS_PCAMR-C- 037_SCI_N_20190925042427_20190925042427_0076_B.2B CE4_GRAS_PCAMR-C- 038_SCI_N_20190925042547_20190925042547_0076_B.2B CE4_GRAS_PCAMR-C- 039_SCI_N_20190925042707_20190925042707_0076_B.2B CE4_GRAS_PCAMR-C- 040_SCI_N_20190925042827_20190925042827_0076_B.2B CE4_GRAS_PCAMR-C- 041_SCI_N_20190925042947_20190925042947_0076_B.2B CE4_GRAS_PCAMR-C- 042_SCI_N_20190925044042_20190925044042_0076_B.2B CE4_GRAS_PCAMR-C- 043_SCI_N_20190925044202_20190925044202_0076_B.2B CE4_GRAS_PCAMR-C- 044_SCI_N_20190925044322_20190925044322_0076_B.2B CE4_GRAS_PCAMR-C- 045_SCI_N_20190925044442_20190925044442_0076_B.2B CE4_GRAS_PCAMR-C- 046_SCI_N_20190925044602_20190925044602_0076_B.2B CE4_GRAS_PCAMR-C- 047_SCI_N_20190925044722_20190925044722_0076_B.2B CE4_GRAS_PCAMR-C- 048_SCI_N_20190925044842_20190925044842_0076_B.2B CE4_GRAS_PCAMR-C- 049_SCI_N_20190925045002_20190925045002_0076_B.2B CE4_GRAS_PCAMR-C- 050_SCI_N_20190925045122_20190925045122_0076_B.2B CE4_GRAS_PCAMR-C- 051_SCI_N_20190925045242_20190925045242_0076_B.2B CE4_GRAS_PCAMR-C- 052_SCI_N_20190925045402_20190925045402_0076_B.2B CE4_GRAS_PCAMR-C- 053_SCI_N_20190925045522_20190925045522_0076_B.2B CE4_GRAS_PCAMR-C- 054_SCI_N_20190925045642_20190925045642_0076_B.2B CE4_GRAS_PCAMR-C- 055_SCI_N_20190925045802_20190925045802_0076_B.2B
Extended Data Fig. 2 PCAM data	CE4_GRAS_PCAML-C- 000_SCI_N_20190827094241_20190827094241_0060_B.2B CE4_GRAS_PCAML-C- 001_SCI_N_20190827094410_20190827094410_0060_B.2B CE4_GRAS_PCAML-C- 002_SCI_N_20190827094539_20190827094539_0060_B.2B CE4_GRAS_PCAML-C-

	003_SCI_N_20190827094707_20190827094707_0060_B.2B CE4_GRAS_PCAML-C-004_SCI_N_20190827094836_20190827094836_0060_B.2B CE4_GRAS_PCAML-C-005_SCI_N_20190827095005_20190827095005_0060_B.2B CE4_GRAS_PCAMR-C-004_SCI_N_20190729012457_20190729012457_0050_B.2B
Extended Data Fig. 3a PCAM data	CE4_GRAS_PCAML-C-000_SCI_N_20190905071818_20190905071818_0067_B.2B CE4_GRAS_PCAML-C-001_SCI_N_20190905071947_20190905071947_0067_B.2B CE4_GRAS_PCAML-C-002_SCI_N_20190905072116_20190905072116_0067_B.2B CE4_GRAS_PCAML-C-003_SCI_N_20190905072359_20190905072359_0067_B.2B CE4_GRAS_PCAML-C-004_SCI_N_20190905072528_20190905072528_0067_B.2B CE4_GRAS_PCAML-C-005_SCI_N_20190905072657_20190905072657_0067_B.2B CE4_GRAS_PCAML-C-006_SCI_N_20190905081132_20190905081132_0067_B.2B
Extended Data Fig. 8	CE4_GRAS_VNIS-VD_SCI_N_20190923090001_20190923110000_0068_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190923123001_20190923130000_0069_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190924021501_20190924035000_0070_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190924060001_20190924061500_0071_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190924073001_20190924080000_0072_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190924094501_20190924101000_0073_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190924113001_20190924115000_0074_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190925022001_20190925024000_0075_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190925030001_20190925054500_0076_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190925080001_20190925100000_0077_B.2B CE4_GRAS_VNIS-VD_SCI_N_20190925110001_20190925113000_0078_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191002030001_20191002043000_0079_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191002052001_20191002054500_0080_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191002070001_20191002072000_0081_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191002083001_20191002090000_0082_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191002103001_20191002105000_0083_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003012001_20191003014500_0084_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003033001_20191003050000_0085_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003051501_20191003053000_0086_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003071001_20191003073000_0087_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003090001_20191003092000_0088_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191003105001_20191003111000_0089_B.2B CE4_GRAS_VNIS-VD_SCI_N_20191004010001_20191004020000_0090_B.2B

Supplementary Fig. 1a PCAM data	CE4_GRAS_PCAML-C-000_SCI_N_20200227111928_20200227111928_0121_B.2B CE4_GRAS_PCAML-C-001_SCI_N_20200227112057_20200227112057_0121_B.2B CE4_GRAS_PCAML-C-002_SCI_N_20200227112226_20200227112226_0121_B.2B CE4_GRAS_PCAML-C-003_SCI_N_20200227112355_20200227112355_0121_B.2B CE4_GRAS_PCAML-C-004_SCI_N_20200227112524_20200227112524_0121_B.2B CE4_GRAS_PCAML-C-005_SCI_N_20200227112653_20200227112653_0121_B.2B CE4_GRAS_PCAML-C-006_SCI_N_20200227112822_20200227112822_0121_B.2B CE4_GRAS_PCAML-C-007_SCI_N_20200227112951_20200227112951_0121_B.2B CE4_GRAS_PCAML-C-008_SCI_N_20200227113120_20200227113120_0121_B.2B CE4_GRAS_PCAML-C-009_SCI_N_20200227113734_20200227113734_0121_B.2B CE4_GRAS_PCAML-C-010_SCI_N_20200227113903_20200227113903_0121_B.2B CE4_GRAS_PCAML-C-011_SCI_N_20200227114032_20200227114032_0121_B.2B CE4_GRAS_PCAML-C-012_SCI_N_20200227114201_20200227114201_0121_B.2B CE4_GRAS_PCAML-C-013_SCI_N_20200227114330_20200227114330_0121_B.2B CE4_GRAS_PCAML-C-014_SCI_N_20200227114459_20200227114459_0121_B.2B CE4_GRAS_PCAML-C-015_SCI_N_20200227114628_20200227114628_0121_B.2B CE4_GRAS_PCAML-C-016_SCI_N_20200227114757_20200227114757_0121_B.2B CE4_GRAS_PCAML-C-017_SCI_N_20200227114926_20200227114926_0121_B.2B

Supplementary Fig. 1c PCAM data	CE4_GRAS_PCAML-C-002_SCI_N_20190429144016_20190429144016_0033_B.2B CE4_GRAS_PCAMR-C-001_SCI_N_20200131030040_20200131030040_0117_B.2B CE4_GRAS_PCAML-C-016_SCI_N_20200227114757_20200227114757_0121_B.2B CE4_GRAS_PCAML-C-000_SCI_N_20200428092933_20200428092933_0128_B.2B CE4_GRAS_PCAML-C-001_SCI_N_20200428093102_20200428093102_0128_B.2B CE4_GRAS_PCAML-C-002_SCI_N_20200428093231_20200428093231_0128_B.2B CE4_GRAS_PCAML-C-003_SCI_N_20200428093400_20200428093400_0128_B.2B CE4_GRAS_PCAML-C-004_SCI_N_20200428093529_20200428093529_0128_B.2B CE4_GRAS_PCAML-C-005_SCI_N_20200428093658_20200428093658_0128_B.2B CE4_GRAS_PCAML-C-006_SCI_N_20200428094248_20200428094248_0128_B.2B CE4_GRAS_PCAML-C-007_SCI_N_20200428094417_20200428094417_0128_B.2B CE4_GRAS_PCAML-C-008_SCI_N_20200428094546_20200428094546_0128_B.2B CE4_GRAS_PCAML-C-009_SCI_N_20200428094715_20200428094715_0128_B.2B CE4_GRAS_PCAML-C-010_SCI_N_20200428094844_20200428094844_0128_B.2B CE4_GRAS_PCAML-C-011_SCI_N_20200428095013_20200428095013_0128_B.2B
Supplementary Fig. 3 HAZCAM data	YSBZZ_20190825_102853_0000_304424877_00c81000.tif YSBZZ_20190825_122339_0000_304431763_00c81000.tif YSBZZ_20190825_133602_0000_304436106_00c31000.tif YSBZZ_20190825_151715_0000_304442179_00c31000.tif YSBZZ_20190826_091127_0000_304506631_00c81000.tif YSBZZ_20190826_153912_0000_304529895_00c31000.tif YSBZZ_20190827_085618_0000_304592121_00c81000.tif YSBZZ_20190827_111820_0000_304600642_00c81000.tif YSBZZ_20190828_092855_0000_304617907_00c81000.tif YSBZZ_20190903_141142_0000_305215833_00c81000.tif YSBZZ_20190903_165626_0000_305225717_00c31000.tif YSBZZ_20190903_223504_0000_305246035_00c31000.tif YSBZZ_20190903_223504_0000_305246035_00c91000.tif YSBZZ_20190904_113654_0000_305292945_00c81000.tif YSBZZ_20190904_144933_0000_305304504_00c31000.tif YSBZZ_20190904_144933_0000_305304504_00c81000.tif YSBZZ_20190904_184004_0000_305318335_00c31000.tif YSBZZ_20190904_213343_0000_305328754_00c31000.tif

Supplementary Table 10.
Reflectance spectra of endmembers listed in Supplementary Table 1.

This table is provided in a separate excel file, see additional supplementary files.

Supplementary Table 11.
Corrected reflectance of ROIs shown in Fig. 1d and Extended Data Fig. 10.

This table is provided in a separate excel file, see additional supplementary files.

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