Constraining the Compositions of Phobos and Deimos Remotely

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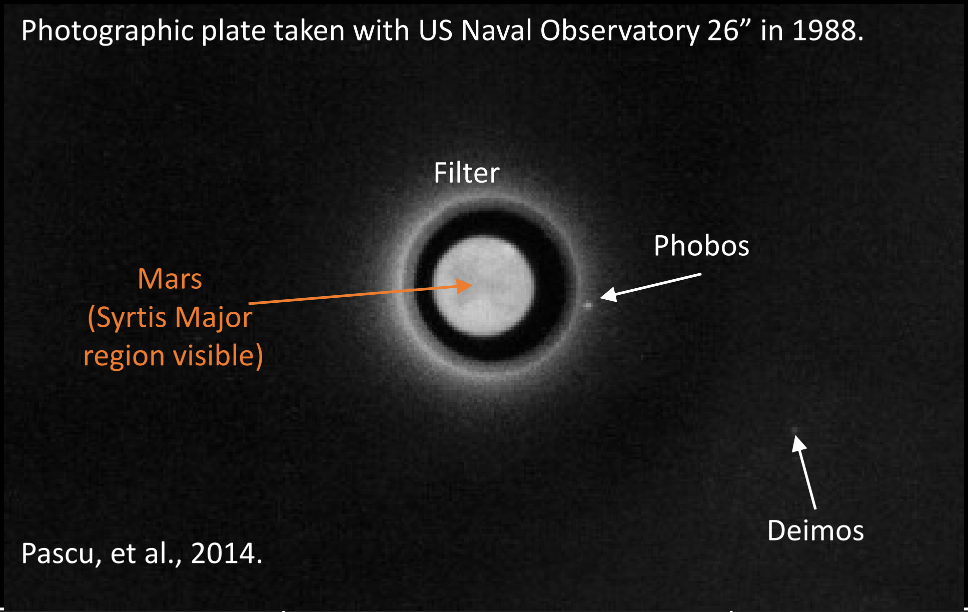
Image credit: NASA/JPL/University of Arizona

Phobos and Deimos Quick Facts



	Phobos	Deimos
Size	26.1 x 22.8 x 18.3 km	10.4 x 12.2 x 15 km
Density	1.86 g/cm^3	1.49 g/cm^3
Orbital period	7.66 hr	30.35 hr
Semi-major axis	9,377 km	23,460 km
Eccentricity	0.0151	0.00033
Inclination	1.093°	0.93°

Murchie et al., 2015 and ref. therein

Spacecraft Observation History

- Mars flybys
  - Mariners 4, 5, and 6
  - Rosetta
- Mars orbiters
  - Mariner 9
  - Viking orbiters 1 & 2
  - Phobos 88
  - Mars Global Surveyor
  - Mars Odyssey
  - Mars Express (MEx)
  - Mars Reconnaissance Orbiter (MRO)
  - MAVEN
- Surface of Mars
  - Viking Landers 1 & 2
  - Pathfinder
  - Spirit & Opportunity
  - Curiosity

Phobos and Deimos as seen from the Martian surface by Curiosity on August 1st, 2013.

Image credit: NASA/JPL-Caltech/Malin Space Science Systems/Texas A&M Univ.

List source: Duxbury et al., 2014

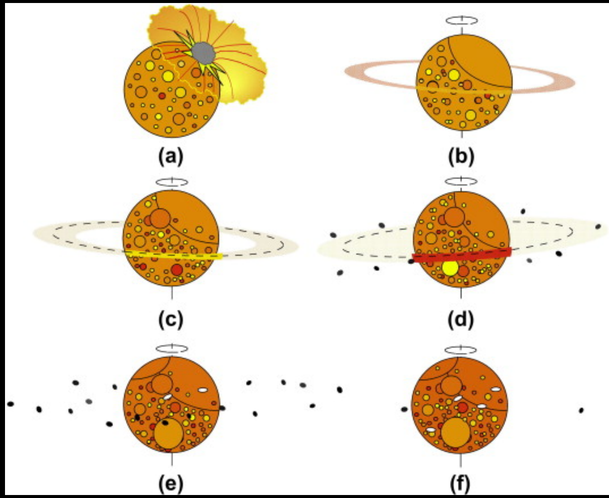
Origin Questions

EXTERNAL

Captured asteroids
Burns, 1978

IN SITU

Formation by co-accretion
Safronov et al., 1986



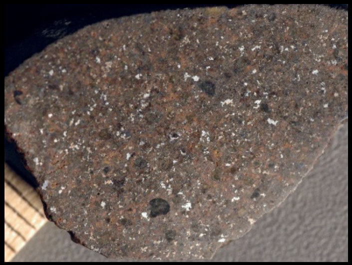
Giant Impact Hypothesis
Craddock et al., 2010

Expected compositions

- Captured primitive bodies: compositions typical of material found in primitive meteorites
- Form by late stage co-accretion with Mars: compositions consistent with bulk Mars chondritic mafic mineralogy, e.g. ordinary chondrites
- Form from differentiated Mars (impact hypothesis): compositions with mafic minerals similar to basaltic Martian crust

Murchison Carbonaceous Chondrite

Image Credit: Randy Korotev



Unnamed Ordinary Chondrite

Image Credit: Randy Korotev

Adirondack

Image Credit: NASA/JPL/Cornell

Expected Composition

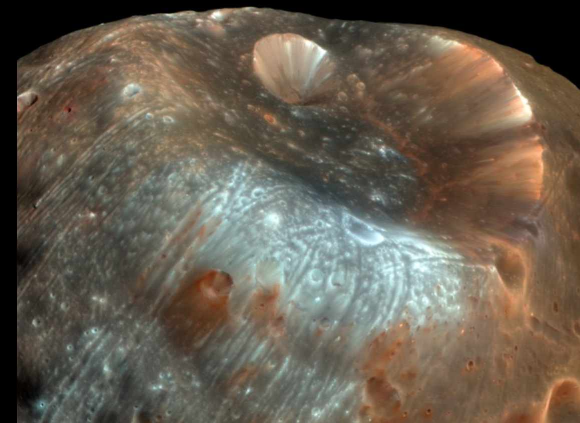
Table 1
Compositions predicted by different models for the origin of Phobos.

Origin Hypothesis	Composition predicted	Elemental abundances	Mineral abundances
Capture of organic- and water-rich outer solar system body	Ultra-primitive composition; Tagish Lake is the best known analog (Brown et al., 2000)	High C; high Zn/Mn; high S; composition possibly unique from known meteorites	Abundant phyllosilicates; carbonates and organic phases; anhydrous silicate phases rare
Capture of organic- and water-poor outer solar system body	Anhydrous silicates plus elemental carbon (Emery and Brown, 2004)	High C; Mg/Fe ratio ~2–4; bulk composition unlike any meteorite analogs	Anhydrous, med. Fe (20–40%) pyroxene+olivine; abundant amorphous carbon or graphite?
Capture of inner solar system body	Composition like common meteorites (e.g. ordinary chondrites) (Brearley and Jones, 1998)	Mg/Si ~0.8–1, Al/Si ~0.05–0.1; Zn/Mn & Al/Mn ratios separate known meteorites; likely low C	Low carbonates, phyllosilicates; pyroxene, olivine probably in range of known meteorites
Co-accretion with Mars	Bulk Mars; similar to ordinary chondrites but specific SNC-derived comp. (Wanke and Dreibus, 1988)	Mg/Si, Al/Si, Fe/Si indicative of bulk Mars; low C; Zn/Mn, Al/Mn like ordinary chondrites	Anhydrous silicates with Fe, Mg of bulk Mars; low abundance of C-bearing phases
Giant impact on Mars	Evolved martian crust or mantle, like SNC meteorites, Mars rocks or soil (McSween et al., 2009)+impactor	High Al/Si, Ca/Si, lower Fe/Si, Mg/Si indicative of evolved igneous materials	Evolved, basaltic mineralogy consistent with many datasets for Mars

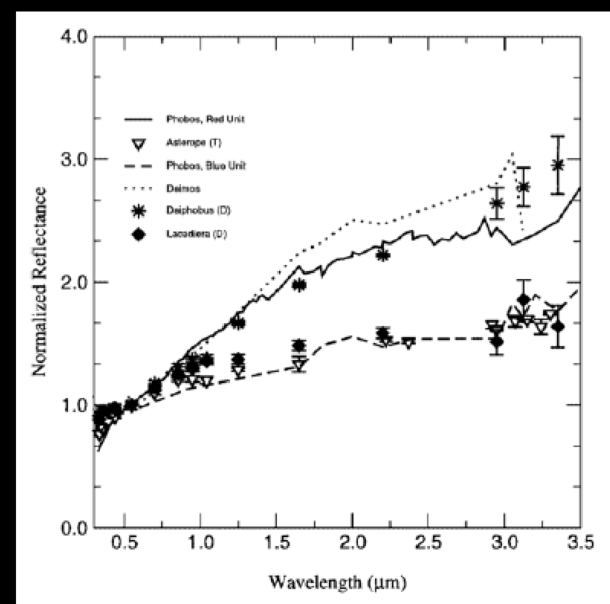
Murchie et al., 2014

Composition: View in Mid-2000s

- Spectral measurements showed Phobos had "blue" and "redder" material; Deimos looks like Phobos
- Redder material looked like D-type primitive asteroids
- No clear diagnostic evidence for mineral absorptions



Thomson et al., 2011



Rivkin et al., 2002

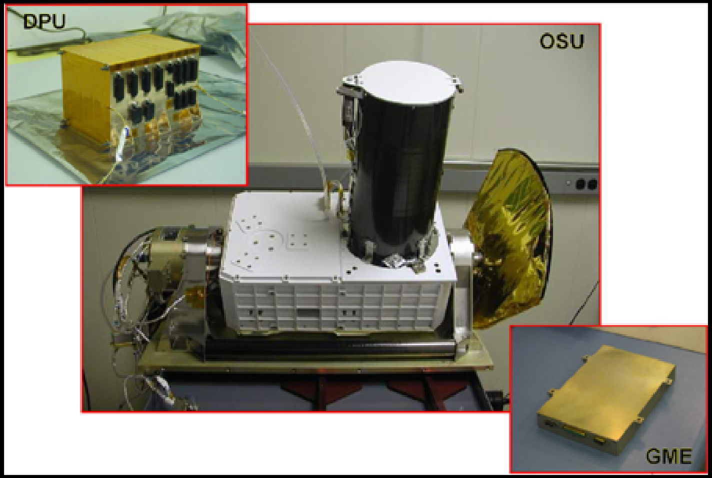
Spectrometers Orbiting Mars: OMEGA and CRISM

	OMEGA	CRISM
Spacecraft	Mars Express	Mars Reconnaissance Orbiter
Wavelength Range	0.35 – 5.0 µm	0.4 – 3.9 µm
Spectral Resolution	0.007 to 0.02 µm/channel	0.00655 µm/channel
Pixel Angular Size	1.2 mrad	0.0615 mrad

OMEGA

Bibring et al., 2004

CRISM



Murchie et al., 2007

Mars Express (and MRO) Observations

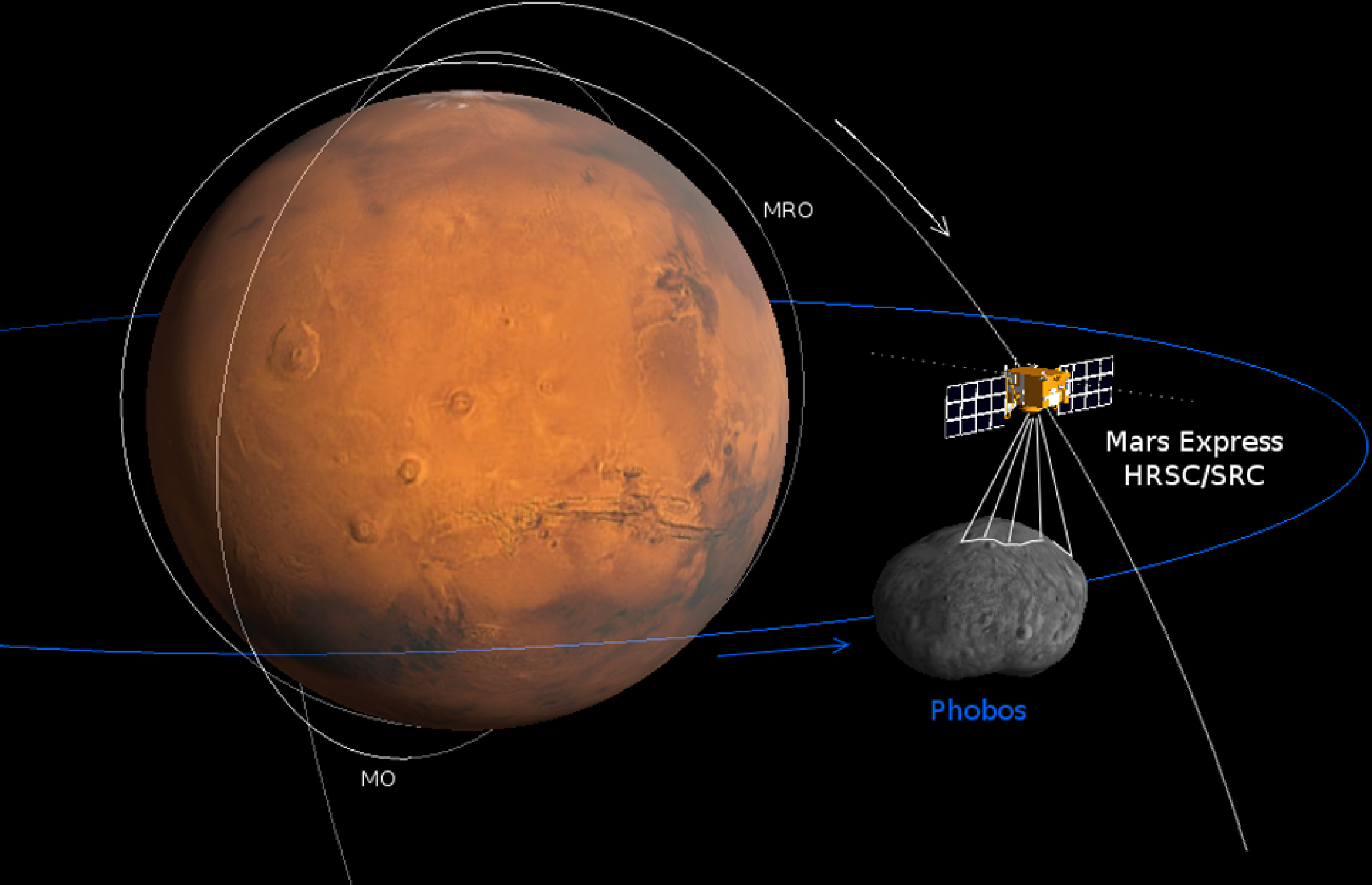
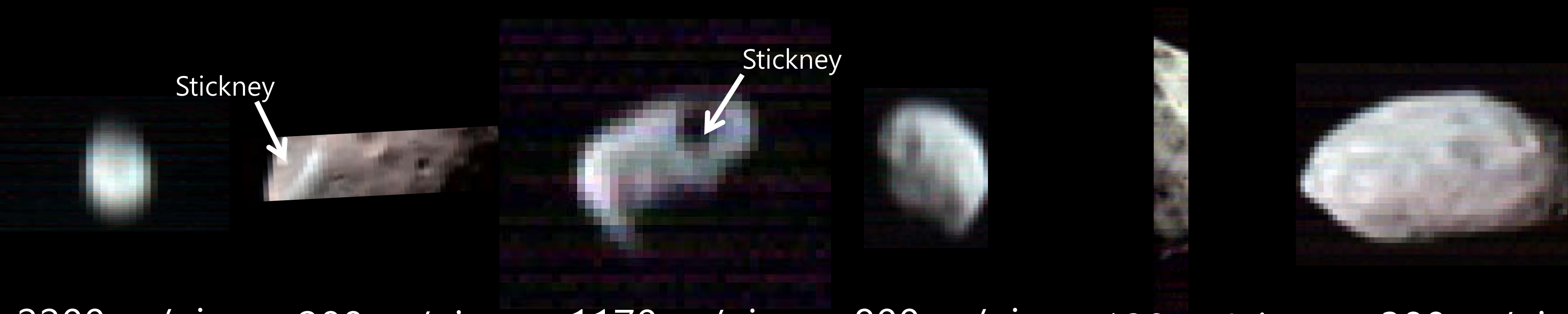


Image credit: ESA/DLR

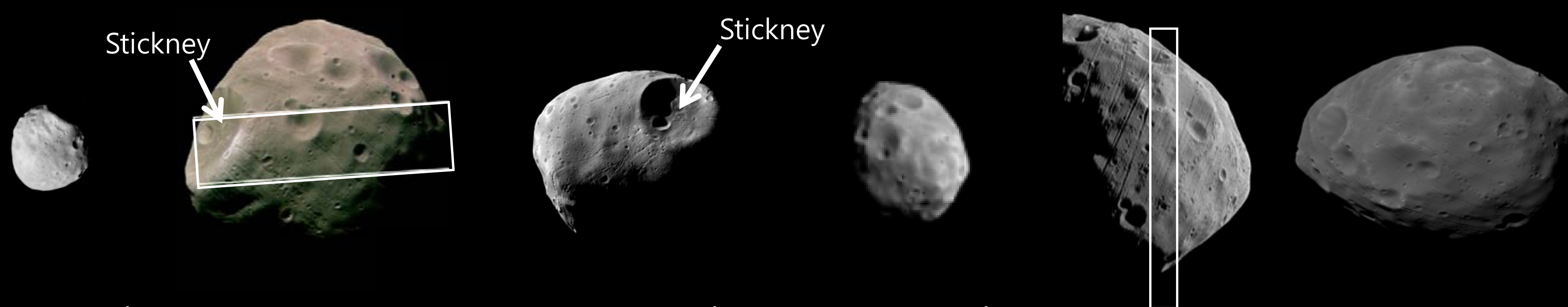
OMEGA Orbital Datasets

OMEGA: High Spectral Resolution



2200 m/pix | 200 m/pix | 1170 m/pix | 800 m/pix | 120 m/pix | 380 m/pix

HRSC: High Spatial Resolution Context



75 m/pix | 7 m/pix | ~40 m/pix | ~27 m/pix | 3.7 m/pix | 9 m/pix

CRISM Orbital Datasets

CRISM: High Spectral Resolution

Phobos

350 m/pixel

Deimos

1200 m/pixel

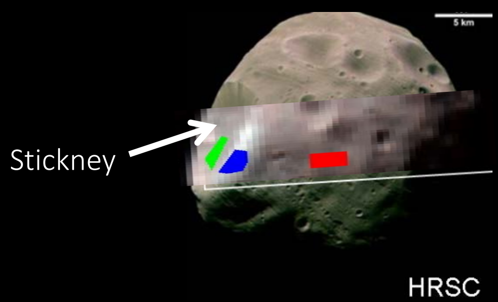
HiRISE: High Spatial Resolution Context

6.8 m/pixel

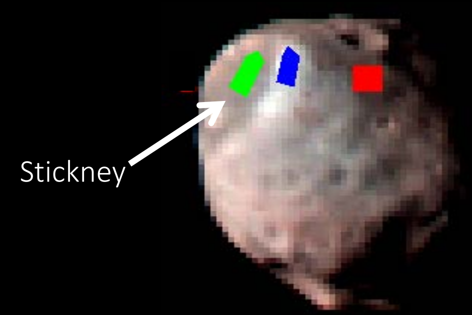
20 m/pixel

Summary Spectra

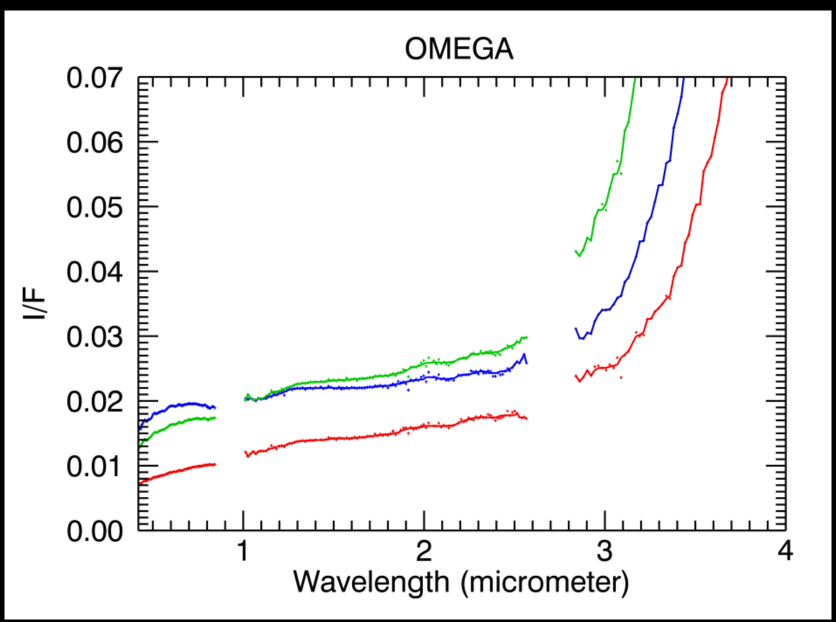
OMEGA Phobos

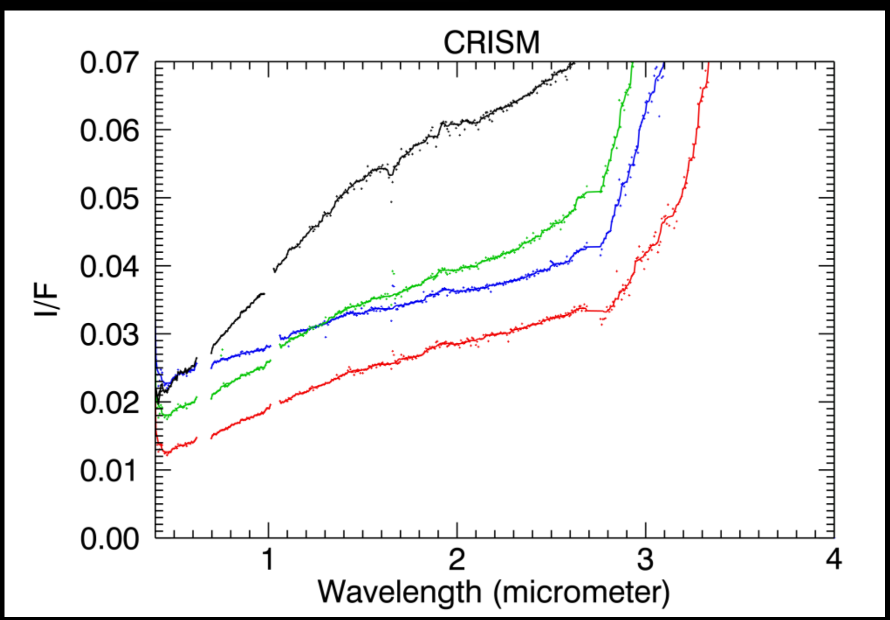


CRISM Phobos

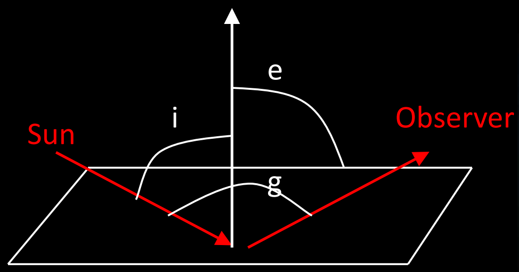


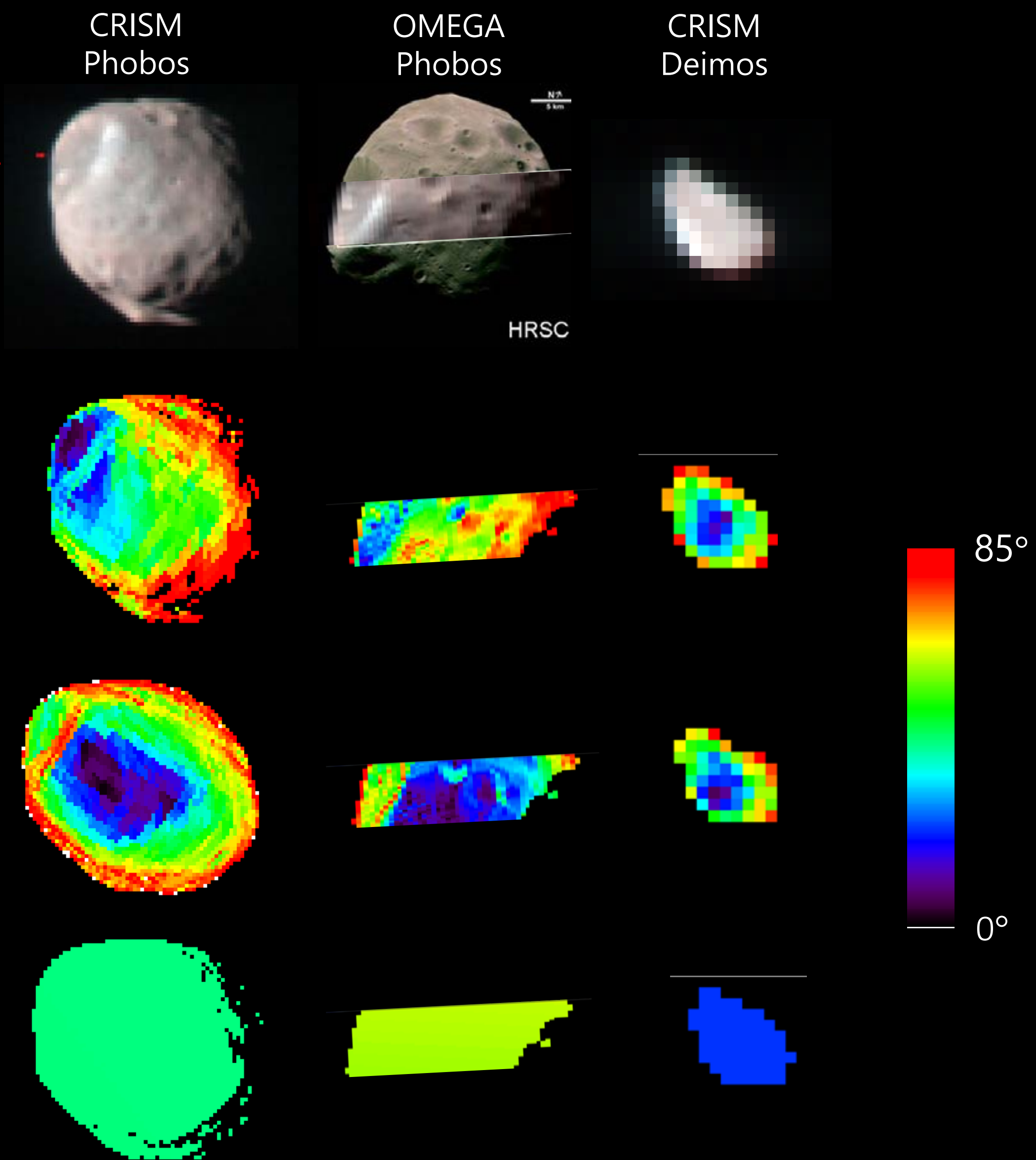
CRISM Deimos





Different Lighting Conditions





Modeling Effects of Viewing Geometry on Reflected Solar Radiance

Hapke's Model for Radiance Factor

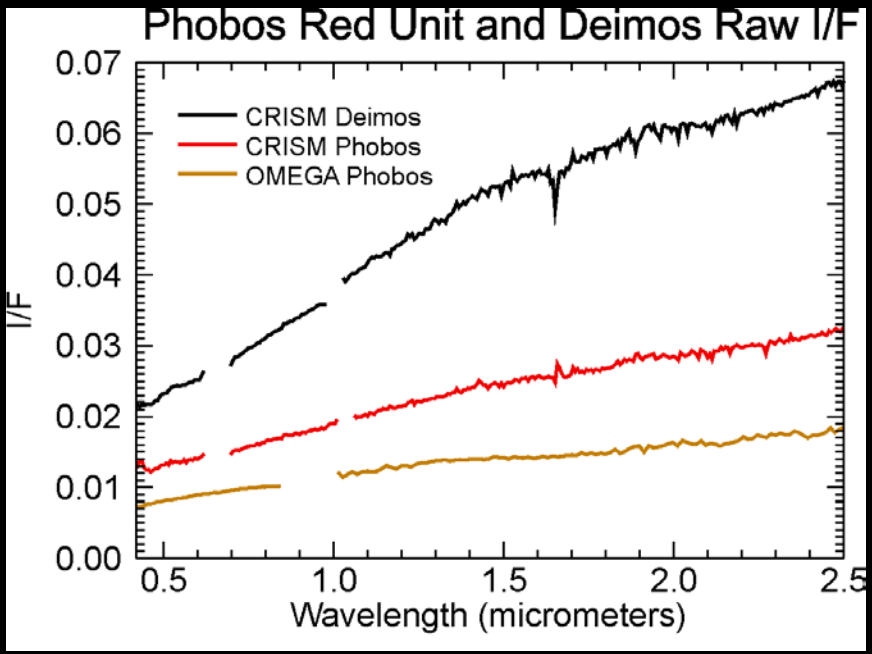
$$r(i,e,\alpha)=\frac{w}{4\pi}\frac{\mu_0}{\mu_0+\mu}[(1+B(g))p(g_1)+H(w,\mu_0)H(w,\mu)-1]\cdot S(i,e,g,\theta)$$

- $\frac{w}{4\pi}$: Single scattering alebdo: ratio of scattering to scattering absorption efficiencies for a single event
- $\frac{\mu_0}{\mu_0+\mu}[(1+B(g))p(g_1)$: Related to viewing geometry
- $H(w,\mu_0)H(w,\mu)$: Approx. for scattering between particles
- $S(i,e,g,\theta)$: Related to surface roughness

Measured/Calculated: r, i, e, g, μ_0, μ
Unknown: w, g_1, Θ

Fraeman et al., 2012

Solve for Single Scattering Alebdo at Every Pixel



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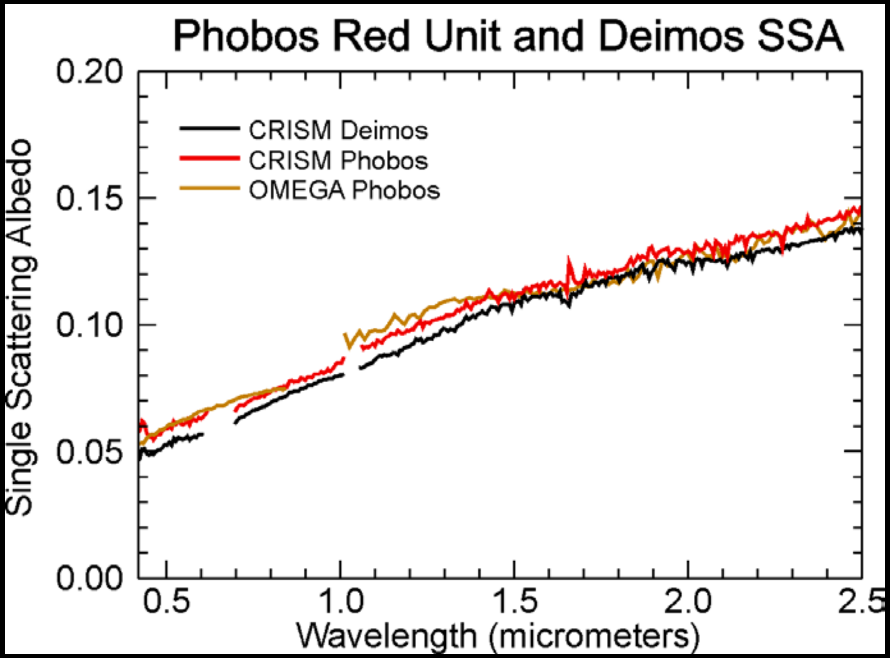
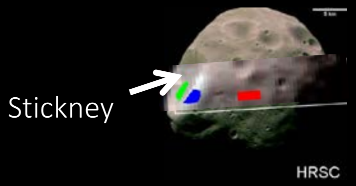
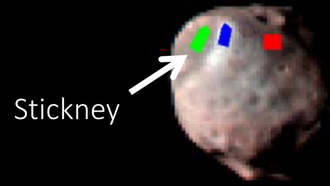




CRISM Phobos

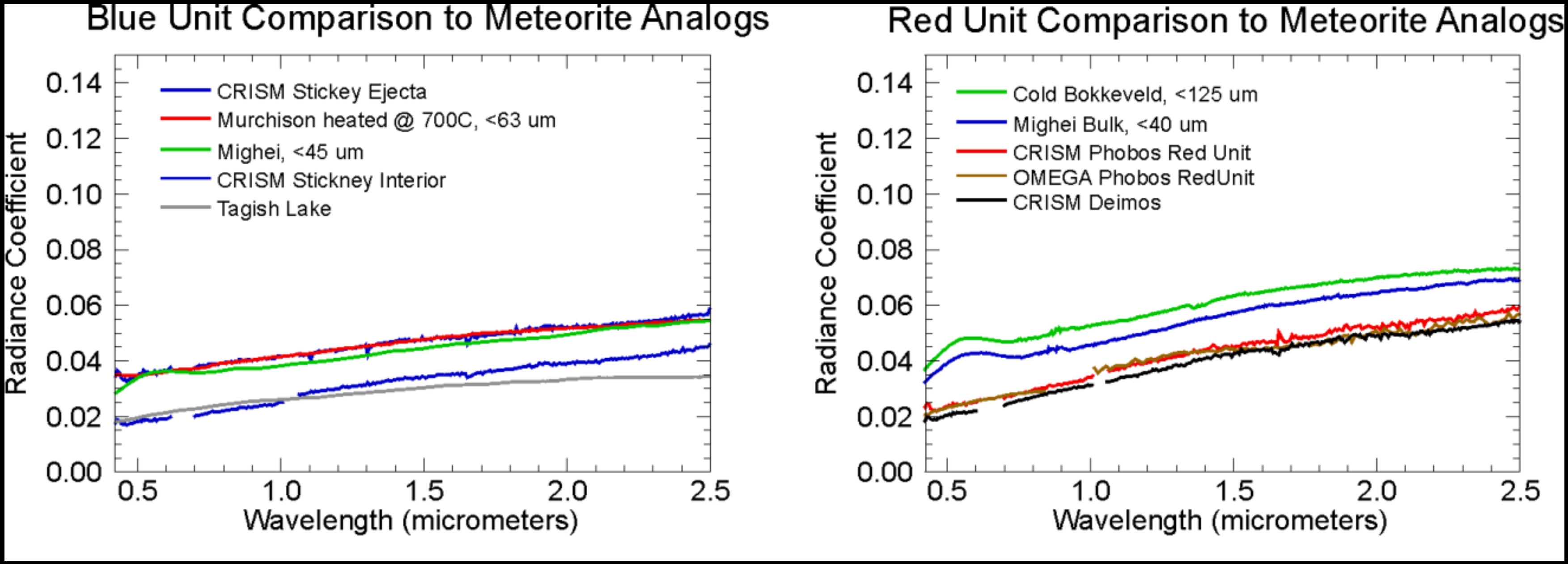


OMEGA Phobos

CRISM Deimos

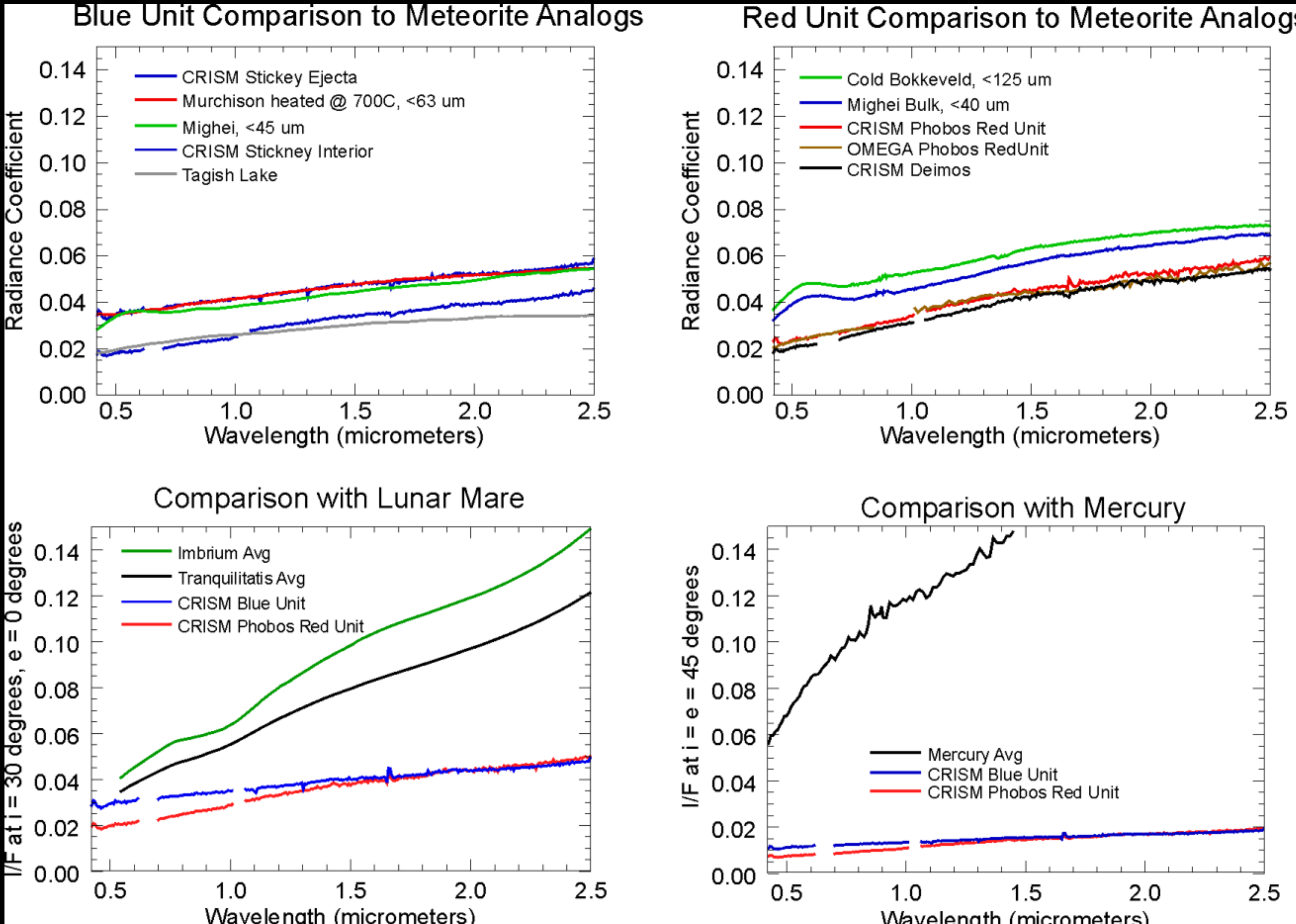
Fraeman et al., 2012

Recast to Any Lighting



Fraeman et al., 2012

Recast to Any Lighting



Fraeman et al., 2012

Space Weathering of Carbonaceous Meteorites

- Telescopic studies of asteroids of different ages suggest opposite trends in spectral slope with age (Nesvorny, et al., 2005; Lazzarin, et al., 2006; Kaluna et al., 2015)
- Experiments on carbonaceous chondrites suggest spectral properties might darken and redden like lunar samples, although details vary between samples (Gillis-Davis et al., 2015; Matsuoka et al., 2016)
- Haven't (yet) examined returned sample from carbonaceous asteroid

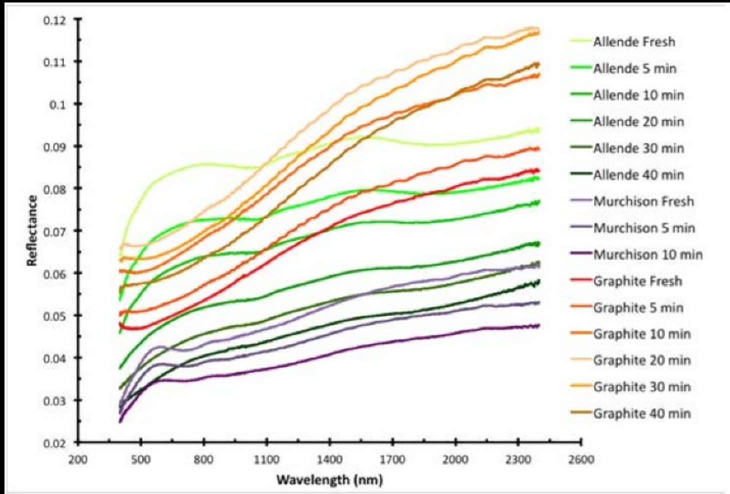
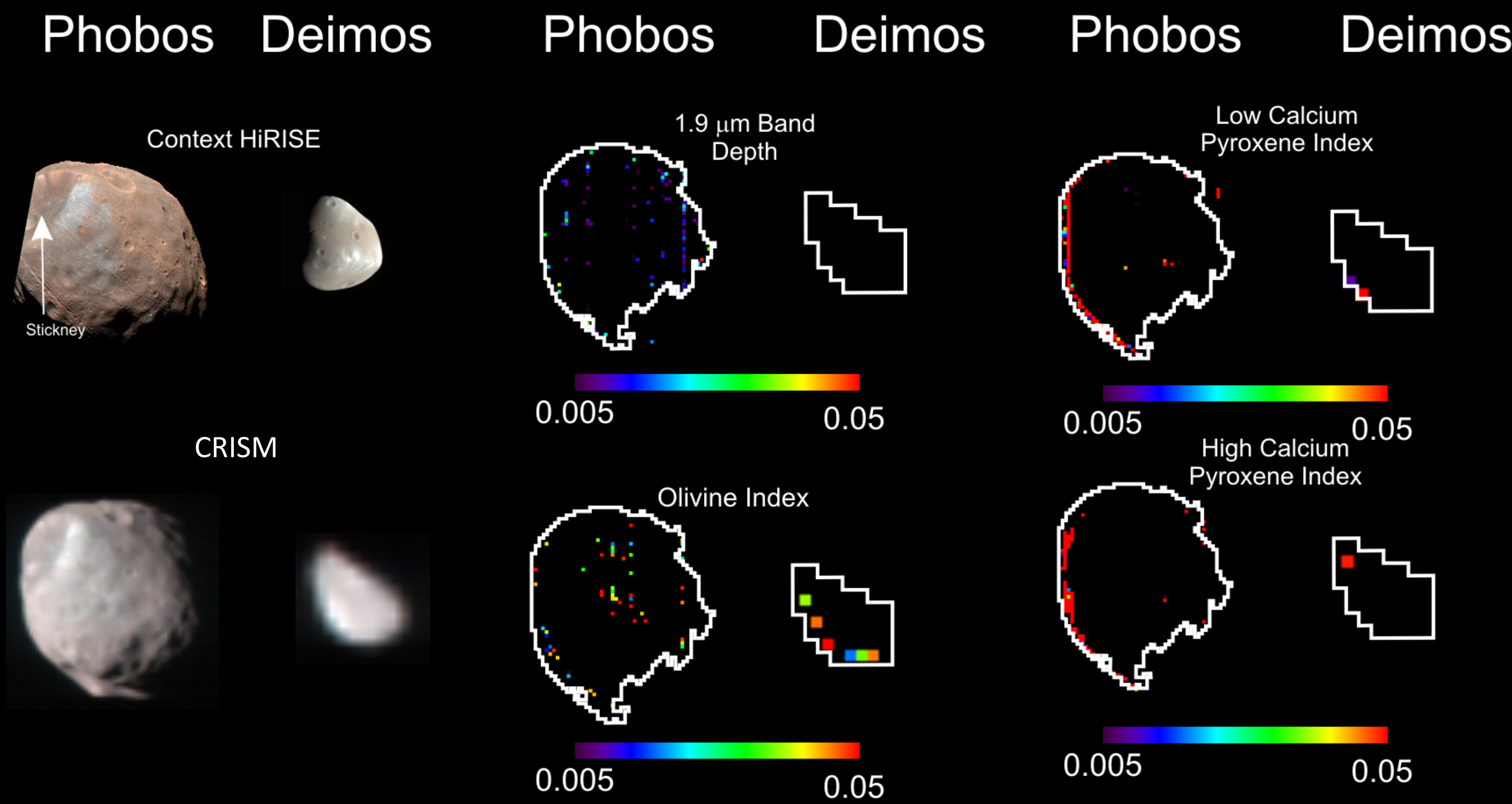


Fig. 1 Reflectance values for Allende, Murchison and Graphite as a function of space weathering.

Gillis-Davis, J. et al., LPSC 2015

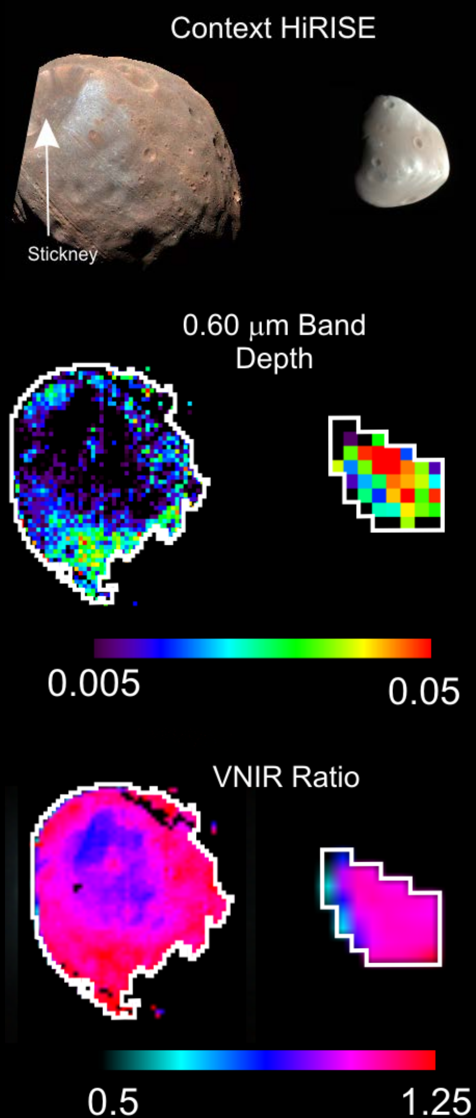
Searching for Features in CRISM Data

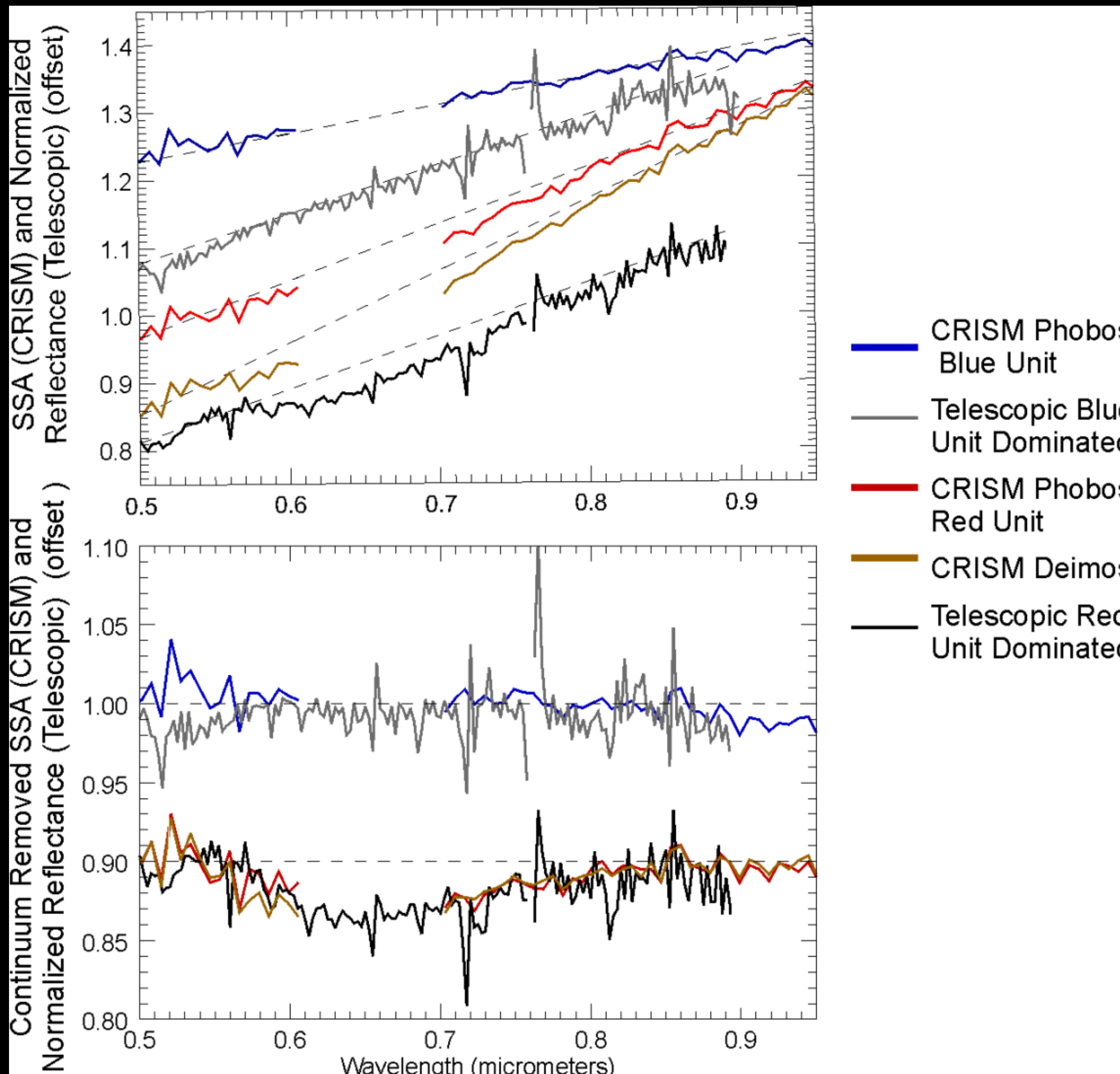


Fraeman et al., 2014

Broad Feature at 0.65 µm

Phobos Deimos





Fraeman et al., 2014

Note: CRISM data@ 0.65 um are compromised by a boundary between detector-mounted filters

OSIRIS Data from Rosetta

- OSIRIS on Rosetta spacecraft also collected spectra from Phobos during Mars flyby
- Data were consistent with previous studies

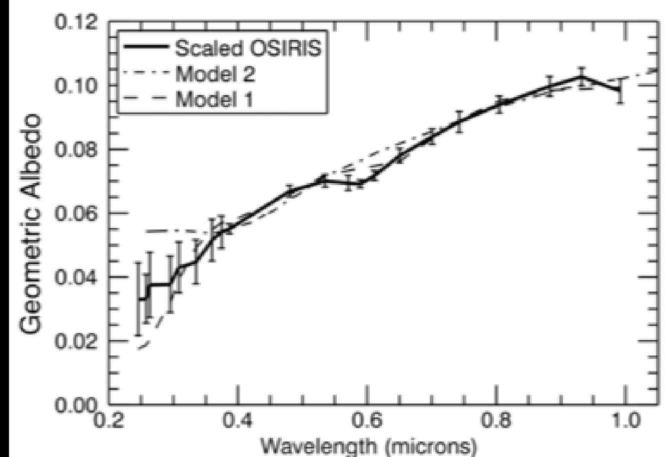


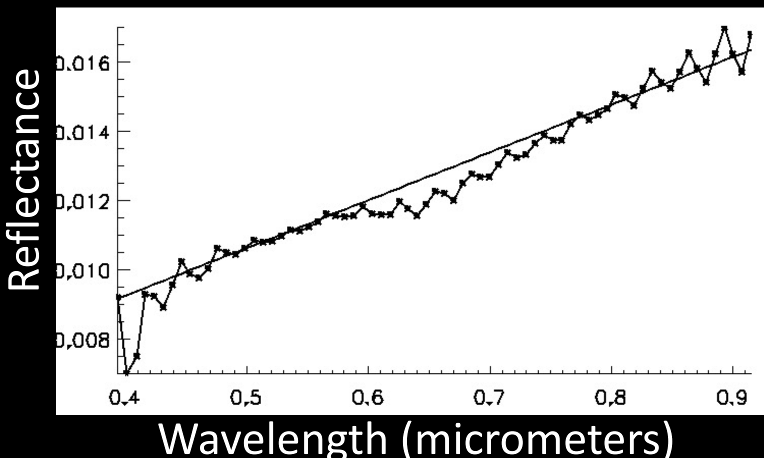
Figure 3. Scaled OSIRIS WAC and NAC data together with the best fitting Models 1 and 2.

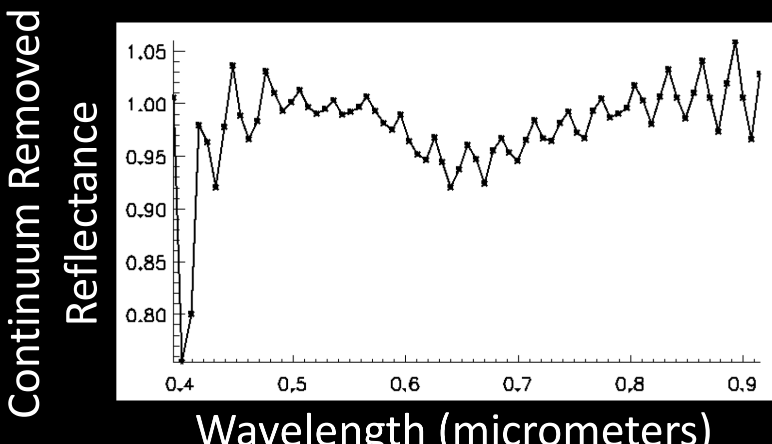
Pajola et al., 2013

Jan. 2016 OMEGA Observation

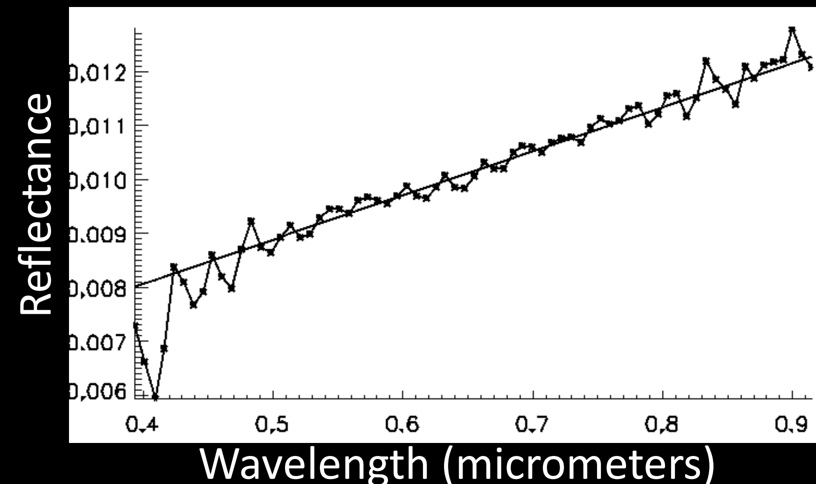
53 km above Phobos (ORB 15260)

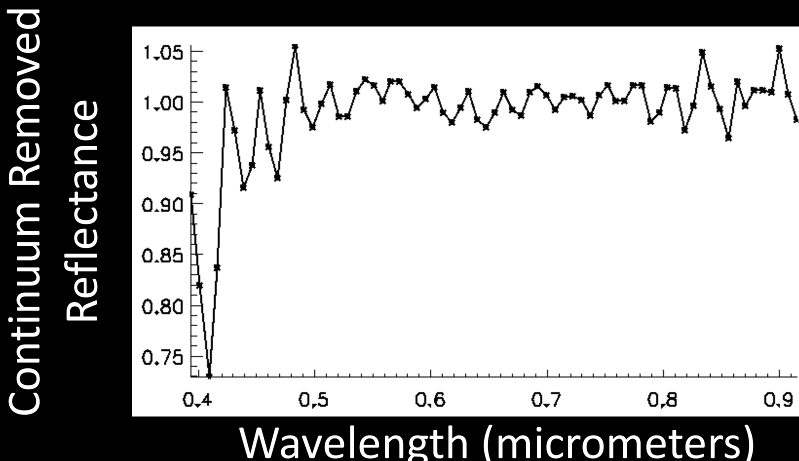
Red Unit





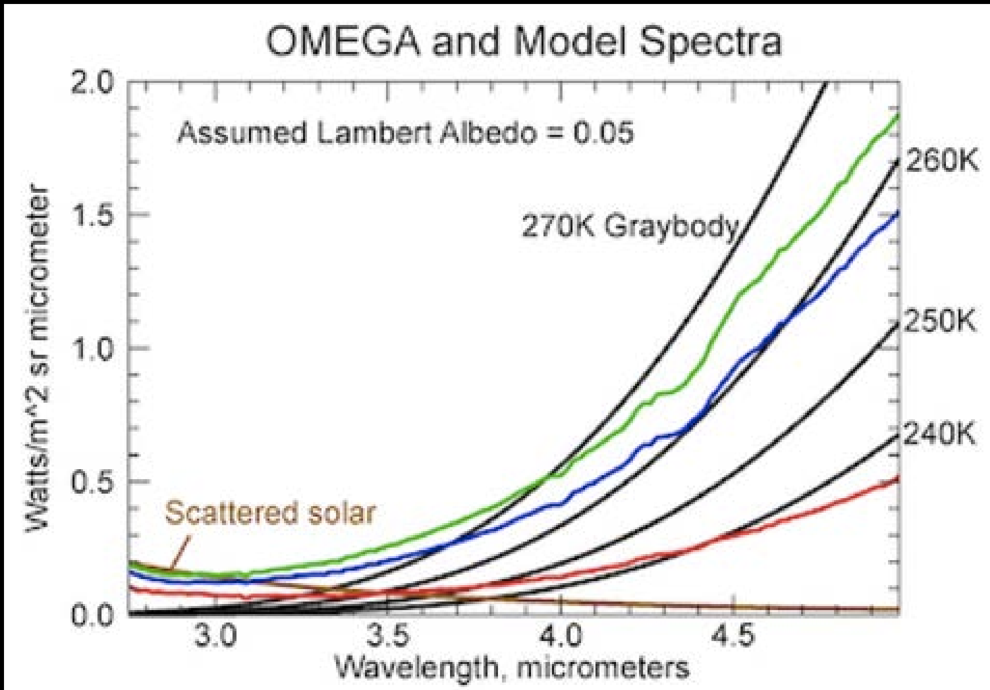
Blue Unit



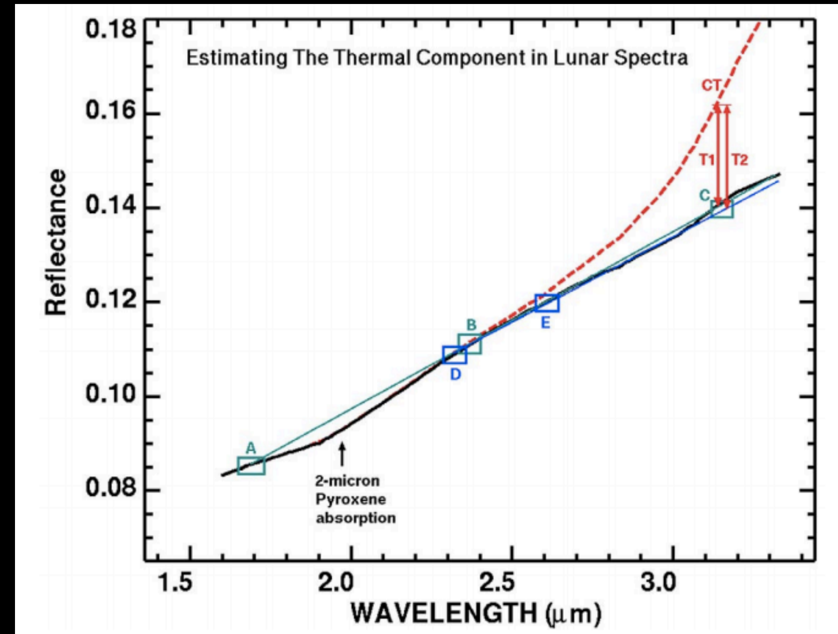


Spectra courtesy B. Gondet

Thermal Emission



At Phobos surface, temperatures reach up to 350 K (Lynch et al., 2007; Kuzmin & Zabalueva, 2003); thermal crossover (equal contributions from reflected solar + emitted thermal) occurs around 2.5 – 3.5 microns.



Estimate temperatures using method of Clark et al. 2011., assume spectrum ~linear and extrapolate to longer wavelengths.

Hapke's Model for Radiance Factor with modeled thermal emission contribution

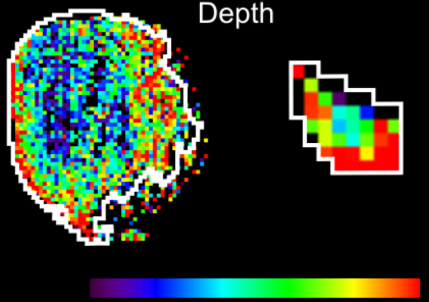
$$r(i,e,\alpha)=\frac{w}{4\pi}\frac{\mu_0}{\mu_0+\mu}\Big[\big(1+B(g)\big)p(g_1)+H(w,\mu_0)H(w,\mu)-1\Big]\cdot S(i,e,g,\theta)+\sqrt{1-w}\cdot H(w,\mu)\cdot\frac{\beta_0(T)}{J/\pi}$$

Feature at 2.8 μm

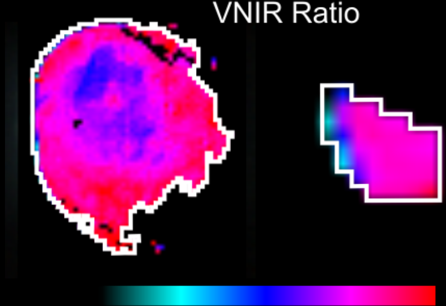
Phobos Deimos

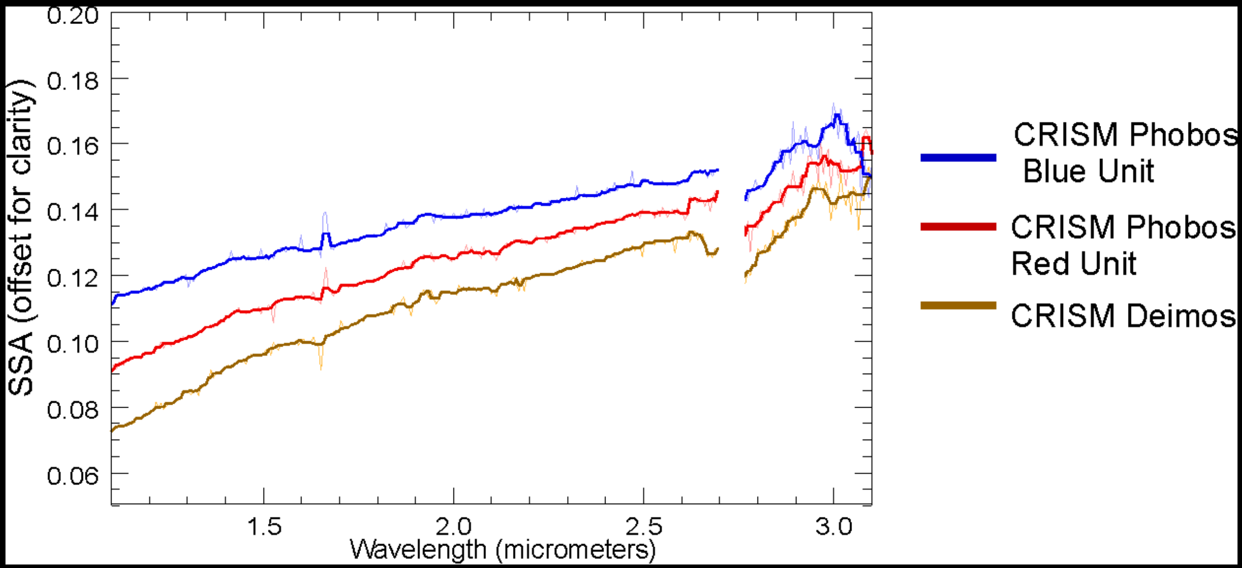
Context HiRISE

2.8μm Band Depth



VNIR Ratio



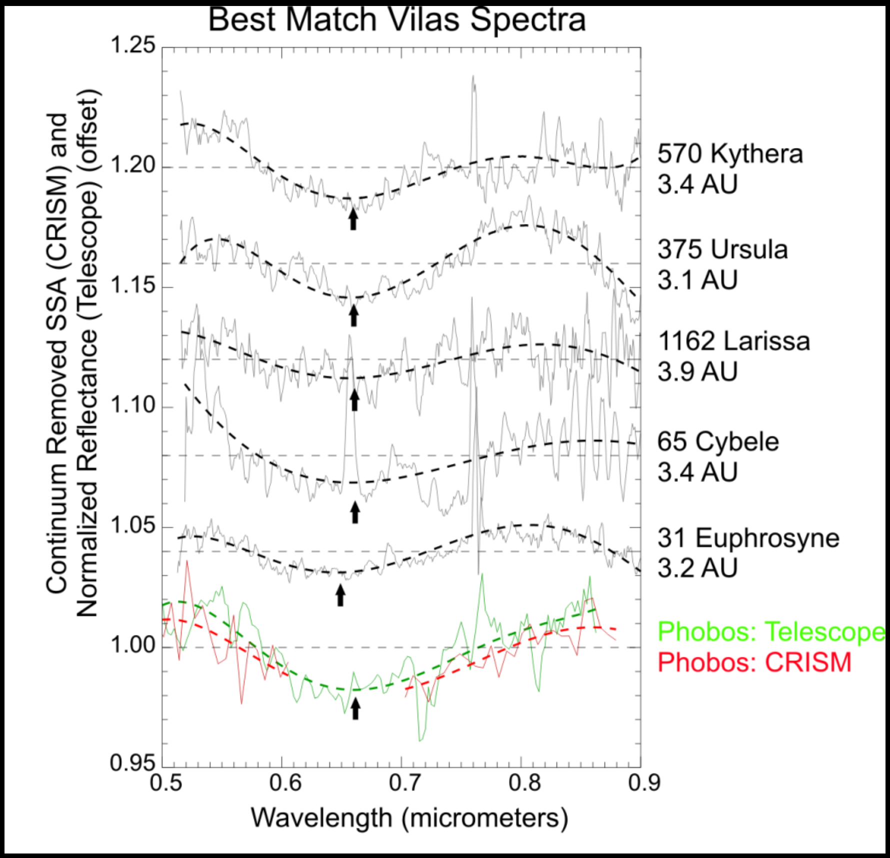


Note: CRISM data @ 2.7 um are compromised by a boundary between filters mounted to the IR detector that blocks higher orders from the diffraction grating; these wavelengths are not routinely downlinked from the instrument.

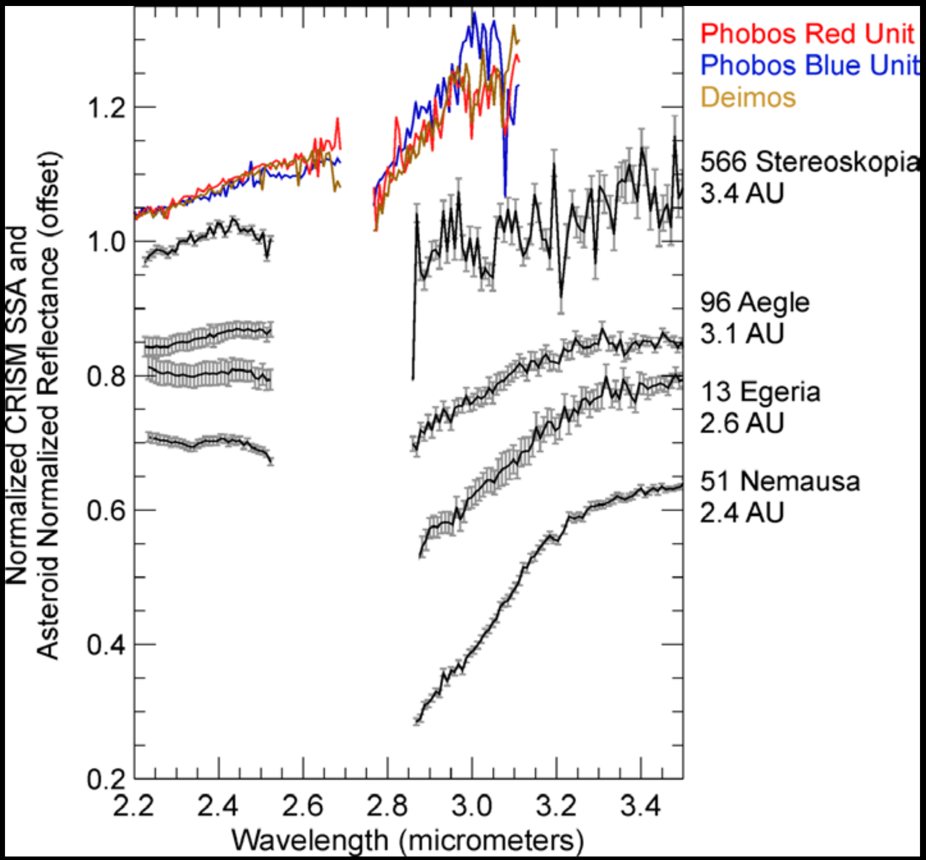
Fraeman et al., 2014

Similarity to Low-Albedo Asteroids

0.65 µm Feature



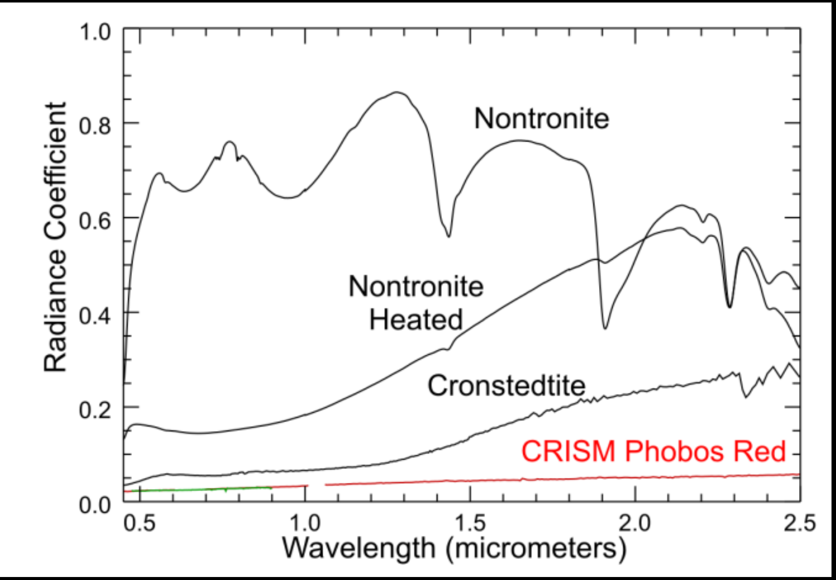
2.8 µm Feature

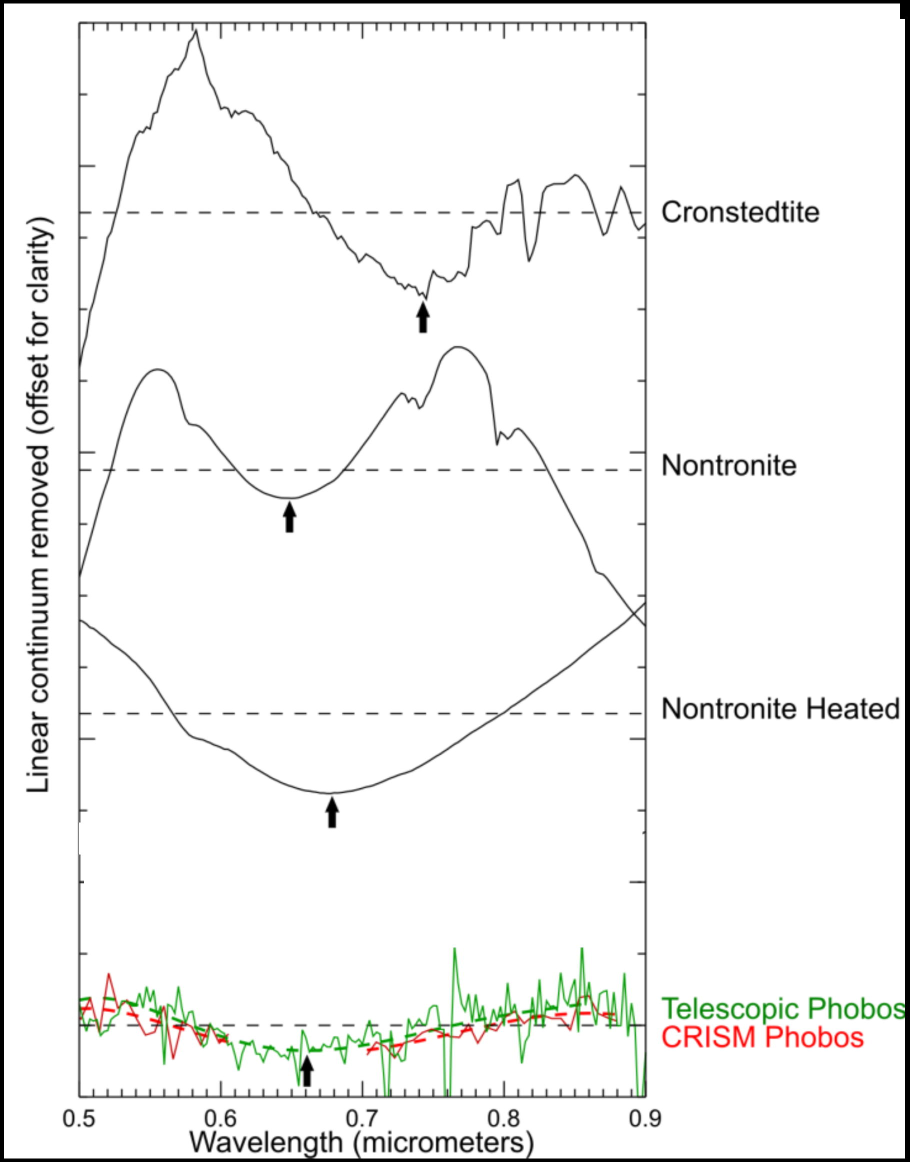


Vilas et al., 1998

Rivkin et al., 1996; Rivkin et al., in prep

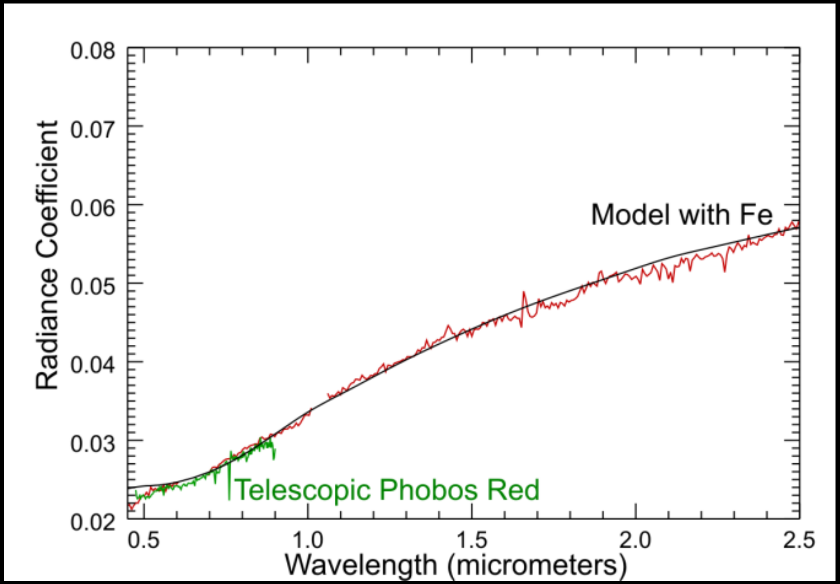
Scenario 1: Phyllosilicate

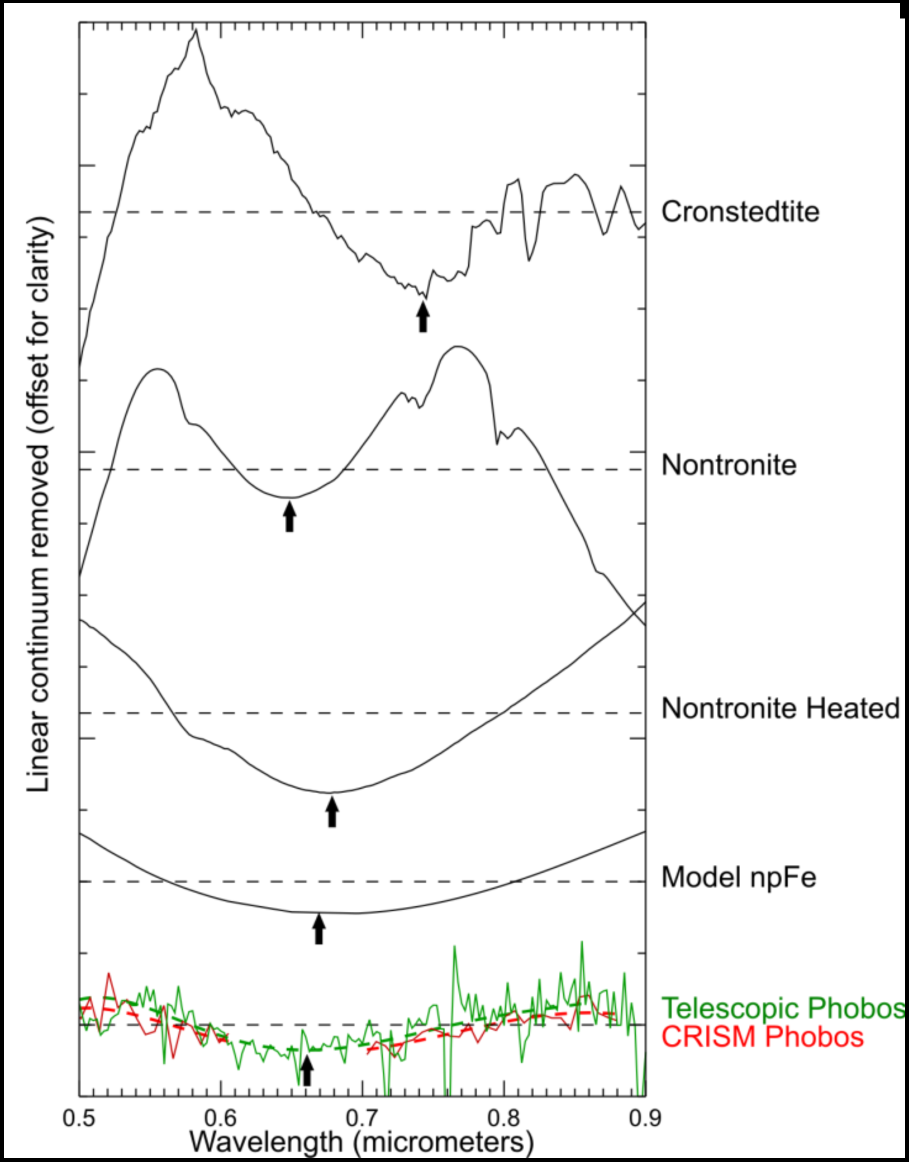




Fraeman et al., 2014

Scenario 2: Space Weathering





Fraeman et al., 2014

Improving Spatial Resolution

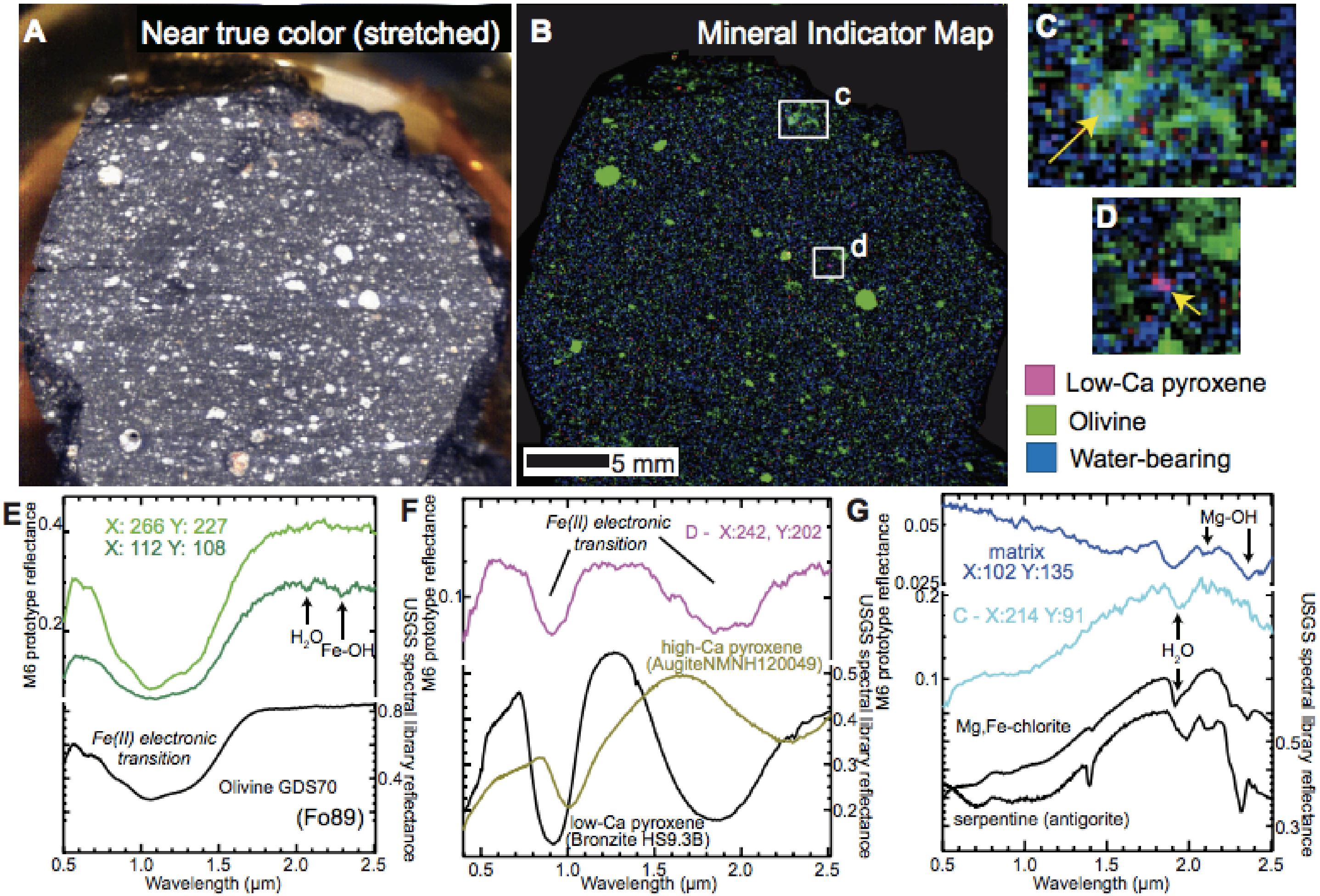


Figure 4. Image of the Murchison meteorite acquired with UCIS. (A) Near true color composite image of a cut face of the meteorite using hyperspectral data. (B) Mineral indicator map in which low-calcium pyroxene appears magenta, olivine is green, and water-bearing materials are blue. Close-up of two interesting regions of the meteorite with a (C) zone of altered olivine and (D) fragment of low-calcium pyroxene. Spectra from the USGS spectral library are shown in black and gold in (E)–(G) for comparison with meteorite spectra (Clark et al., 2007). (E) Spectra of olivine-bearing spots with (dark green) and without (light green) spectral features indicative of hydration. (F) Spectrum of low-Ca pyroxene (shown in D), likely from a chondrule fragment. (G) Matrix materials within the chondritic sample are clearly water-bearing but are distinctive in composition from typical terrestrial chlorites and serpentines. The light blue spectrum is from (C).

Greenberger et al., GSA today 2015; Green et al., LPSC 2015; Ehlmann et al., LPSC 2016

Thermal Infrared Measurements

Surface hydration?

Indicates low Si content if space weathered

Carbonates + silicates

Glotch et al., 2015

Key Conclusions

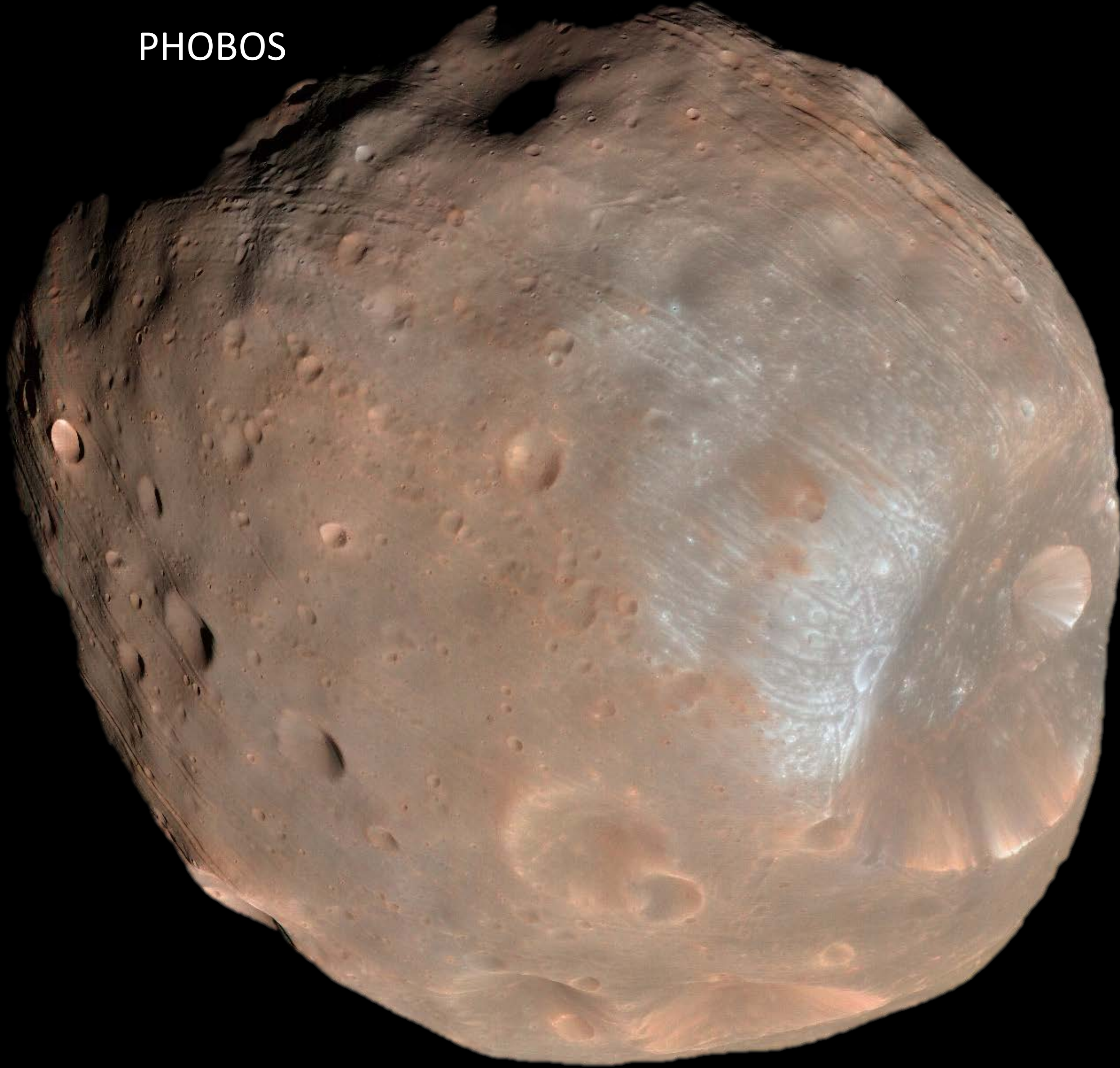
- Phobos and Deimos are darker than even most space weathered materials
- Likely have carbonaceous chondrite-like compositions because they lack mafic absorptions and are spectrally similar to CM carbonaceous chondrites or Tagish Lake
- Pair of spectral features observed similar to those on low albedo asteroids
- To argue that moons formed *in situ* rather than by capture of primitive bodies requires carbonaceous materials to have been added to the Martian system during accretion or a late stage impact

Want to learn more?

- http://sservi.nasa.gov/event/planetary-evolution-phobos-and-deimos/

- The "Science and Exploration of Phobos and Deimos" series was jointly organized and led by SSERVI teams at University of Central FL and Brown University/MIT with many SSERVI-affiliated institutions participating.
- 13 recorded seminars given by leaders in the field with associated discussion.
- Also includes great reading list.

PHOBOS



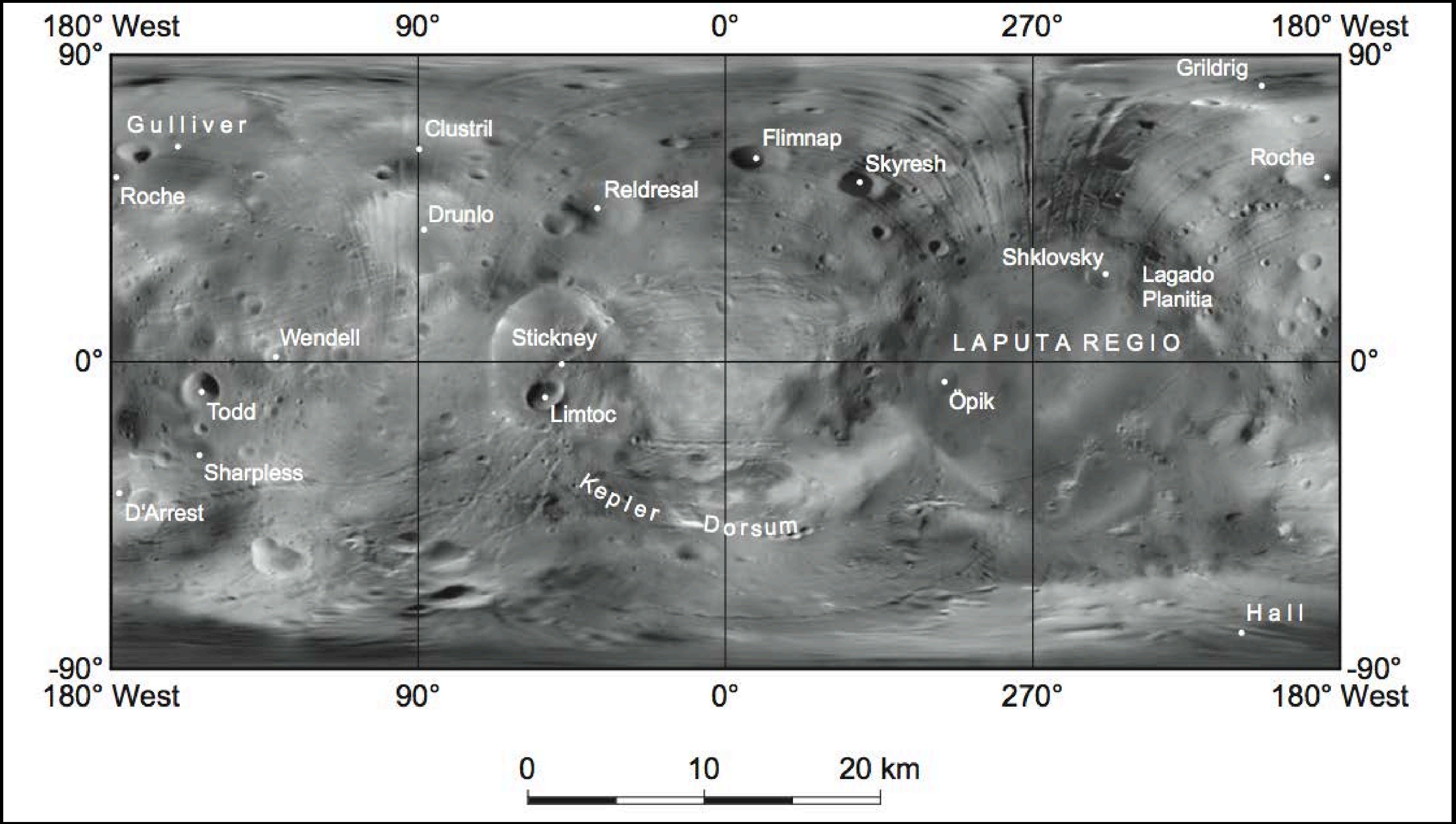
6.8 m/pixel

DEIMOS

20 m/pixel

Image credit: NASA/JPL/University of Arizona

Phobos Surface Geology



Wählisch, M., et al., (2013), http://dx.doi.org/10.1016/j.pss.2013.05.012i

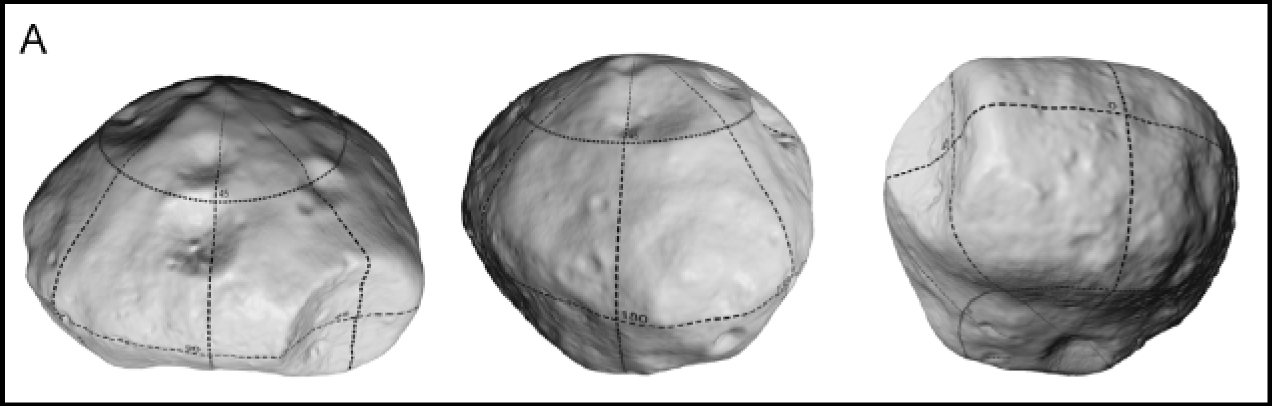
Space Weathering

- Catch all phrases for processes that affect spectral properties of materials due to their exposure in the space environment
- Biggest drivers are solar-wind irradiation and micrometeorite impacts
- Effects of space weathering known to be different for different solar system bodies
    - Moon = production of nanophase Fe that darkens and reddens, observed in returned lunar samples (Hapke, 2001; Pieters, et al., 2000)
    - Itokawa = production of FeS as well (Noguchi et al., 2011)
    - Vesta = little evidence for space weathering (Pieters et al., 2012)

Composition to help Constrain Internal Structure

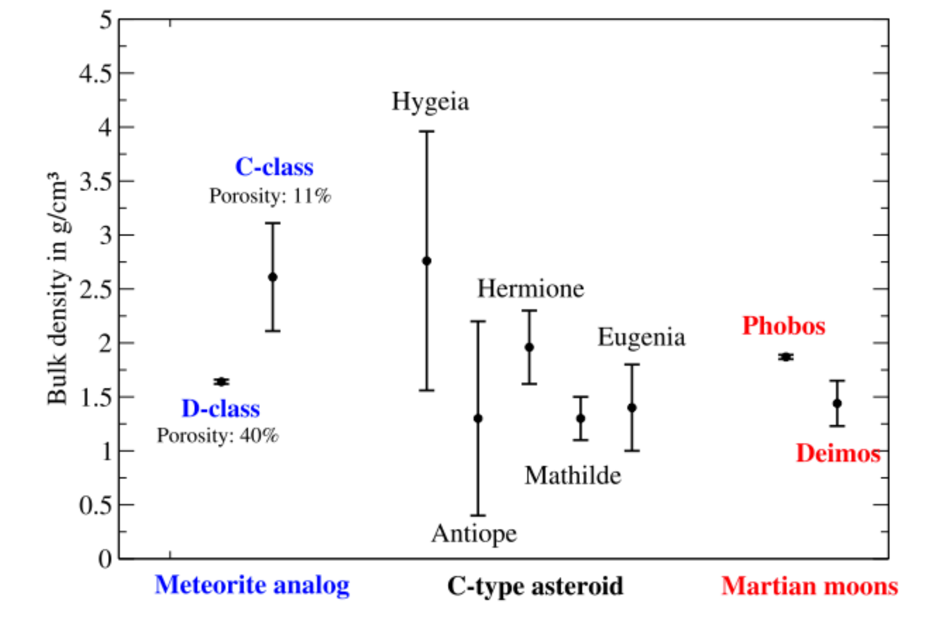
- Once we know composition, we can use it to make assumptions about other physical properties, like internal structure
- Helps constrain knowledge of dissipative orbital properties, which is key to understanding past evolution of orbits (e.g. Lambeck 1979; Mignard 1981)
- See Rosenblatt, 2011 for thorough review of links between internal structure and origin

Internal Structure



DTM of Phobos from Willner, et al. 2013 created using stereo-photogrammetric analyses of 100m/pixel HRSC and Viking Orbiter data

- MRO and MEx allow for improved estimates for Phobos mass and volume (Andert, et al., 2011; Jacobson, et al., 2010, Willner, et al., 2013)
- Ph density: 1.86 ± 0.013 g cm^{-3}
- D density: 1.490 ± 0.190 g cm^{-3}



Rosenblatt, 2011

Internal characteristics & surface manifestations

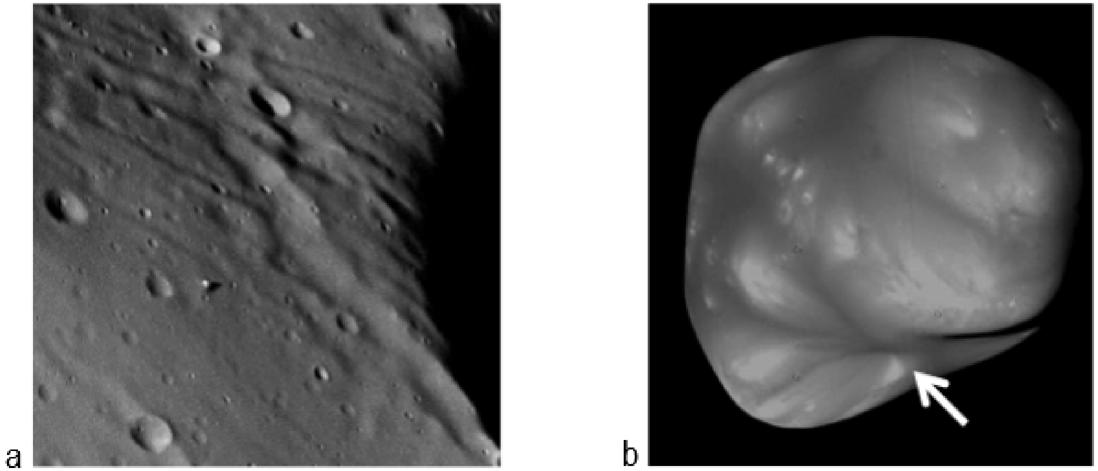


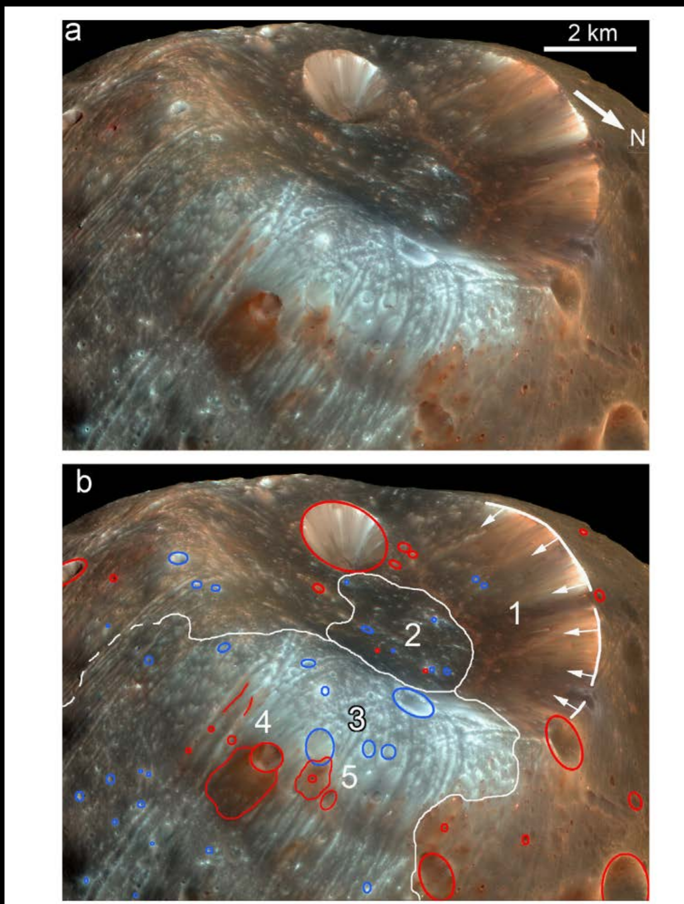
Fig. 1. Viking Orbiter images showing (a) Phobos' well-organized pattern of grooves [20] and (b) Deimos' surface dominated by bright streaks due to mass wasting, with a large depression in the south polar region that is thought to be a large impact crater [21].

Body	R_m, km	Assumed composition	Est. macro-porosity	Est. total porosity	Coherent ridge/ groove patterns?	Craters >1.3 R_m?	Fragment-dominated surface?	Refs.
Coherent to fractured but coherent								
Lutetia	49	E	≤15%	≤17%	Y	N	N	25,26
Phobos	11.1	CM	17±4%	35±3%	Y	N	N	13,17,18
Eros	7.3	LL	17±7%	24±4%	Y	N	N	7,10
Fractured but coherent to transitional								
Mathilde	26.5	CI	18±14%	55±9%	insufficient resolution	Y	insufficient resolution	5,22
Ida	15.7	LL	20±20%	26±16%	Y (only regionally)	N	N	27,28
Loosely consolidated								
Deimos	6.2	CM	34±11%	48±8%	N	Y	Y	14,16-18
Itokawa	0.18	LL	41±8%	46±6%	N	N	Y	8,9,11

Table 1. Sizes, assumed compositions, estimated porosities calculated using meteorite densities reported by [4], and morphology of asteroids <110 km in diameter having well-determined densities and coverage by spacecraft images. R_m=mean radius.

Murchie et al., 2013

Red and Blue Units



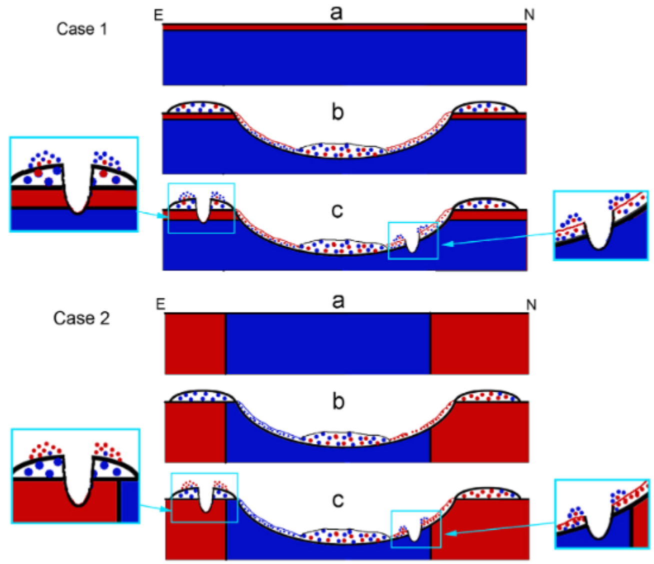
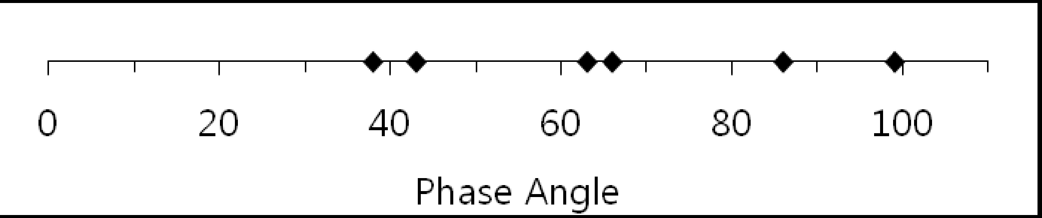
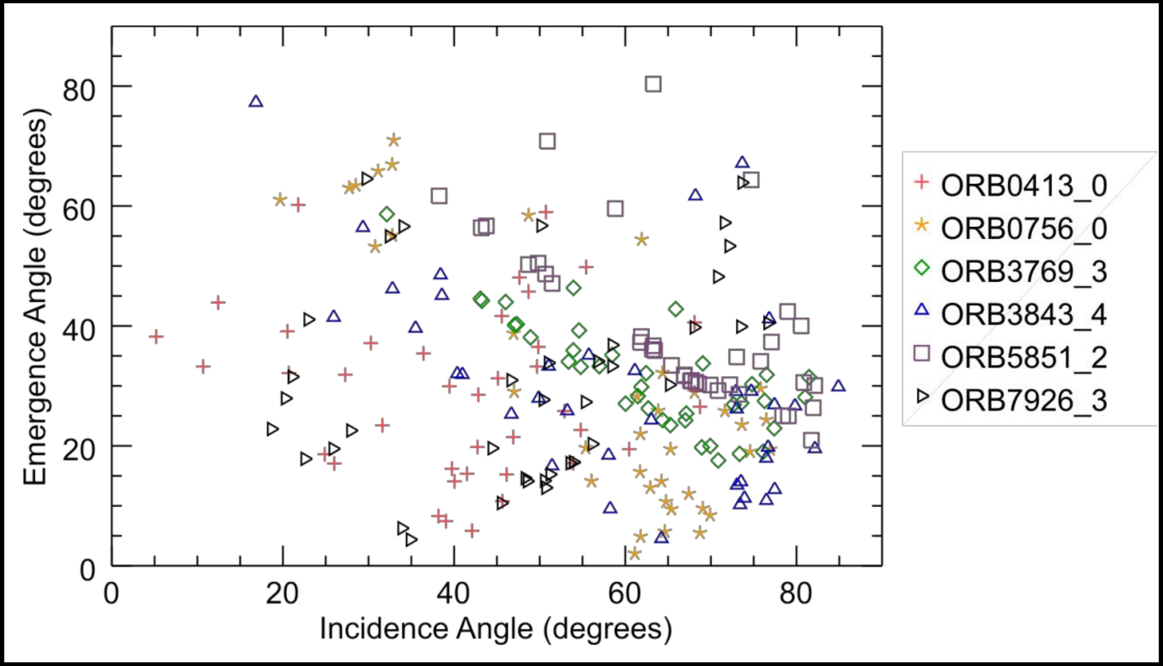


Fig. 17. Schematic illustrative diagram of a profile from the eastern rim of the crater Stickney towards the crater center and then to its northern rim. Rim structure and bedrock deformation has been omitted. The stages of formation of the observed morphology and distribution of the red and blue units are shown: (a) stage 1, (b) stage 2 and (c) stage 3 for two cases (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Basilevsky et al., 2014

Range of OMEGA Lighting Geometries





Fraeman et al., 2012