A Primer – Remote Observations of Primitive Bodies from Spacecraft

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Scope / What We'll Focus On

- Low-albedo, irregular objects for which "high resolution data" were taken by a spacecraft during flyby and rendezvous
  - **<u>Phobos and Deimos</u>** (D-type - Mariner 9, Viking, Phobos 2, Mars Express, MGS, MRO)
  - **<u>Mathilde</u>** (C-type - NEAR)
  - Lutetia (D-like – Rosetta)
  - **<u>Phoebe</u>** (Centaur/KBO-like – C/D + ice – Cassini)
  - Comets Borelly, Wild 2, Tempel 1, Hartley 2 (DS-1, Stardust, Deep Impact)

- Remote sensing
  - **<u>Imaging</u>**, mostly to understand morphology
  - **<u>Spectroscopy</u>**, to attempt to constrain
    - **<u>Composition, from albedo and absorptions</u>**
    - Texture, from surface temperature

Challenges in Remote Observations

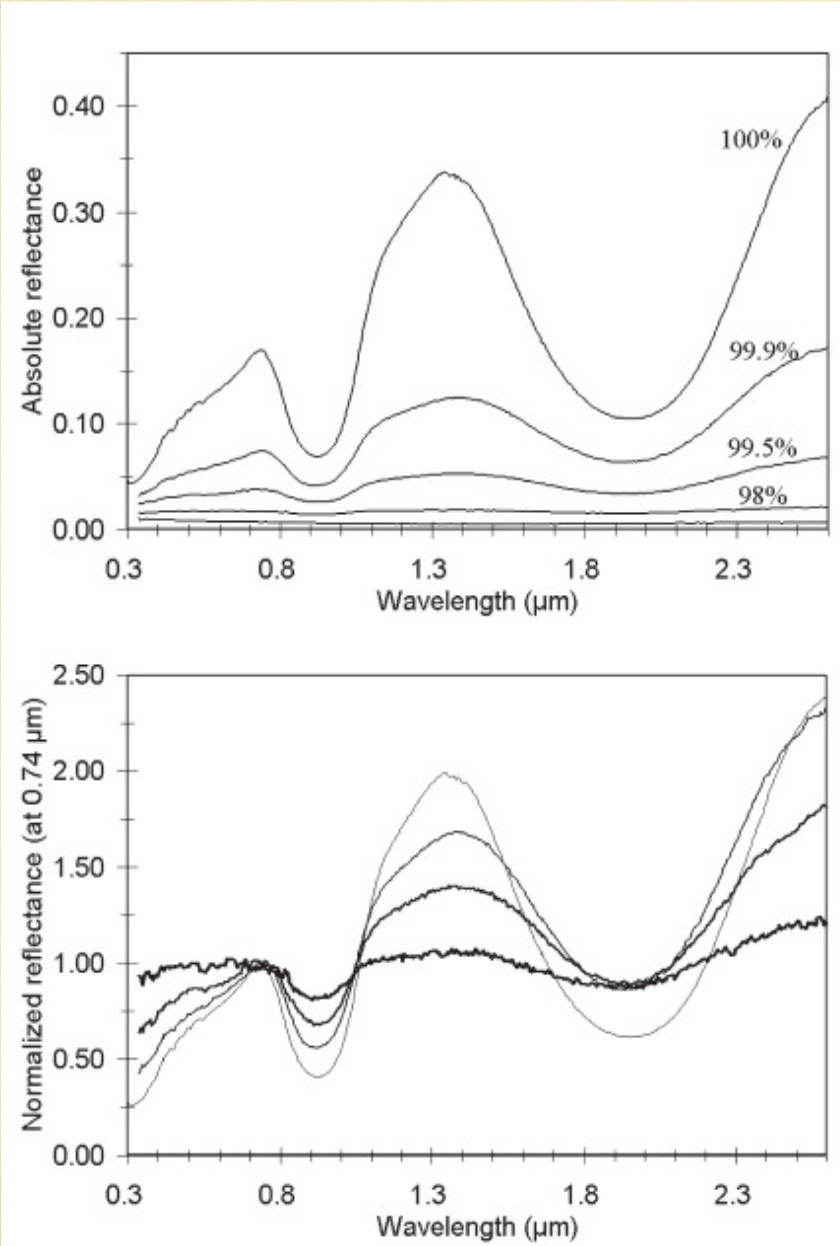
- So far, nearly all observations of primitive bodies have been flybys in heliocentric or planetocentric orbit

- You plan simultaneously to high relative velocities, brief encounters, and positional uncertainties. These limit spatial coverage, viewing geometryies, resolution, and time to integrate photons in spectral measurements
  - Phobos and Deimos are exceptions by virtue of repeat encounters

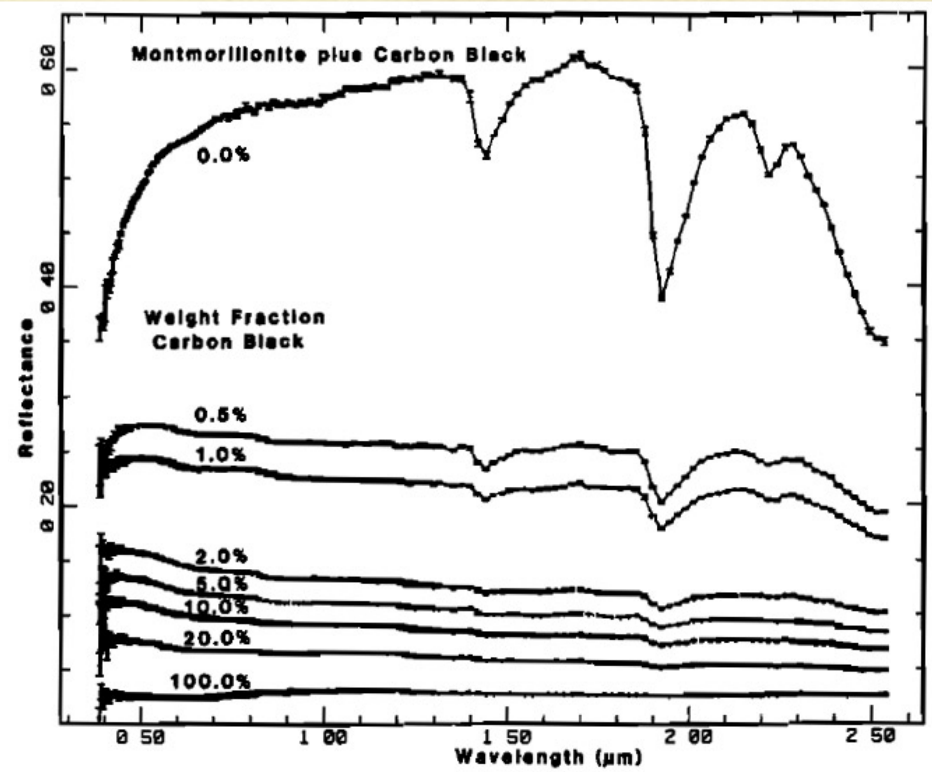
- Opaques causing low albedo also attenuate diagnostic absorptions

- For bodies inside the asteroid belt, the surfaces can be baked of volatiles and the strongest absorptions – water, OH, organics – at 3-4 μm are obscured by thermal crossover

Obscuration by Opaques...



Cloutis et al. 2010



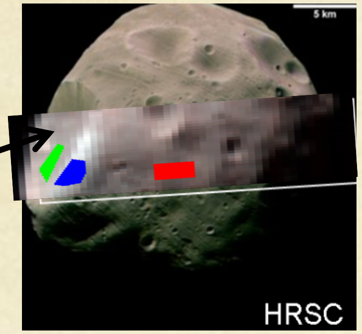
Clark et al. 1983

Absorptions that are strong in terrestrial, lunar, and even Martian spectra become reduced in strength...

...Makes Mineral Signatures the Strength of Artifacts

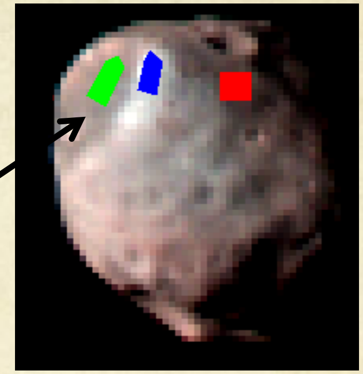
OMEGA ORB 756

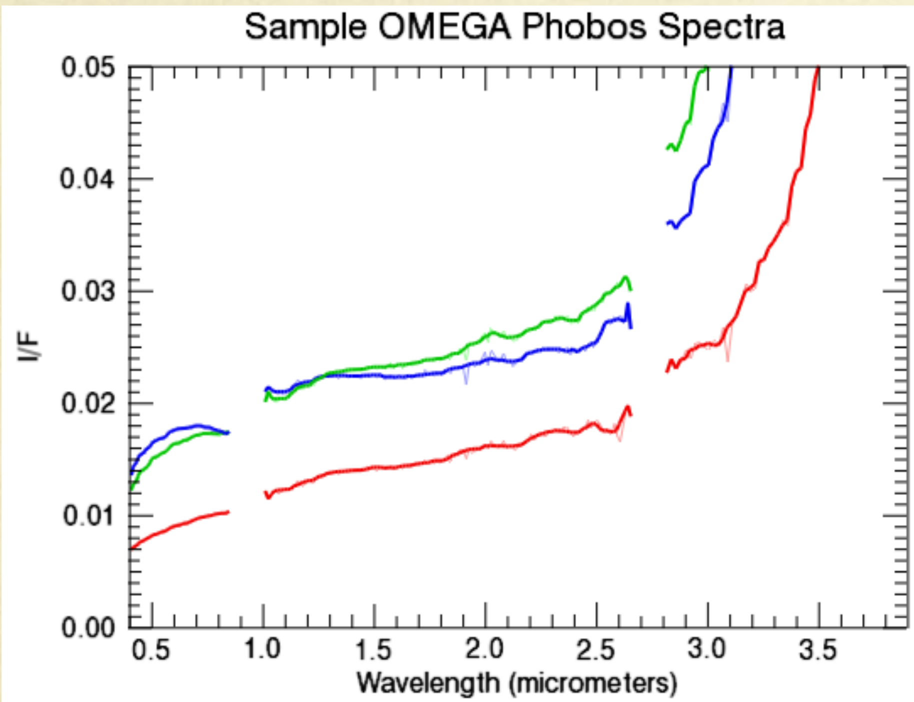
Stickney Crater



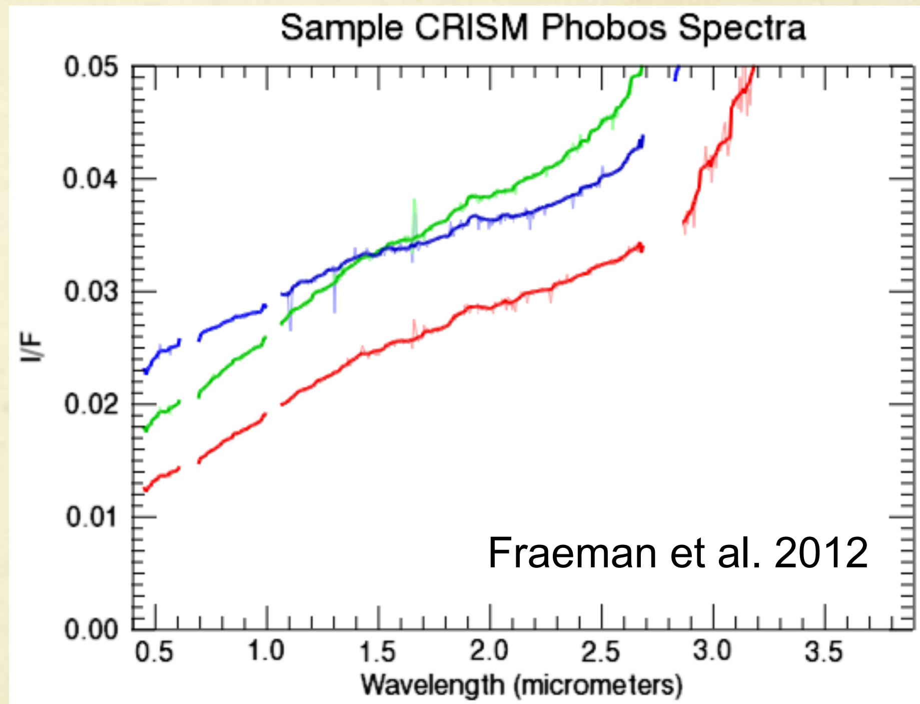
CRISM FRT00002992

Stickney Crater





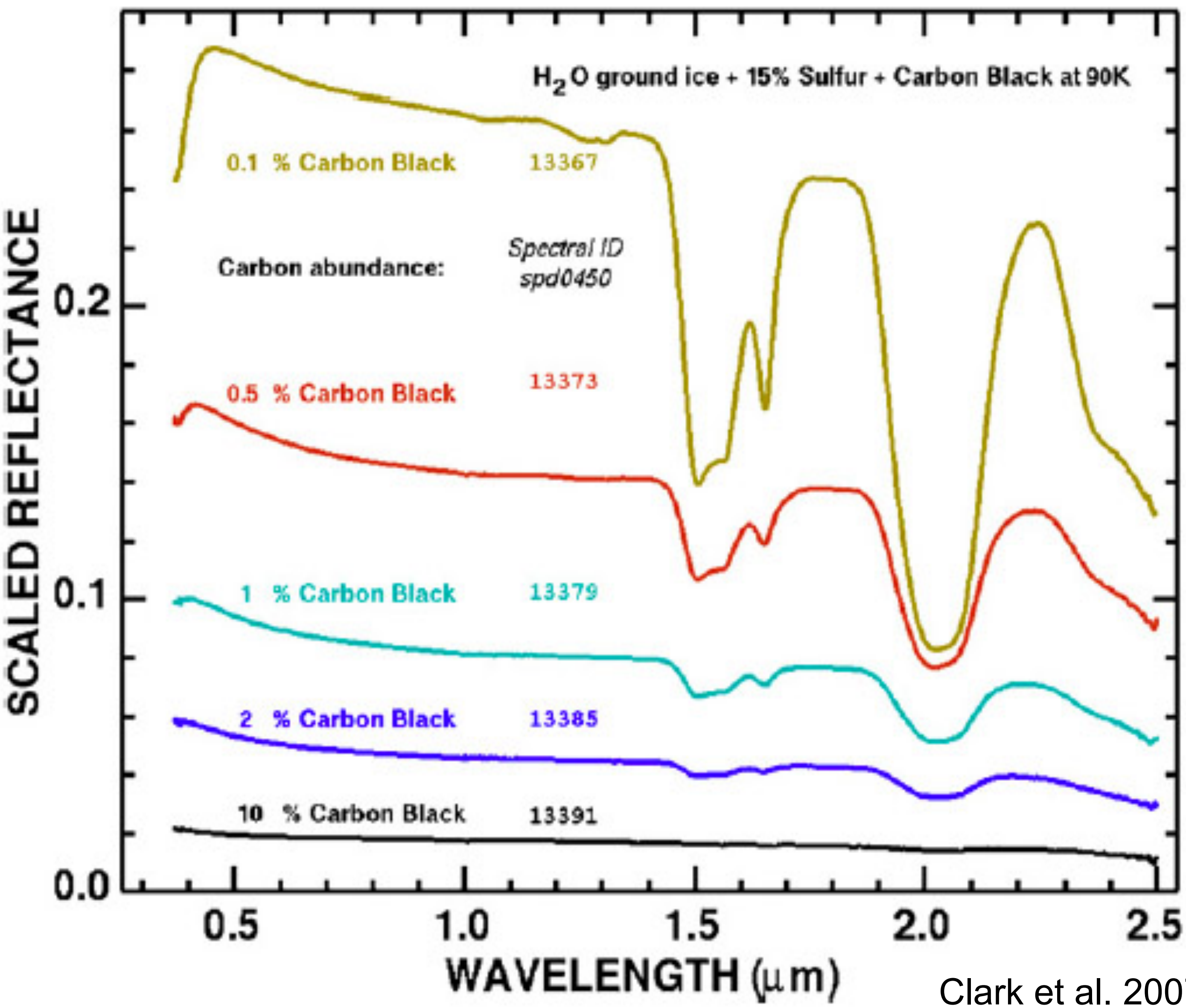
Phase angle ~ 63°



Phase angle ~ 41°

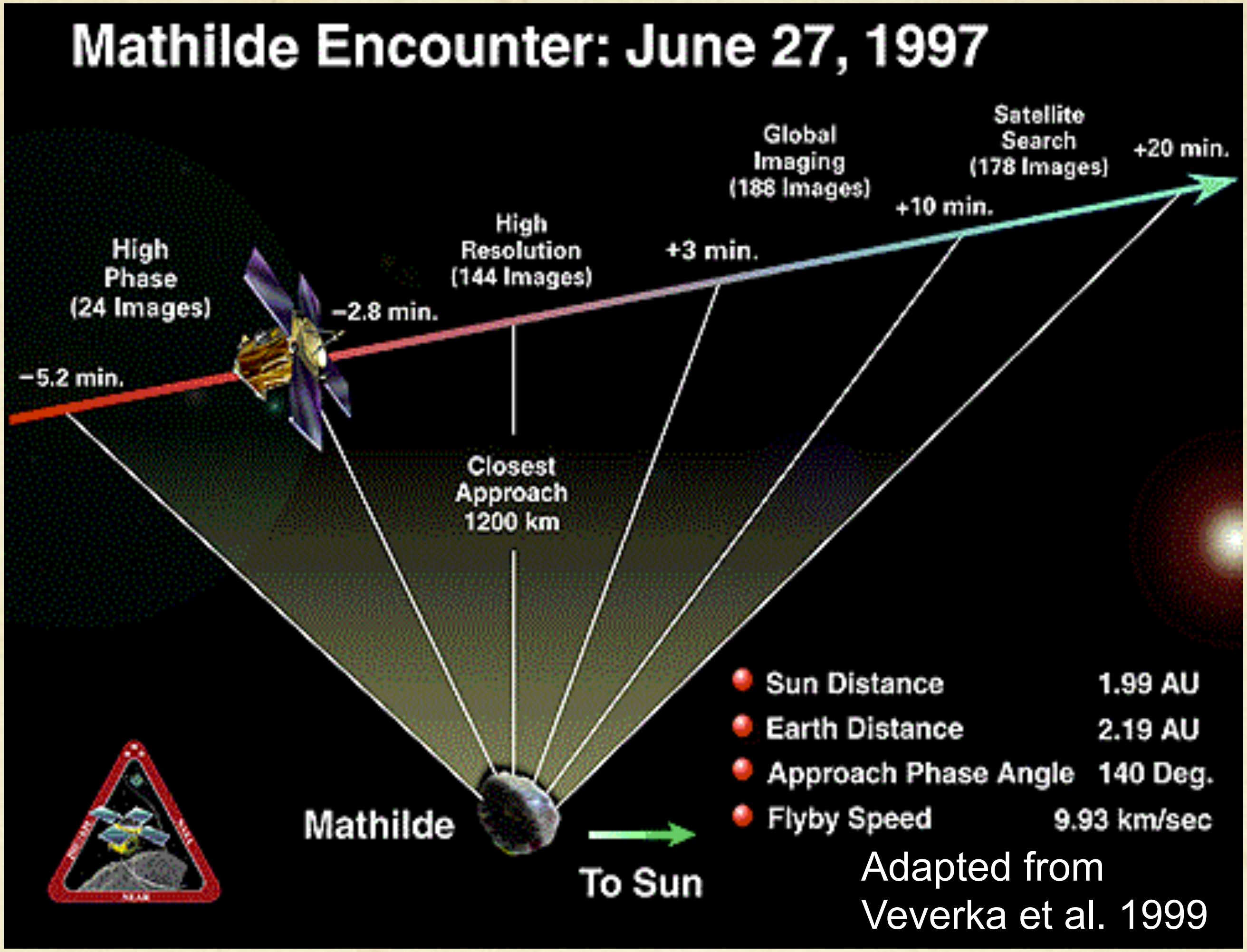
...to about the same as the difference between CRISM and OMEGA spectra of the same part of Phobos, due to calibration uncertainties, making ID challenging

Strong Absorptions in Ice are Harder to Obscure



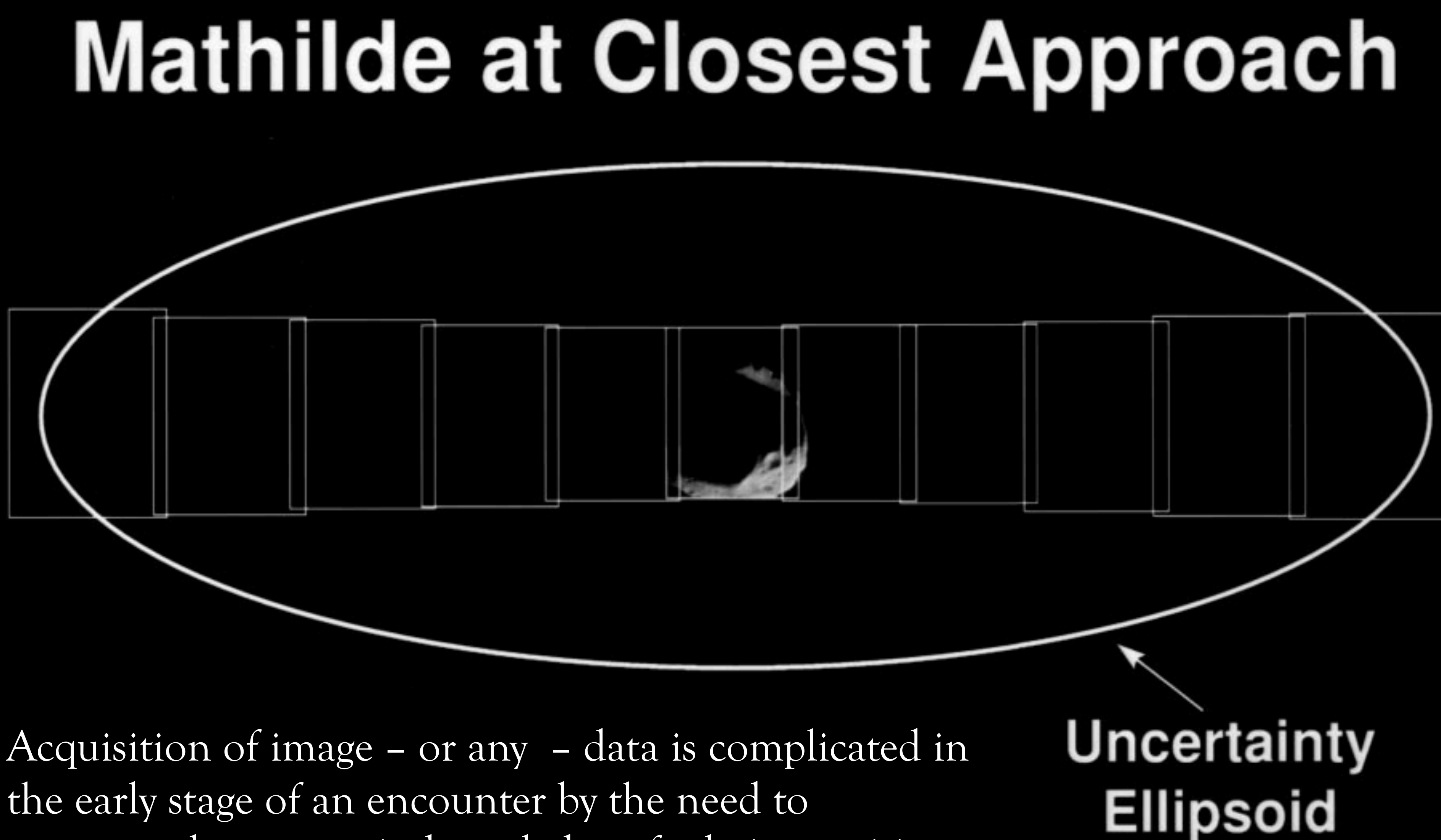
Clark et al. 2007

NEAR at Mathilde – Timeline



- This was the first (and only) encounter with a C-type asteroid.
- At a 10 km/s, the target miss distance was 1200 km to enable spacecraft slewing to track Mathilde with a fixed camera. This limited resolution of smaller features to ~200 m/pixel due to NEAR having only a <u>medium-angle camera</u> (for coverage at Eros)

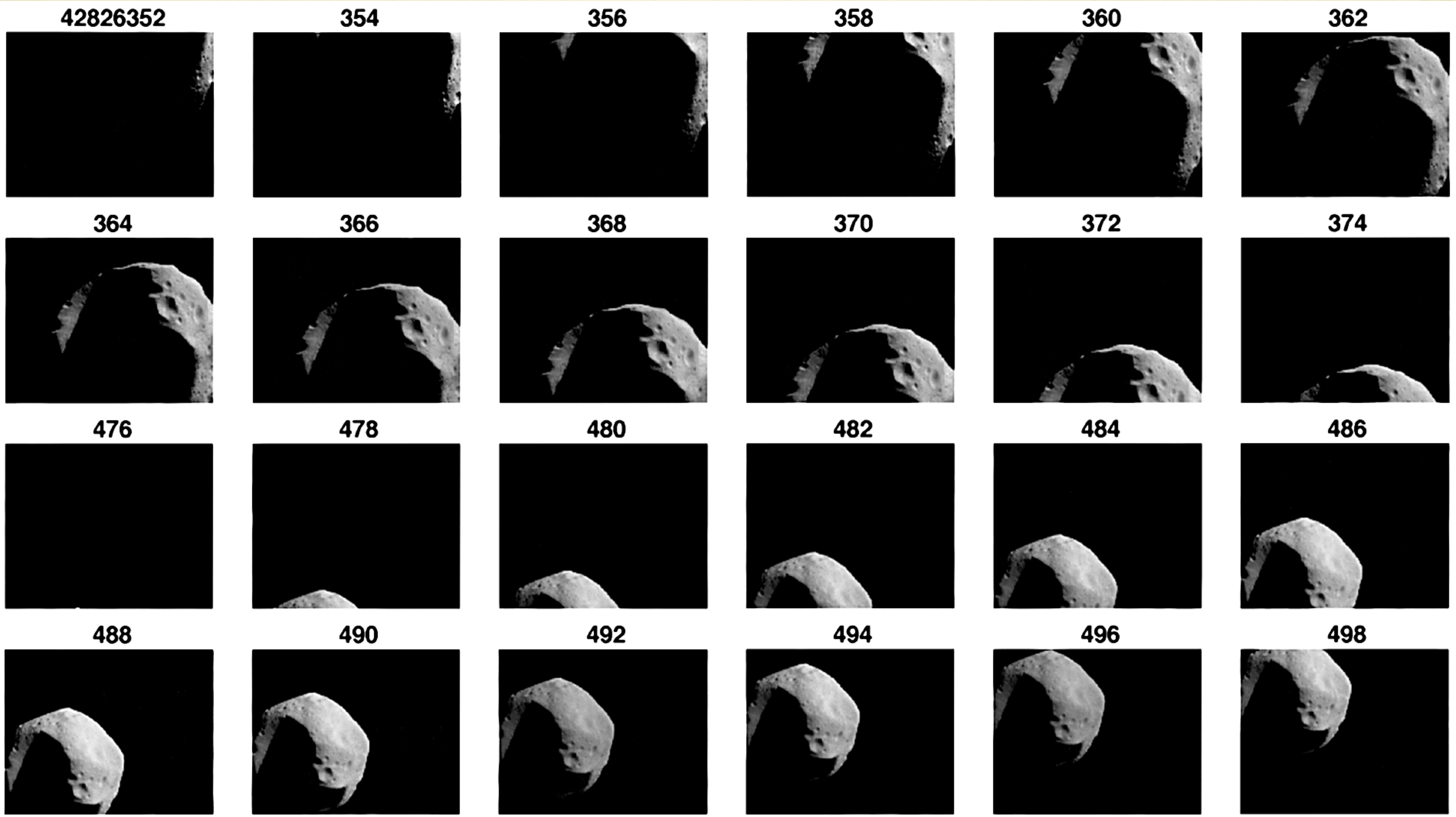
Covering the Uncertainty Ellipse



Acquisition of image – or any – data is complicated in the early stage of an encounter by the need to accommodate errors in knowledge of relative position. In a flyby a large uncertainty ellipse has to be measured.

Adapted from Veverka et al. 1999

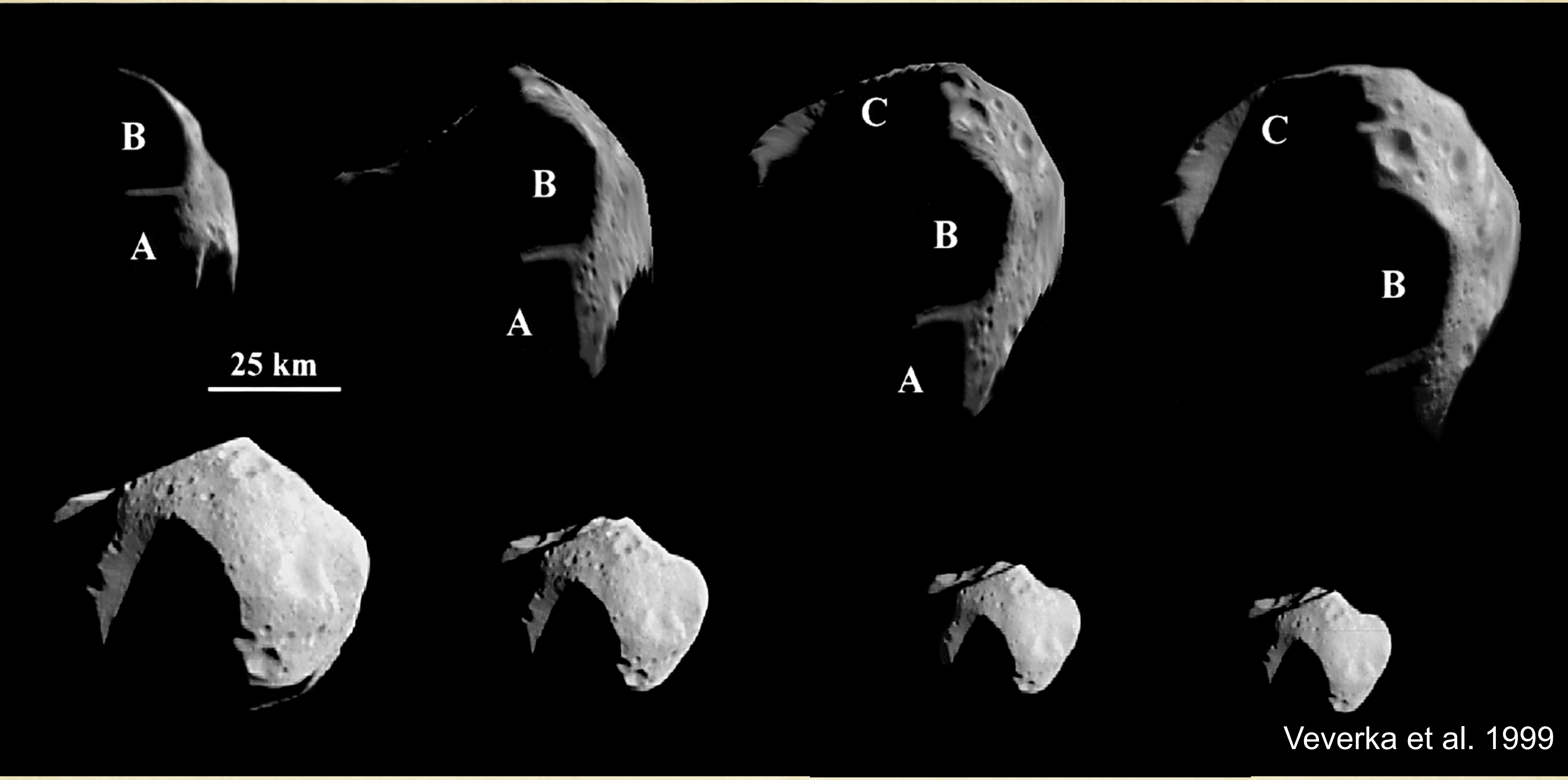
Covering the Uncertainty Ellipse



Veverka et al. 1999

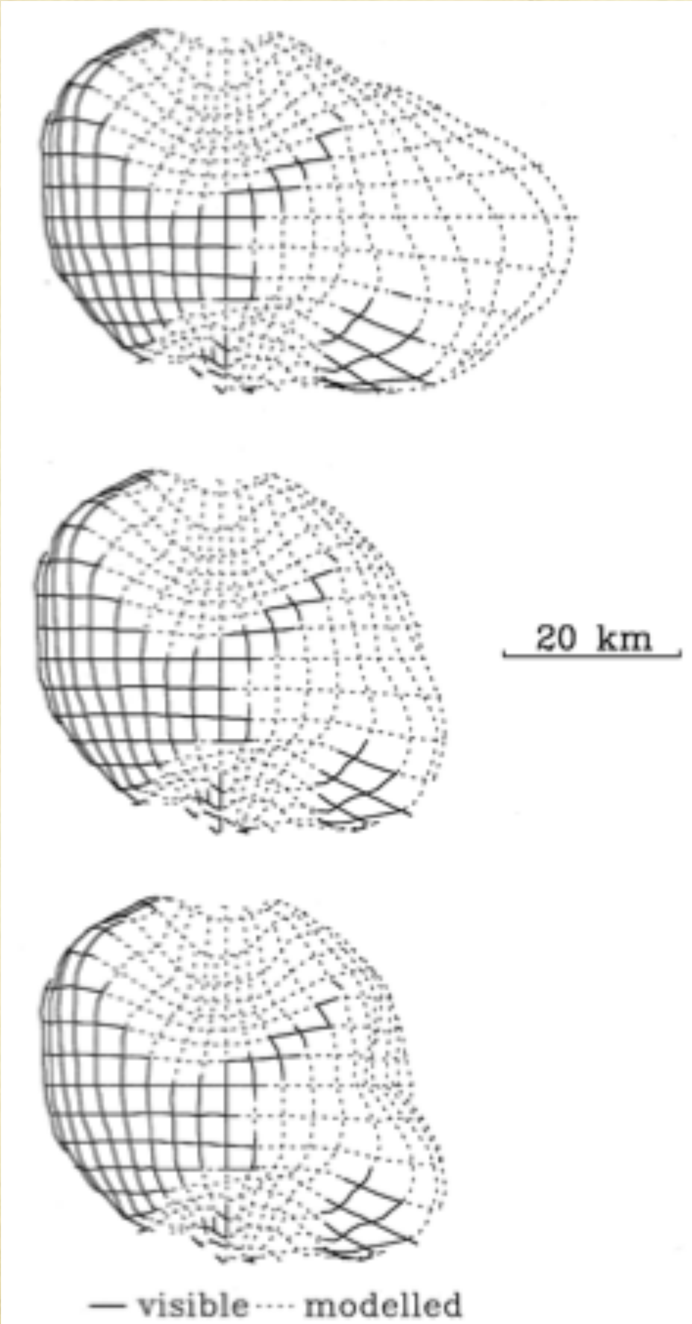
You get a few good views for morphology, but time-intensive color/spectral observations tend to be few and/or distant

Mathilde Montage: Views Limited by Sequencing



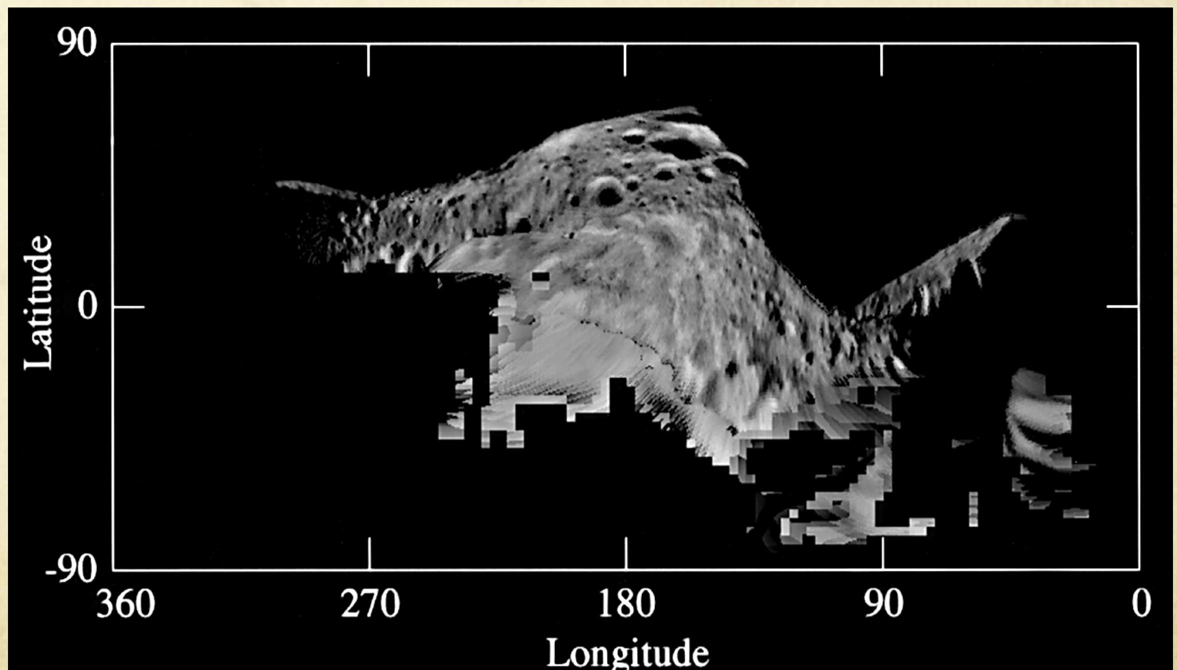
- Furthermore the shape proved complicated and large areas were in shadow

Shape, Density, Coverage

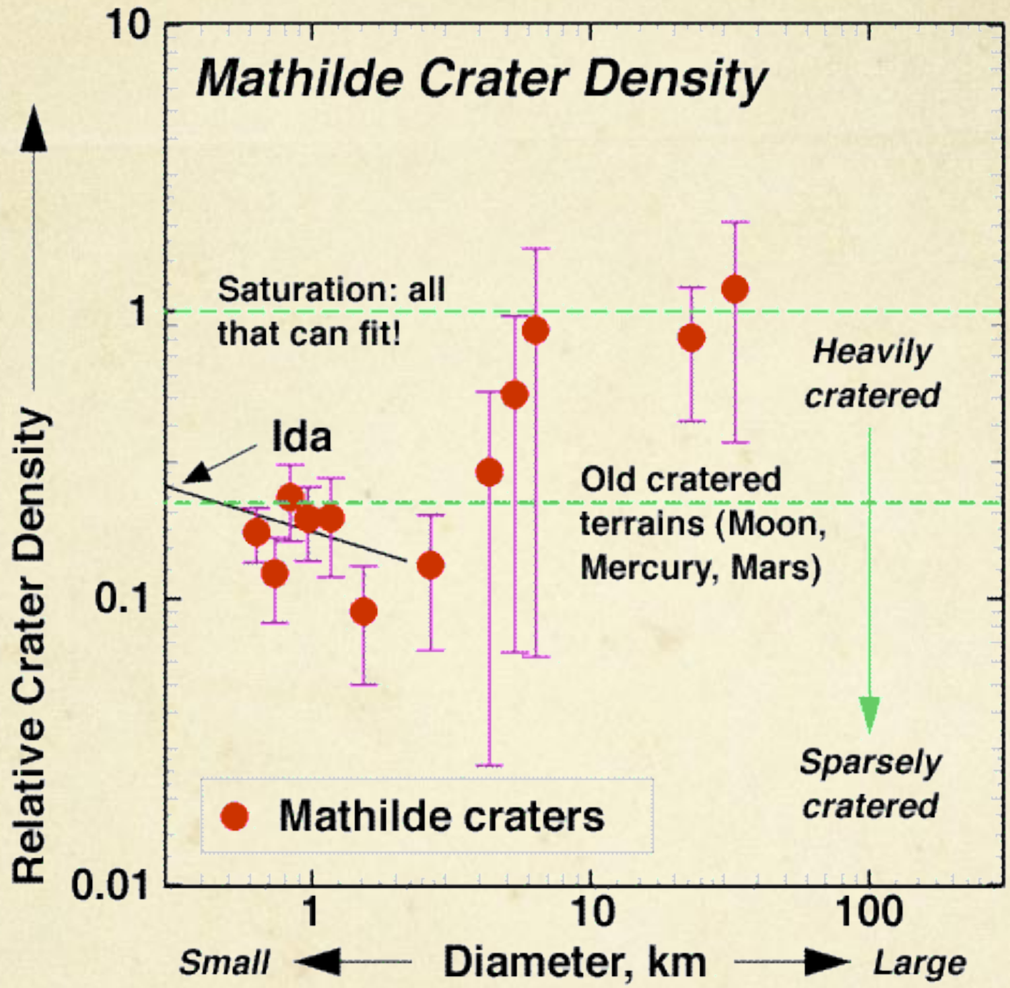


Thomas et al. 1999

- Best estimate 66 x 48 x 46 km
- Mathilde's long rotation period of 17.4 dys exposed little of the surface to imaging over the few-hour encounter
- The limited coverage of the surface left a great deal of uncertainty in shape
- Mass was measured to 3% by RS but the volume uncertainty translated to a density with a large uncertainty 1300±200 kg/m^3



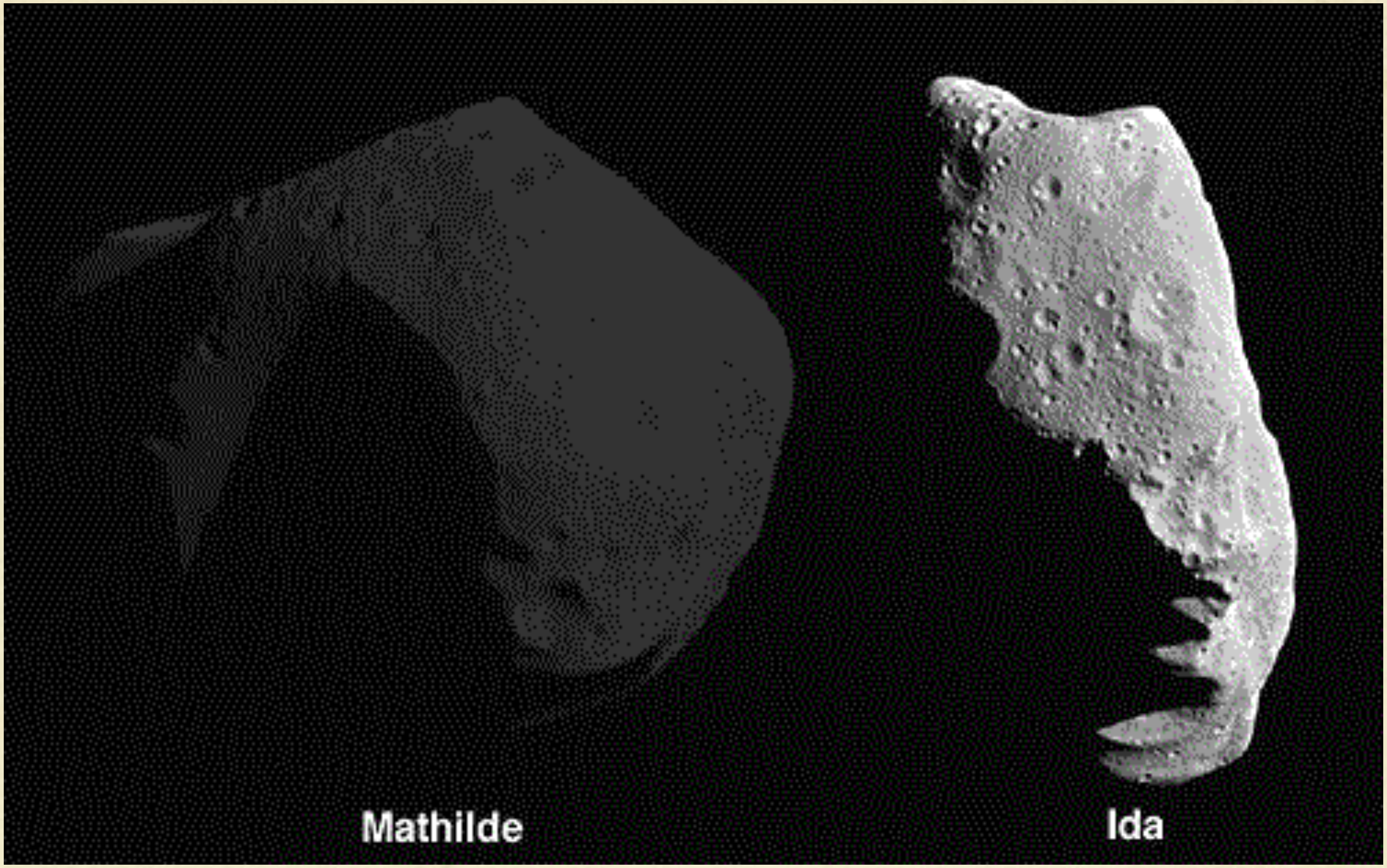
Mathilde is as Cratered as Possible



Adapted from Veverka et al. 1999

- Higher density of craters than "empirical saturation" in major-planet cratered terrains
- "Geometric saturation" – all that can fit
- Mathilde's not being shattered may be a consequence of low density / rubble pile / compressibility

Mathilde is Very Dark

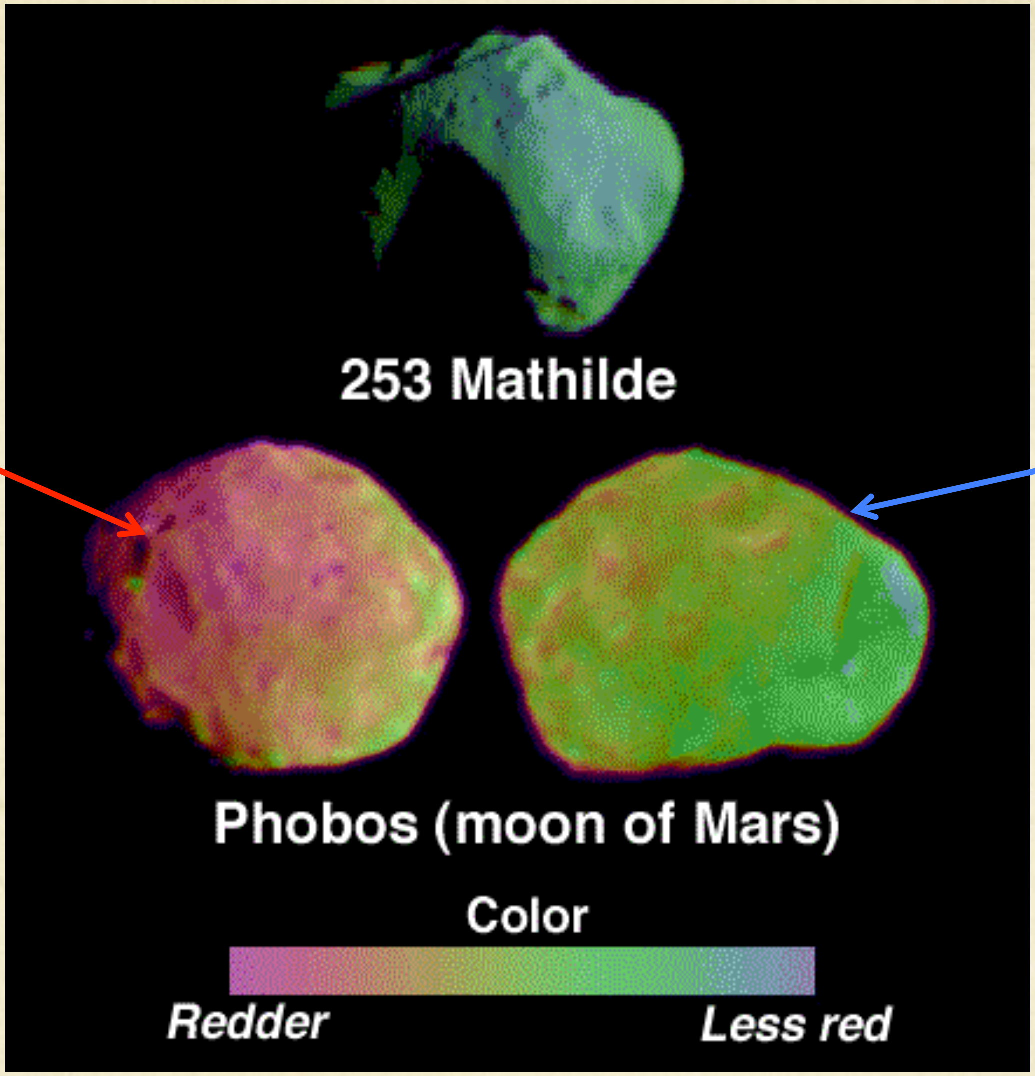


near.jhuapl.edu

- Albedo estimated to be 3.8%
- It is shown here with the correct brightness relative to Ida

Mathilde is Spectrally Bland

Redder unit

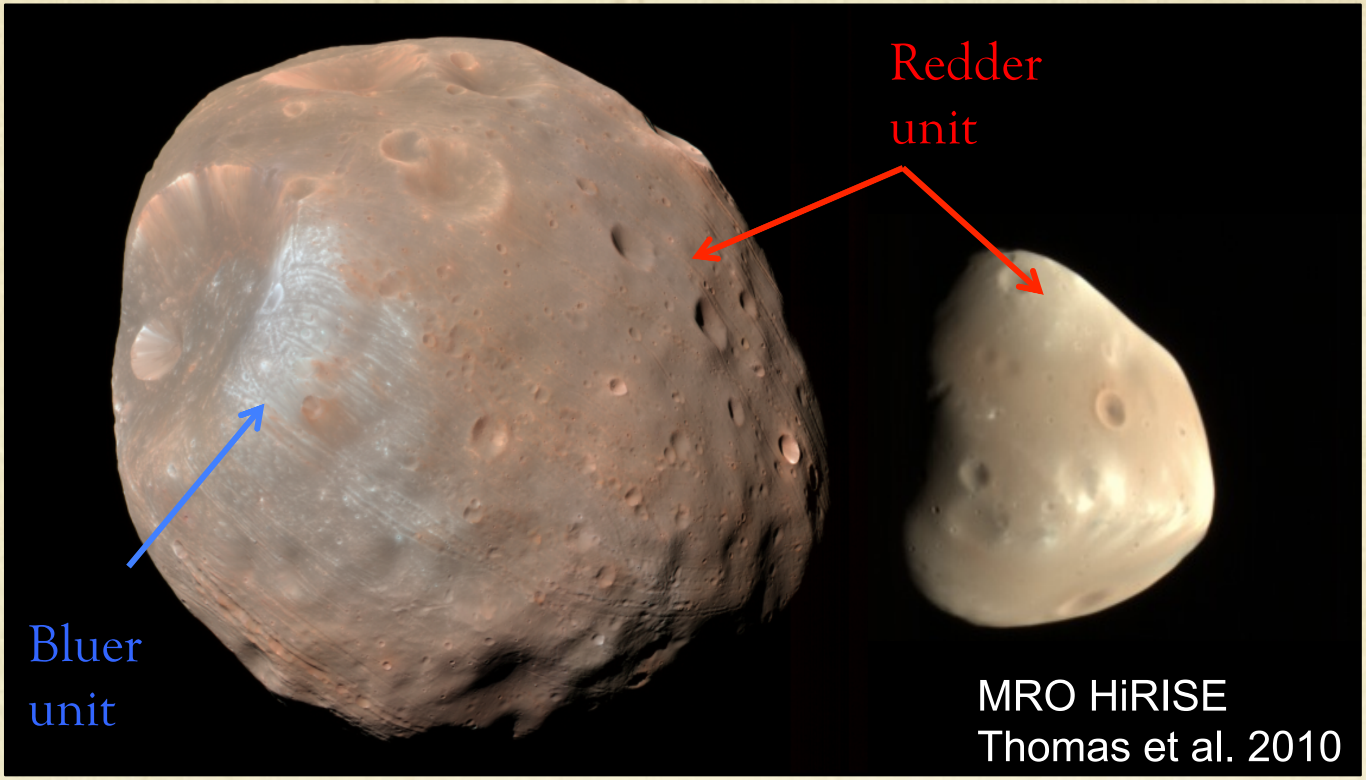


Bluer unit

near.jhuapl.edu

- Previously to NEAR's Mathilde encounter, the only other good color/spectral image coverage of a primitive small body was of Phobos by Phobos 2
- In comparison, Mathilde is an order of magnitude blander.
- FYI – Mathilde is type C, Phobos is type D

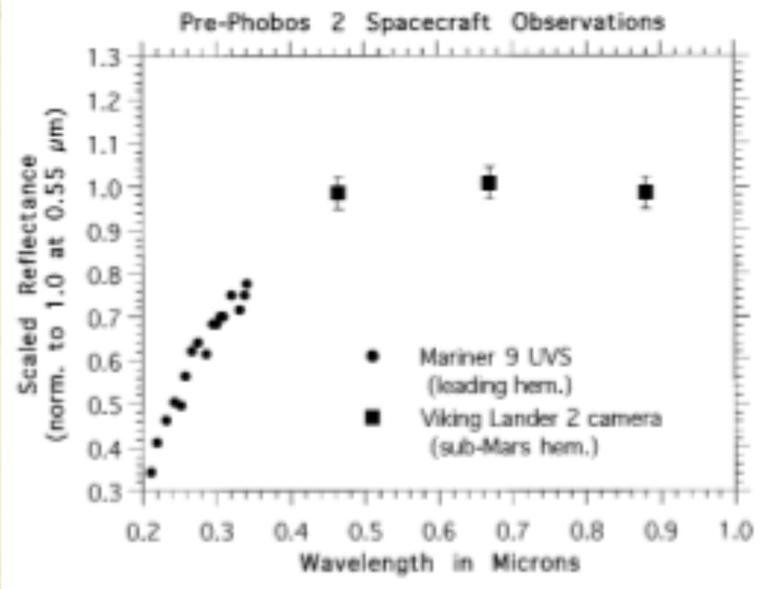
Phobos and Deimos



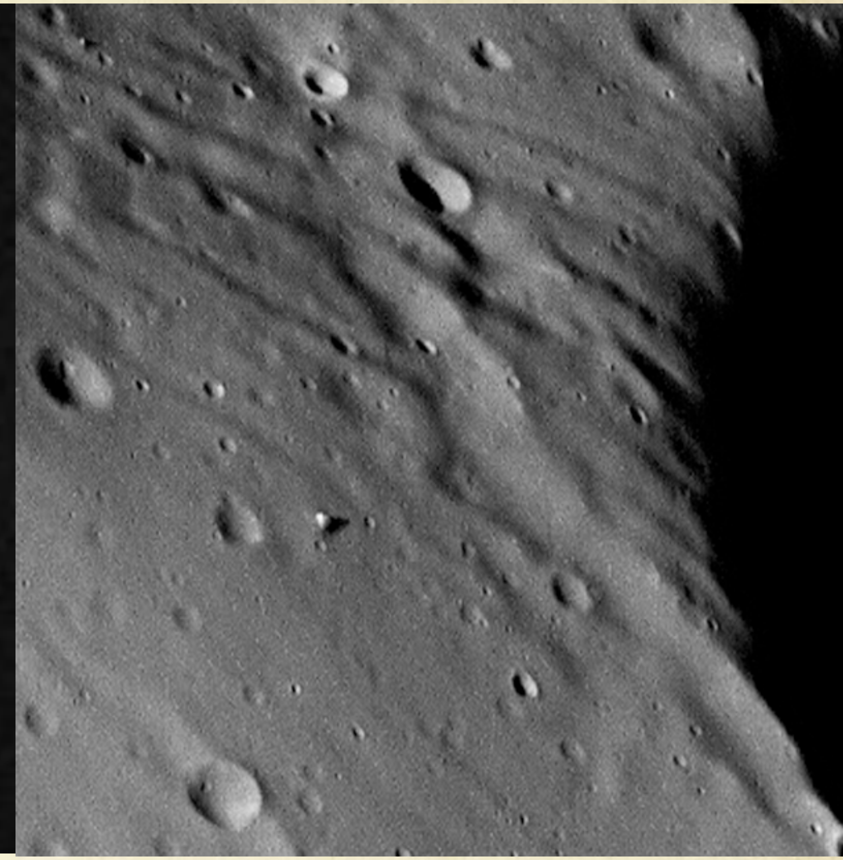
- Mars' moons Phobos and Deimos are small, irregularly shaped, low-density bodies with low albedo and spectra characteristic of D-type bodies
- Two main formation hypotheses predict distinct compositions:
  - Capture of primitive solar system body → primitive, carbon- and maybe volatile-bearing composition; depending on model, may be dominated by phyllosilicates
  - Co-accretion with Mars or by impact → similar to Mars (co-accretion) or dominantly Martian crustal and upper mantle (impact)

Phobos and Deimos – What When

- Mariner 9 (P,D)
  - Shape and general geology from distant images
- Viking (P,D)
  - Most of the imaging coverage to date
  - Major "gap" was west of Stickney
  - In hindsight, spectral measurements leading to a C-type classification were in error
- Phobos 2 (P)
  - First good color images
  - First UV-NIR disk-resolved spectra
- MGS (P)
  - TES thermal IR spectra
  - High-res images from MOC – much like Viking
- Mars Express (P)
  - HRSC images fill the Stickney gap
  - OMEGA and PFS spectra
  - Best mass/density
- MRO (P,D)
  - HiRISE color
  - CRISM spectra

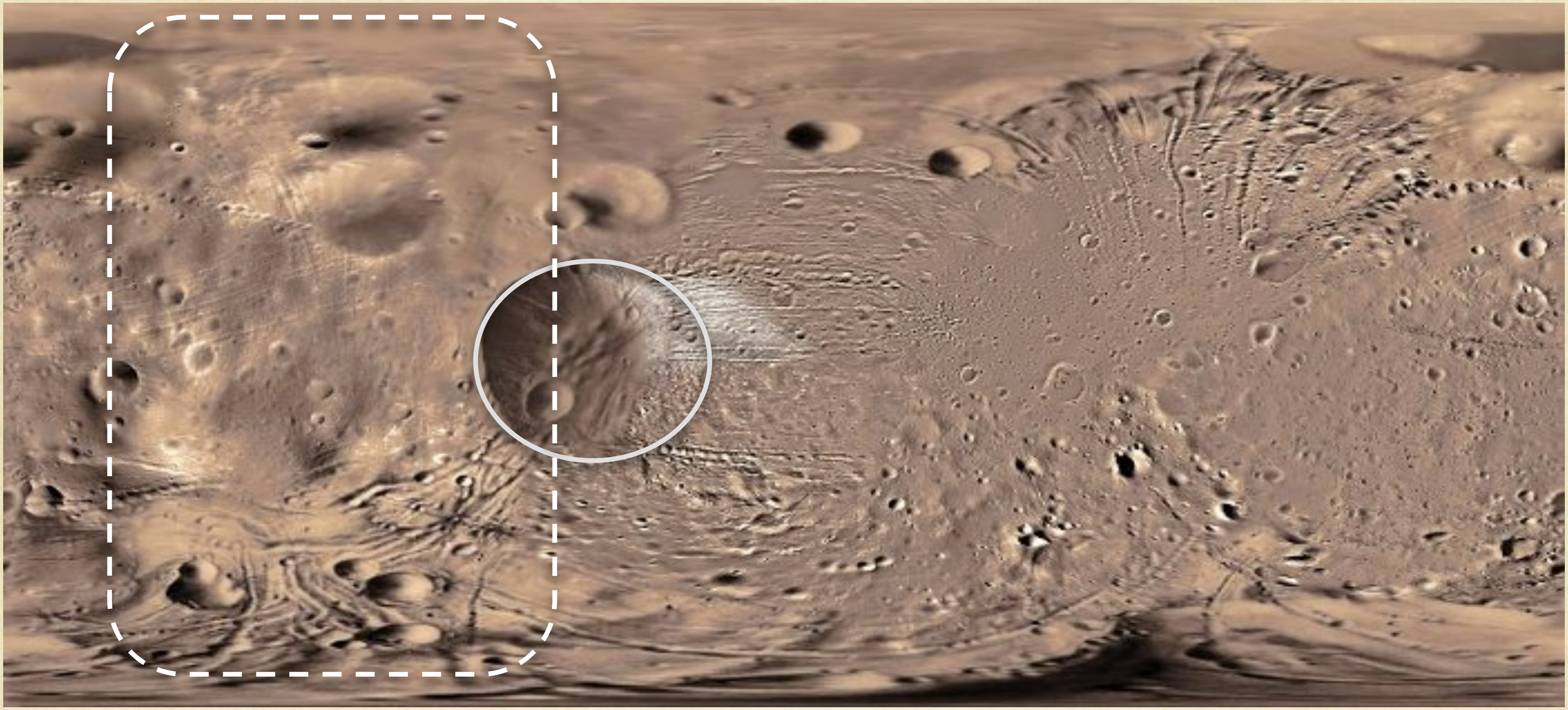


Phobos Overview



- 27 x 22 x 19 km
- Density 1.88±0.02 (Jacobsen 2010)
- ~6% albedo
- 9-km Stickney
- Globally distributed grooves – many hypotheses, controversial

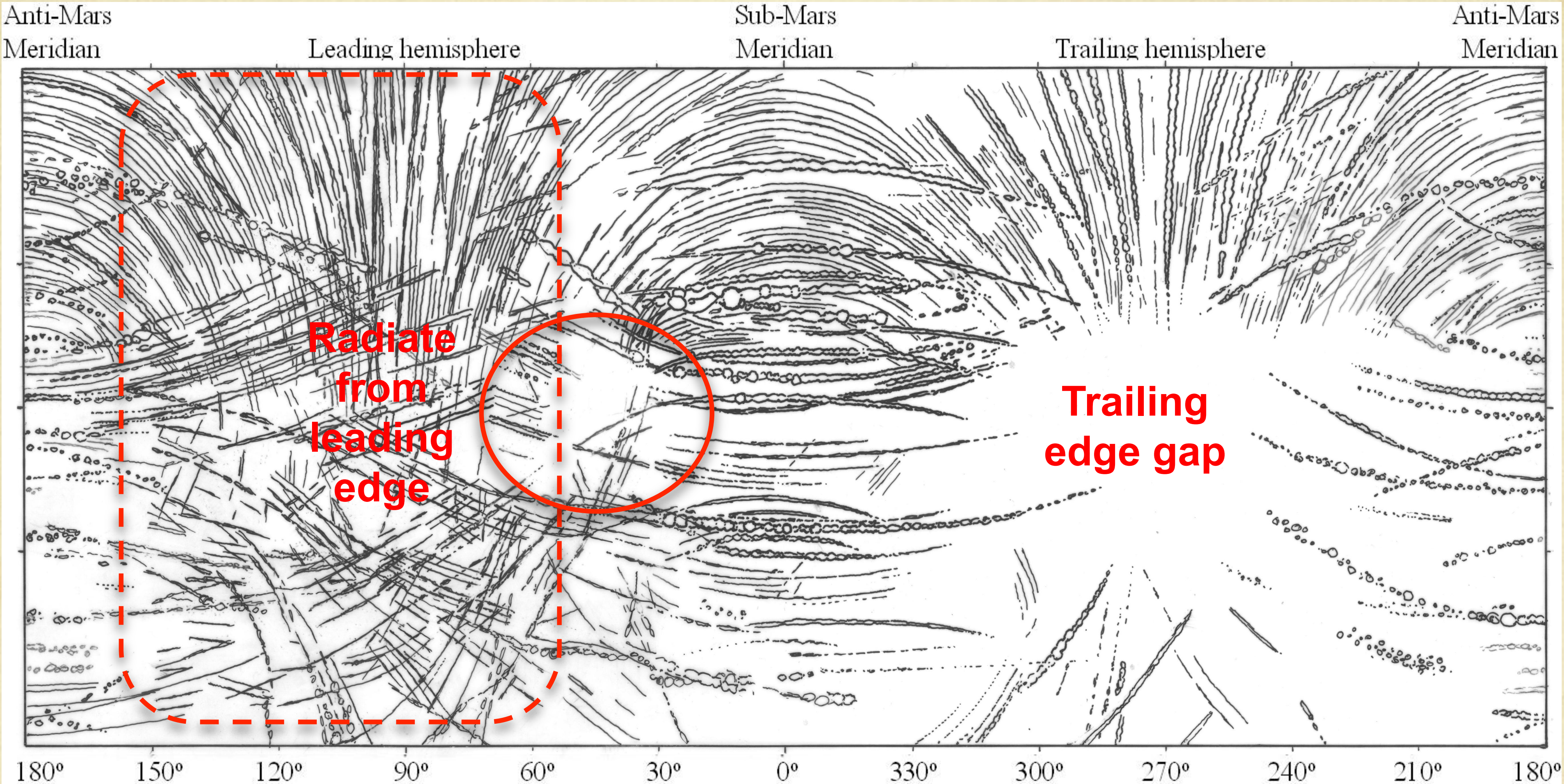
Phobos Global Mosaic - Grooves



Murray et al. 2010

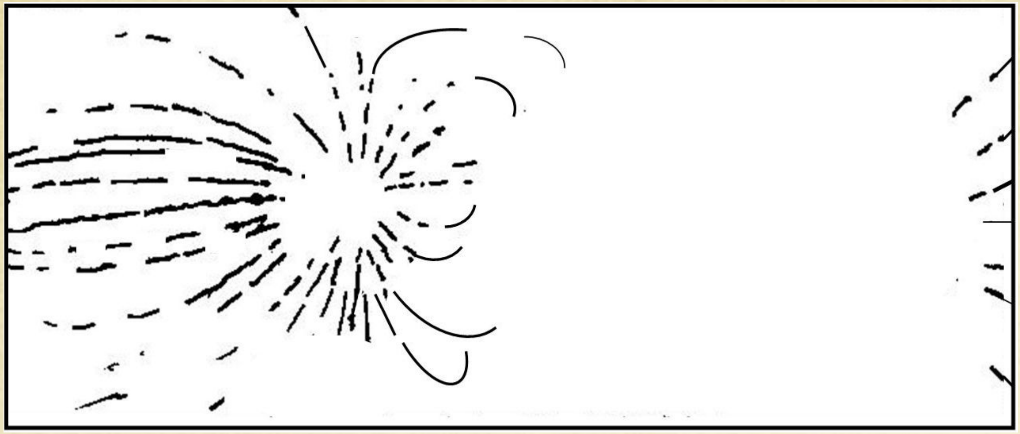
- Viking + HRSC + HiRISE coverage
- Took 30 yrs to build global data set like that needed to rigorously evaluate genetic mechanisms for grooves

Phobos Global Map - Grooves

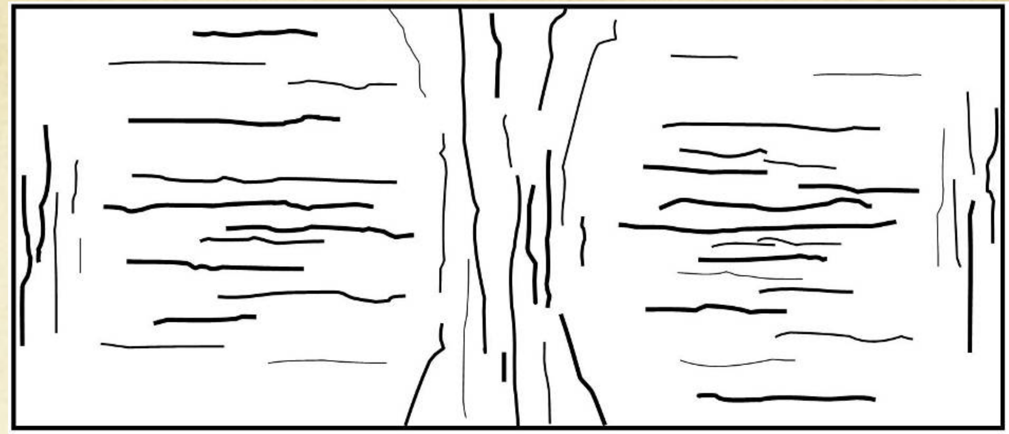


Murray et al. 2010

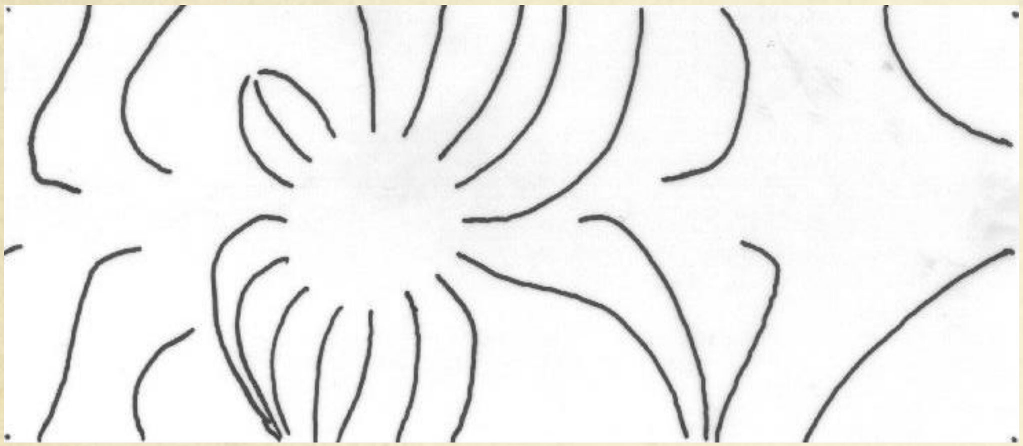
- Grooves were initially though the be arranged around Stickney and genetically related
- New HRSC coverage threw into turmoil ideas that grooves are formed by Stickney



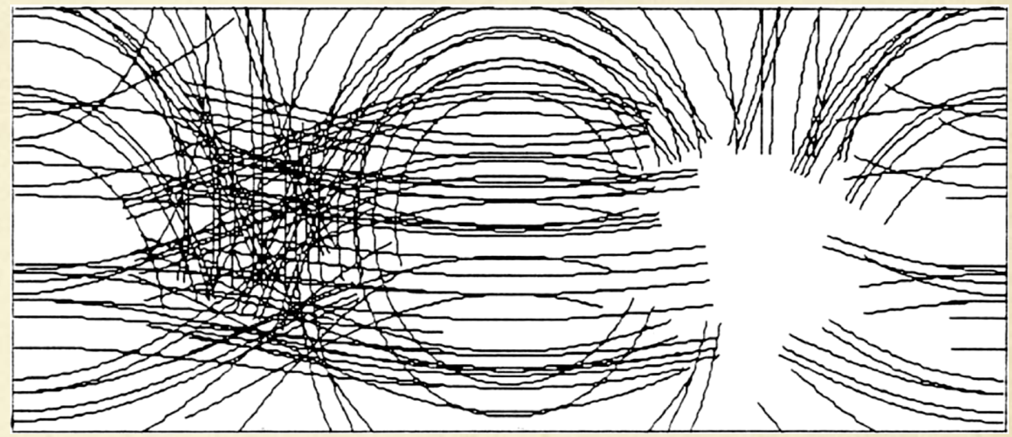
STICKNEY EJECTA (after Thomas 1988)



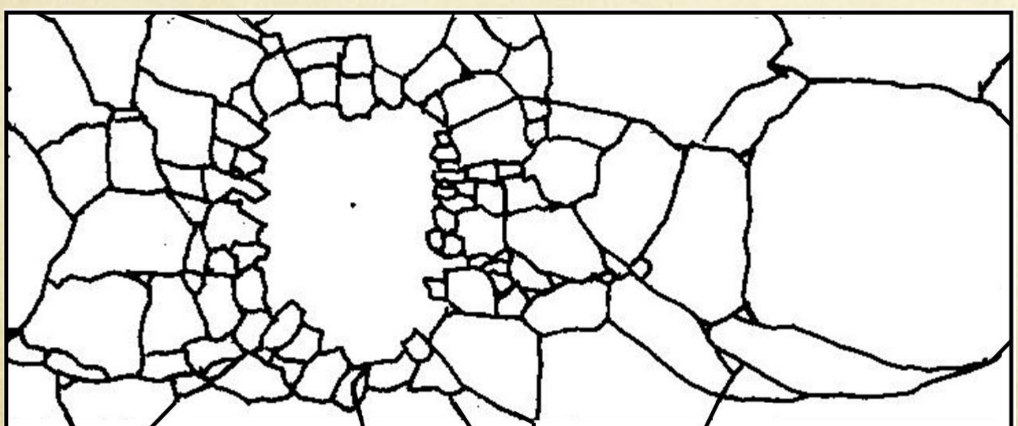
TIDAL STRESS (Dobrovolskis 1982)



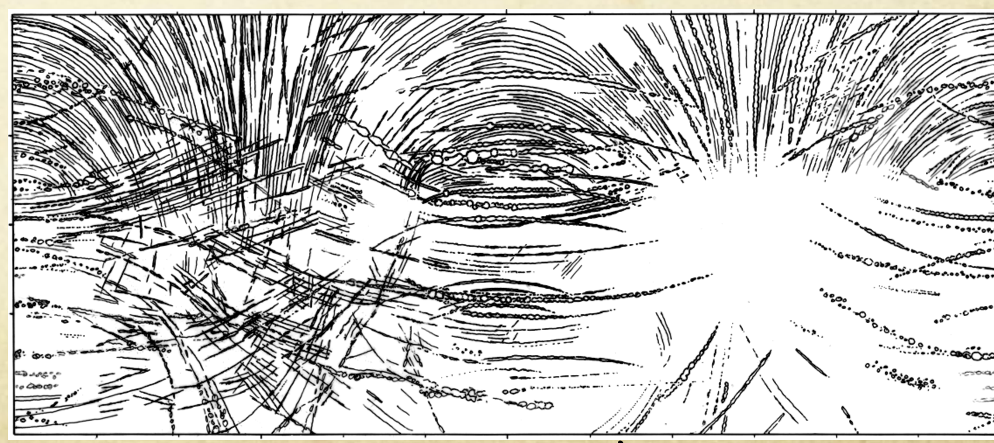
STICKNEY ROLLING BOULDERS (Head & Wilson)



SECONDARY IMPACTS FROM MARS (Murray 1994)

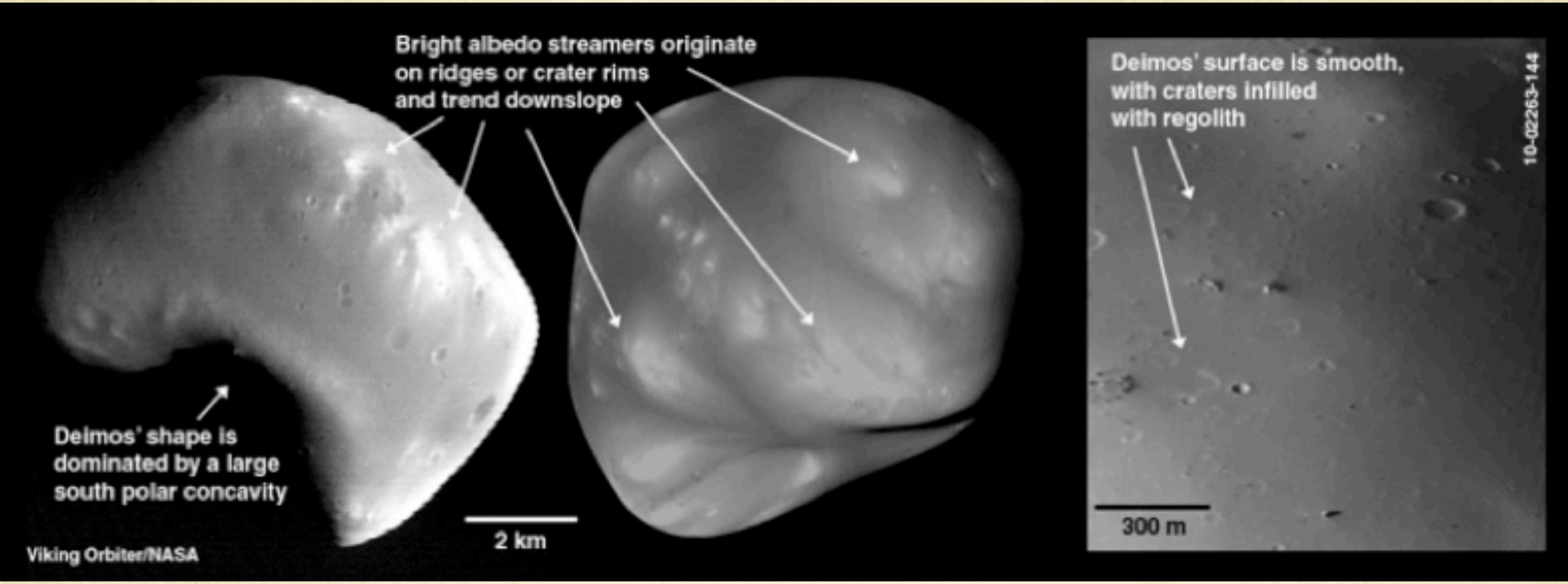


STICKNEY FRACTURING (Fujiwara & Asada 1983)



MAP OF PHOBOS' GROOVES

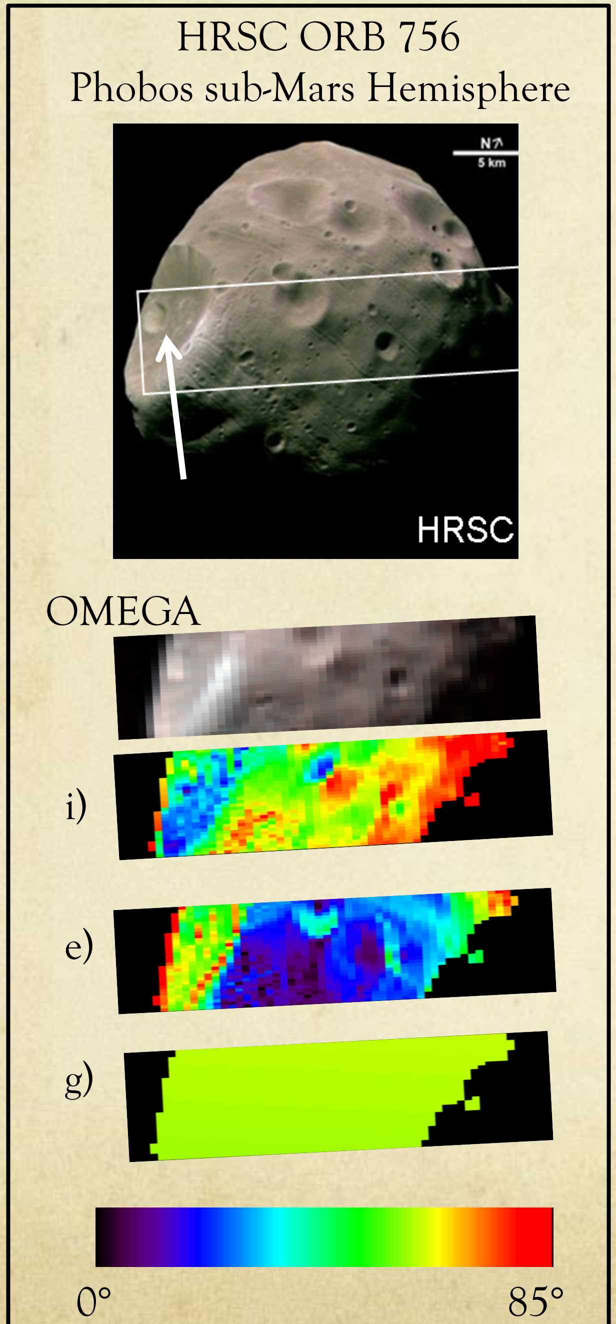
Deimos Overview

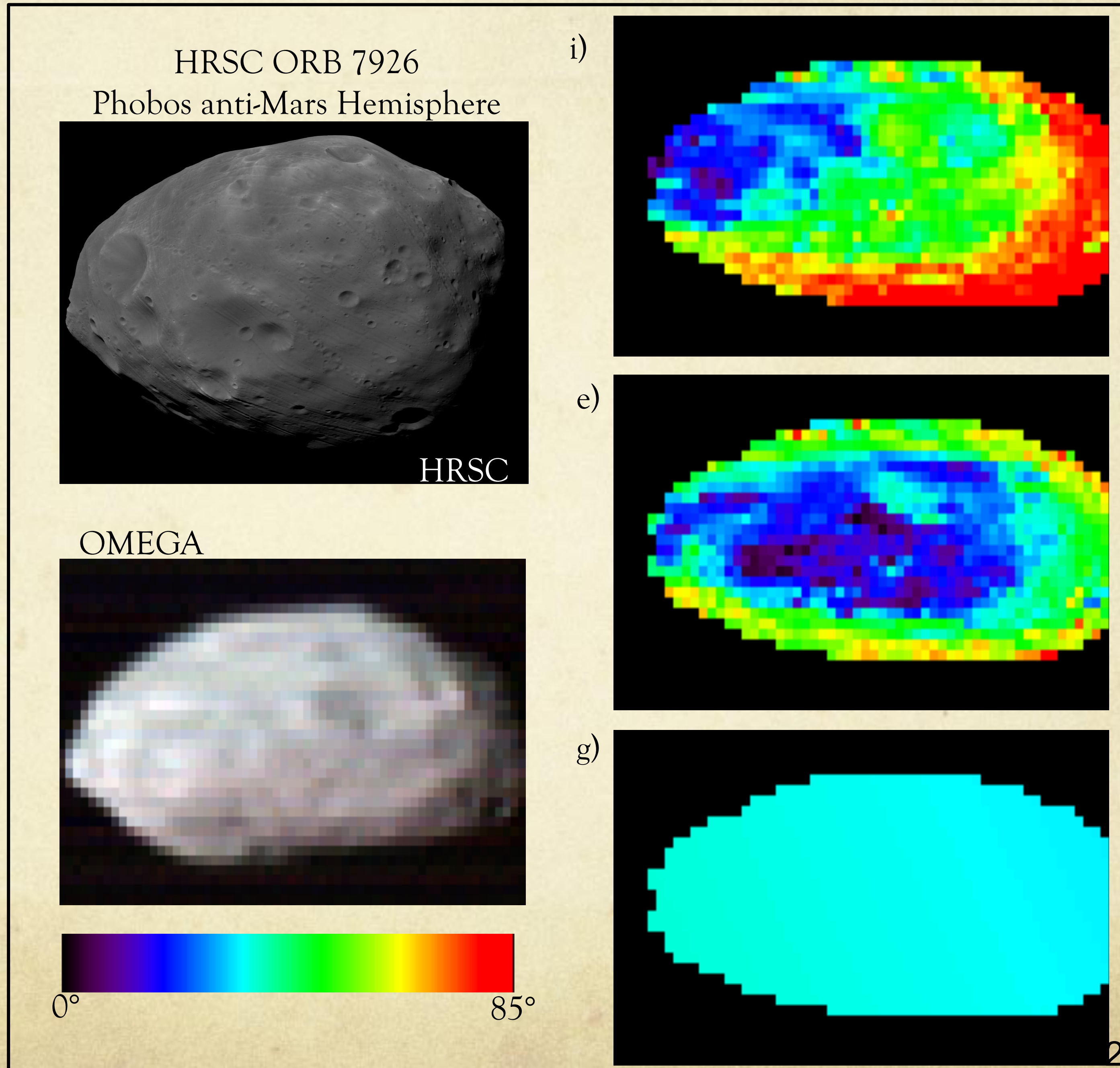


- 15 x 12 x 10 km
- Still have poor image coverage of anti-Mars hemisphere, lead to volume uncertainty
- Density 1500±200 kg/m^3
- ~6% albedo
- South polar crater / concavity
- No grooves; craters mostly infilled by smooth regolith
- Large albedo features thought to form by mass wasting

OMEGA Phobos Observations

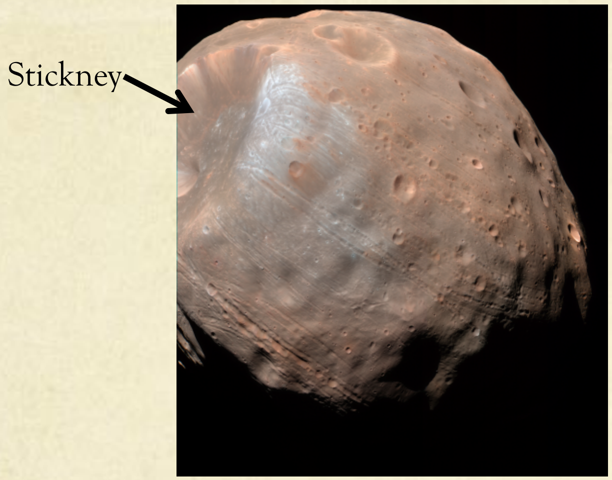
Fraeman et al. 2012



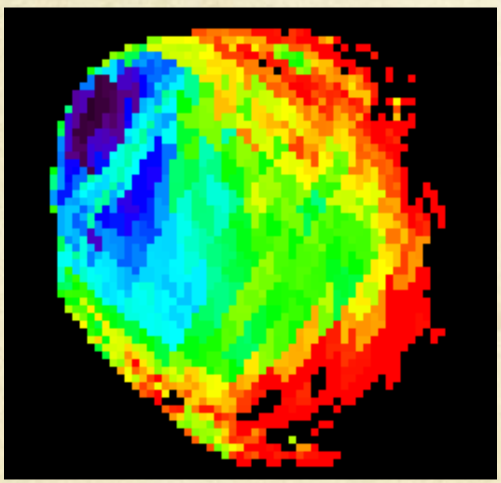


CRISM Phobos Observations

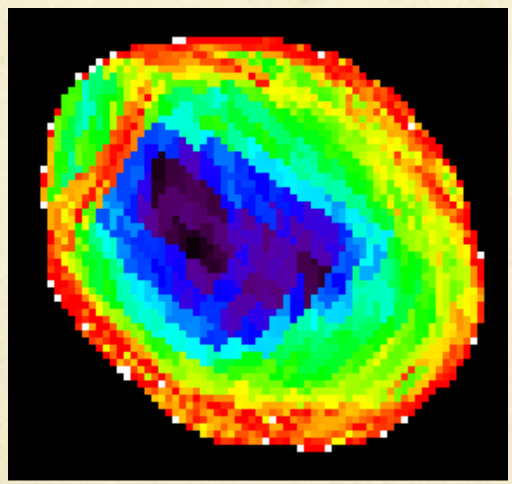
HiRISE
Phobos sub-Mars Hemisphere



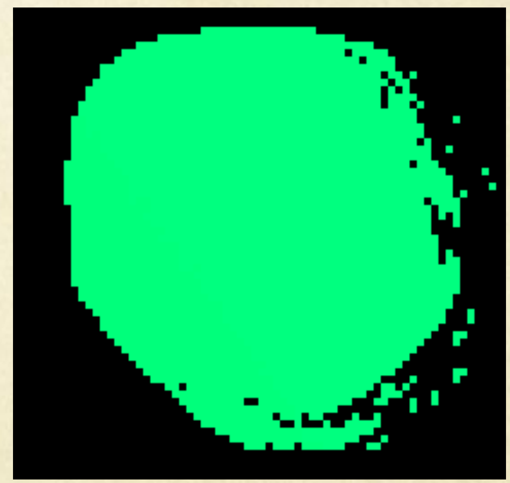
CRISM FRT00002992



Incidence Angle (i)



Emergence angle (e)

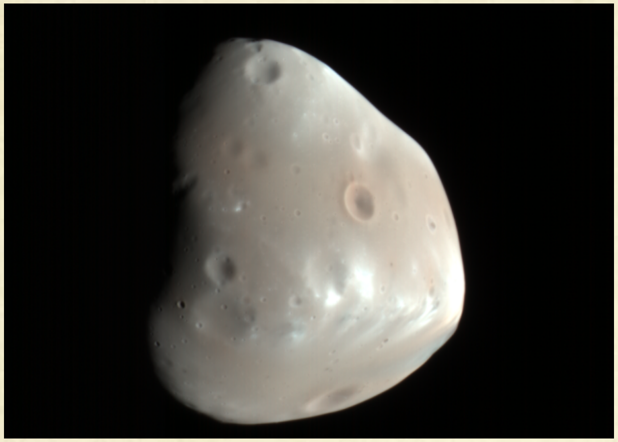


Phase angle (g)

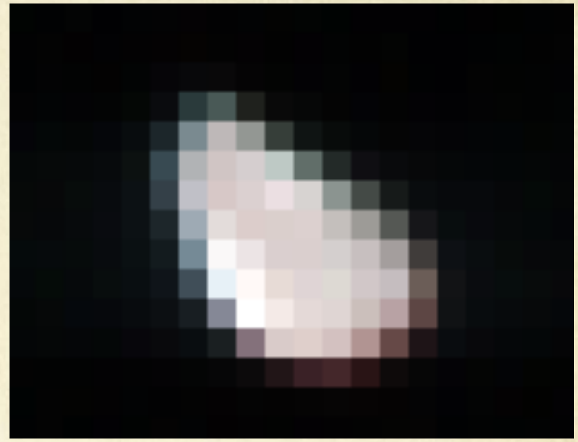
Fraeman et al. 2012

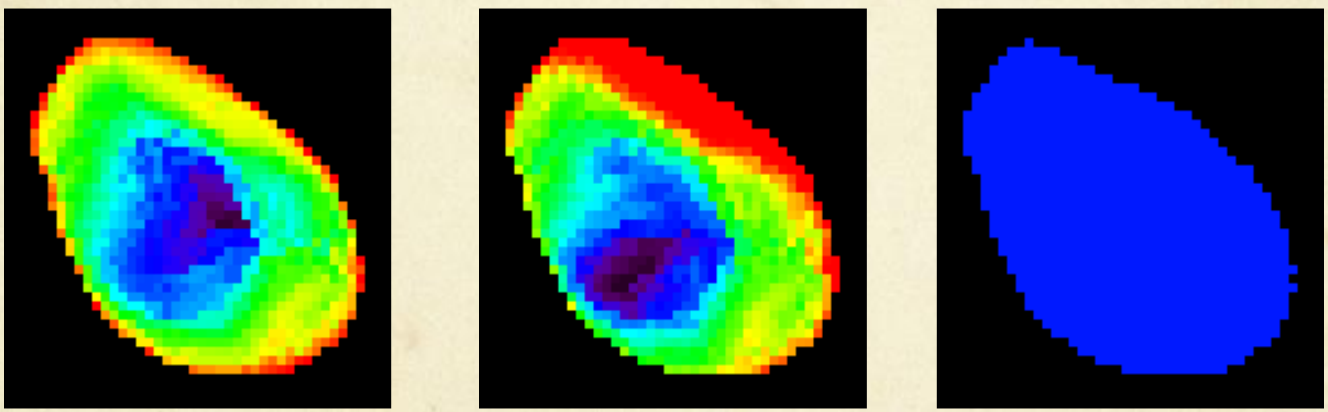
CRISM Deimos Observations

HiRISE Deimos sub-Mars Hemisphere



CRISM FRT00002983

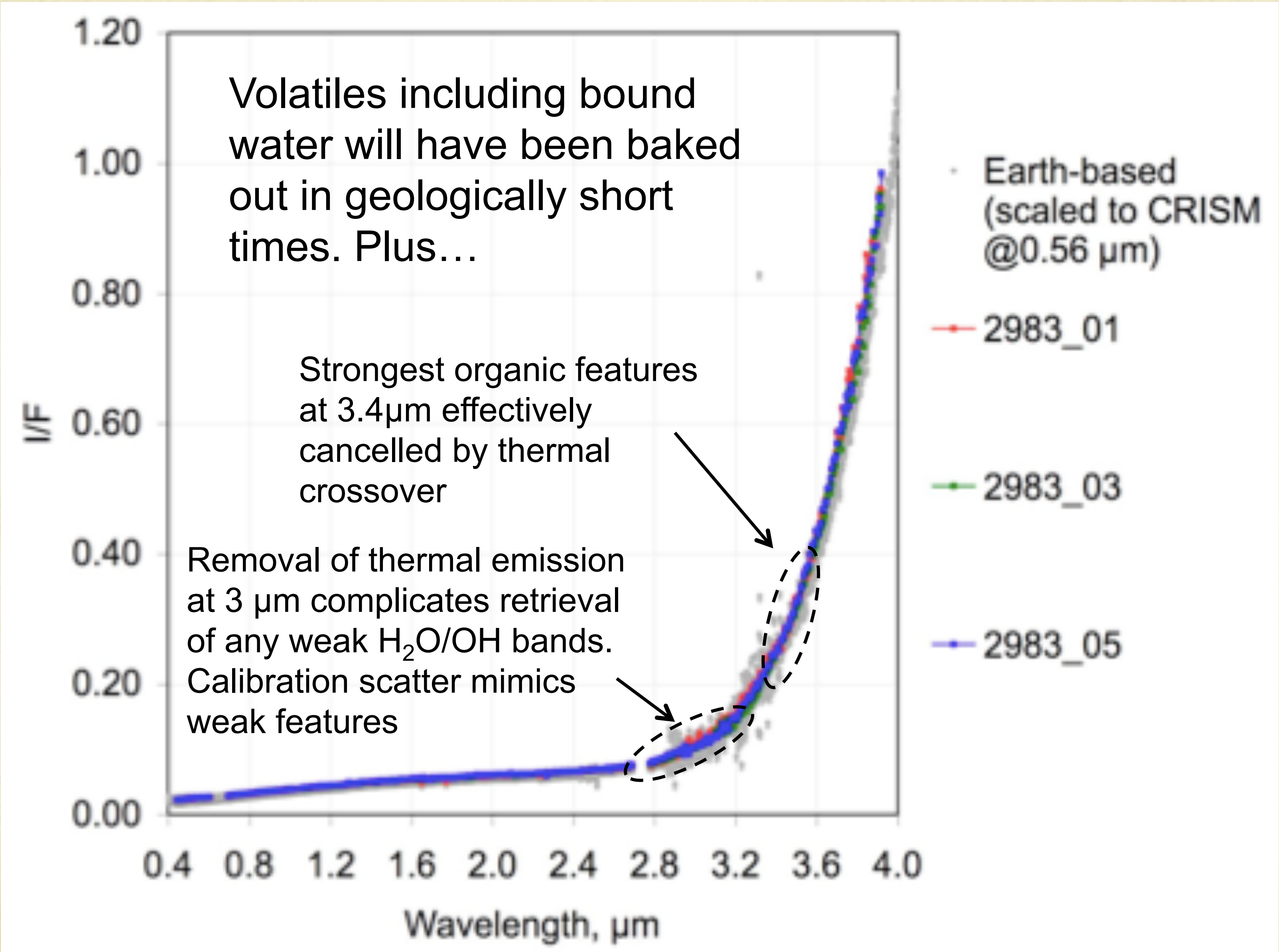




Incidence Angle (i) Emergence angle (e) Phase angle (g)

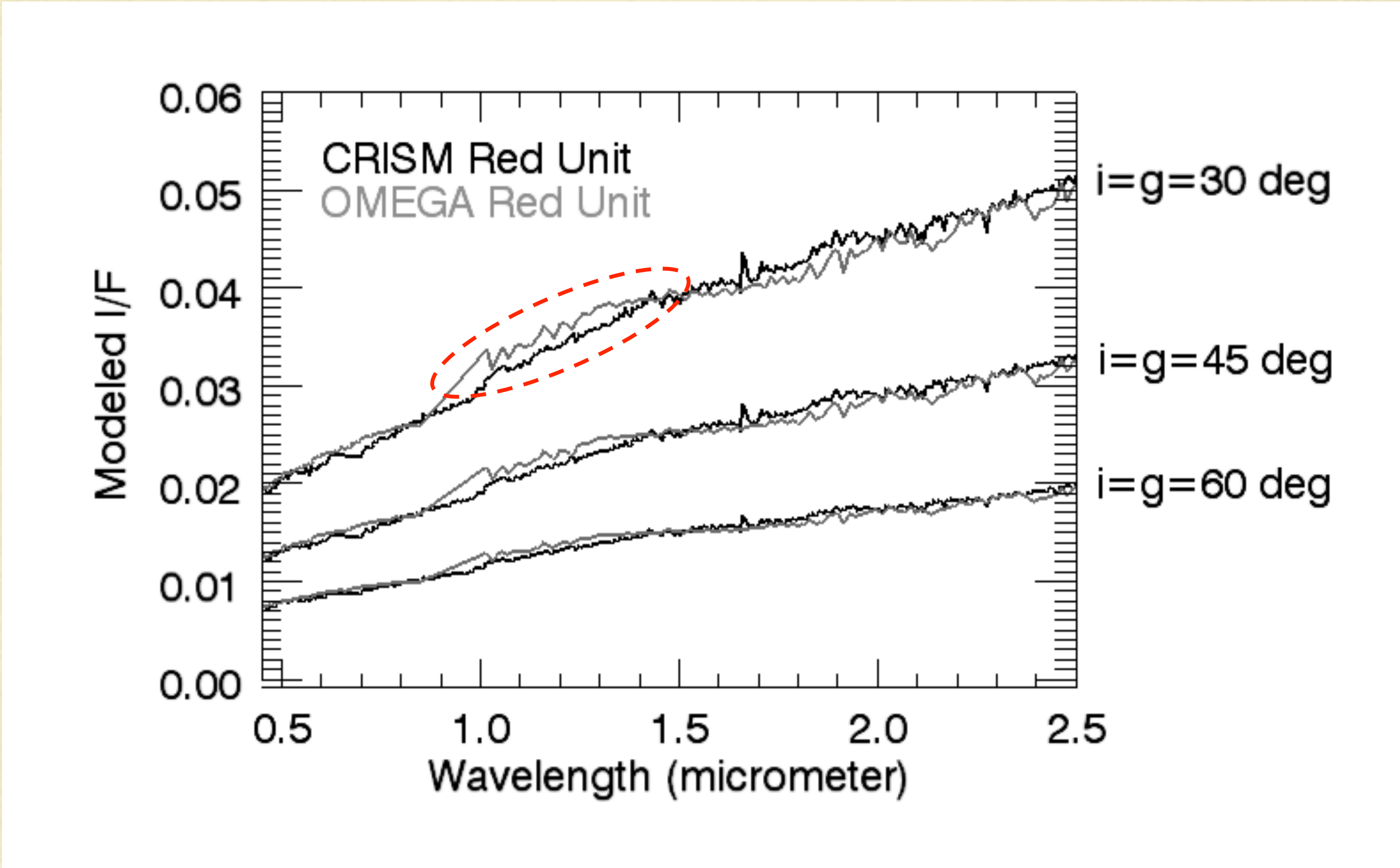
Fraeman et al. 2012

Fundamental Issue from Low Albedo, 290-340K Temperature (Phobos, Deimos, or primitive NEOs)



Murchie et al. 2008

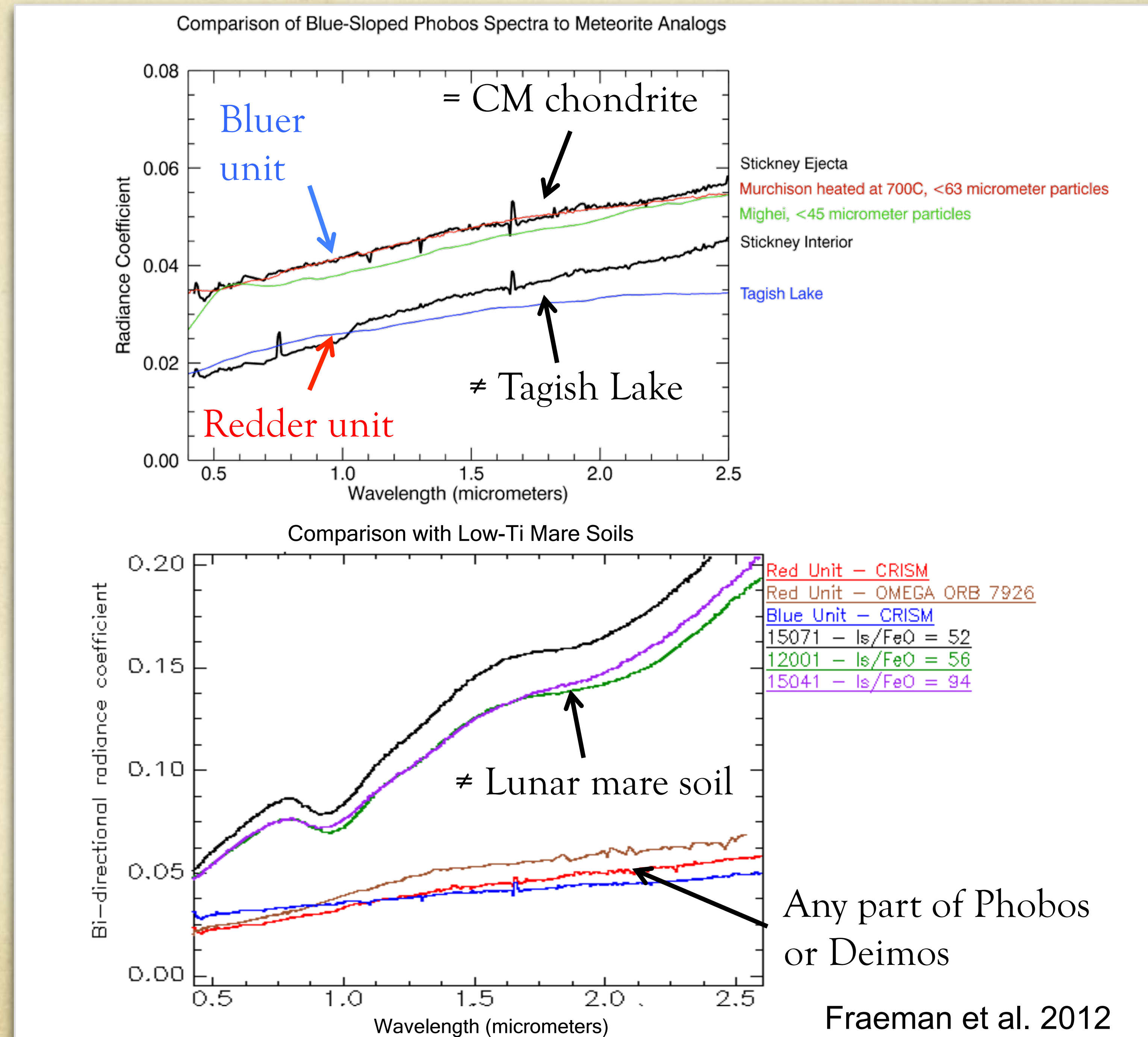
Accurate Photometric Model from OMEGA Data



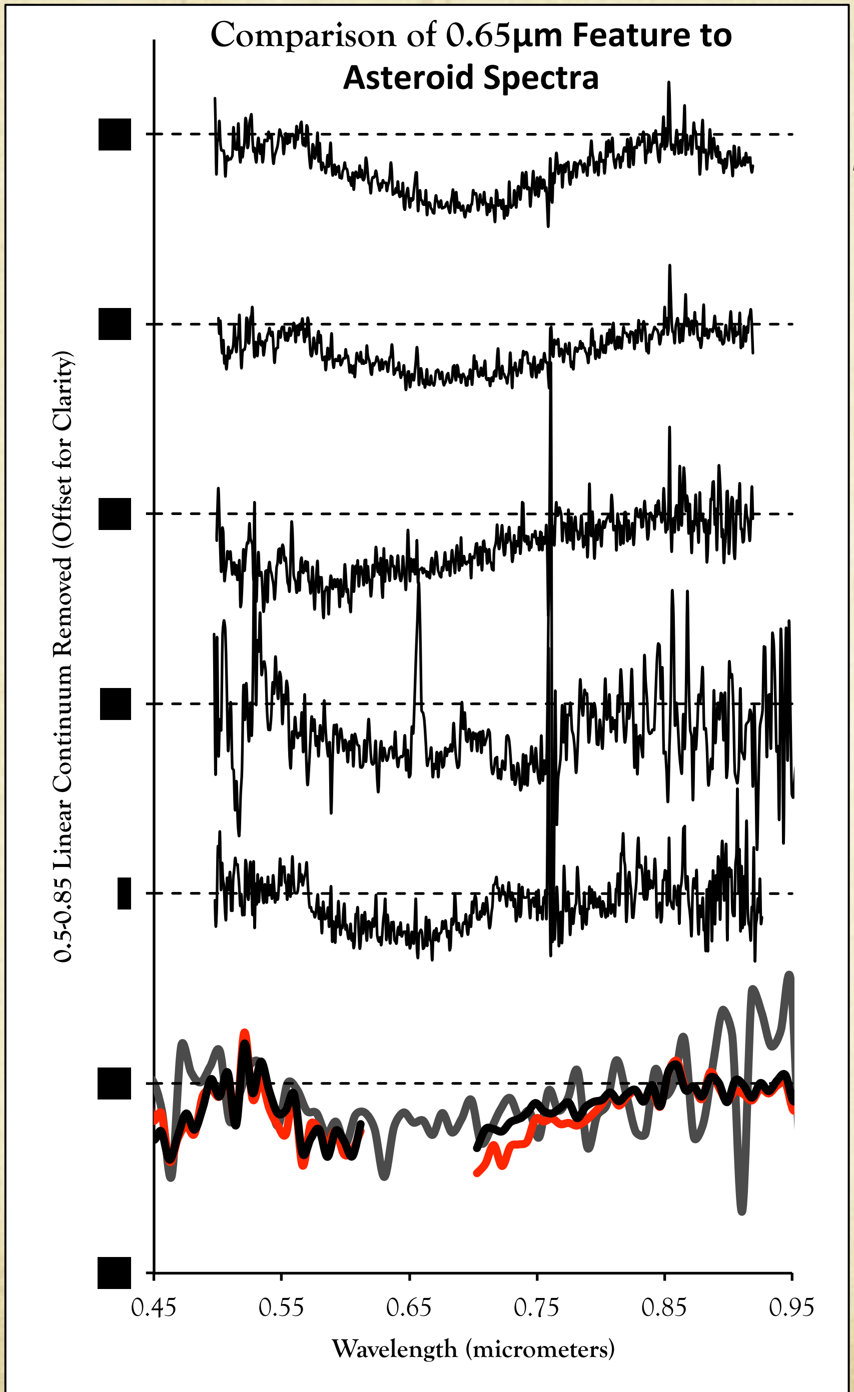
Fraeman et al. 2012

- 6 OMEGA phototmetric geometries at 38°-99° phase angle support a solid photometric model
- Correction of CRISM and OMEGA data to same geometries nearly makes data overlie – but note systematic differences. CRISM – bland, OMEGA – weak pyroxene bands.
- Can correct data to laboratory geometry (i=30°, e=0°)

Comparison to Proposed Analogs



Comparison with Selected Other C/D-types



54 Alexandra
Tholen Class: C
Main Belt

187 Lamberta
Tholen Class: C
Main Belt

624 Hektor
Tholen Class: D
Jupiter Trojan

65 Cybele
Tholen Class: P
Outer Main-belt

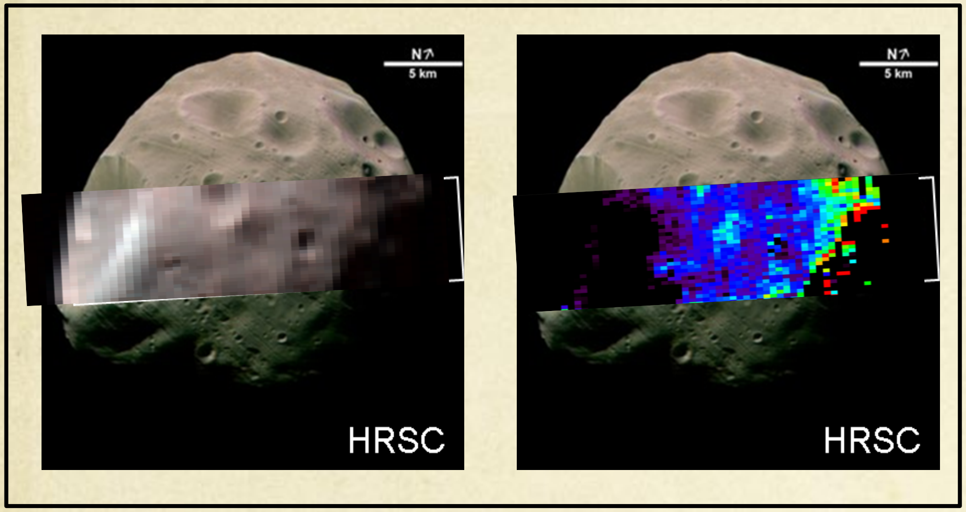
570 Kythera
Tholen Class: ST
Outer Main-belt

OMEGA Phobos Red Unit
CRISM Phobos Red Unit
CRISM Deimos

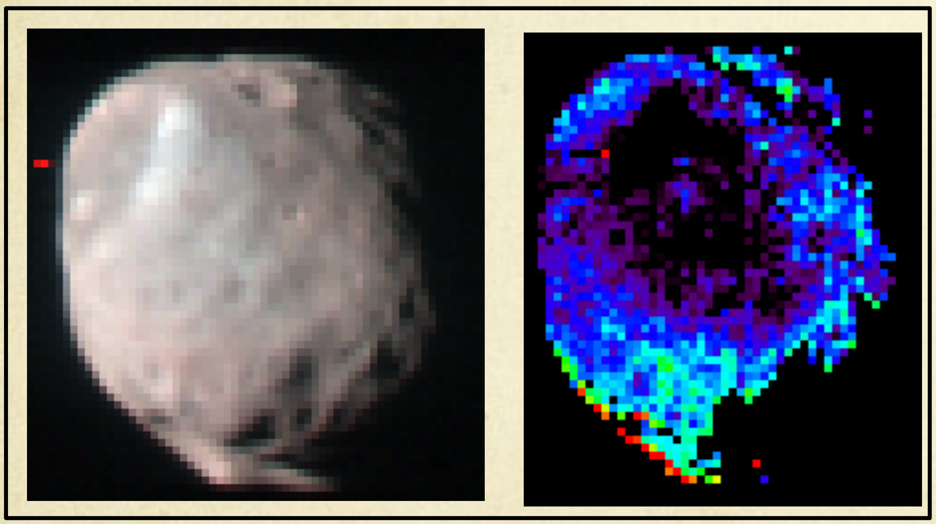
Fraeman et al. 2012

Broad Feature at 0.65 μm (red unit only)

Phobos Sub-Mars Hemisphere



OMEGA ORB0756

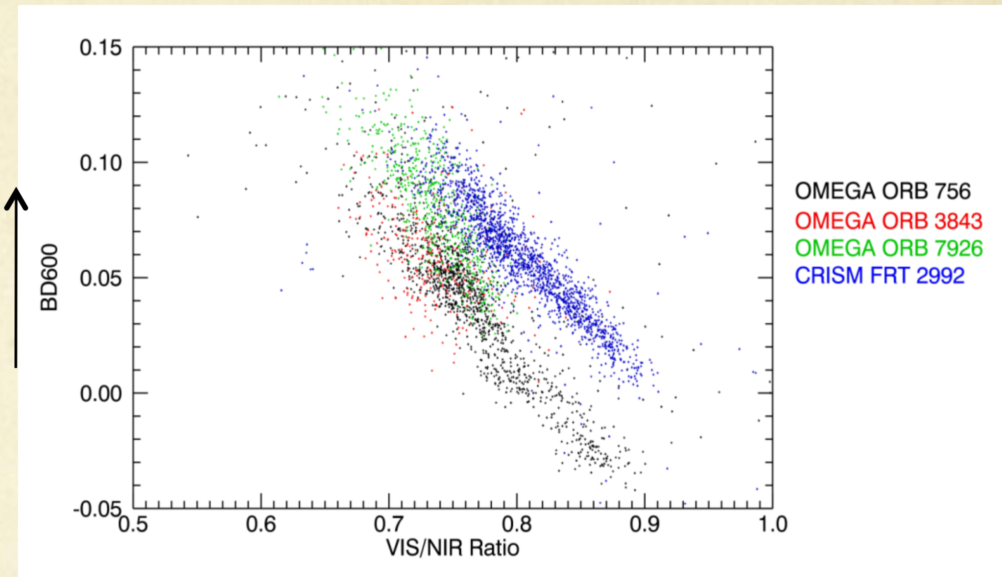


CRISM FRT2992

<1% >10%

Phobos

Deeper Band



Redder

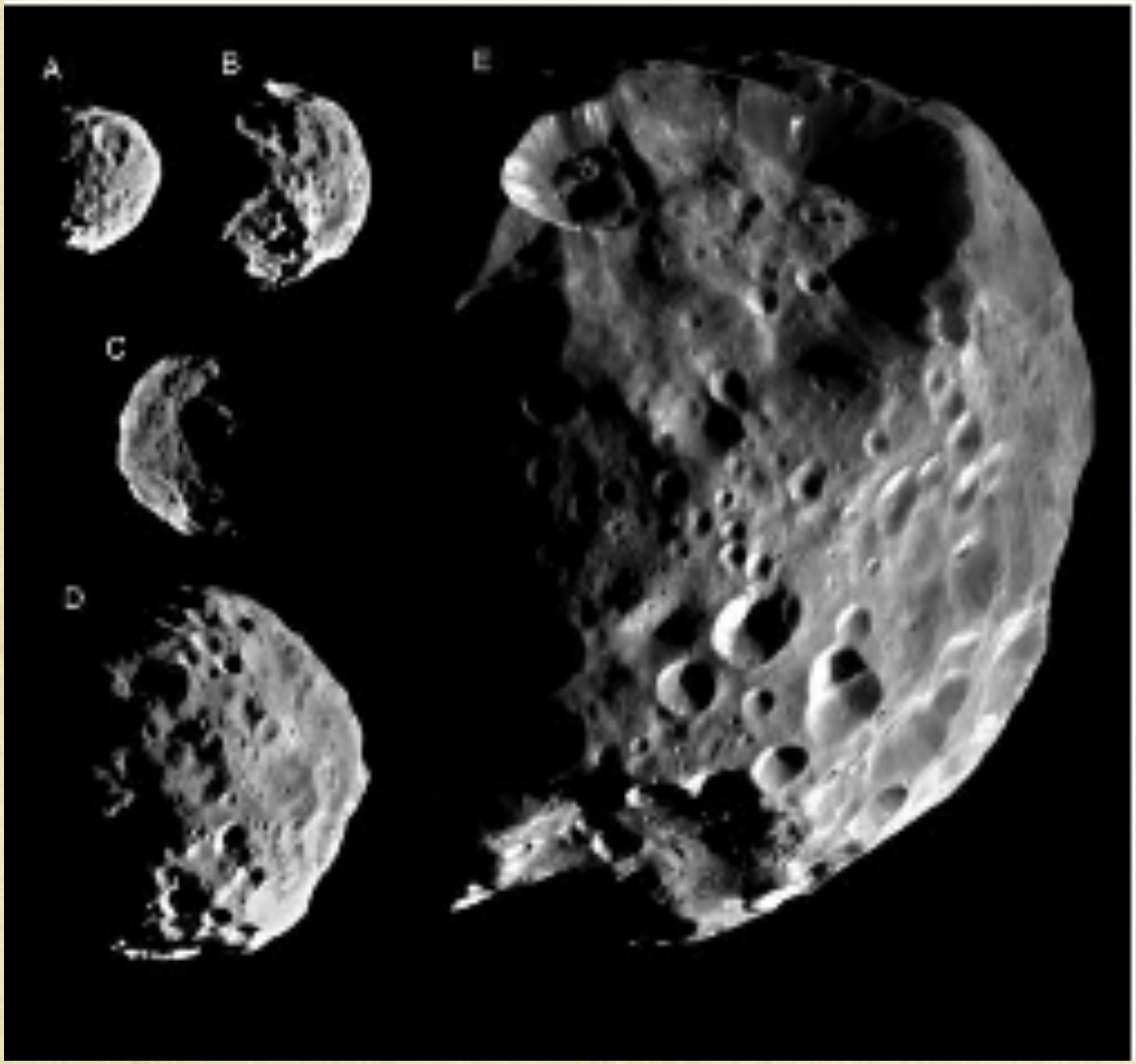
$$\frac{VIS}{NIR} = \frac{R_{0.4:0.5}}{R_{0.75:0.85}}$$

Fraeman et al. 2012

Implication and Limitations

- 2 classes of models for the origin of Phobos and Deimos
  - x Space weathered material like bulk Mars or Mars mantle
  - ✓ Primitive, carbon-bearing D-type material, perhaps captured
- So…what KIND of D-type composition? Two hypotheses
  - Hydrated: CM- or CI-like with organics, carbon, Fe phyllosilicates, some olivine and pyroxene
  - Anhydrous: Fine-grained silicates plus elemental carbon (e.g. graphite)
- What is not observed
  - Olivine, pyroxene, bound water or hydroxyl, organics
- What fits the 0.65-µm band (within the noise)? EITHER Hypothesis!
  - Fe phyllosilicate
  - Graphite
- The blue unit is matched with a CM analog by albedo and continuum ONLY. Not by any distinct absorption feature.
- **Bottom line: Either very distinct proposed D-type composition is within uncertainties in the data. Spectral data indicate spatial variations and constrain compositions somewhat, but are highly ambiguous.**

Phoebe Overview



Porco et al. 2005

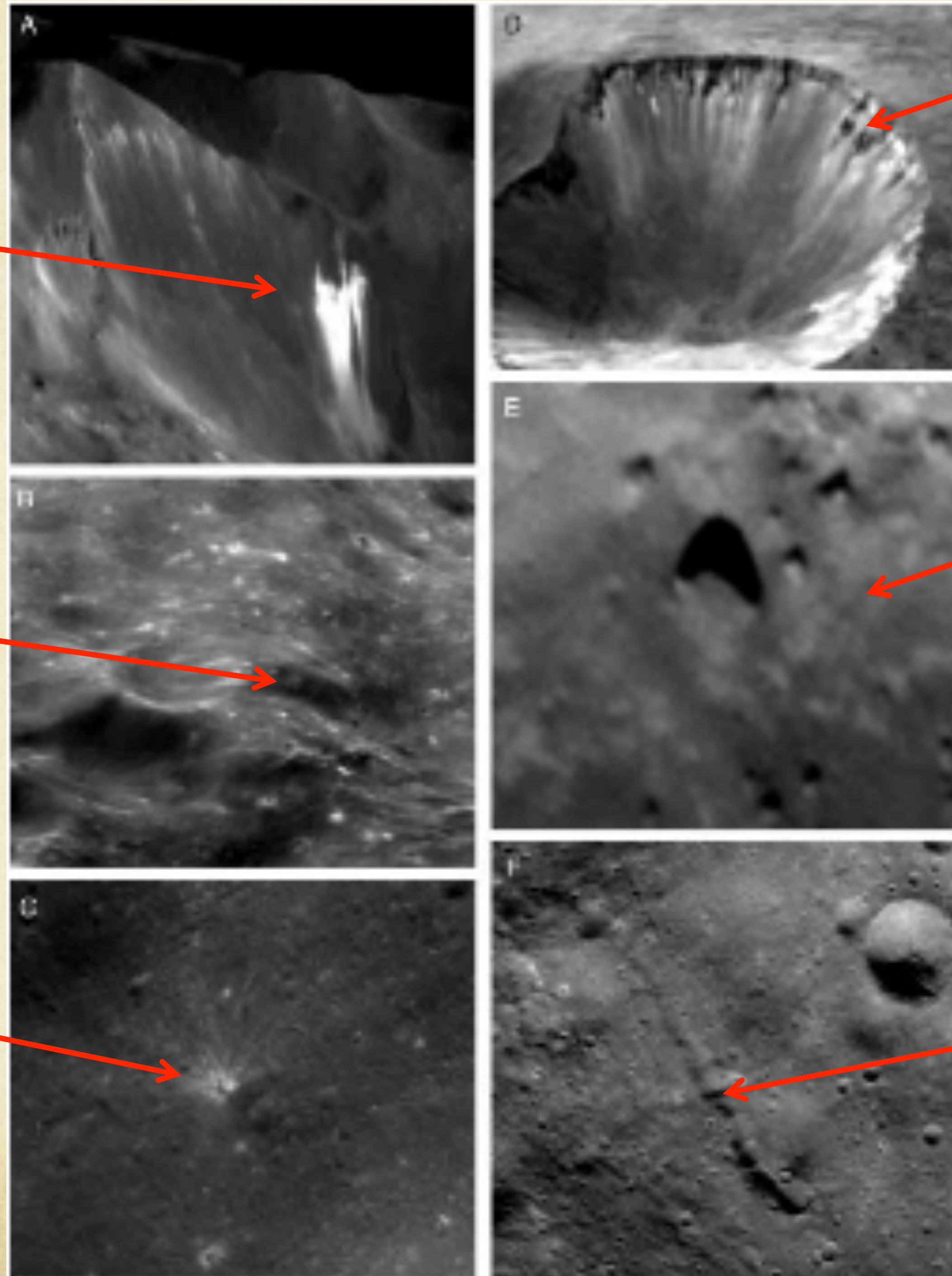
- 220 km diameter
- 1630±45 kg/m3, requiring an ice fraction for porosity ≤40%
- Ice is observed spectroscopically
- Albedo 7-30% (extreme dynamic range compared to earlier bodies)
- Densely cratered with a size-frequency distribution different from a heliocentric or Jovian population
- Resolution as good as 15 m/pixel (narrow-angle camera)

Phoebe Geology Gallery

Bright ice exposed by mass wasting

Patchy ice and non-ice material

Bright icy fresh rayed crater



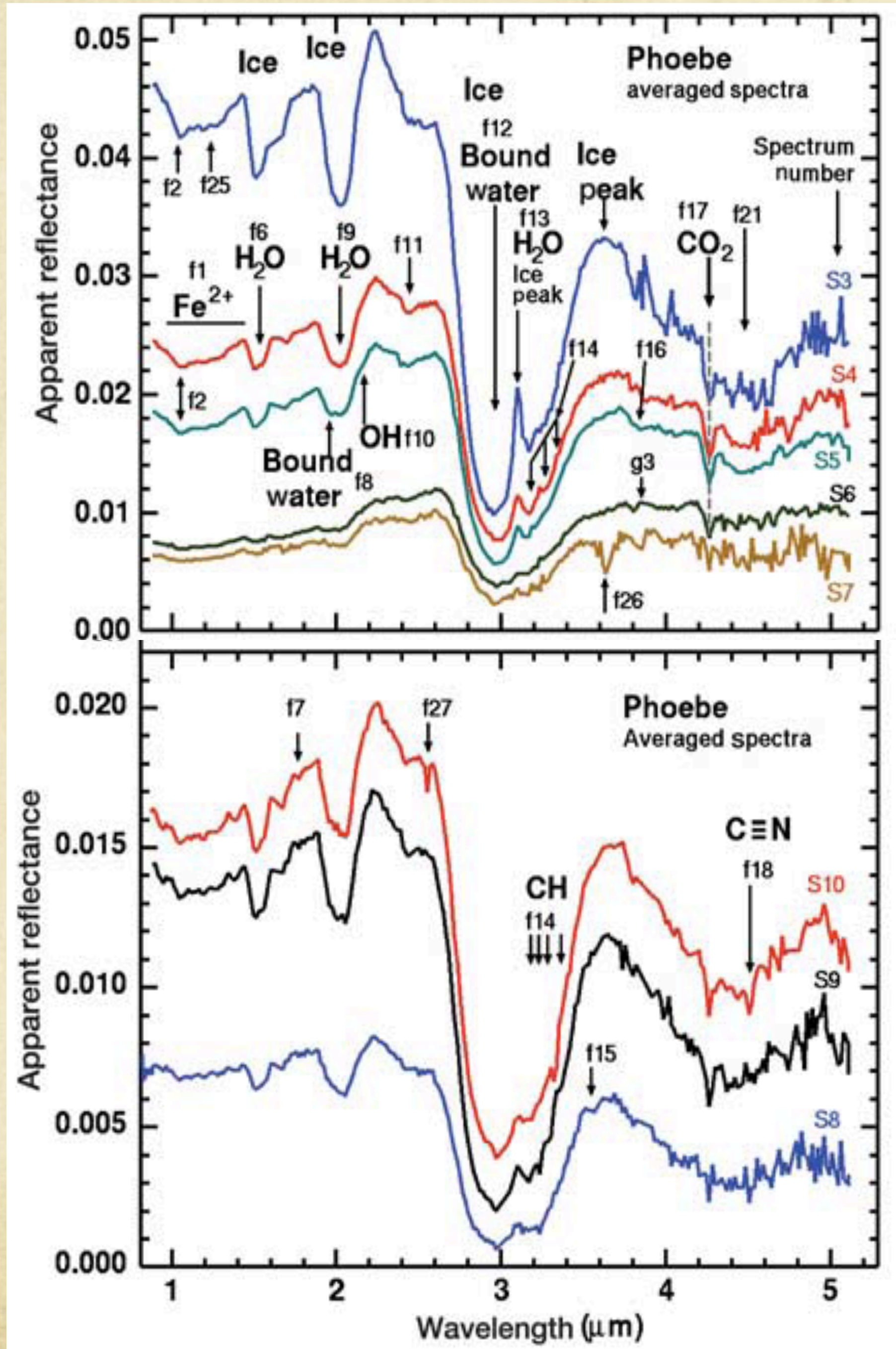
Layering or stratification

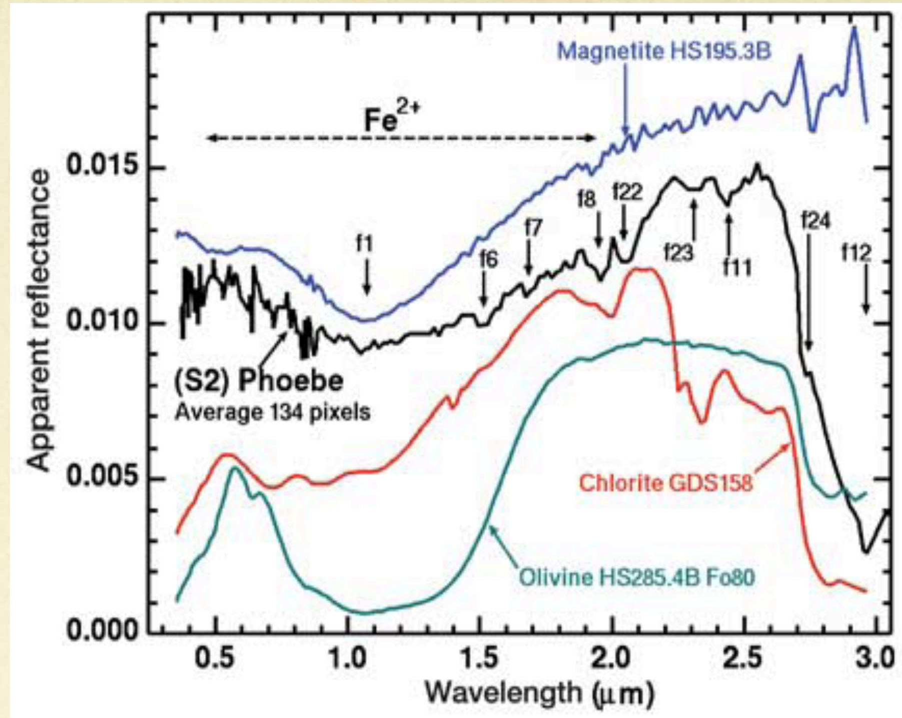
Blocks

Grooves

Porco et al. 2005

Extreme Spectral Contrast and Diversity





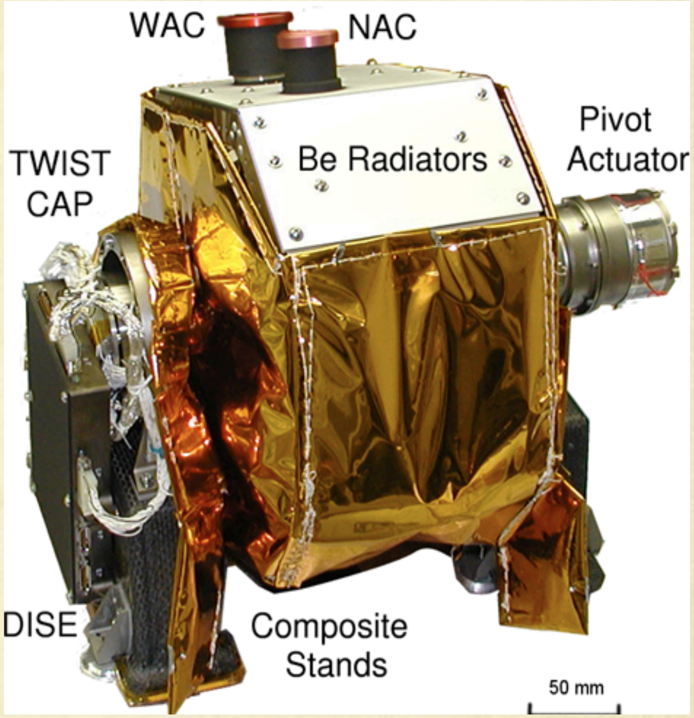
- H_2O ice, CO_2 ice, CN compounds, bound water, organics, Fe^{2+} minerals
- Underlying causes
  - Surface not baked of volatiles
  - Albedo segregations
  - Inherent features of ices
  - Lack of thermal crossover

Clark et al. 2005

Lessons: Future Remote Sensing of Primitive Small Bodies

- So far there is no “typical”.
- Nature of encounter
  - Coverage for mapping, structural analysis, and photometry requires rendezvous, repeated encounters, or at bare minimum prolonged encounter at low velocity
- “Imaging science”
  - A non-fixed imager is extremely valuable if possible. Even one with just a pivot and stepper motor. Especially if the encounter is a flyby.
  - A narrow-angle camera is essential for resolution. It can be paired with a medium-angle camera for coverage or data-intensive imaging (e.g. color)
  - Pole position or topography can hide large parts of a body. For an unknown target lidar or radar greatly increases the robustness of investigation of shape, density, and maybe even morphology.

MESSENGER/MDIS



- Spectroscopy (inner solar system)
  - This can help map out spectral units. Maybe. Calibration accuracy is paramount.
  - Understanding composition requires in situ measurements (Raman, XRD, Mossbauer)
- Spectroscopy (outer solar system)
  - Likely to be scientifically rich if temperature is low, ices are present.