Dawn at Vesta

Horst Uwe Keller

Institut für Geophysik und extraterrestrische Physik
TU Braunschweig

IGEP TU Braunschweig

DAWN NASA UCLA JPL Orbital asi agenzia spaziale italiana DLR INAF MPS

The Discovery Dawn Mission

PI C. T. Russell

University of California

Institute of Geophysics and Planetary Physics

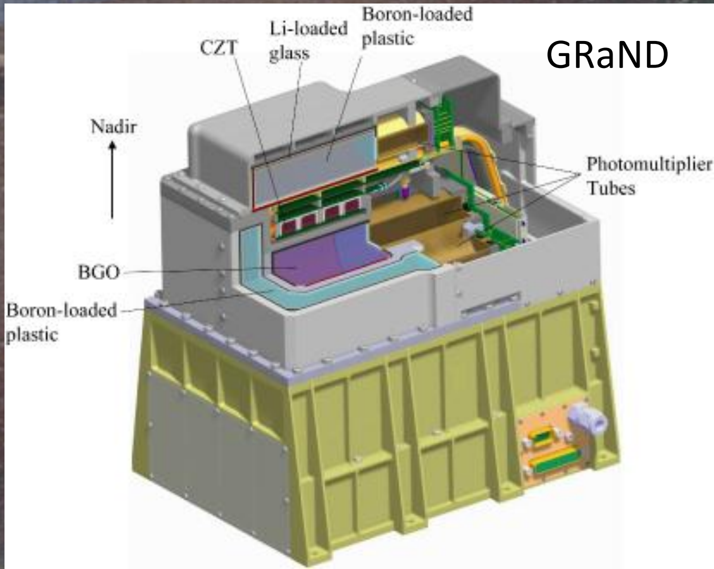
Strong European contributions to the payload:

Framing Camera(s) for science and navigation

Visible and Infrared mapping spectrometer

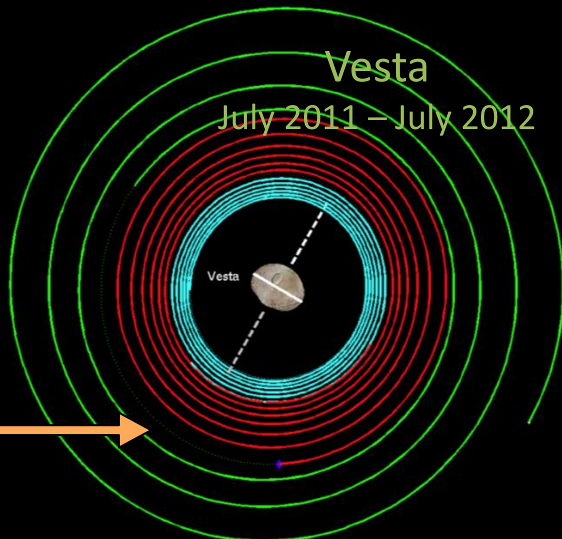
Dawn's Payload

- Two redundant framing cameras (1024 x 1024 pixels and 7 color filters plus clear) provided by Germany (MPS and DLR)
- A visible and infrared mapping spectrometer (UV to 5 microns) provided by Italy (INAF and ASI)
- A Gamma Ray and Neutron Detector built by LANL and operated by PSI
- A Radio Science Package provides gravity information
- Topographic model derived from off-nadir imaging

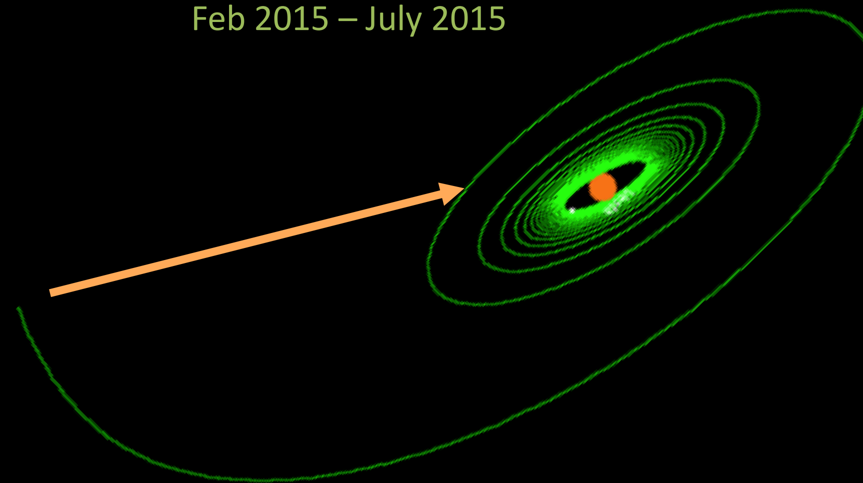


Dawn Mission Itinerary

Vesta
July 2011 – July 2012



Ceres
Feb 2015 – July 2015



Mars Gravity Assist
Feb 2009

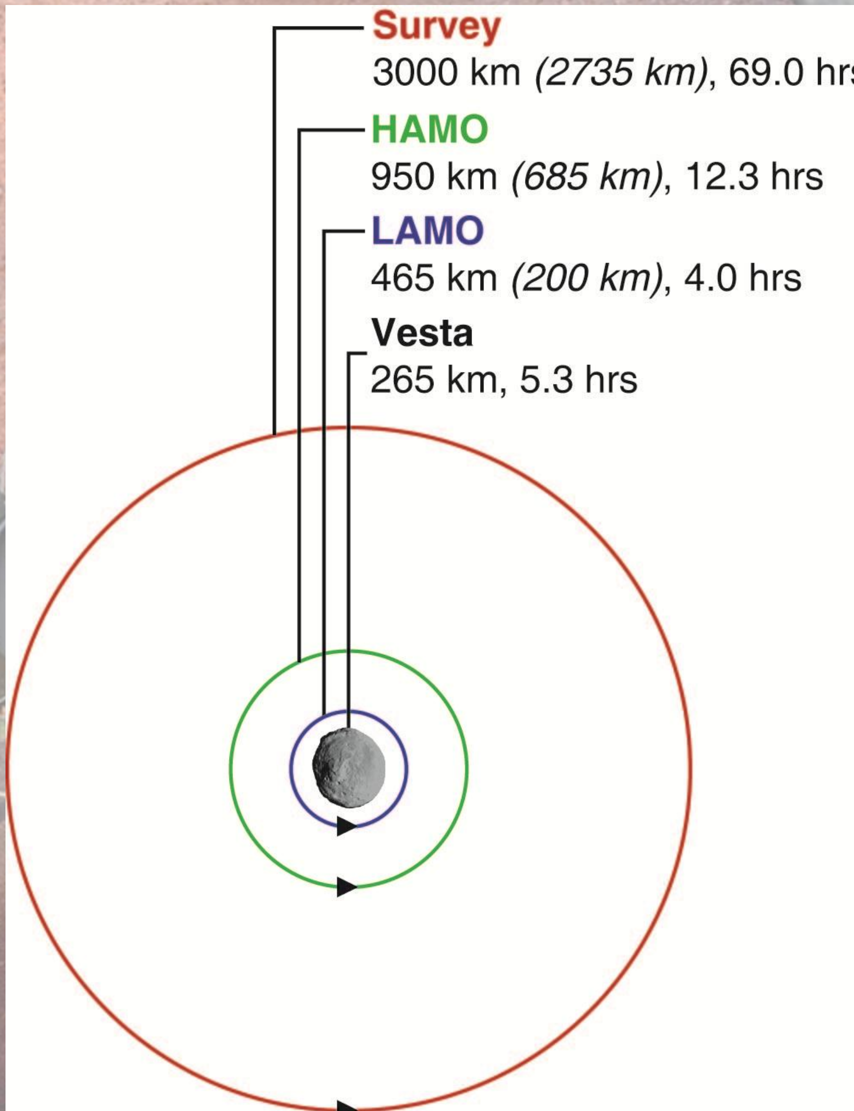
Launch
Sep 2007

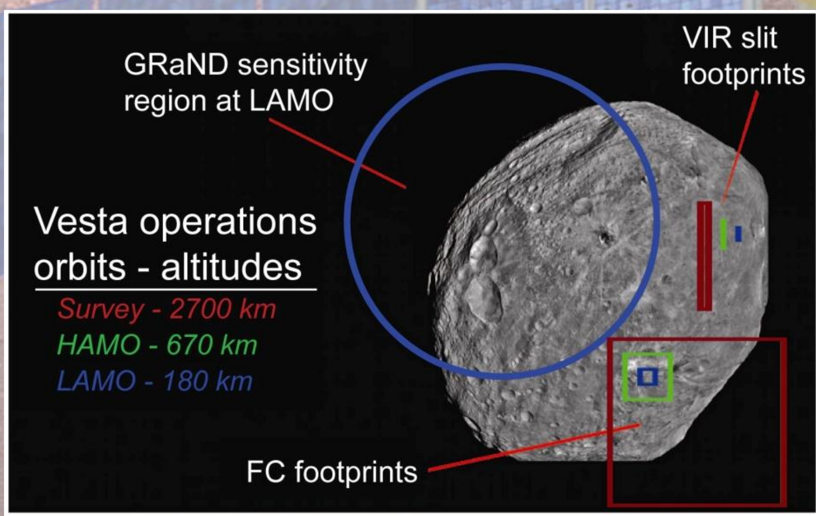
At each target, Dawn will:

- Acquire color images
- Compile a topographic map
- Map the elemental composition
- Map the mineralogical composition
- Measure the gravity field
- Search for moons

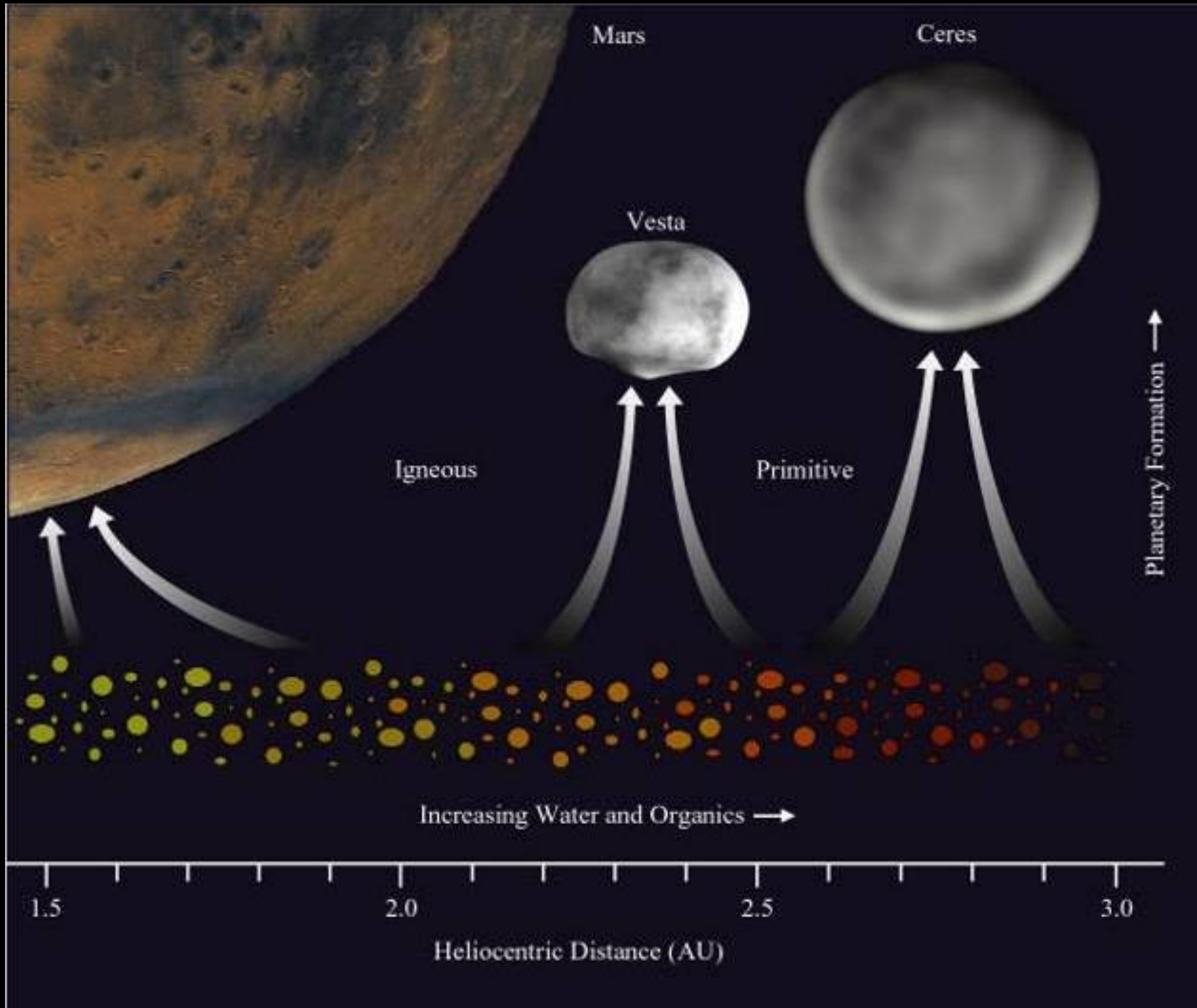
Vesta Science Orbits

- **Dawn began taking science data in a high *Survey* orbit on 11. August 2011**
- **It then used the ion propulsion system to transfer to the *High Altitude Mapping Orbit (HAMO)* beginning 30. September.**
- **Next it transfered to the *Low-Altitude Mapping Orbit (LAMO)* beginning 12. December.**
- **Dawn will then raise its orbit to perform a second HAMO, depart from Vesta, and repeat the same orbital strategy at Ceres**



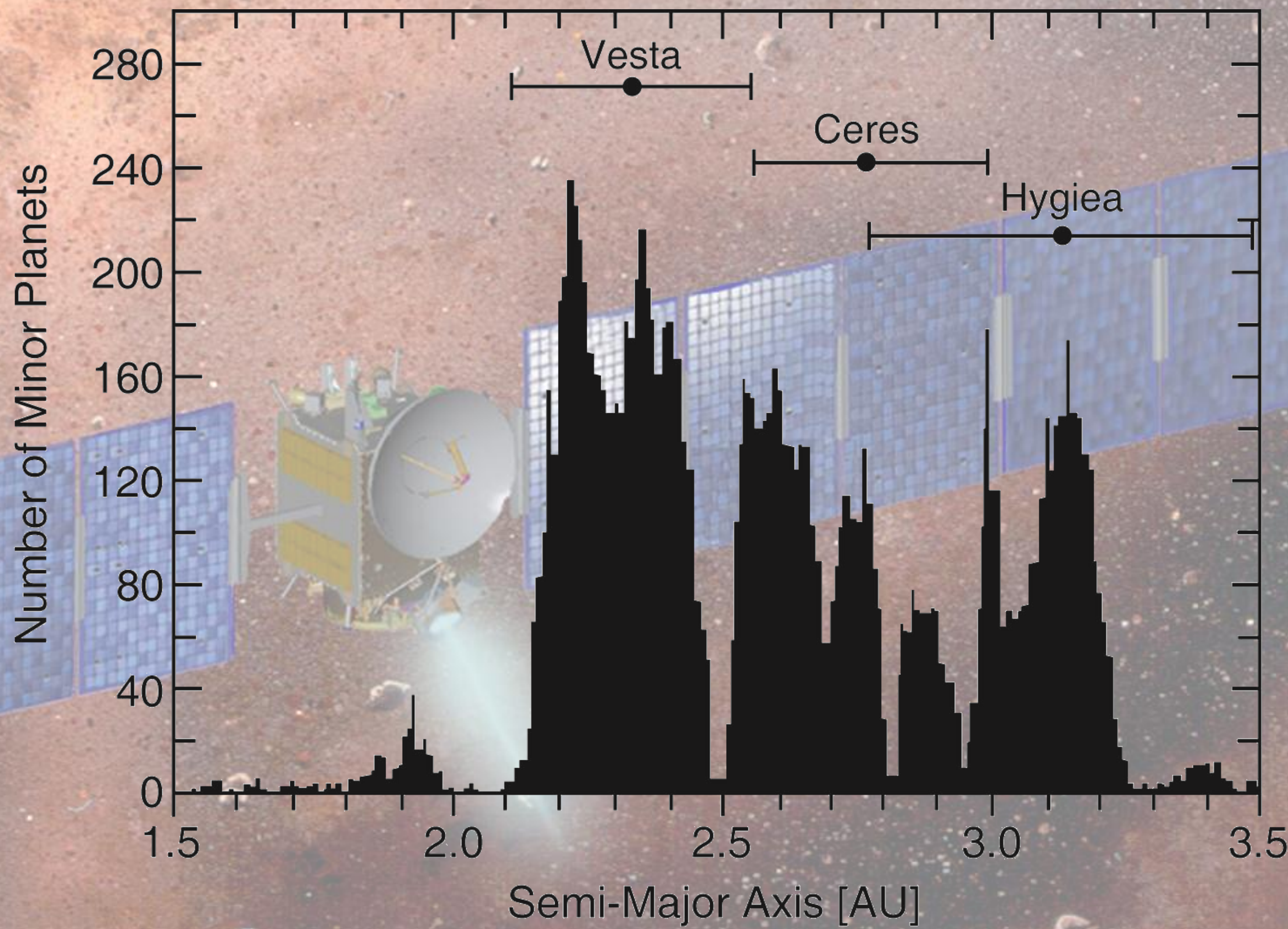


Planetary Perspective



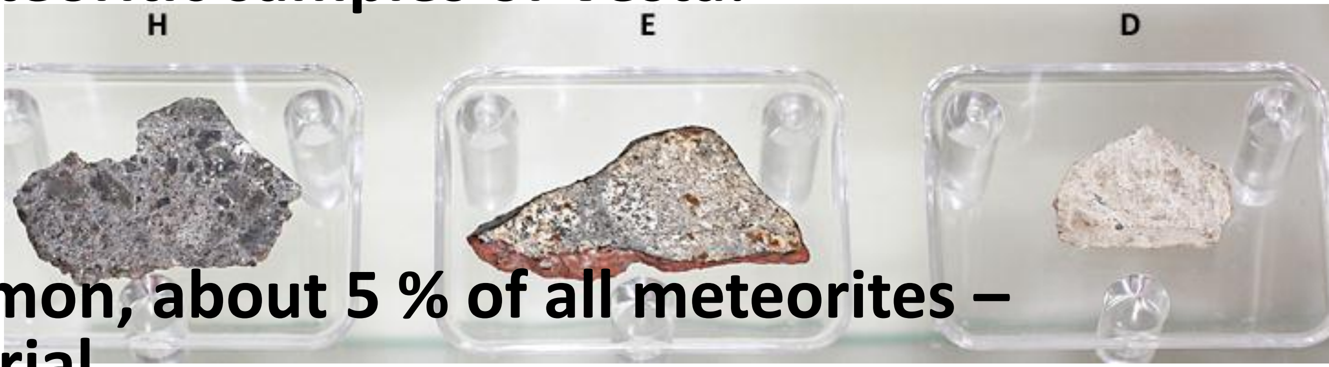
Asteroid Belt Today

- **Stirring by Jupiter's gravitational field produced the Kirkwood gaps where orbital periods are integral ratios of Jupiter's orbital period.**



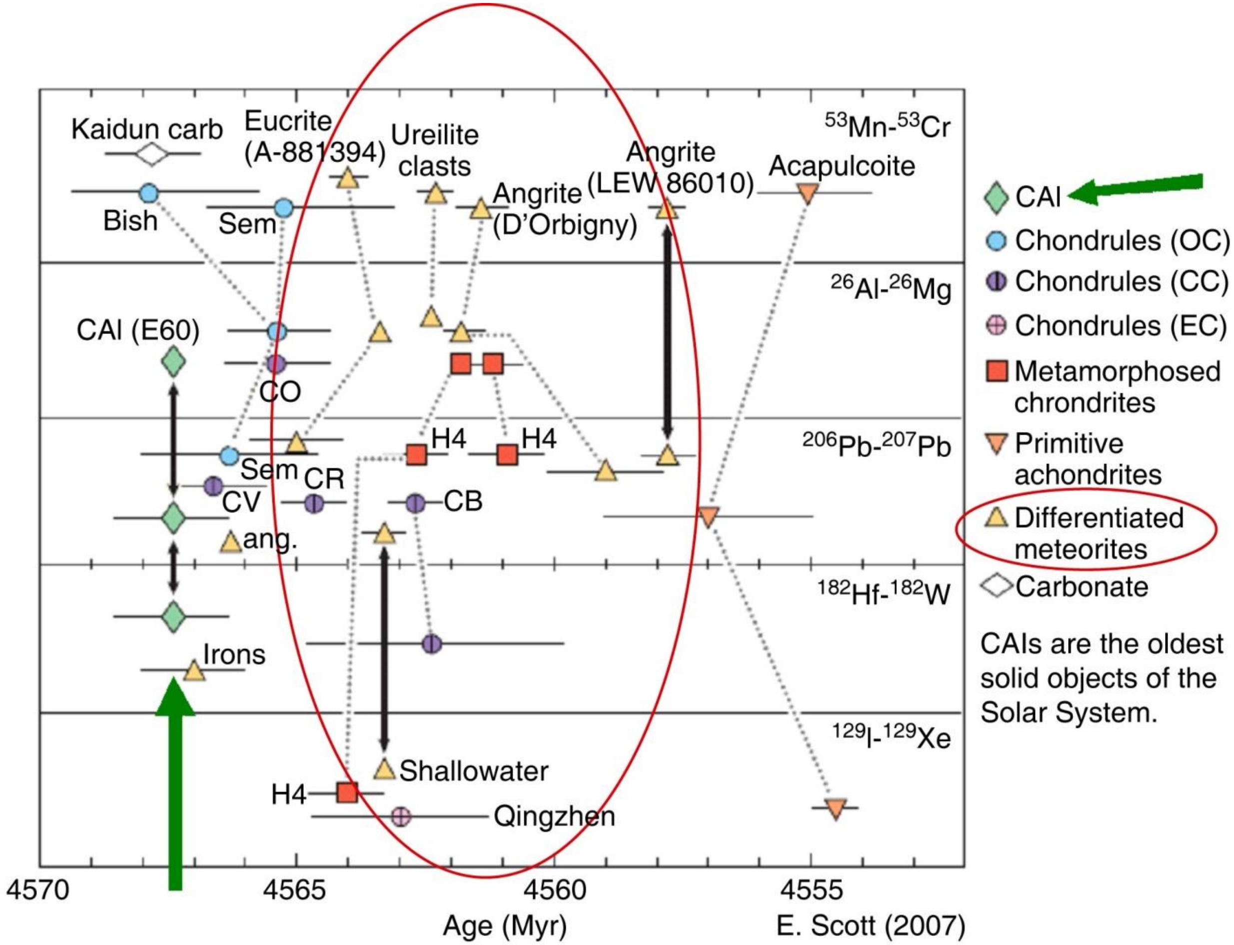
Ground Truth

- There are meteoritic samples of Vesta:
  - Howardites
  - Eucrites
  - Diogenites



- HED are common, about 5 % of all meteorites – basaltic material
- Crystallization age is about 4.56 Ga ago
- Eucrites are about the oldest meteorites
- Vesta is differentiated and is the parent body of HEDs
- Decay of ^{26}Al and ^{60}Fe leads to a molten core topped by a shell of partially or totally molten silicates
- A magma ocean is not expected

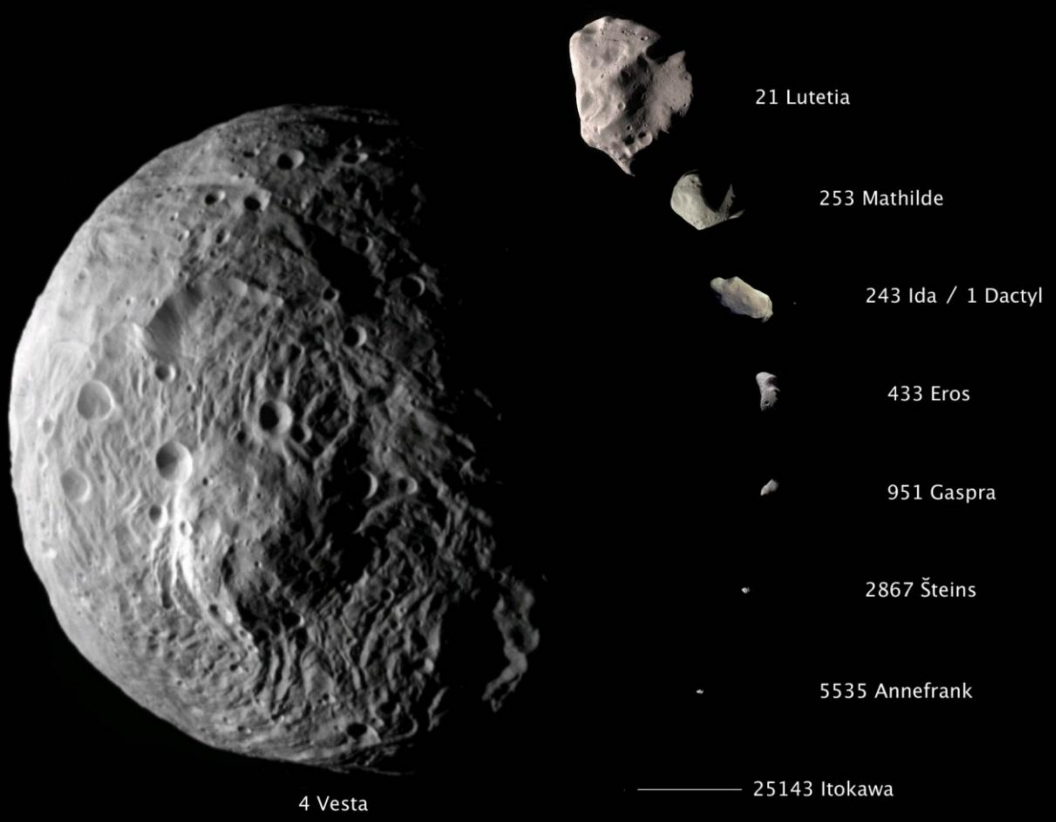
Early Planetary System Mineralogy

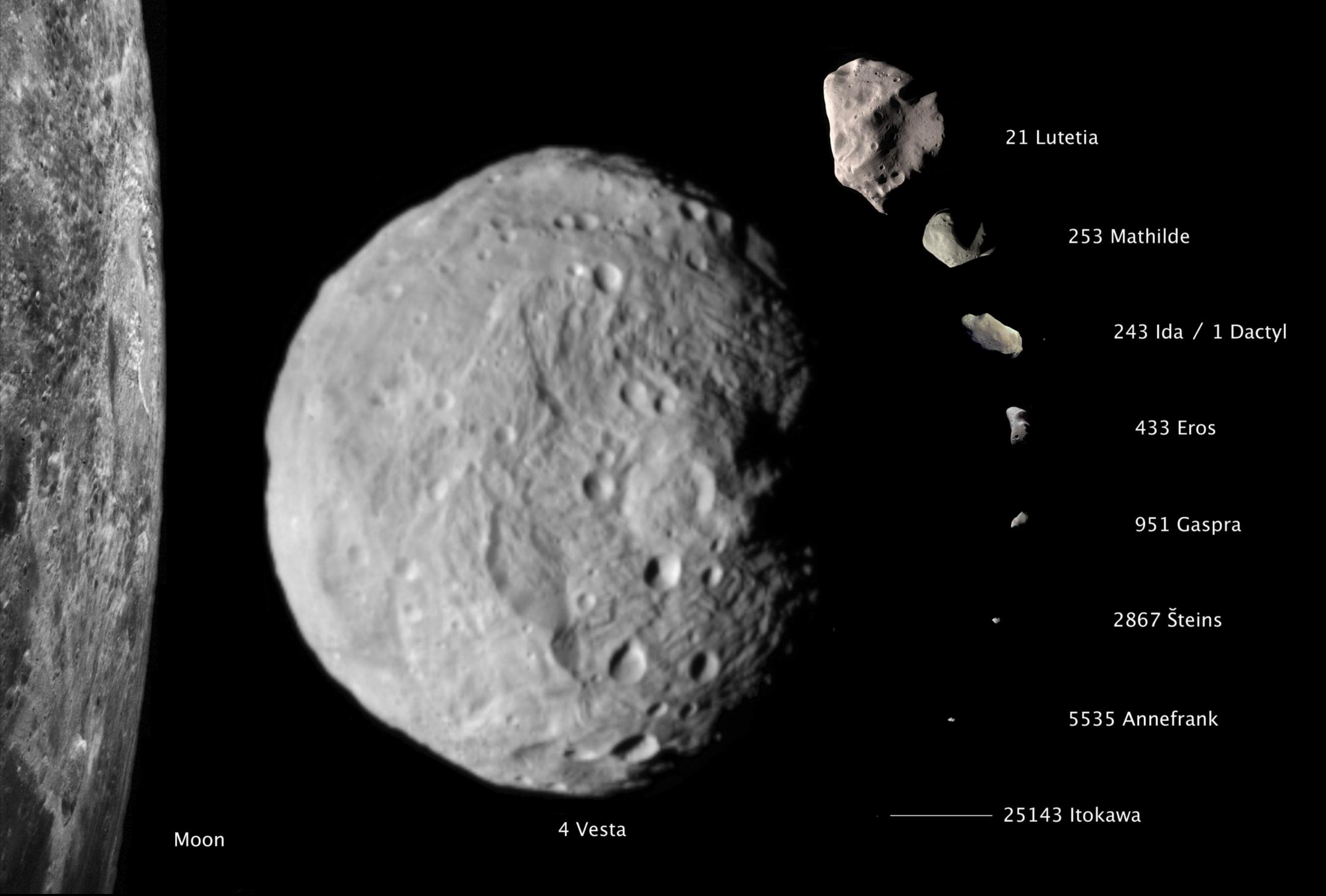


- When bodies began to grow, they trapped the radioactive heat inside, melted and differentiated.
- The formation of the Earth-Moon system was not until almost 50 M yrs later.

Vesta and its Siblings: Asteroids Visited to Date

- Vesta seen here from above its south pole is the largest asteroid visited to date.
- Previous orbital missions went to much smaller, near-Earth asteroids, 433 Eros and 25143 Itokawa.
- As begins to be seen in this image, Vesta is not just a chunk of rock but is a small planet with many of the geophysical processes we expect on a planet

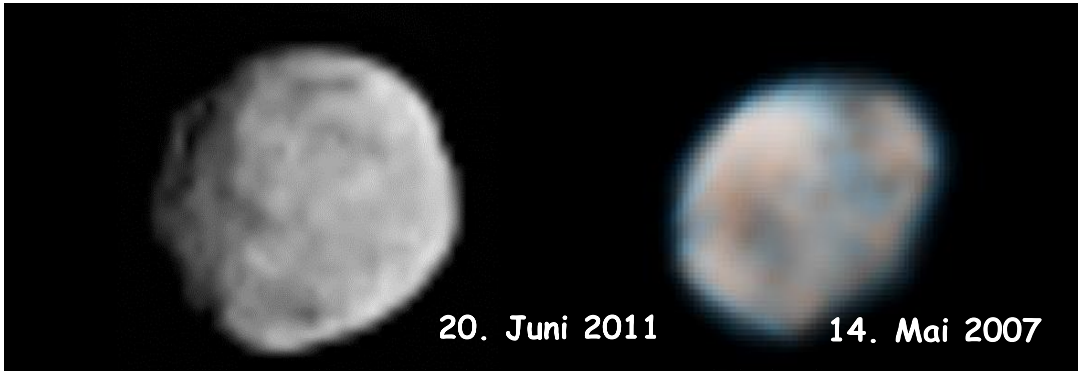



21 Lutetia
253 Mathilde
243 Ida / 1 Dactyl
433 Eros
951 Gaspra
2867 Šteins
5535 Annefrank
25143 Itokawa
Moon
4 Vesta

Vesta
What did we expect:

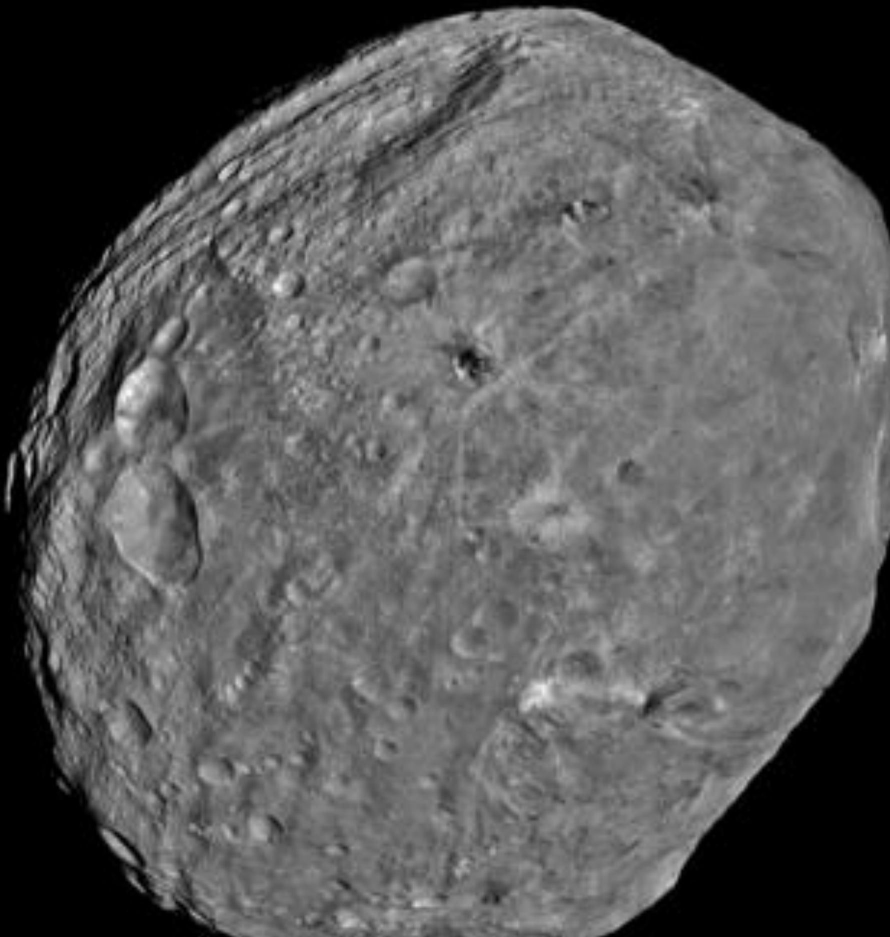
Vesta is the parent body of the HED meteorites. According to the chronology of the HEDs, melting and fractionating occurred in the early stage (4.56 Ga) of Vesta's geologic history, during which the asteroid is thought to have completely differentiated and formed a silicate-bearing crust.

Size: 289/280/229 km
Density: 3.4 ± 0.8 g/cm^3
Escape: 350 m/s
Albedo: 0.42



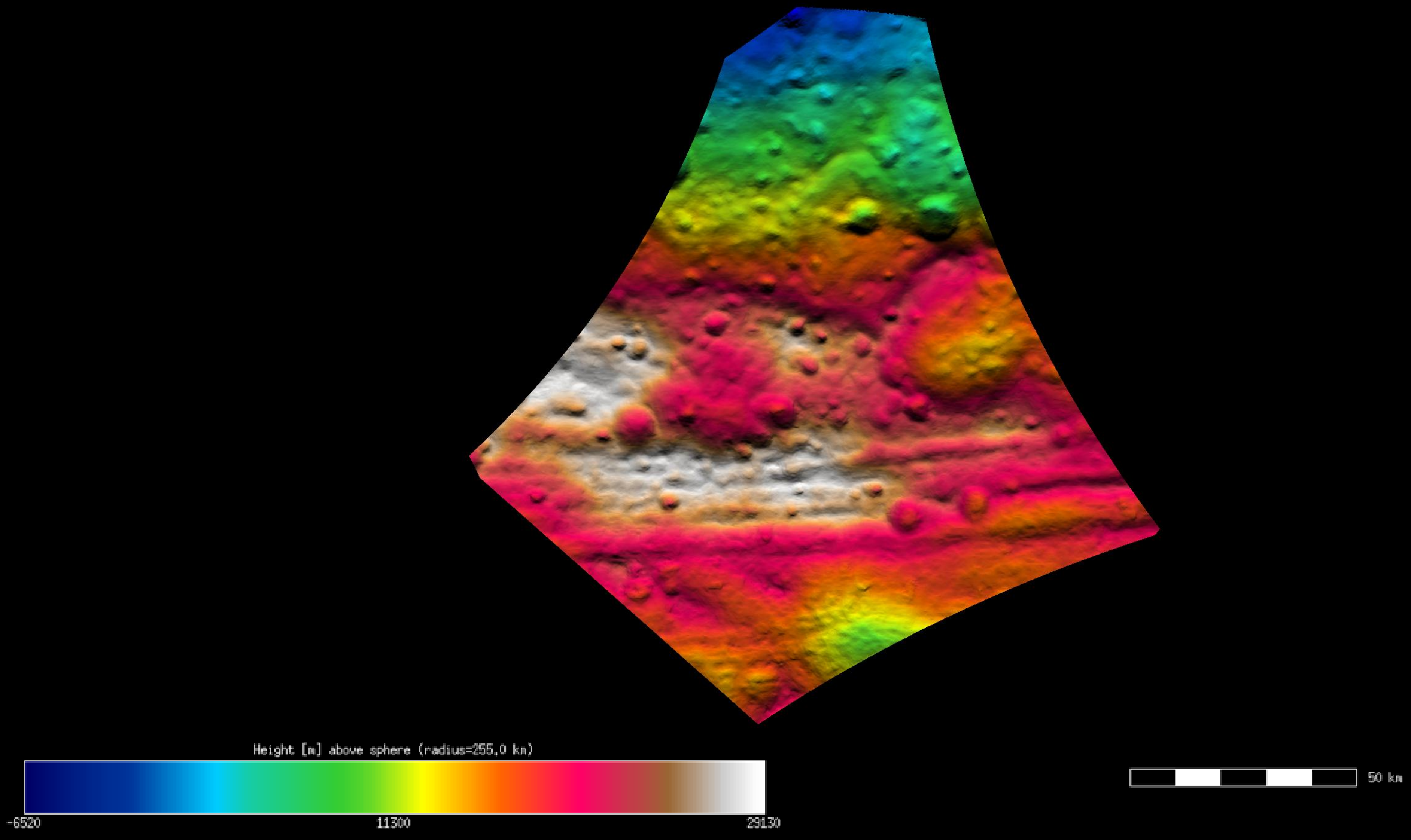
(e.g. Gaffey, 1997, Bogard and Garrison, 2003; Thomas et al., 1997; Wilson and Keil, 1996)

Vesta fills the FOV

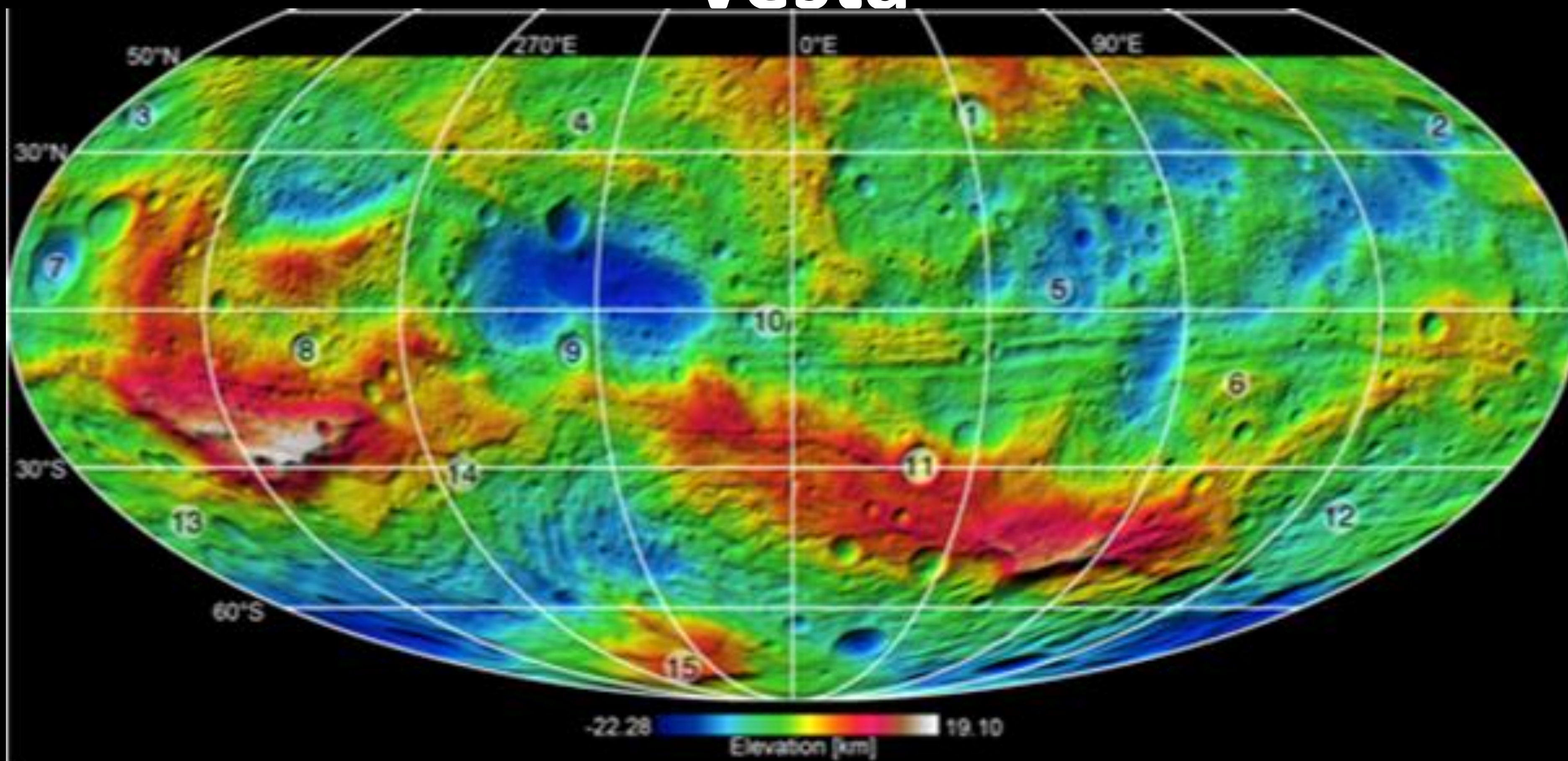


5,200 km

Stereo Example

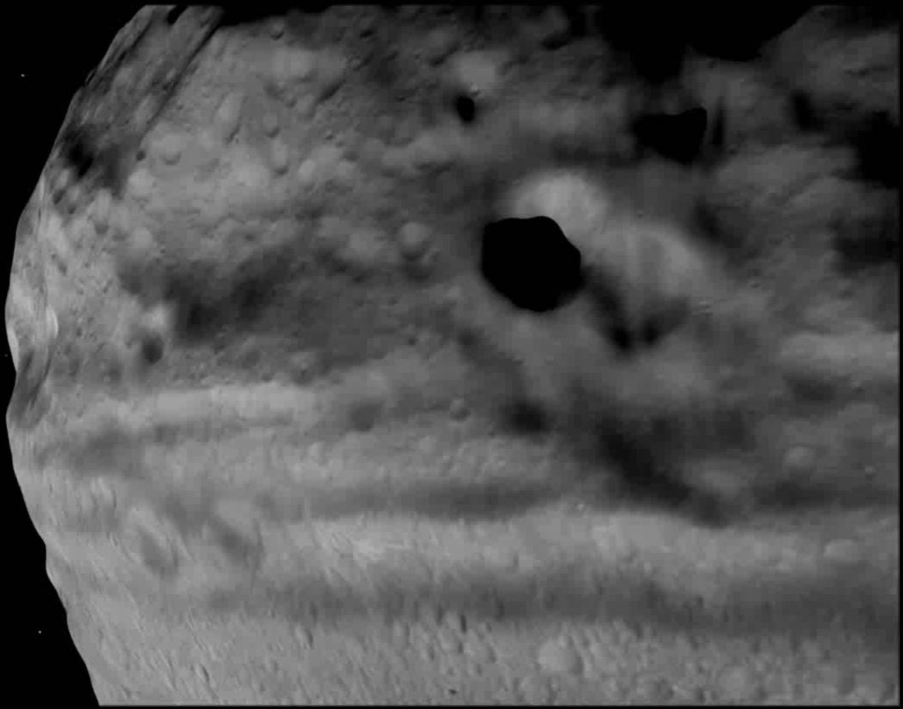


Vesta



1Bellicia, 2Caparronia, 3Domitia, 4Floronia, 5Gegania, 6Lucaria Tholus, 7Marcia, 8Numisia, 9Oppia, 10Claudia, 11Pinaria, 12Sextilia, 13Tuccia, 14Urbinia, 15Rheasilvia

Vesta's surface
What do we expect:

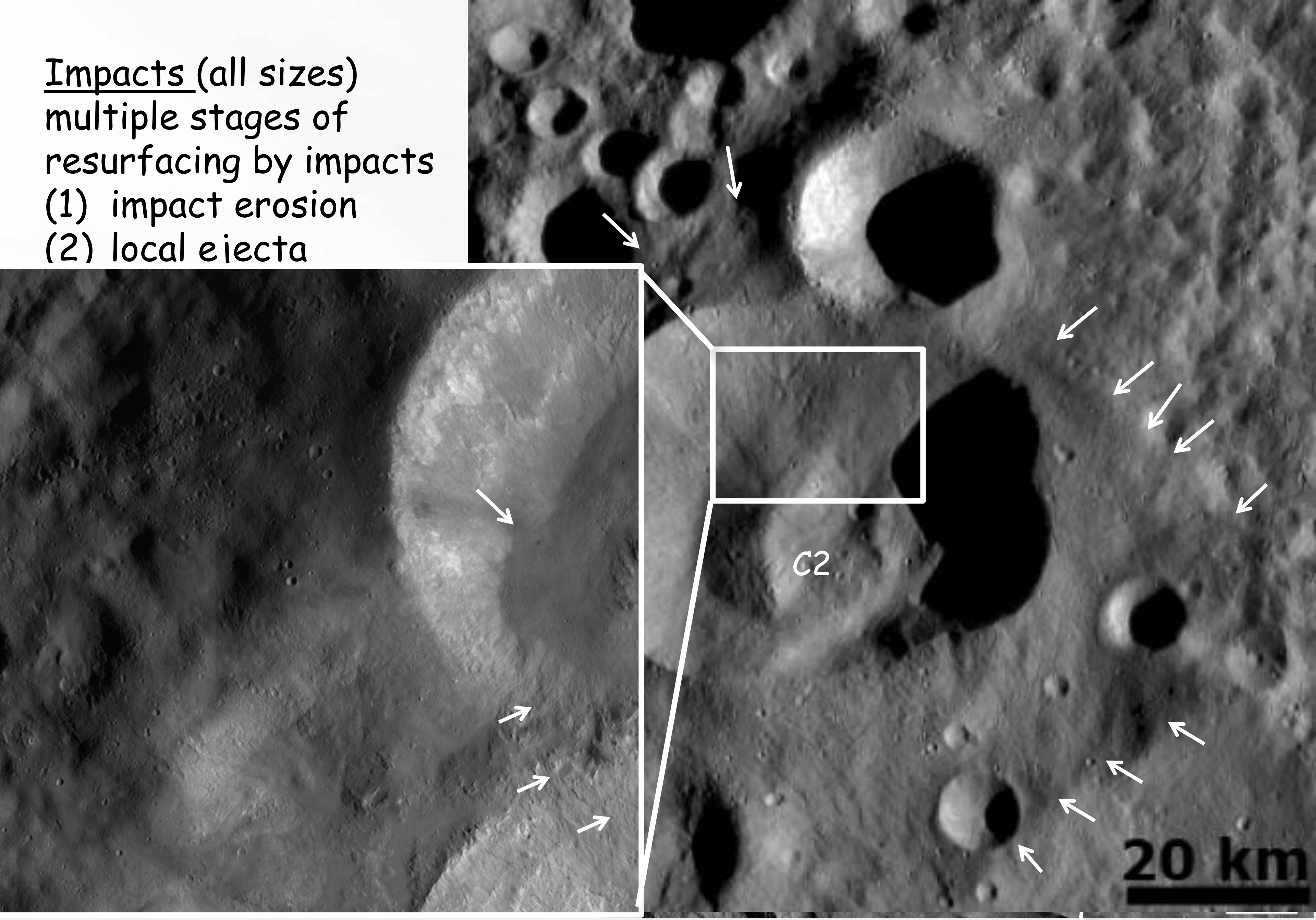


Impacts (all sizes)
including regolith formation and large scale resurfacing
(1) impact erosion
(2) ejecta deposition
(3) material redistribution by gravity
(4) impact melt (small amounts <1%)

Tectonics
related to
(1) impact disruption
(2) differentiation (?)
(3) remains of volcanic processes (?)

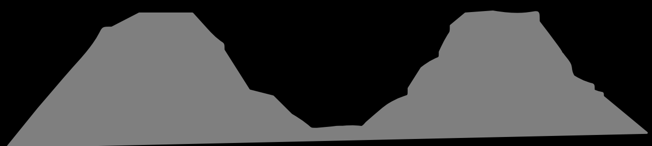
Volcanism (remnants) ?
(1) magma intrusions by small dikes (km x m)
(2) surface flows (10th of km 100th of m)
(Wilson and Keil, 1996)

Impacts (all sizes)
multiple stages of
resurfacing by impacts
(1) impact erosion
(2) local ejecta



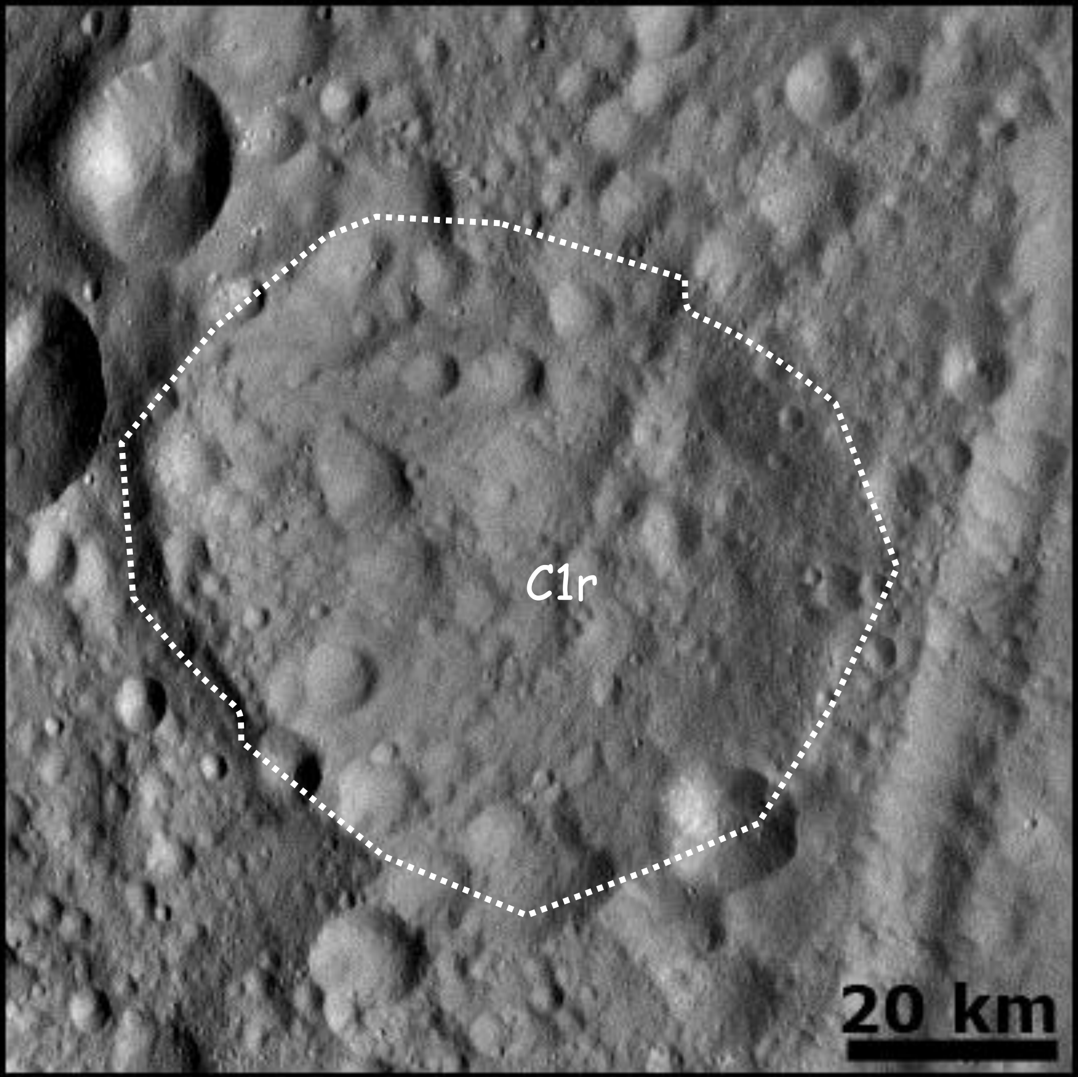
<u>Impacts</u> (all sizes)
multiple stages of resurfacing by impacts

(1) impact erosion
(2) local ejecta partly preserved



C1 heavily degraded subdued rim craters

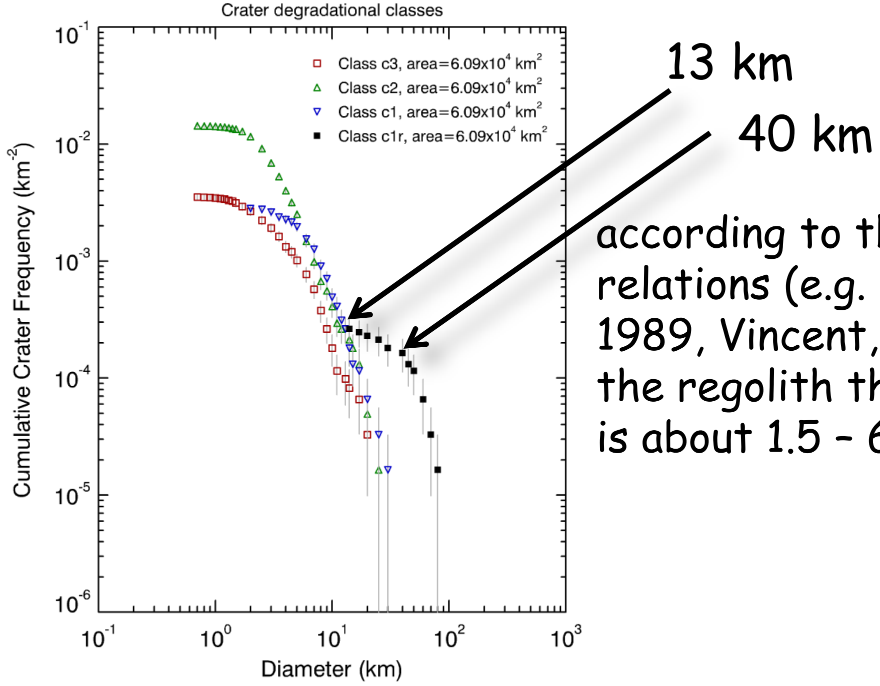
C1r ruin eroded crater



Impacts (all sizes)

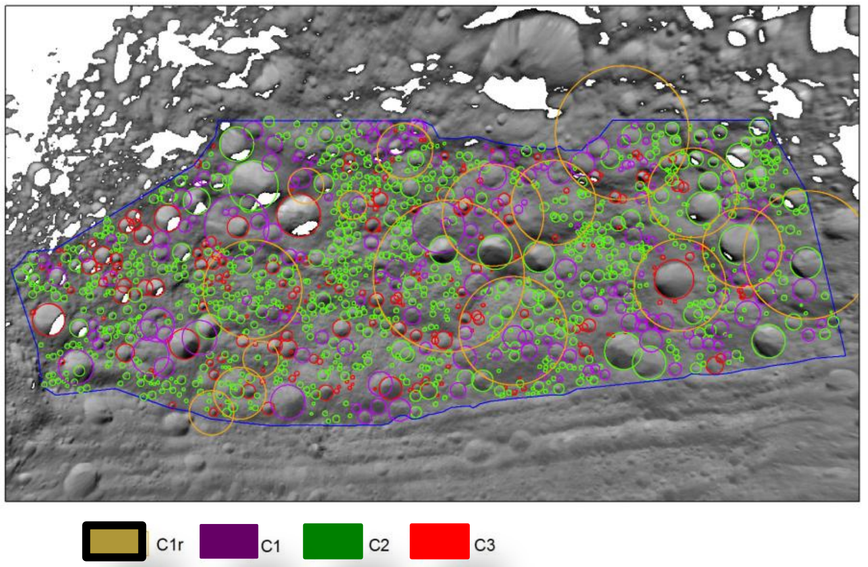
erosion/sedimentation by impact:
impacts erode craters and
ejecta of larger basins build layers
of different materials and thickness

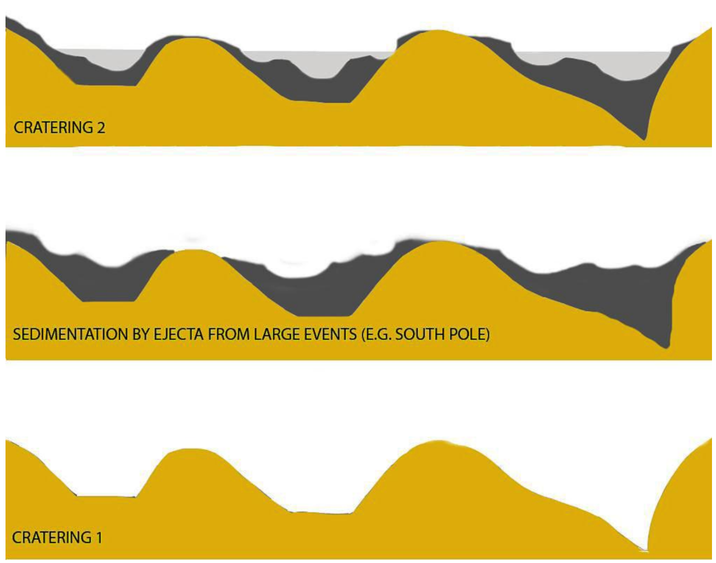
Vesta Approach - RC3 / Frame 364765868 / Unit HCT



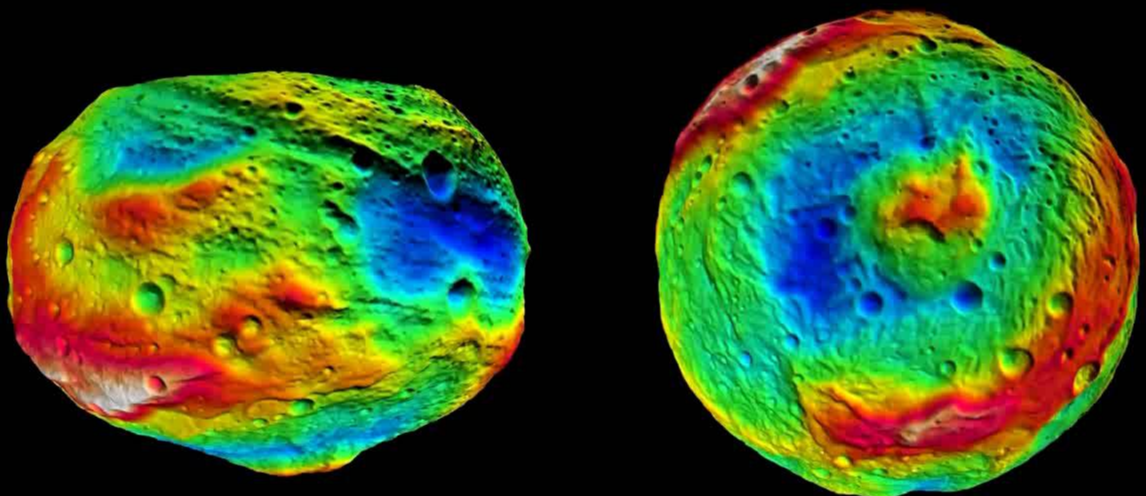
according to the d/D relations (e.g. Melosh, 1989, Vincent, 2011) the regolith thickness is about 1.5 – 6 km

Vesta Approach - RC3 / FC2 frame 364765868 / Unit HCT





Topography



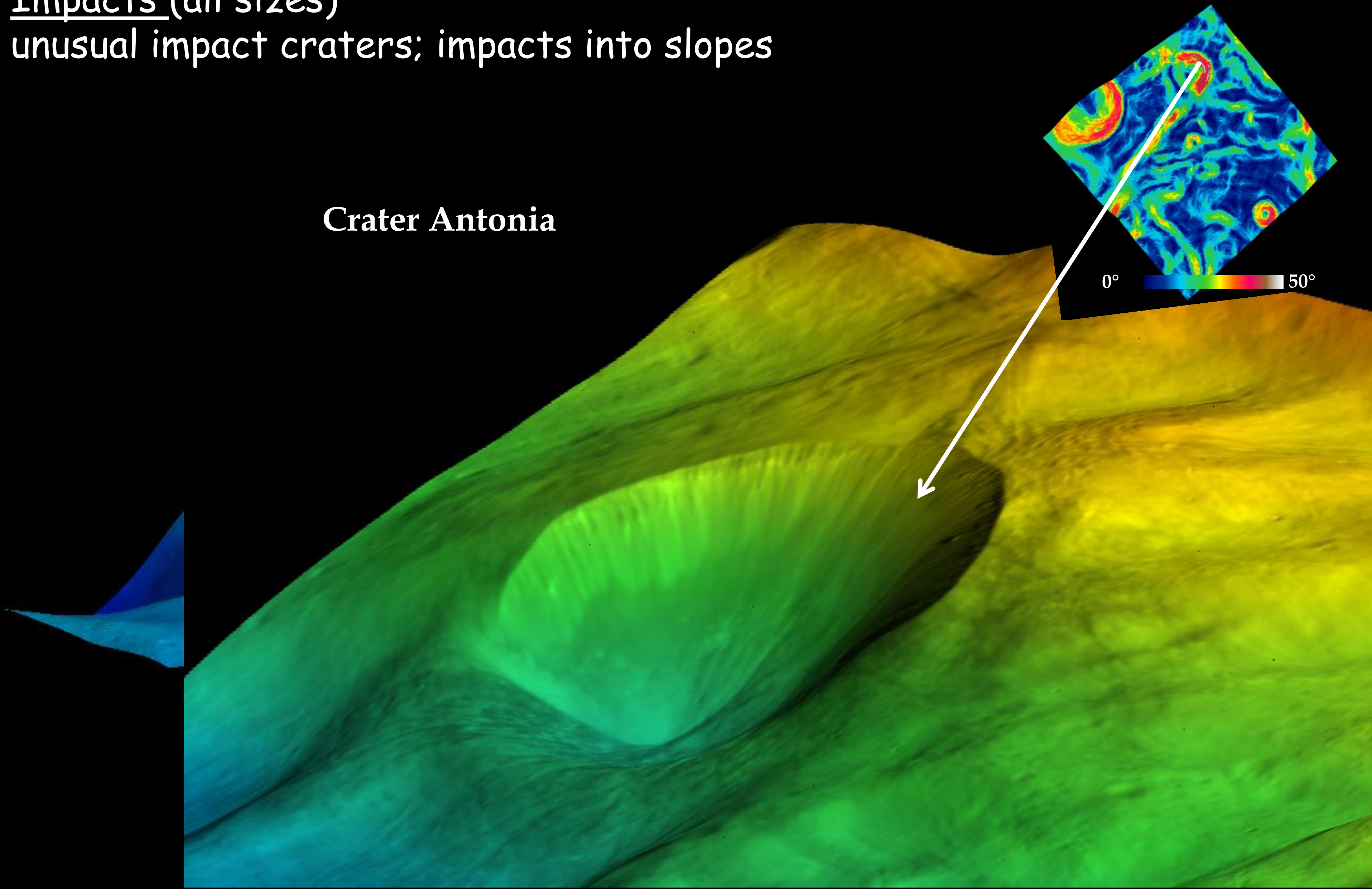
-22,25 km 20.19 km

Color-coded heights

heights above ellipsoid (289/280/229 km)

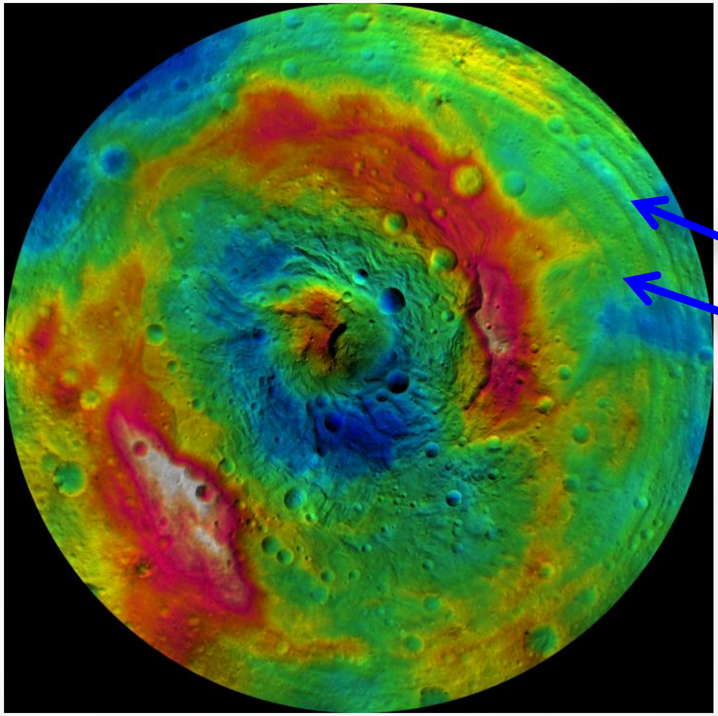
4 Vesta using survey data (movie (DLR))

<u>Impacts</u> (all sizes)
unusual impact craters; impacts into slopes

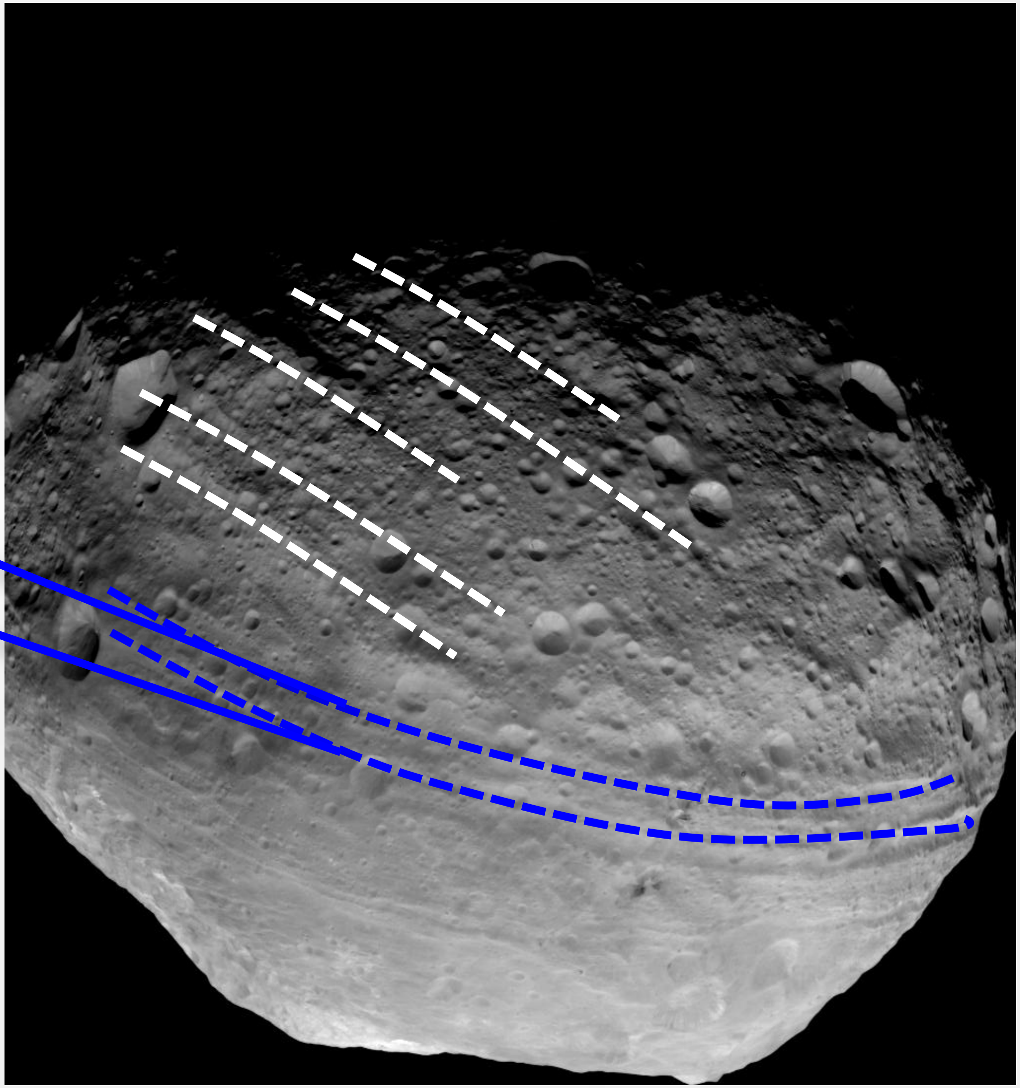


Tectonics

Large trough systems related to
(1) impacts
(2) differentiation (?)
(3) volcanic processes (?)



-22,25 km 20.19 km
Color-coded heights (additional hill-shading)
heights above ellipsoid (289/280/229 km)



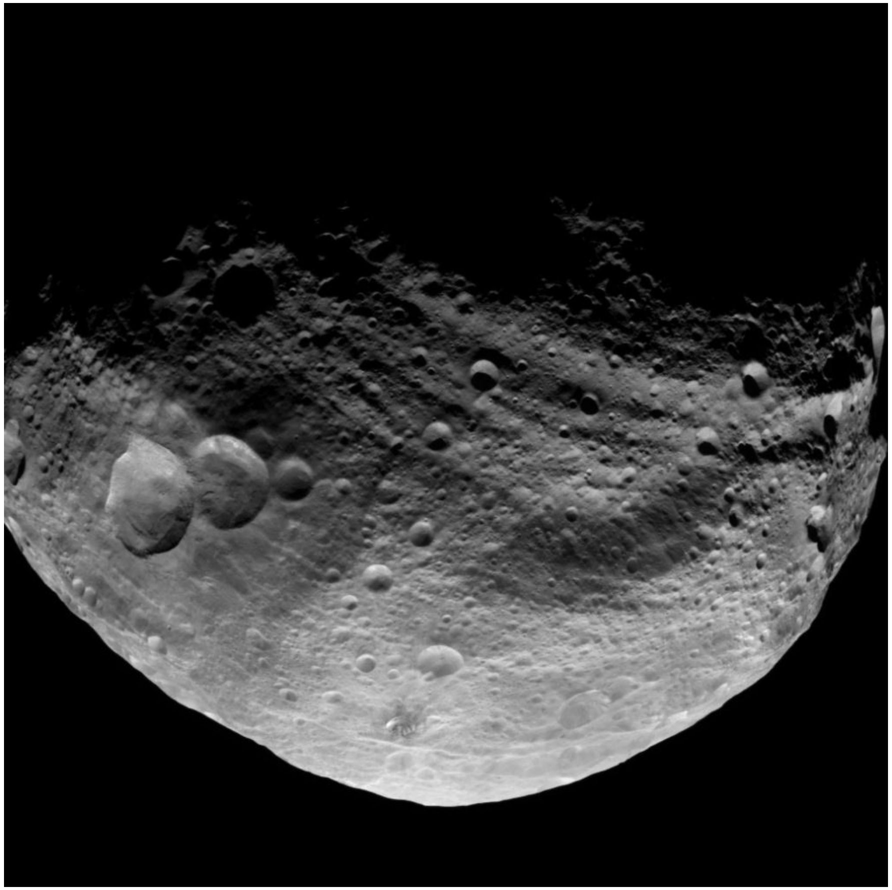
Equatorial Troughs

- Linear structures encircle the asteroid, roughly aligned with the equator
  - Wide flat-floor troughs bounded by steep scarps are expressed for ~240º longitude
  - Muted troughs, grooves and pit crater chains from ~150ºE to ~270ºE
  - Lengths vary from 19 - 380 km and widths up to 15 km
  - Have currently mapped 86 linear structures with this orientation
- Analysis indicates that most of these features are co-planar, suggesting a common formation mechanism
- **Poles cluster at 78º ± 10º**

Buczkowski et al.

Northern Trough

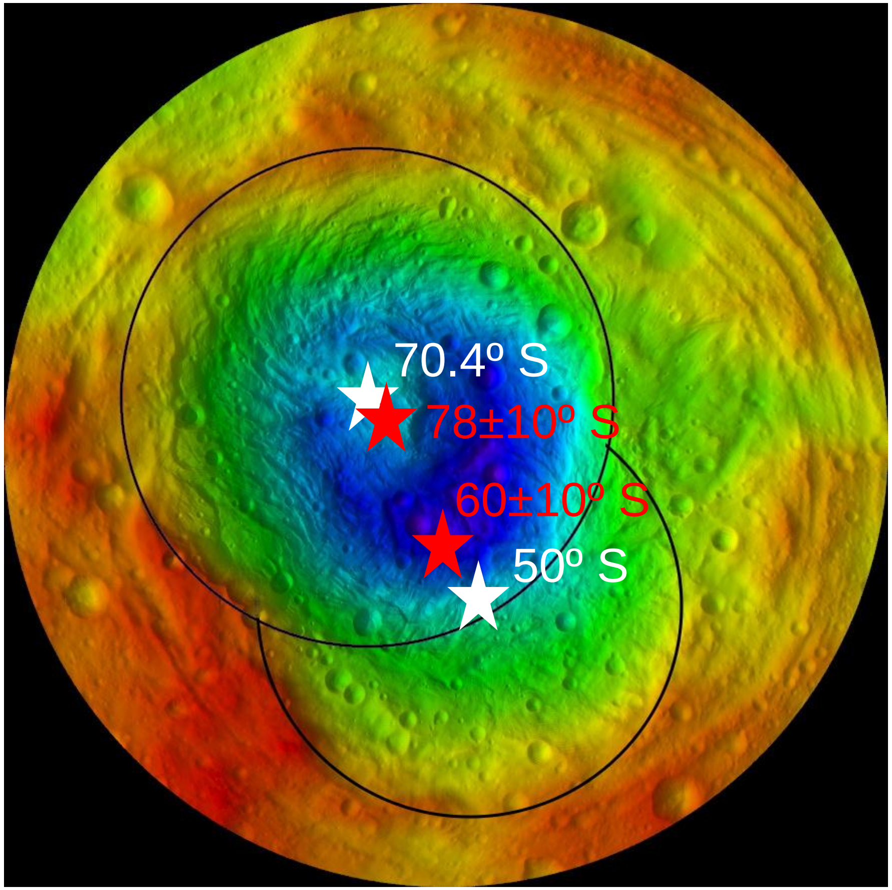
- Other linear structures extend to the NW at an angle from the equatorial troughs, starting at ~300ºE longitude
  - Shallower walls, rounded edges, infilling and heavy cratering, suggesting older features
  - Primary structure in this group is 390 km long and 38 wide
  - Other features are grooves and range from 31-212 km long
  - Have currently mapped 7 linear structures with this orientation
- Analysis indicates that most of these features are co-planar, suggesting a common formation mechanism
- **Poles cluster at 60º ± 10º**



Buczkowski et al.

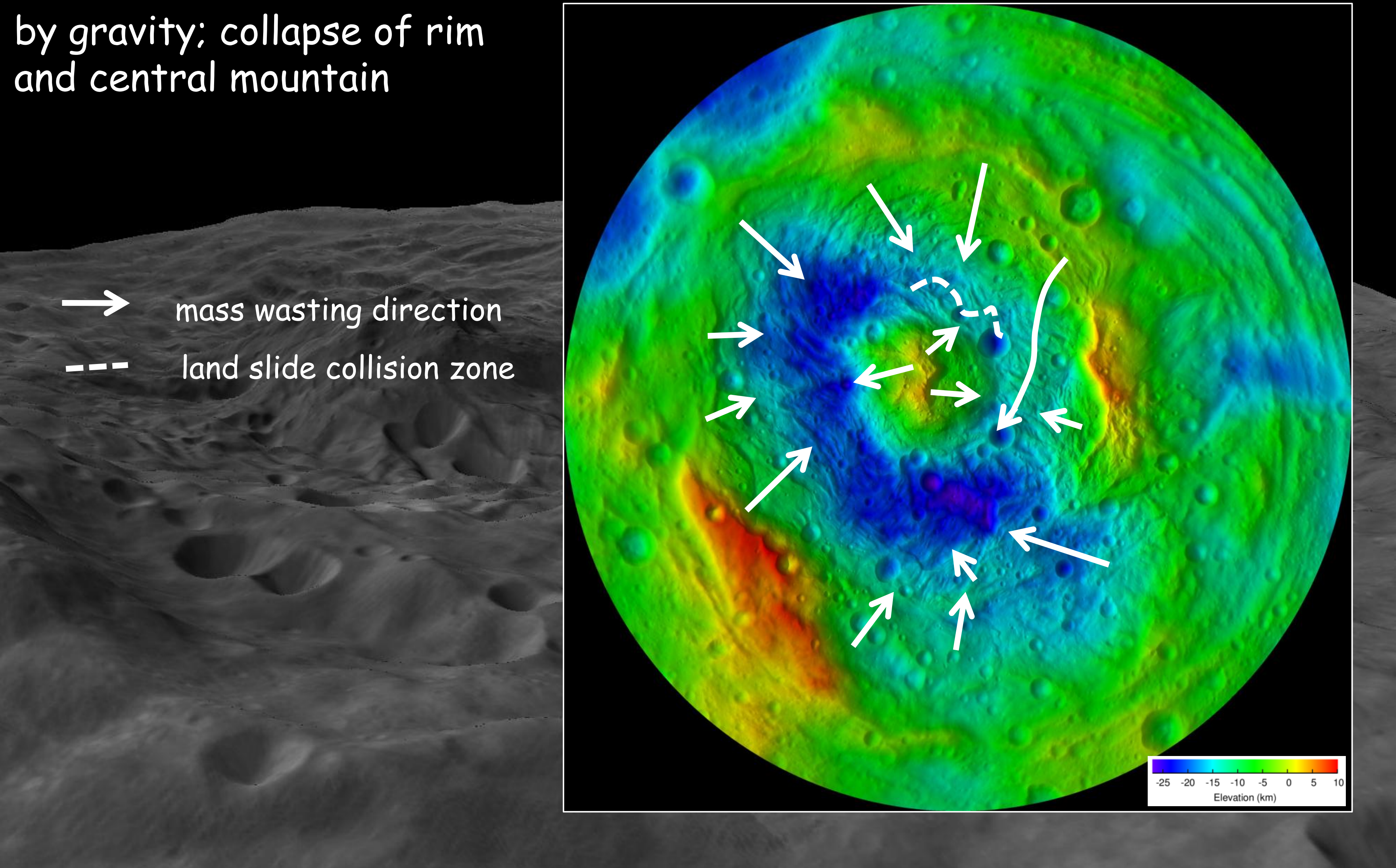
Implications

- Orientation of both sets of linear structures is consistent with formation due to giant impact(s) in the polar region
- Two basins in the southern hemisphere of Vesta
  - Rheasilivia and an older underlying basin
- Poles of the two fracture planes cluster roughly at the latitude of the two basin centers
  - Older northern troughs correspond to the older basin



Buczkowski et al.

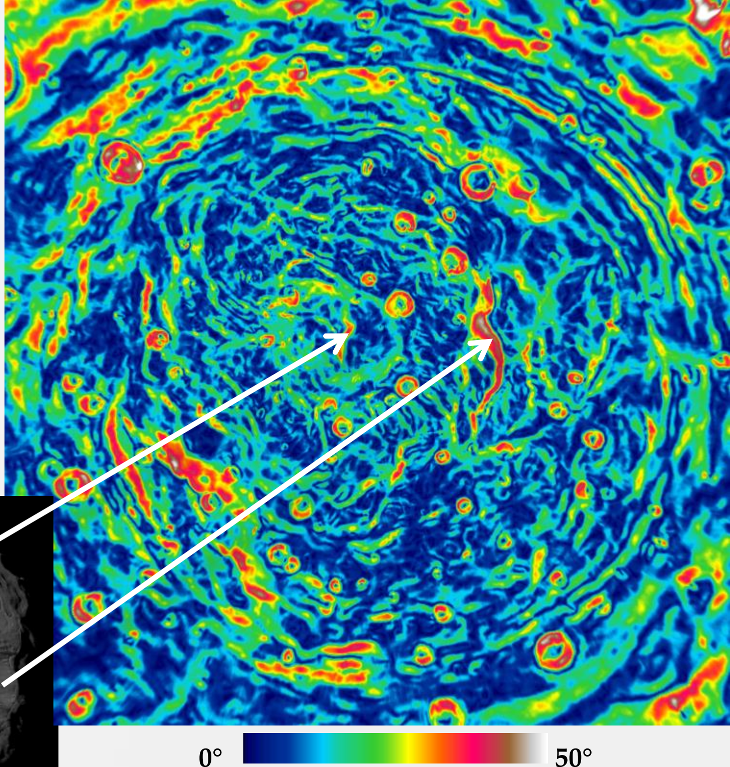
South polar scarps
material redistribution by gravity; collapse of rim and central mountain



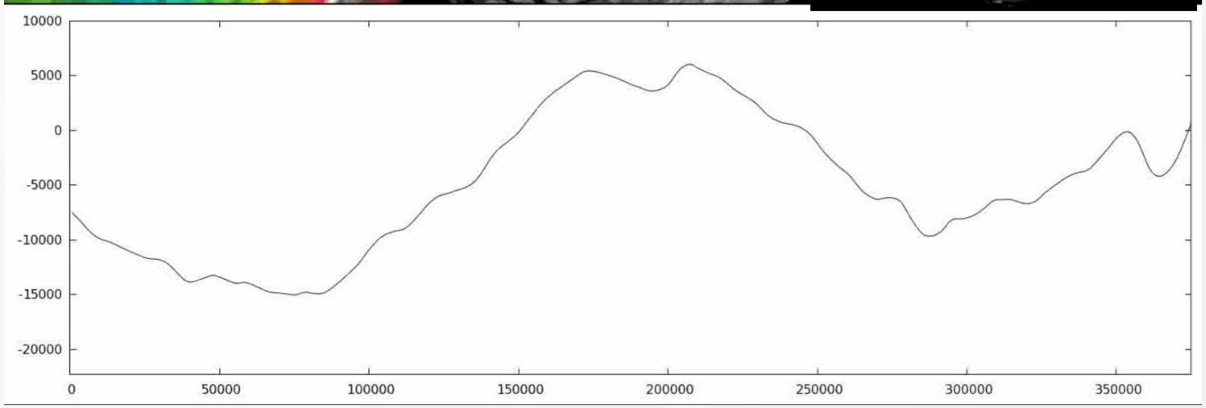
South polar impact

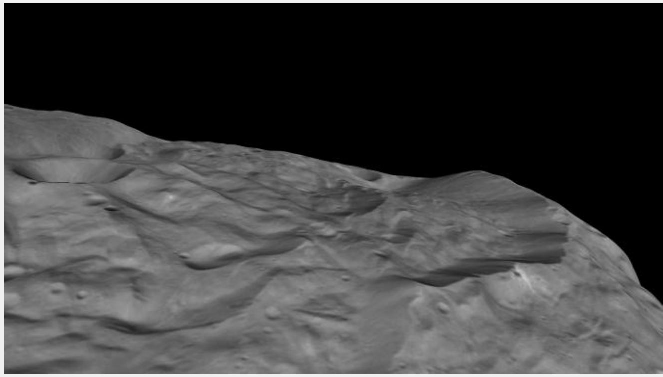
regolith formation and large scale resurfacing by global erosion and ejecta deposition

material redistribution by gravity
mass wasting due to steep slopes and slope failure



Bi-directional slopes w.r.t. ellipsoid
(289/280/229 km)

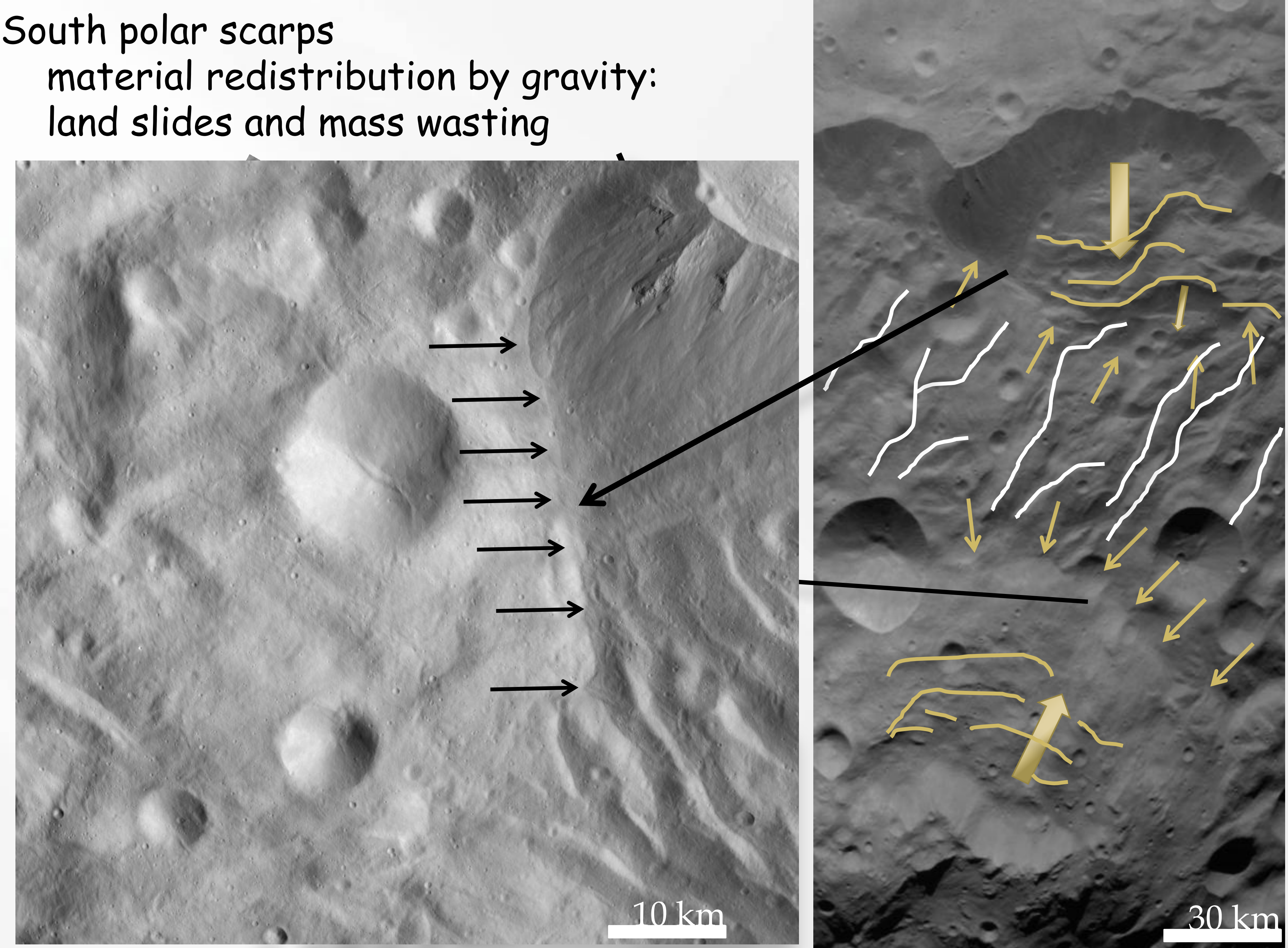




South polar scarps

material redistribution by gravity:

land slides and mass wasting



Volcanism -the theory

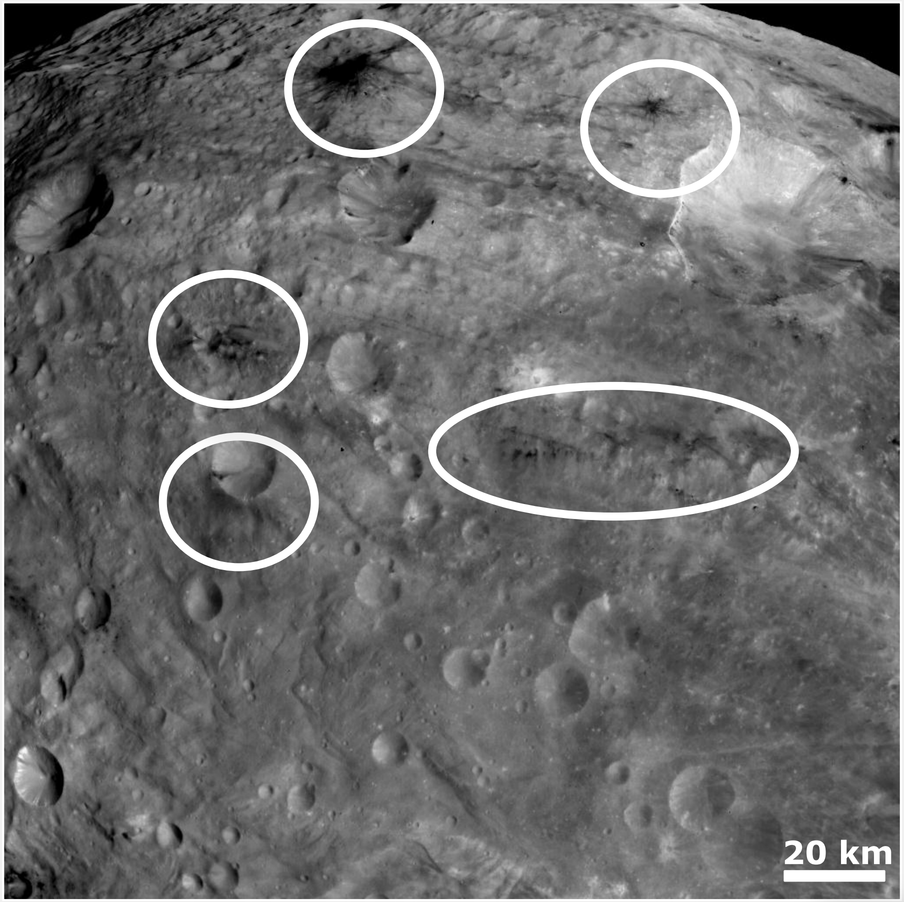
Based on principles of volcanic fluid dynamics on a body with Vesta's physical properties (Wilson and Keil 1996):

- basaltic magma flows upward from zones of partial melting by dikes; extending 1 -30 km with width of mm to m;

- surface flows might have had length of km to tens of km, width of a few hundred m and thicknesses of a few m

- expected eruption rates up to $3\ m^3 s^{-1}$ with volume per single eruption ~ $3 km^3$

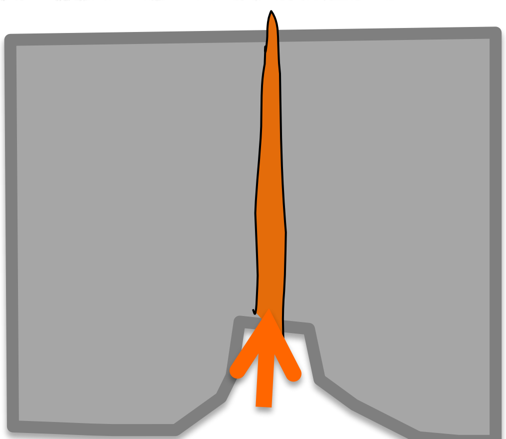
- basaltic partial melt on dry Vesta is expected to have <3.8% volatiles (minimum needed to reach the escape velocity of 350 m/s)

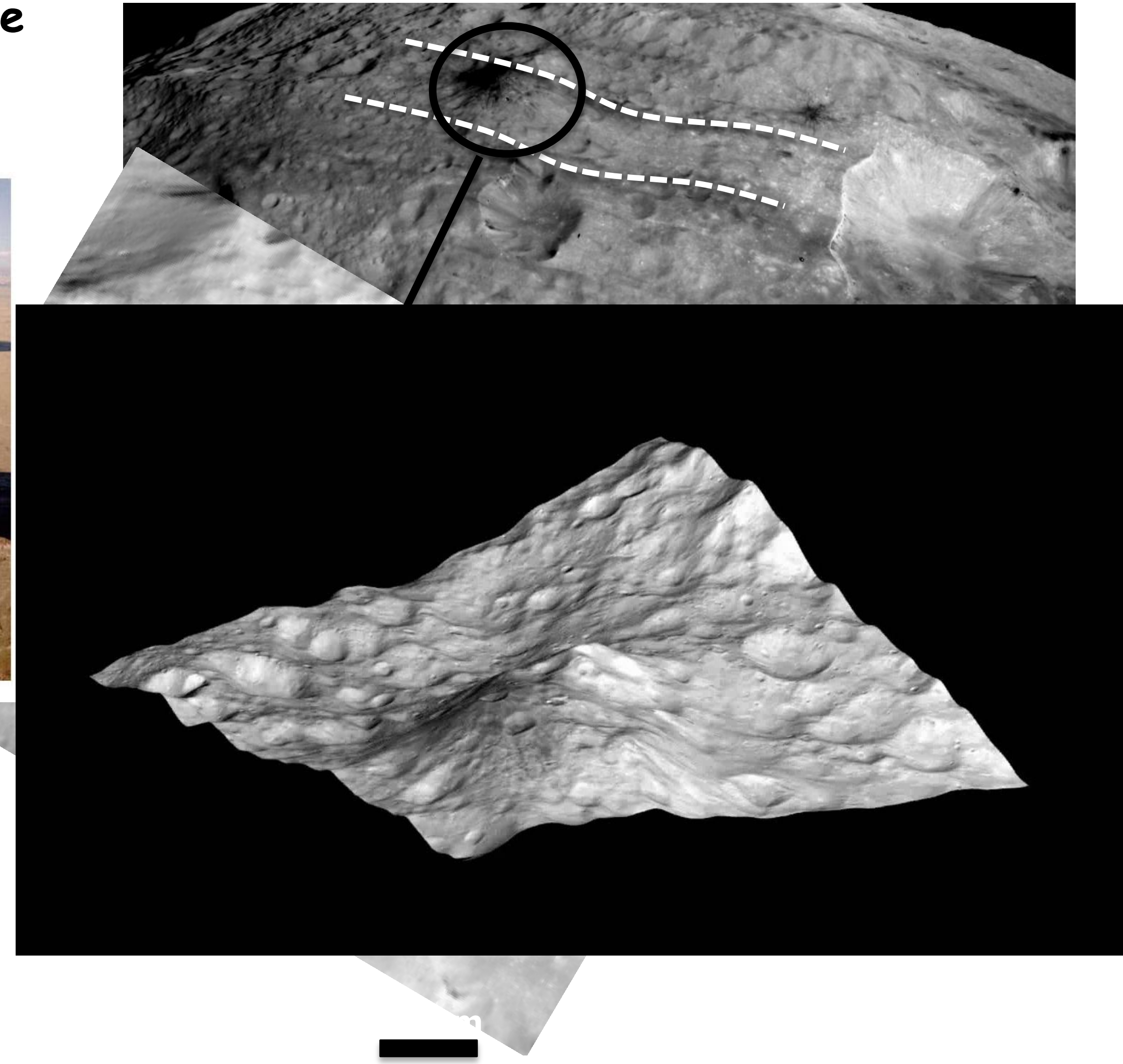


Volcanism

(1) hill: a possible subsurface dike hit by impacts

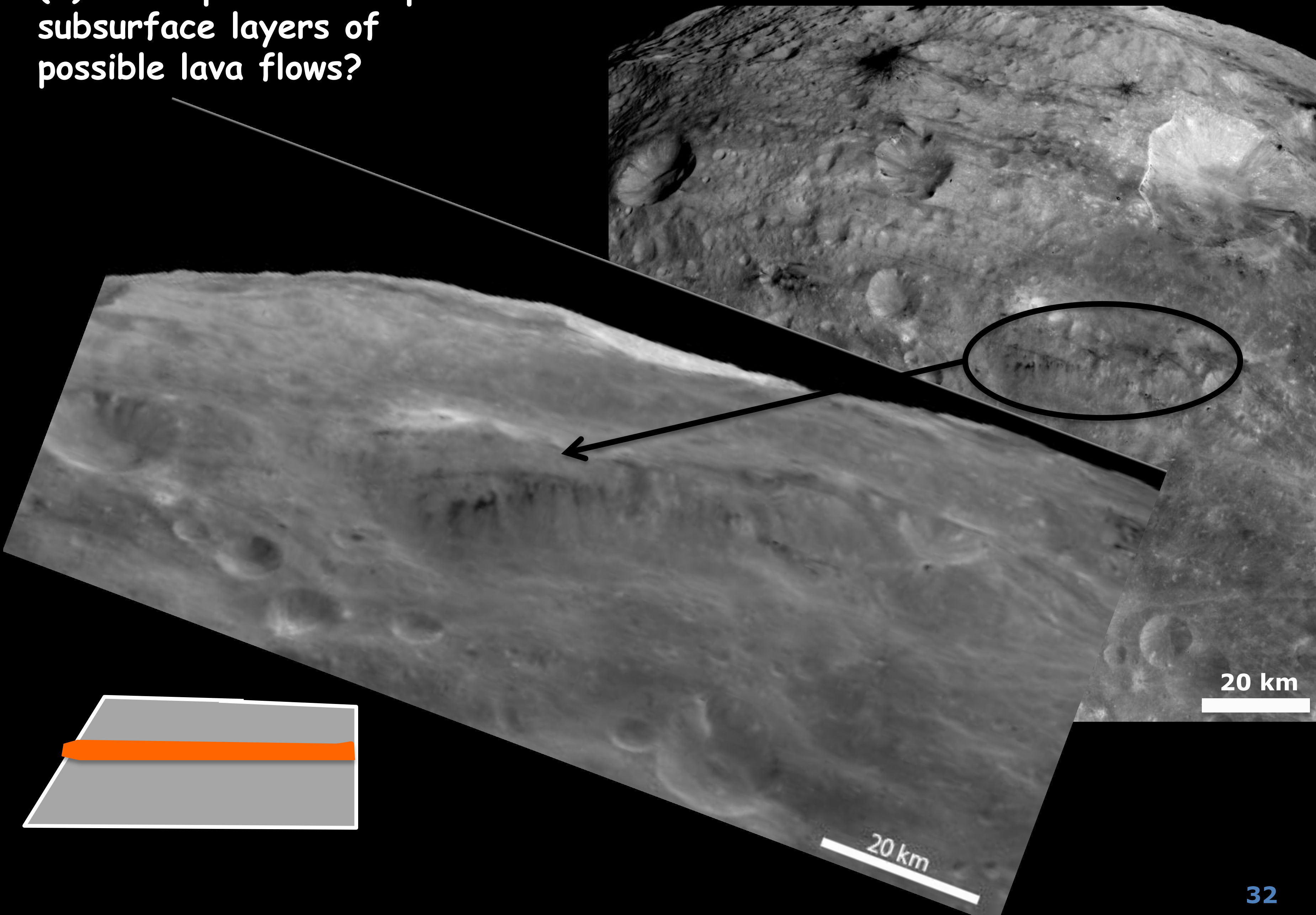
photo copyright Paul Logsdon collection, used with permission





Volcanism

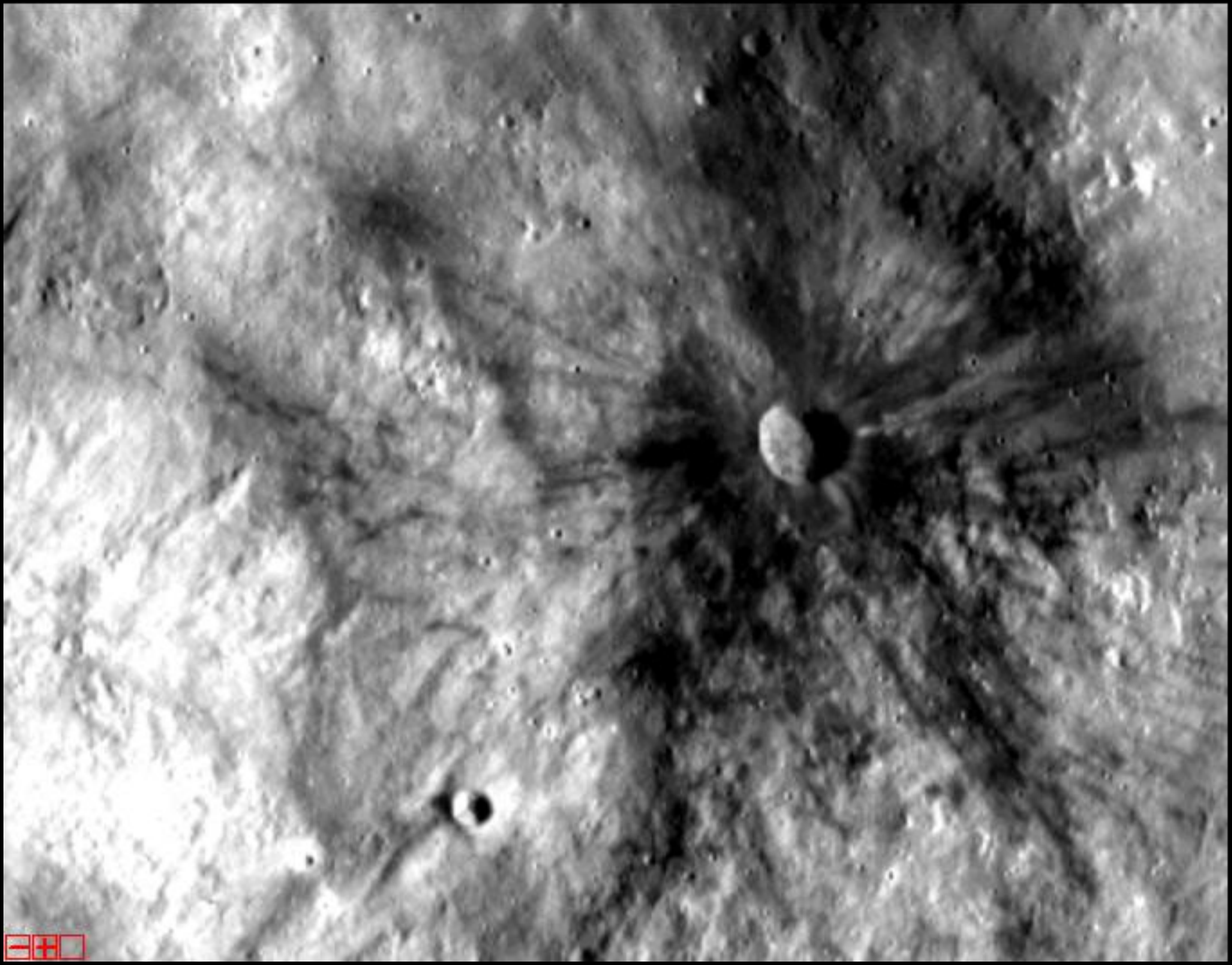
(2) outcrops on a scarp: subsurface layers of possible lava flows?



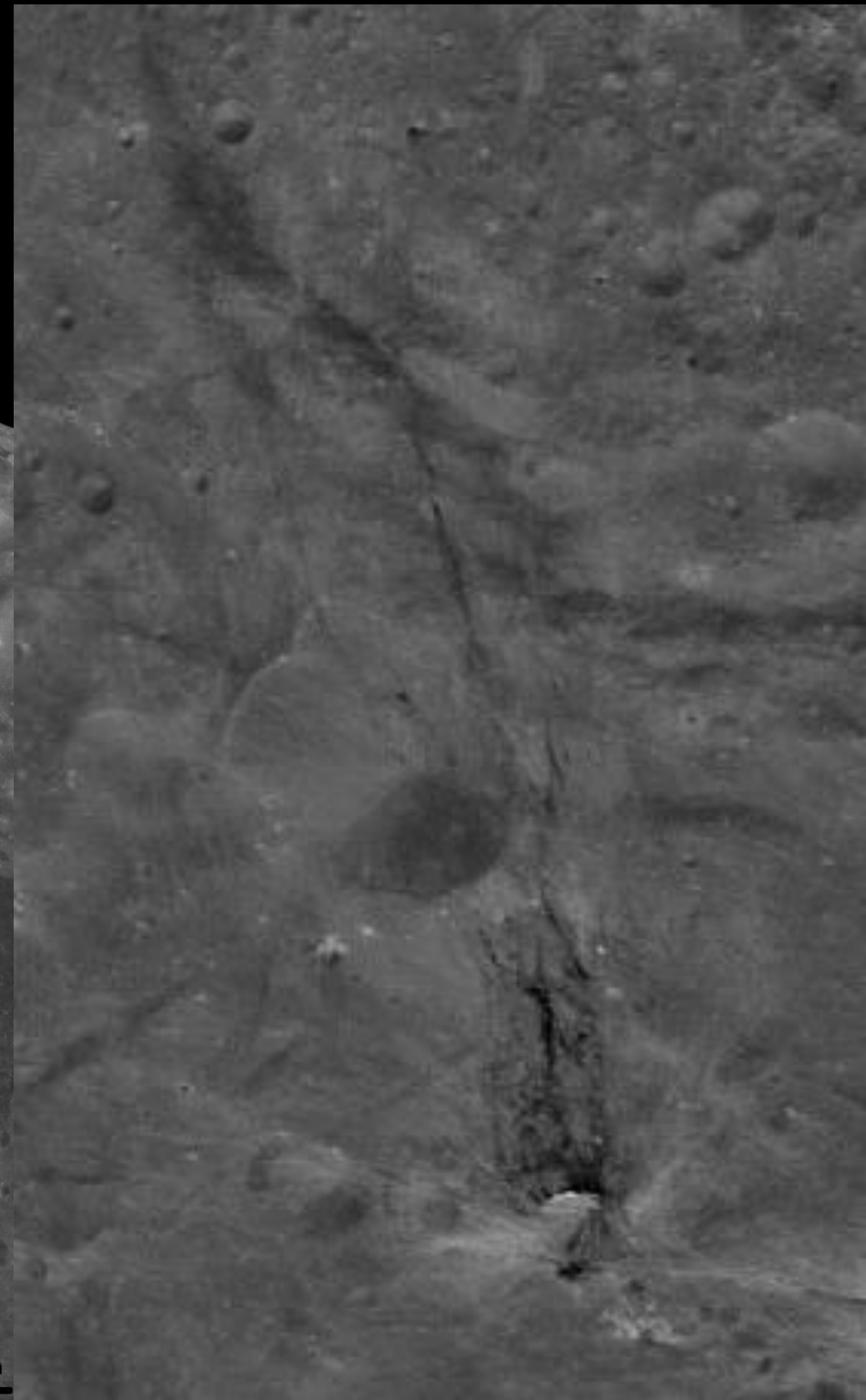
Volcanism

however, other dark material deposits indicate remnants of impactor material

More Dark Material Examples

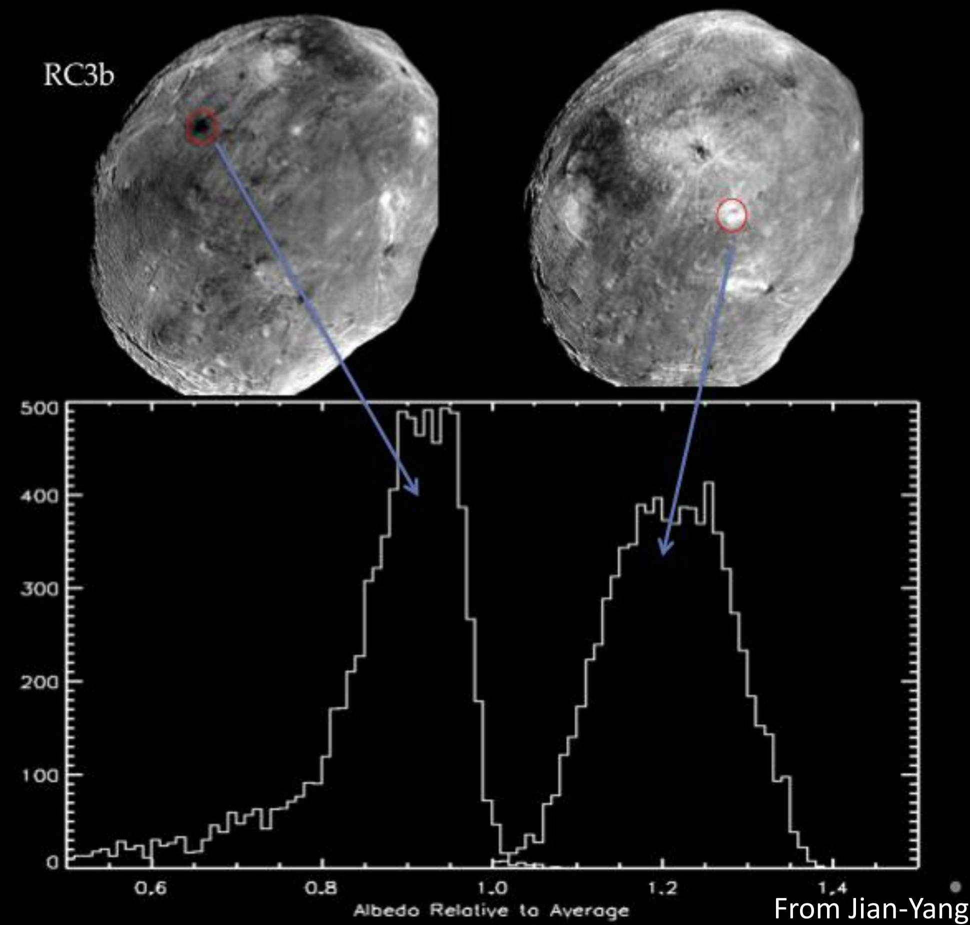


Dark Bands



Photometry Investigations

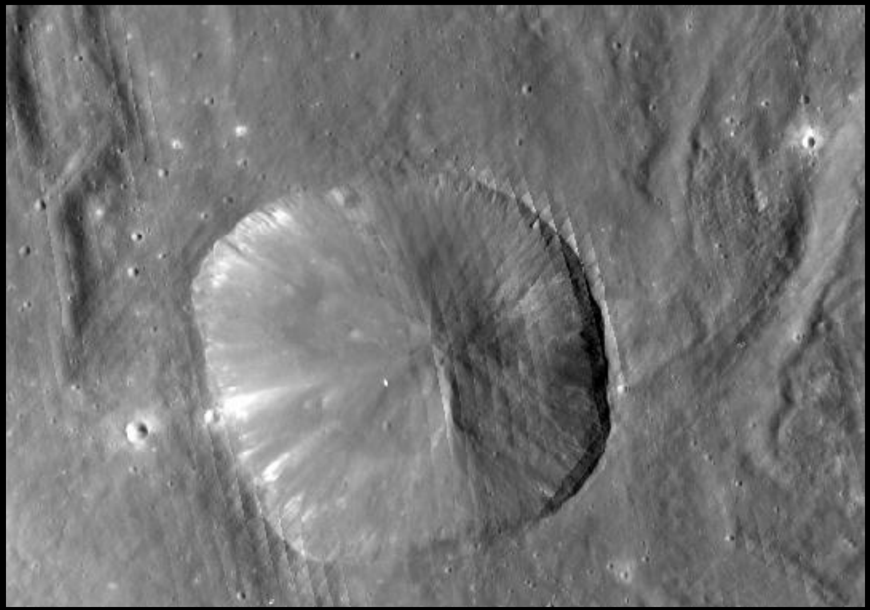
- Dark material is 10-50 % darker than surroundings at this lighting conditions.
- The average brightness is set to 1.0.
- Note the long dark tail => some pixels are very dark (more pure DM?), up to 50% of the average.



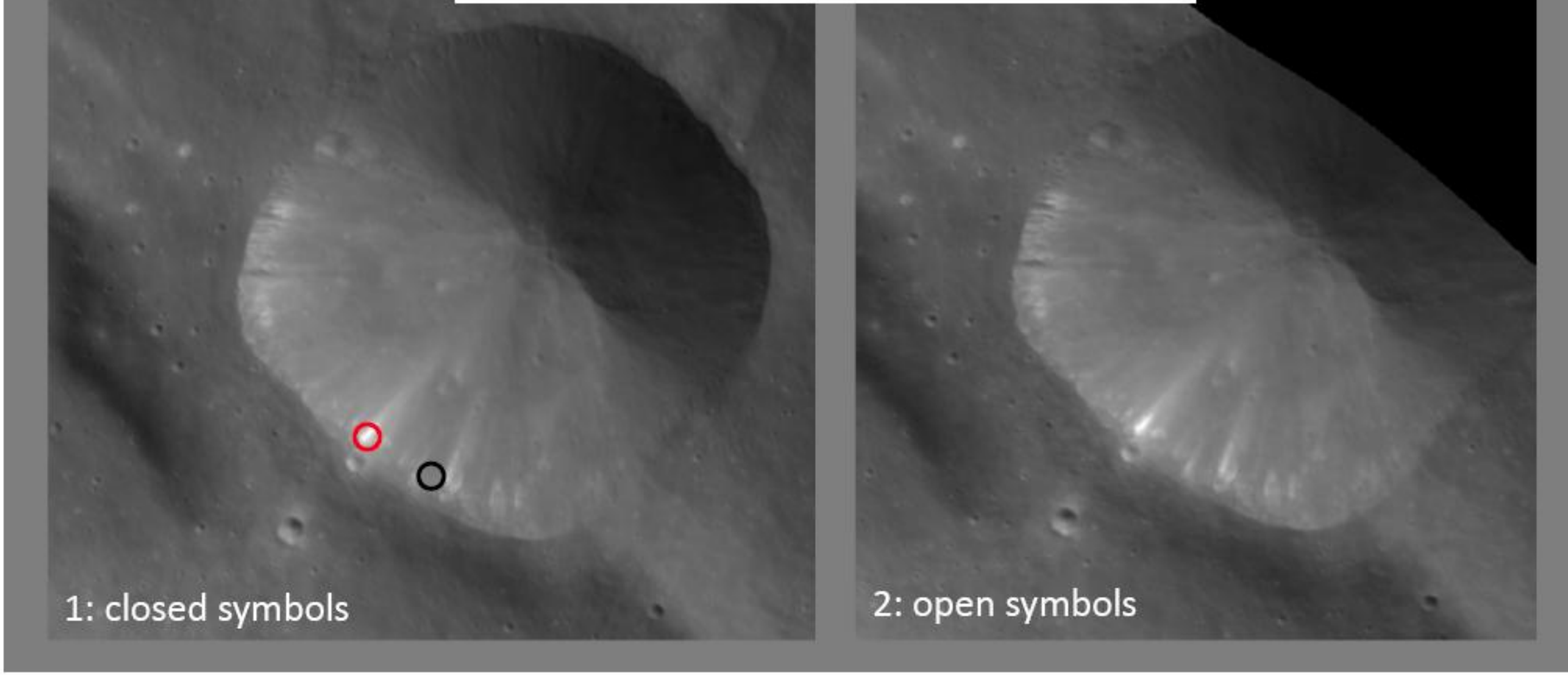
From Jian-Yang Li

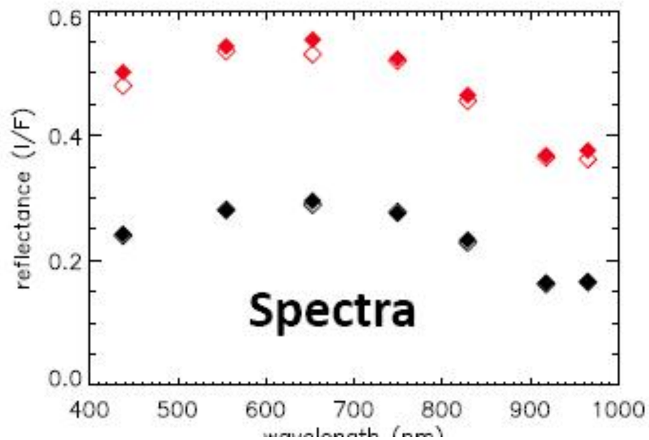
Extremely bright materials

- Extremely bright materials on crater wall in Rheasilvia (358º, -66º)
- Albedo 2-3x global average
  – But that's SSA>1 (unphysical)!
  – Multi-scattering involved, reflectance is non-linear to SSA
- Many bright spots nearby, 1.8-2x average albedo



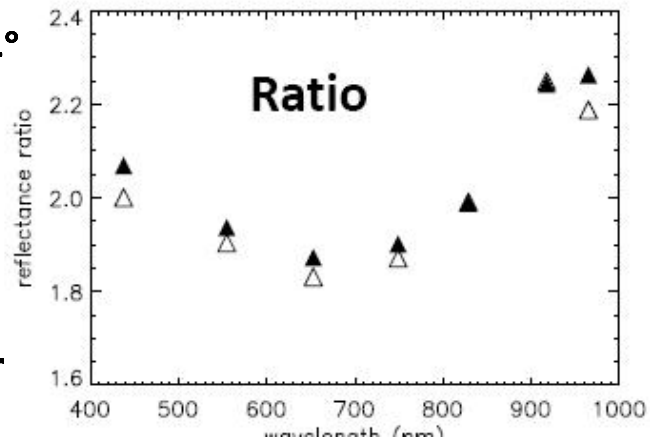
Two FC color cubes from HAMO

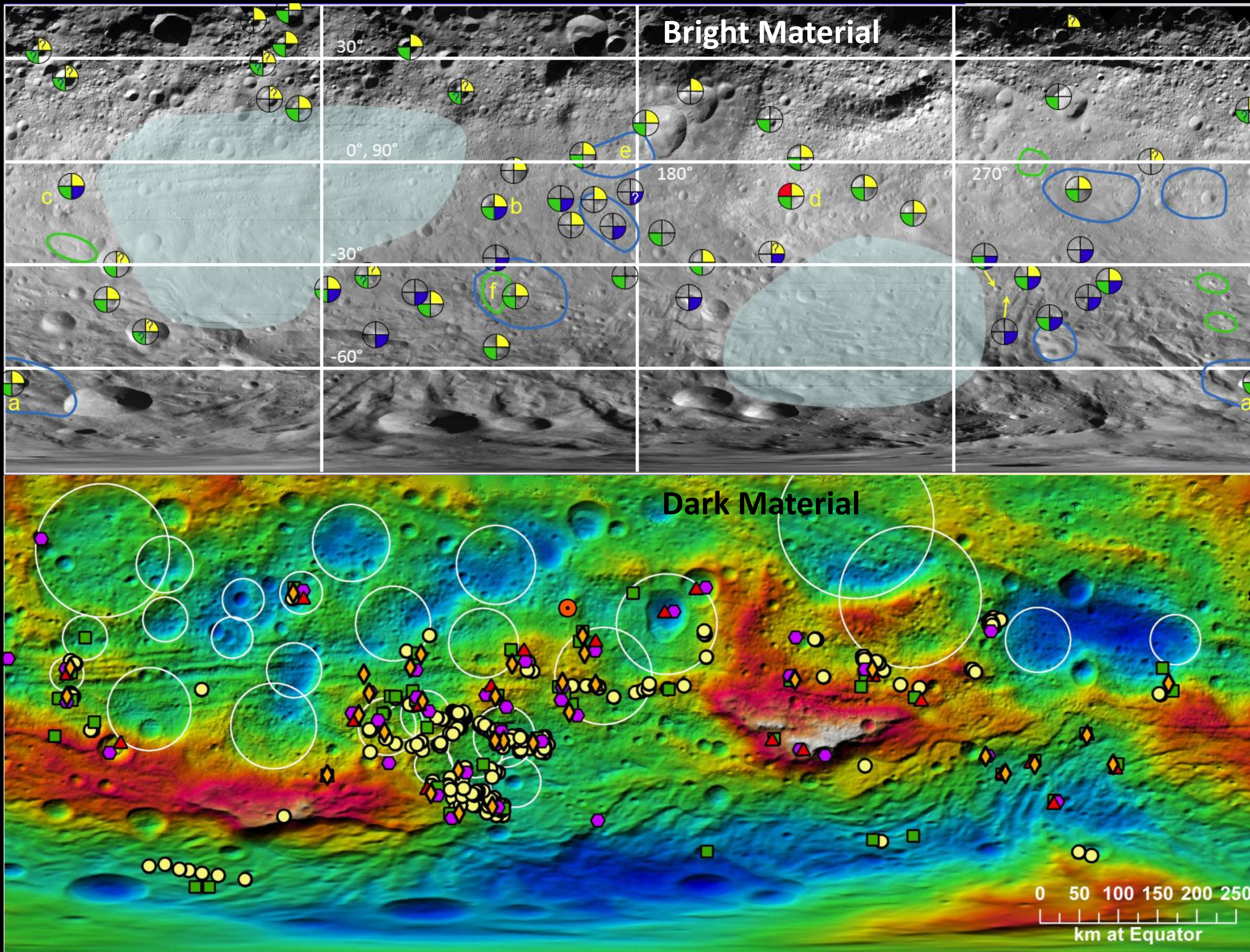




64.27°S, 1.54°

S.E. Schröder



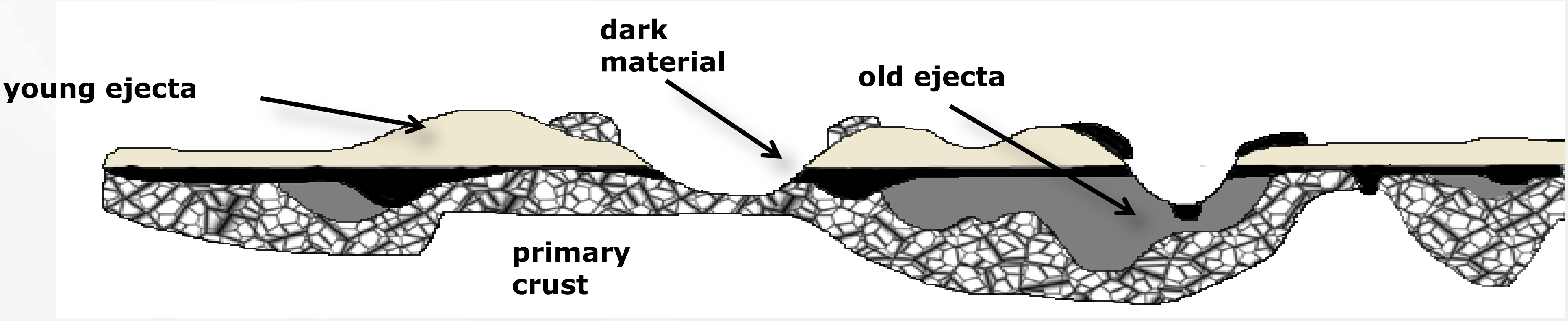

Bright Material
30°
0°, 90°
180°
270°
-30°
-60°
a
b
c
d
e
f
Dark Material
0 50 100 150 200 250
km at Equator

Preliminary geomorphology conclusions:

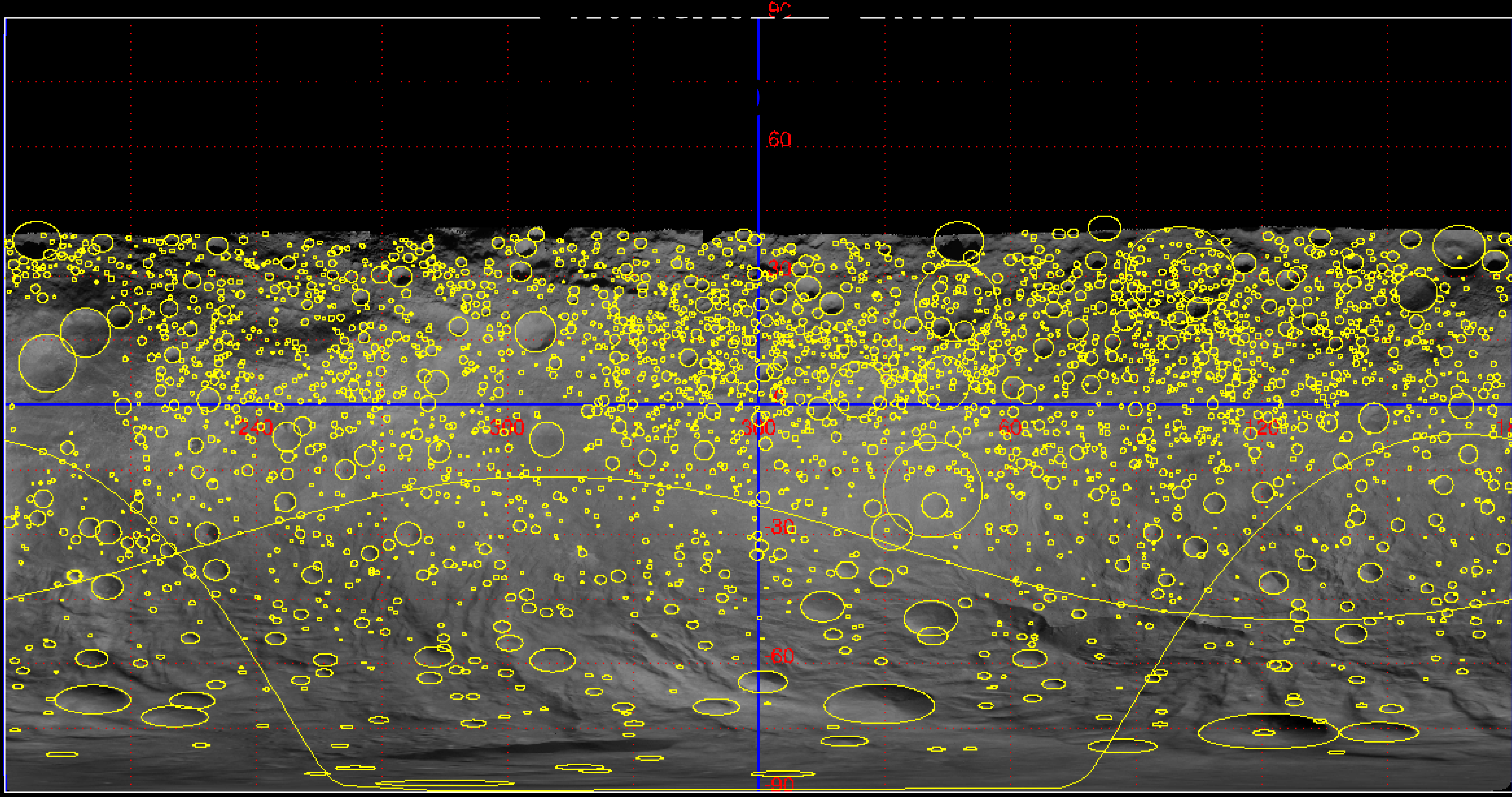
- Primary crust is covered by global/regional distributed ejecta: craters are eroded by impacts and covered by subsequent ejecta of larger impacts -> impacts induced resurfacing by the formation of multiple regolith layers

- Steep slopes and failure support mass wasting and scarp formation -> additional resurfacing by landslides

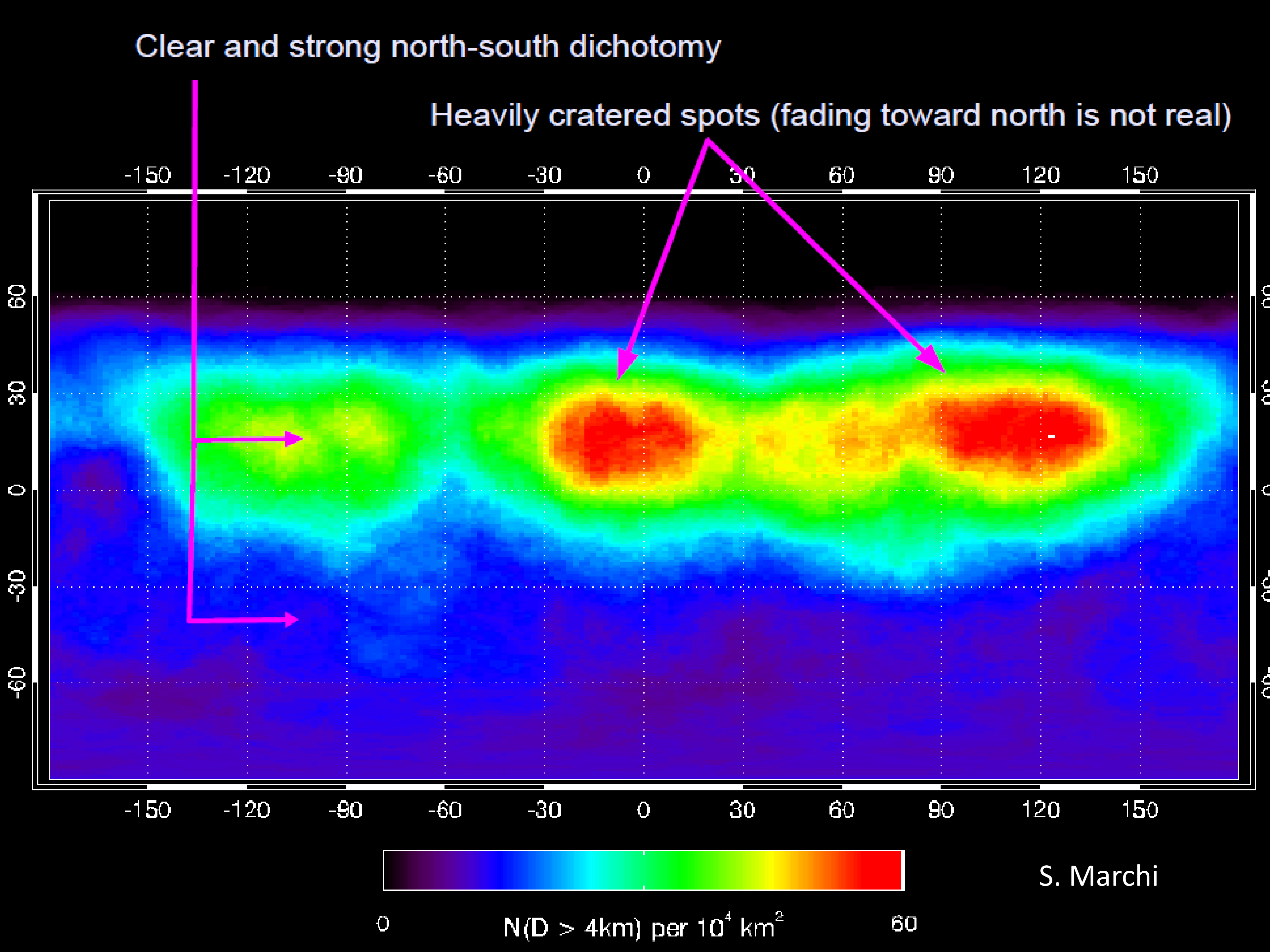
- source of dark material is either remnant impactor material (fresh or buried an excavated by impact) or impact excavated volcanic material or may originate from both processes (compositional information is needed)



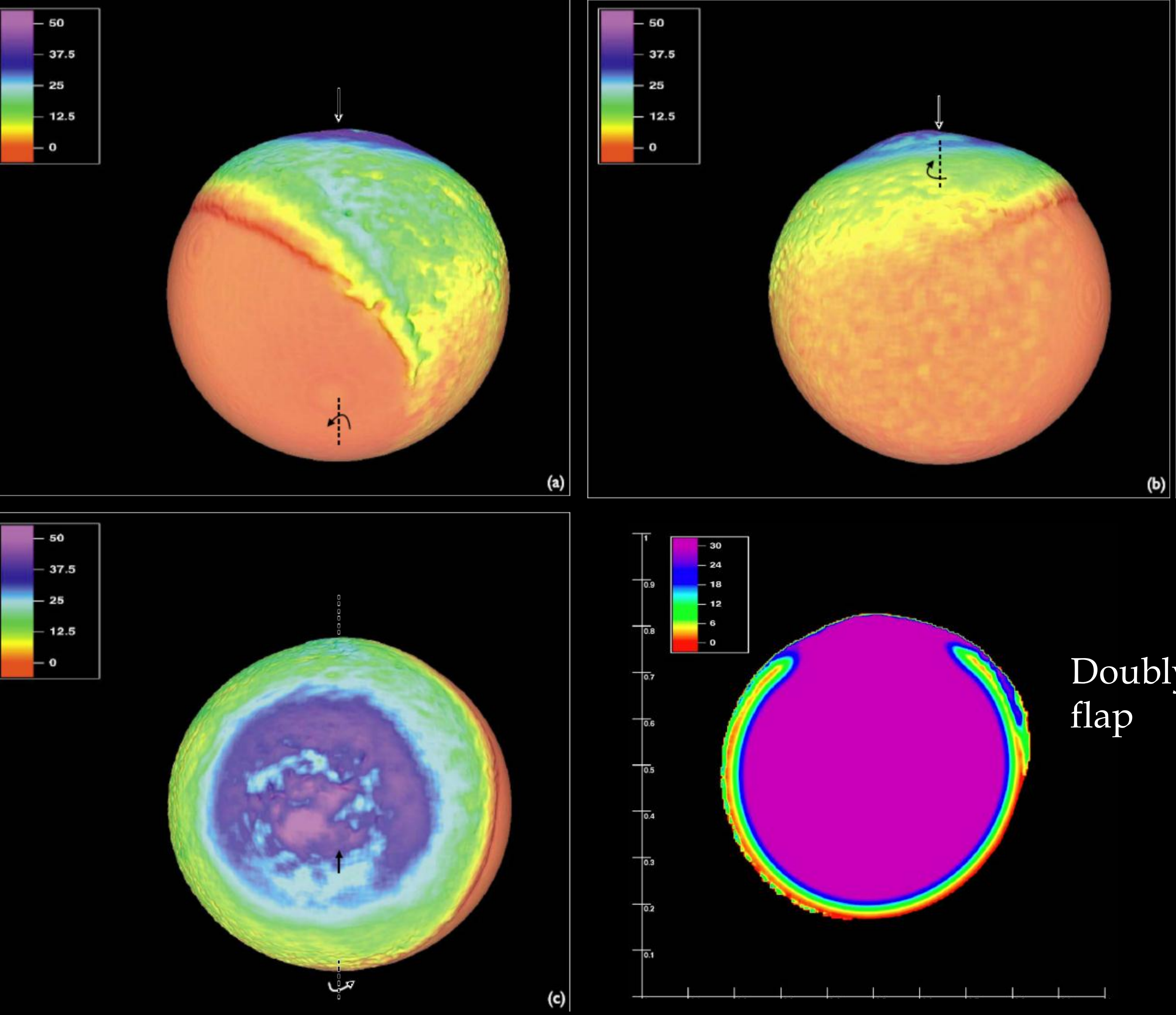
Craters with diameters > 4 km



S. Marchi

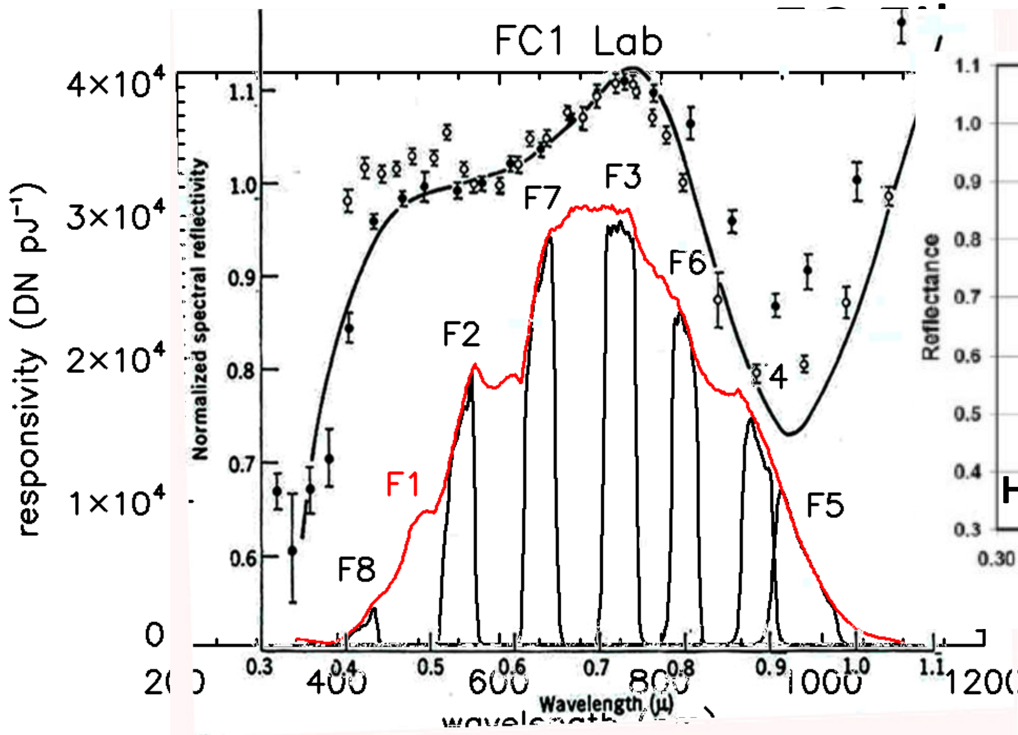


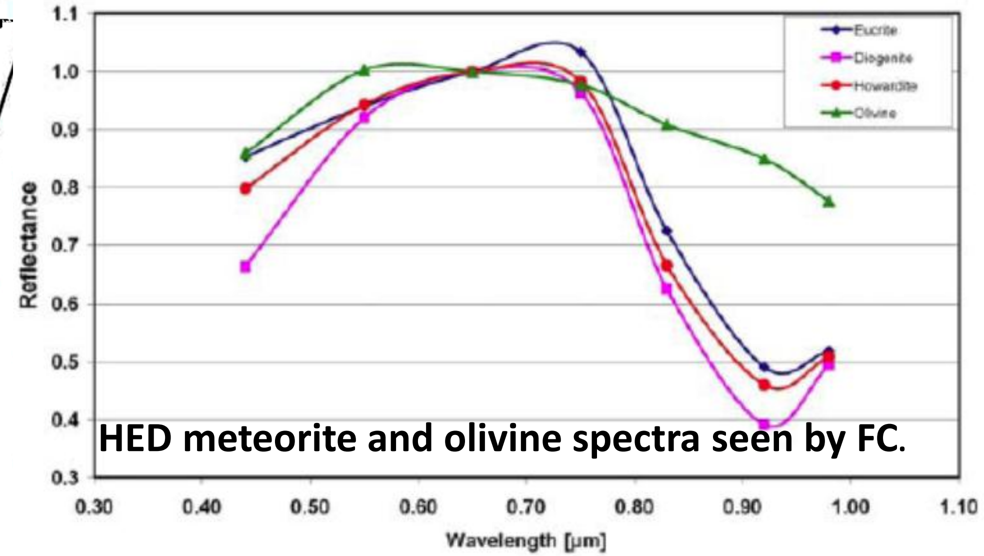
Clear and strong north-south dichotomy
Heavily cratered spots (fading toward north is not real)
-150
-120
-90
-60
-30
0
30
60
90
120
150
60
30
0
-30
-60
0
N(D > 4km) per 10^4 km^2
60
S. Marchi



Doubly-overturned flap

Mega impact (50 km impactor), 45°, rotation (Jutzi and Asphaug (2011))





HED meteorite and olivine spectra seen by FC.

F1: 1 [DN/s] = 1.99E–5 [W m^{-2} sr^{-1}]
F2: 1 [DN/s] = 5.52E–7 [W m^{-2} nm^{-1} sr^{-1}]
F3: 2.69
F4: 5.67
F5: 5.82
F6: 4.39
F7: 3.30
F8: 4.81E-6

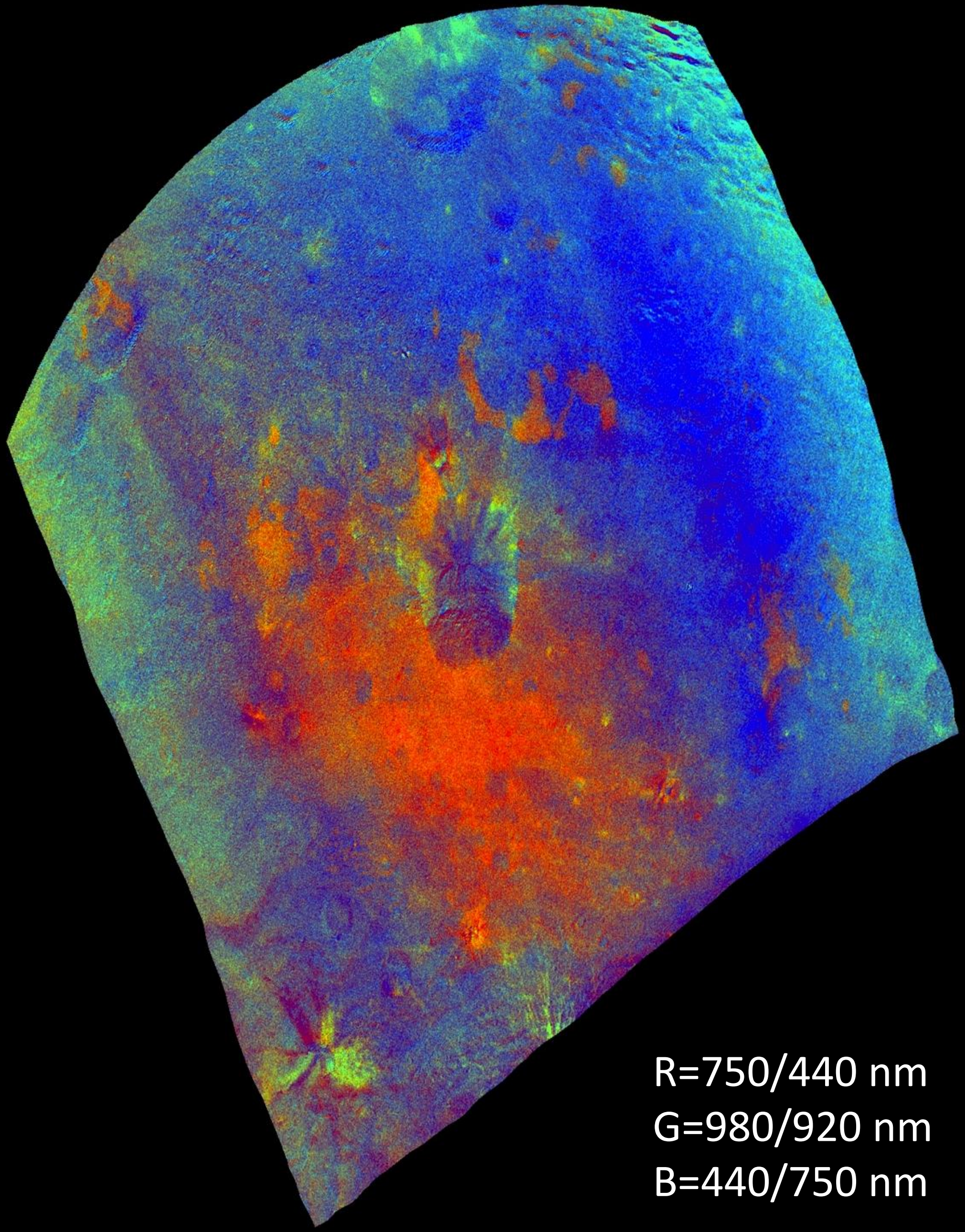
Filter responsivity to solar spectrum rather uniform

Diverse terrains on Vesta

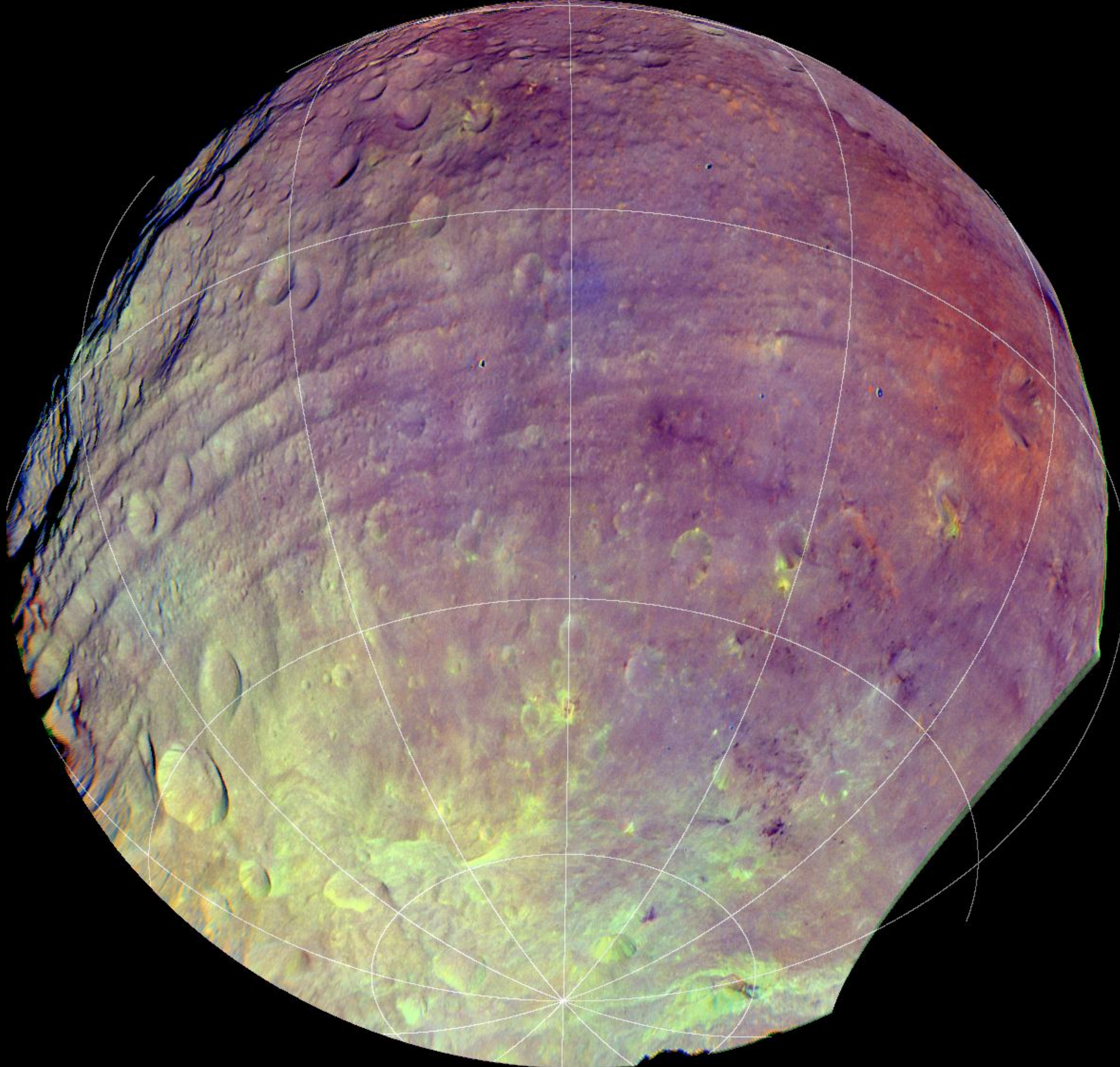
- Vesta has one of the most diverse terrains among small bodies
- Here we present examples of these terrains
- We classify these terrains as bright, dark, gray, and orange.
- Non-photometric, photometrically-corrected, Clementine, Gas Pedal

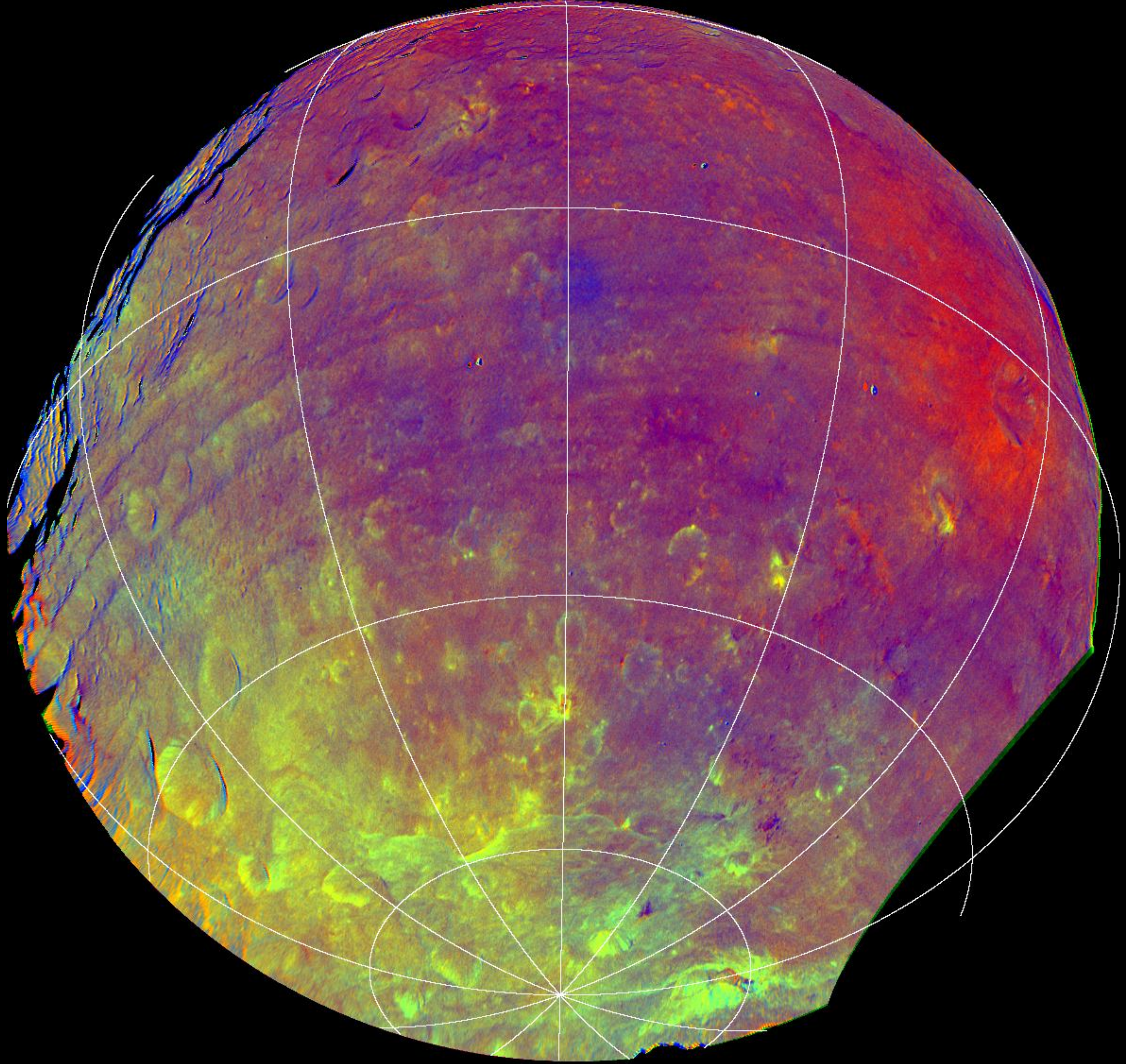
Oppia crater

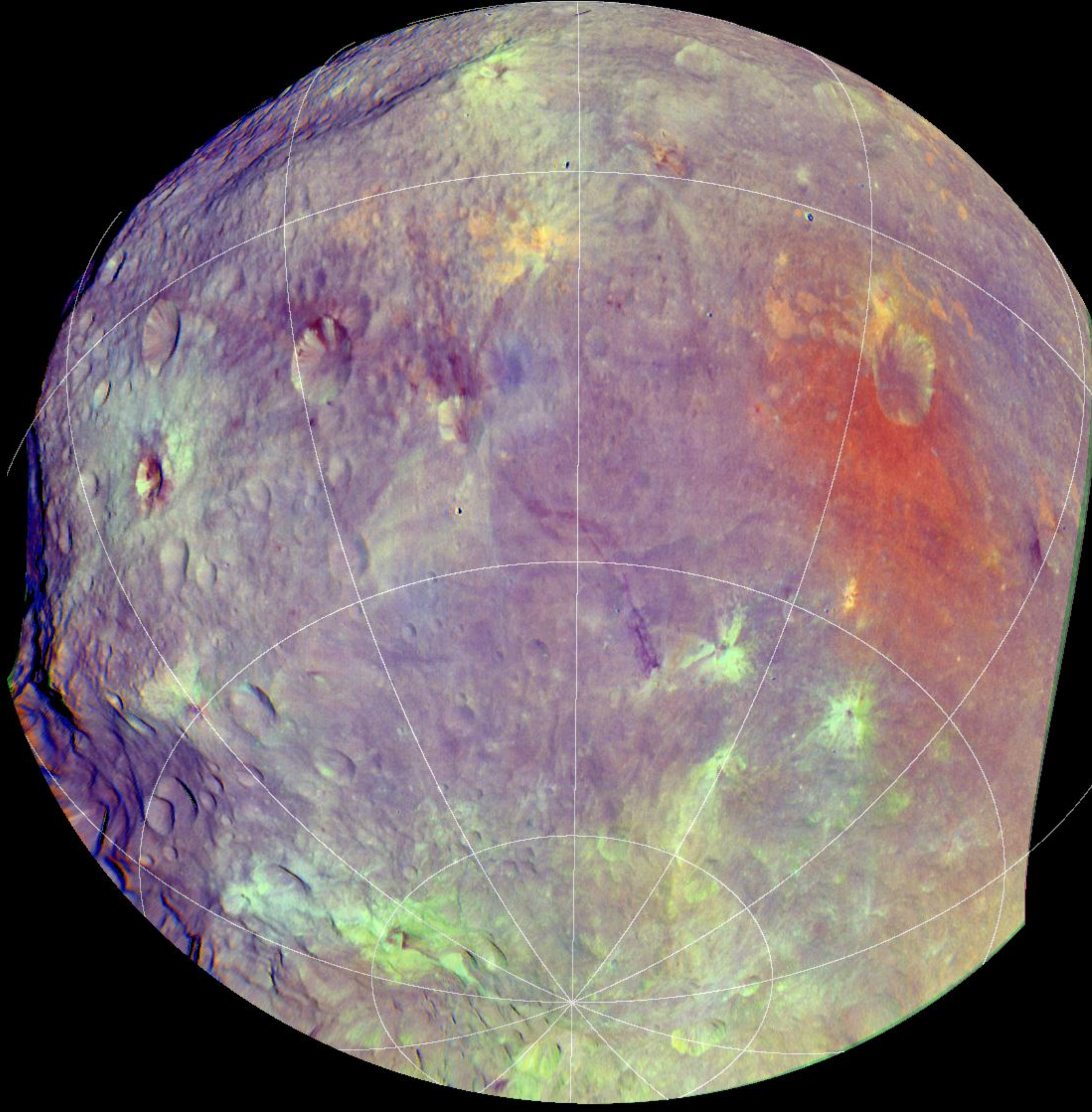
- Diameter 35 km E-W, 40 km N-S
- Oblique impact with a large ejecta blanket “red/orange” in color ratio
- Similar orange patches also found around this crater
- Orange/red color suggests steeper visible spectral slope.
- Possible origin: Excavation of buried layer with different composition.

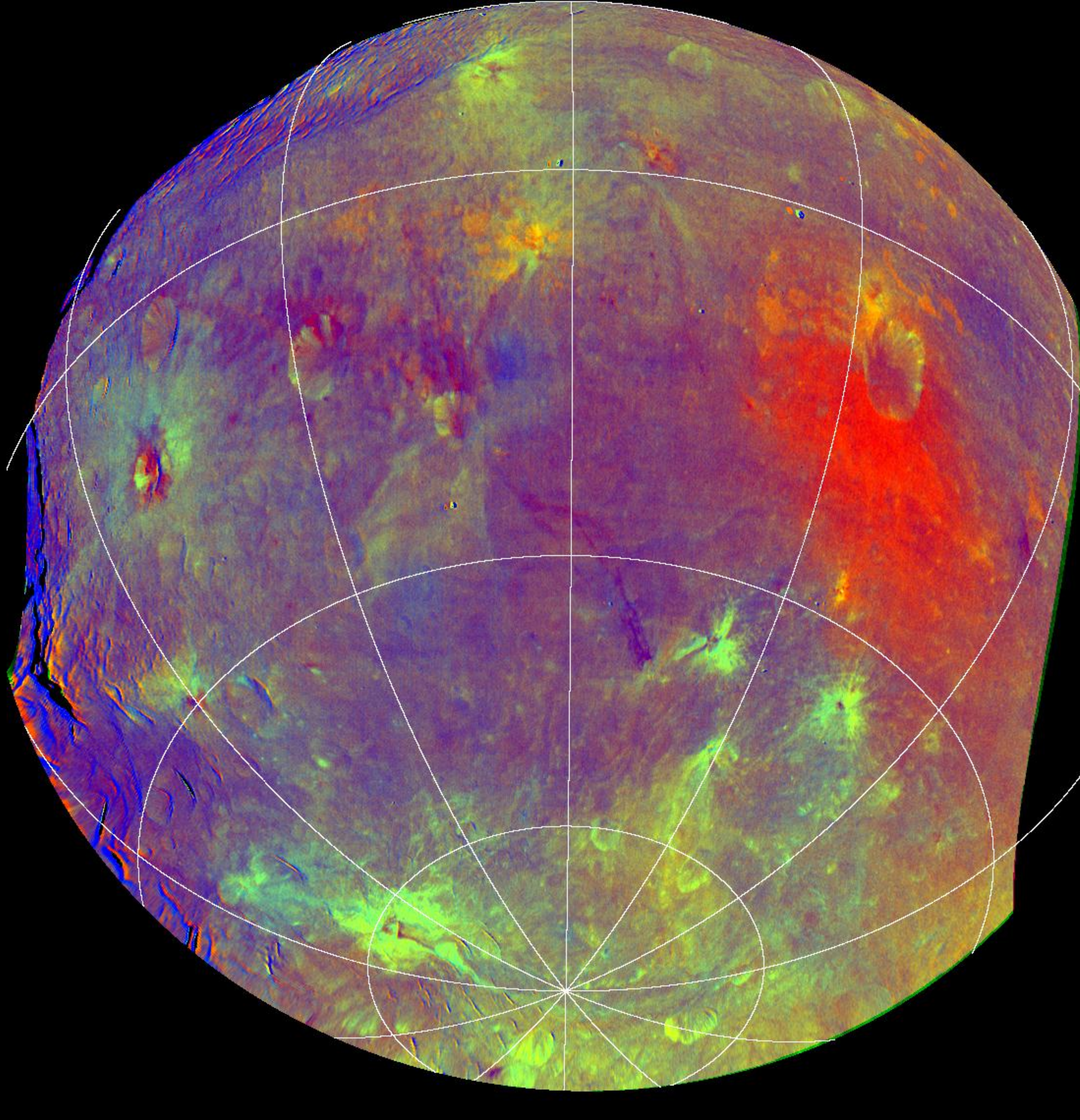


R=750/440 nm
G=980/920 nm
B=440/750 nm

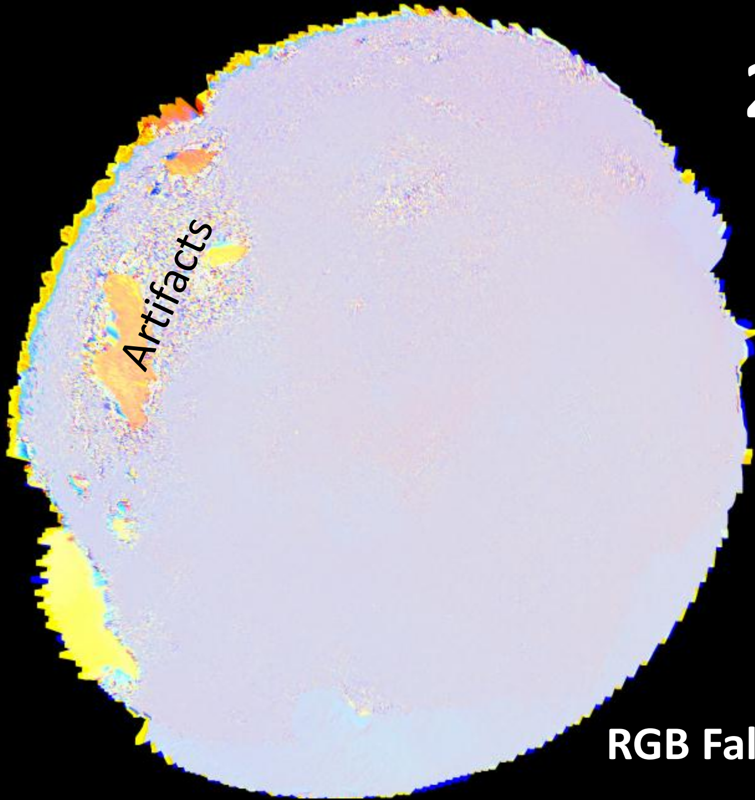






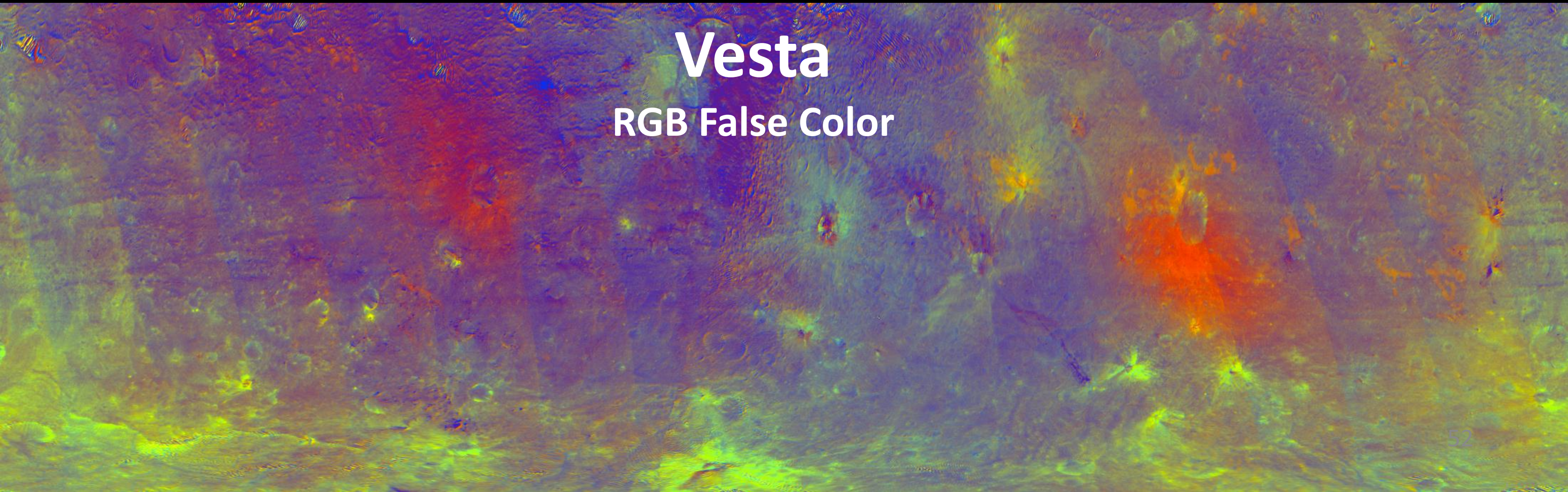


21 Lutetia

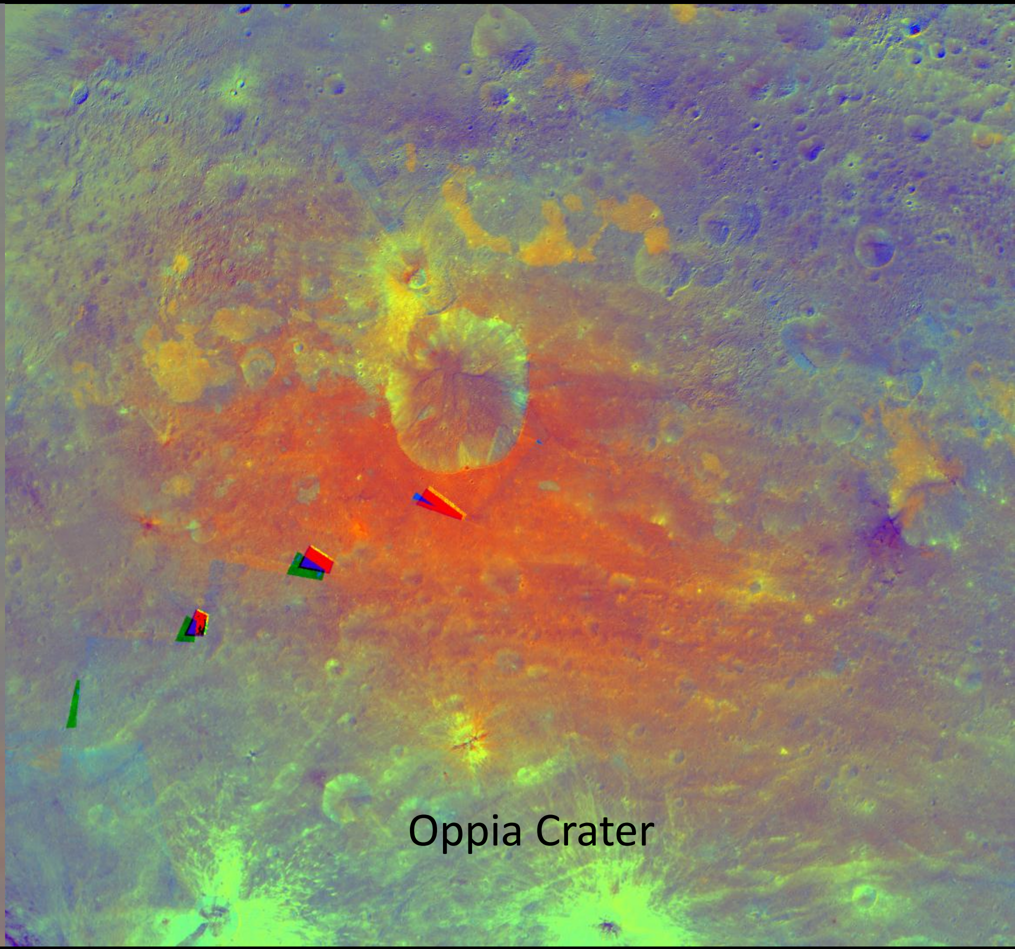


RGB False Color

Ortho Image

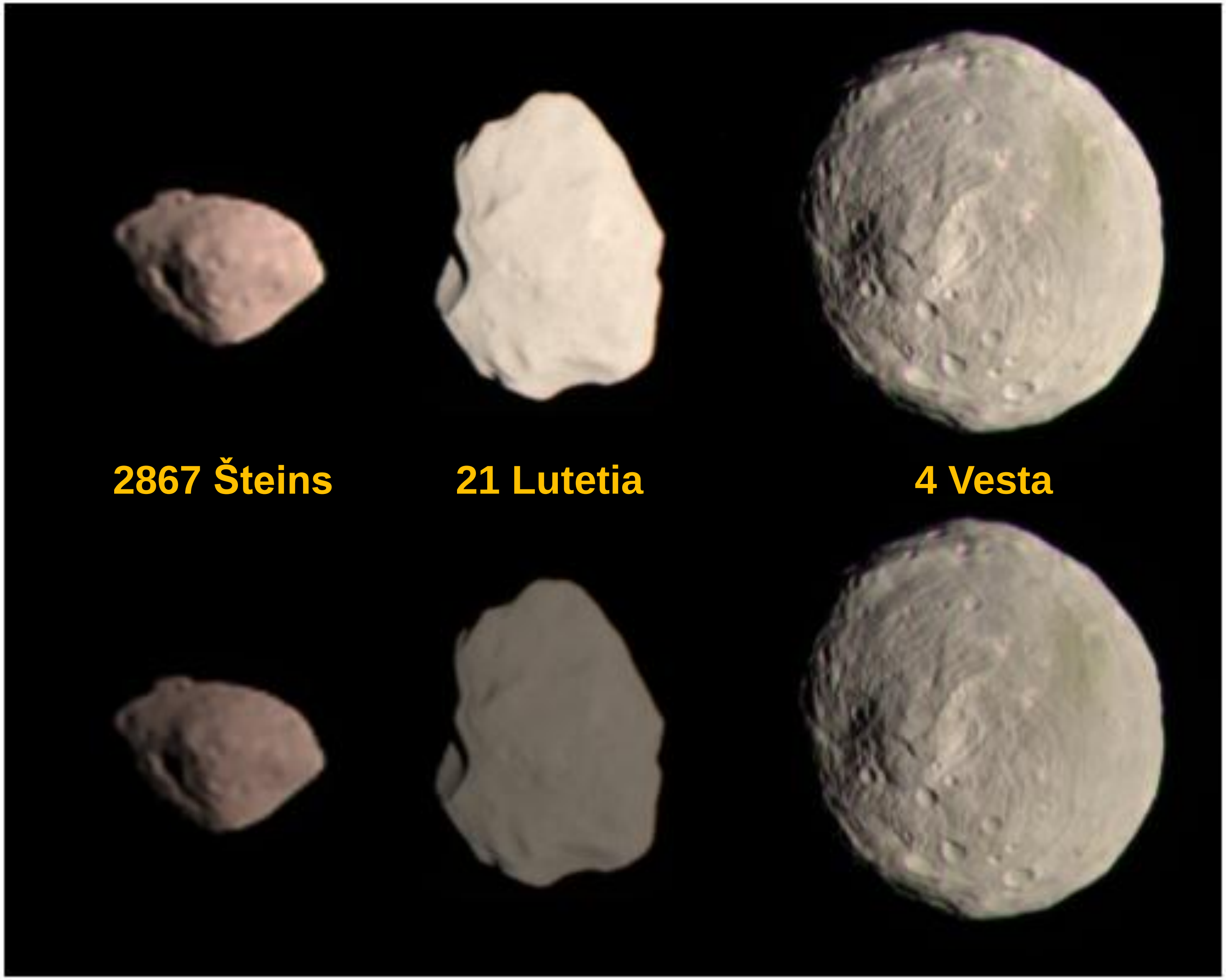


Lutetia and Vesta Colours



Clementine ratios

“True” Colour Comparison

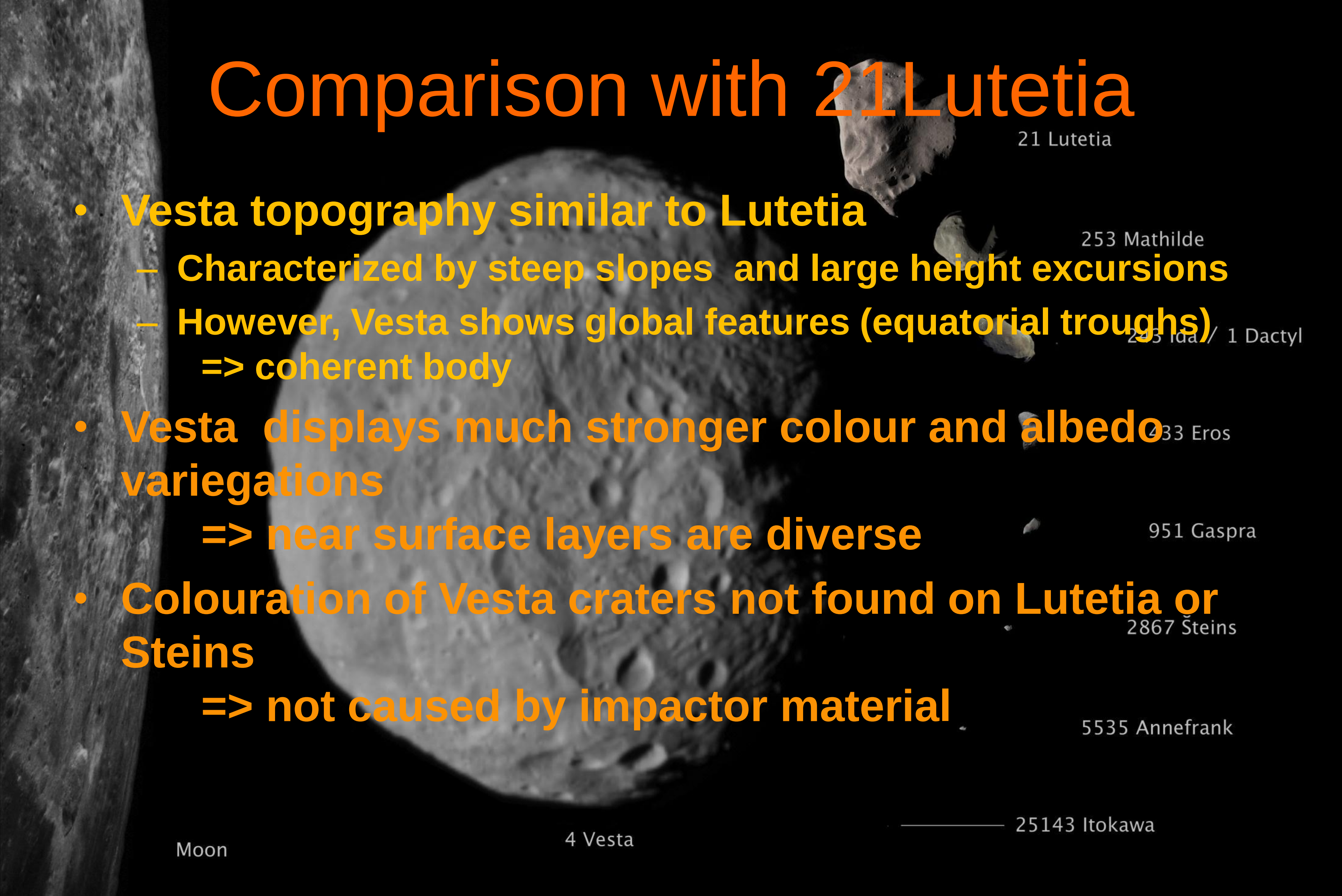


Oppia
Leslie
Gaffey (1979)

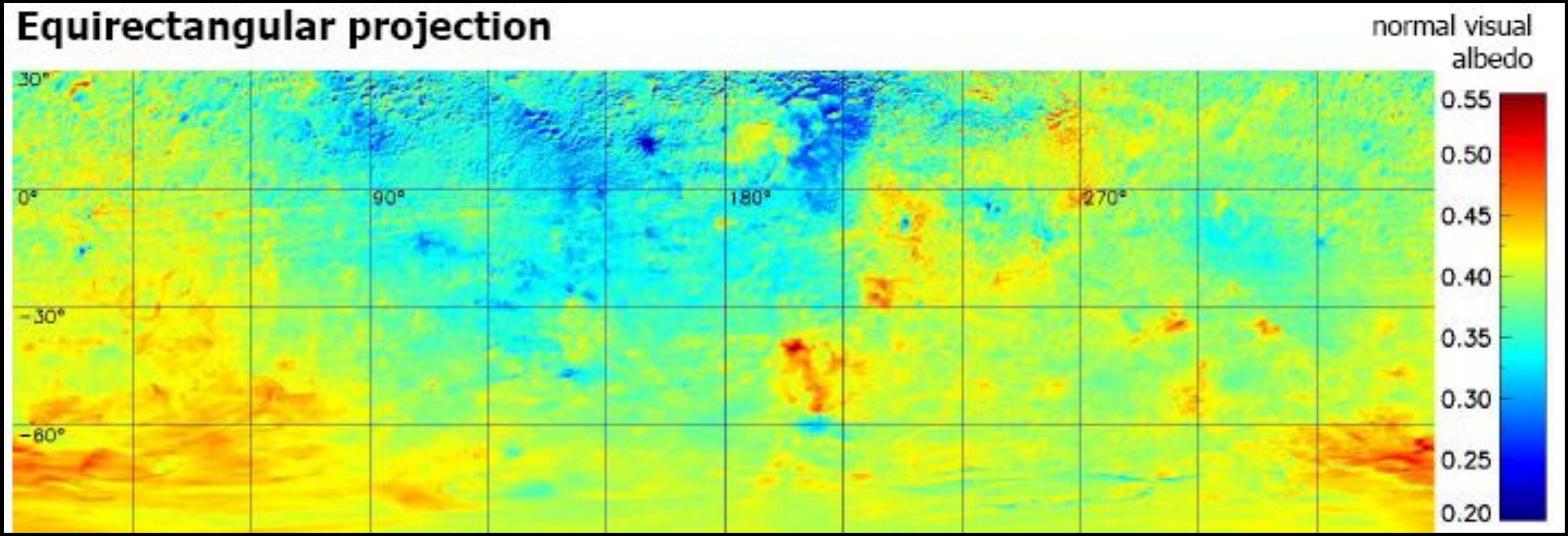
Steins - Lutetia - Vesta (S. E. Schröder)

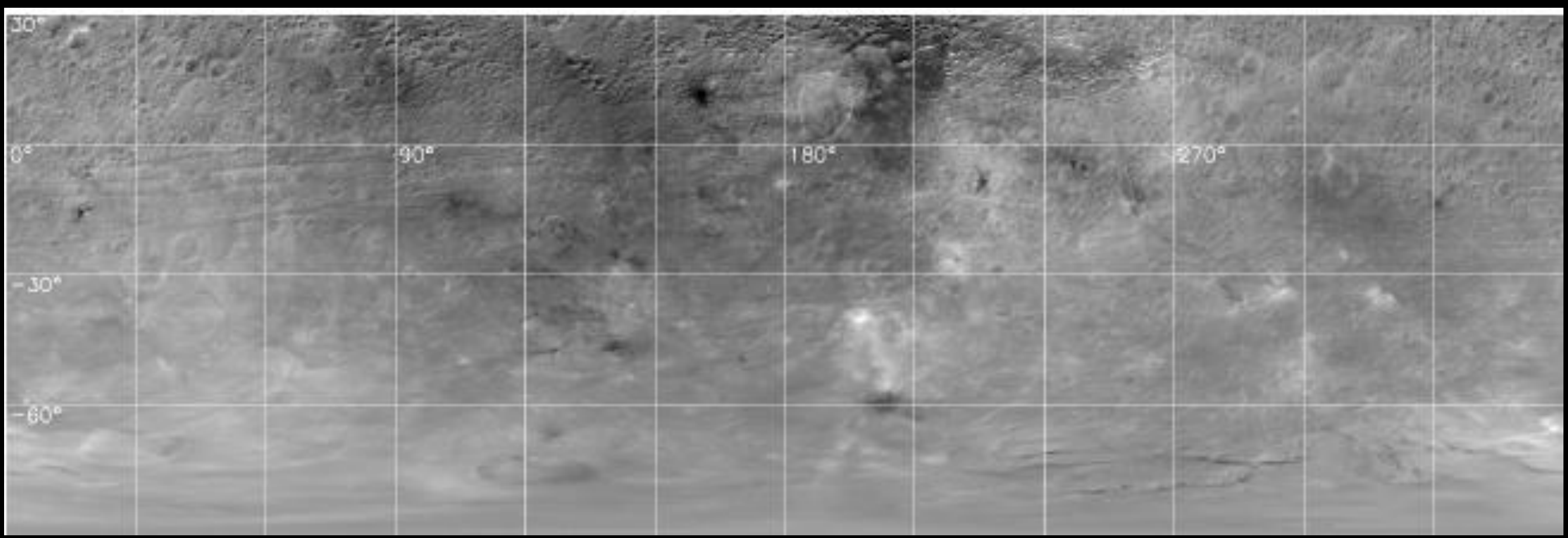
Comparison with 21Lutetia

- **Vesta topography similar to Lutetia**
  - **Characterized by steep slopes and large height excursions**
  - **However, Vesta shows global features (equatorial troughs)**
    => coherent body
- **Vesta displays much stronger colour and albedo variegations**
  => near surface layers are diverse
- **Colouration of Vesta craters not found on Lutetia or Steins**
  => not caused by impactor material



Albedo Map

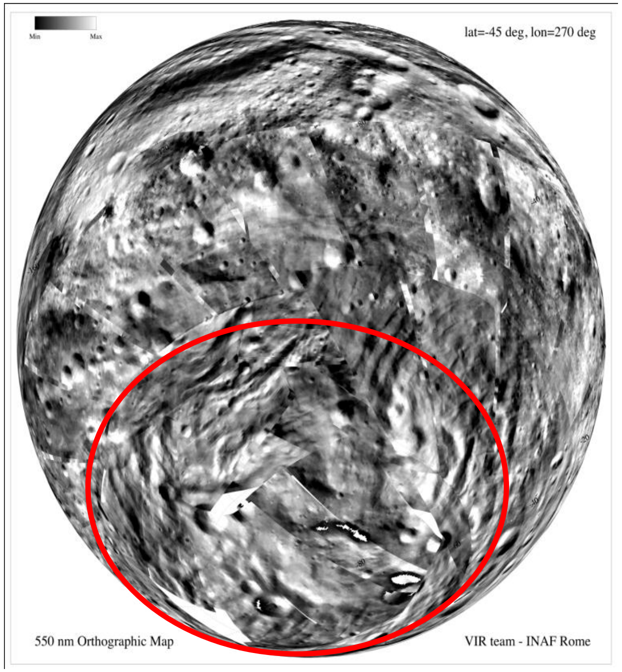

Equirectangular projection
normal visual albedo
30°
0°
90°
180°
270°
−30°
−60°
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20


30°
0°
90°
180°
270°
−30°
−60°

South polar region

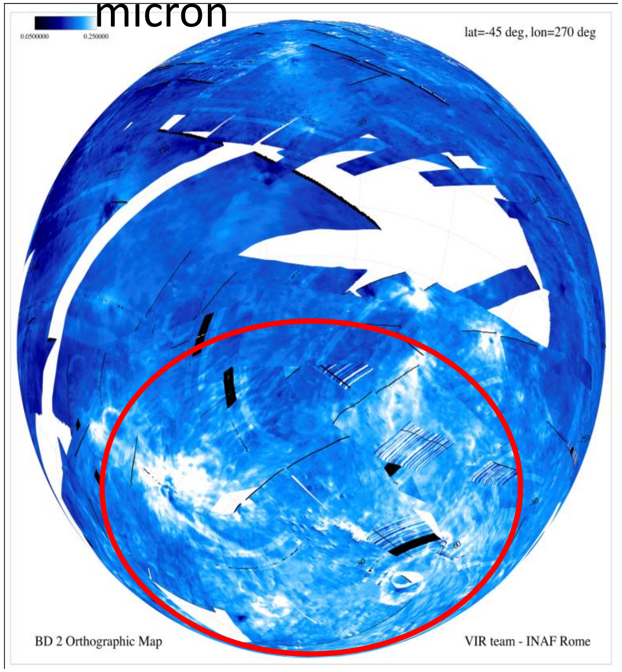
- Band depths dichotomy: the south polar regions has larger band depths with respect to the equatorial regions

I/F @ 550 nm



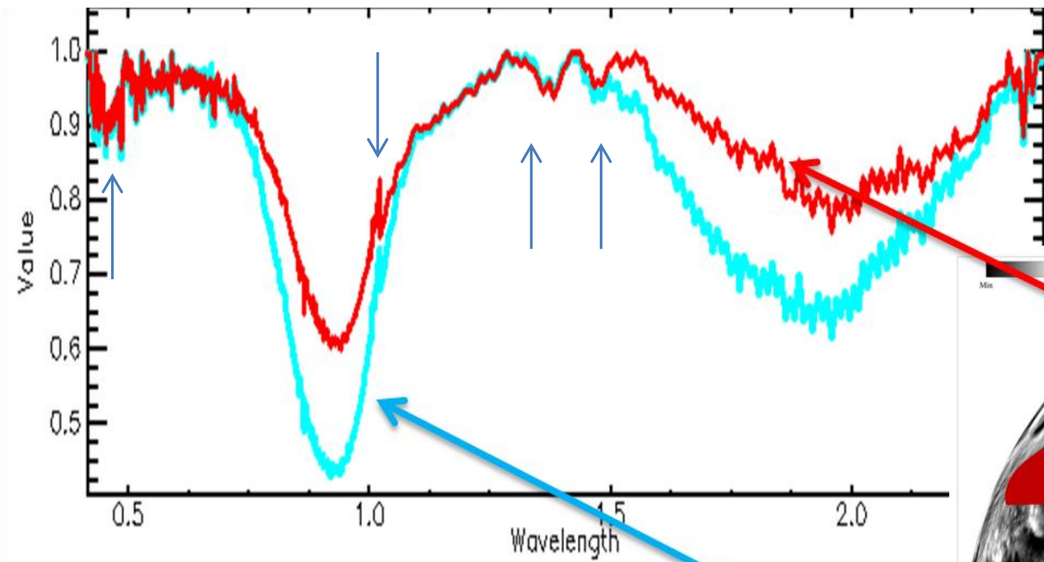
Band Depth @ 1 micron

Band Depth @ 2 micron

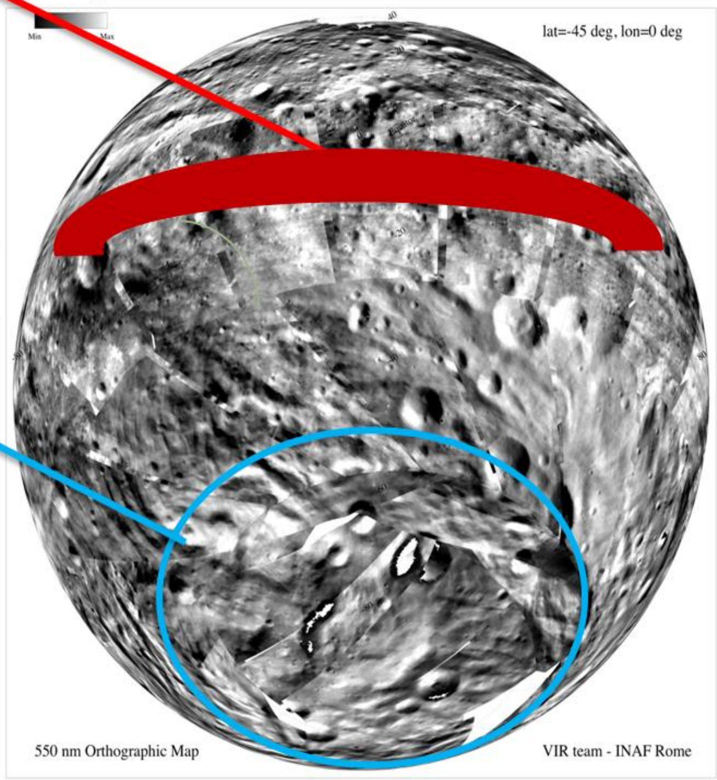


Coradini et al.

Spectral differences south/equator



Arrows indicate calibration residuals



Coradini et al.

Southern regions show:
- larger band depths
- Larger band widths
- Different shapes (2μ)

Vesta – Parent Body of HEDs

FC and VIR data confirm:

- Vesta’s average spectrum resembles that of howardites, strong pyroxene absorption
- Dichotomy
  - Southern hemisphere with Rheasilvia characterized by diogenite component
  - Equatorial region shows enhanced eucrite composition
- Ultramafic diogenite at lower crust or upper mantle: magmatic ocean or episodic plutonic intrusions?
- Spectra and filter images allow us to map the various lithographies

Vesta's internal structure

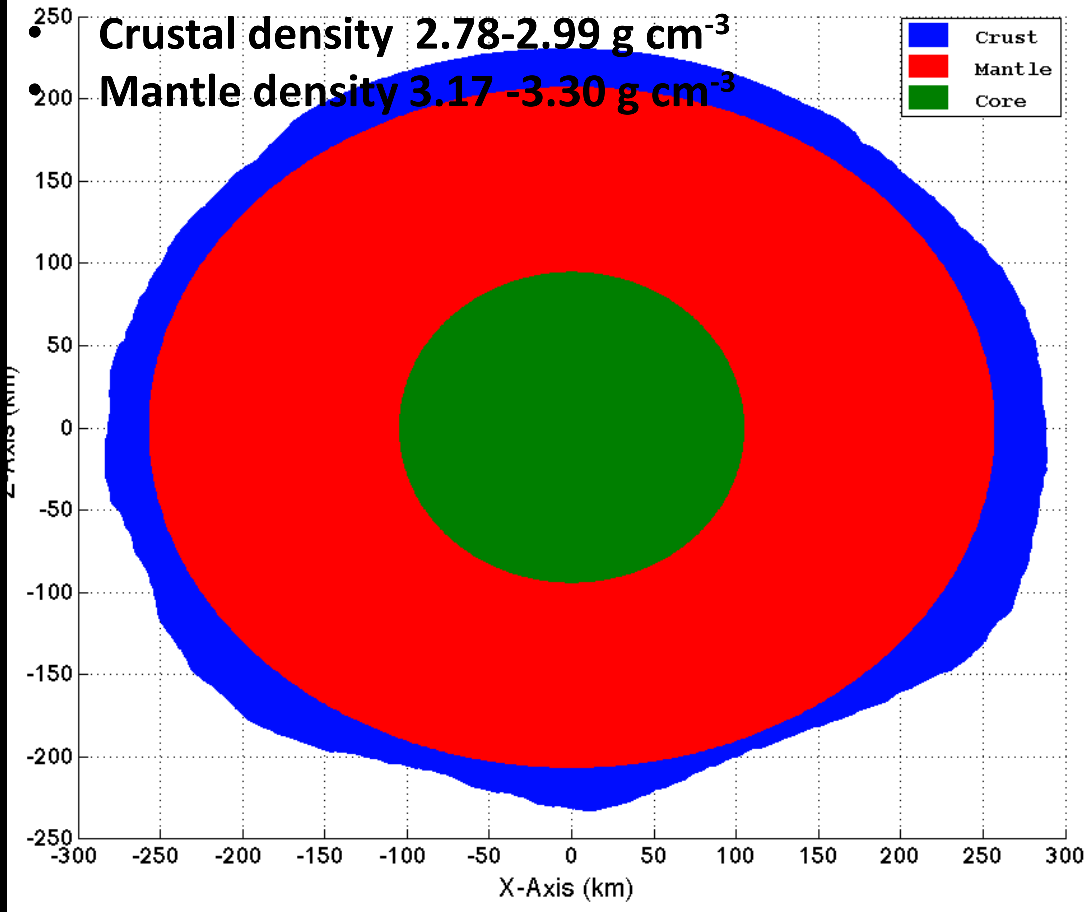
Three layer models structures have been explored to derive bounds on the density and thickness of the core, mantle and crust

For an assumed core density of 7.4 g/cm^3, and an mantle size of 207x257 km

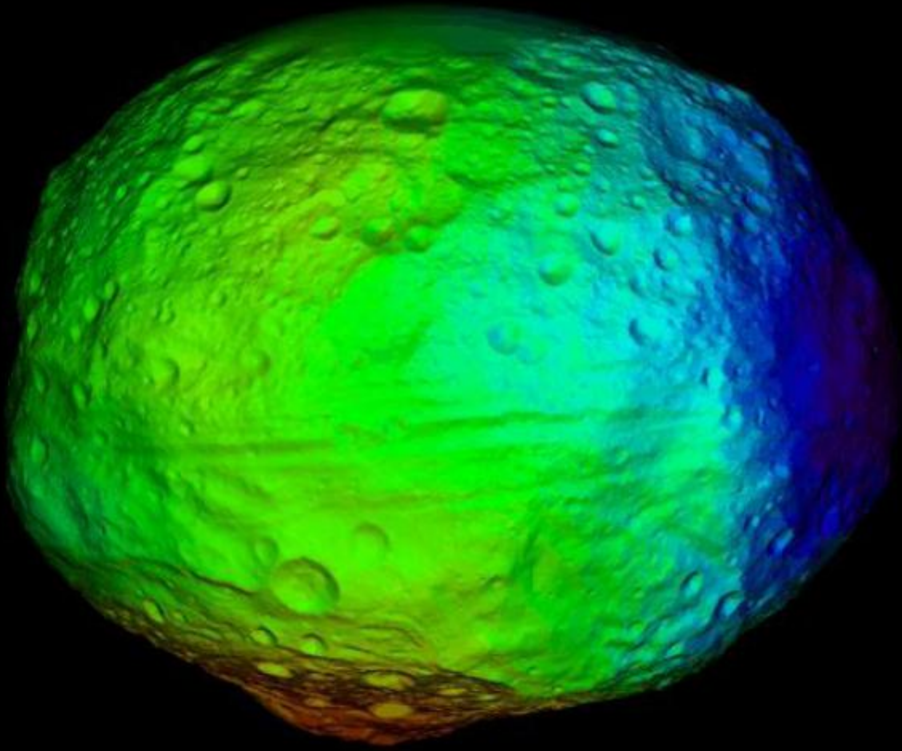
Best fit appears to be:

- ρ_m = 3.17 g/cm^3
- ρ_c = 2.99 g/cm^3
- average crustal thickness of ~19 km

- **Core radius ~109-114 km**
- **Crustal density 2.78-2.99 g cm^{-3}**
- **Mantle density 3.17 -3.30 g cm^{-3}**



GRaND



Integration of neutron flux shows enhancement at Rheasilvia

Summary

- The strong variegation of Vesta's surface clearly points to a differentiated body with diverse materials near its gardened surface
- Spectral findings confirm Vesta as parent body of the HED meteorites
- Rhesilvia reveals diogenite minerals from the lower crust/upper mantle
- Age of Rheasilvia (1 Gy) still under discussion
- Comparison with resolved asteroids (recently Steins, Lutetia) sets Vesta apart from asteroid bodies
- Vesta is a small planet-like body rather than an "asteroid"
- Vesta (5 x larger than Lutetia, but 7 x smaller than the Moon) represents a new unexplored regime for geomorphology interpretations and geophysics
- The Dawn instruments provide key data for these investigations