MESSENGER

MErcury Surface, Space ENvironment, GEochemistry, and Ranging

MESSENGER's View of Hollows on Mercury, and Links to the Planet's High Volatile Content

David T. Blewett

Planetary Exploration Group

Johns Hopkins Applied Physics Laboratory

Laurel, Maryland USA

Arizona State University – School of Earth and Space Exploration
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Outline: Mercury Hollows

- Short introduction to *MESSENGER*.
- Review of an unusual surface feature known from flybys.
- Show examples of the unexpected landform (*hollows*) that turn out to be present when these areas are examined in higher-resolution images from orbit.
- Look at depth measurements, implications.
- Discuss possible mechanisms of formation, link to Mercury’s volatile content.
- Look at the rates at which the hollows may be forming.

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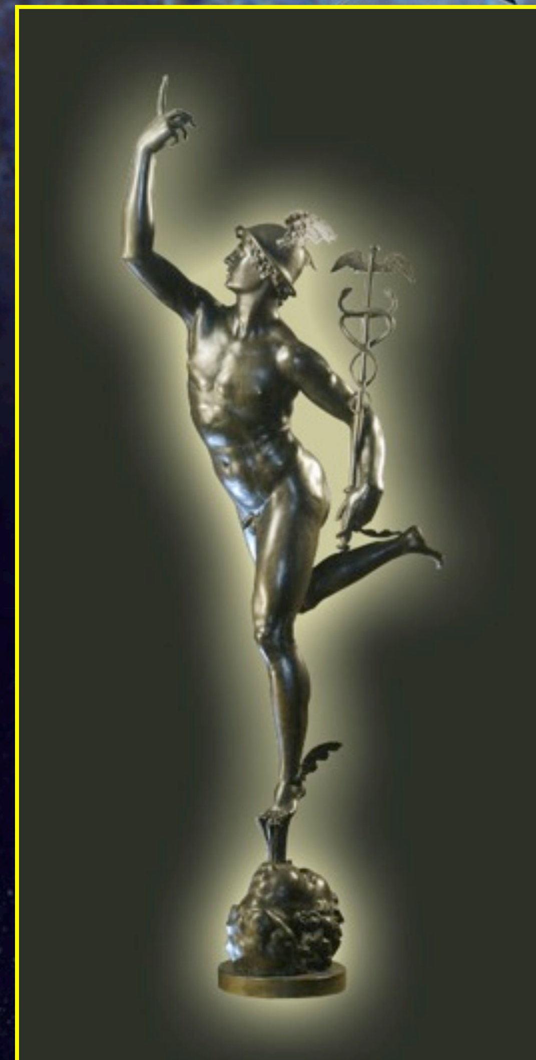
- Mercury was the messenger of the gods.
- MErcury Surface, Space ENvironment, GEochemistry, and Ranging
- A NASA Discovery mission
- PI: Sean Solomon, Lamont-Doherty Earth Observatory/Columbia Univ.
- First spacecraft to orbit Mercury, only the second to visit.



Giambologna, *Mercury*, bronze, 1580, Museo Nazionale Del Bargello, Florence, Italy.

MESSENGER Initial Questions

- Why is Mercury so dense?
- What is the geologic history of Mercury?
- What is the structure of Mercury's core?
- What is the nature of Mercury's magnetic field?
- What are the unusual materials at Mercury's poles?
- What is the composition of Mercury’s thin atmosphere?

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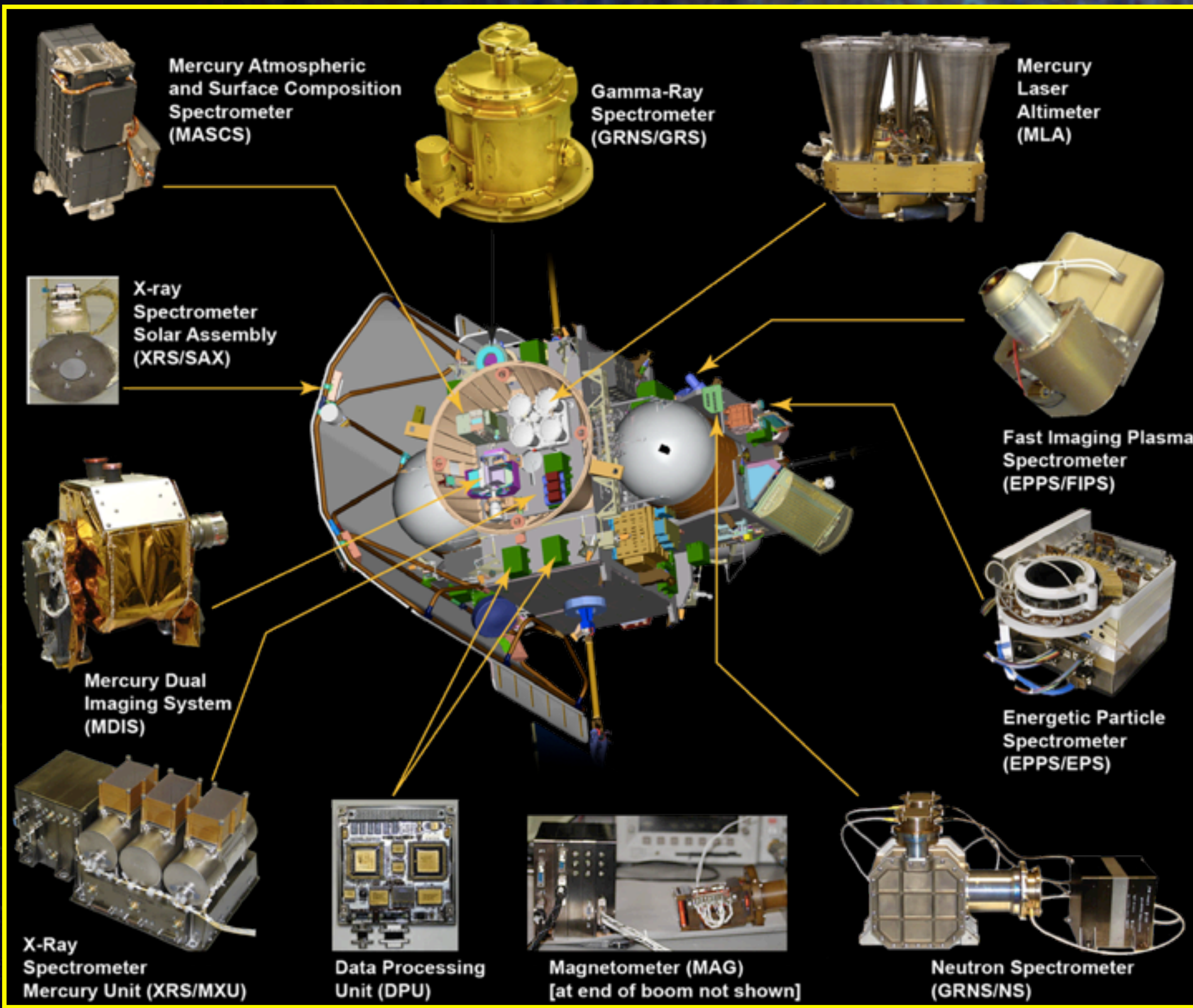


Instruments

MDIS

MASCS

MLA

MAG

XRS

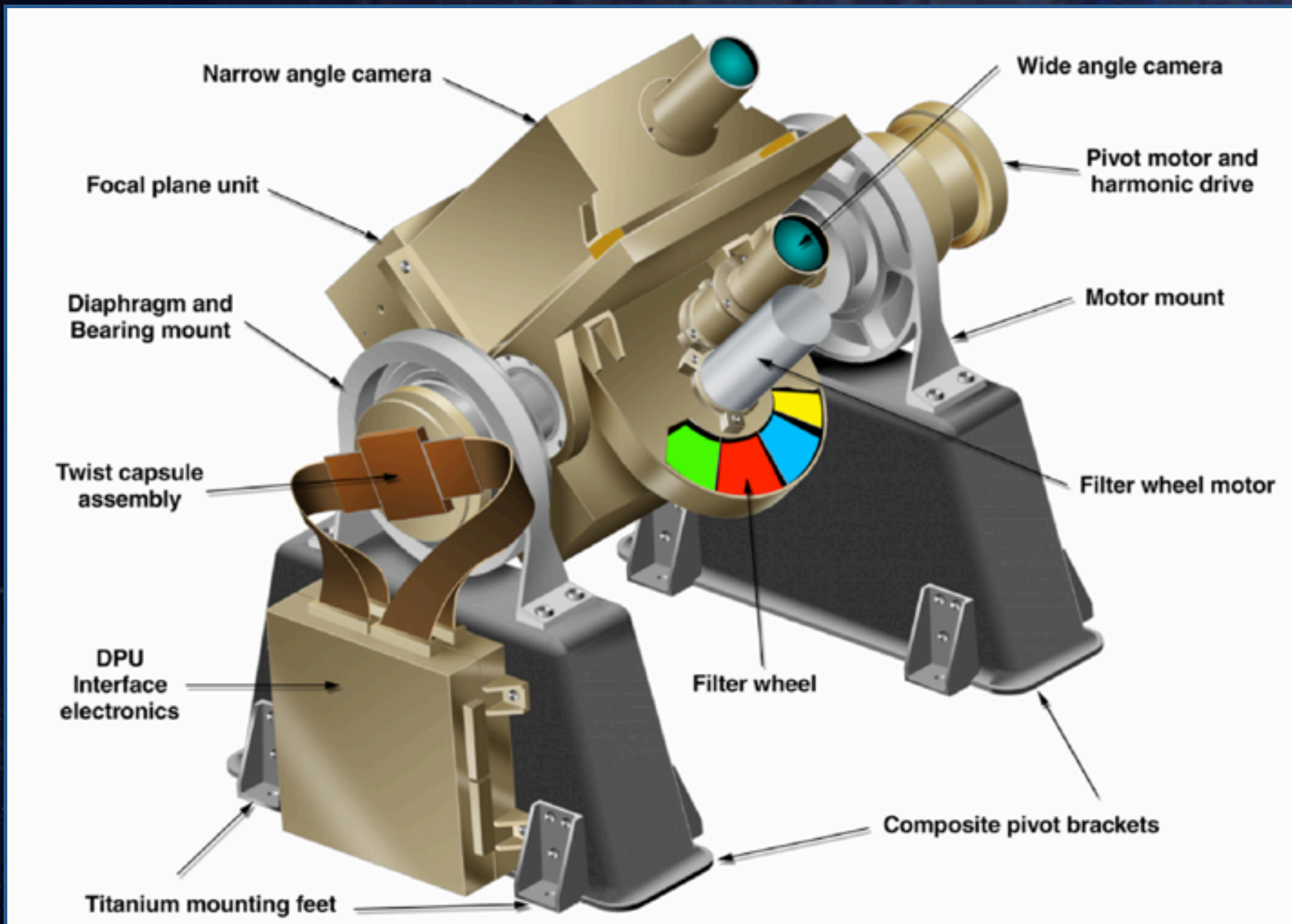
GRS

NS

FIPS

EPPS

- **Mercury Dual Imaging System (MDIS):** Consists of wide-angle and narrow-angle framing cameras. WAC has 11 color filters covering 430-1020 nm. NAC is monochrome at 7× higher spatial resolution.



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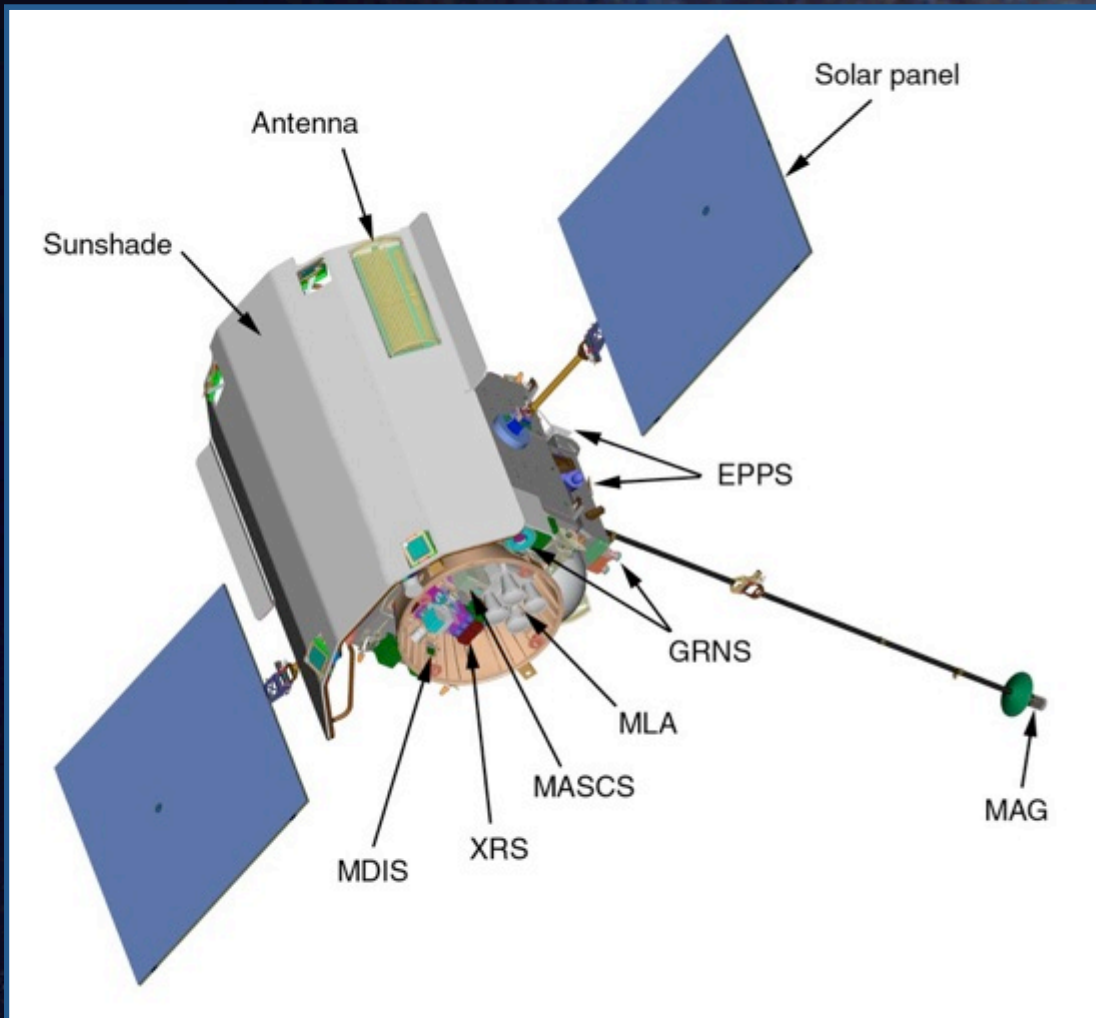


http://messenger.jhuapl.edu

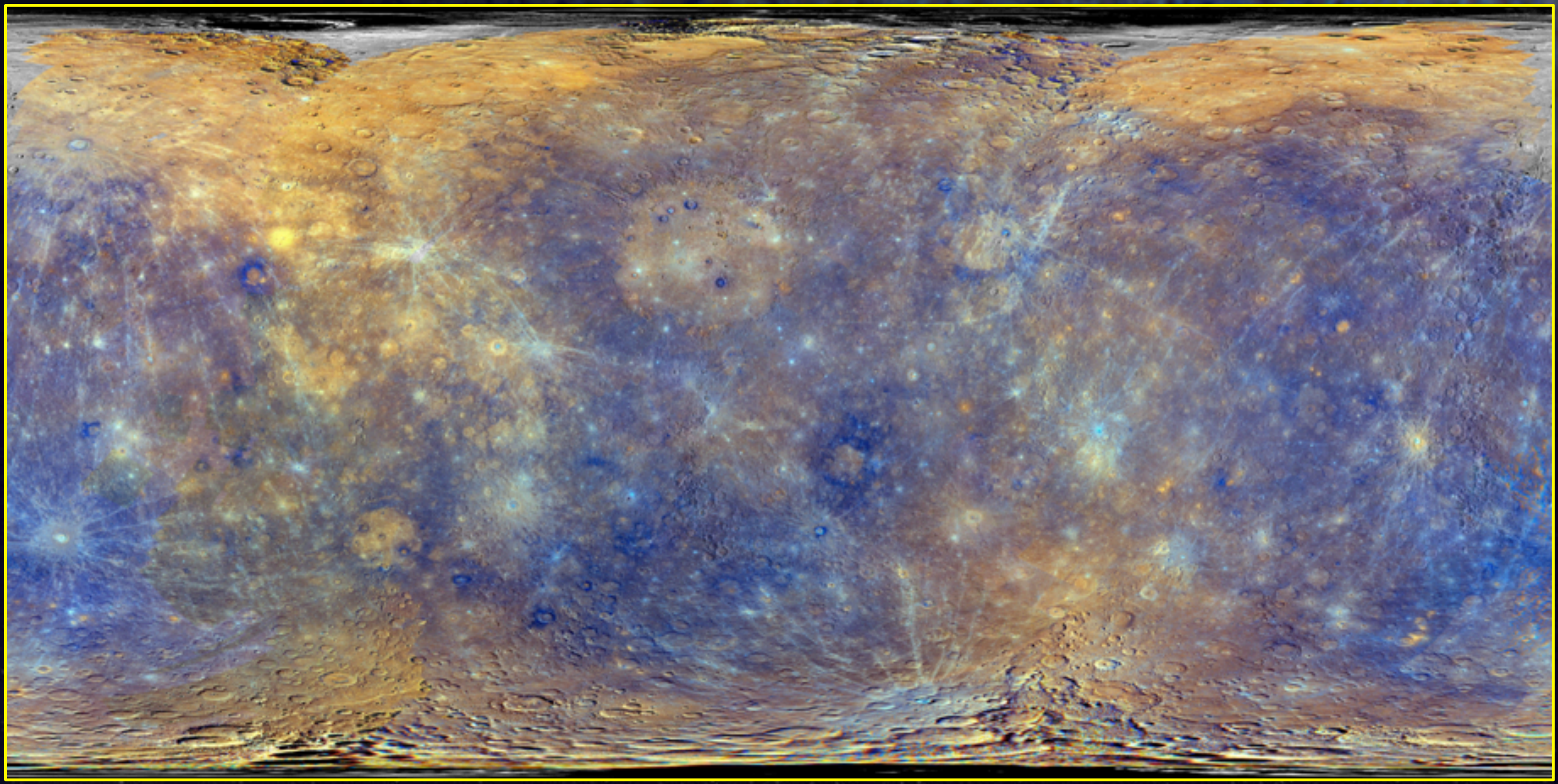
- Built & operated by APL.
- Launch August 2004.
- One Earth, two Venus flybys.
- Mercury flybys in Jan and Oct 2008, Sept 2009.
- Orbit insertion March 18, 2011.
- One Earth-year prime mission.
- Mission extensions to April 30, 2015: fuel expended, spacecraft hit the surface.

MESSENGER Spacecraft

Getting ready for vibration testing at APL

MESSENGER – Global Mapping

Enhanced Color



PC2, PC1, 430-nm/1000-nm as R, G, B

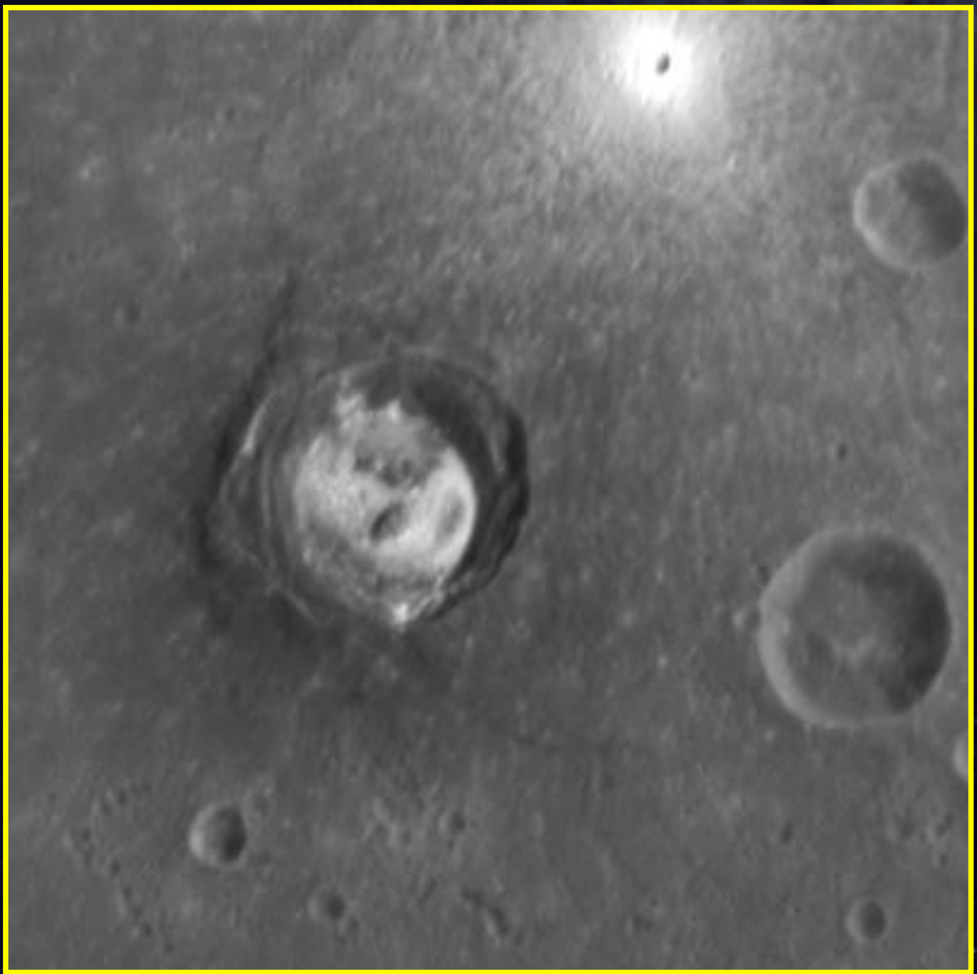
Mercurian Bright Patches

- *Mariner 10* UV/orange ratio images
  - Dzurisin (1977 *GRL*), discussed bright, bluish patches within certain large craters.
  - Also noted by Schultz (1977 *PEPI*) and Rava & Hapke (1987 *Icarus*).
- *MESSENGER* flybys provided 11-color multispectral images and better spatial resolution: Robinson et al. (2008 *Science*), Blewett et al. (2009 *EPSL*, 2010 *Icarus*). Called "bright crater-floor deposits (BCFD)".
- Several styles of occurrence were seen.

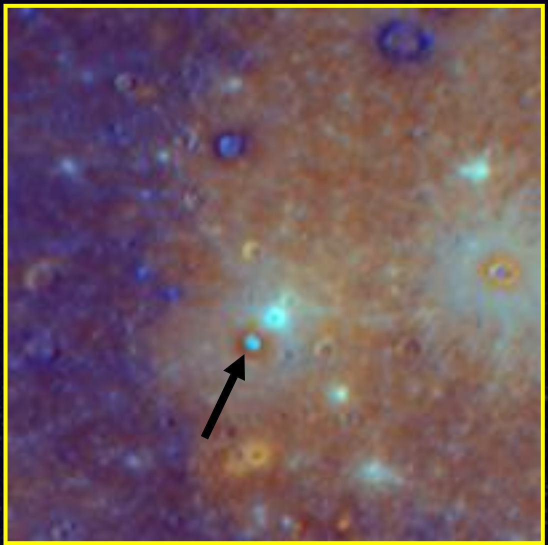
Major Morphological Types:

1. Bright floor

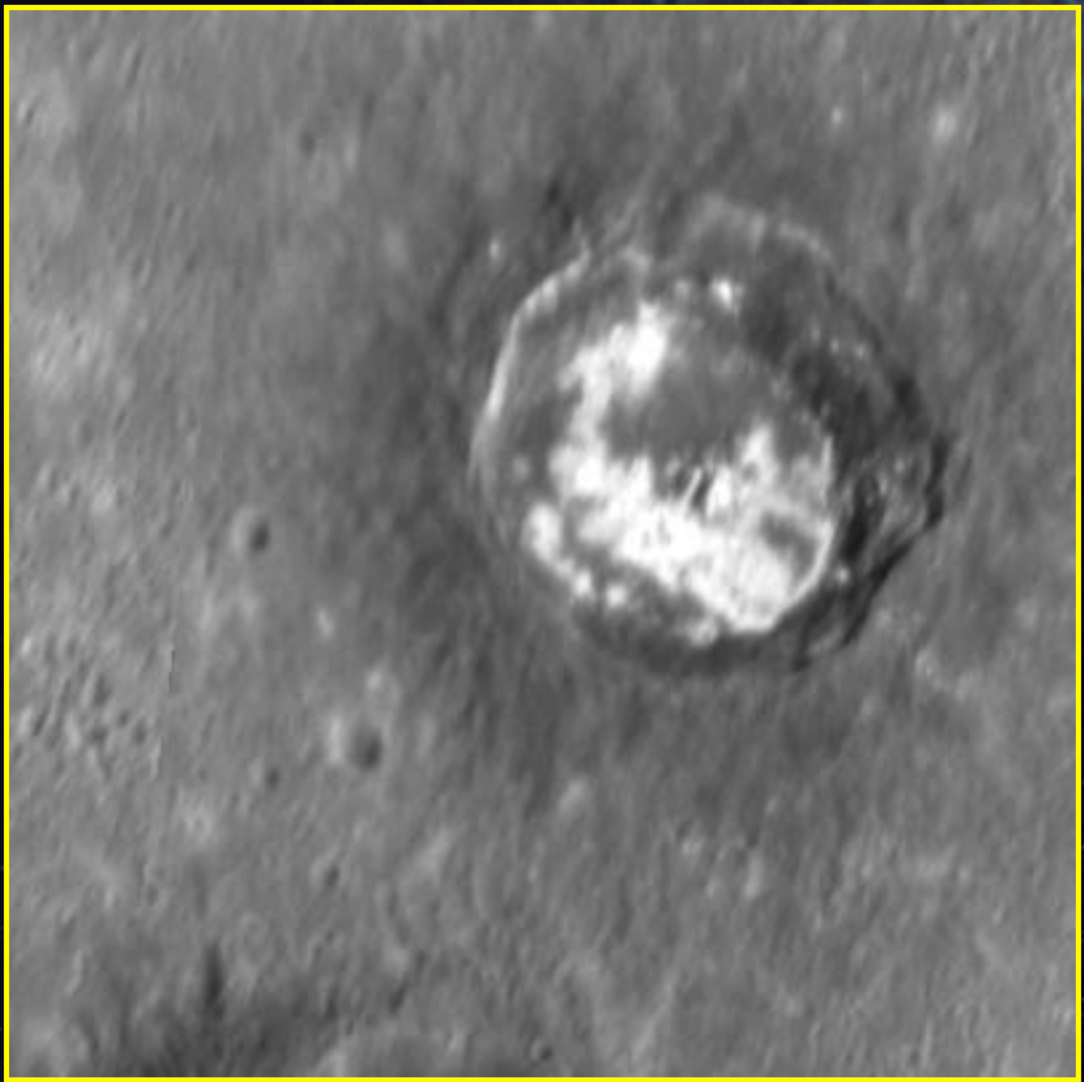
- Kertesz
- 33 km diam
- 27°N, 145°E



Monochrome
nac_depart3_pho_orth

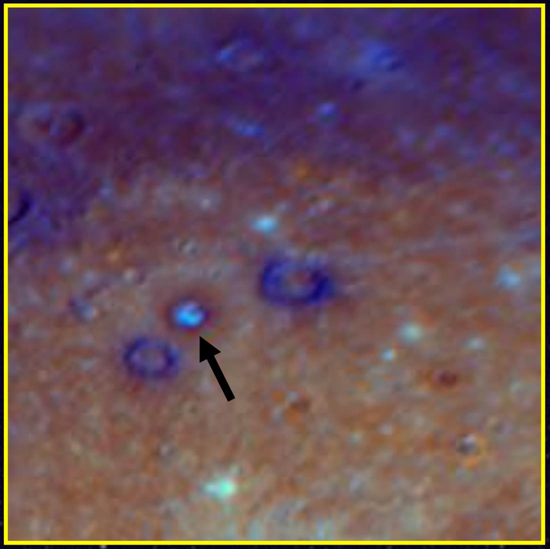


Multispectral principal components enhanced color

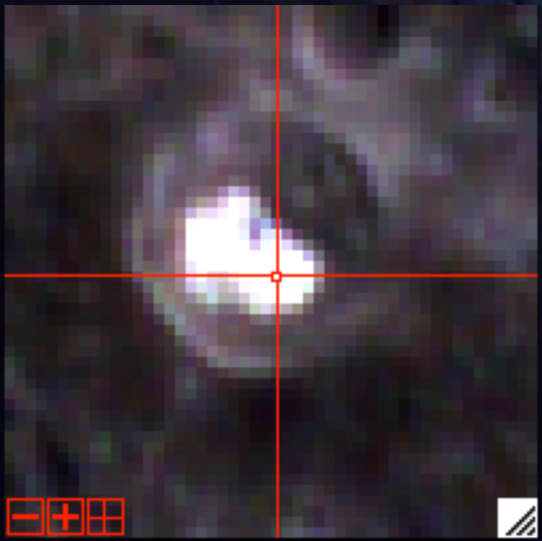


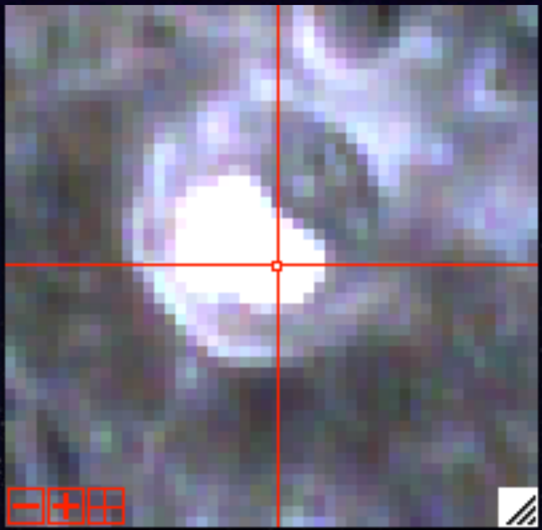
Major Morphological Types:
1. Bright floor

- Sander
- 50 km diam
- 43°N, 154°E



nac_hires2_pho_orth





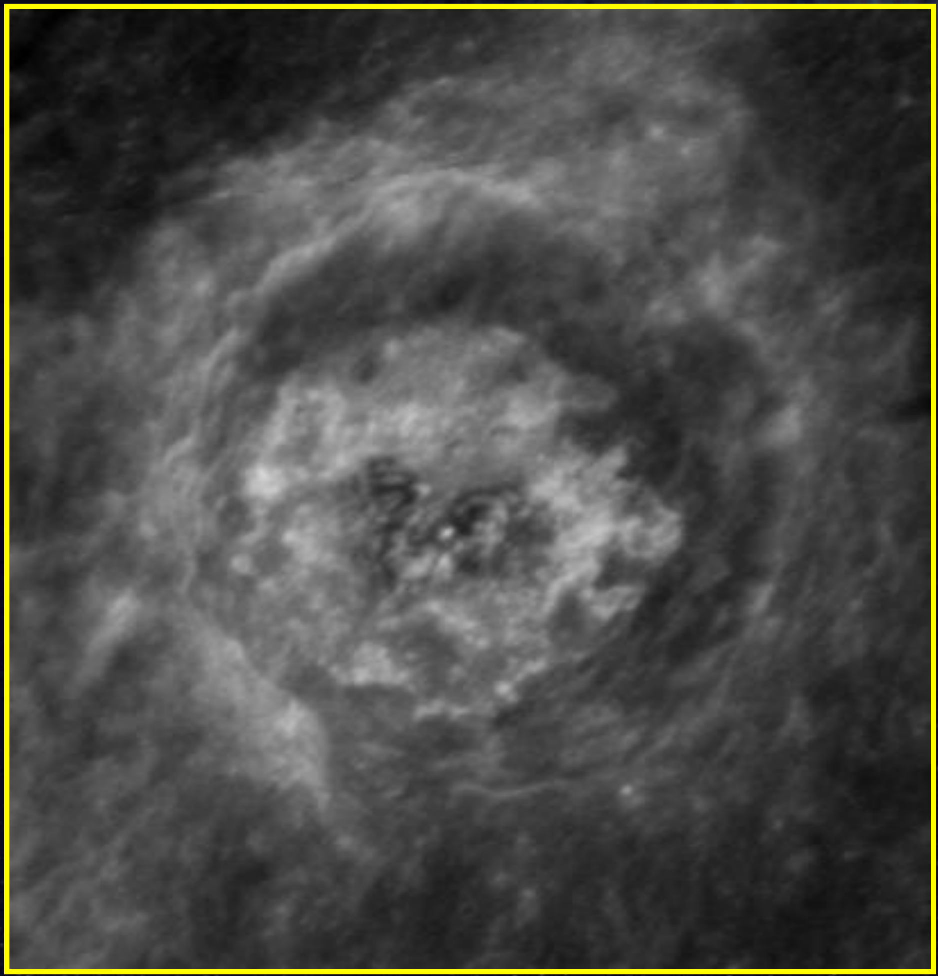
EW0211063878I

Major Morphological Types:
1. Bright floor

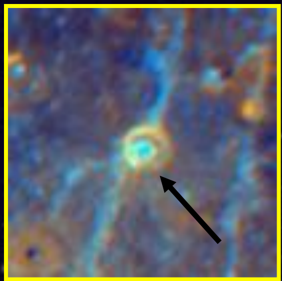
- 900-560-430 nm as RGB
- Hopper, 34 km diam

two different stretches

Major Morphological Types:
1. Bright floor



- de Graft
- 65 km diam
- 1.7° N, 2.0° E



Multispectral principal components enhanced color

M2_DepNAC2_simp_pho

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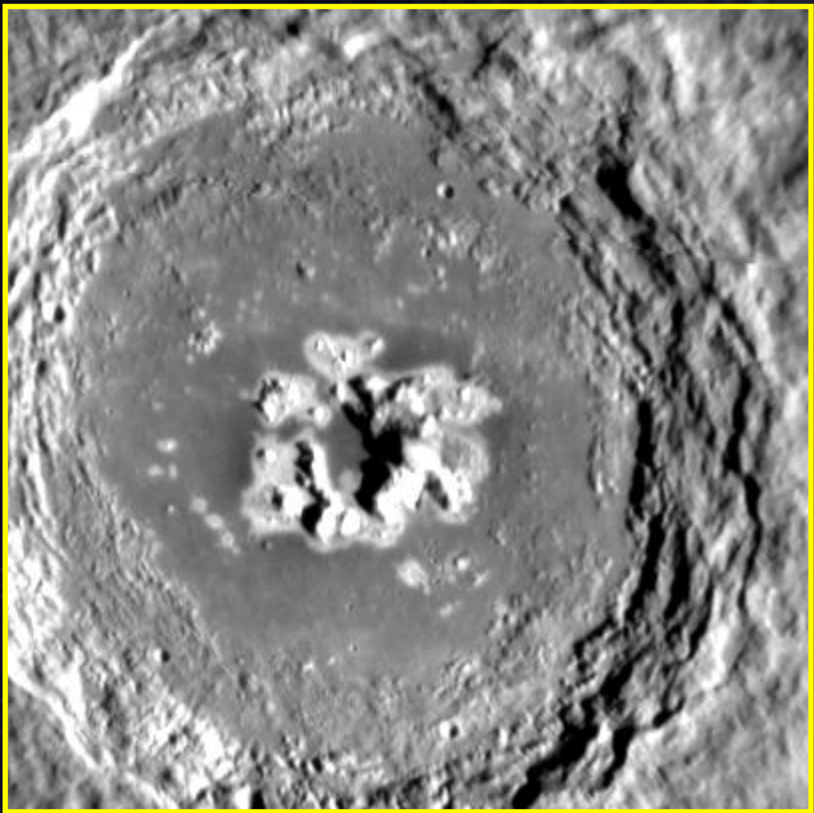
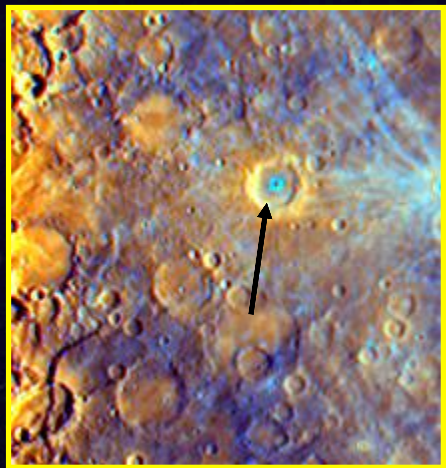
Major Morphological Types:
2. Bright peaks or peak-rings

- Eminescu
- 130 km diam.



monochrome
nac_hires2_pho



Multispectral principal components enhanced color

Bright peaks or peak-rings

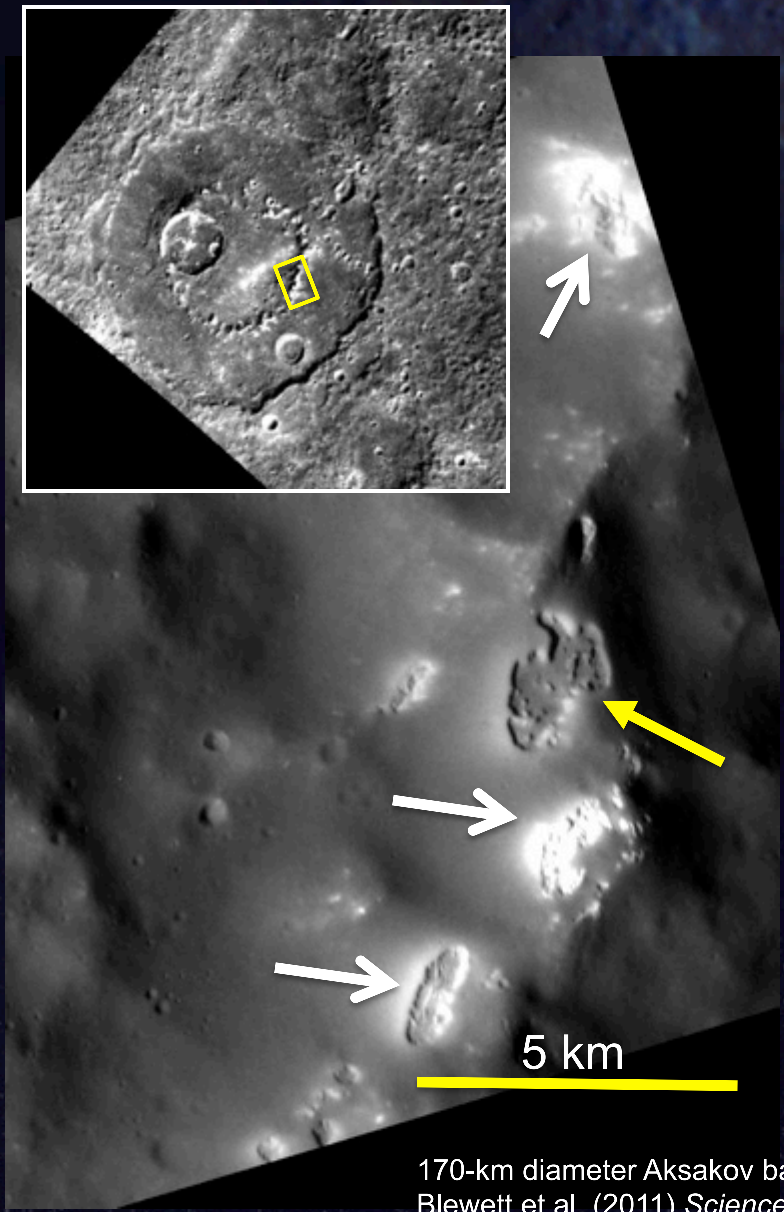
900-560-430 as R-G-B
1.3 km/pixel
EW0211414876I

- Vivaldi

- basin diam 200 km
- peak ring diam 100 km

first flyby

New landform: "Hollows"



170-km diameter Aksakov basin
Blewett et al. (2011) *Science*.

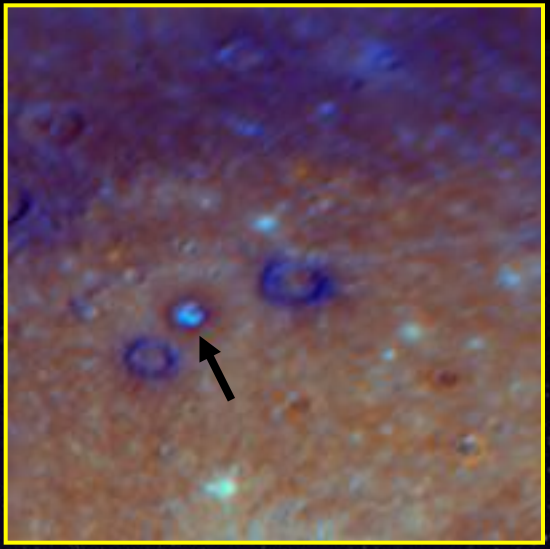
- Once in orbit, high-resolution images showed that the unusual bright, blue areas consist of irregular, shallow depressions with bright interiors and haloes.
- Name "hollows" adopted to distinguish these from other pit-like depressions on Mercury.
- Tens of meters to a few kilometers across, flat floors, rounded edges.
- On crater/basin floors, peaks, walls, rims, ejecta.
- Occur singly and in small clusters, as well as in larger groups.

Sander: Orbit

- Targeted NAC
- 30 m/pixel

EN0218289182M.map

Flyby color



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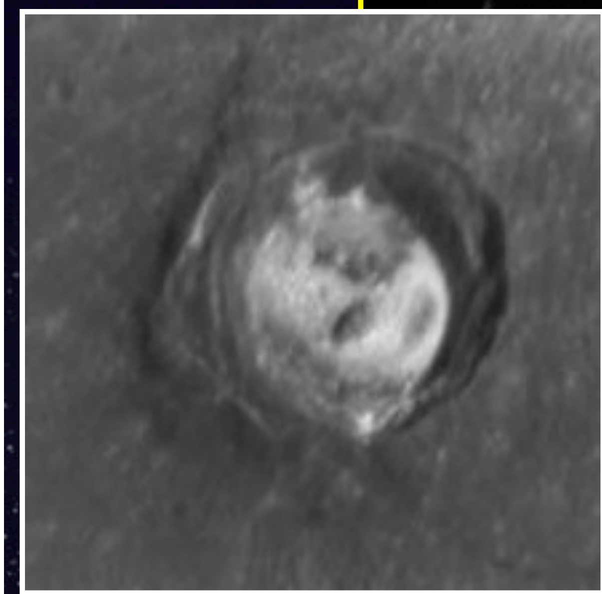
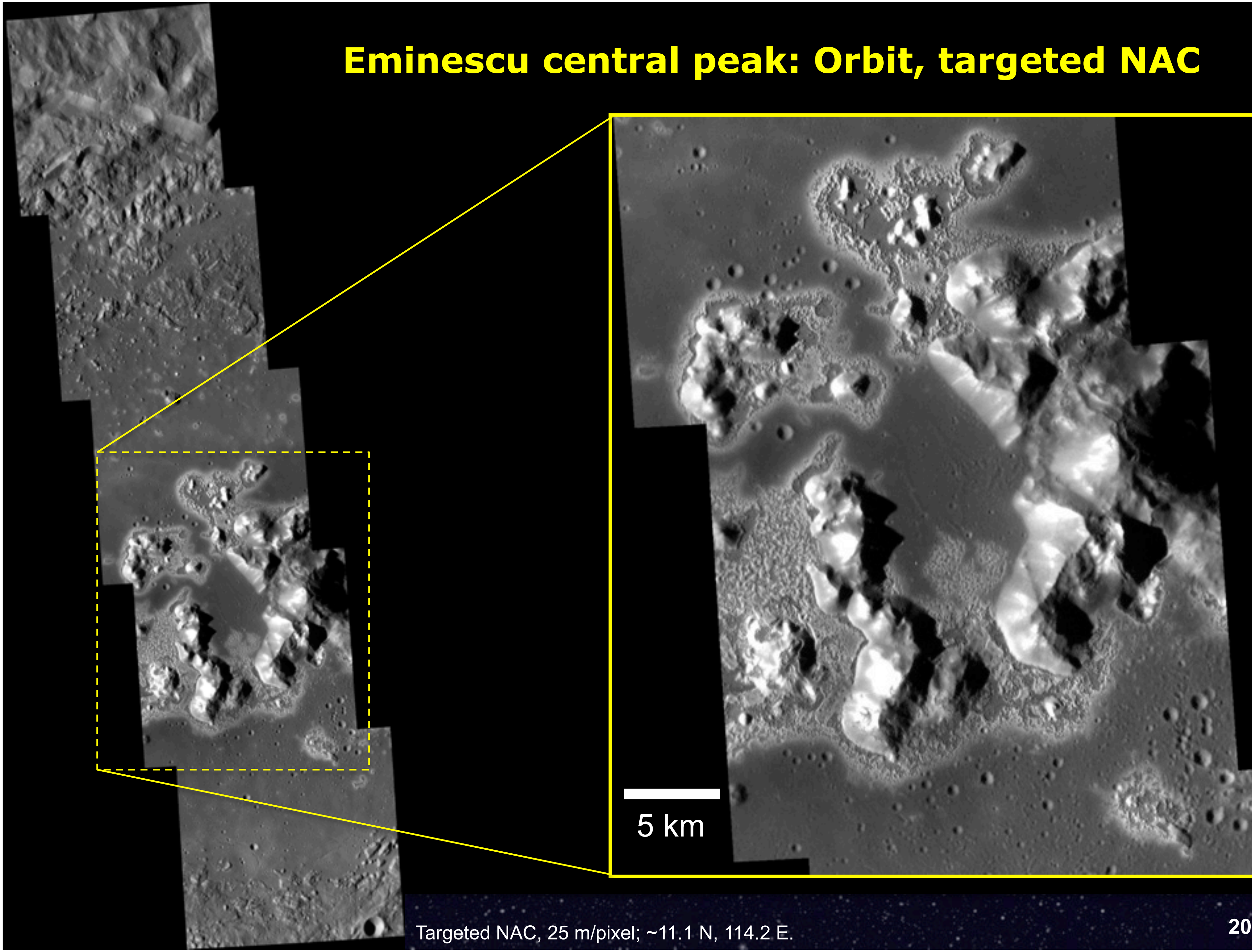
Kertesz: Orbit

Targeted NAC: EN0220591163M, 18 m/pixel

Flyby



Eminescu central peak: Orbit, targeted NAC



Targeted NAC, 25 m/pixel; ~11.1 N, 114.2 E.

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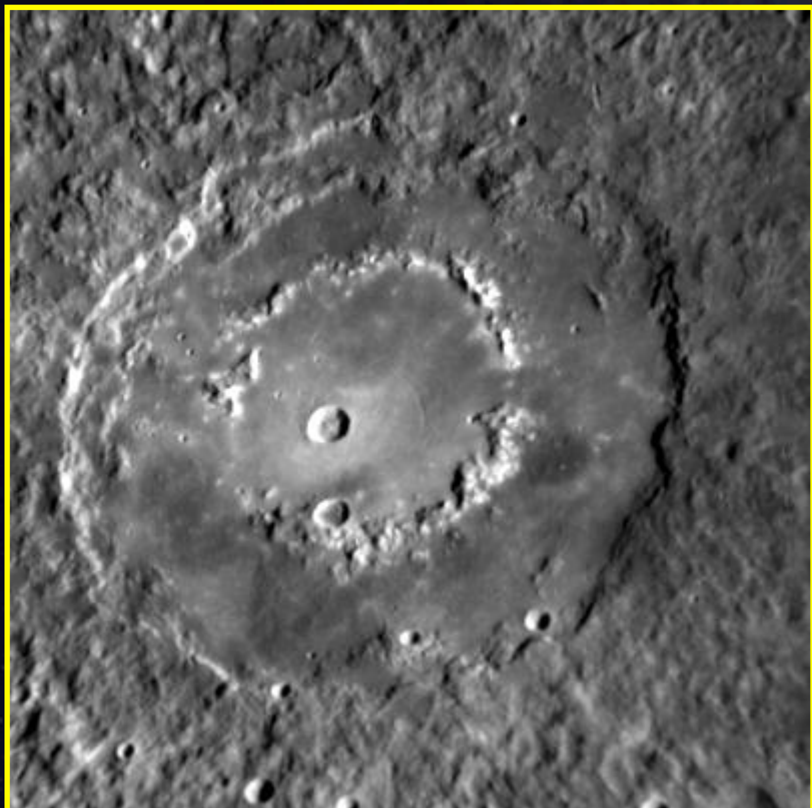
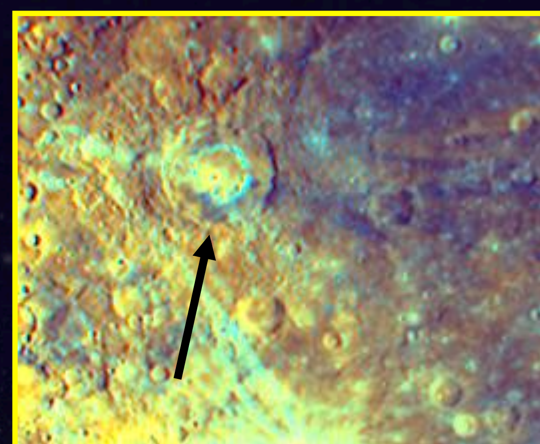
Raditladi basin: flyby



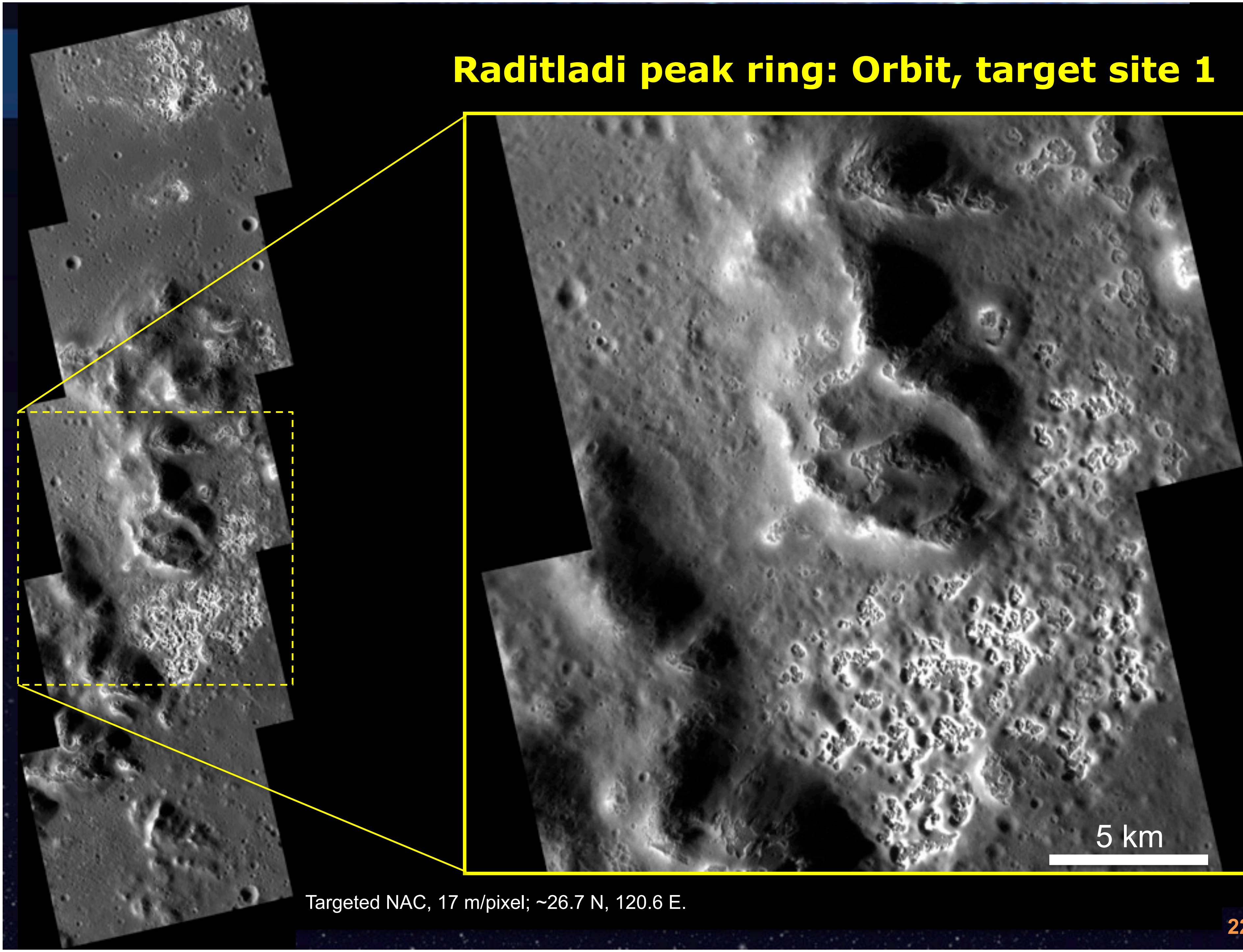
nac_depart3_pho

- 258-km diam.

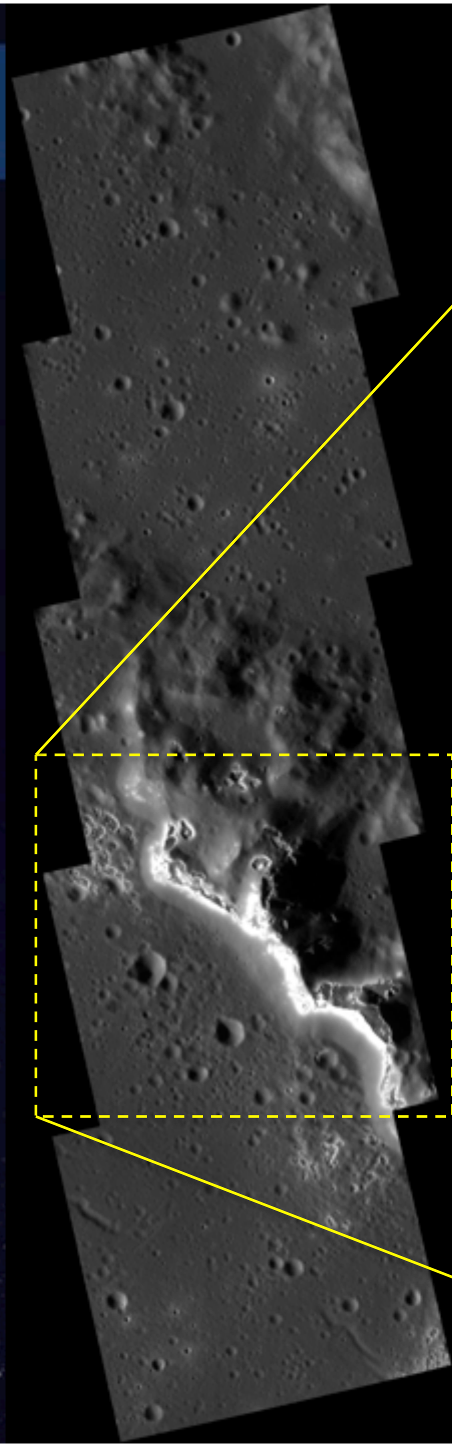


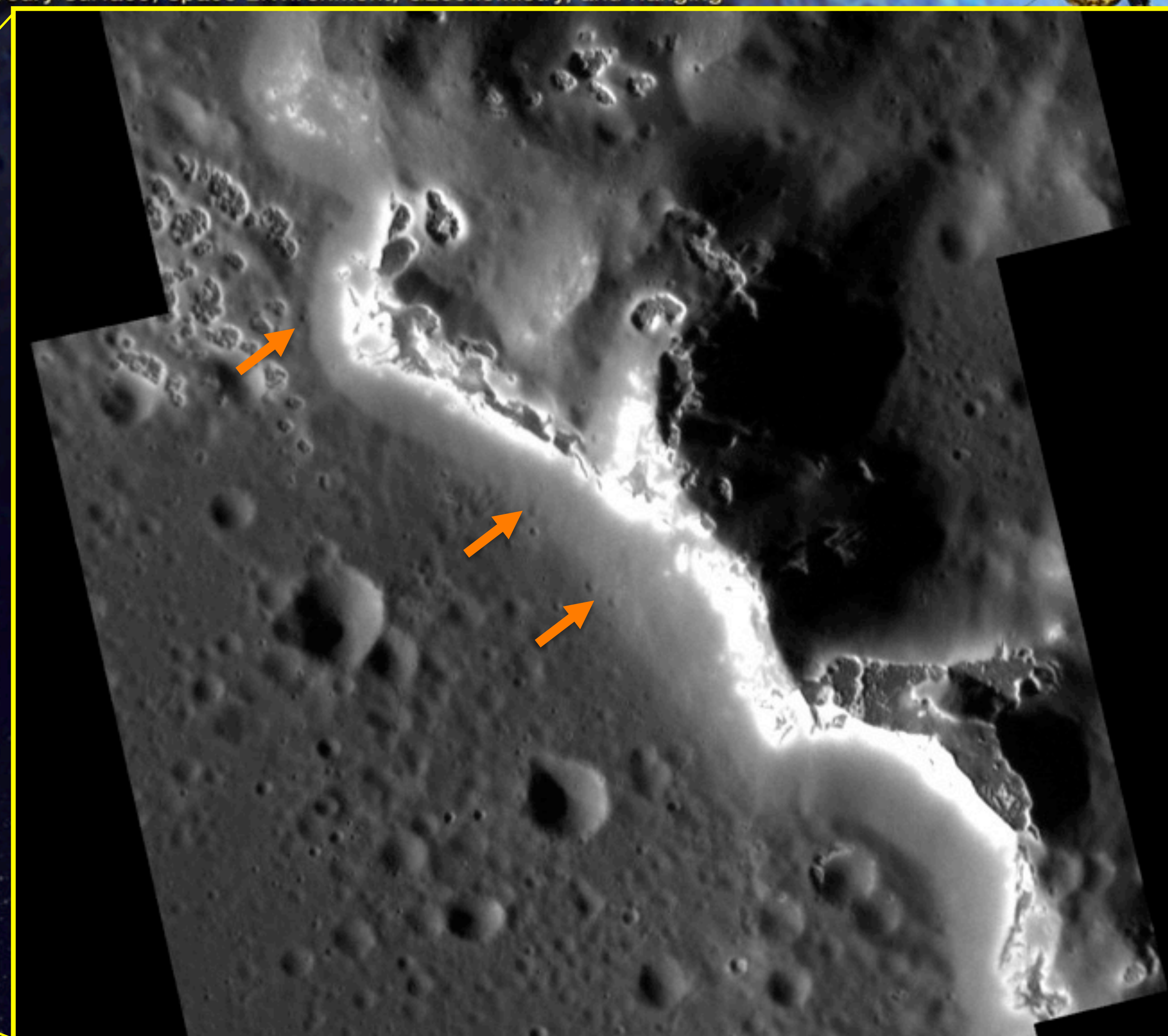
Multispectral principal components enhanced color

Raditladi peak ring: Orbit, target site 1



Targeted NAC, 17 m/pixel; ~26.7 N, 120.6 E.

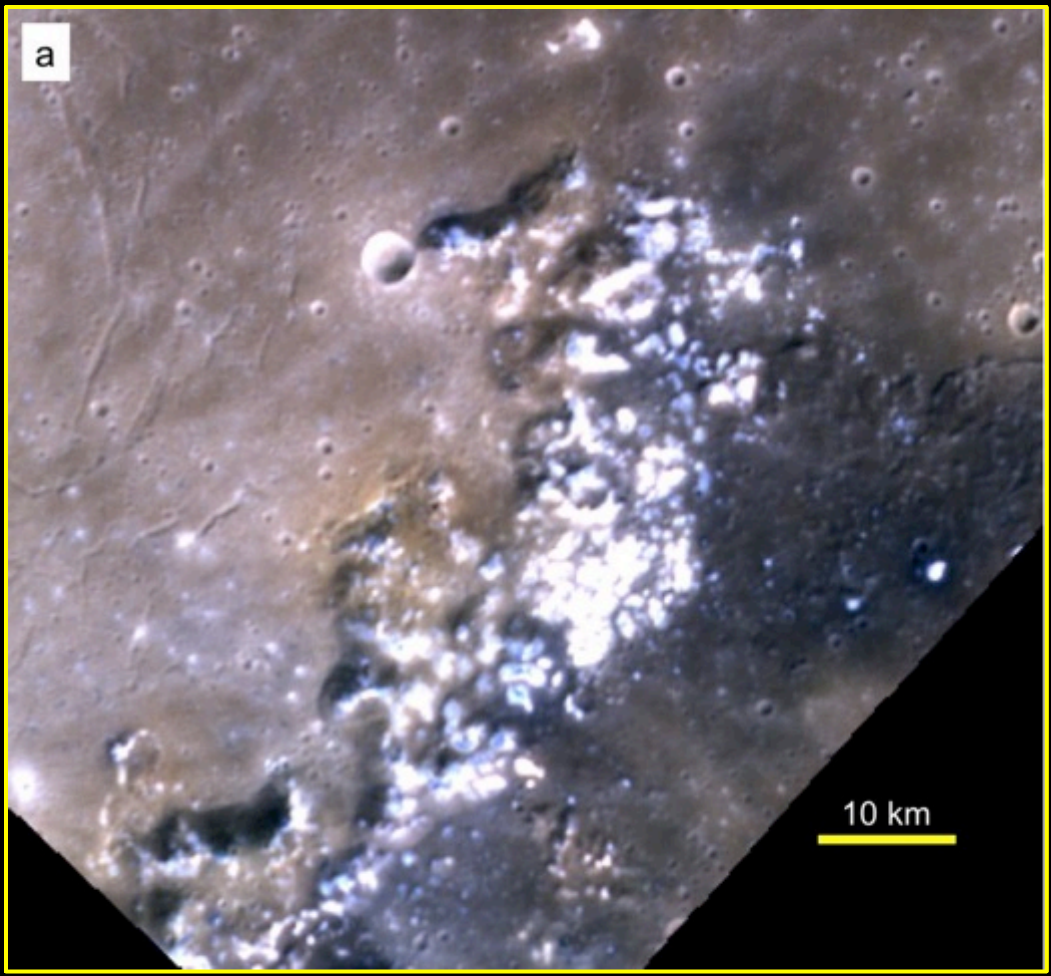




Targeted NAC, 15 m/pixel; ~28.8 N, 120.0 E.

Photo by Vivian Stockman, Oct 19, 2003. http://www.ohvec.org

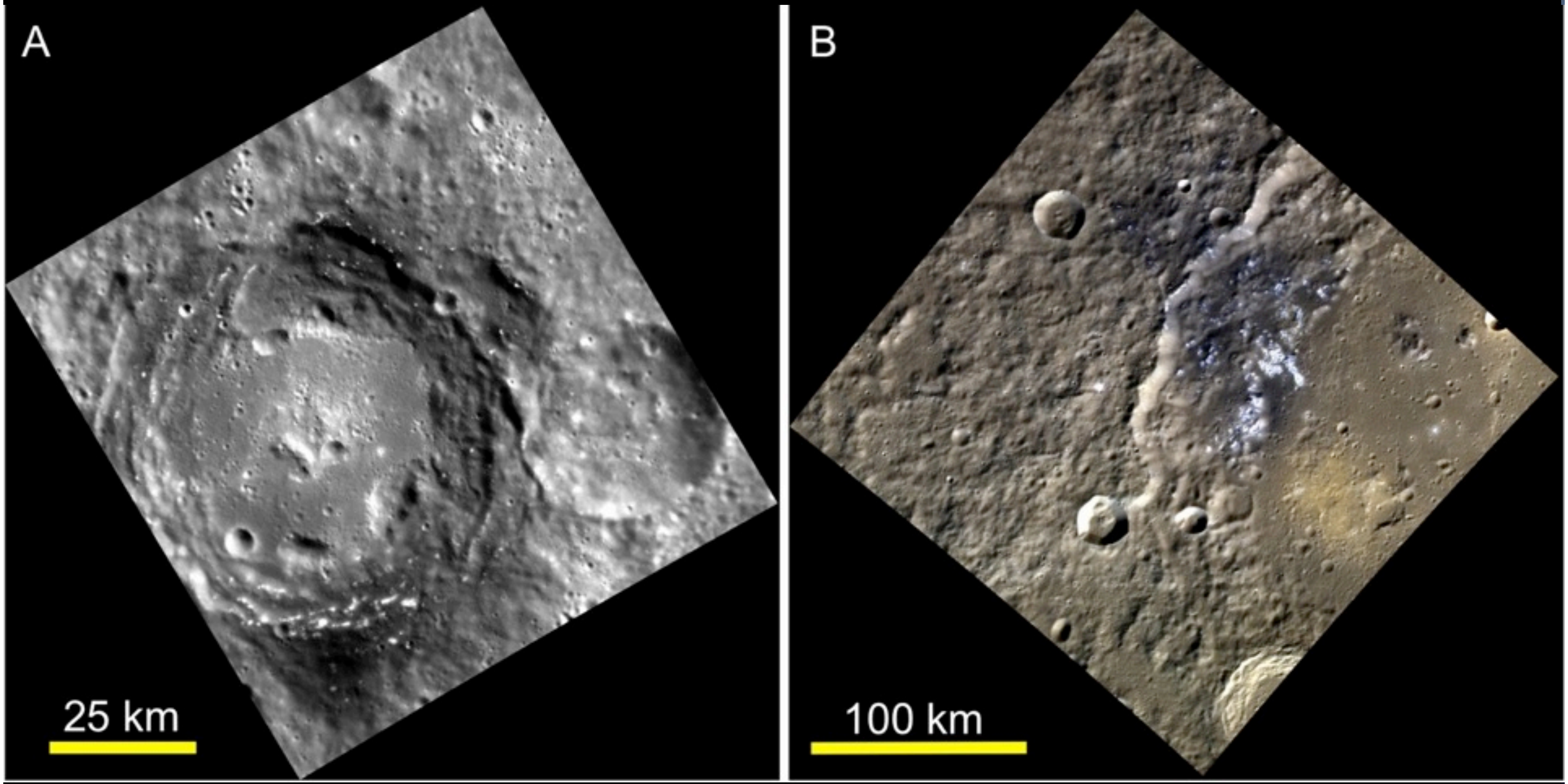
Association with Low-Reflectance Material (LRM)



- Raditladi basin interior
- Red plains to the left, LRM to the right.
- Hollows in the LRM on the basin floor.
- Hollows on LRM that forms the mountains of the central peak ring.

WAC composite with images EW1013234506I (997 nm), EW1013234498G (749 nm), and EW1013234494F (430 nm) as RGB, 186 m/pixel

Association with Low-Reflectance Material



Left: Hollows on the dark portions of the walls and ejecta of Sher-Gil crater (76 km diameter). : 45.1 S, 135.3 E, 102 meters/pixel. *Right*: LRM and hollows on western rim of Sholem Aleichem crater (196 km diam). 50.1 N, 266.4 E, 148 m/pixel.

APL

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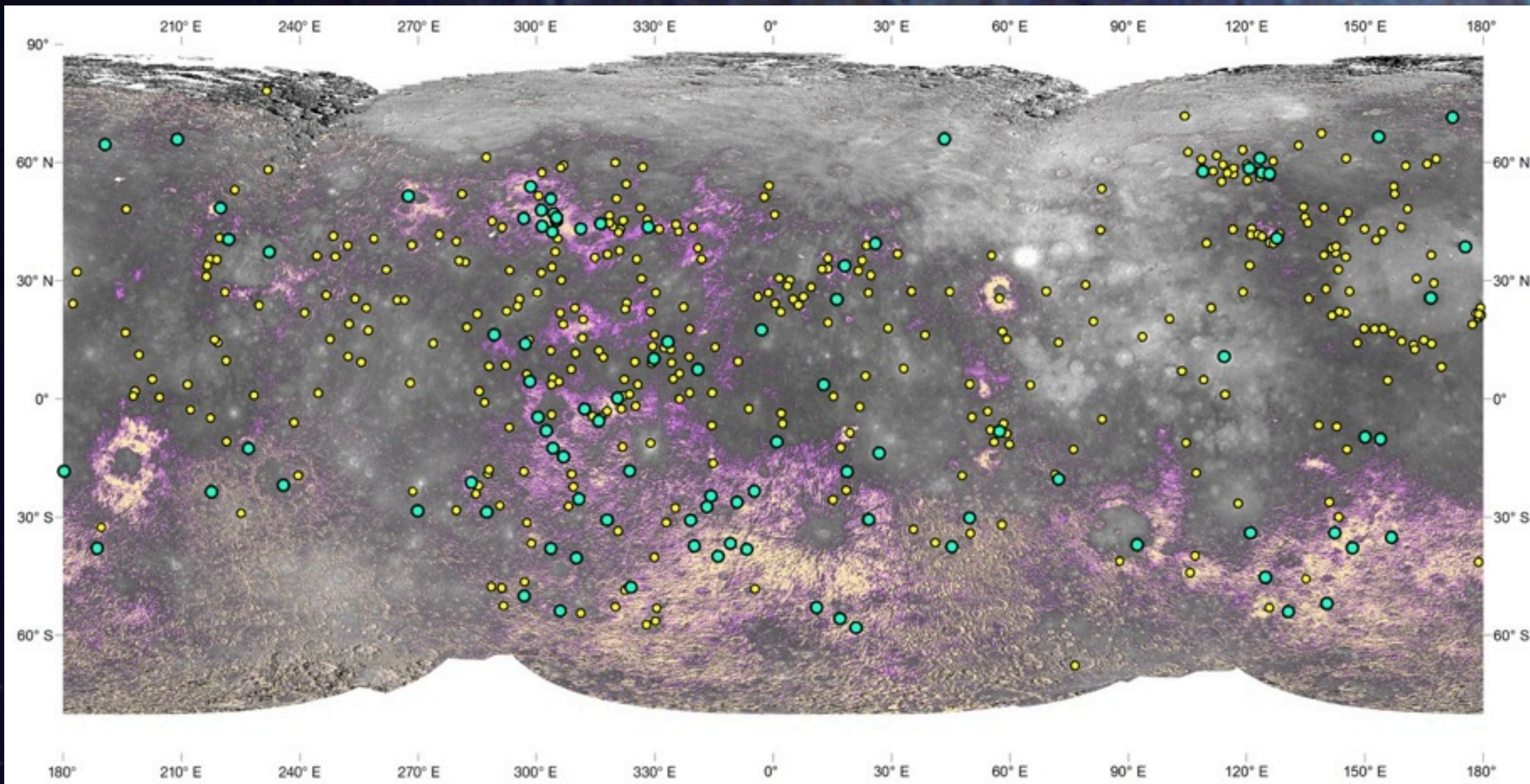
Hollows: Essentially global distribution

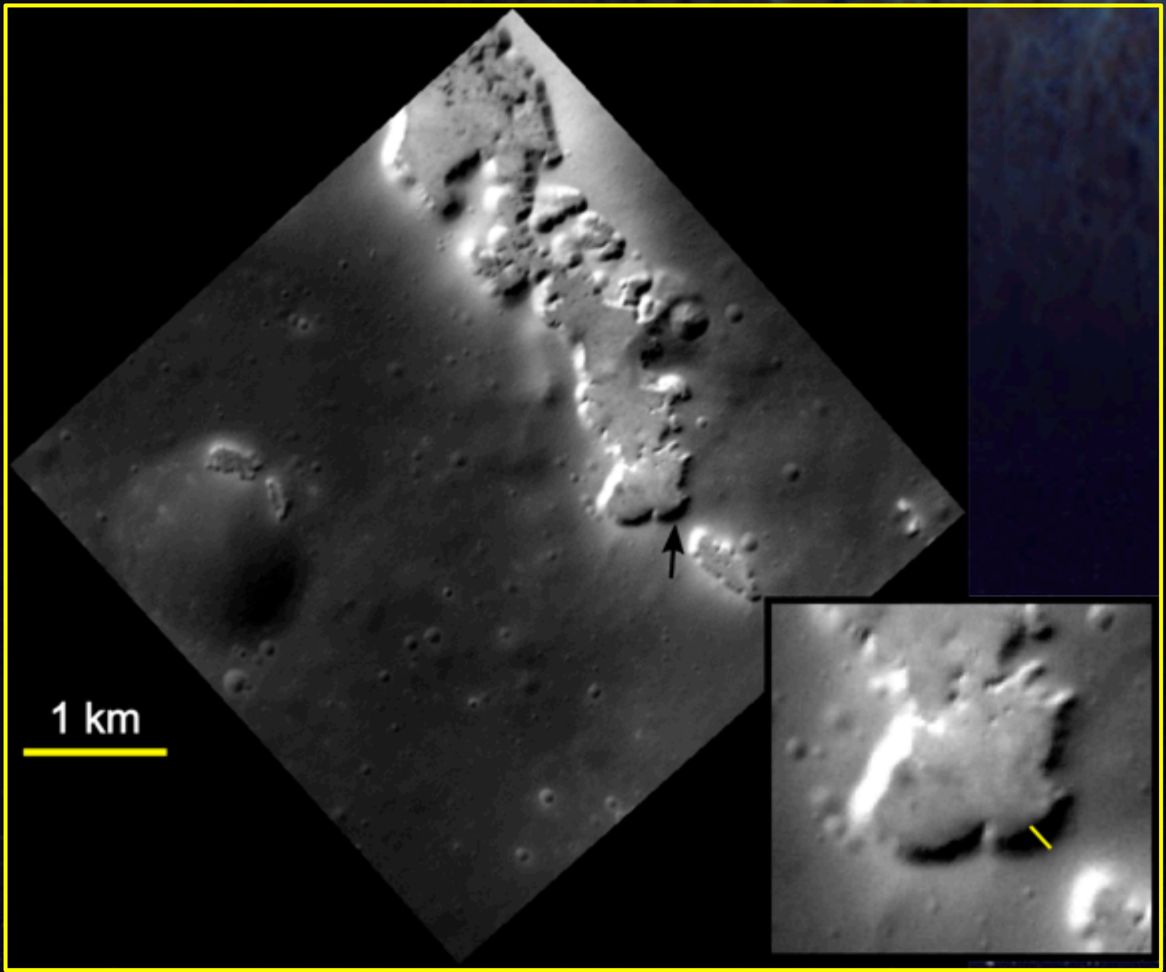


Cyan = Hollows in LRM or LBP. Yellow = Hollows not in LRM or LBP at scale of global images. Peach = LRM, Purple = LBP.

Light and medium grey: Reddish smooth and intermediate plains units.

Hollows locations: Blewett et al. (2013 *JGR*) and Thomas et al. (2014 *Icarus*). Figure from forthcoming Blewett et al. Cambridge UP Mercury book chapter.

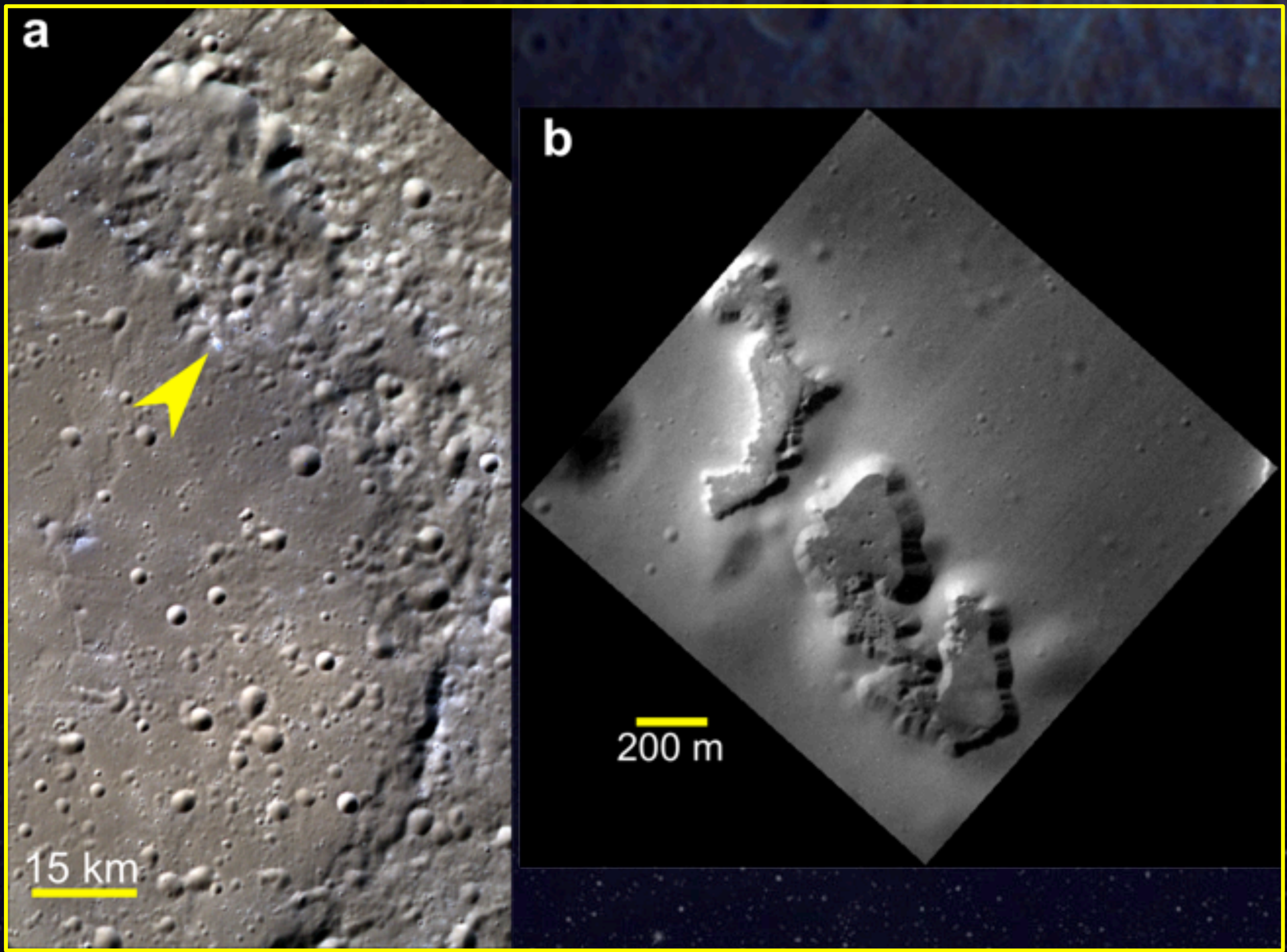
Highest-Resolution Views



- Near Dali basin
- 9 m/pixel
- Note straight walls (brink to floor)
- Flat floors
- No craters! Must be very young.
- Good for shadow-length depth measurement. 55 m deep at arrow.

EN1058851700M, targeted NAC
Blewett et al. (2016) *JGRP*

Highest-Resolution Views

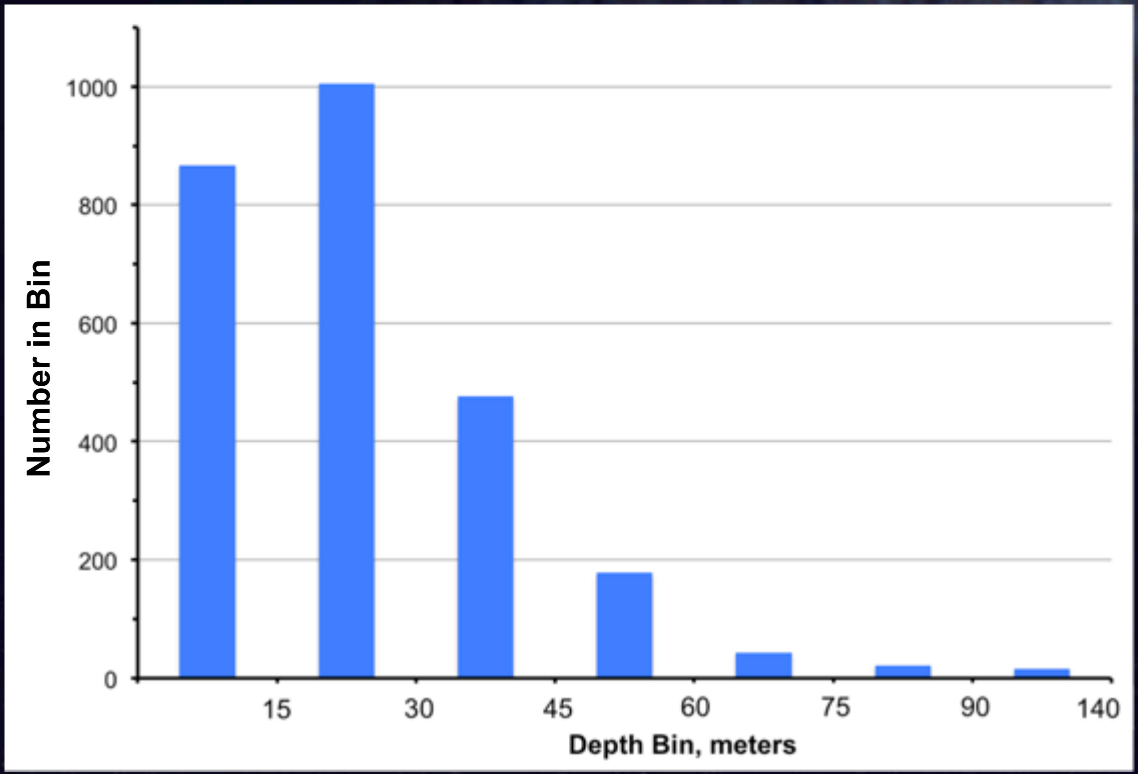


Blewett et al. (2016) *JGRP*

NAC ride-along image EN1051631967M

- In Sholem Aleichem basin
- 3.1 m/pixel
- ~21 m deep
- Straight walls suggest scarp retreat.
- No visible craters on floor; lots on surroundings.
- Hollows likely to be actively forming today.

Survey of Depths



Blewett et al. (2016) *JGRP*

- Screened all MDIS images with pixel dimensions <20m and solar incidence angles <85º for the presence of hollows (~51,000 images). *
- Hollows found in 882 images. 565 were suitable for shadow-length depth measurements. Made 2518 depth measurements.
- Mean depth = 24 m.
- Consistent with prior findings using lower-resolution images: typical depth of a few tens of meters.

*Amanda Stadermann, now at Univ of Arizona

Formation Mechanisms

- How to form irregular depressions on planetary surfaces?
  - Secondary impact craters

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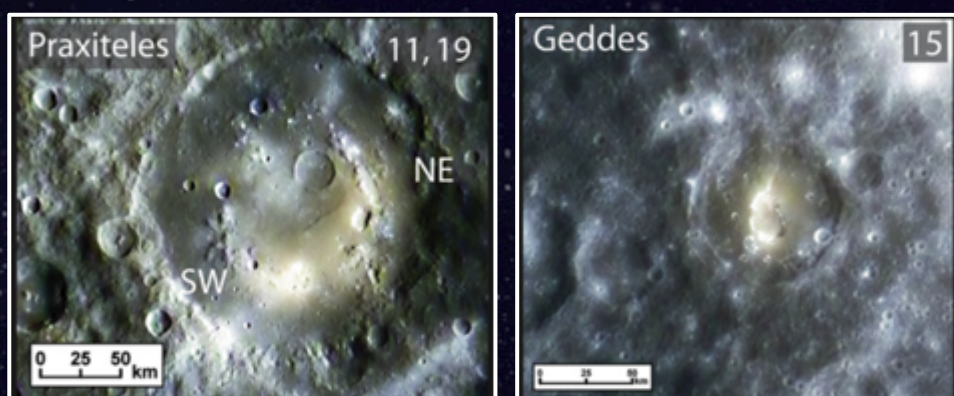
  - Secondary impact craters
  - Volcanism: vents, collapse pits. But morphology and colors are different from pits associated with pyroclastic volcanism. Crater peaks, walls, ejecta are unlikely places for eruptions.



Pyroclastic vents
Kerber et al. 2011 *PSS*.

Formation Mechanisms

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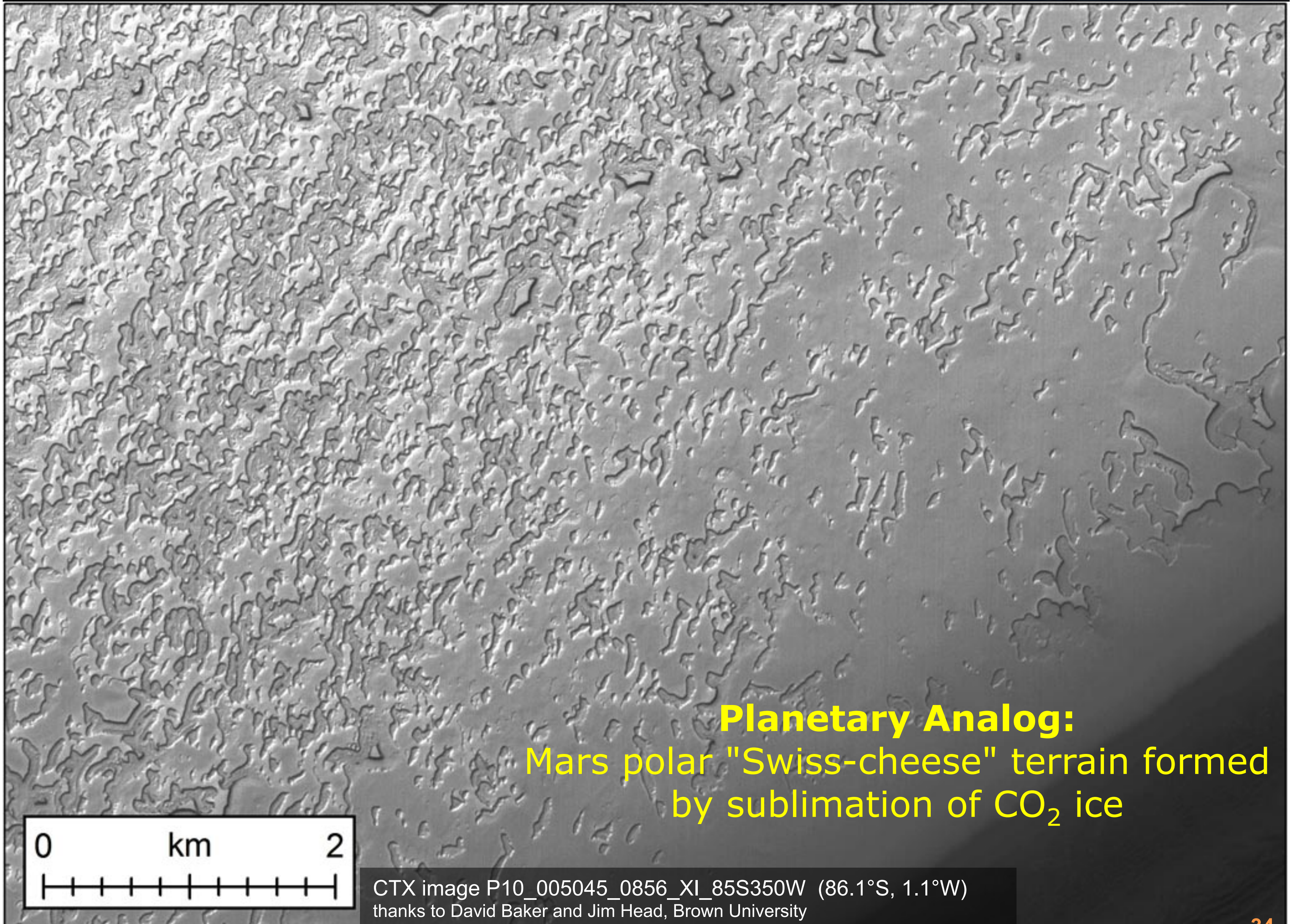
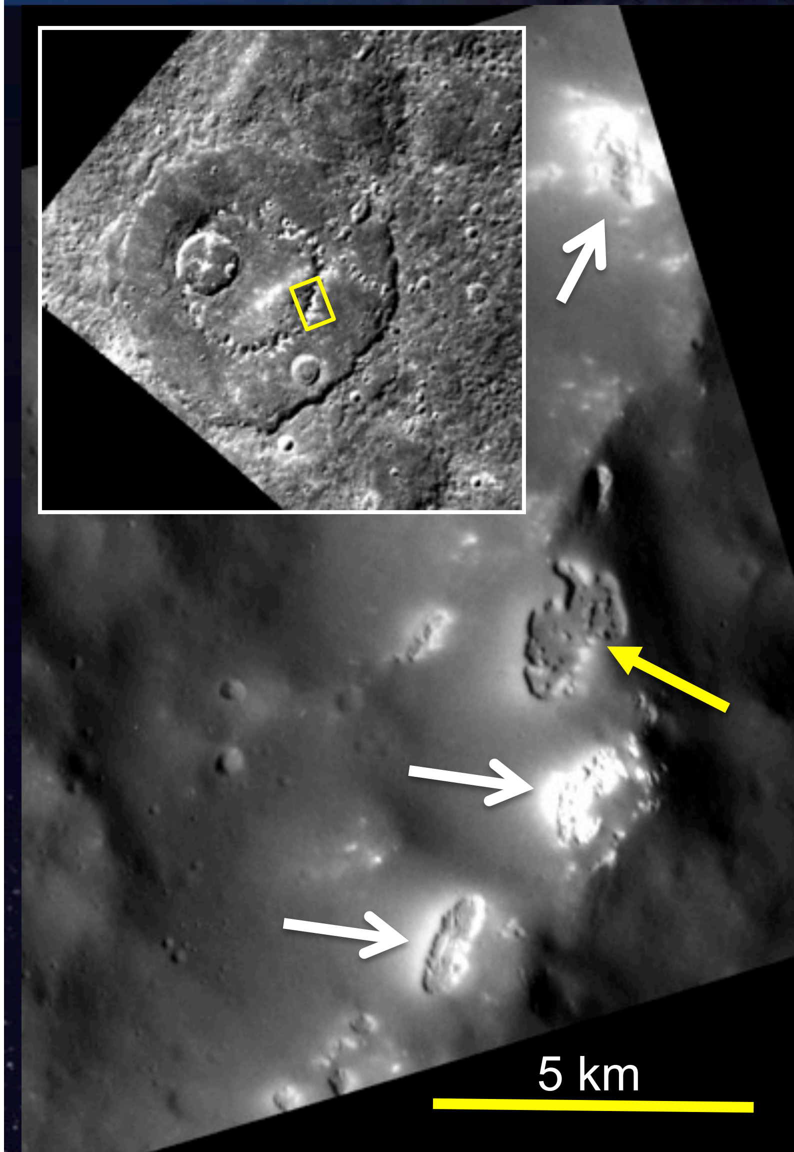
  - Secondary craters
  - Volcanism: vents, collapse pits. But morphology and colors are different from pits associated with pyroclastic volcanism. Crater peaks, walls, ejecta are unlikely places for eruptions.
  - Sublimation / loss of volatiles



Planetary Analog:
Mars polar "Swiss-cheese" terrain formed by sublimation of CO_2 ice

CTX image P10_005045_0856_XI_85S350W (86.1°S, 1.1°W)
thanks to David Baker and Jim Head, Brown University

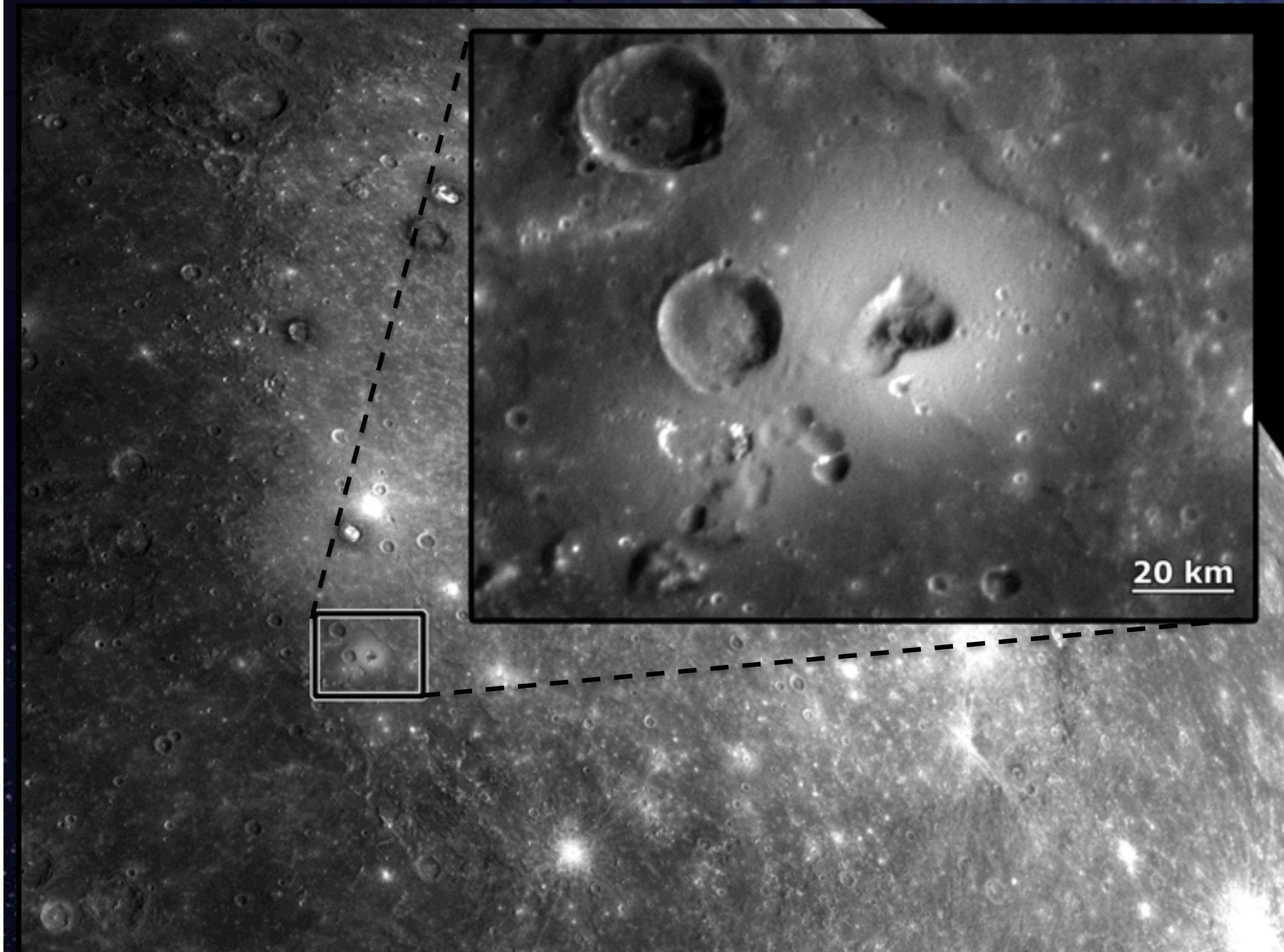


170-km diam. Aksakov basin

Loss of Material

- White arrows: hollows with bright interiors and haloes
- Yellow arrow: interior and exterior reflectance like the background
  - Suggests may no longer be active.
  - Protection by a lag, or exhaustion of the phase susceptible to destruction.
- Hollows are barely cratered, and appear to be younger than the craters in which they are found.

Geological Evidence for Volatiles: Pyroclastic Volcanism



Vent in Caloris Basin

Amount of magmatic gas needed to propel pyroclasts is on par with the measured content in eruptions at Kilauea.

Kerber et al. 2009 *EPSL*, 2011 *P&SS*

Evidence that Mercury is not Volatile-Depleted

- *MESSENGER* elemental sensing
  - X-Ray Spectrometer: Global average 2% sulfur in Mercury's surface (~4% max). Many times higher than in bulk silicate Earth, or lunar rocks. (Nittler et al., 2011; Weider et al., 2015)

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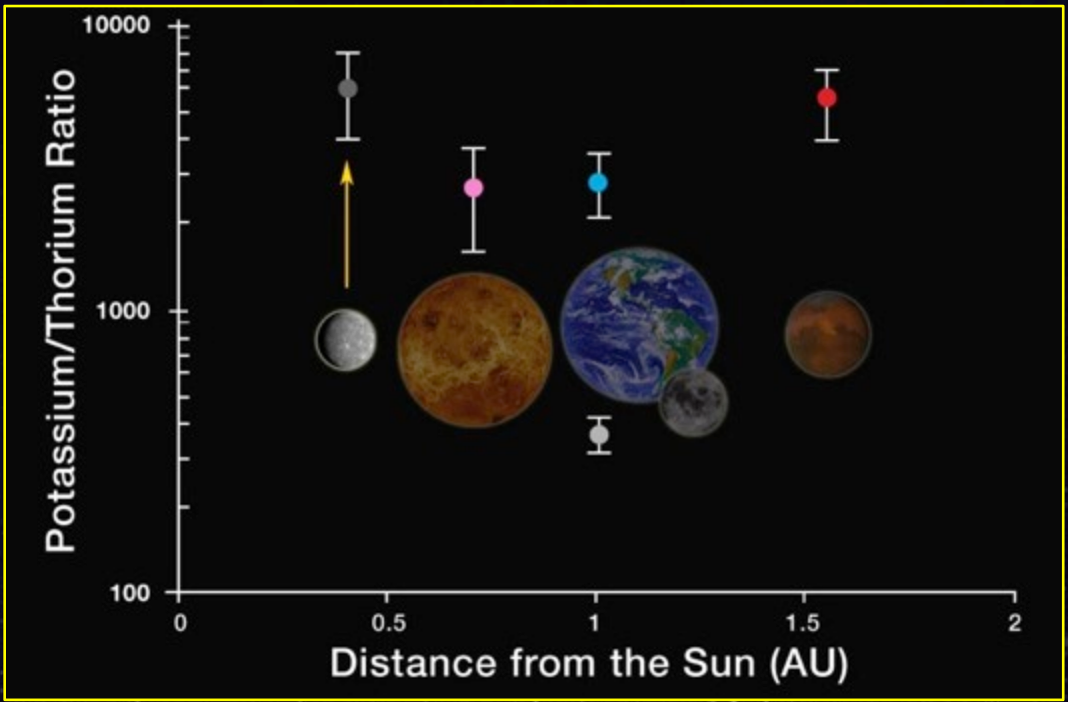
  - Gamma-Ray Spectrometer: High potassium.
  - Also relatively high abundances of sodium, chlorine, carbon. (Peplowski et al., 2014, 2015, 2016; Evans et al. 2015)



data from
Peplowski et al., 2011
Science

Composition of Low-Reflectance Material

- Spatial resolution of compositional sensing is too low to resolve small features like hollows.
- LRM: Global unit that hosts hollows
- Enriched in magnesium, calcium, sulfur.
  - Correlations suggest that sulfides are present (MgS, CaS)
  - Sulfides could undergo thermal decomposition, destruction by space weathering

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- Carbon
- Mercury is surprisingly dark, given the low iron and titanium content of the surface.
- Carbon is enriched in the LRM relative to other terrains.
- Graphite darkening agent is consistent with color/spectral properties.
  - Graphite could be converted to CH_4 by solar-wind protons, and lost.

Conjectures on Origin of Hollows

- Loss/destruction of a volatile-bearing phase that is unstable at/near surface because of
  - Heating by impact melt or lava or intrusive magma (contact metamorphism)
  - Ion sputtering and/or micrometeoroid bombardment
  - Solar heating, solar-UV destruction

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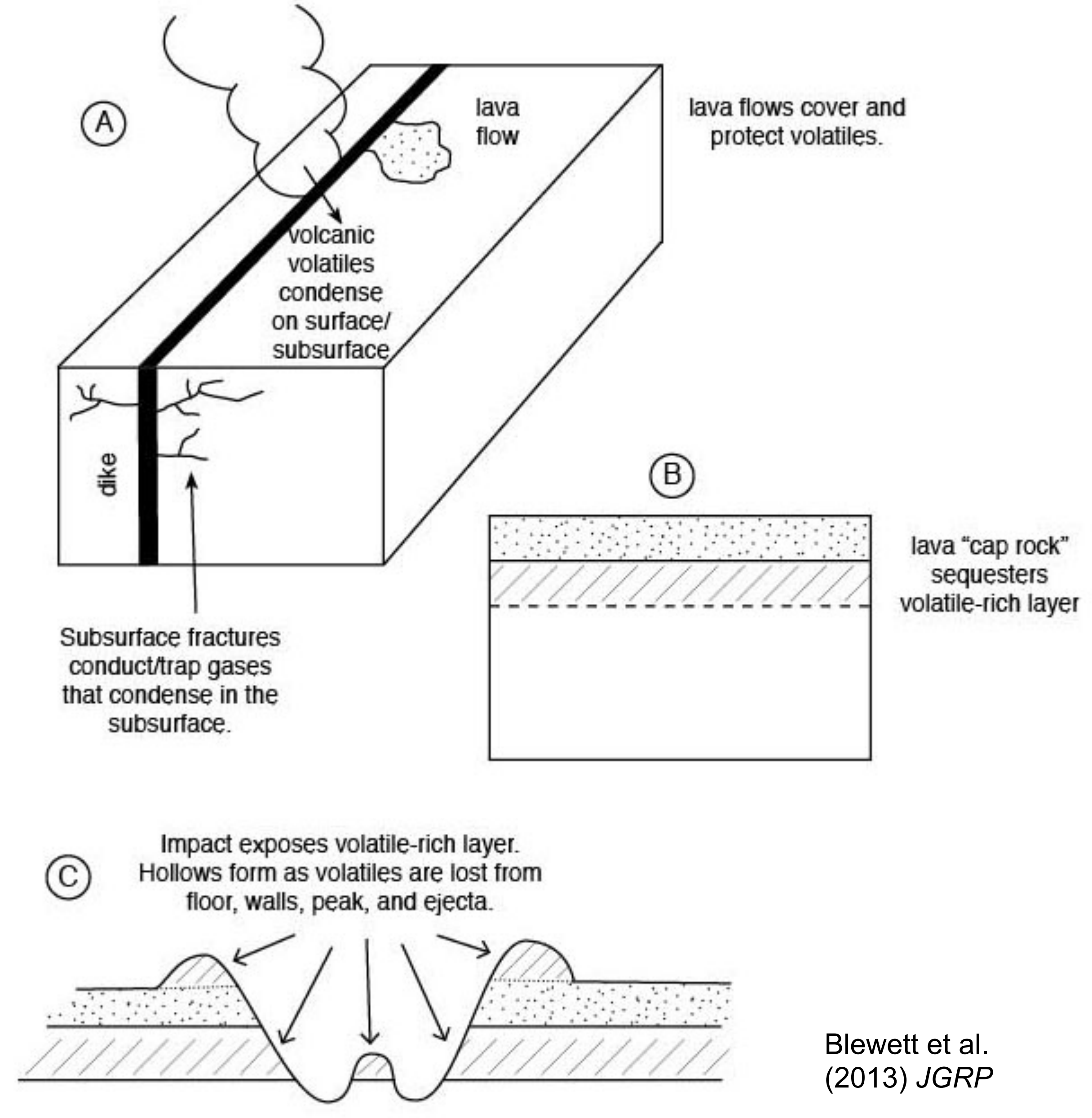
Preference for Equator-facing Slopes

Blewett et al. (2011) *Science*

- 15-km diameter crater
- 66.6°N, 153.2°E
- Hollows & bright material on south-facing slope.
- Suggests link to maximal solar heating.
- Thomas et al. (2014 *Icarus*) found a preference for hollows on equator-facing slopes.

18 m/pixel



Blewett et al. (2013) *JGRP*

Possible Source of Volatiles:

a) Volcanism

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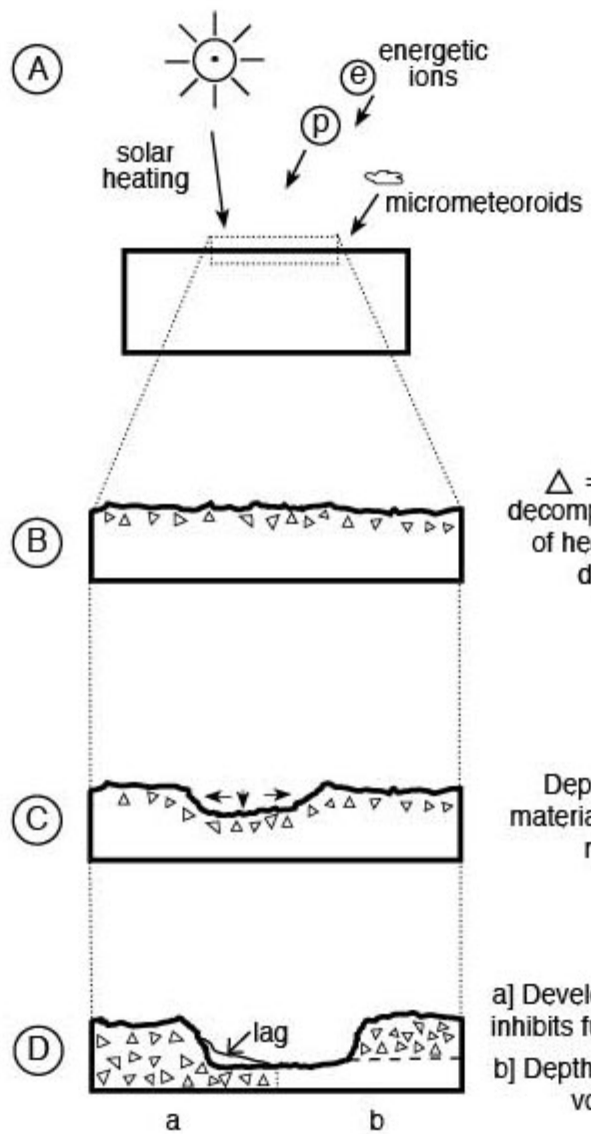


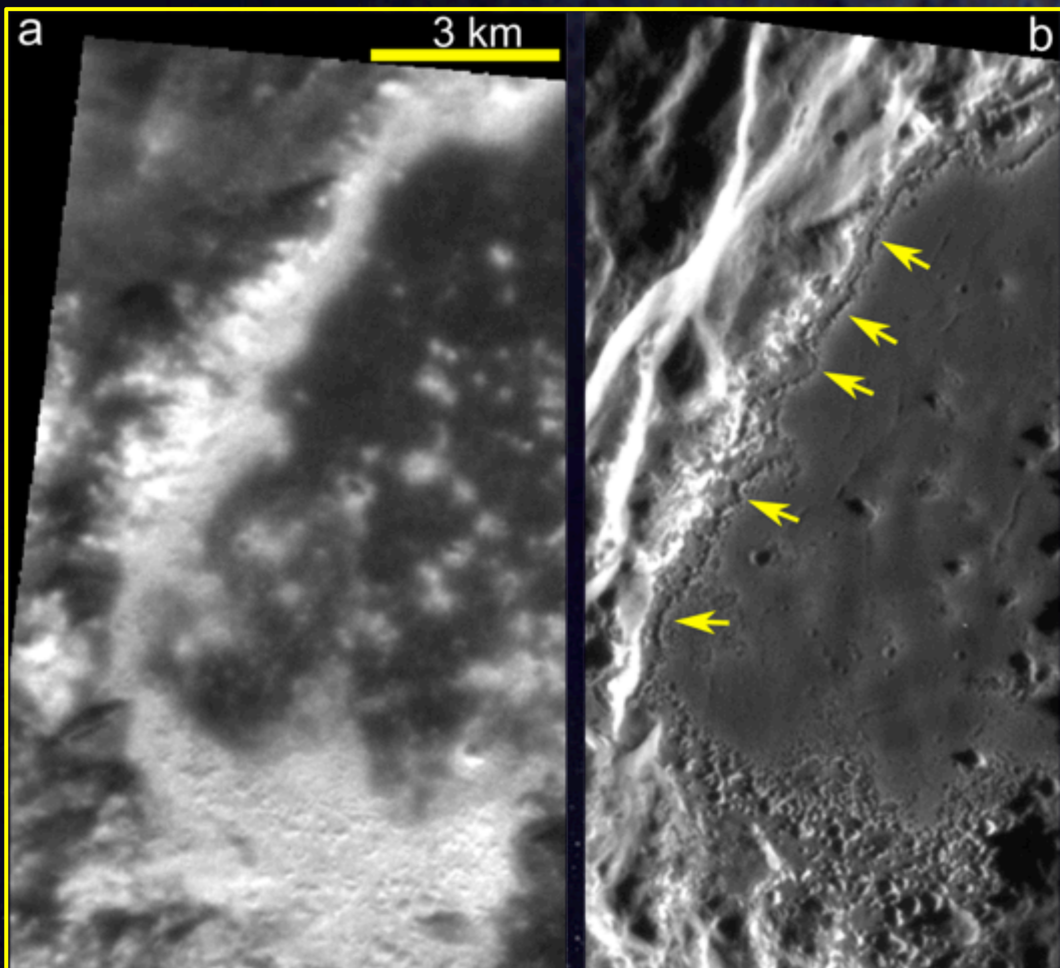
Blewett et al. (2013) *JGRP*

Possible Source of Volatiles:

b) Phase inherent in the rocks

- Harsh thermal and space-weathering environment
- Micrometeoroid flux and velocity much higher than at the Moon.
- Greater UV and solar wind flux, and also higher ion energies because of magnetospheric processes.

Rate of Formation



- Balanchine: 41-km rayed crater.
- Rayed = Kuiperian
- Base of Kuiperian ~300 Ma (Banks et al., 2016 *LPSC*)

- Hollows have retreated from crater wall a distance of ~300 m.

- If crater is 300 Ma old, and hollows began to form immediately, enlargement rate is 1 cm/10,000 Earth years.

Blewett et al. 2016 *JGRP*.

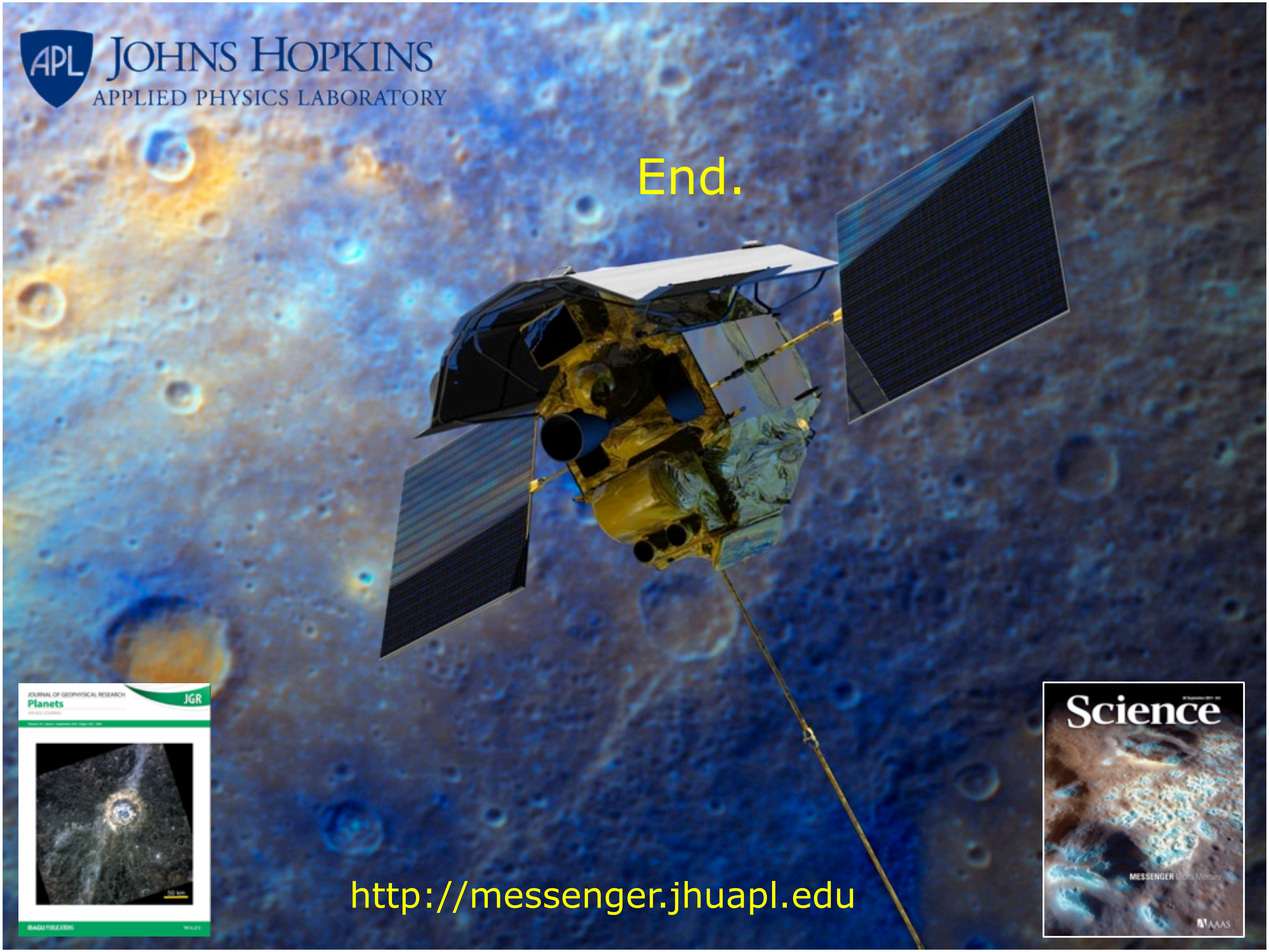
Rate of Formation

- Assuming linear growth by scarp retreat
  - 1 cm in 10,000 years

- Abrasion of lunar rocks by micrometeoroids
  - 1 cm in 10 million years (Ashworth, 1977)
- Formation of martian "Swiss cheese" depressions
  - 1 m per Earth year (Malin et al., 2001)

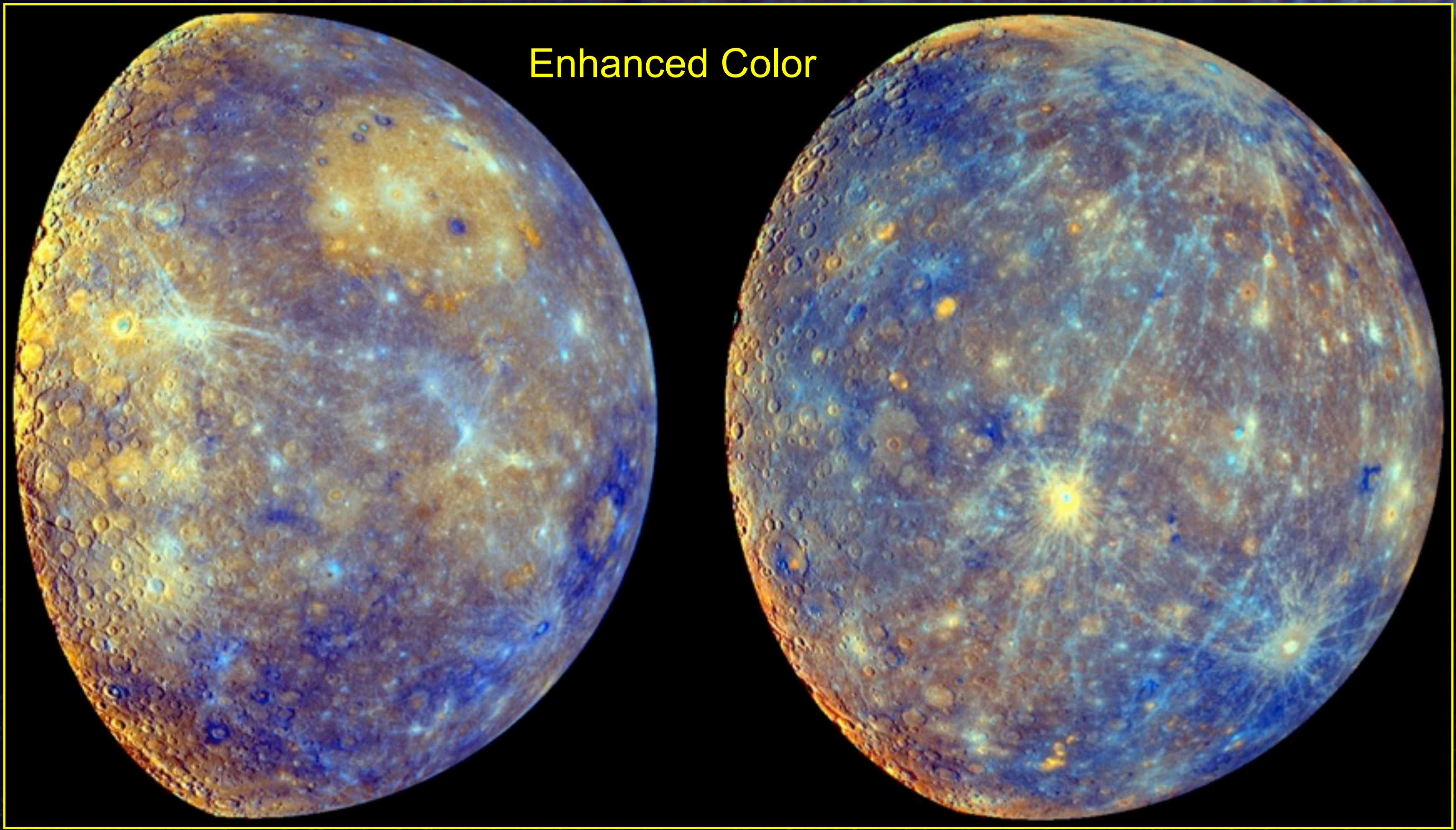
Summary - Hollows

- High spatial-resolution observations from Mercury orbit have revealed an unusual and unexpected landform.
- Hollows appear to be common, are globally distributed, and are associated with a particular color unit.
- Likely formation mechanisms involve loss of volatiles.
- Similar, shallow depths of hollows around the planet suggest that depth is controlled by formation of a protective cover of devolatilized material (lag).
- Evidence for high volatile abundances in Mercury also comes from from *MESSENGER* geochemical sensing, and from analysis of pyroclastic deposits.
- Hollows are relatively young and some may be forming today.


APL JOHNS HOPKINS
APPLIED PHYSICS LABORATORY
End.
JOURNAL OF GEOPHYSICAL RESEARCH
Planets
JGR
Science
MESSENGER
http://messenger.jhuapl.edu

Bonus Material

MESSENGER - Mercury Flybys 1 & 2

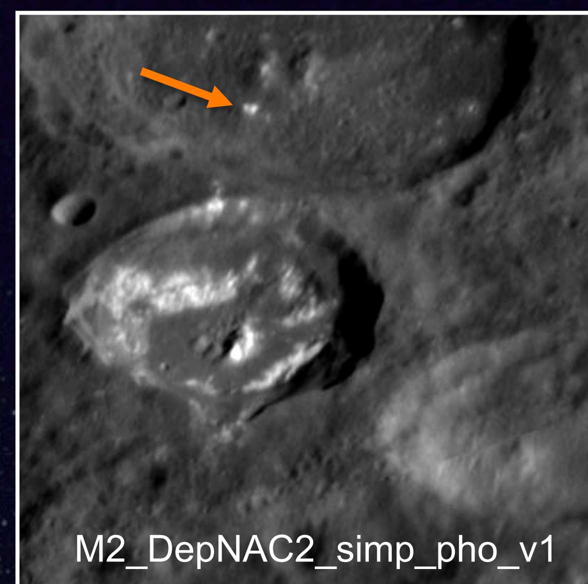


PC2, PC1, 430-nm/1000-nm as R, G, B

Major Morphological Types: 3. Base of Wall

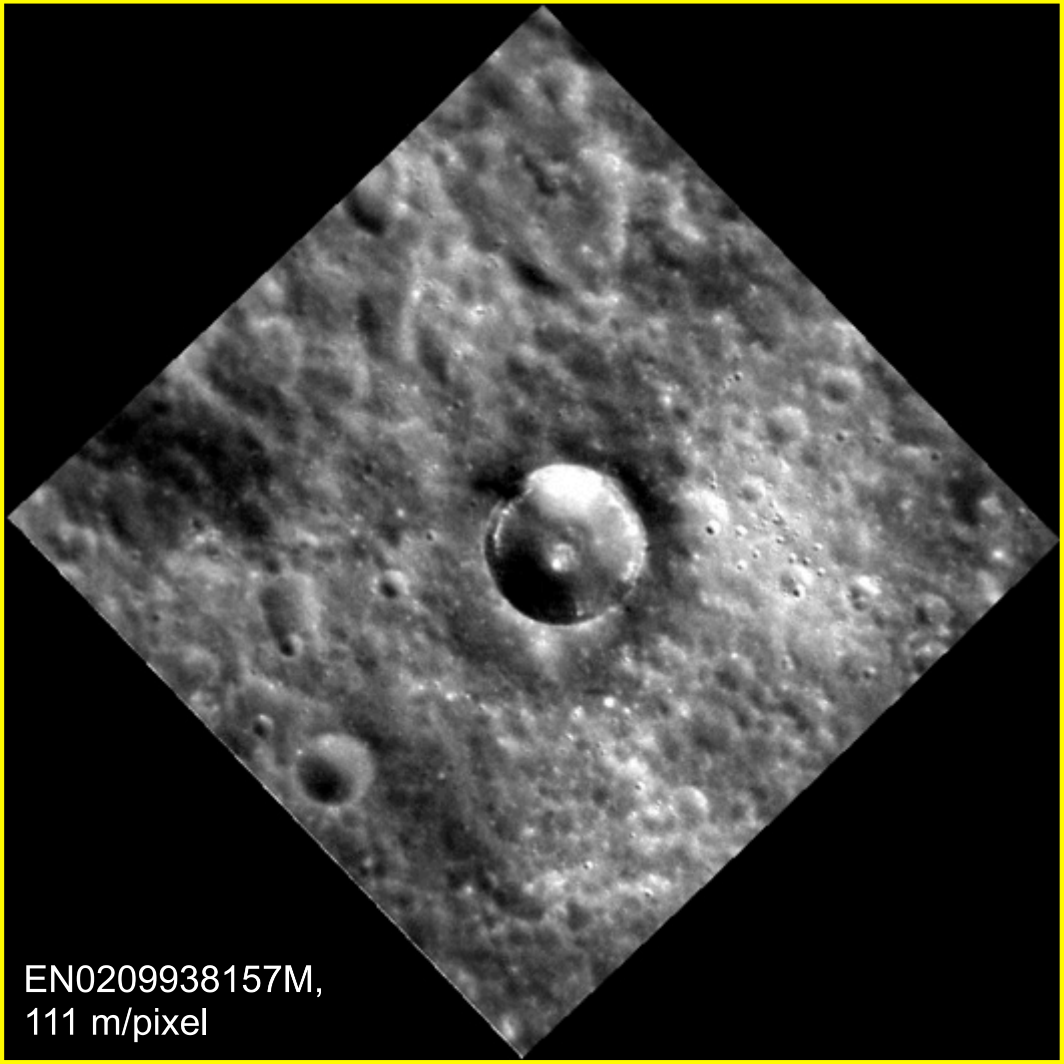
EW0210895009I, 214 m/pixel
1000-750-430 as R-G-B

- At floor-wall intersection, concentric.
- 50.7°N, 320.3°E.
- 34-km diam. crater
- Note outcrop in larger crater to the north (arrow).



M2_DepNAC2_simp_pho_v1

Major Morphological Types: Interior Stratum



EN0209938157M,
111 m/pixel

- 27.9°N, 19.9°E.
- 12-km diameter crater.
- Bright material forms a partial ring on inner wall, just below the rim.
- Bright patch on flat floor.

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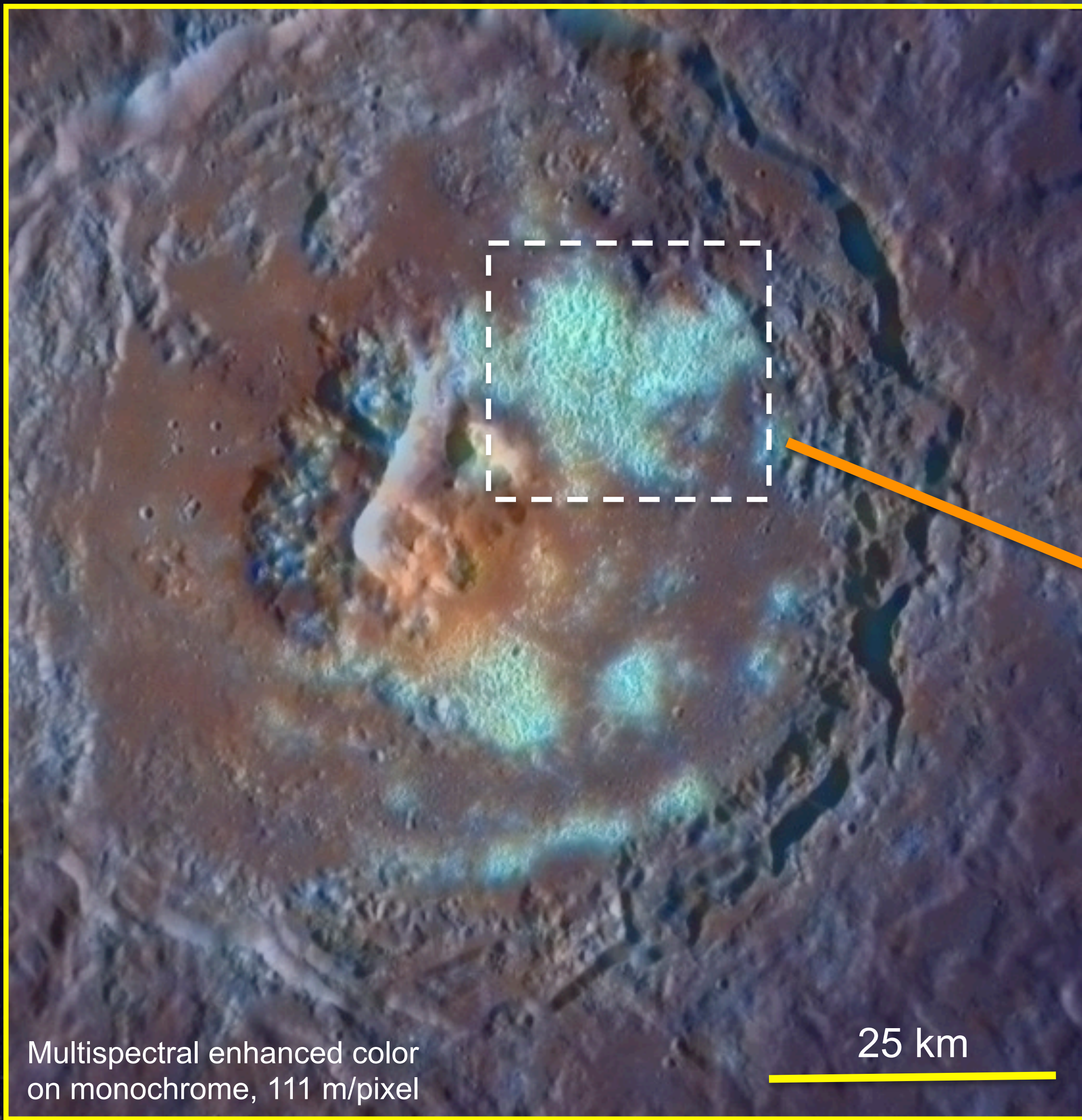


Tyagaraja

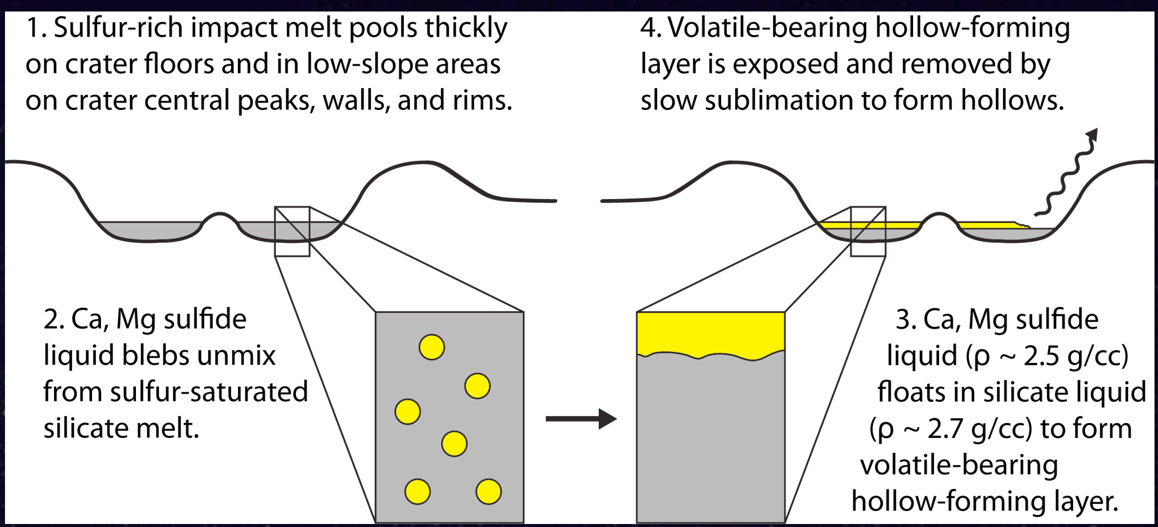
97 km diameter

Coalesced hollows on floor: "etched terrain"

EN0212327089M

- What is source of volatile-bearing material?
  - Volcanic exhalations condensed on cold surroundings and buried by further eruptions.
  - The lithology brought up from depth by impact contains a phase unstable at the surface, possibly sulfide minerals.
    - X-Ray Spectrometer has measured surprisingly high abundance of sulfur (~4%, Nittler et al., 2011 *Science*)

- What is source of volatile-bearing material?
  - Volcanic exhalations condensed on cold surroundings and were buried by further eruptions.
  - The lithology brought up from depth by impact contains a phase unstable at the surface, possibly sulfide minerals.
    - X-Ray Spectrometer has measured surprisingly high abundance of sulfur (~4%)
  - Differentiation of impact melt pool, flotation of sulfide-rich layer.
    - Calculations on Mercury-composition melts indicate that sulfide melt is less dense than silicate liquid & would float.

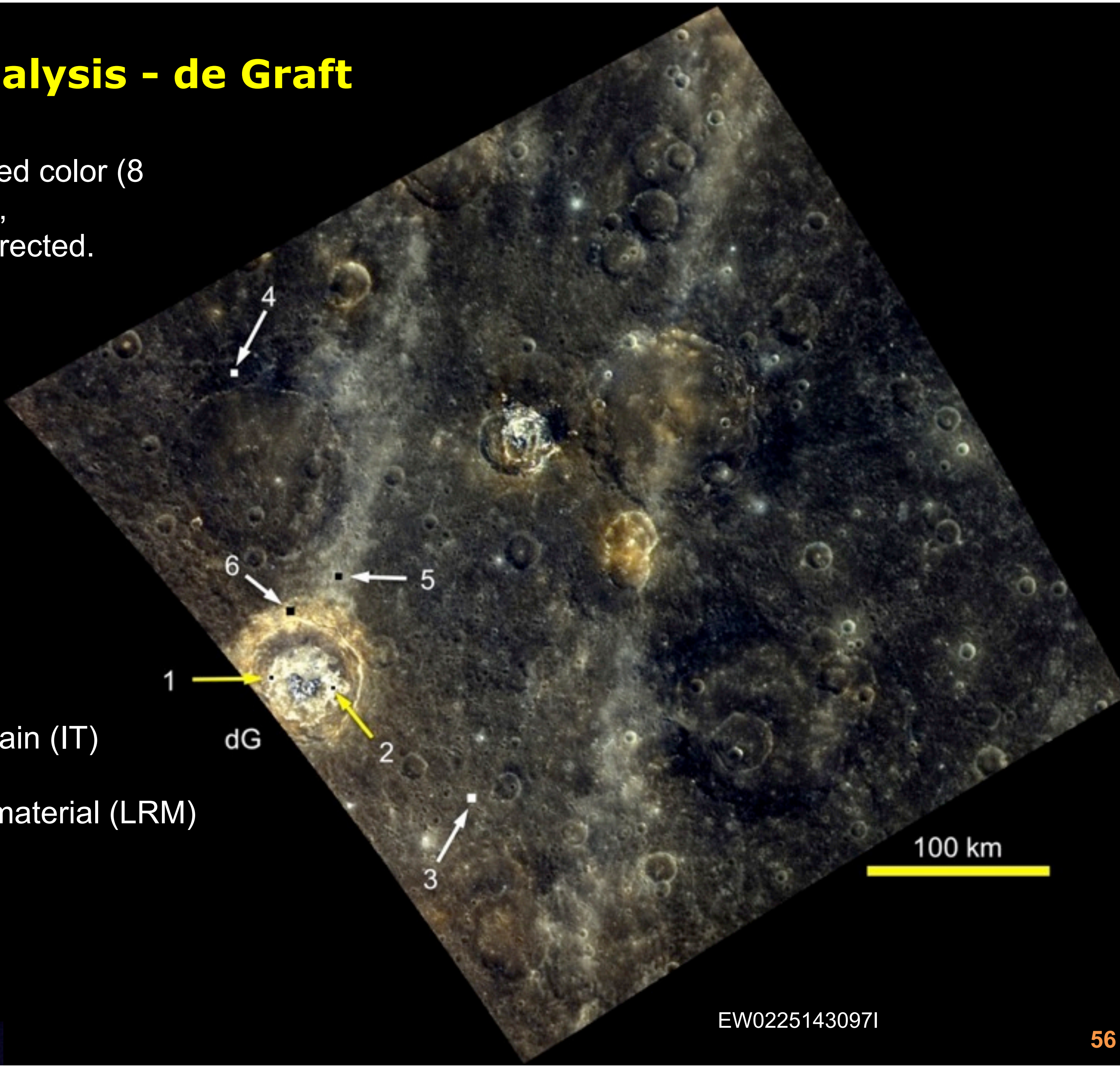


Will Vaughan, Brown University

Spectral Analysis - de Graft

24° N, 5° E, Targeted color (8 filters), 434 m/pixel, photometrically corrected.

996-749-433 nm as R-G-B.



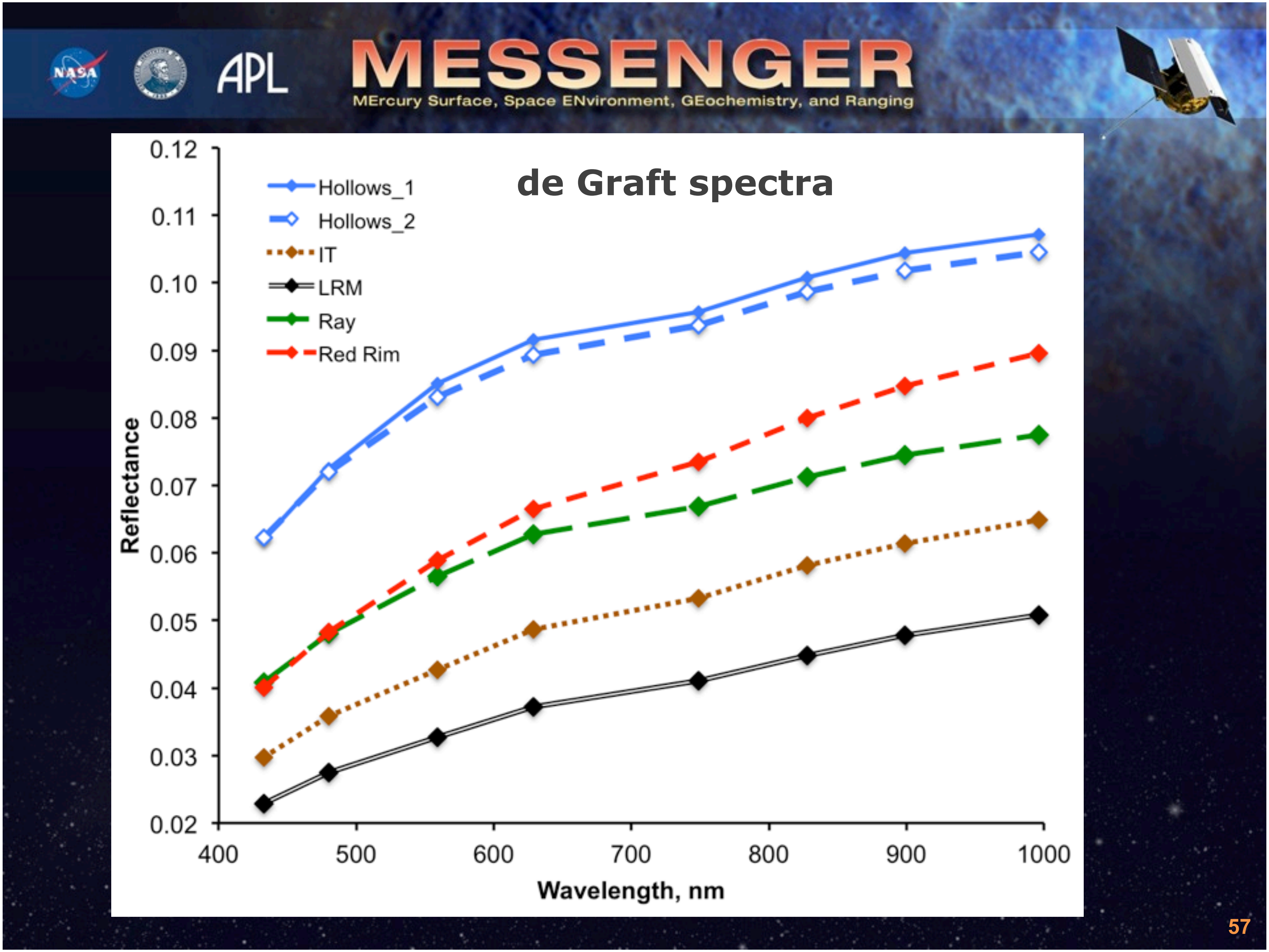
1, 2: hollows

3: intermediate terrain (IT)

4: low reflectance material (LRM)

5: ray

6: reddish rim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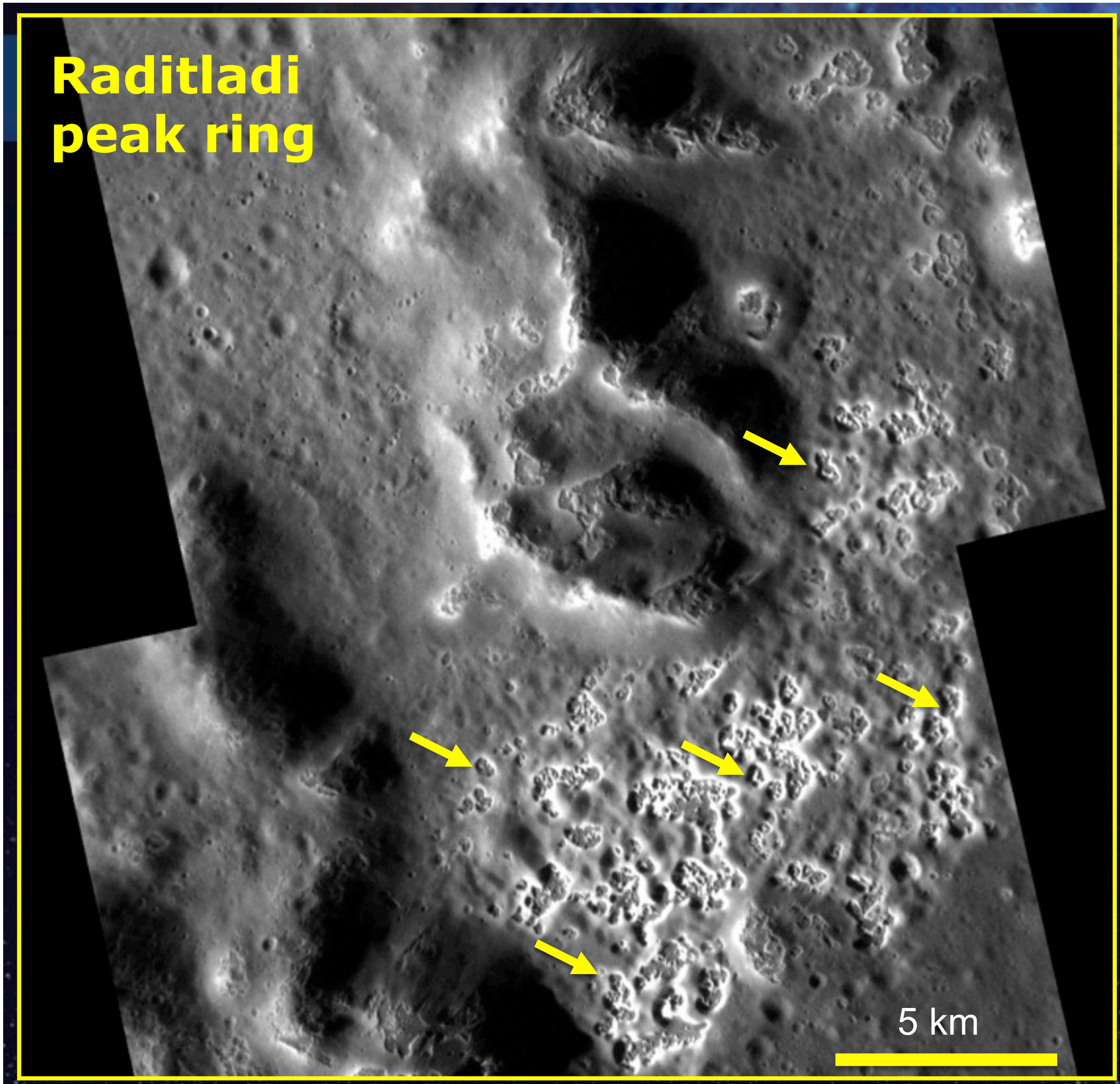
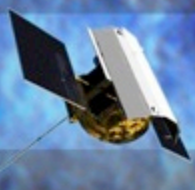
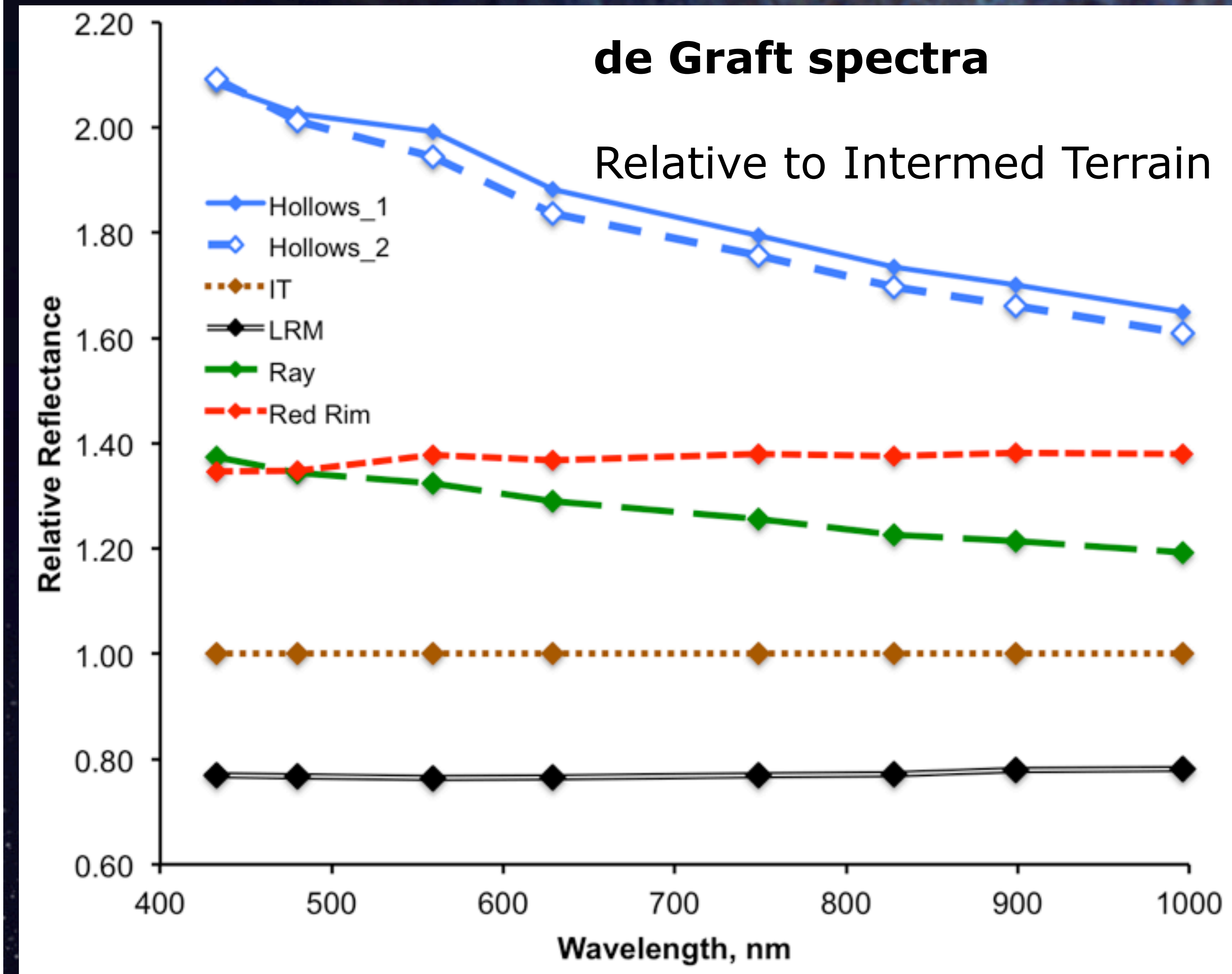
de Graft spectra
Hollows_1
Hollows_2
IT
LRM
Ray
Red Rim
Reflectance
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
400
500
600
700
800
900
1000
Wavelength, nm



Targeted NAC, 17 m/pixel; ~26.7 N, 120.6 E.



- Hollows on floor
- Characteristic size 200-300 m


de Graft spectra
Relative to Intermed Terrain
Hollows_1
Hollows_2
IT
LRM
Ray
Red Rim
Relative Reflectance
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
400
500
600
700
800
900
1000
Wavelength, nm

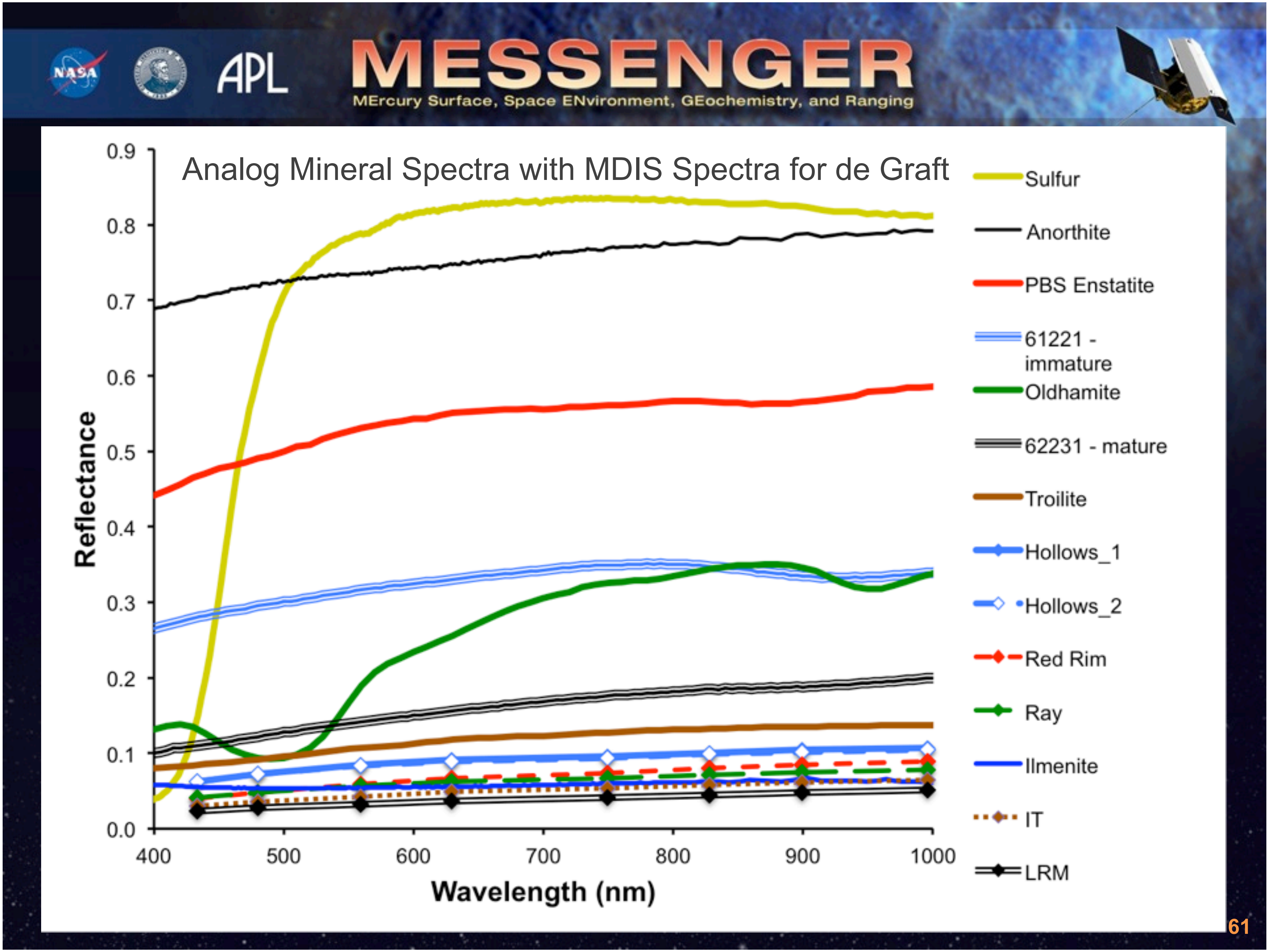
Lab Spectra

- *Apollo 16* highland soils, enstatite (from Pena Blanca Spring aubrite), oldhamite (CaS from Norton County aubrite), and troilite (FeS) are from RELAB.

- 61221: immature (I_s/FeO=9.2), ~4.5 wt.% FeO
- 62231: mature (I_s/FeO=91), ~5 wt.% FeO

- Reagent grade sulfur, ilmenite, and anorthite are from the USGS spectral library.

- Fe-free enstatite, oldhamite (CaS), troilite (FeS) shown in Burbine et al. (2002), Spectra of extremely reduced assemblages: Implications for Mercury, *M&PS* **37**, 1233-1244.



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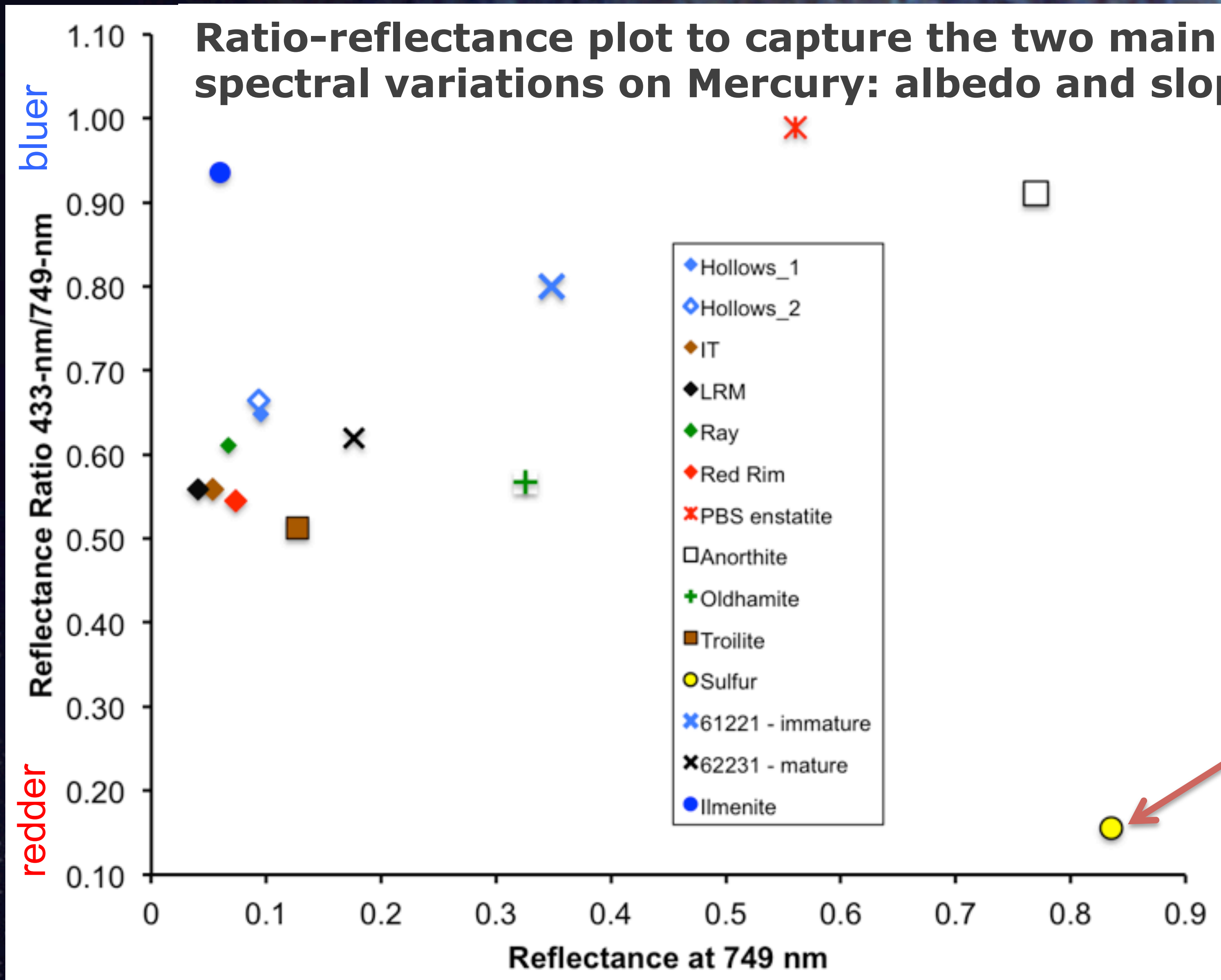
APL
Analog Mineral Spectra with MDIS Spectra for de Graft
Reflectance
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
400
500
600
700
800
900
1000
Wavelength (nm)
Sulfur
Anorthite
PBS Enstatite
61221 - immature
Oldhamite
62231 - mature
Troilite
Hollows_1
Hollows_2
Red Rim
Ray
Ilmenite
IT
LRM

Ratio-reflectance plot to capture the two main spectral variations on Mercury: albedo and slope



Sulfur: very steep (red) slope

Notes & Observations

- Mercury is dark:
  - The bright hollows have lower reflectance than a mature *Apollo 16* soil.
  - Mature LRM and IT have about the same reflectance as pure ilmenite.

- If Mercury's surface is dominantly an Fe-free silicate (like enstatite), then we need a darkening and reddening agent to pull the mineral's spectrum down and to the left to make the observed surface of Mercury.

- Troilite (FeS) is in the same neighborhood as the Mercury surfaces, but results from geochemical sensors preclude large amounts of FeS (gamma-ray spectrometer limit on Fe is a few wt.%).

Notes & Observations, 2

- Micro- and nanophase metallic iron coatings produced by space weathering, resulting in a dark, red surface (Lucey & Riner 2011 *Icarus*). Source of Fe: Mercury rocks, or meteoritic.

- Carbon delivered by comets/micrometeoroids (Bruck-Syal & Schultz, LPSC 2013).

- Exogenic sources cannot explain major terrain color differences (High-Reflectance Red Plains vs. Low-Reflectance Material).

- Need to perform intimate mixture models of various candidate constituents.

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Notes & Observations, 2

- Potentially could have small amounts of troilite that feed micro- and nanophase metallic iron coatings produced by space weathering, resulting in a dark, red surface. Need to perform intimate mixture models of various candidate constituents.

- Pure sulfur is bright but extremely red in the visible (yellow dot on ratio-reflectance plot). Hollows are blue relative to average Mercury, so pure sulfur can’t be the phase responsible for the bright haloes and interiors of the hollows. (Plus, daytime is too hot.)

Notes & Observations, 2

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- The hollows could be bright by subtraction, i.e., destruction of a dark phase by a thermal or space-weathering process.
  - General space weathering trend on Mercury is "darken & redden" -> fading of crater rays.

Rate of Formation

- We examined examples in Raditladi basin
  - Rough constraint on age of basin from crater size-frequency distribution
  - Strom et al. (2008) *Science*; Prockter et al. (2010) *Science*; Marchi et al. (2011) *P&SS*
  - Basin model age ~1 Gyr