The surface of Mercury:
Using deep learning to explore its challenging flat spectra

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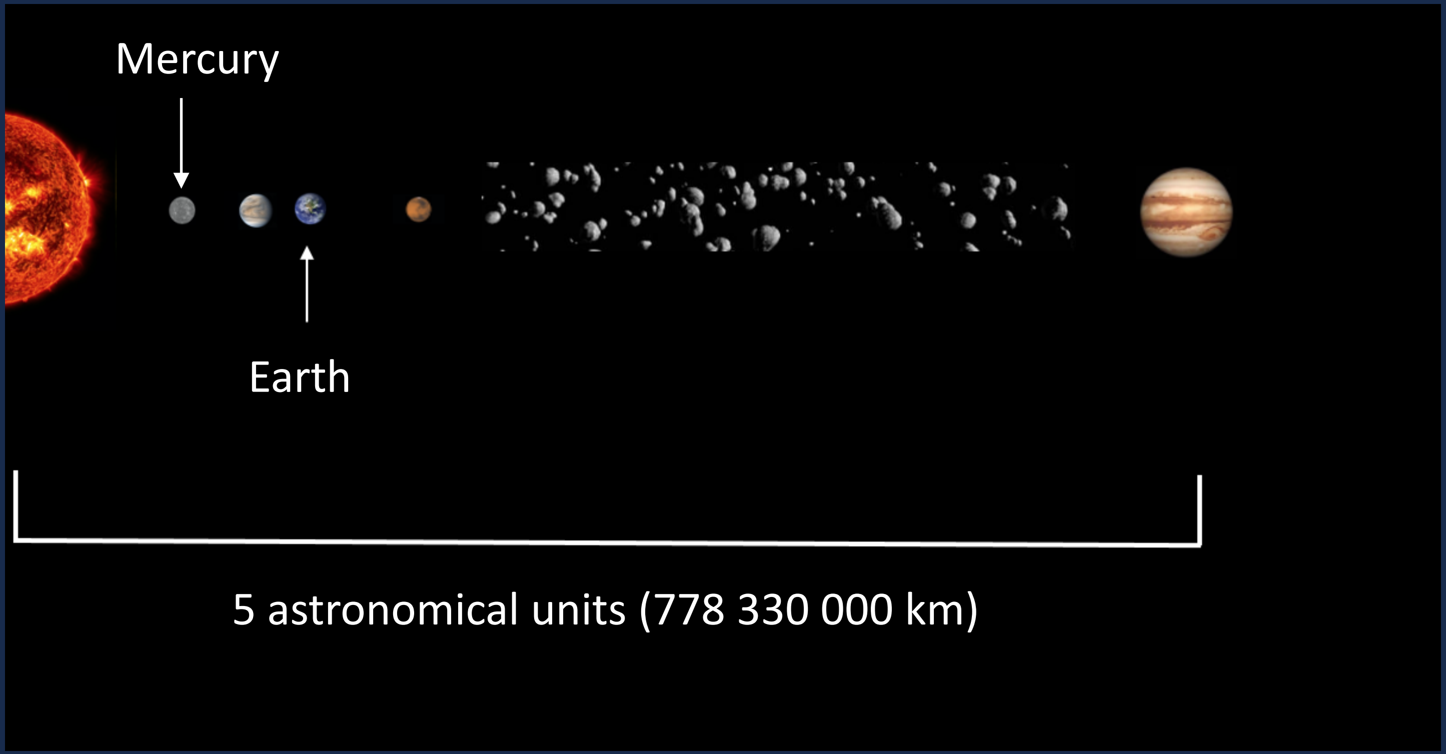
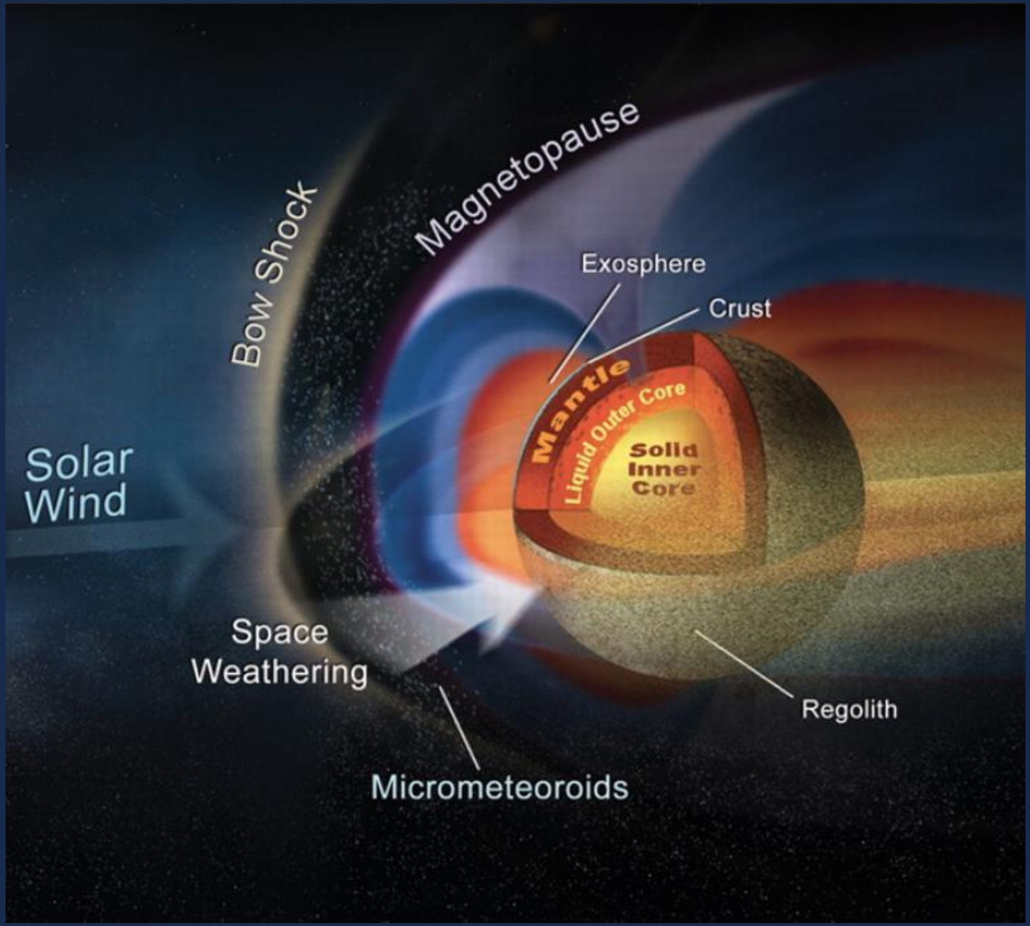
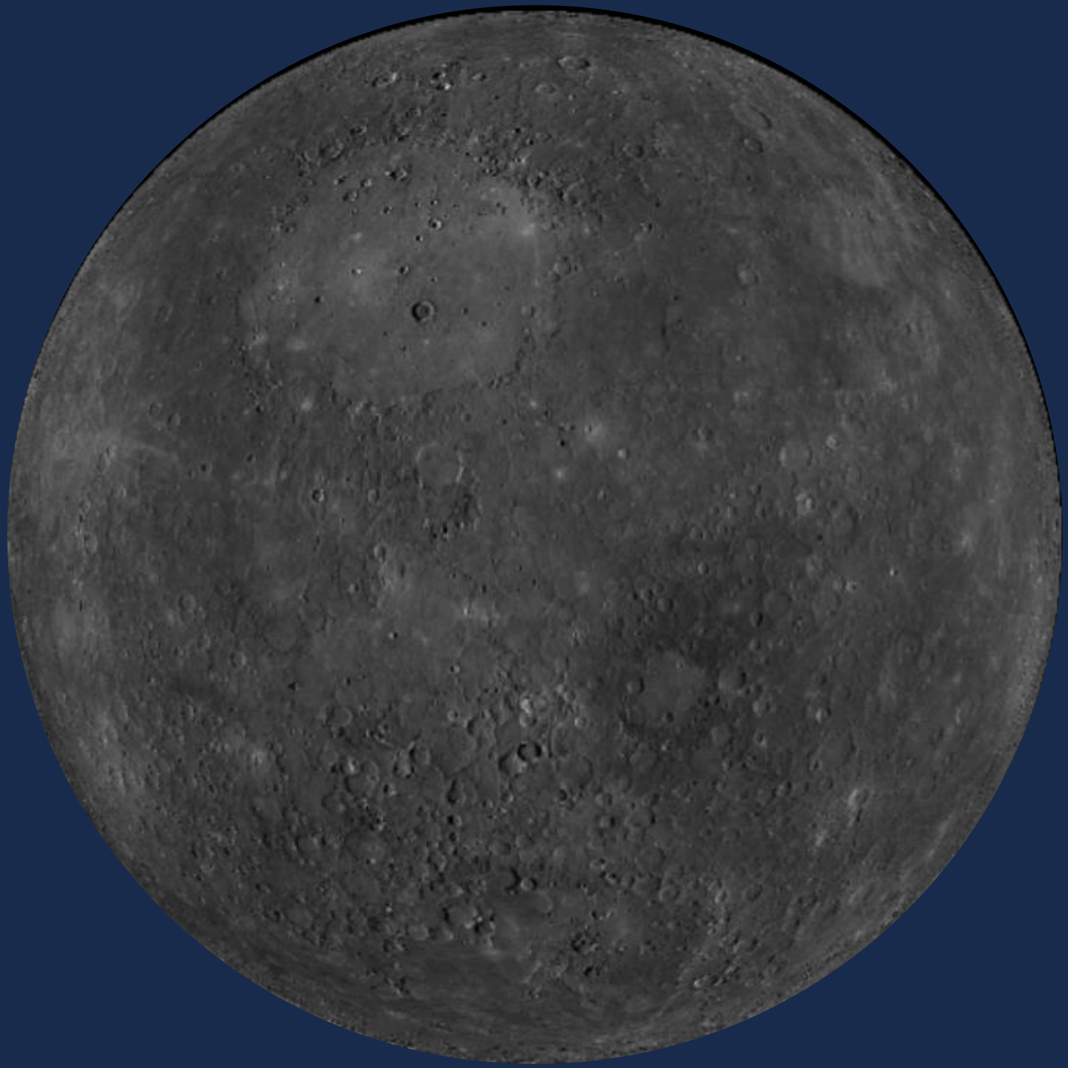
Mercury: the innermost planet

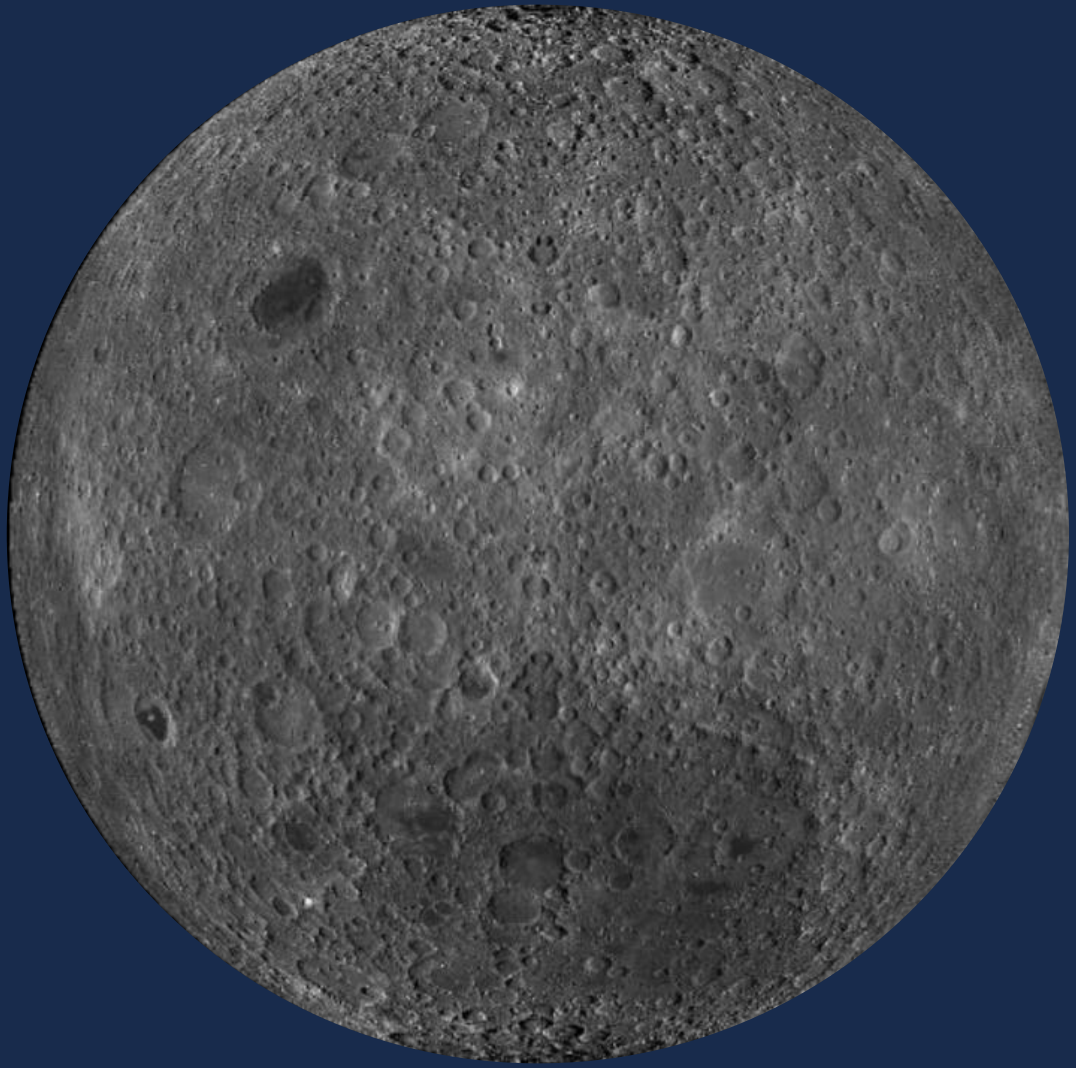




Credit: University of Virginia

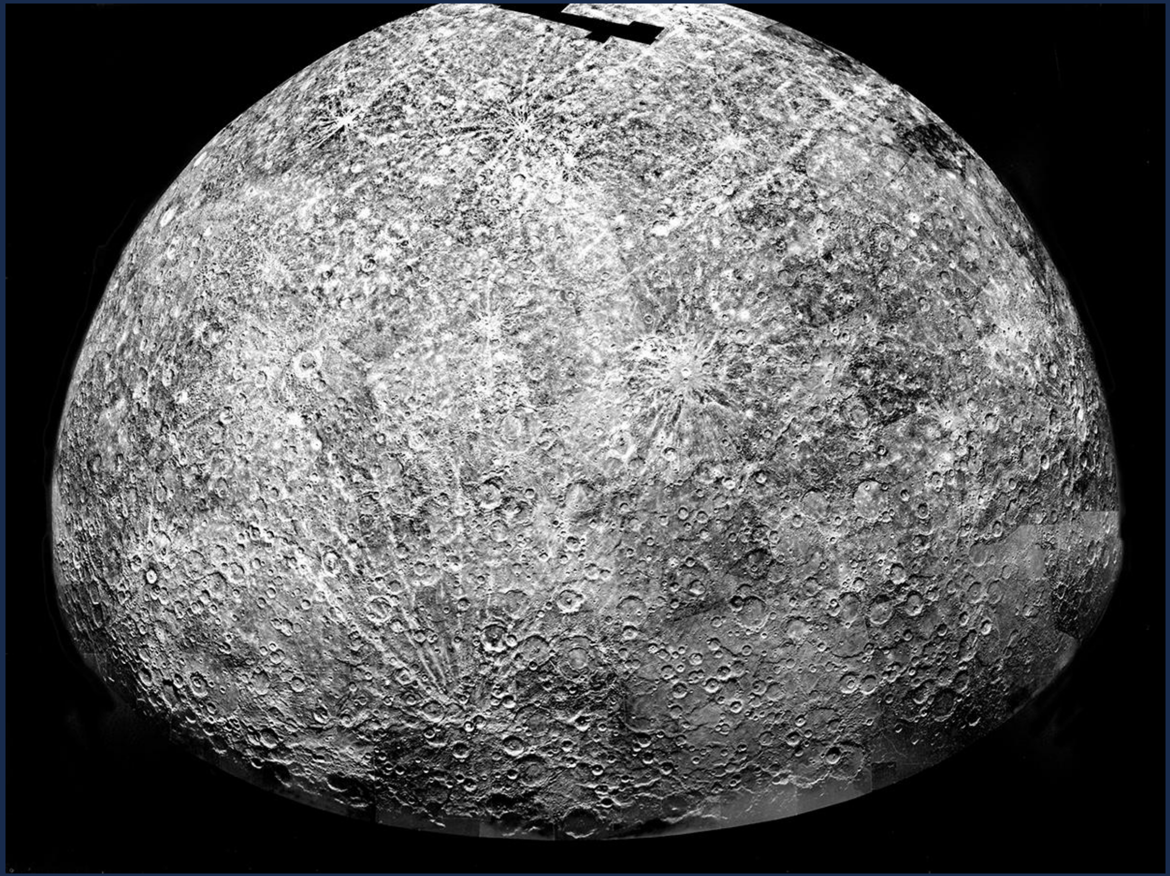
Mercury or the Moon?





Credit: Quickmap

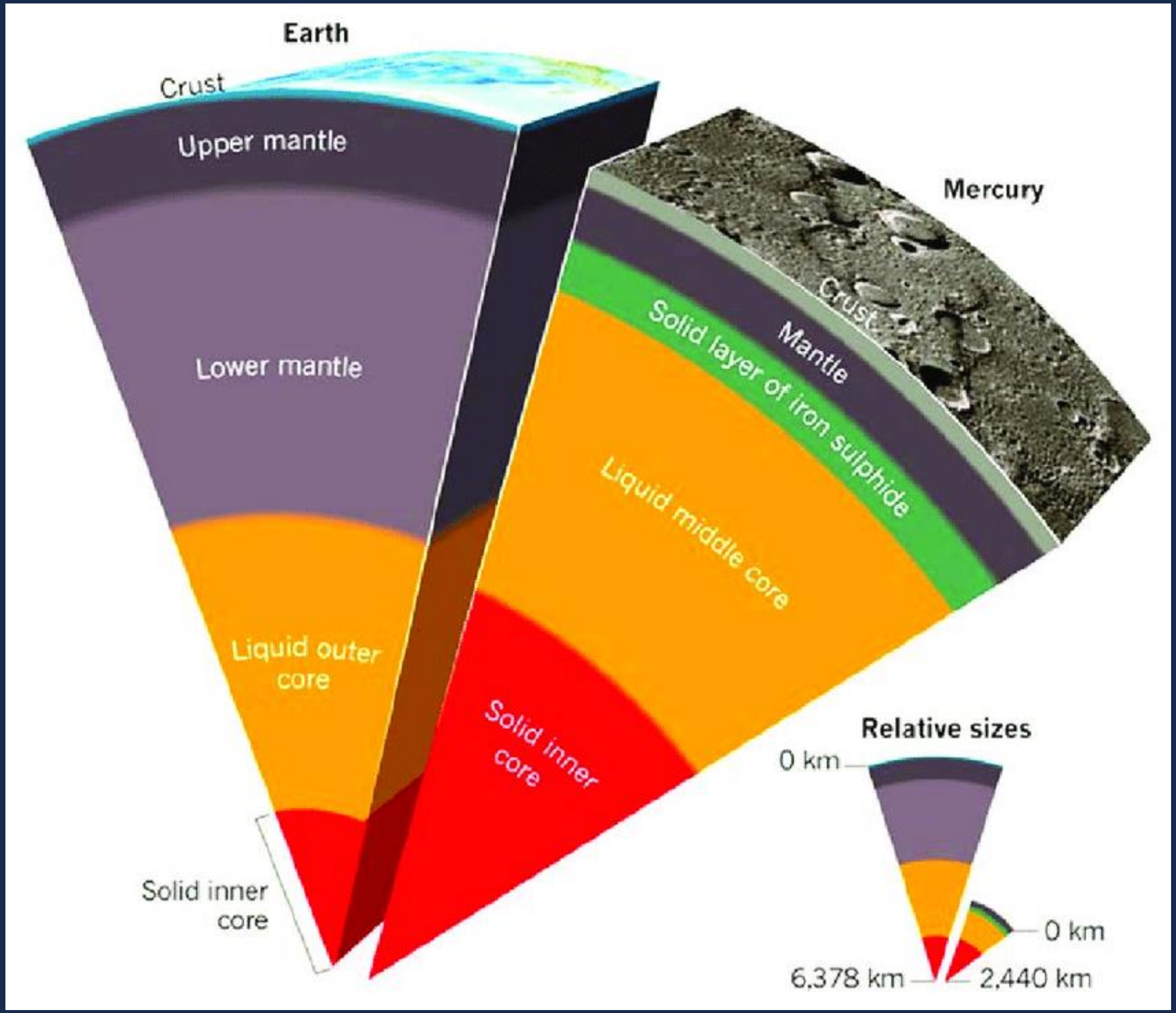
First exploration by the Mariner 10 mission



MARINER 10 (NASA, 1974)

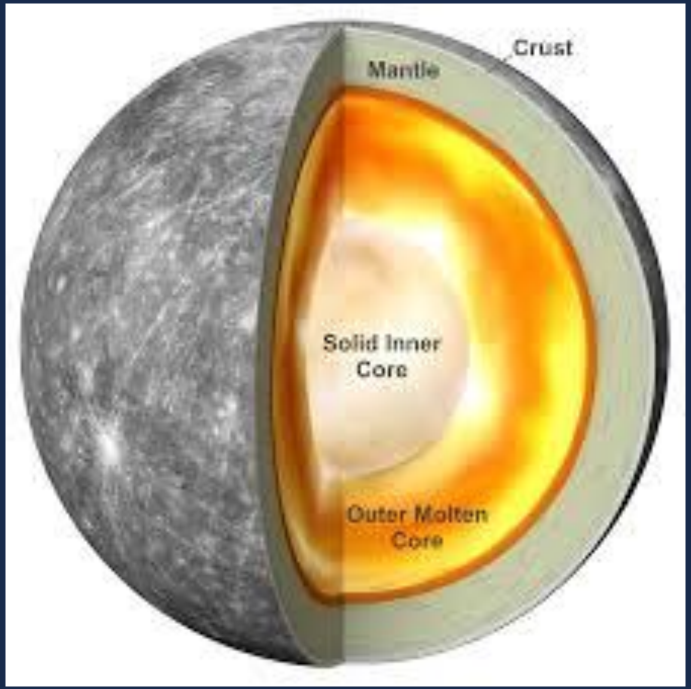
- 3 Mercury flybys
- Closest approach of 327 km
- Imaged 40% of the surface
- Discovery of Mercury's exosphere
- Discovery of Mercury's magnetic field
- Discovery of Mercury's large core

First exploration by the Mariner 10 mission



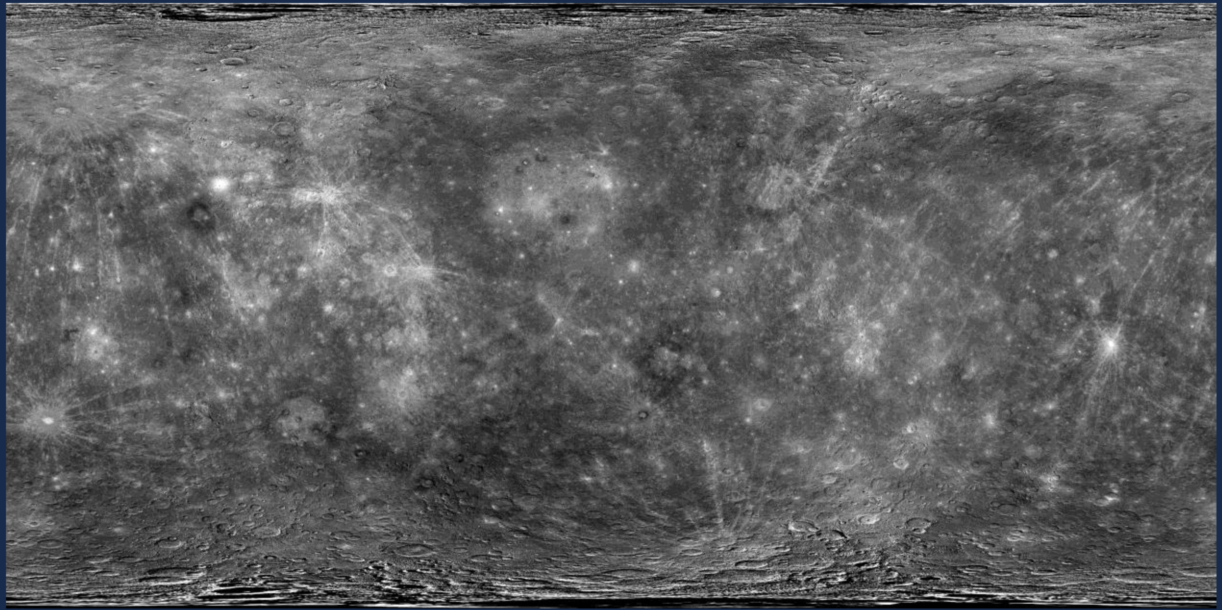
Stevenson et al., 2012

Mercury's large core is currently interpreted as the result of mantle extracted in collision or impact events (Benz et al., 2007, Asphaug & Reufer., 2014,Chau et al., 2018, Hyodo et al., 2021)



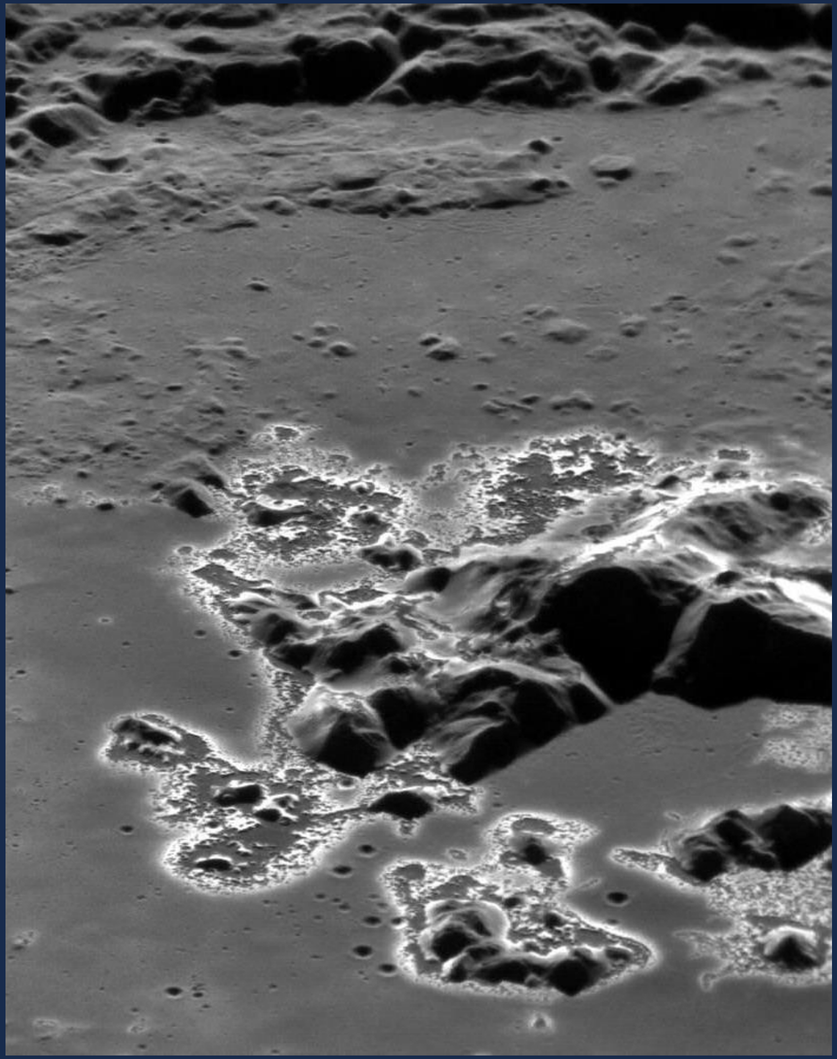
Credit: NASA

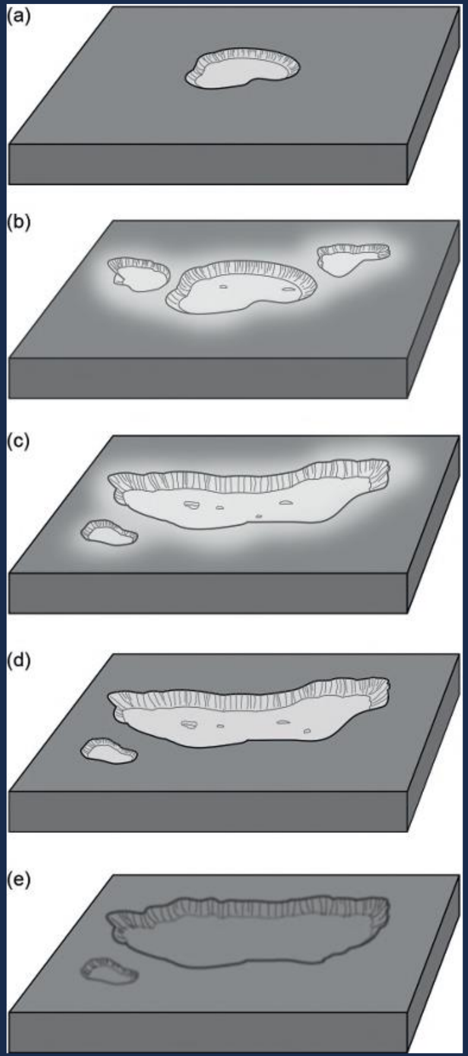
Revisiting Mercury with the MESSENGER mission


MESSENGER (NASA, 2017)

- 4 years in Mercury orbit
- Mapping of the surface
- Compositional information
- Discovery of Hollows
- Discovery of water ice in Mercury's North pole

Results from MESSENGER: discovery of hollows





Blewett et al., 2018

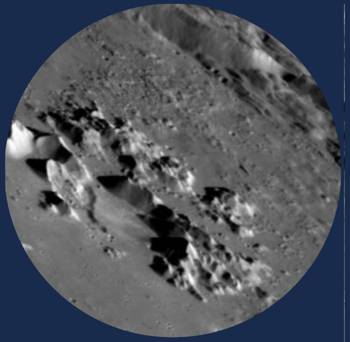
Upcoming exploration of Mercury: BepiColombo

- 2 spacecraft to explore Mercury's surface, exosphere and magnetic field
- Arrival to Mercury in December 2025
- 16 scientific instruments
- Global mapping of the surface

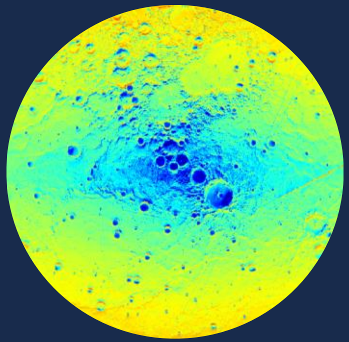

Credit; ESA

Main characteristics

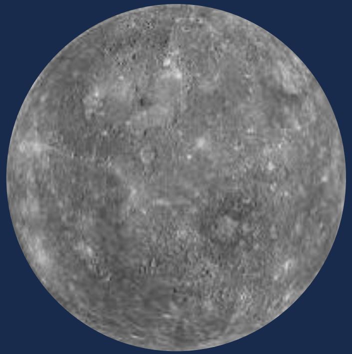
Rocky planet



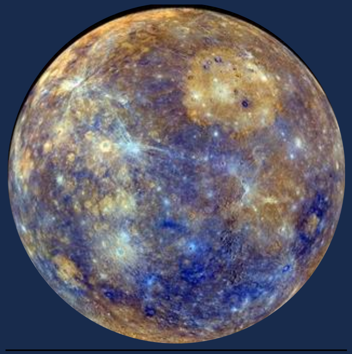
Night: -170 ˚C
Day: 430 ˚C



Diameter: 4,900 km
(~40% of Earth's)

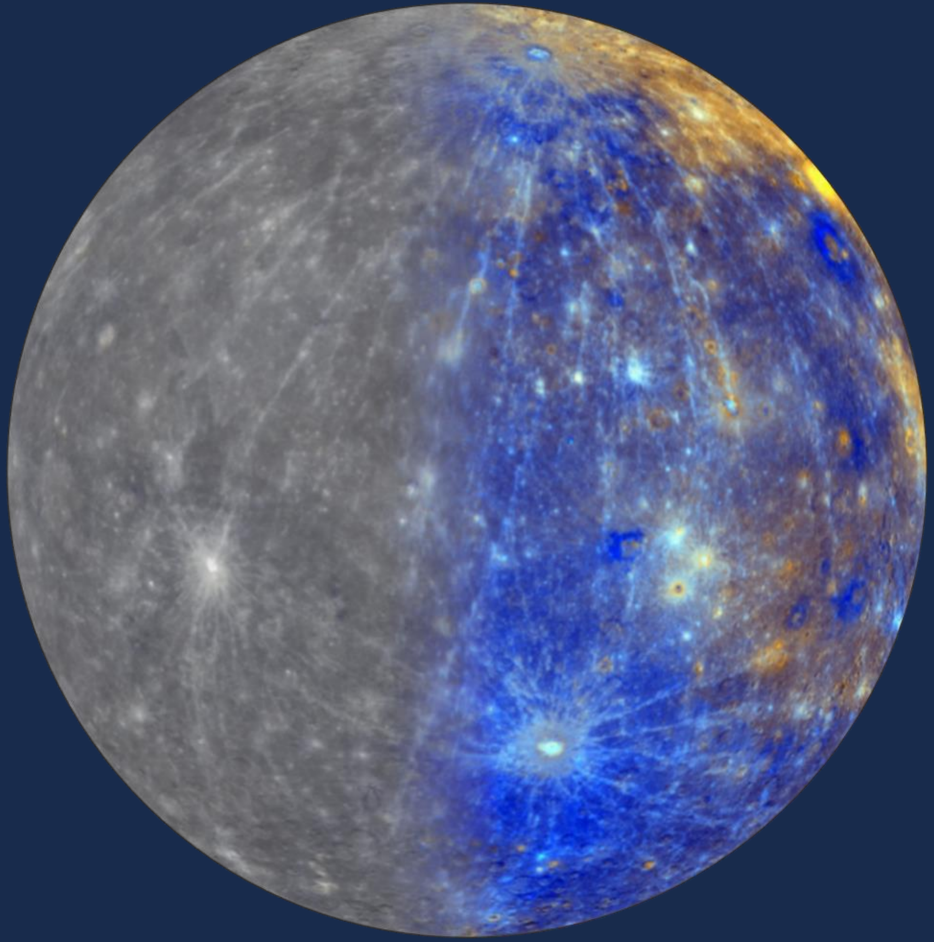


1 Mercury day lasts 59 Earth days



1 Mercury year lasts 88 Earth days

Exosphere and magnetic field



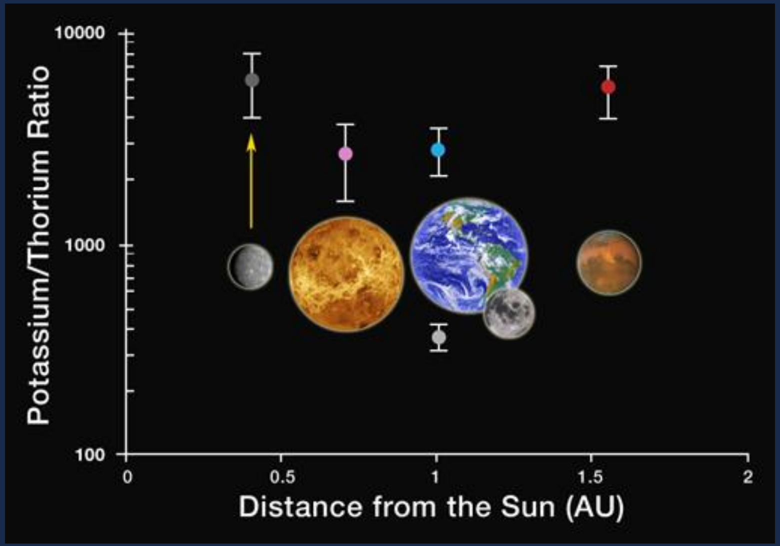
Mercury: a volatile depleted planet?

Formation models of Mercury predicted a volatile-depleted planet (Cameron., 1985, Benz et al., 1988, Boynton et al., 2007, Solomon et al., 2007)

→ Planet formation in the inner solar nebula

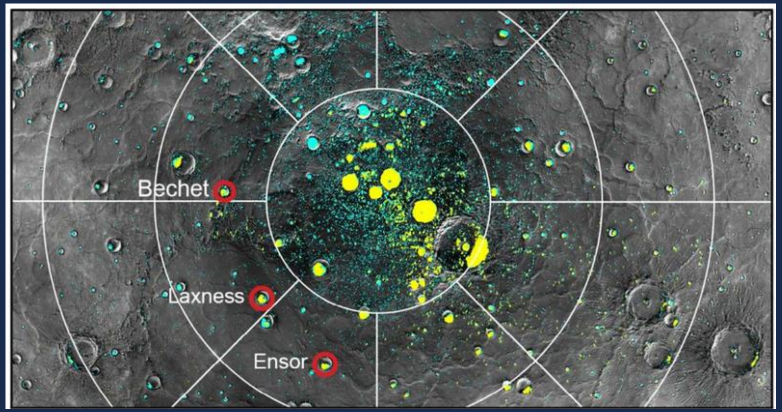
→ Heating (collision or by the nebula)

→ Loss of volatiles



Credit: NASA

Polar ice deposits



Hollows

Volcanic deposits

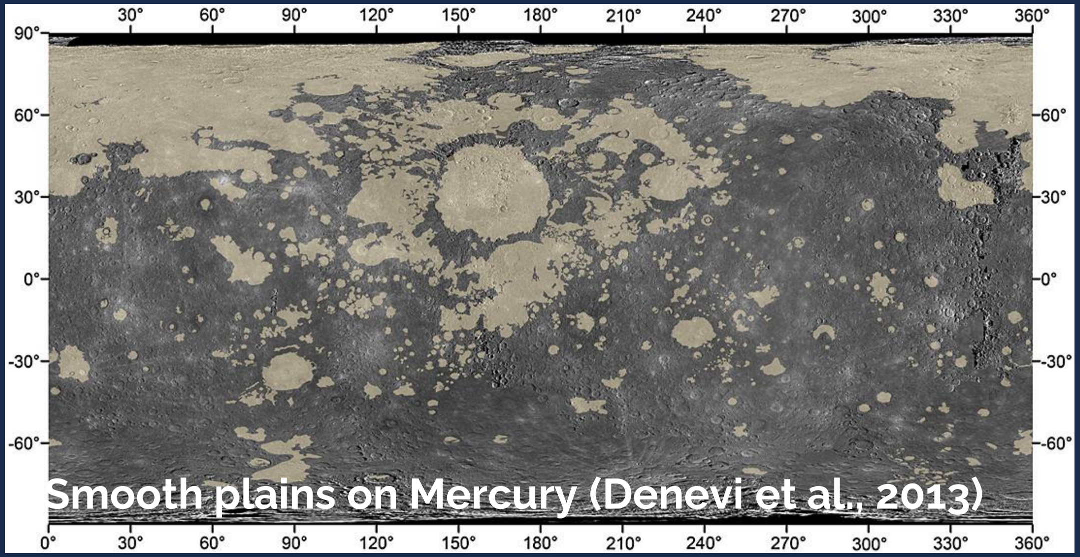
Deutsch et al., 2019

MDIS monochrome images retrieved from Quickmap *(https://messenger.quickmap.io)*

Volcanism on Mercury

Fagradalsfjall (Iceland) by Chris Burkard

Sarytchev volcano (Russia) from the ISS

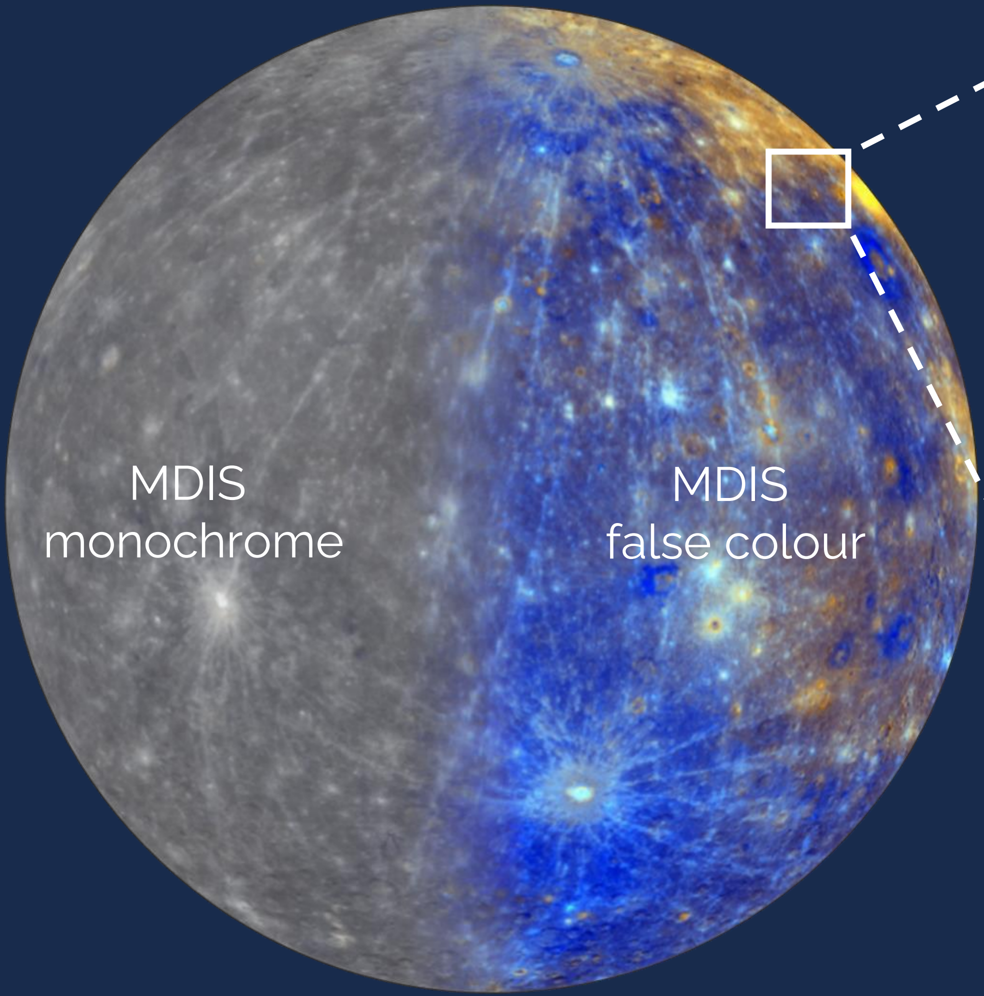


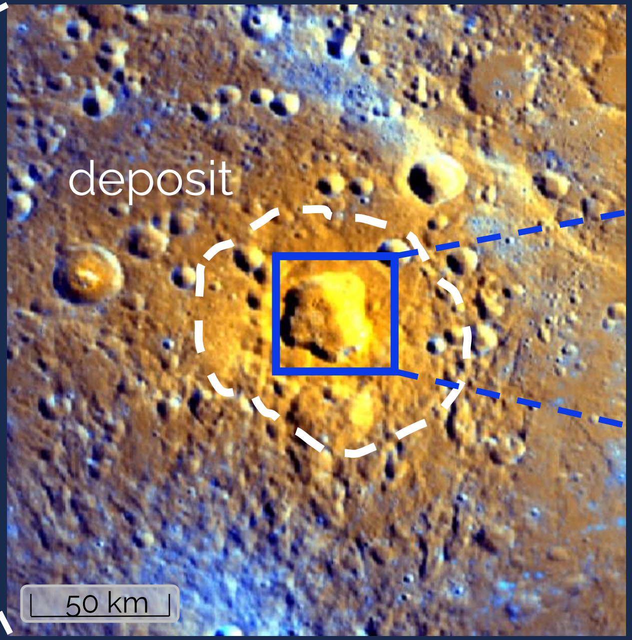
Smooth plains on Mercury (Denevi et al., 2013)

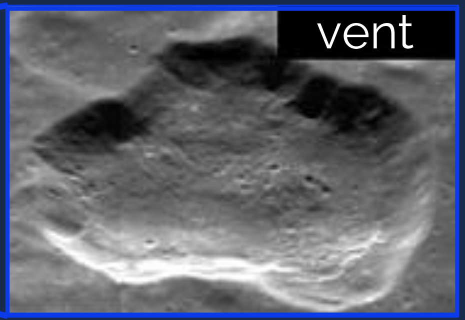

Agwo facula imaged by MESSENGER

Explosive volcanism on Mercury

>180 vents and deposits identified (Kerber et al., 2011, Goudge et al., 2014, Thomas et al., 2014, Jozwiak et al., 2018)





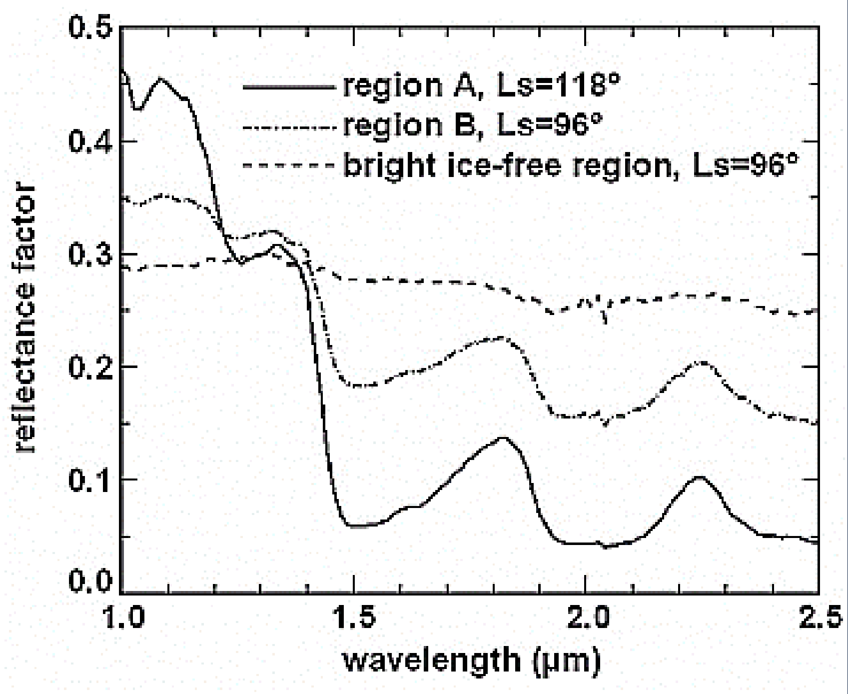


Deposit
- Diffuse margins
- High reflectance
- Red spectral slope

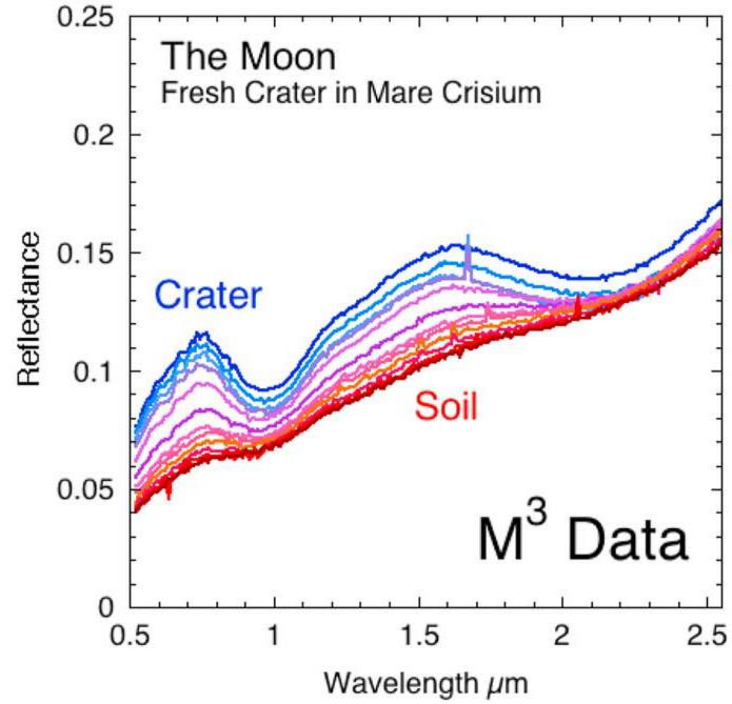
Vent
- Rimless pit
- Irregular
- Single or compound

(Pegg et al., 2021)

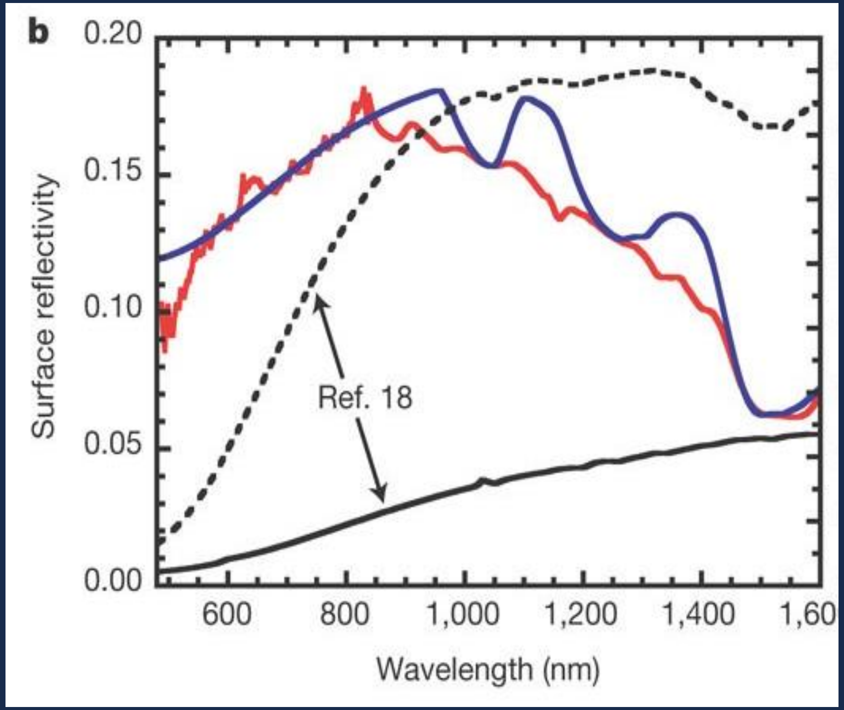
Surface spectra of rocky solar system bodies



Mars Express/OMEGA spectra (Vincendon et al., 2007)

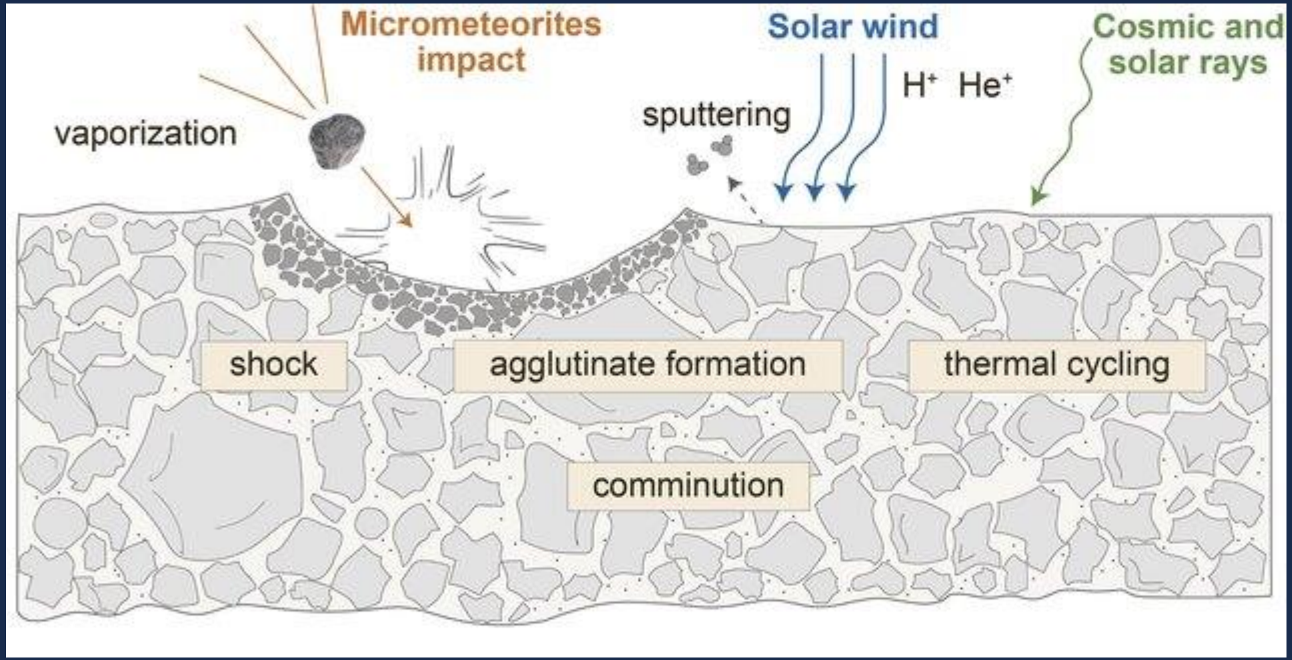


Chandrayaan-1/Moon Mineralogy Mapper spectra (Pieters et al., 2016)



Cassini DISR spectra (red) (Tomasko et al., 2005)

Airless bodies are heavily altered by space weathering



Gu et al., 2022

On Mercury, Space Weathering is dominated by **micrometeoroid bombardment** and **solar wind** irradiation (Blewett et al., 2009, Domingue et al., 2014)

Micrometeoroid bombardment:
- Gardening
- Glass production
- Submicroscopic iron formation
- Penetration depth ~1 cm (Jordan et al., 2022)

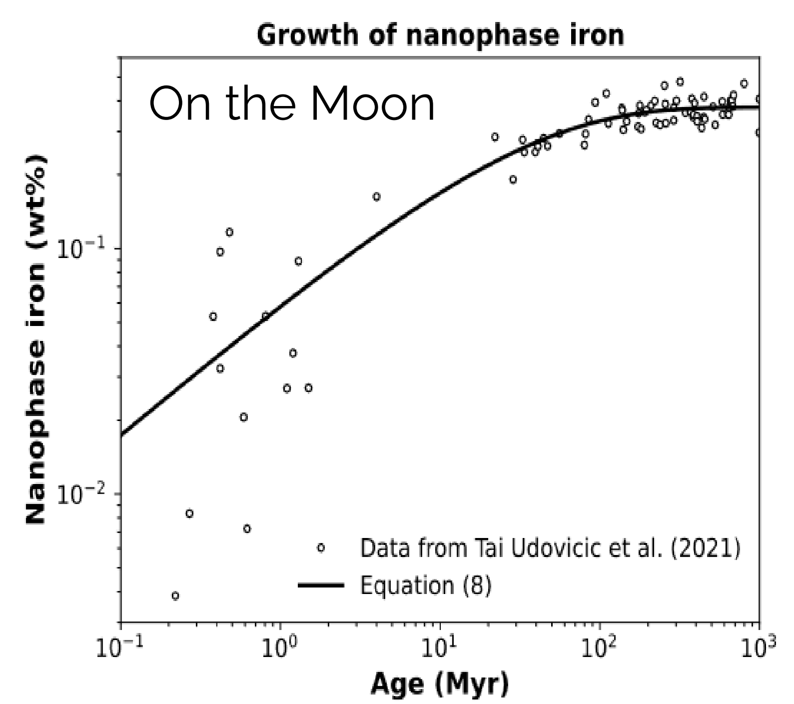
Solar wind ion irradiation:
- Ion implantation
- Sputtering
- Submicroscopic iron formation
- Penetration depth ~10 nm (Domingue et al., 2014)

Spectral effects of space weathering

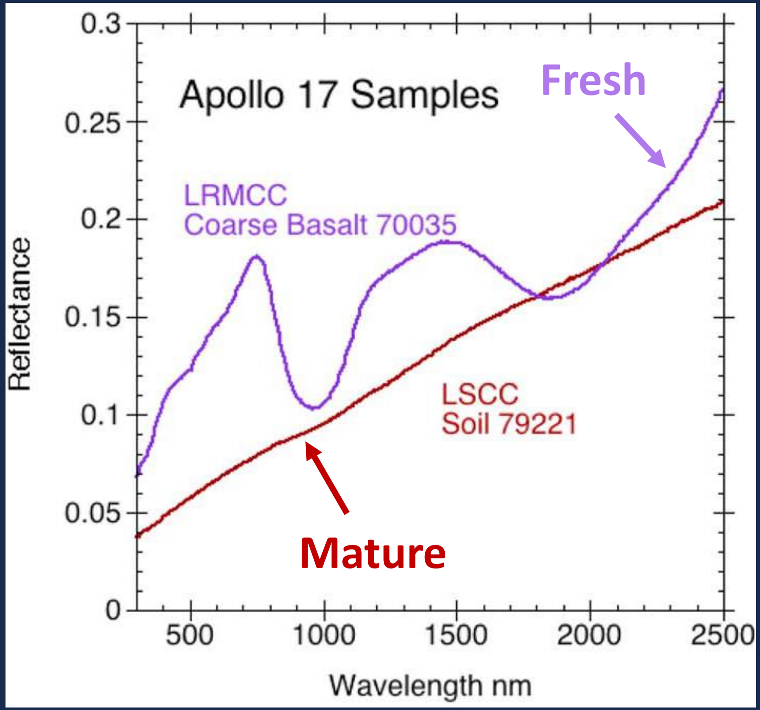
Over time, space weathering produces an accumulation of submicroscopic iron, until saturation

Submicroscopic iron accumulation on the Moon results in: (Hapke et al., 2001, Noble et al., 2001, Noble et al., 2007)

- Spectral darkening
- Spectral reddening (for small submicroscopic particles)
- Spectral flattening and weakening of absorption bands



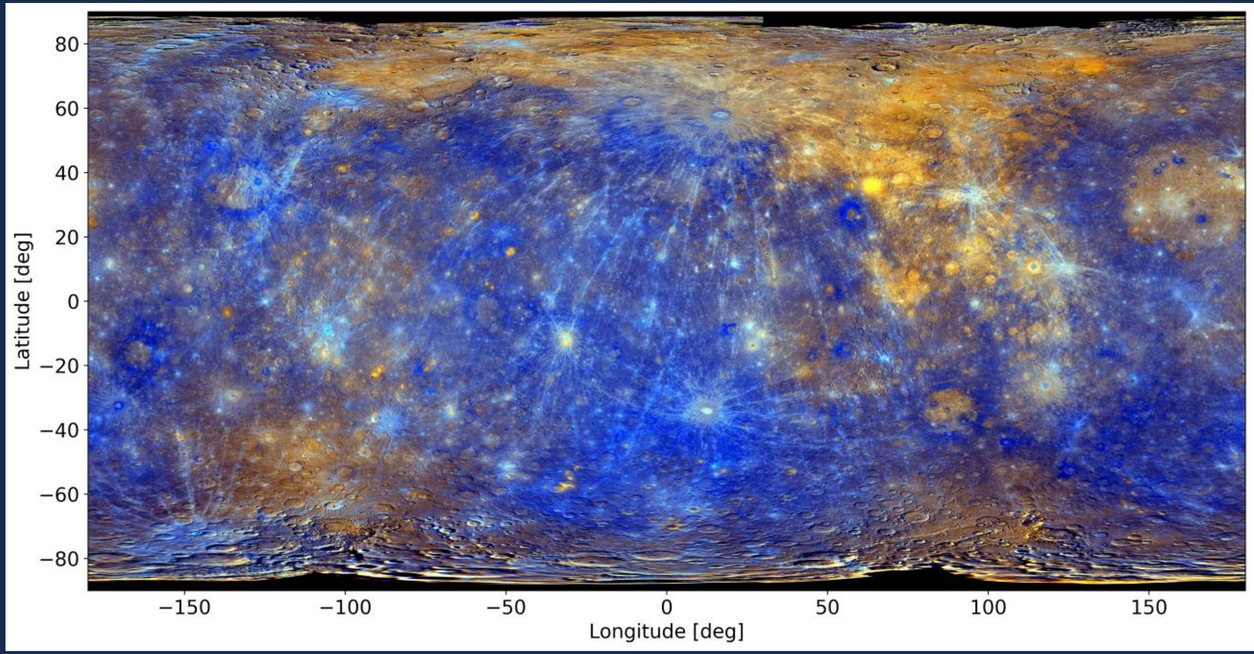
Jordan et al., 2022



Apollo 17 lunar samples spectra spectra (Pieters et al., 2016)

Spectral measurements of Mercury

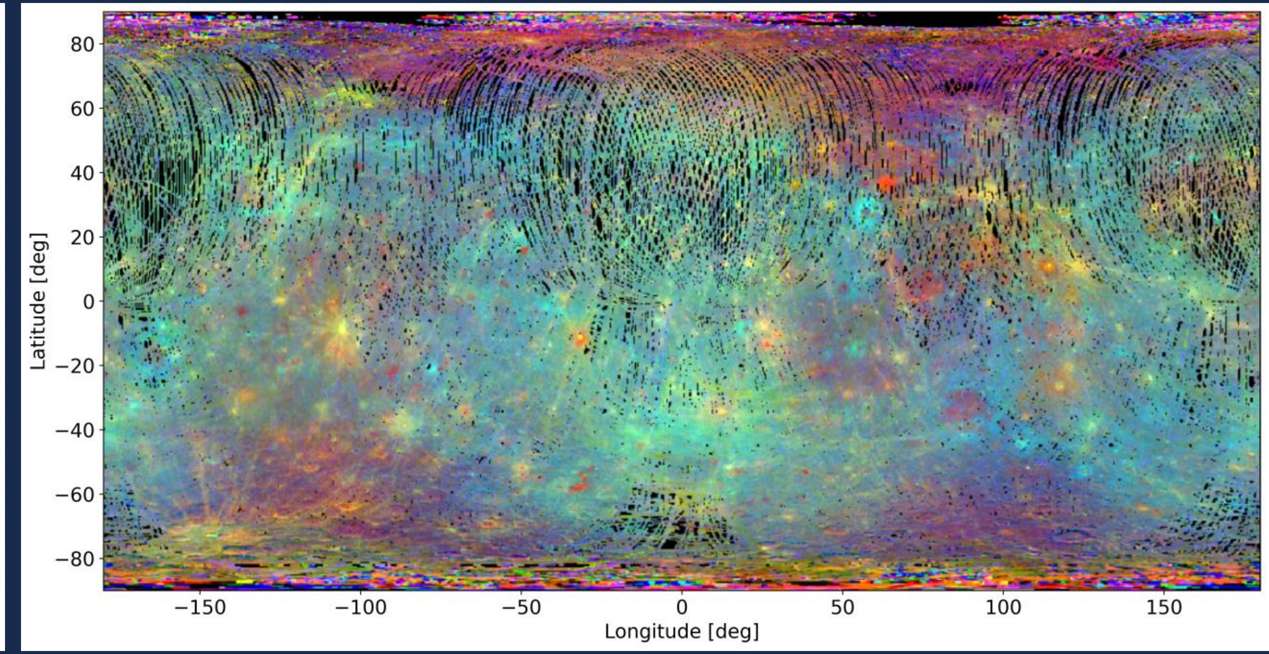
MDIS



MDIS Enhanced color map (NASA)

- Monochrome NAC + Multispectral WAC camera
- 12 filters
- 395 – 1040 nm

MASCS/VIRS

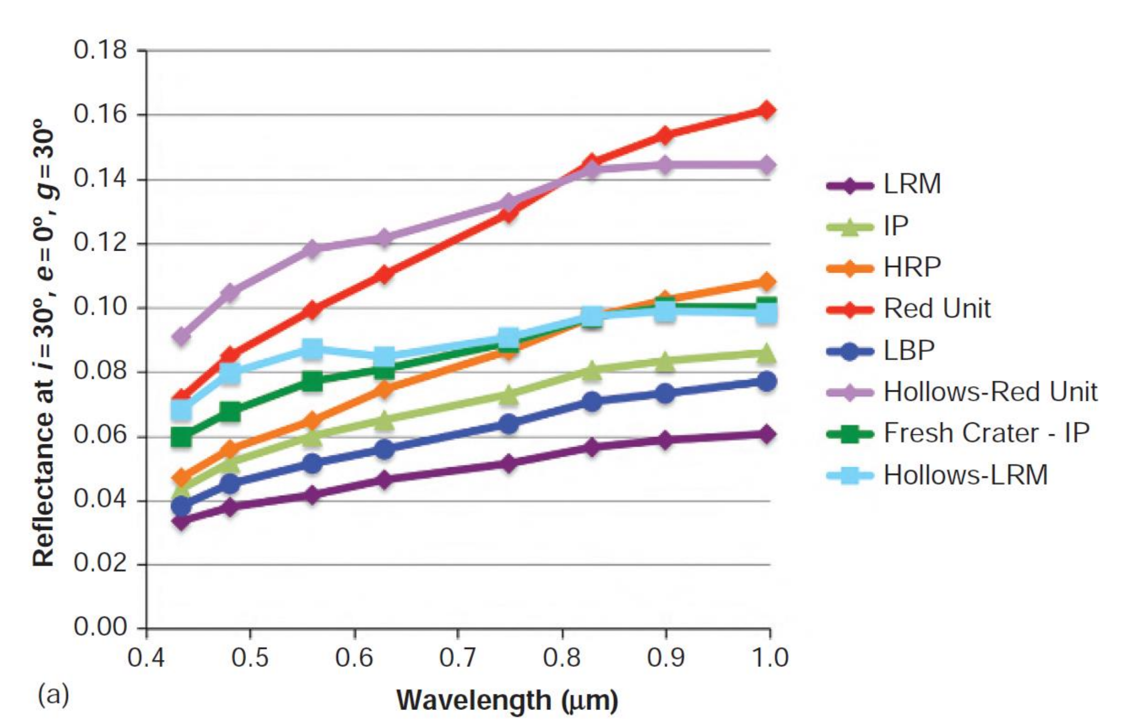


MASCS color mosaic (Izenberg et al., 2014)

- Point spectrometer
- Spectral resolution: 4.7 nm
- 300 – 1450 nm

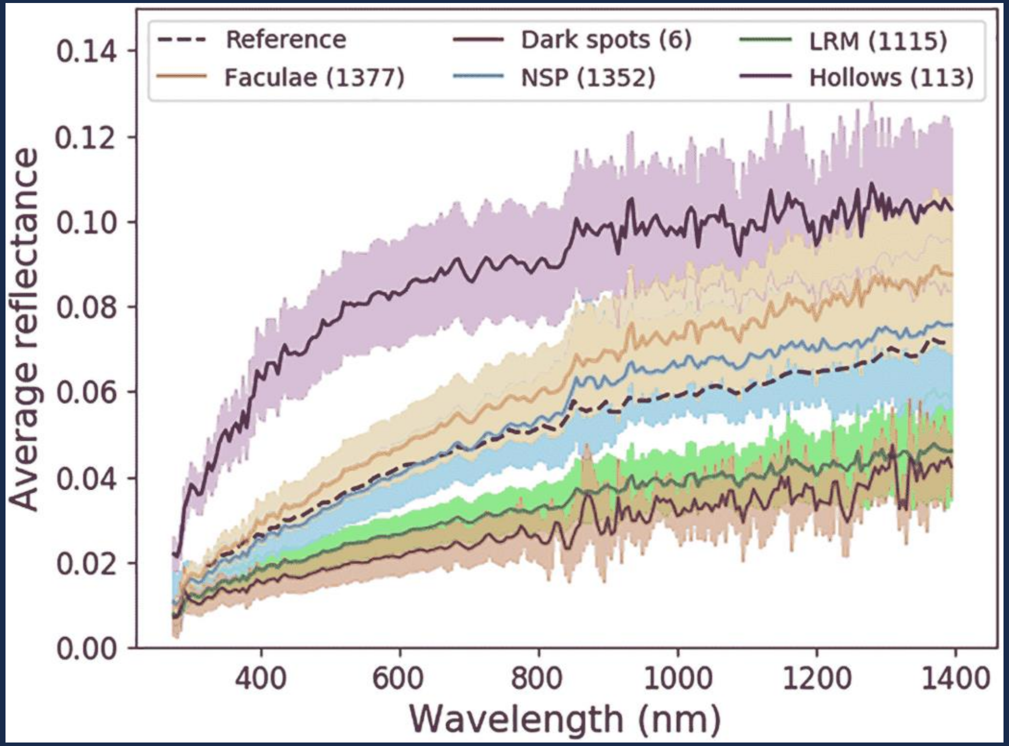
Spectral units

Spectral units by MDIS



Murchie et al., 2018

Spectra of geological units by MASCS



Barraud et al., 2020

Spectra of Mercury are featureless: characterized by brightness and slope

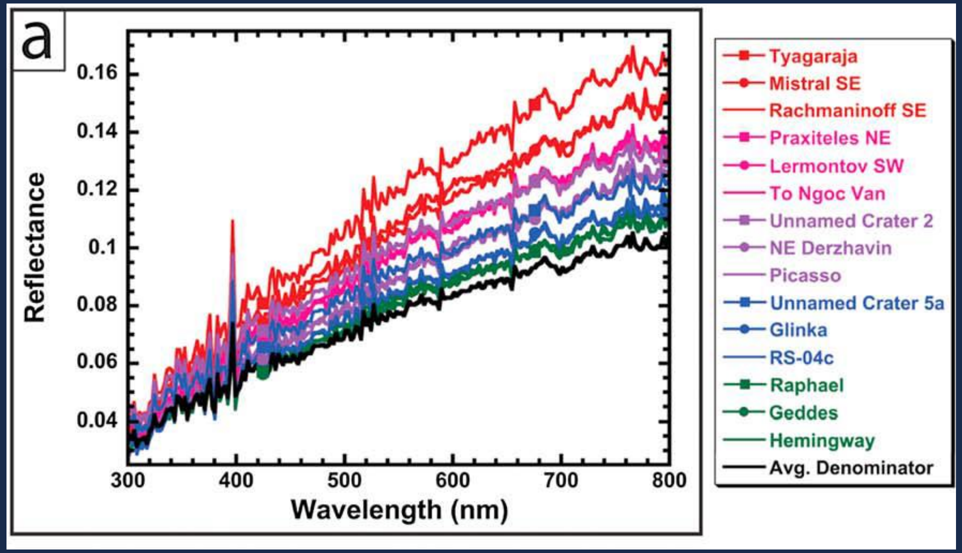
Objectives

Instead of volatile depleted: volatiles are required to place the observed pyroclasts on Mercury

To constrain Mercury's evolution we study:

→ The deposit size: determines volatile abundances required

→ Eruption timing



Goudge et al., 2014

Deposits are diffuse and present different spectral properties, complicating their identification

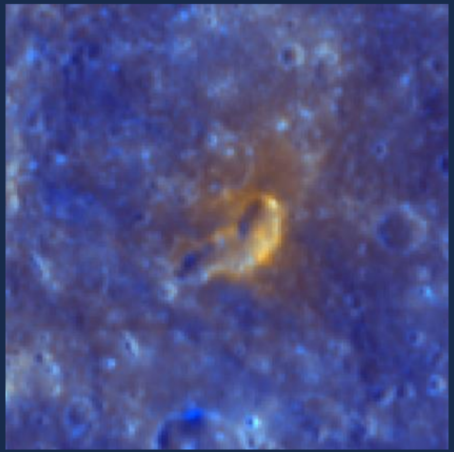
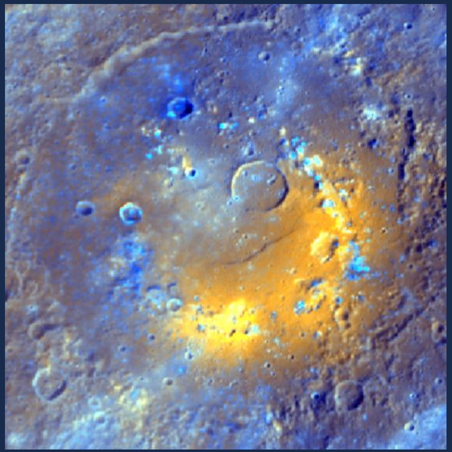
Our objective is to define the **extent** and identify any **defining spectral properties** of pyroclastic deposits

Challenge: variety of morphological and spectral properties

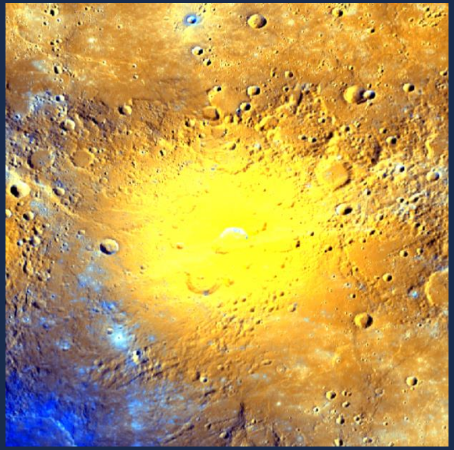
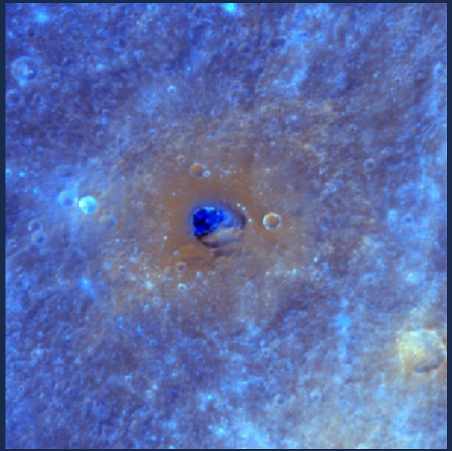
Vent morphology



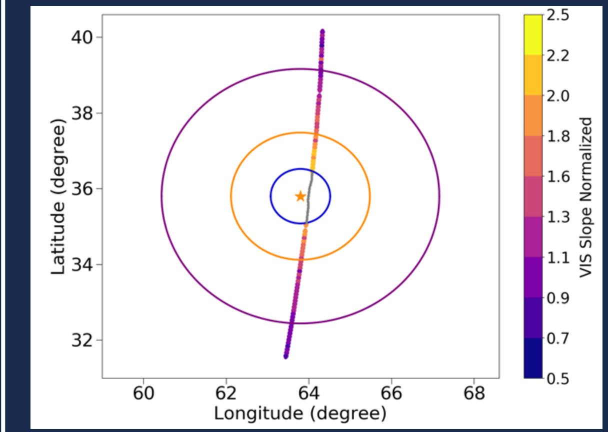
Irregular/Overlapping deposits

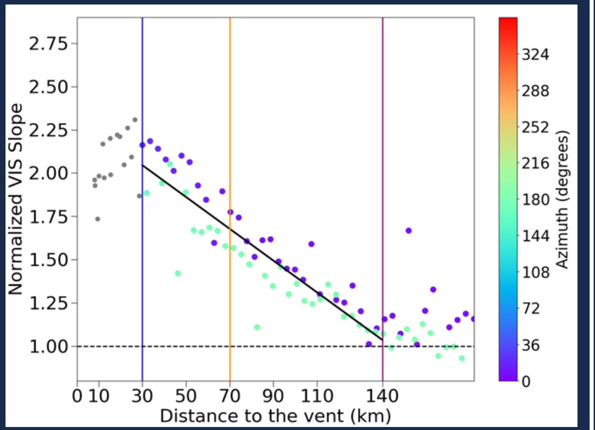



Inter-deposit spectral variability

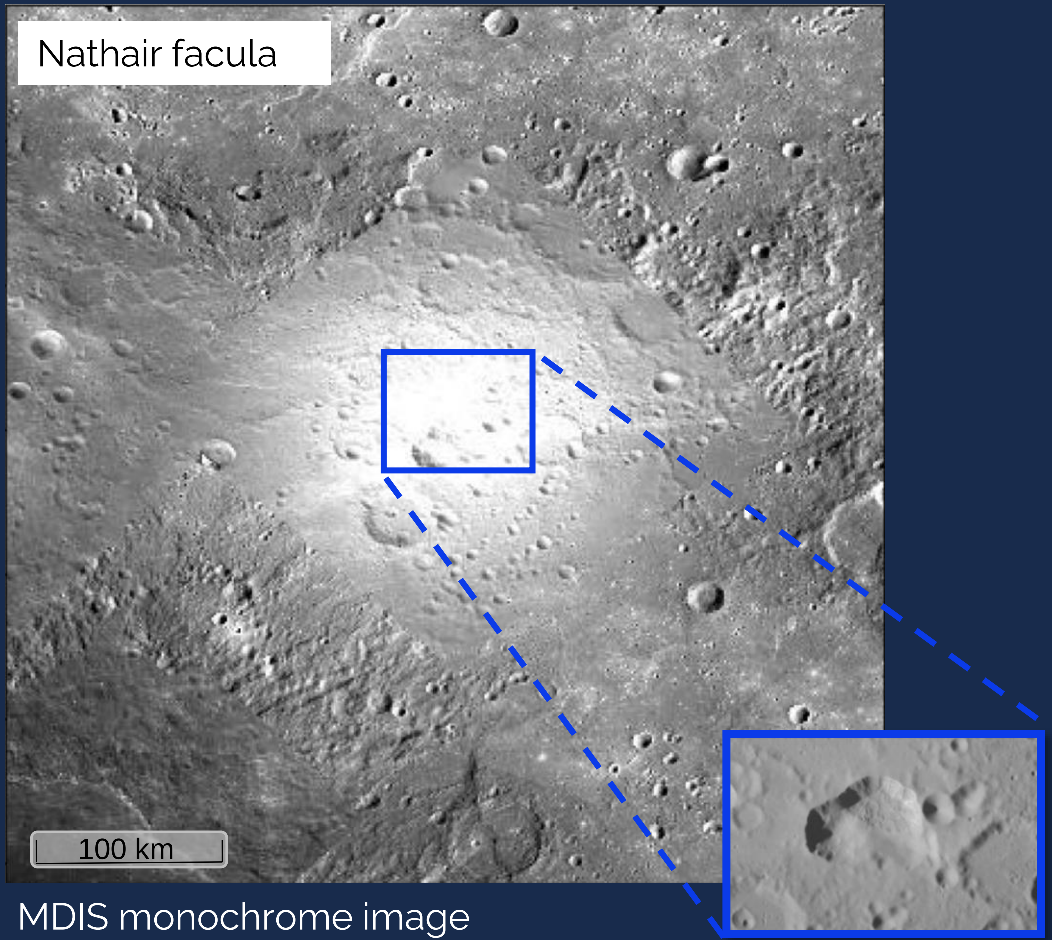
Intra-deposit spectral variability



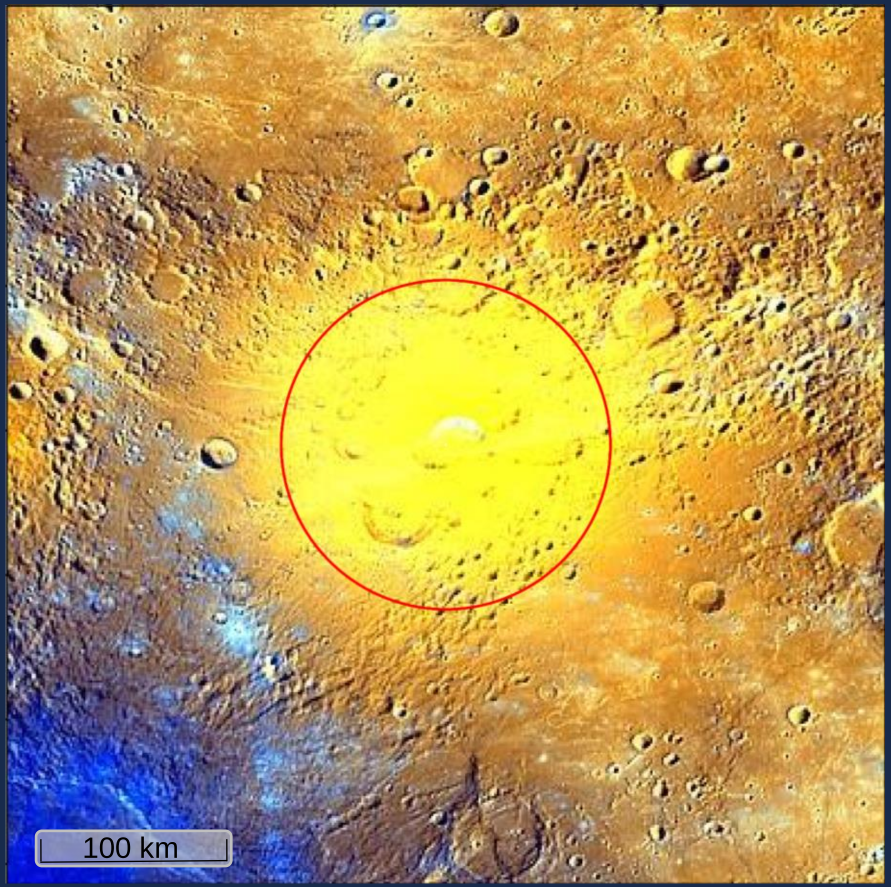


Besse et al., 2020

Previous studies: using MDIS false color



MDIS monochrome image



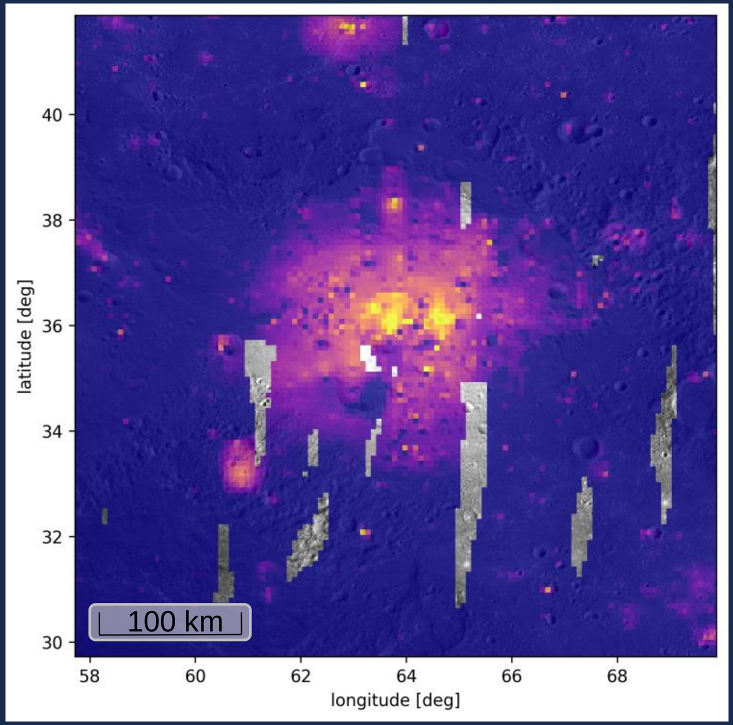
MDIS false color image

Extent defined by Kerber et al. 2011

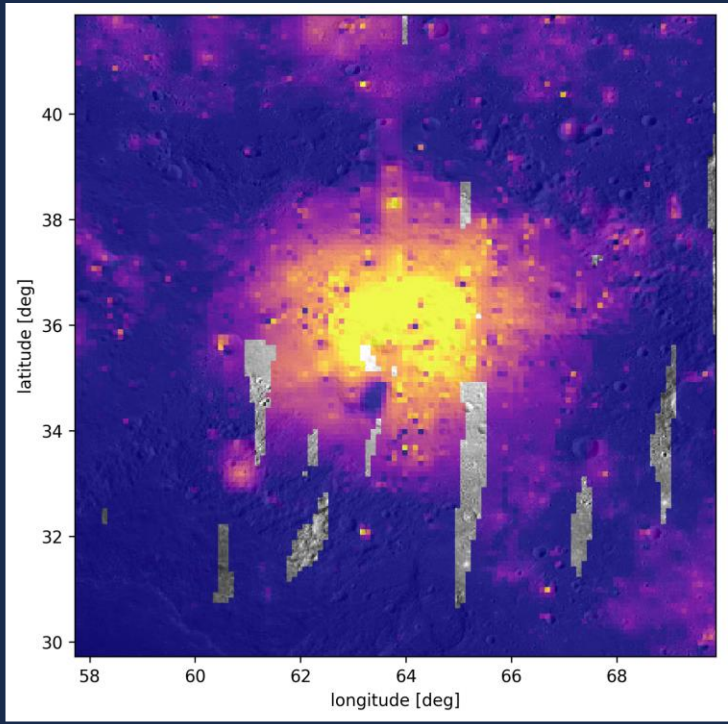
Previous studies: using MDIS false color

Limitation: deposits present a diverse behaviour in different spectral channels

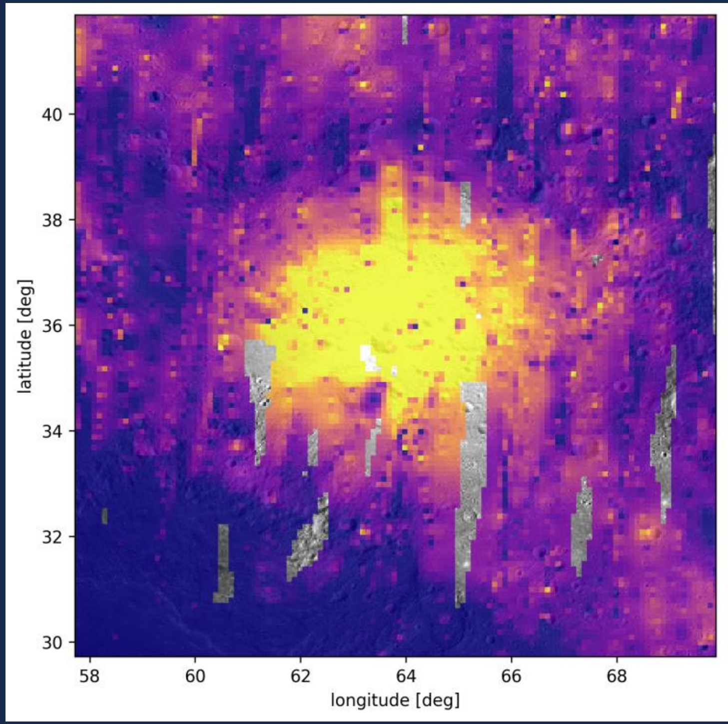
320 nm



750 nm

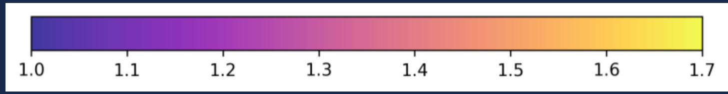


1400 nm



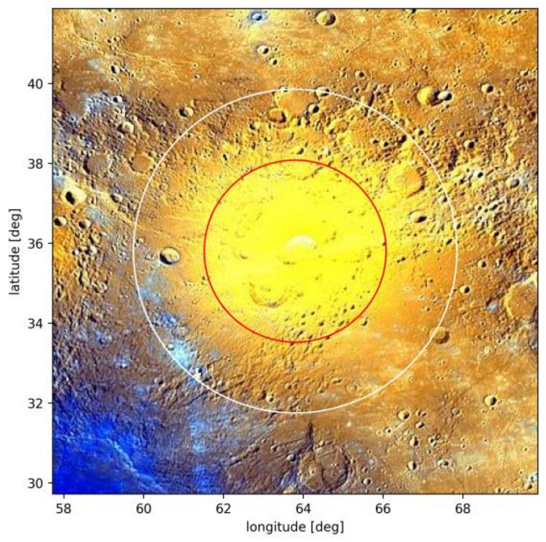
MESSENGER/MASCS interpolation map

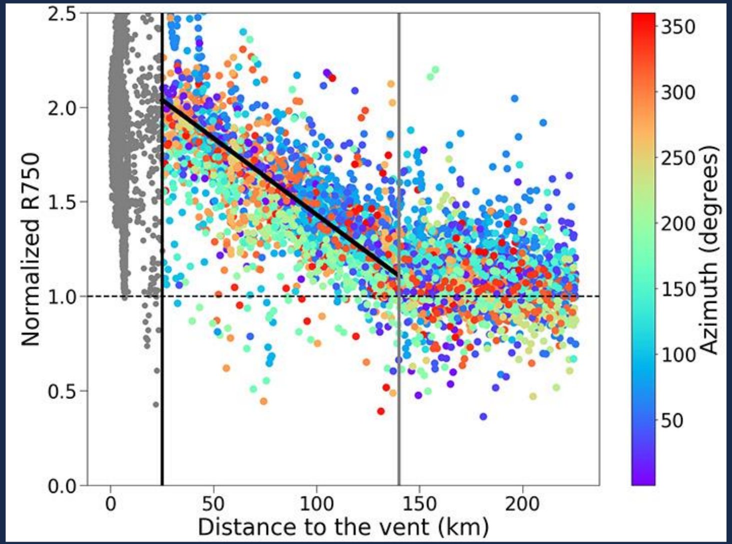
Normalised reflectance



Previous studies: using MASCS footprints

MASCS spectra revealed larger radius than MDIS false colour images (Besse et al., 2020, Barraud et al., 2021)





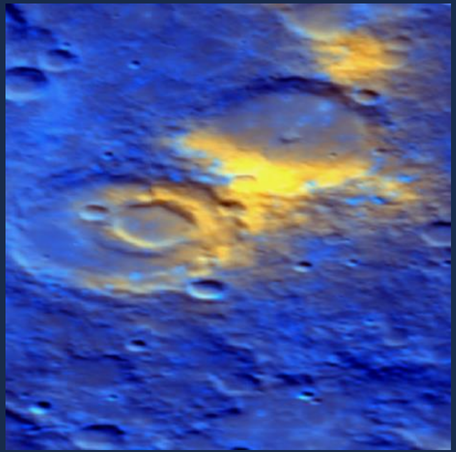
Barraud et al., 2021

- Extent defined by Kerber et al. 2011 (red circle)
- Extent defined by Barraud et al. 2021 (white circle)

Limitation: Not all deposits are **circular** →

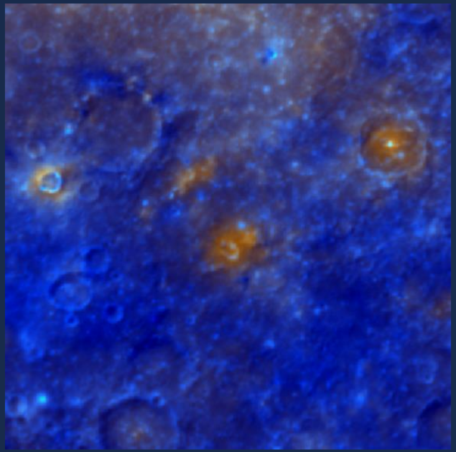
- Overlapping deposits
- Compound vents
- Oblique eruptions
- Topography

Pampu facula



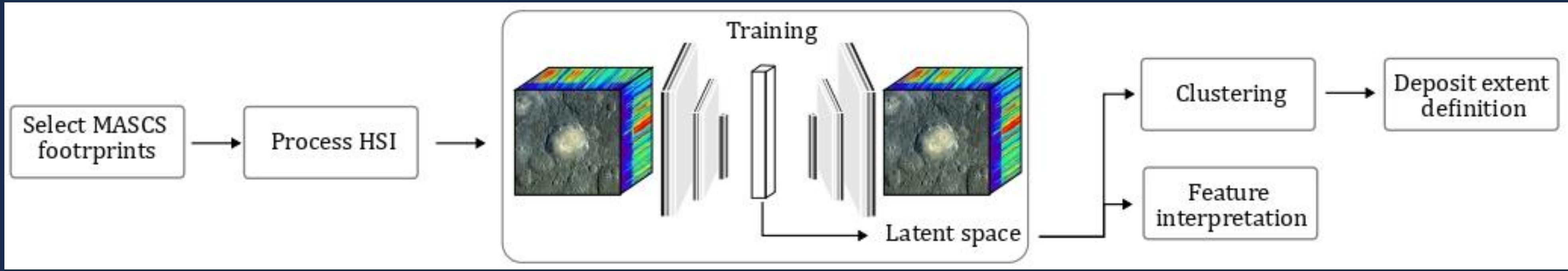
Scarlatti crater

Tolstoj basin



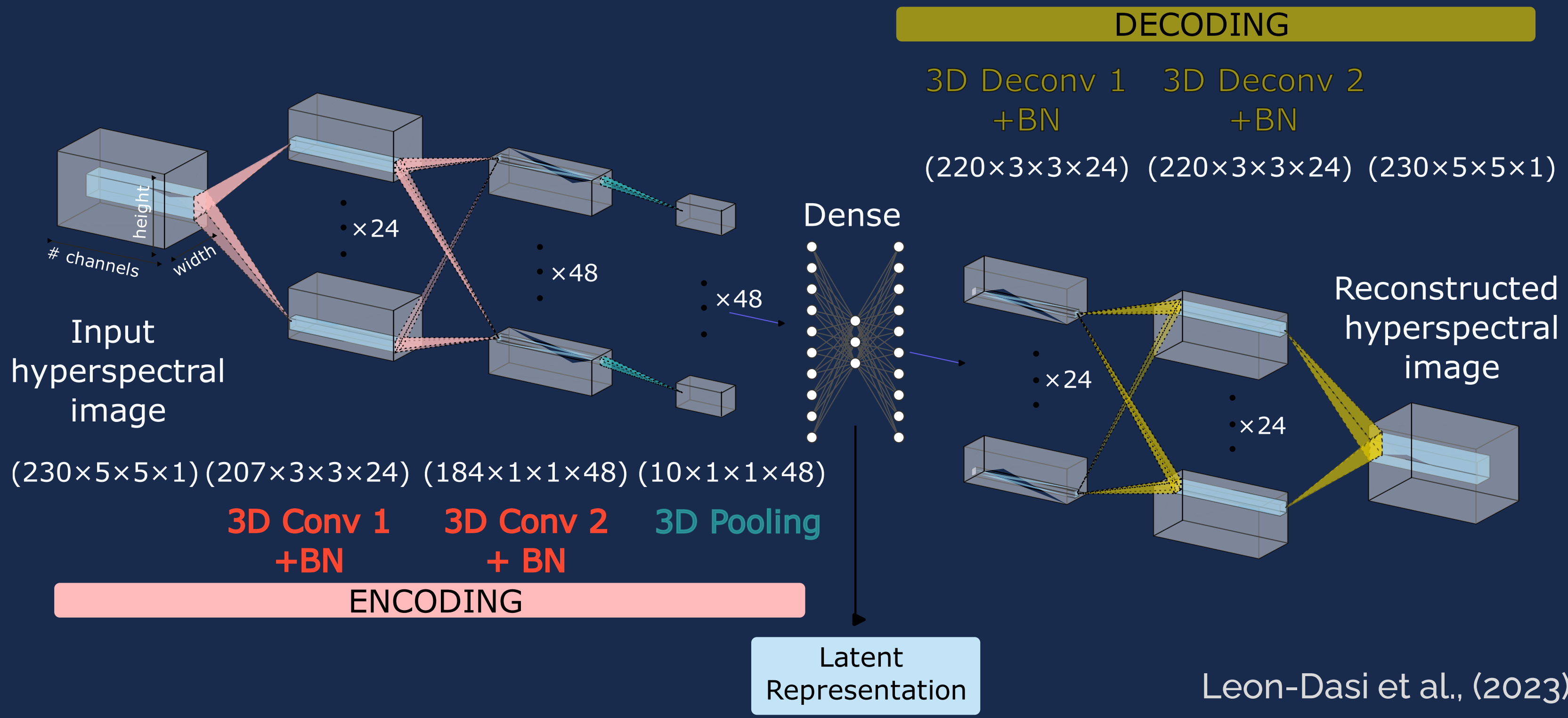
Picasso crater

Deep Learning approach



Process:

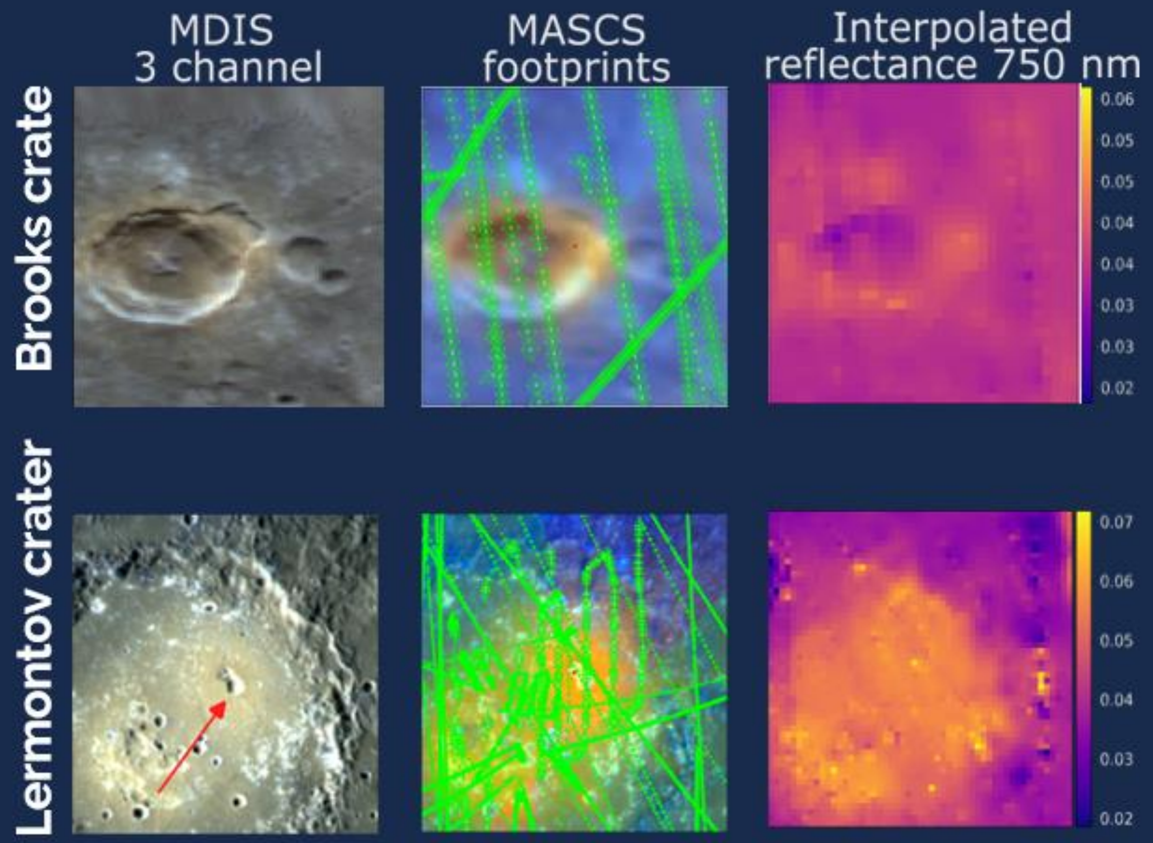
1. Processing footprints into **Hyperspectral** Images
2. Training
3. Latent space extraction
4. Clustering and feature analysis
5. Deposit extent definition



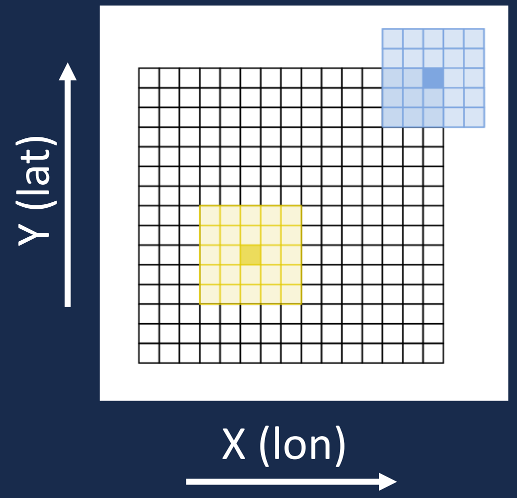
Leon-Dasi et al., (2023)

Deep Learning approach: input

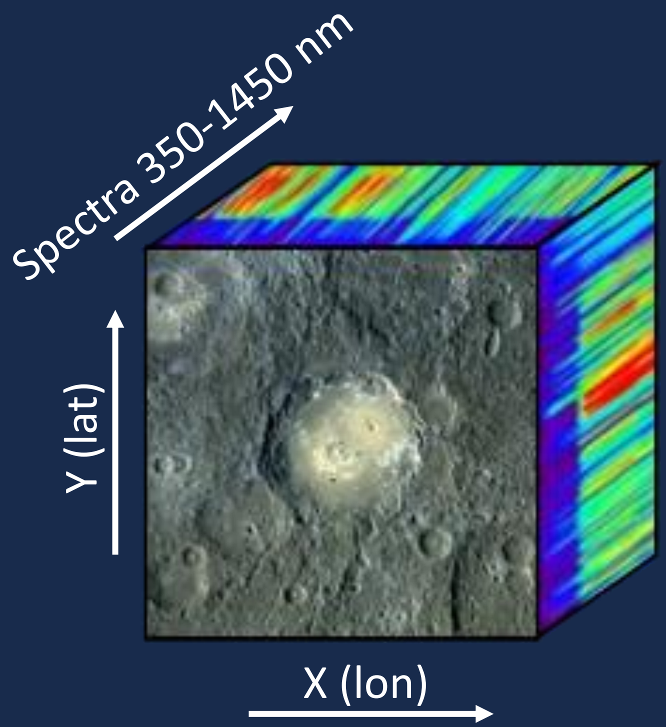
1. Processing footprints into hyperspectral images



2. Splitting into patches



Input HSI



Training the network

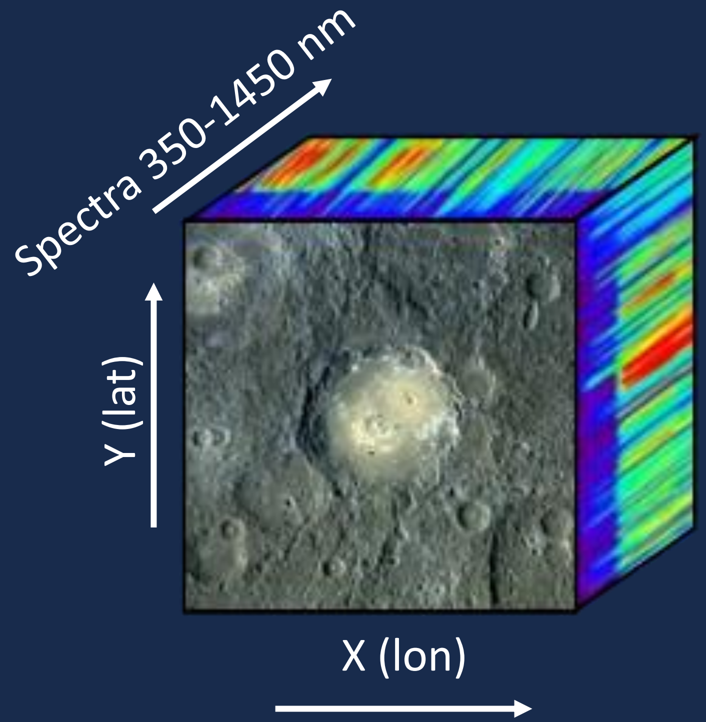
Input

→ 50,000 samples

→ Sample: HSI subpatch (5 x 5 x 230)

→ Spatial resolution: 0.1 deg/px

→ Spectral resolution: 5 nm



Output

For each pixel:

→ 20 latent dimensions

→ Cluster classification

Training

→ Training for 15 epochs

→ Training loss: 0.0018

→ Validation loss: 0.0027

Studied parameters

→ Patch size

→ Latent space dimension

→ Number of clusters

→ Clustering algorithm

→ Number of filters

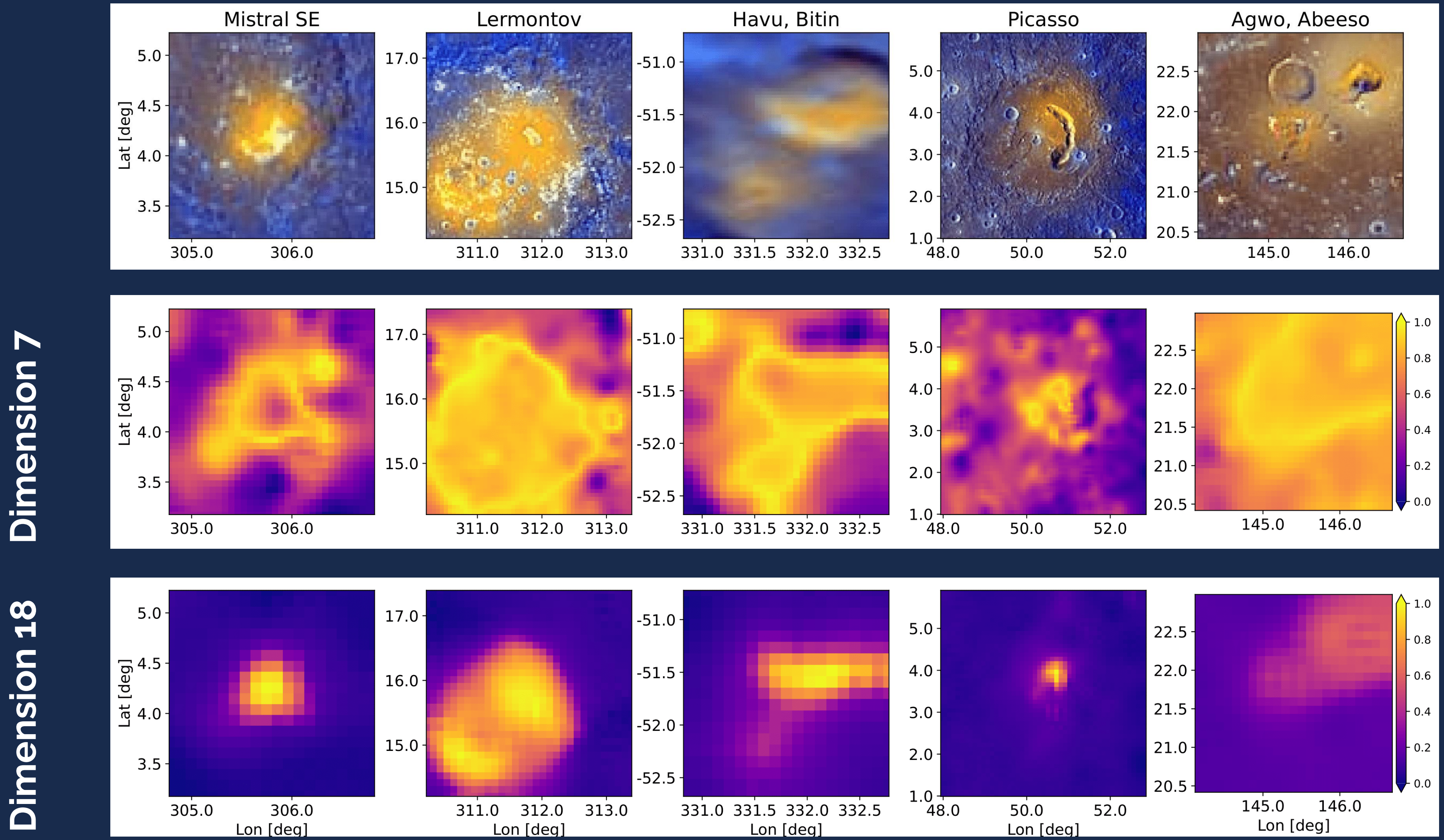
Fixed parameters (Mei et al., 2019)

→ Number of layers

→ Weight decay

→ Activation functions

Latent dimensions: highlight spectral and spatial information



Highlighting the deposit edge (?)

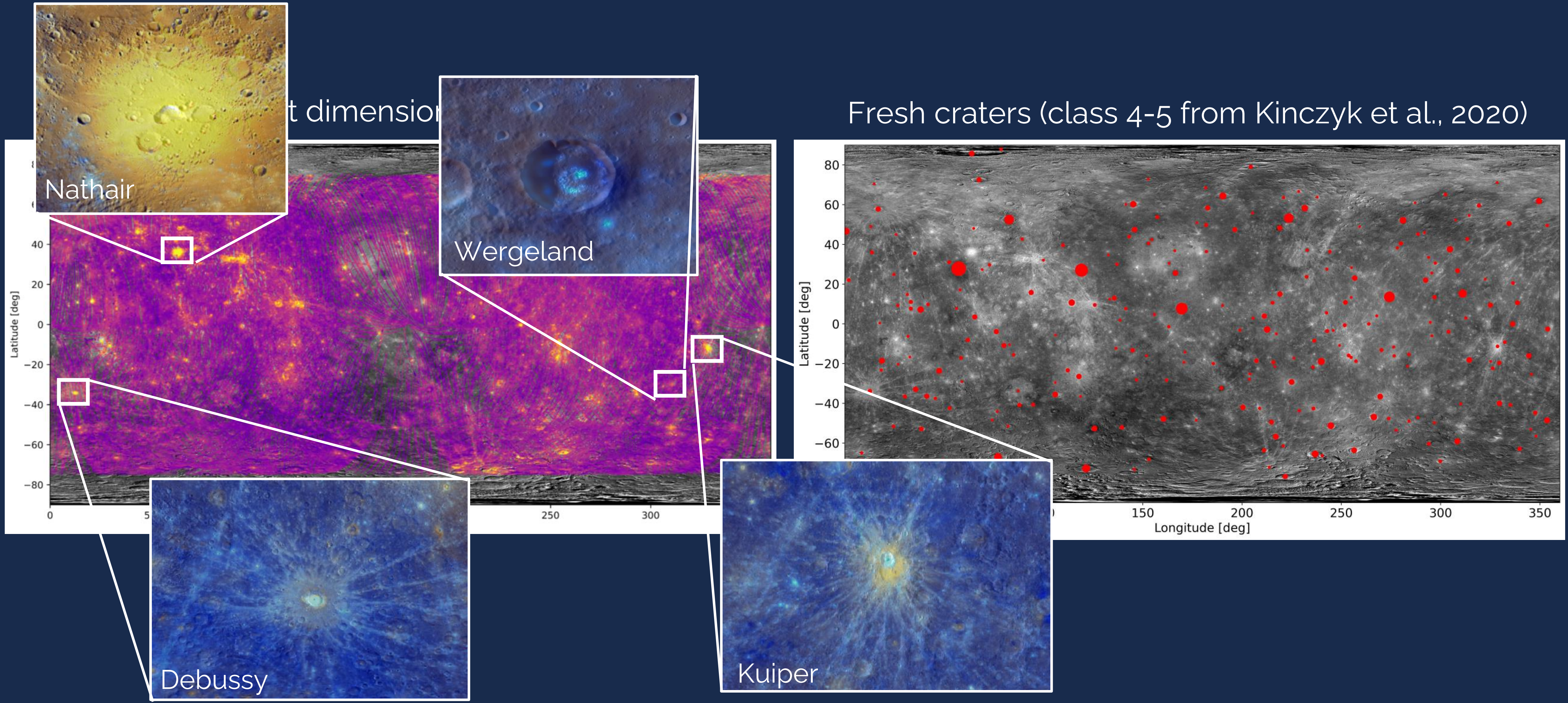
Highlighting the deposit interior (?)

Leon-Dasi et al. (2023)

Global latent dimensions

Latent dimension #6 highlights fresh terrains (fresh crater ejecta, young pyroclastic deposits, etc)

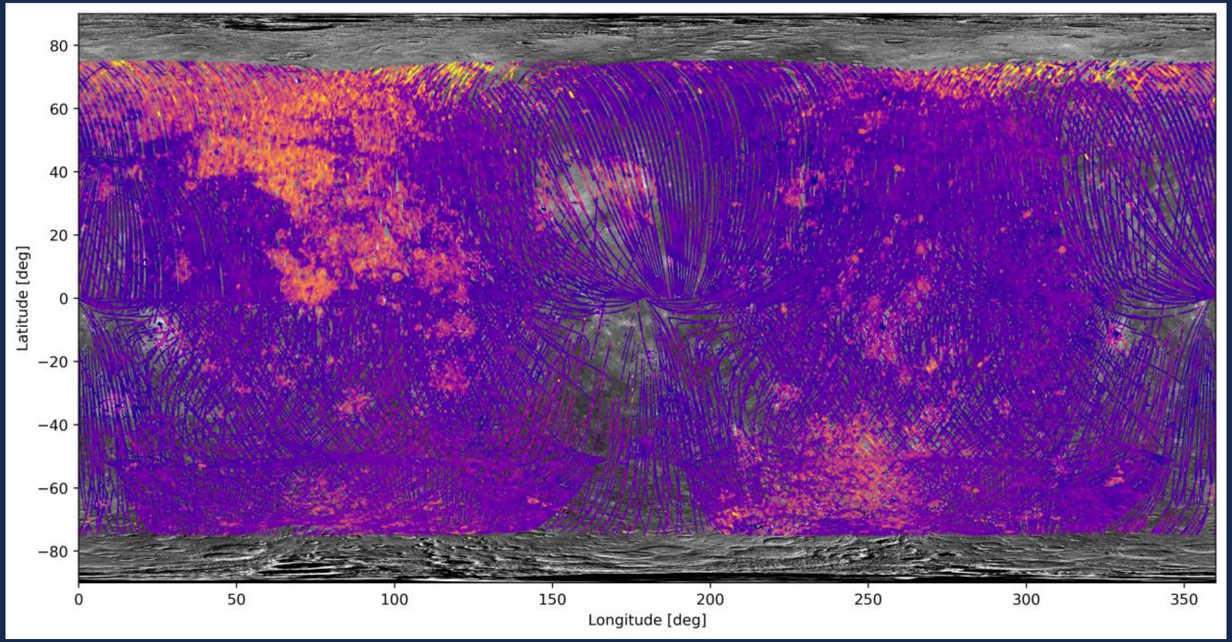
Fresh craters (class 4-5 from Kinczyk et al., 2020)



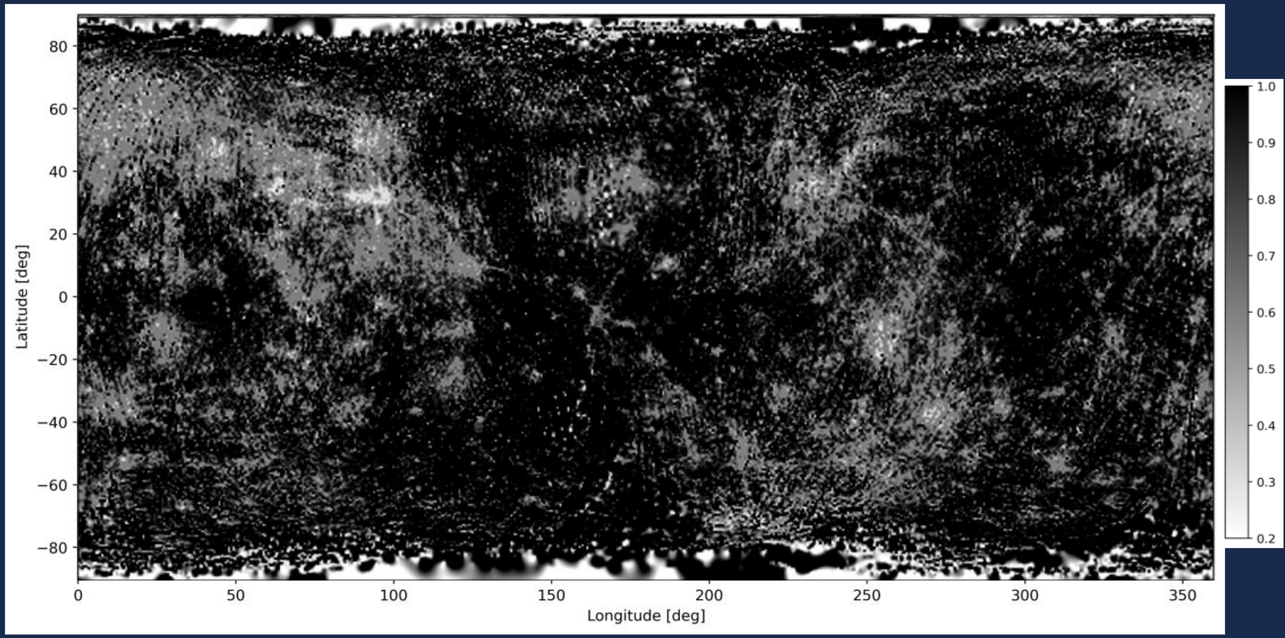
Global latent dimensions

Latent dimension #4

Latent dimension #4 map



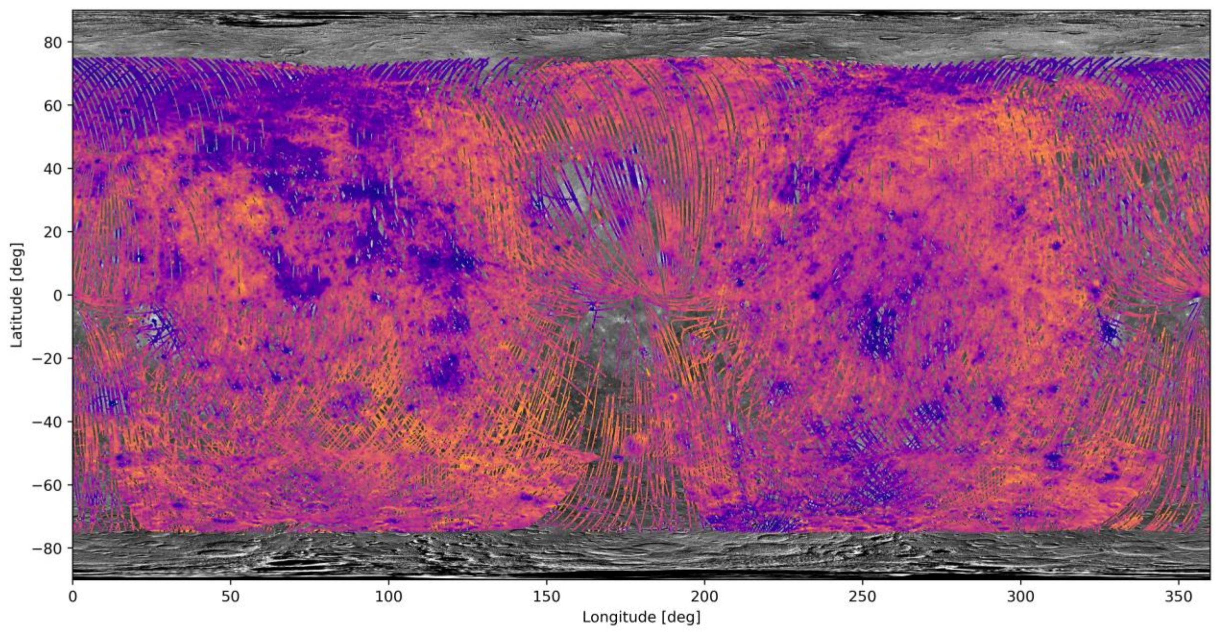
Nanophase iron abundance (wt %) (From Trang et al., 2017)



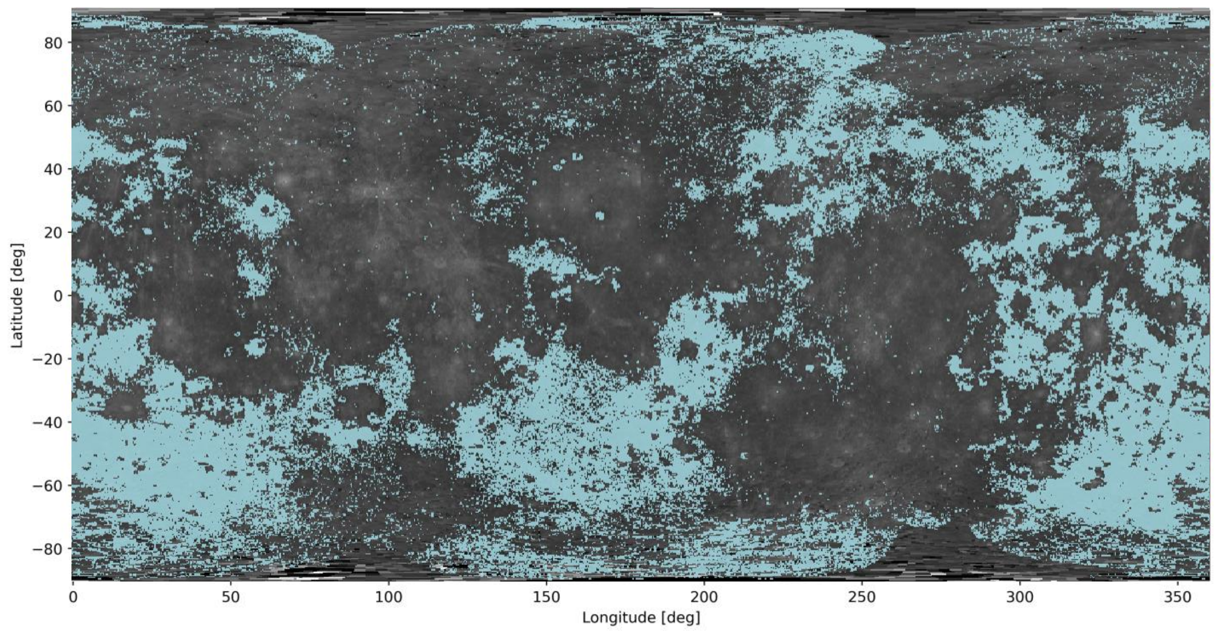
Global latent dimensions

Latent dimension #15

Latent dimension #15 map

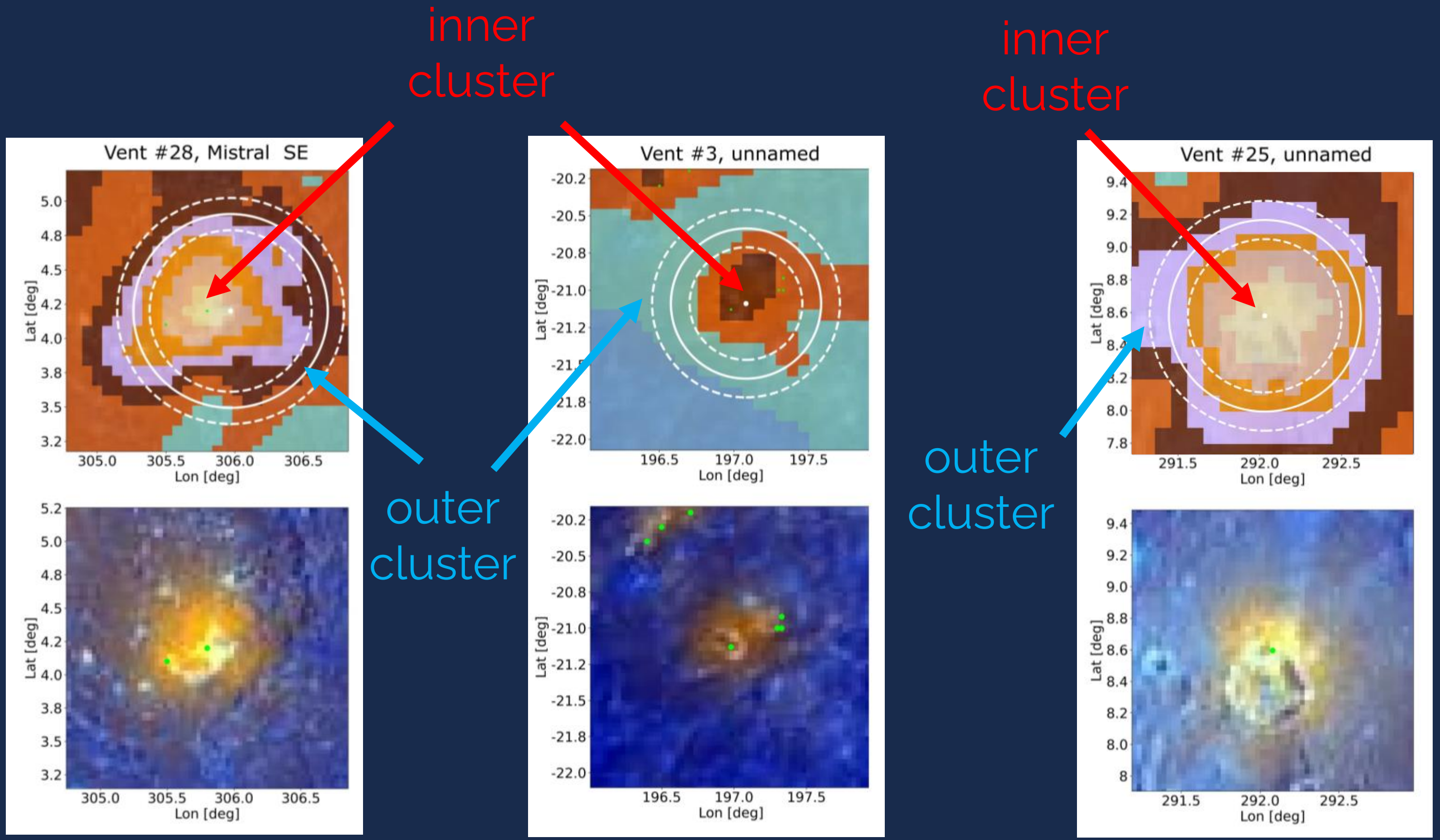


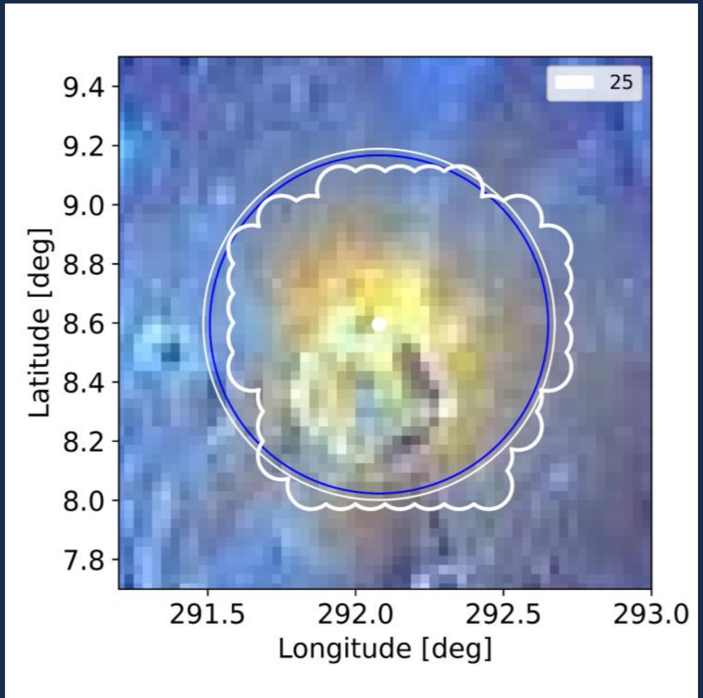
Low Reflectance Material map (From Klima et al., 2018)



From cluster maps to deposit limits

For each deposit, an **inner cluster** and **outer cluster** are identified





Extent defined by Thomas et al. 2014

Extent defined by Barraud et al. 2021

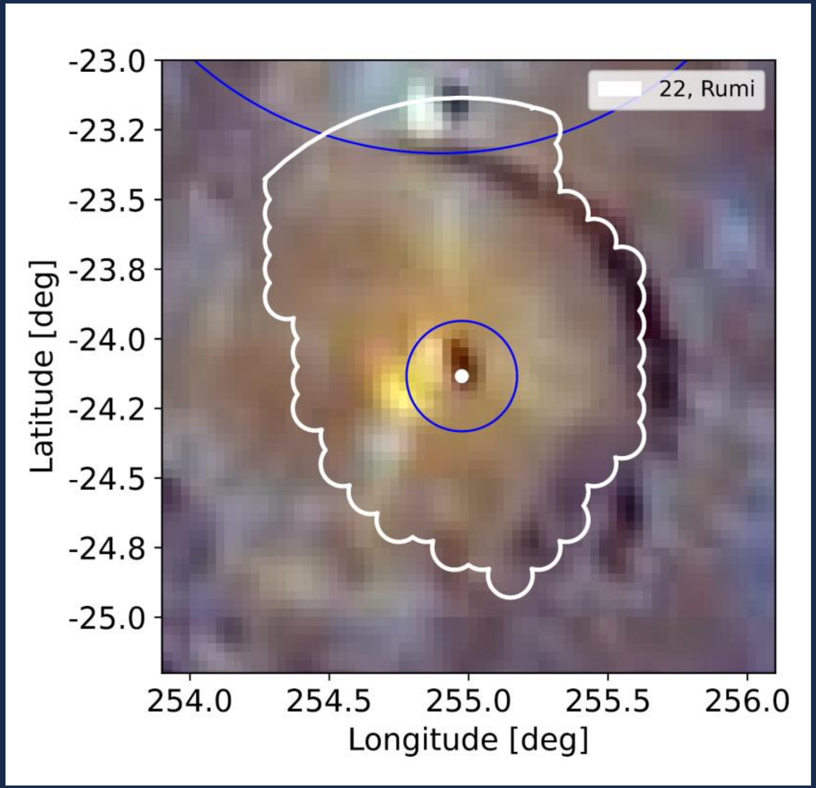
Extent defined by this work

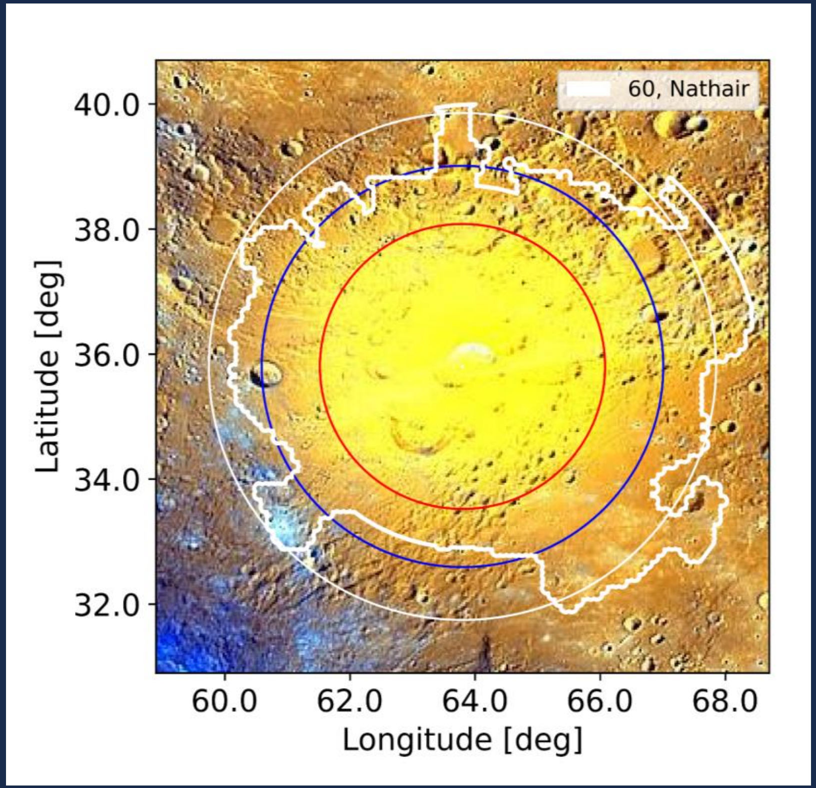
Leon-Dasi et al., (2023)

Defined the extent of 55 deposits
→ 35 isolated and 20 groups
→ 110 vents
→ 36 first observed here with MASCS
→ 17 first measured overall

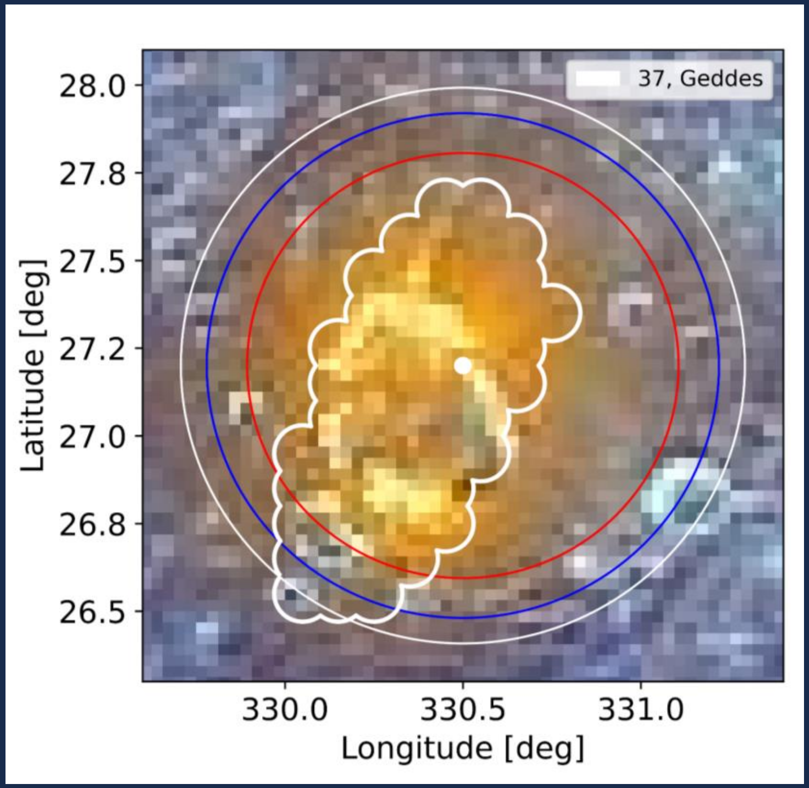
Results: delimiting the deposit extent

Overcoming deposit underestimation





Irregular deposits



Extent defined by Kerber et al. 2011

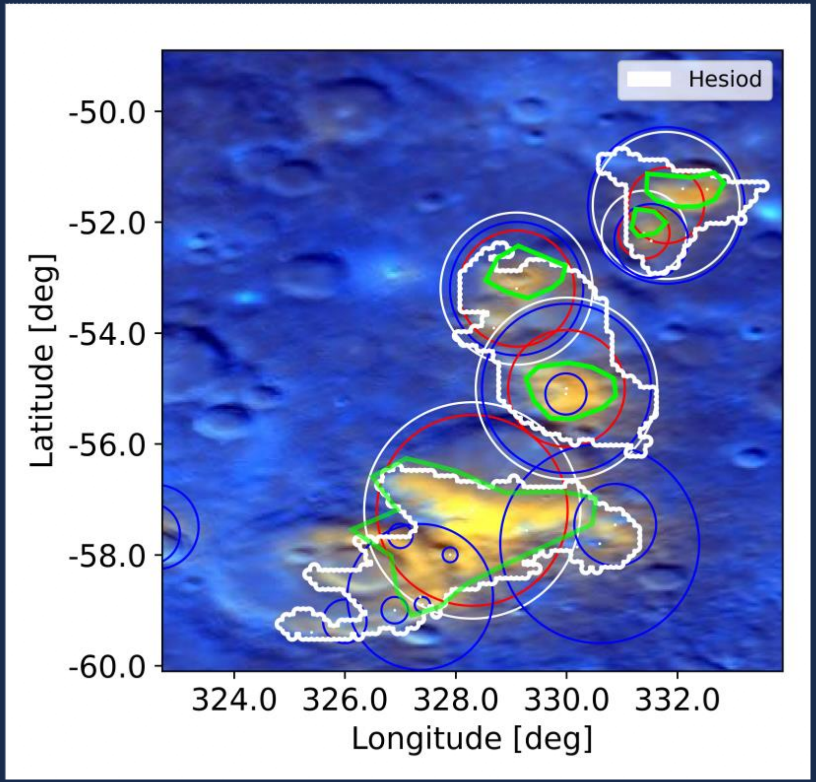
Extent defined by Thomas et al. 2014

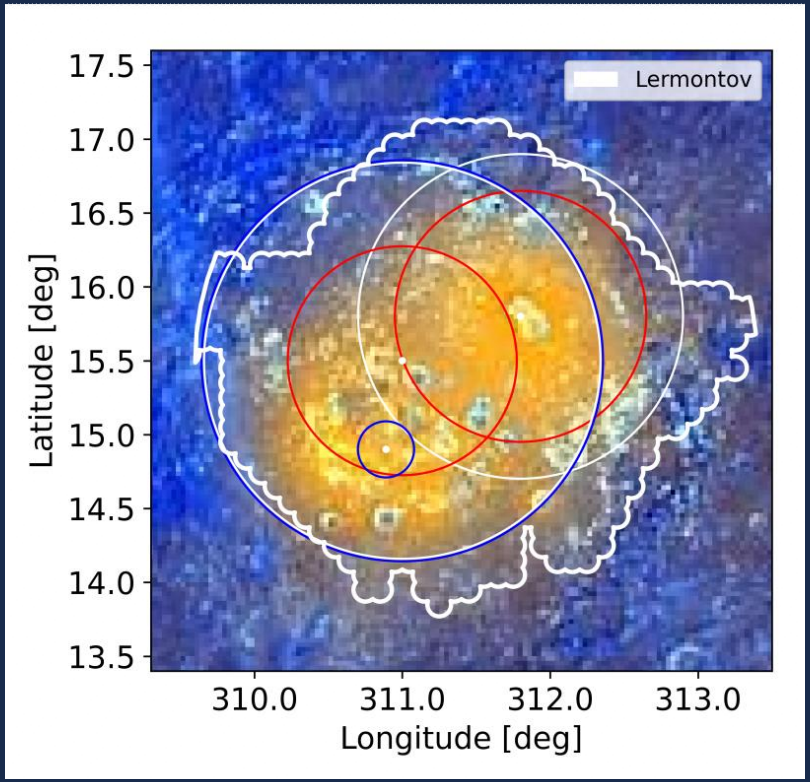
Extent defined by Barraud et al. 2021

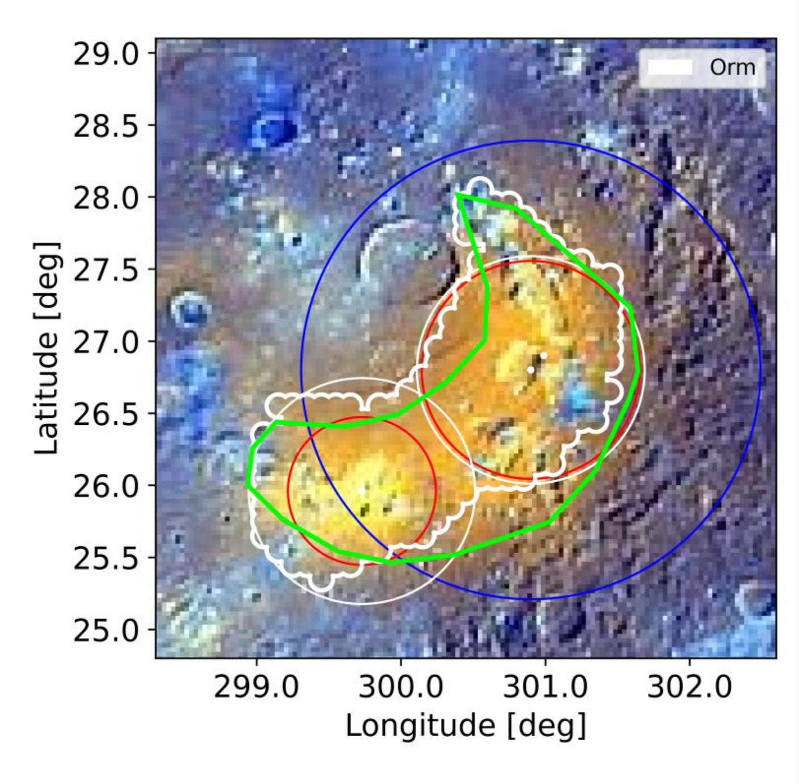
Extent defined by this work

Leon-Dasi et al., (2023)

Results: overlapping deposits



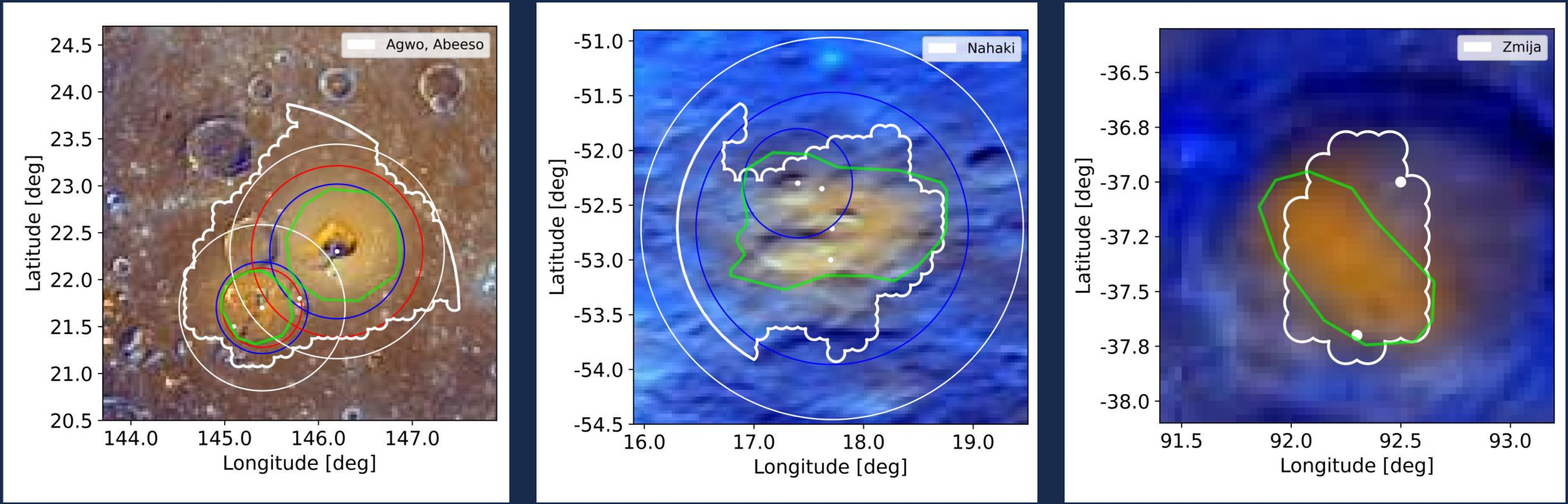




Leon-Dasi et al., (2023)

- Extent defined by Kerber et al. 2011
- Extent defined by Thomas et al. 2014
- Extent defined by Barraud et al. 2021
- Extent defined by this work
- Facula identified by the IAU

Results: overlapping deposits



Extent defined by Kerber et al. 2011

Extent defined by Thomas et al. 2014

Extent defined by Barraud et al. 2021

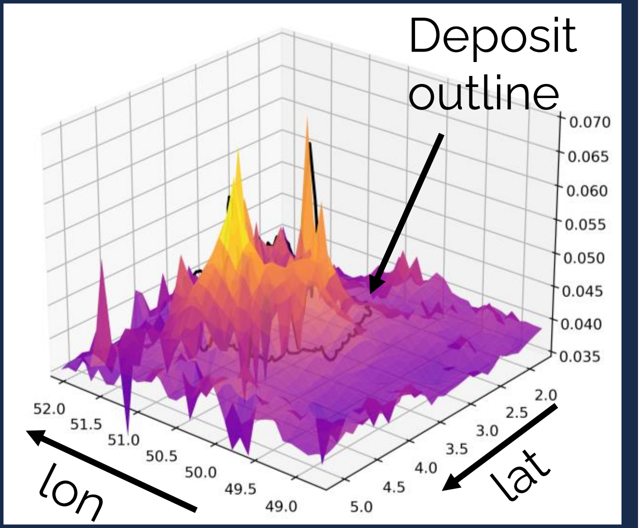
Extent defined by this work

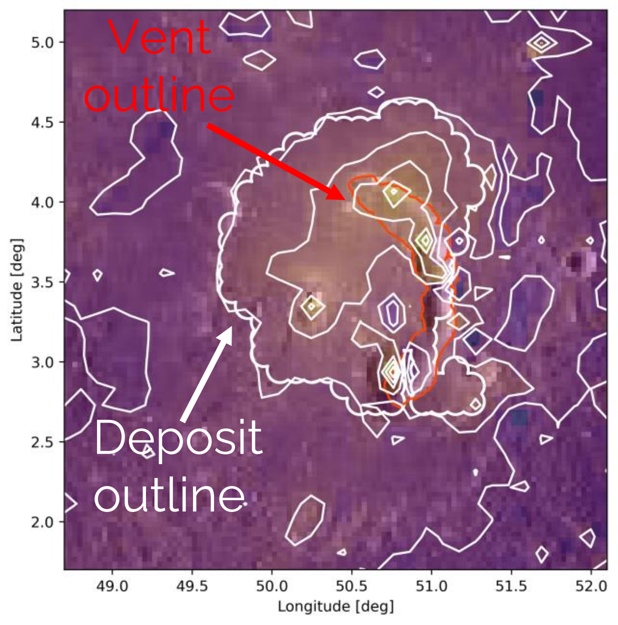
Facula identified by the IAU

Leon-Dasi et al., (2023)

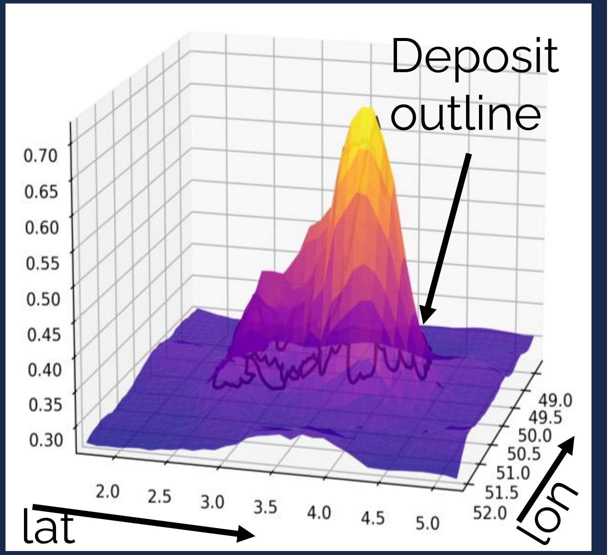
Latent inside deposits

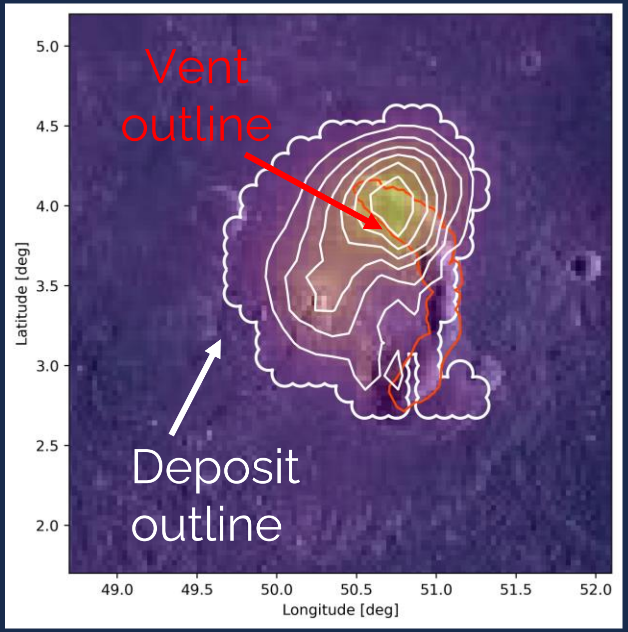
Reflectance at 750 nm





Latent dimensions mean



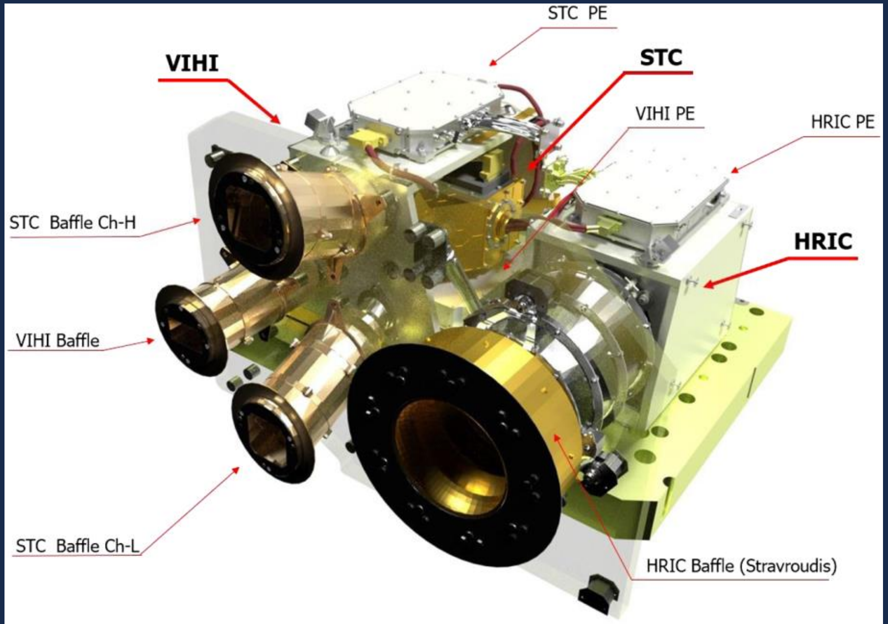


Upcoming BepiColombo measurements

This approach will be useful to treat the upcoming BepiColombo/SIMBIO-SYS data

SIMBIO-SYS/VIHI: VIS-NIR hyperspectral imager
- Global mapping at 400m spatial resolution
- 6.25 nm spectral resolution

SIMBIO-SYS will observe at higher resolution specific targets including:
- Pyroclastic deposits
- Hollows



Cremonese et al., 2020

BepiColombo to better constrain pyroclastic deposits

Observations from bepicolombo to answer these questions:

SIMBIO-SYS Geological context (vent morphology, degradation etc.)

Pyroclast size and deposit roughness

Spectral data, submicroscopic iron estimates etc.

MERTIS Deposit mineralogy, glass content, pyroclast size

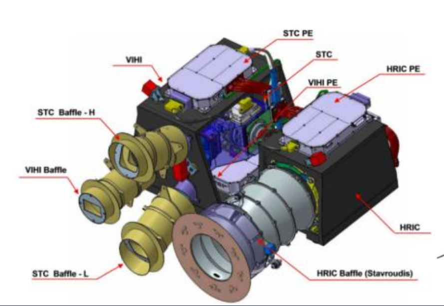
BELA Deposit thickness

MIXS/MGNS Deposit composition

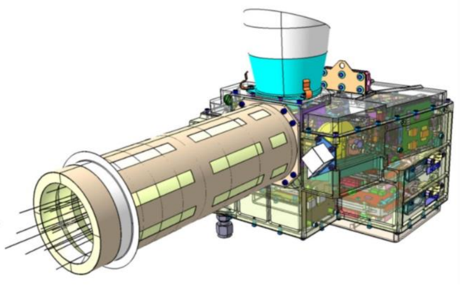
SERENA-MIPA Ion precipitation and response to solar wind

\+ Laboratory measurements
Simulations
Other?

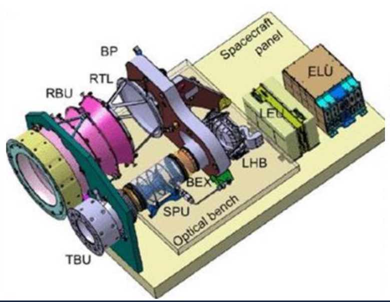
SIMBIO-SYS



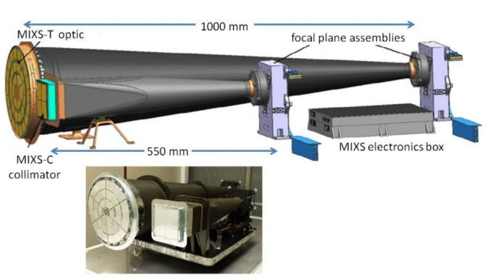
MERTIS



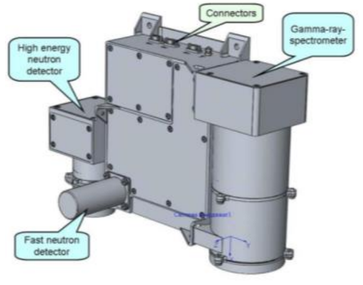
BELA



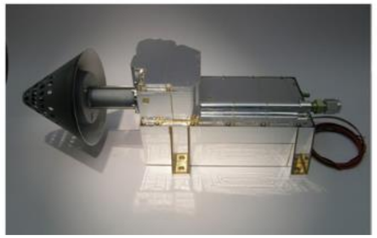
MIXS



MGNS



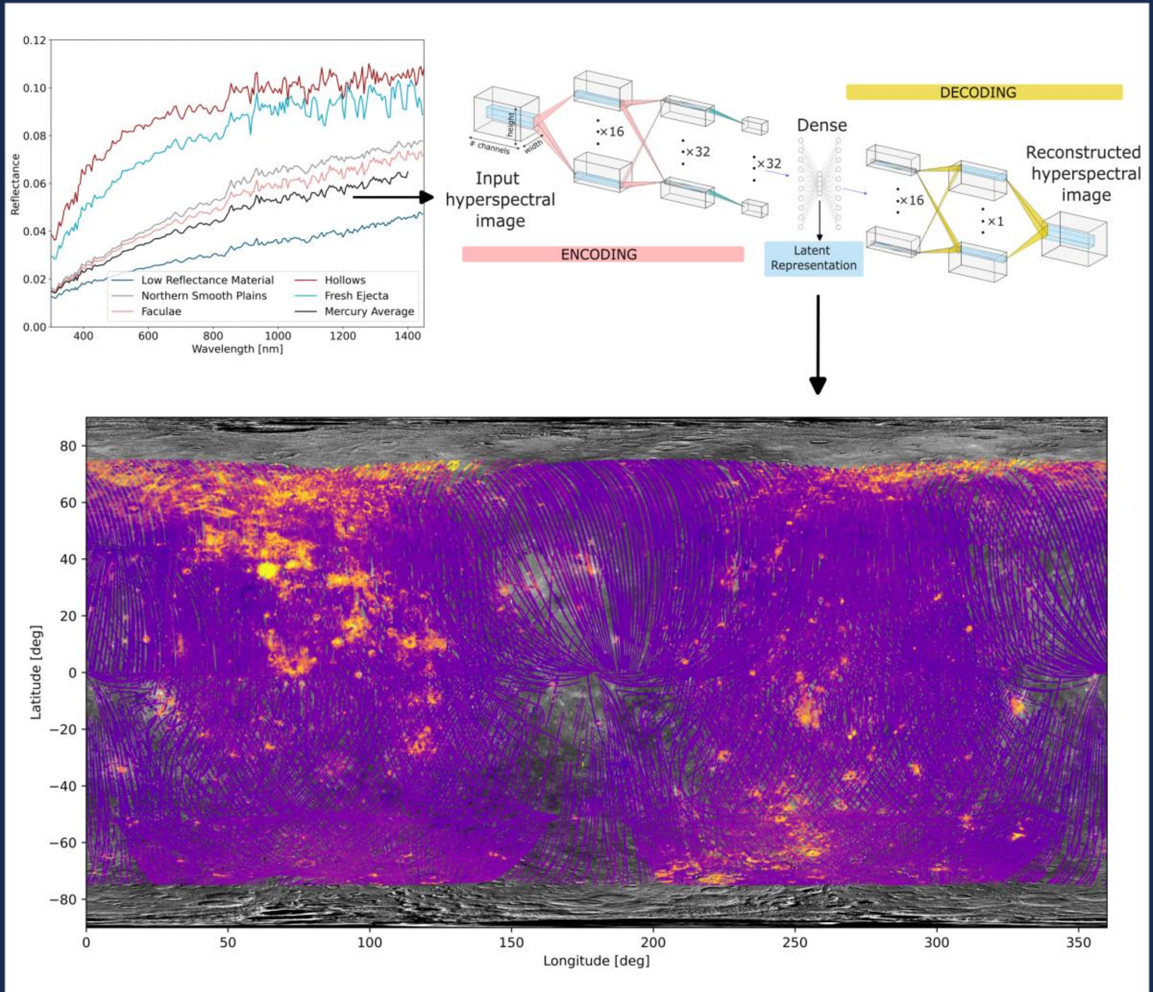
SERENA/MIPA



Summary

Deep Learning approach to:
- **Explore** Mercury's flat spectra
- Extract reduced dimensional representation
- Define the **extent** of pyroclastic deposits

Outcome:
- Defined the extent of 55 deposits
- Identified spectral properties within the depost
- Latent dimensions as a promising tool to examine the spectral properties of Mercury



Feel free to reach out for more information!

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