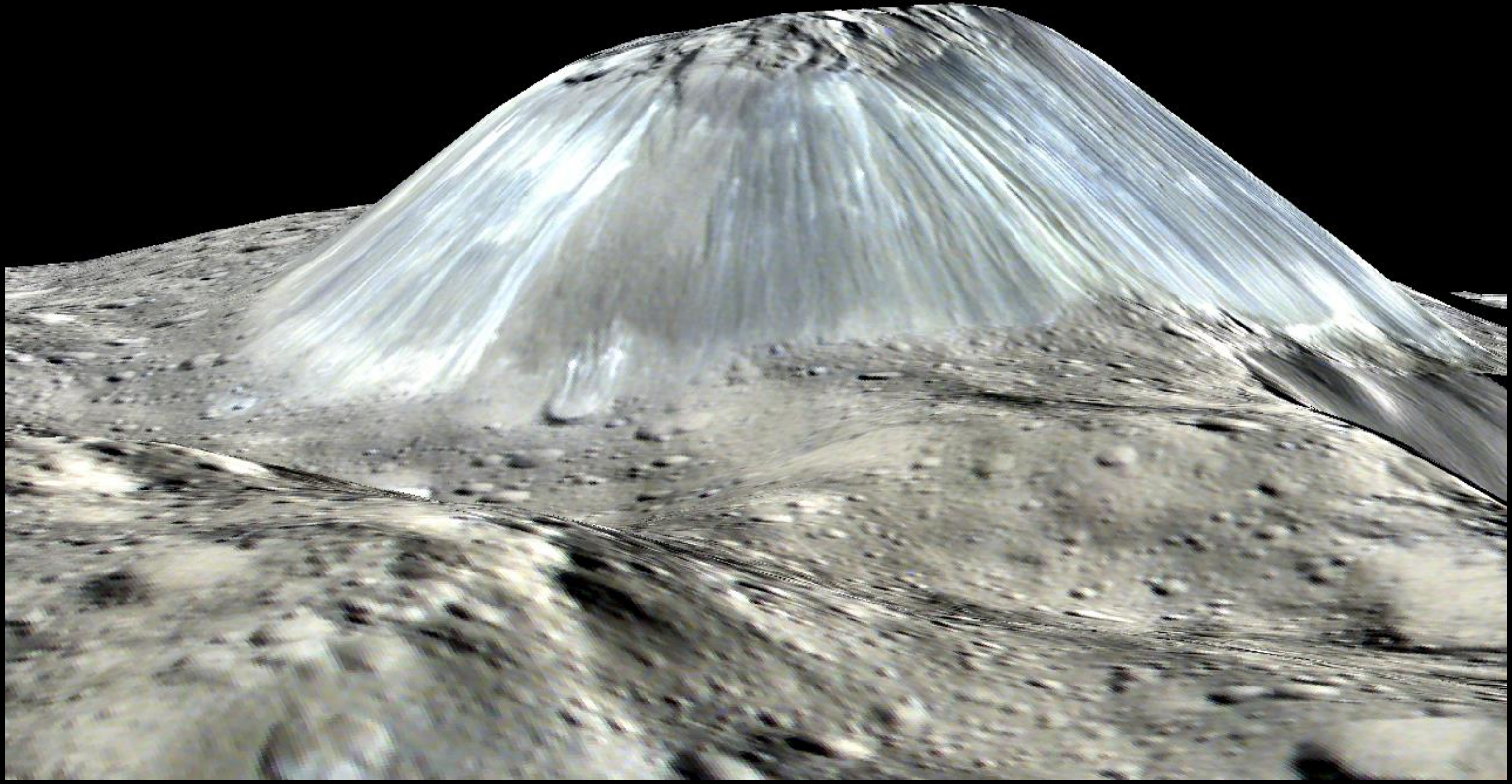
Ceres from Dawn's Data



M.C. De Sanctis

Istituto di Astrofisica e Planetologia Spaziali – INAF Rome, Italy

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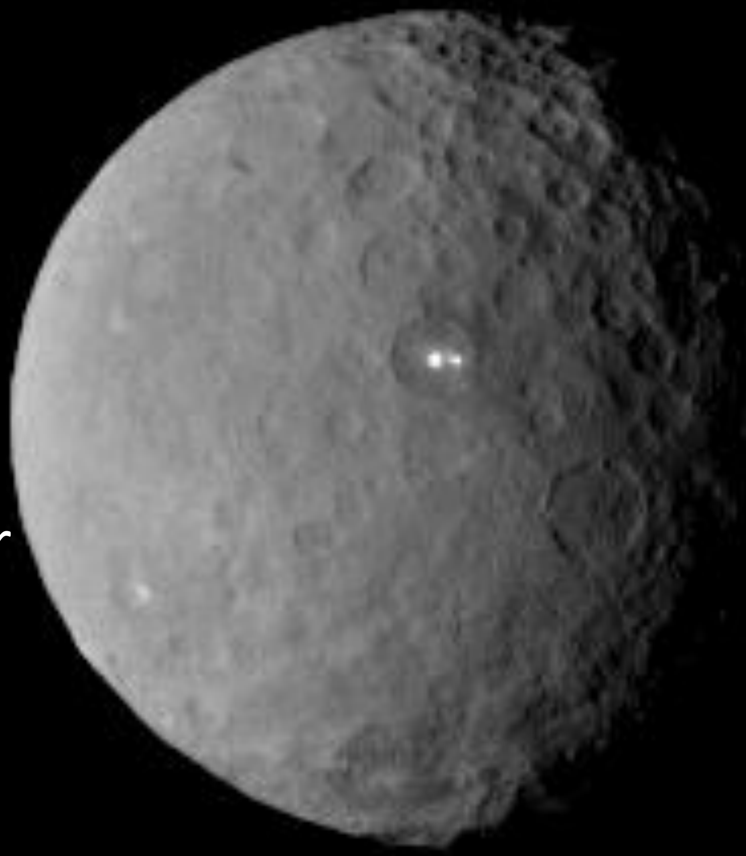
Ceres - The Basics

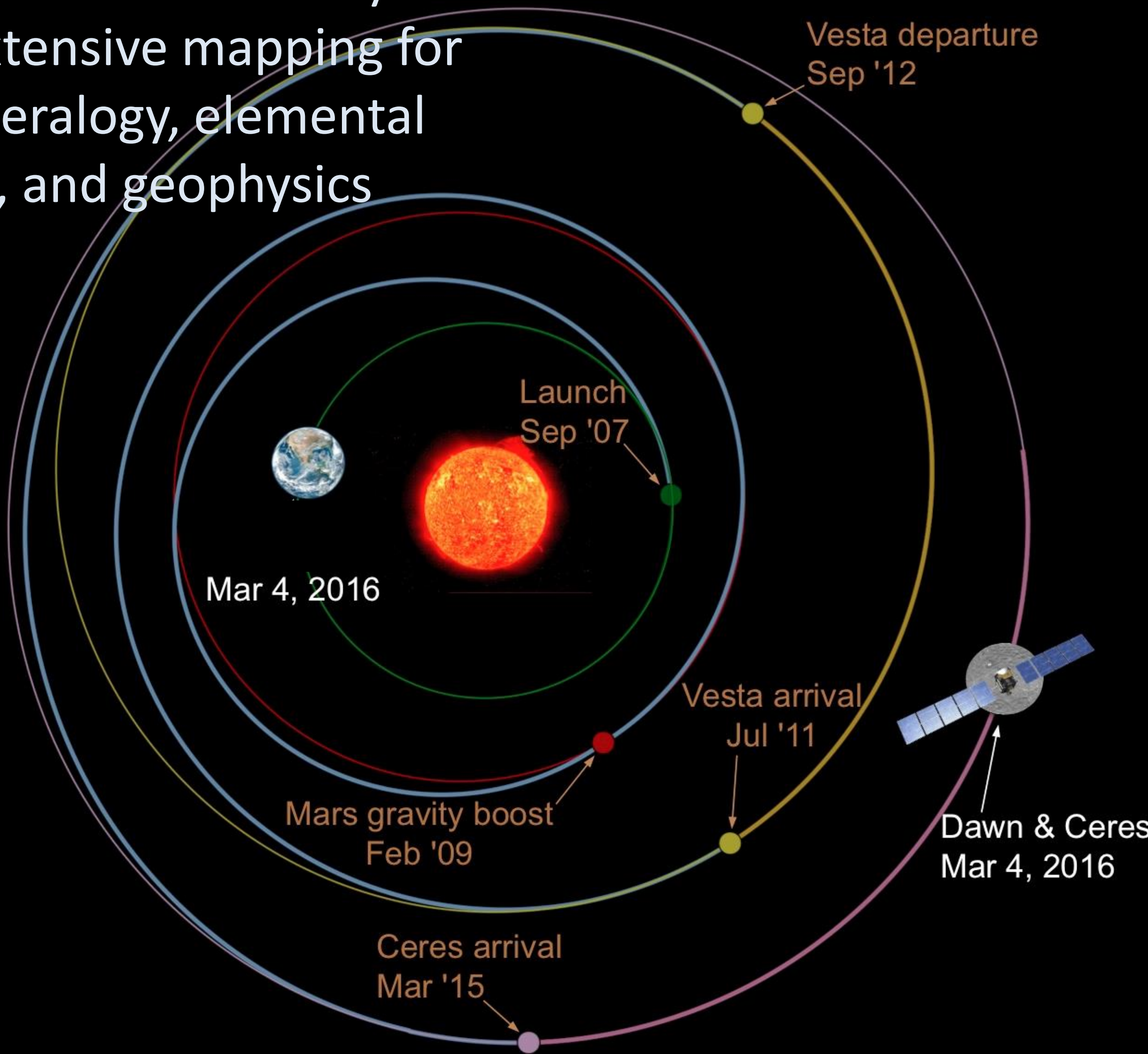
- 482 x 482 x 446 km
- mean radius 470 km
- Rotation period 9.074 hr
- Ceres' surface reflects <10% of incident sunlight
- Average surface temperature 110-155K-Maximum at equator-subsolar point ~230-240 K
- Density 2.162 kg m^{-3}
- Ceres as a whole is ~50 vol.% water
- Early models suggested Ceres could have a 50-100 km thick ice shell



NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

Road Map to Vesta and Ceres

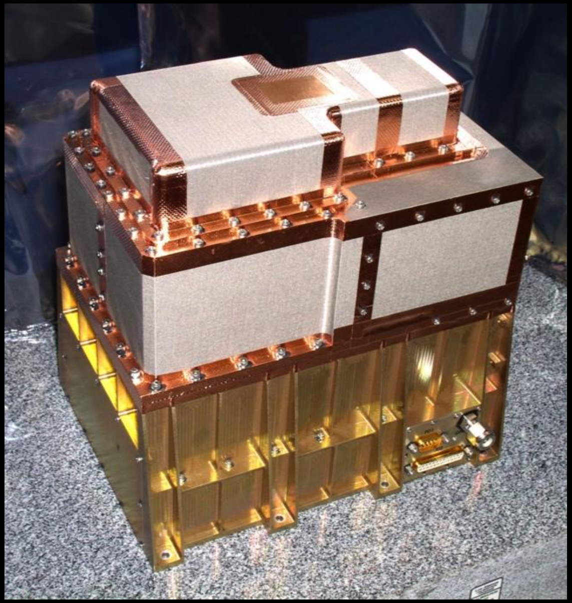
Ceres is the first ice-rich body subject to extensive mapping for geology, mineralogy, elemental composition, and geophysics



Dawn Instruments + Radio Antenna

Camera

Provided and operated by the German Aerospace Agency and the Max Planck Institute for Solar System Research



Gamma Ray and Neutron Spectrometers

Provided by Los Alamos National Labs and operated by the Planetary Science Institute

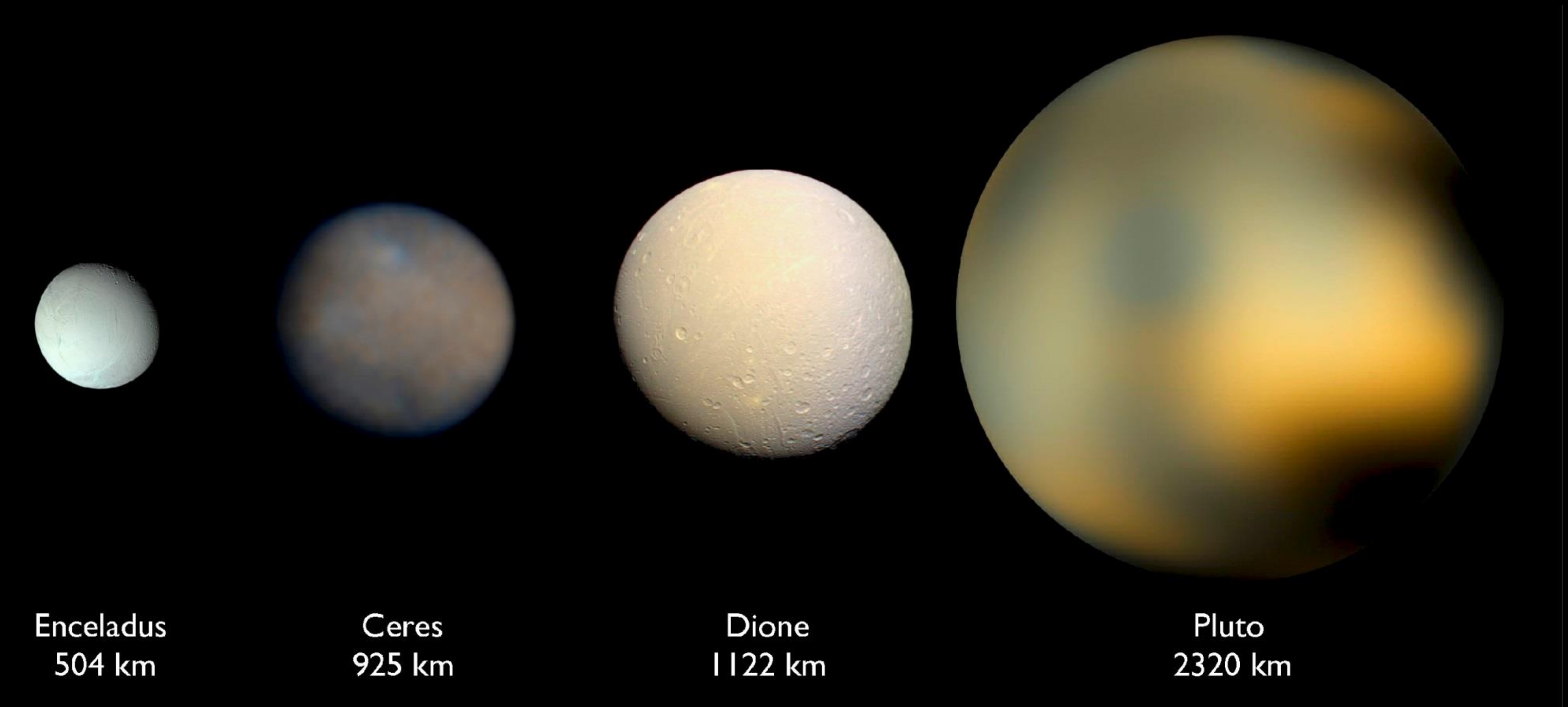
Visible and Infrared Mapping Spectrometers

Provided by the Italian Space Agency and the Italian National Institute for Astrophysics, and operated by the Italian Institute for Space Astrophysics and Planetology

Why Ceres ?

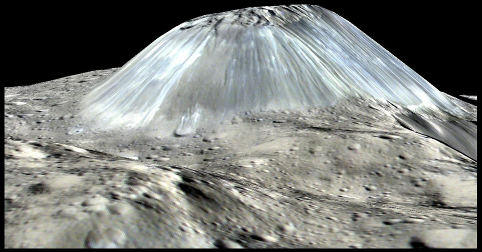
- The early asteroid belt may have been scoured by icy bodies, scattered by the formation of the remaining gas giants.
- Today only some of the largest asteroids remain relatively undisrupted, and Ceres has a very primitive surface, water-bearing minerals, and possibly a very weak atmosphere and frost.

Ceres' Peer Group: Icy Moon and Dwarf Planets



- Ceres is expected to have water and ice in its interior, but more rock than the icy moons Enceladus and Dione. It has been classified as a dwarf planet by the IAU, like Pluto.

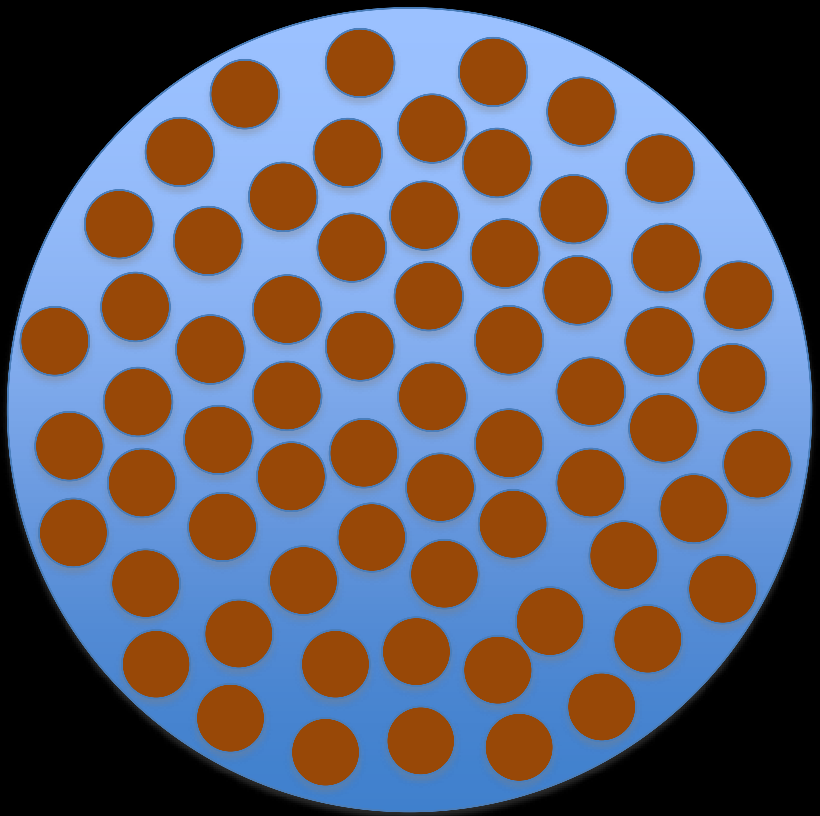
Outline



Observational Constraints

Open Questions

Context to keep in mind

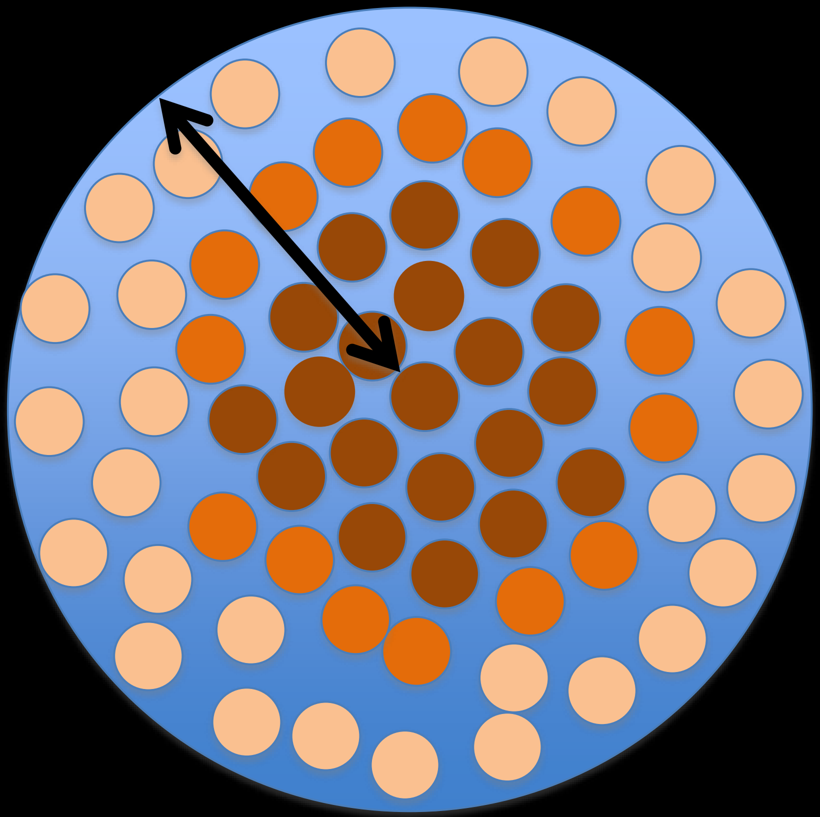


Mixture of rock and ice

Which rocks?
Which ices?

Function of origin

Context to keep in mind



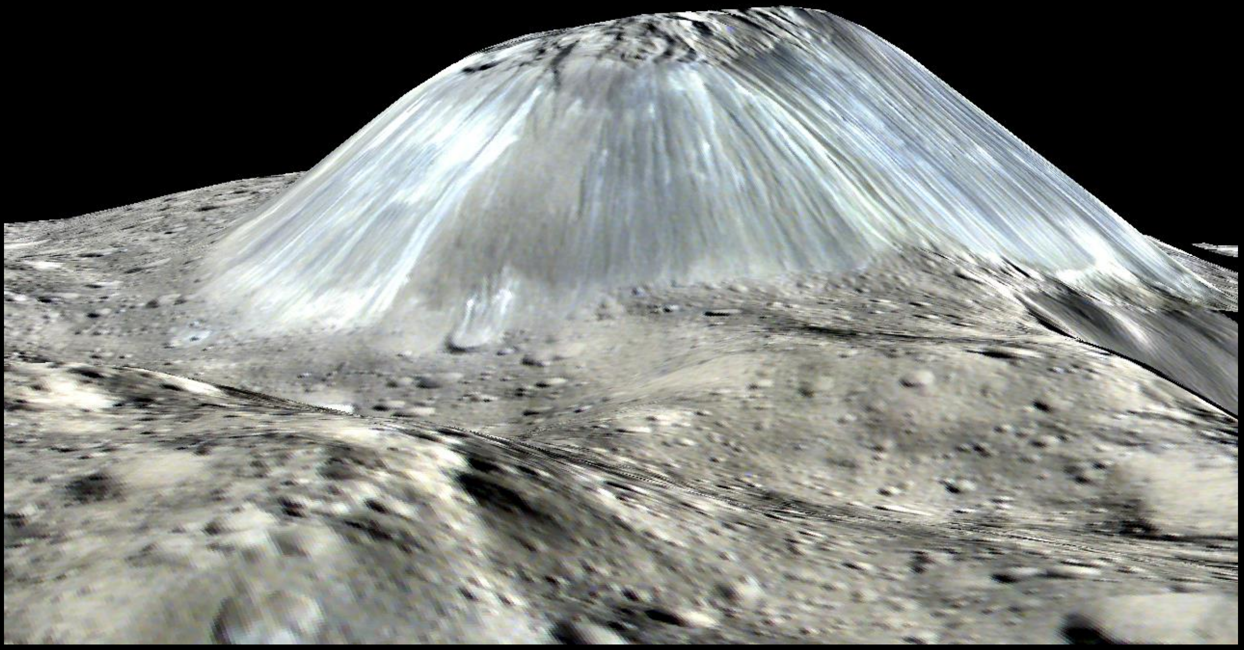
Heat sources?

Relative movements ?

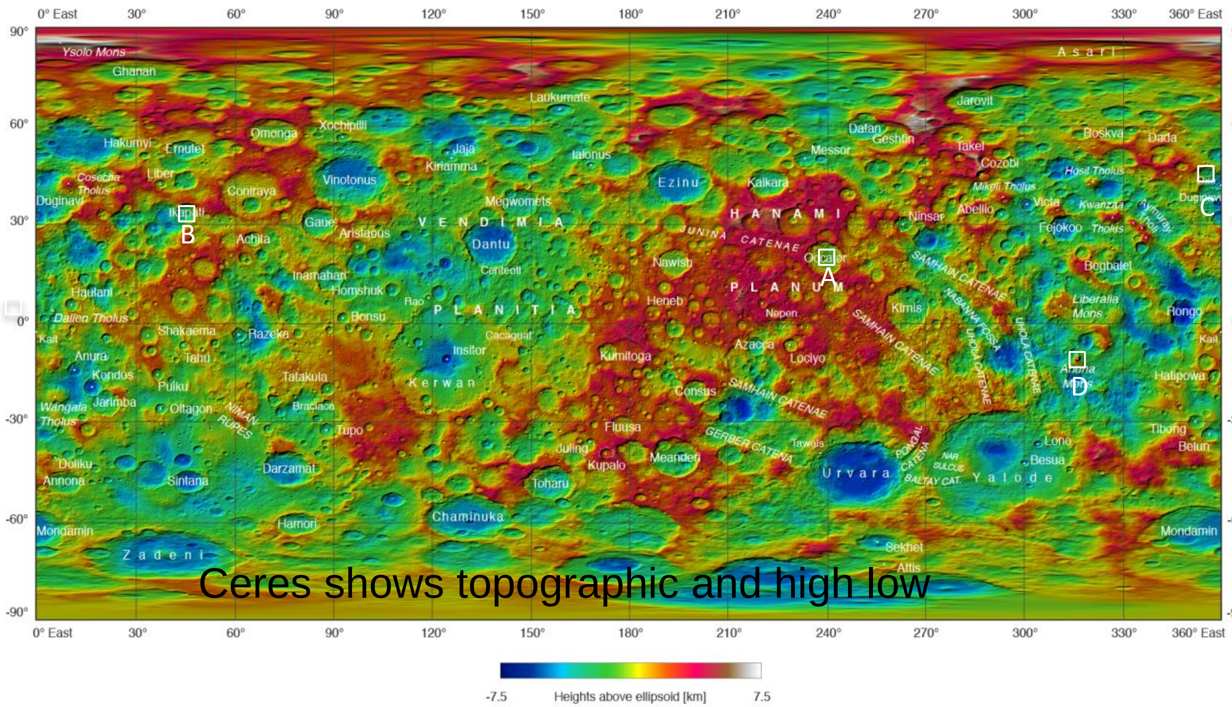
Chemical fractionation?

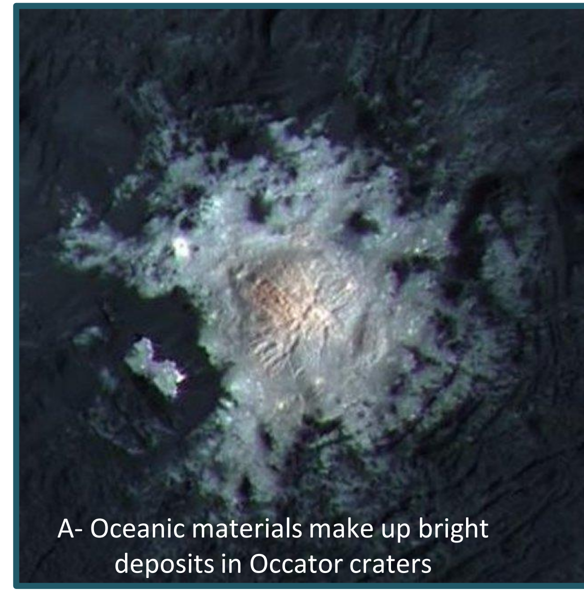
Function of parent-body processes

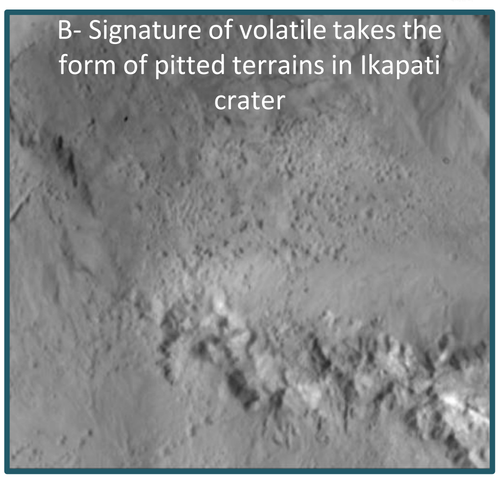
Observational Constraints



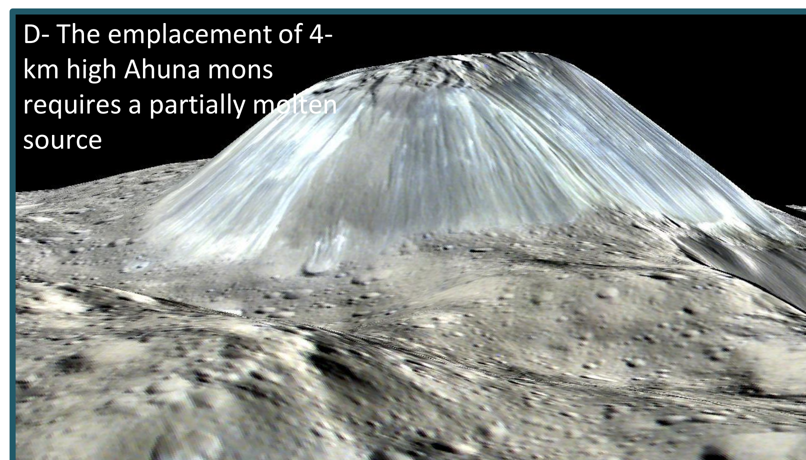
Dawn Revealed an Evolved and Volatile-Rich New World!




A- Oceanic materials make up bright deposits in Occator craters


B- Signature of volatile takes the form of pitted terrains in Ikapati crater

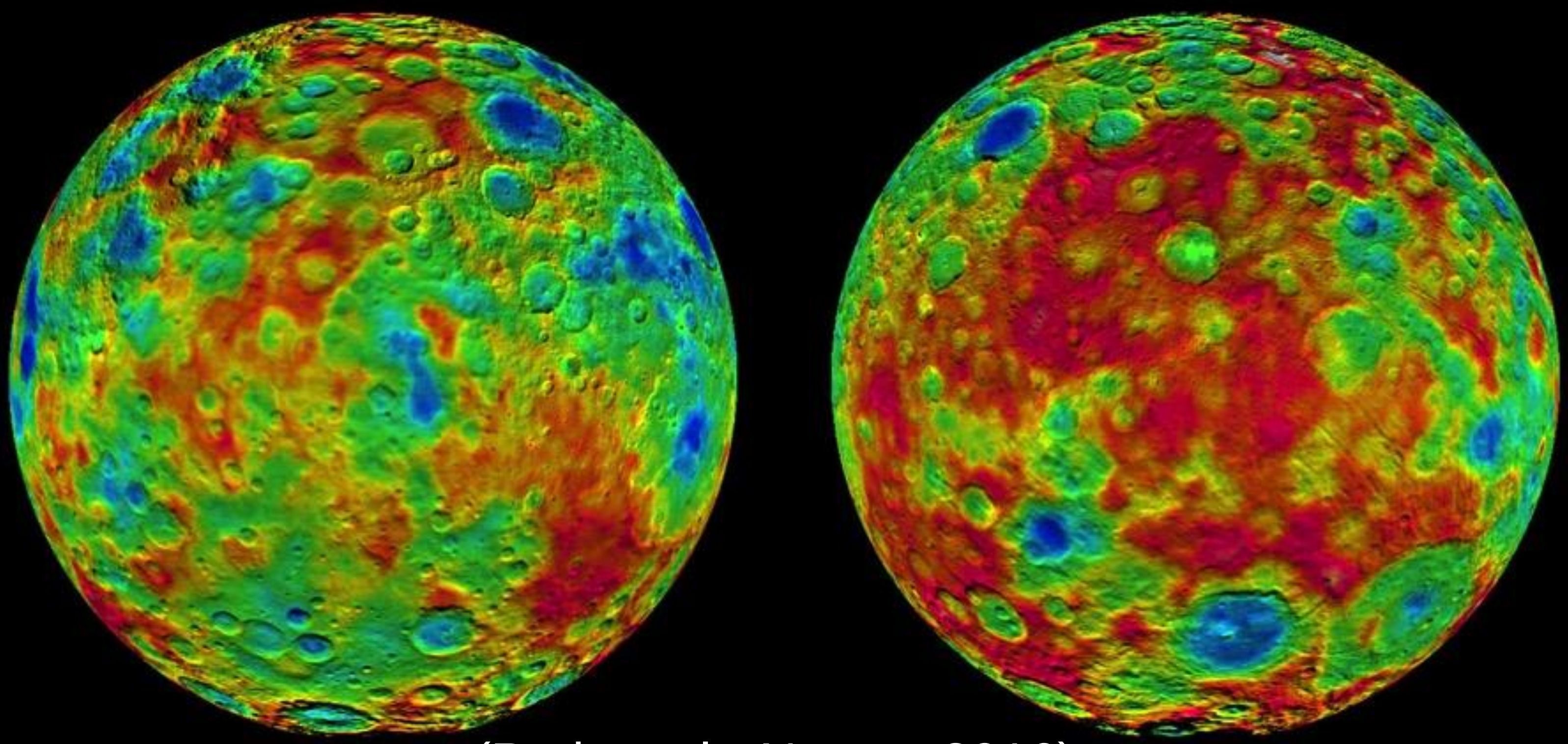

C- A large landslide reveals water ice at Oxo crater


D- The emplacement of 4-km high Ahuna mons requires a partially molten source

Castillo Rogez, 2017

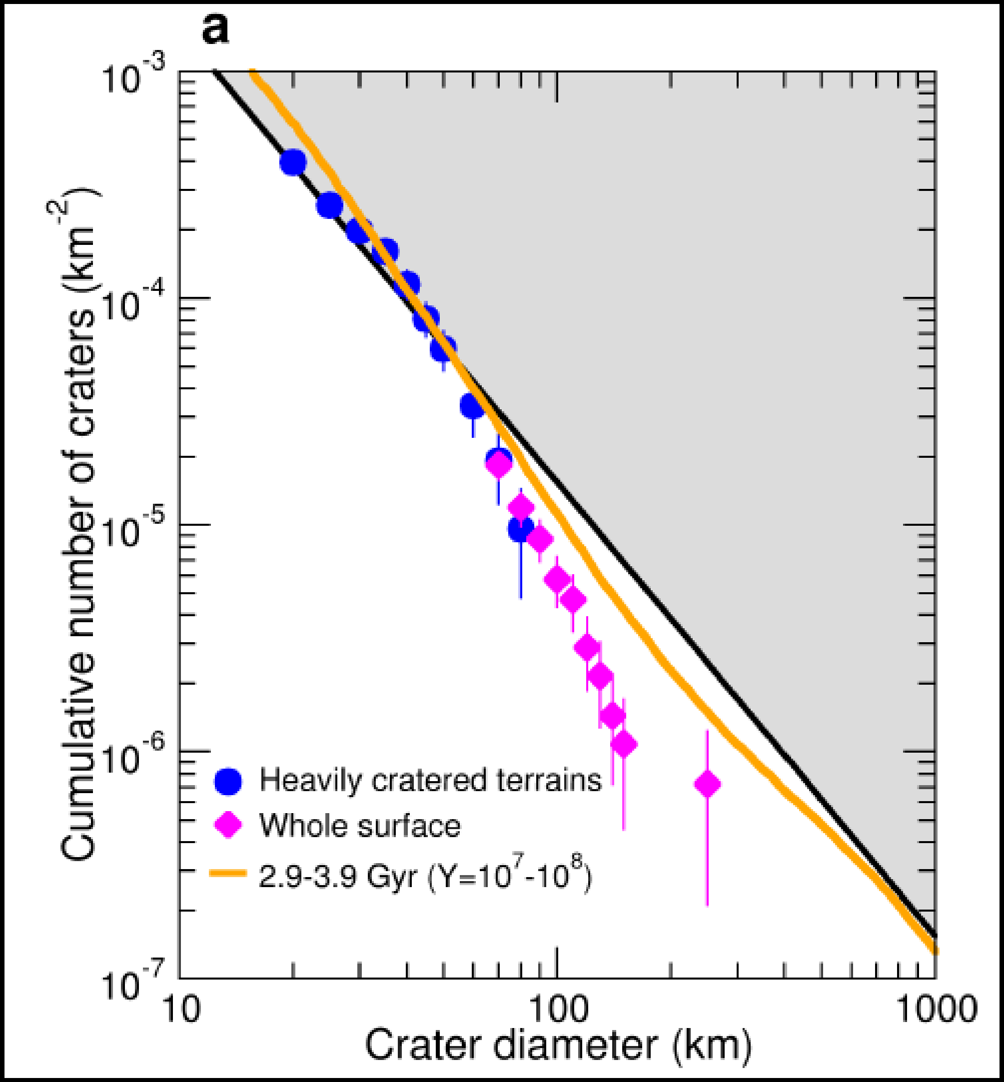
Properties of the outer shell?

- Ceres has +7.2 to -6.4 km of topography relative to geoid
- Gravity data indicate Ceres is close to hydrostatic equilibrium



(Park et al., *Nature*, 2016)

Rheology of the outer shell?



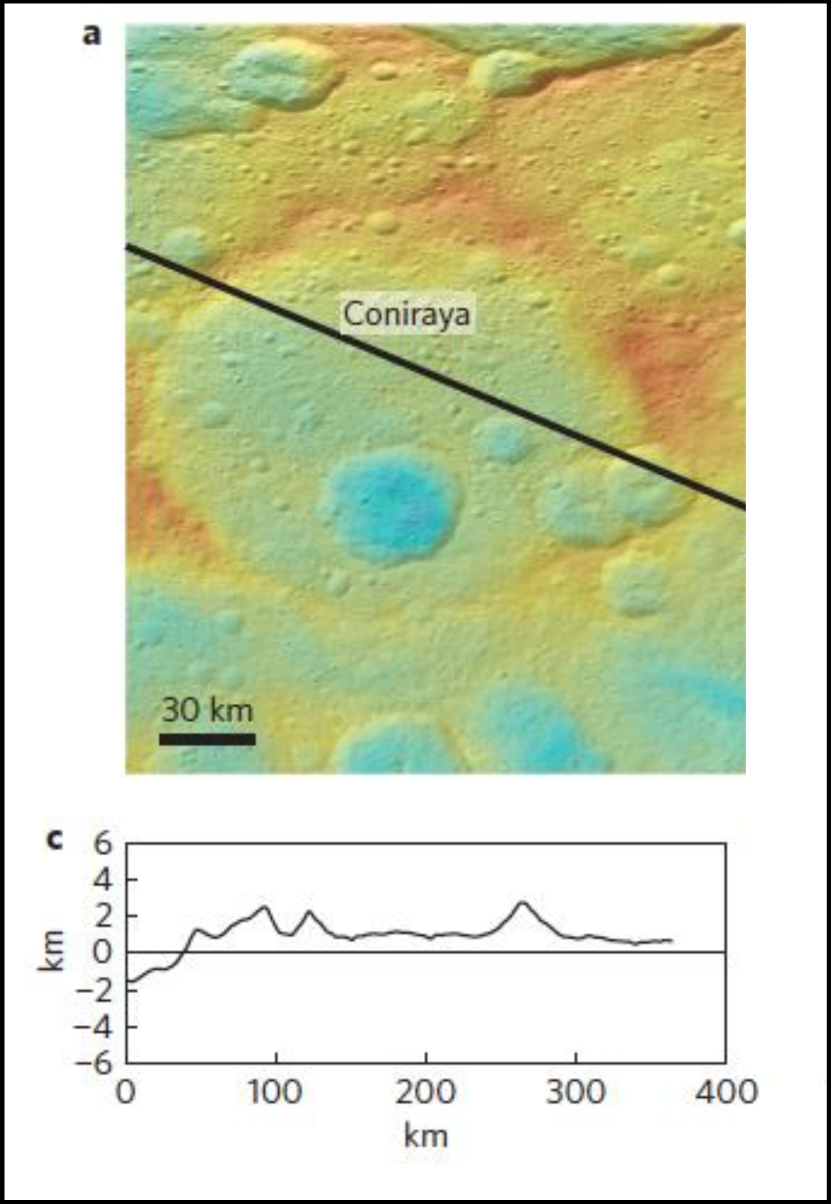
Largest craters are ‘missing’

(Marchi et al., *Nature Comm.*, 2016)

Rheology

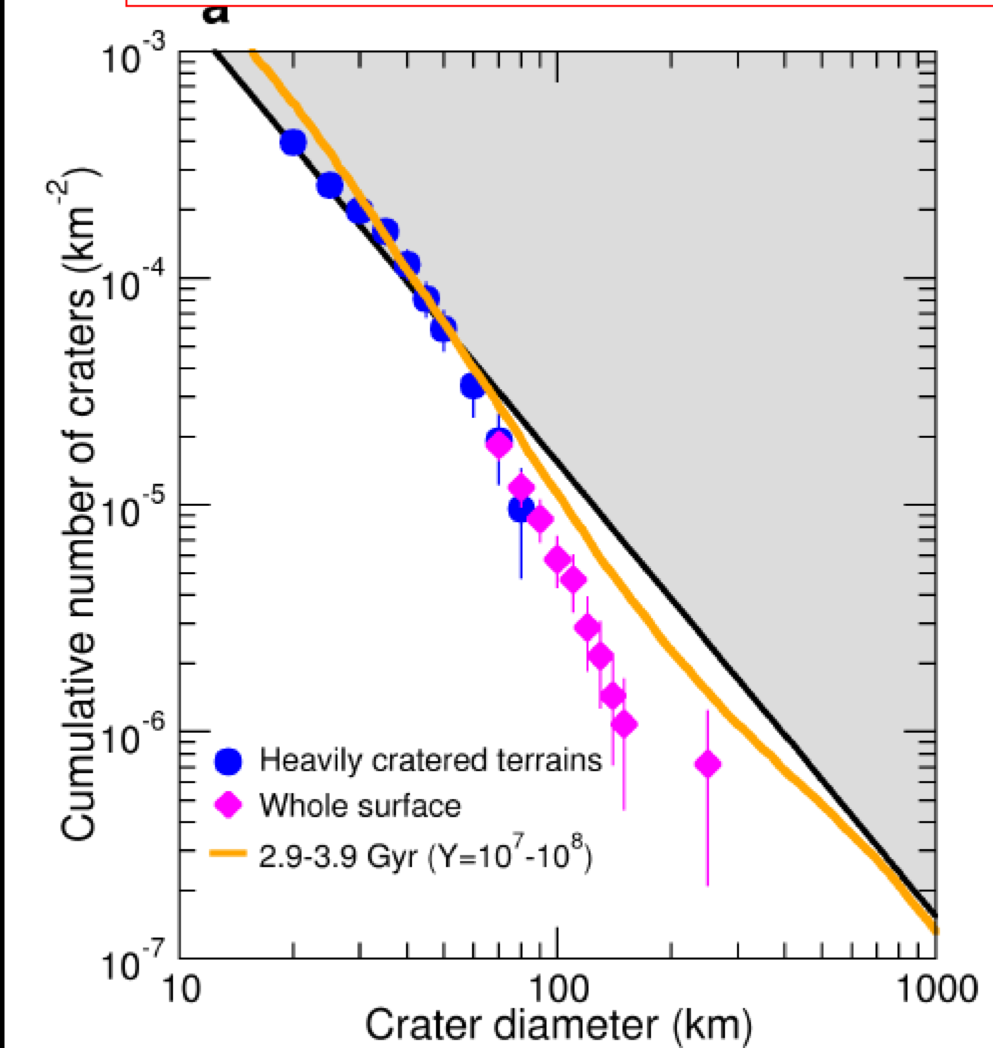
Largest observed craters can be fully relaxed

(but not the case for smaller craters)

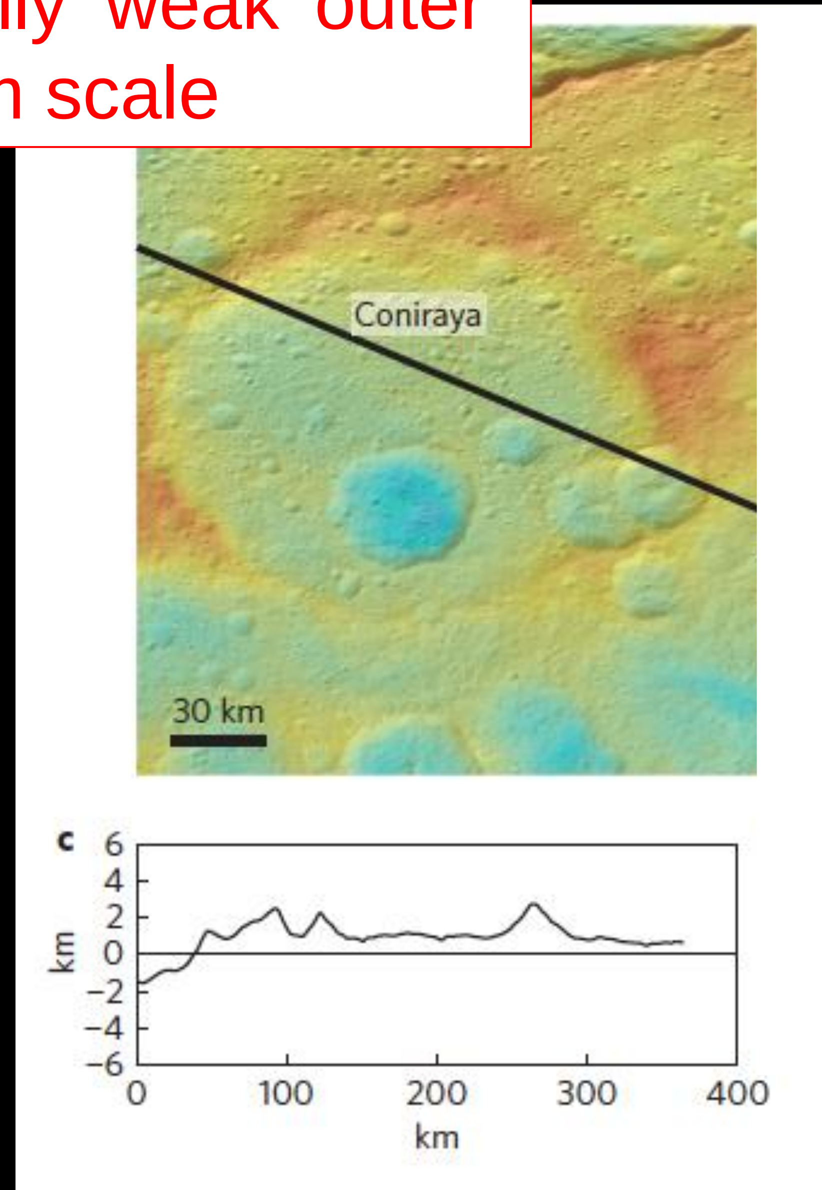


(Bland et al., *Nature Geoscience*, 2016)

Evidence for a rheologically ‘weak’ outer shell at the 100km scale

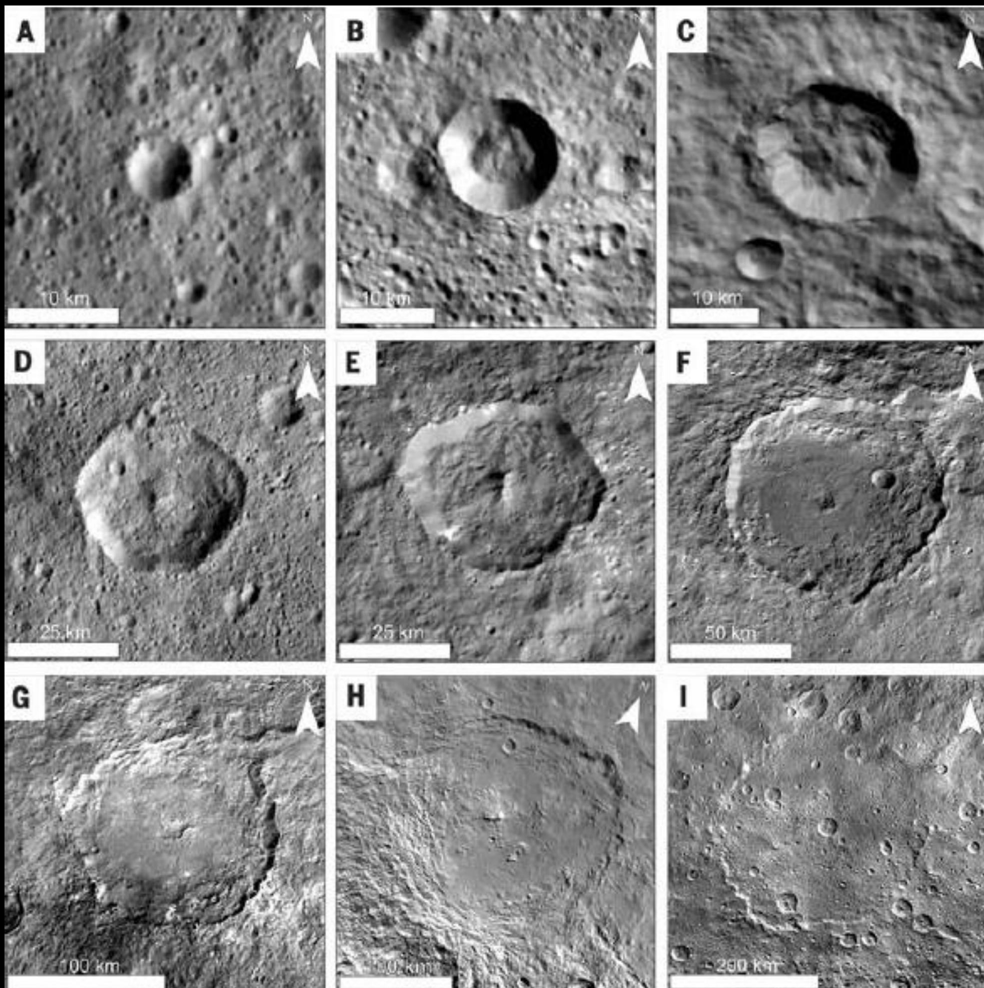


(Marchi et al., *Nature Comm.*, 2016)



(Bland et al.,
Nature Geoscience, 2016)

Water in the outer shell? Some indications

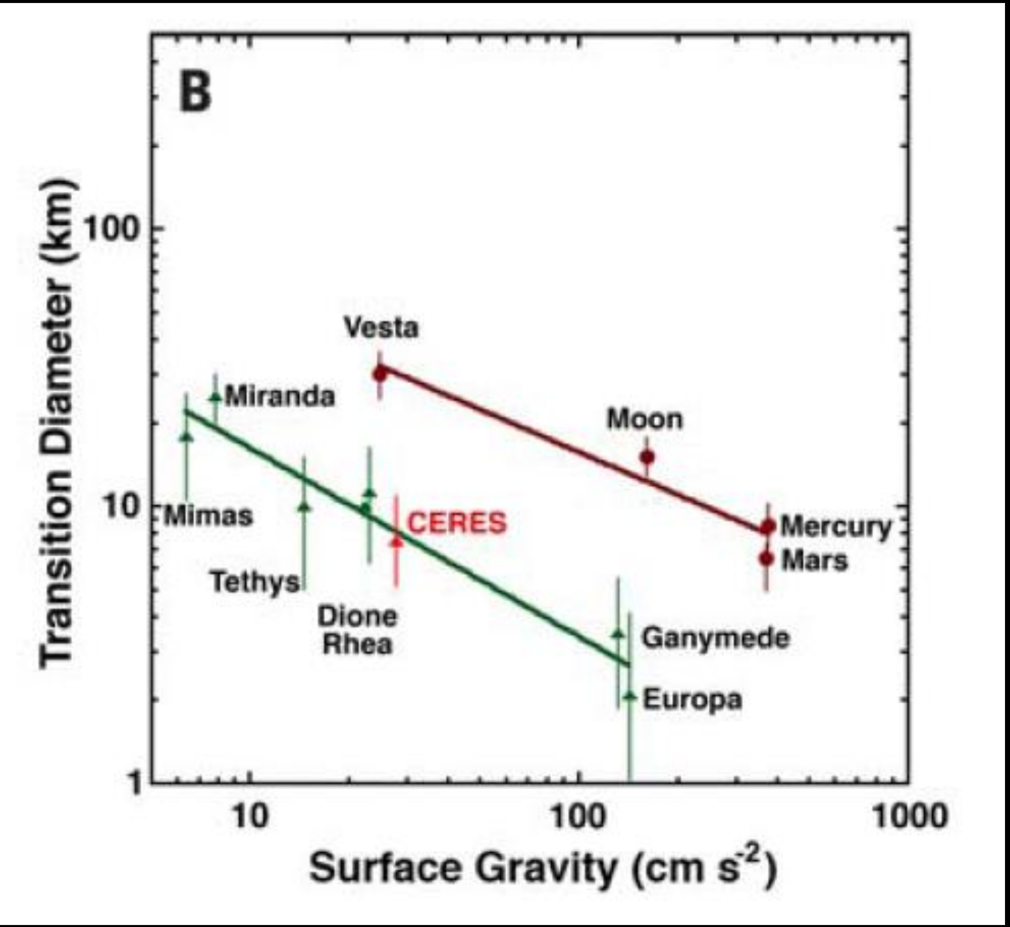


Transition observed from simple to complex craters

(Hiesinger et al., *Science*, 2016)

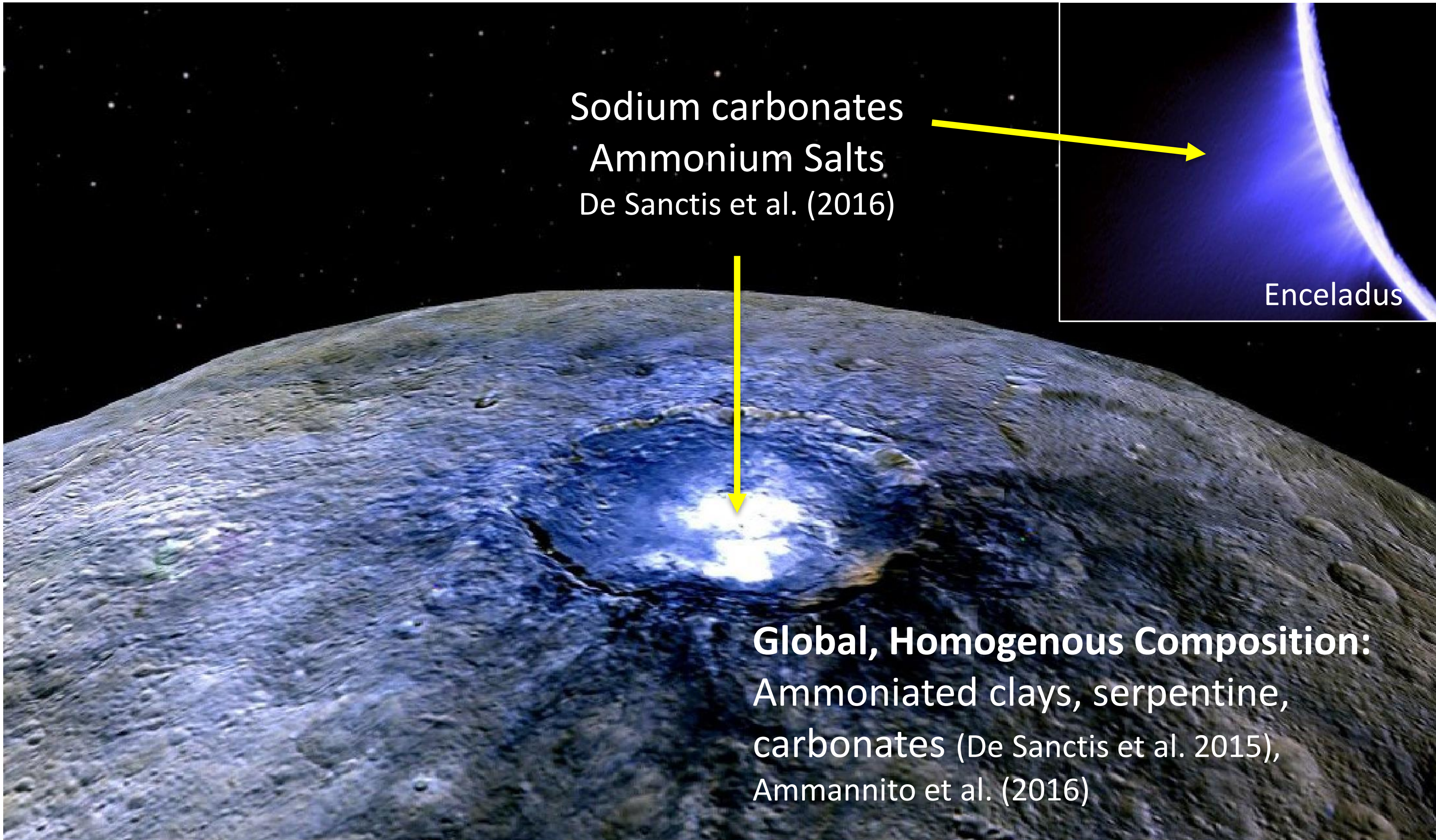
Water in the outer shell? Some indications

Transition compatible with those observed on « icy » bodies



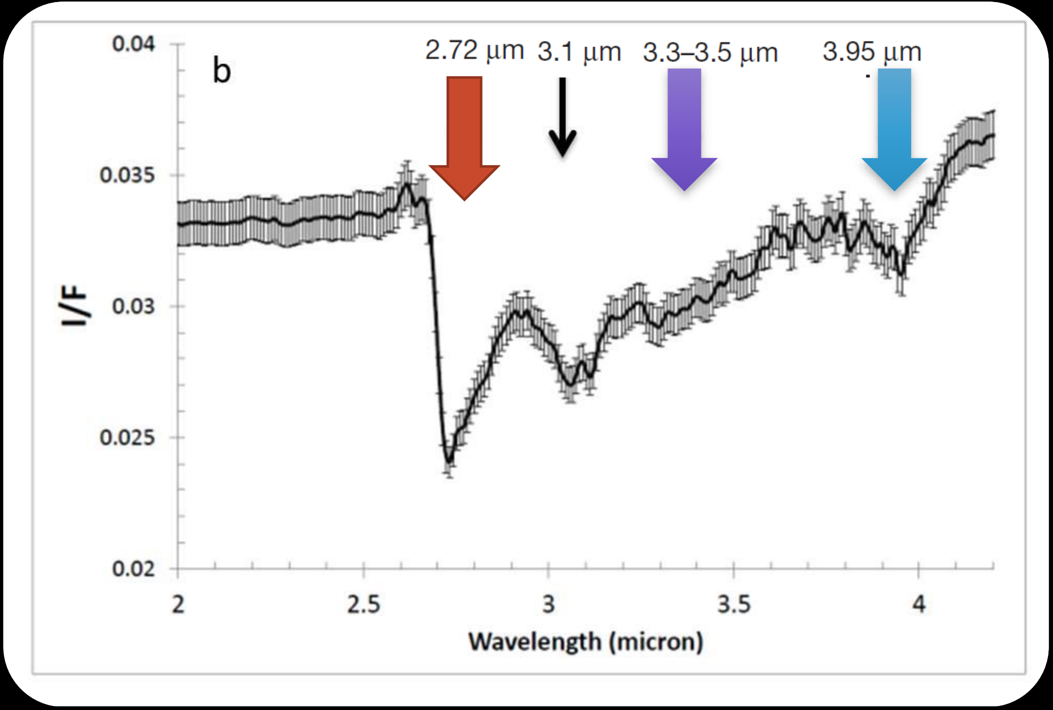
(Hiesinger et al., *Science*, 2016)

Ceres' Surface Shows Evidence for Mineralogy Formed at Depth



Ceres' Average Surface Composition Suggests Advanced Aqueous Alteration

- Distinct absorptions bands at **2.72, 3.1, 3.3-3.5, and 3.95 µm.**
- **2.72 µm**: OH-stretching vibrations (Mg-phyllosilicates)
- **3.3-3.5 µm**: very broad - overlapping absorptions of several species
- **3.95 µm**: Carbonate band-Mg-Ca carbonate



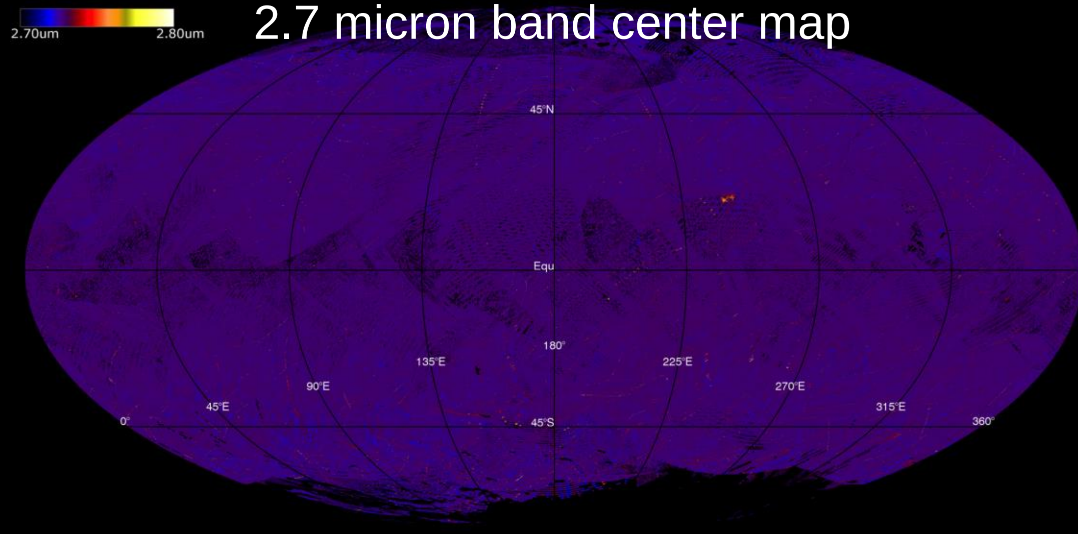
(De Sanctis et al., *Nature*, 2015)

Composition is evidence for aqueous alteration

Surface Composition

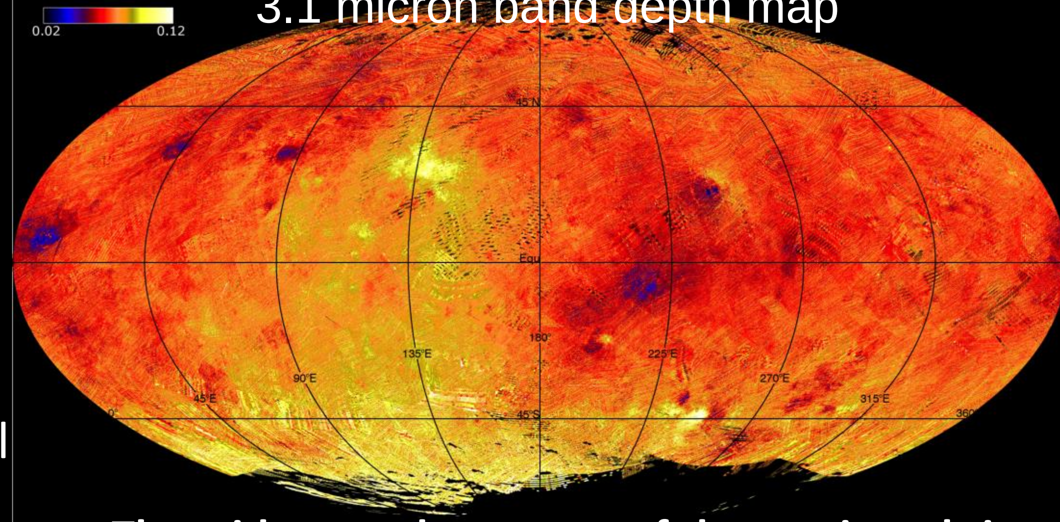
Band Center maps at 2.7 and 3.1 microns show ubiquitous presence of phyllosilicates. The position indicate Mg- phases, like Mg-serpentine or Mg-smectite

2.7 micron band center map



Band Depth maps show local variations in proportions of ammonia-rich and Mg-rich clays. Such variations are likely due to spatial variability in relative mineral abundance.

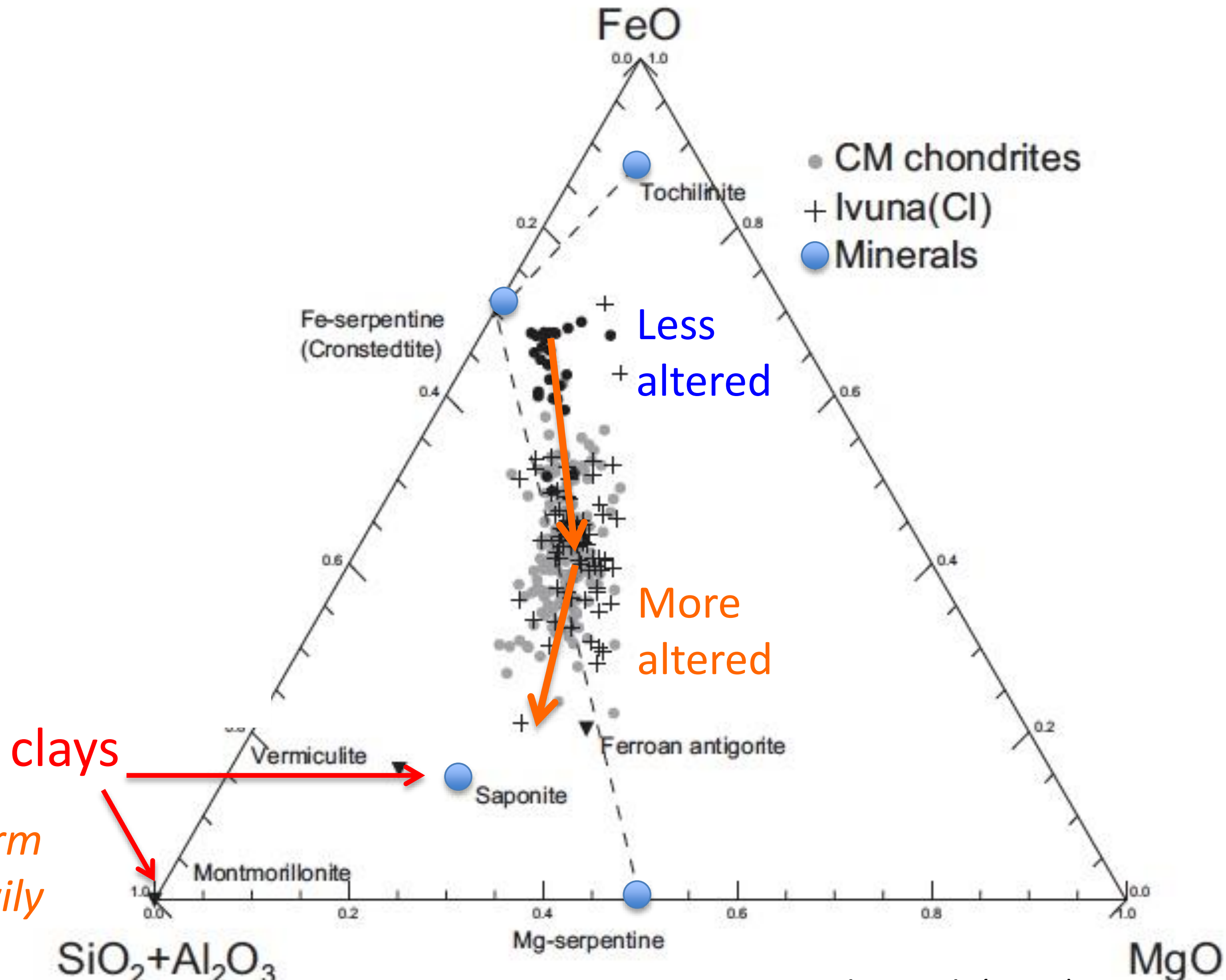
3.1 micron band depth map



(Ammannito et al., Science, 2016)

The widespread presence of these minerals is a strong indication of a global and extensive aqueous alteration.

CM/CI carbonaceous chondrites still provide the best compositional analogy for Ceres, except for the NH_4-clays

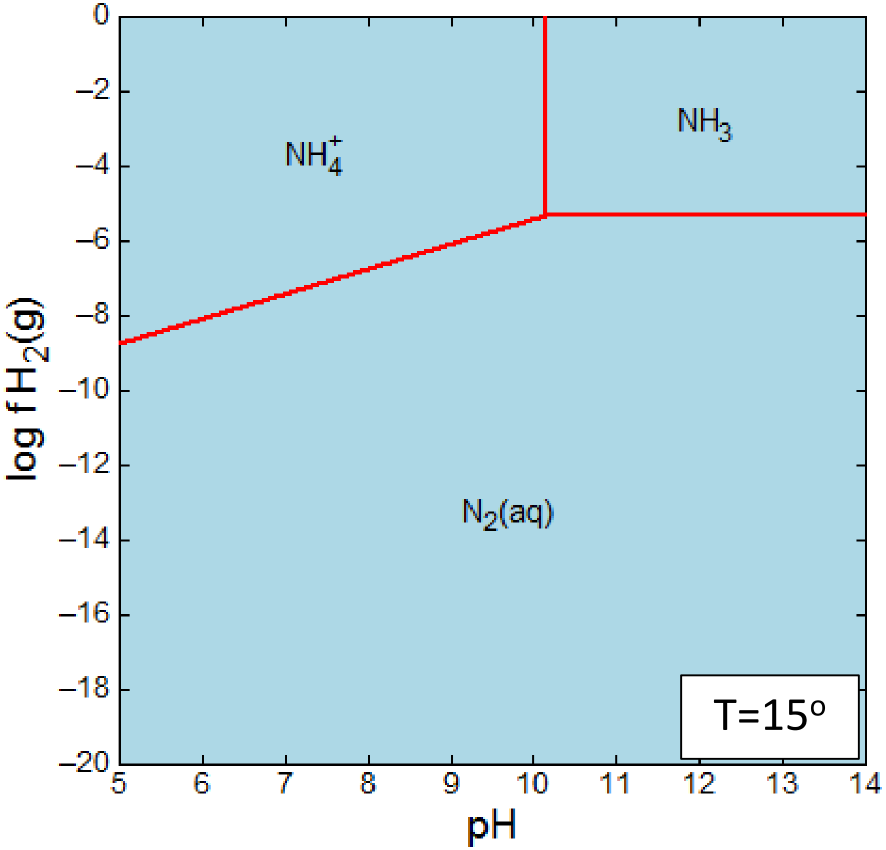


Clay minerals form in the most heavily altered CM/CIs

Takir et al. (2013)

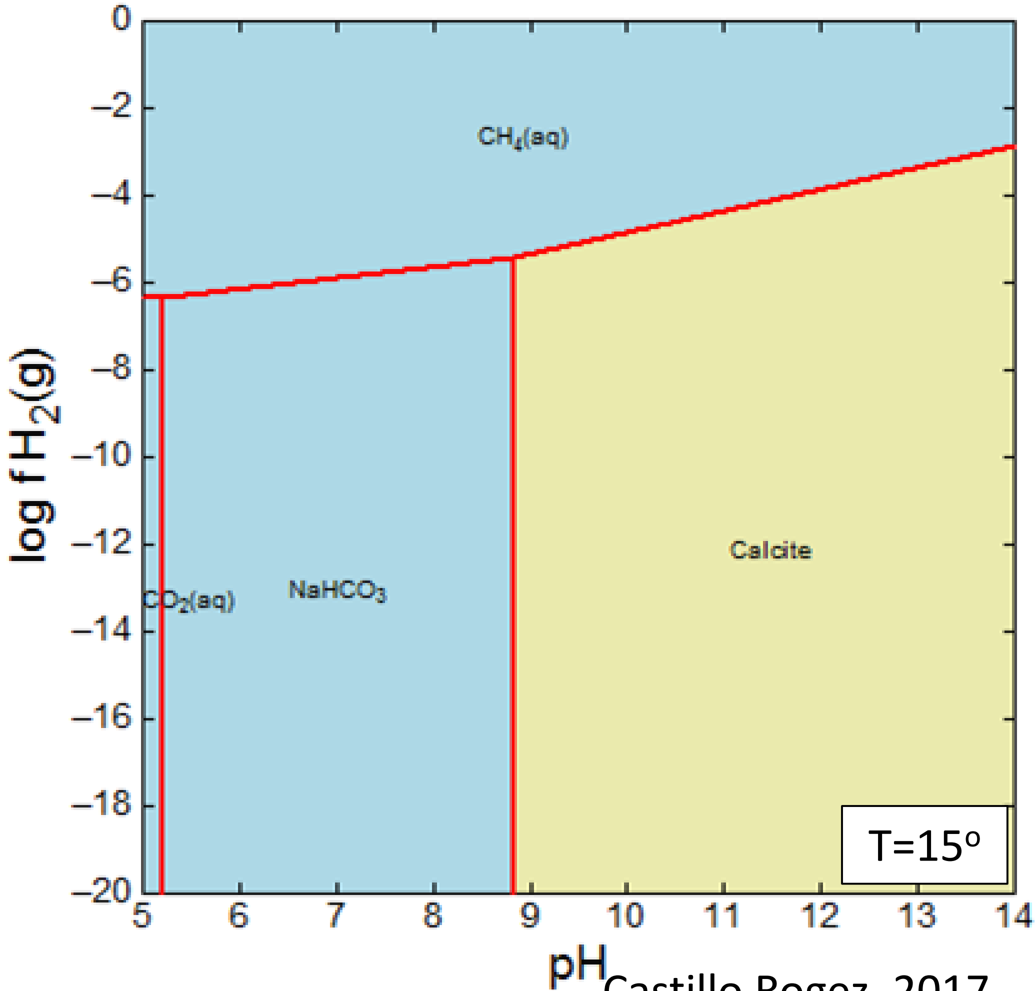
Ammoniated Clays Are Strong Diagnostic of Environmental Conditions

- Requires high partial pressure of hydrogen
- Consistent with previous modeling of large ice-rich bodies (e.g., McKinnon and Zolensky 2003)
- Ammonium exchanges with Na, Ca, K
  - Abundant salt production
- Implies temperatures < 50 deg. C (Neveu and Desch 2015)



Carbonates Help Narrow Down the redox-pH Space

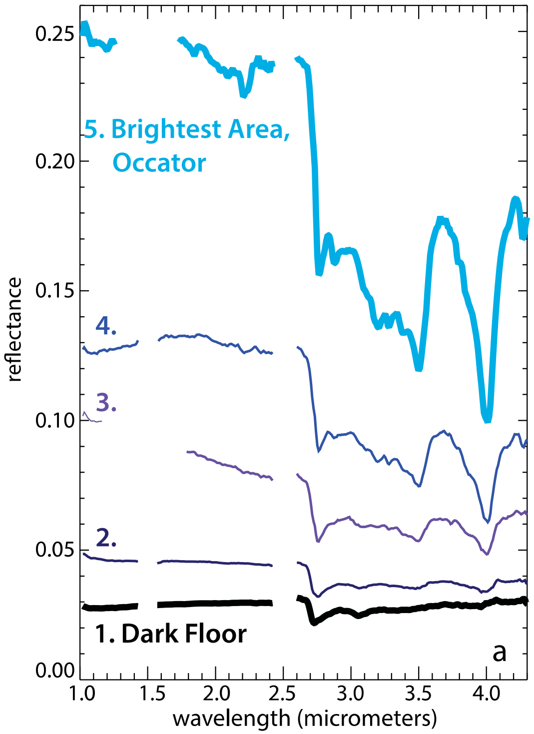
- Evidence for accretion of CO_2 and/or organics
- Ca/Mg carbonate formed with rock as part of global hydrothermal event
- Other type of carbonate: $NaHCO_3$ condenses upon freezing of original ocean



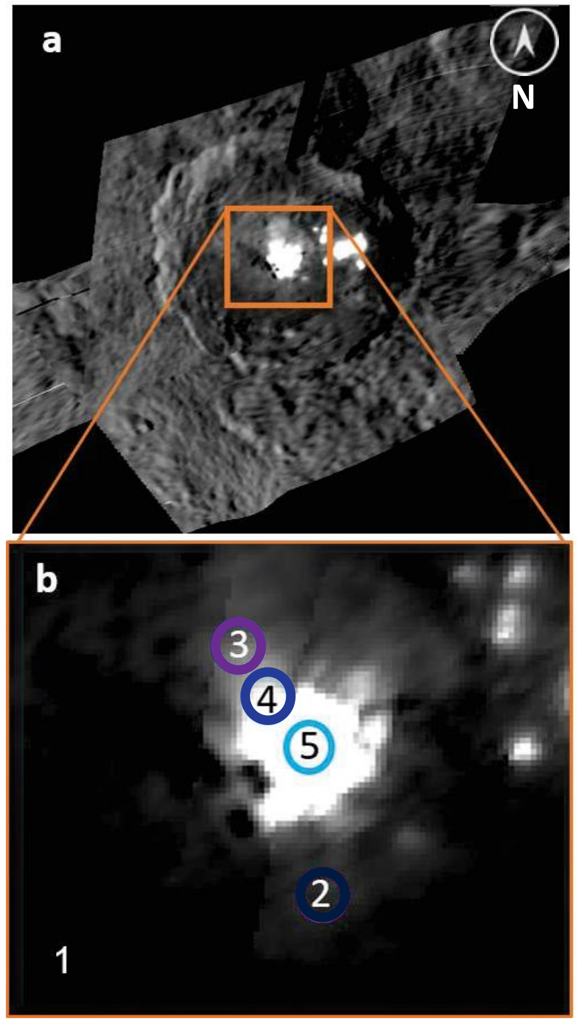
Castillo Rogez, 2017

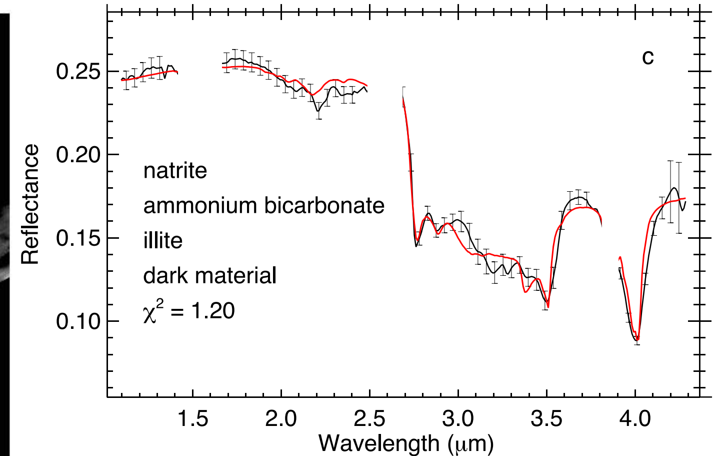
Occator Bright Deposits are Rich in Carbonates

(De Sanctis et al., *Nature*, 2016)



Infrared absorptions within Occator crater correlate with brightness indicates concentration of Na-carbonate



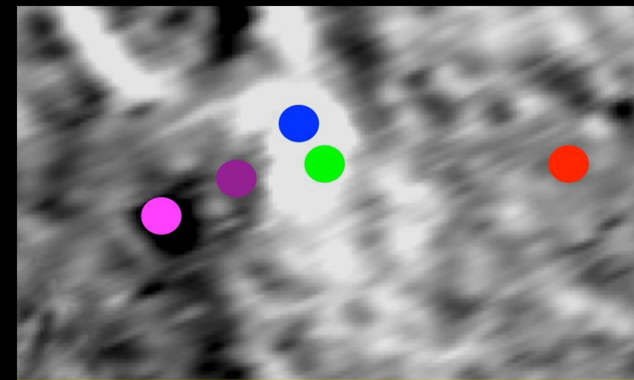


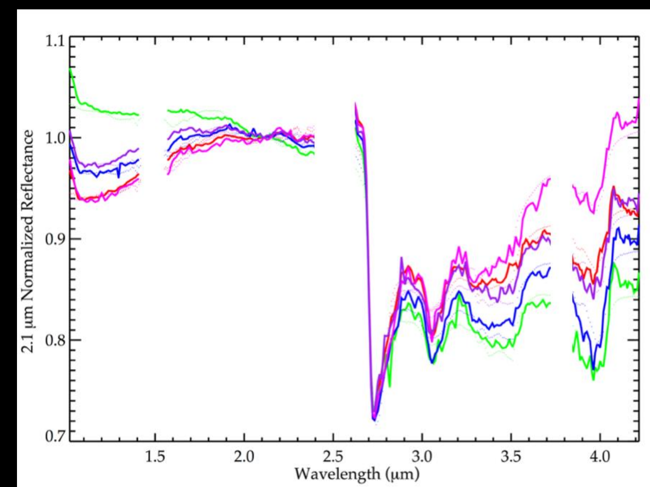
- Largest carbonate deposit known outside Earth
- Formed in alkaline aqueous environment
- Similar to Enceladus plume chemistry

Na-carbonate is the major species (45-80 vol.%) In addition there is ammonium carbonate or chloride

Local variations: Ahuna Mons

- Ahuna Mons appears to be a viscous cryvolcanic dome.
- The extrusion of the dome is recent (Ruesch et al., Science, 2016).



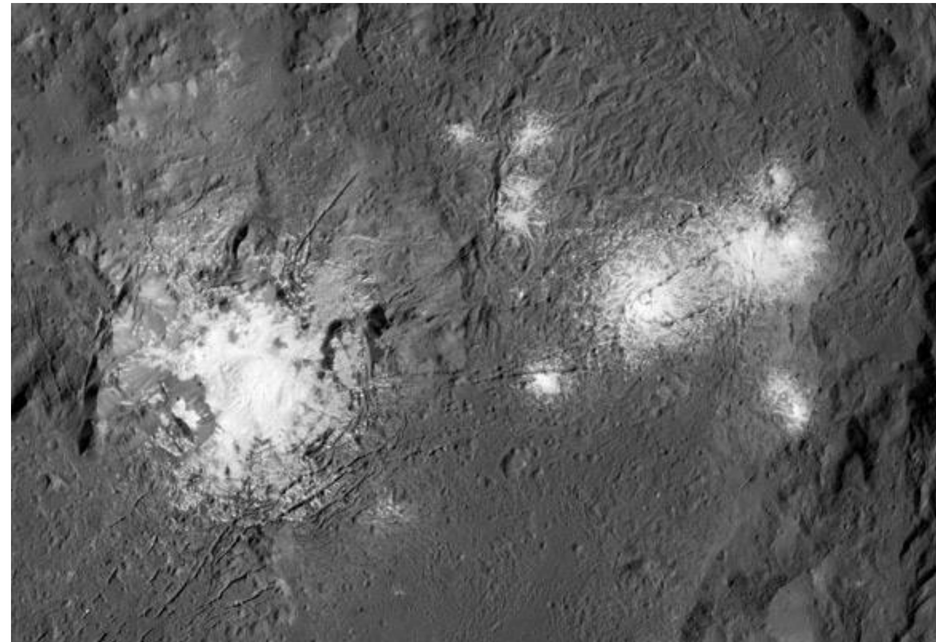


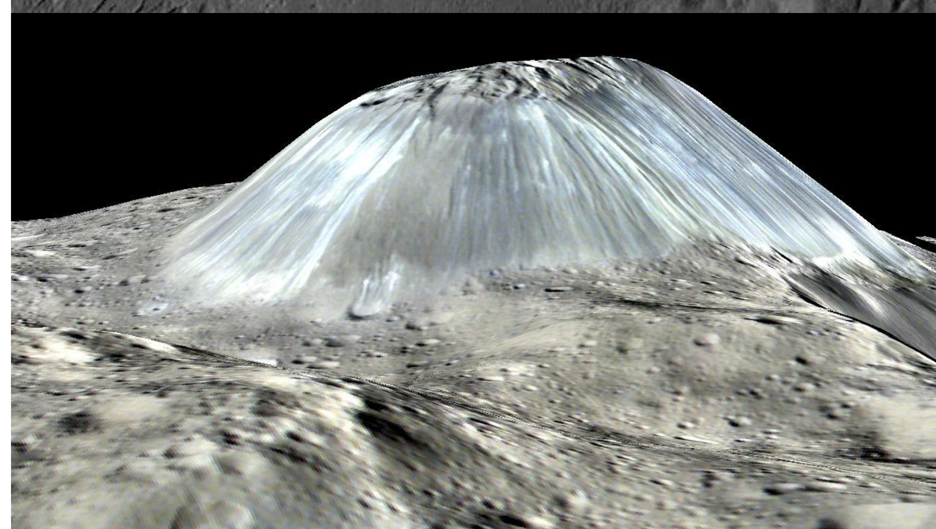
Ascending subsurface fluids?

The spectra indicate the presence of Na-carbonate as in Occator.
(Zambon et al., 2016)

Ceres’ Subsurface is Enriched in Salts

- Sodium bicarbonate and ammonium salts found in bright deposits at Occator and other places (De Sanctis et al. 2016)
- The emplacement of Ahuna Mons implies the presence of brines at depth (Ruesch et al. 2016)
- Occurrence of salts in many settings suggest near-surface abundance (Stein et al. 2016)

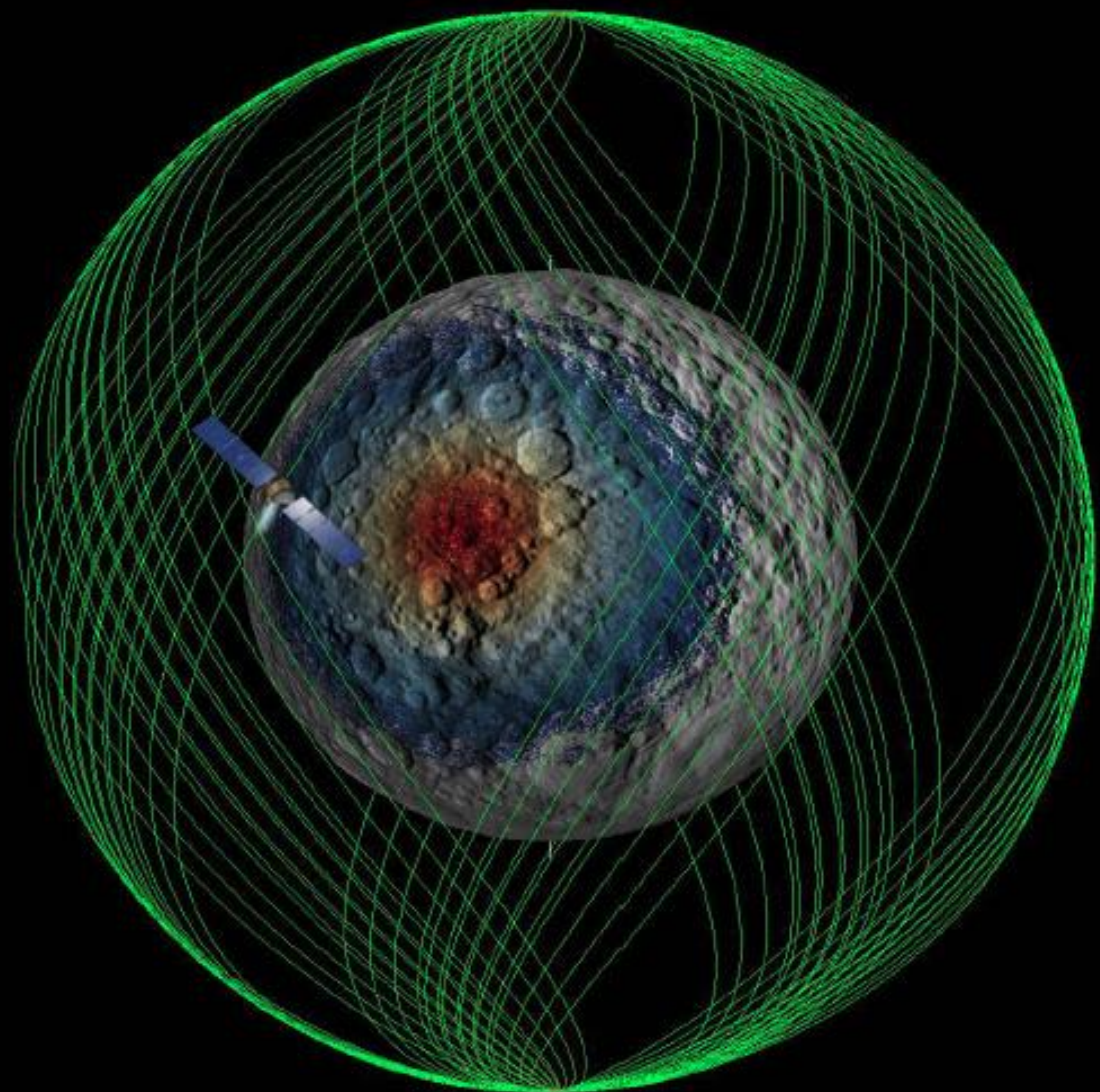




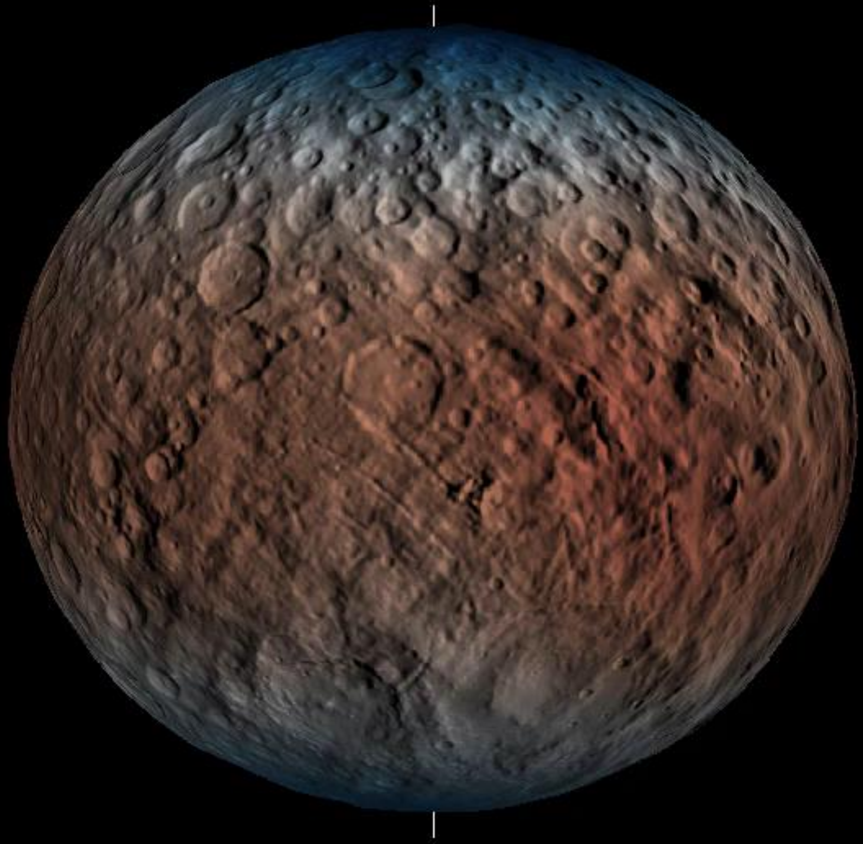
Low altitude mapping orbit (LAMO)

GRaND

- Over 9 months accumulation with full coverage in a 1.8 body radii orbit
- Resolution: Field of view (blue), FWHM (yellow)



Grand H count



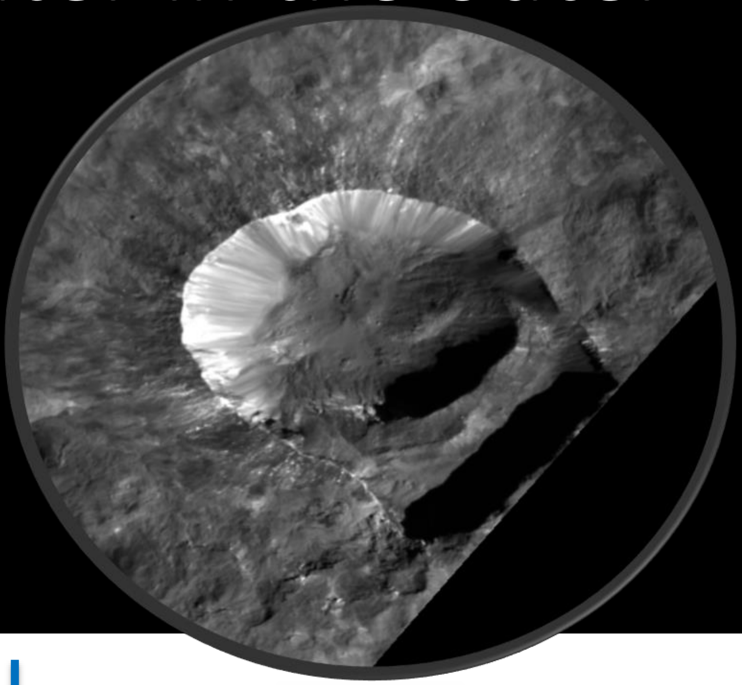
Neutron counts drop towards the poles

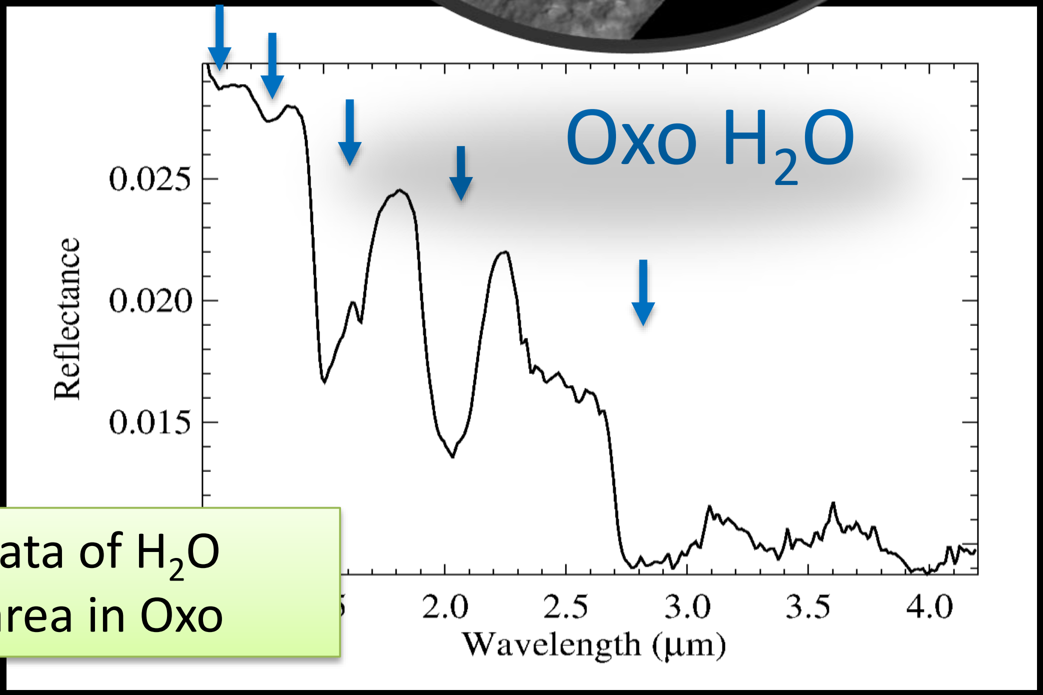
Evidence for water ice at high latitudes
(at depth <1m)

(Prettyman et al., 2016)

Direct evidence for water in the outer shell

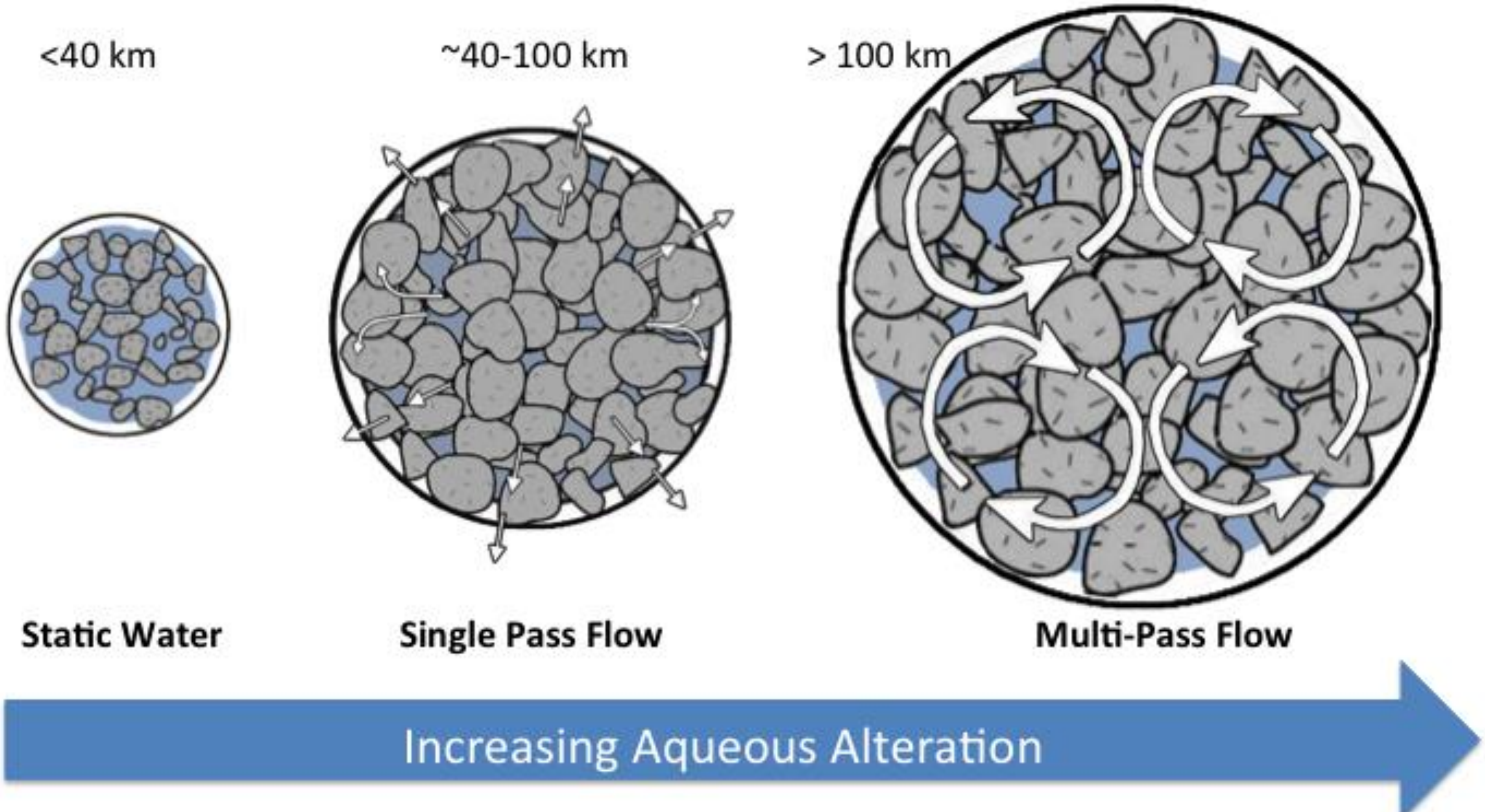
- Reflectance spectra VIR reveal the presence of **exposed surficial H_2O on Ceres**





VIR data of H_2O rich area in Oxo

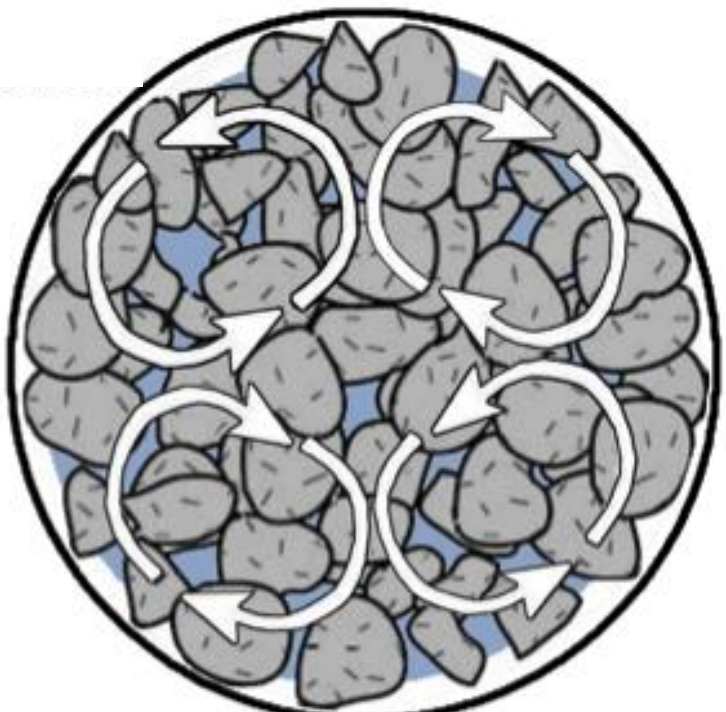
Chemical Fractionation Points to Advanced Hydrothermal Activity



Cb? Ch? Ceres

After Young et al. (2003)

Mineralogy points to global episode of hydrothermal activity in Ceres' early history



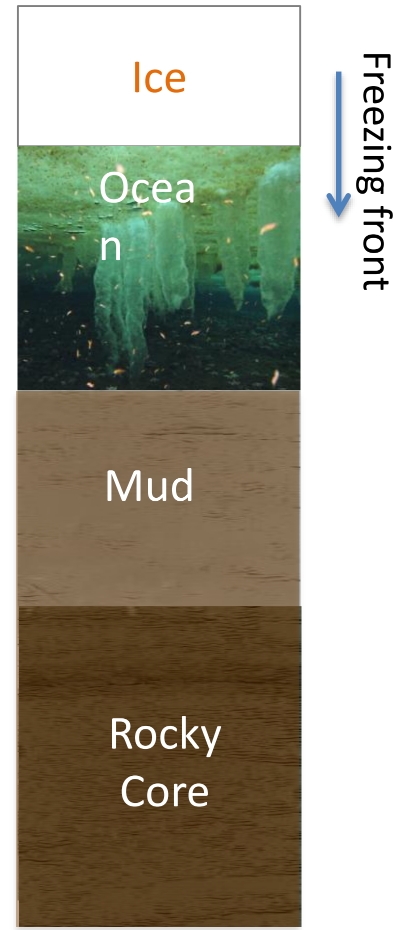
After Young et al. (2003)

- Large scale hydrothermal circulation supported by GRaND data (Prettyman et al. 2016)
- Activity fueled by ^{26}Al decay heat ?
  - Formation within a few My after CAIs
- Water-to-rock ratio is > 2 (Castillo-Rogez et al., in prep)
  - Release of huge amounts of H_2
  - Leaching of soluble elements from rock, yields ~5 wt.% salinity (average)

Castillo Rogez, 2017

Ice Shell Formation is the Expected Outcome of Differentiation in Large Ice-Rich Bodies

- Large rock particles sink, fines stay in the ocean (Kirk and Stevenson 1987)
  - Flocculation also promotes clay sedimentation
- Slow freezing over ocean leads to mostly pure ice shell, except for soluble salts at grain boundaries
  - Rock particles cannot be accommodated at ice grain boundaries
- **There is no evidence for silicates on Enceladus, Dione, Europa, etc.**



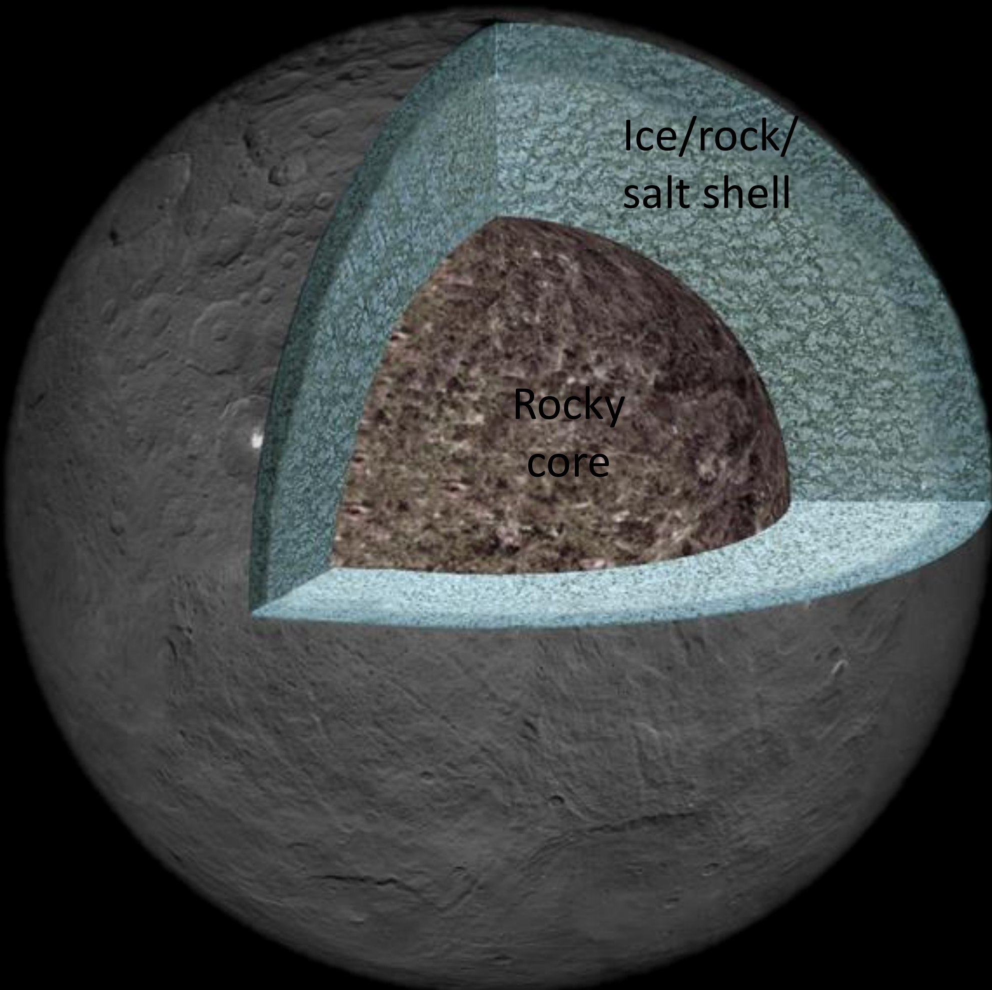
Salt Rejection by Sea Ice during Growth[1]

R. A. Lake and E. L. Lewis

Department of Energy, Mines and Resources, Atlantic Oceanographic Laboratory
Bedford Institute, Dartmouth, Nova Scotia

Castillo Rogez, 2017

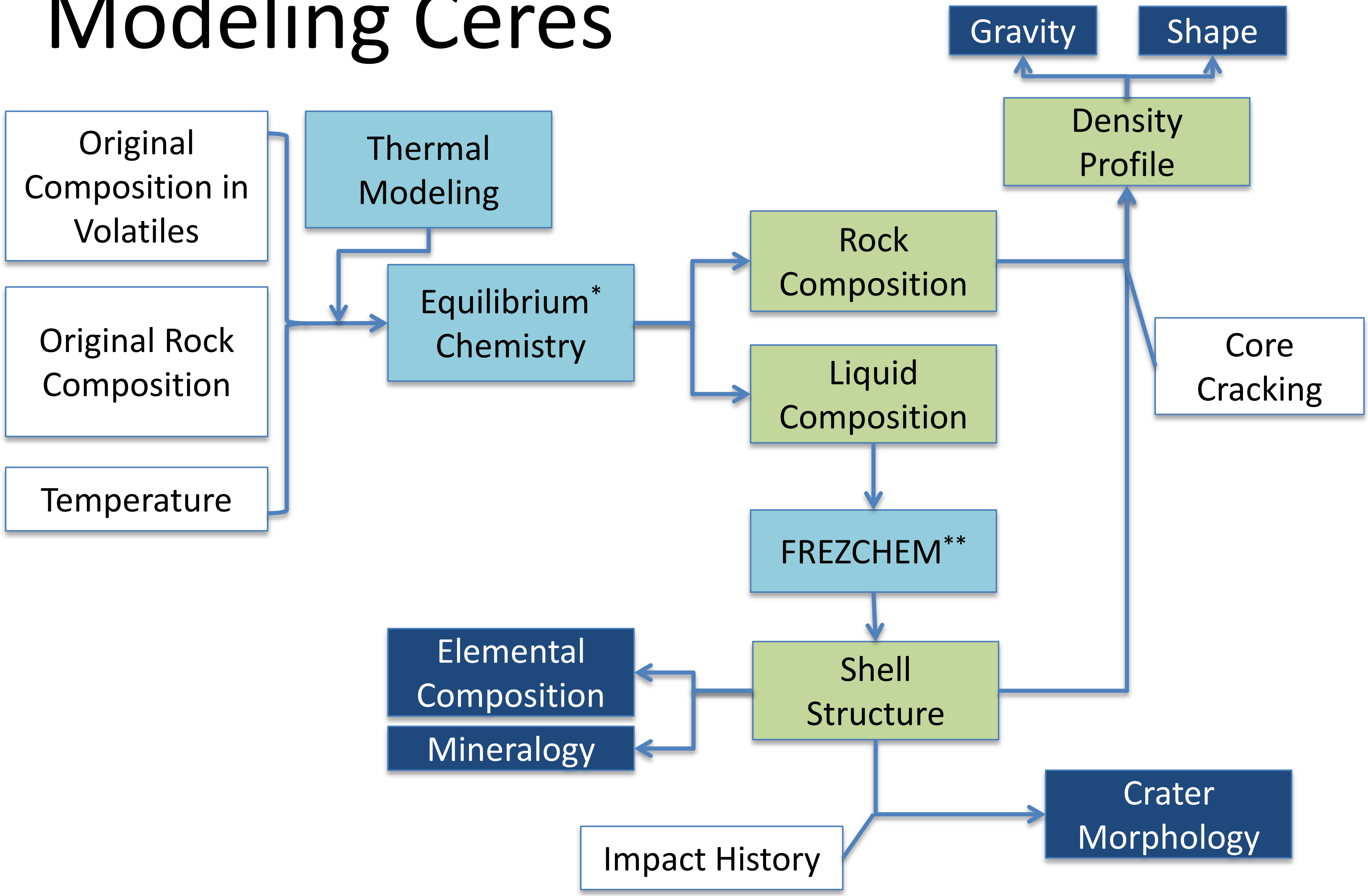
But Geophysical Data suggest Ice is not a Dominant Component of the Shell



- Crater morphology indicates ice content <40% (Bland et al. 2016)
- Gravity suggests partially differentiated interior (Park et al. 2016)
  - Shell density ranges from 1.1 to 2.0 g/cm^3
- Topography can be explained by strong shell (40-50 km) over soft interior (Fu et al. 2016)
  - Shell density narrowed down to 1.35 - 1.65 g/cm^3
- Ceres could have lost its ice shell (impacts? accelerated sublimation?)

Castillo Rogez, 2017

Modeling Ceres



* *Geochemist's Workbench* by Bethke – also works for non-equilibrium chemistry
** Marion and Mironenko (2015), freely available

Castillo Rogez, 2017

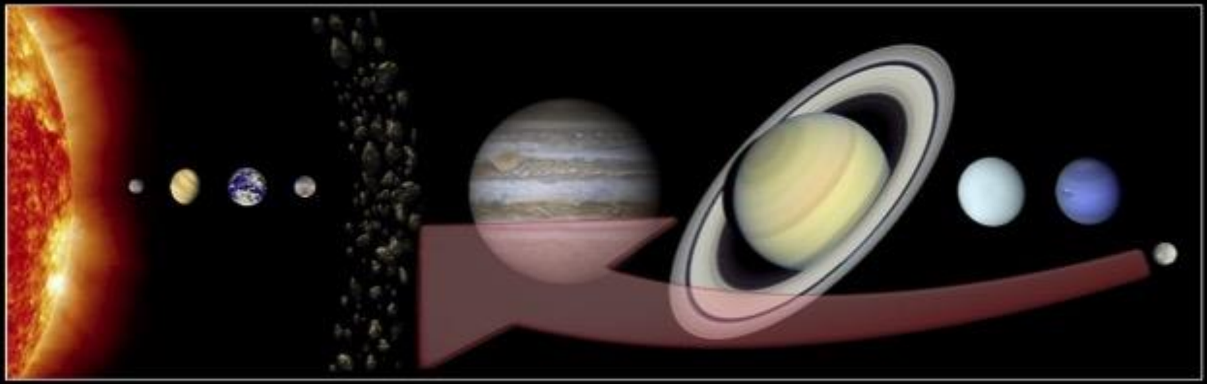
Models results

- Ceres' Surface Composition Requires an original Water/Rock > 2
- Magnetite is the dominant form of the final **iron**
  - Most abundant mineral with the clays
  - Iron also captured in the form of sulfide, about three times less (molality) than magnetite
- Sulfates are not expected
- Chloride salts are expected
- Potassium is leached from the silicates way before equilibrium is reached

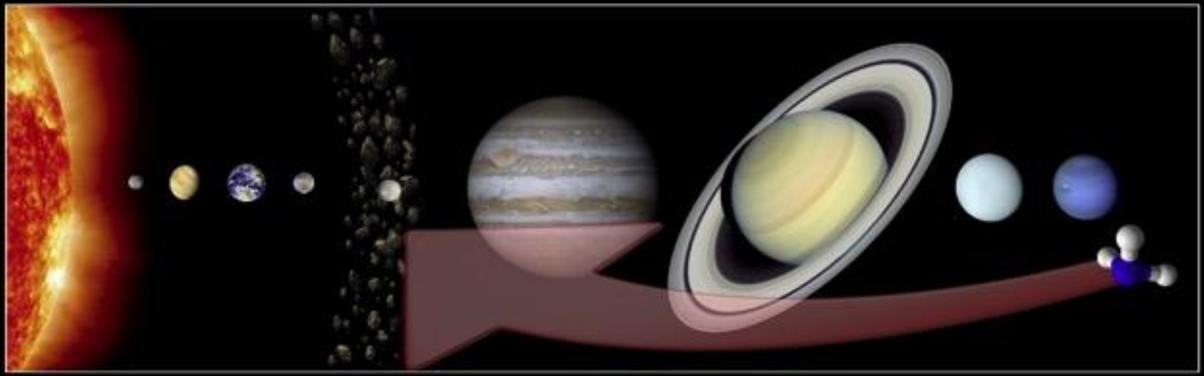
Science questions at Ceres

- Where did Ceres form?
- Is it physically/chemically differentiated?
- Where’s the water and what role did it play?
- Can there be Meteorites from Ceres ?
- Is Ceres of astro-biological interest ?

Where did Ceres Form?



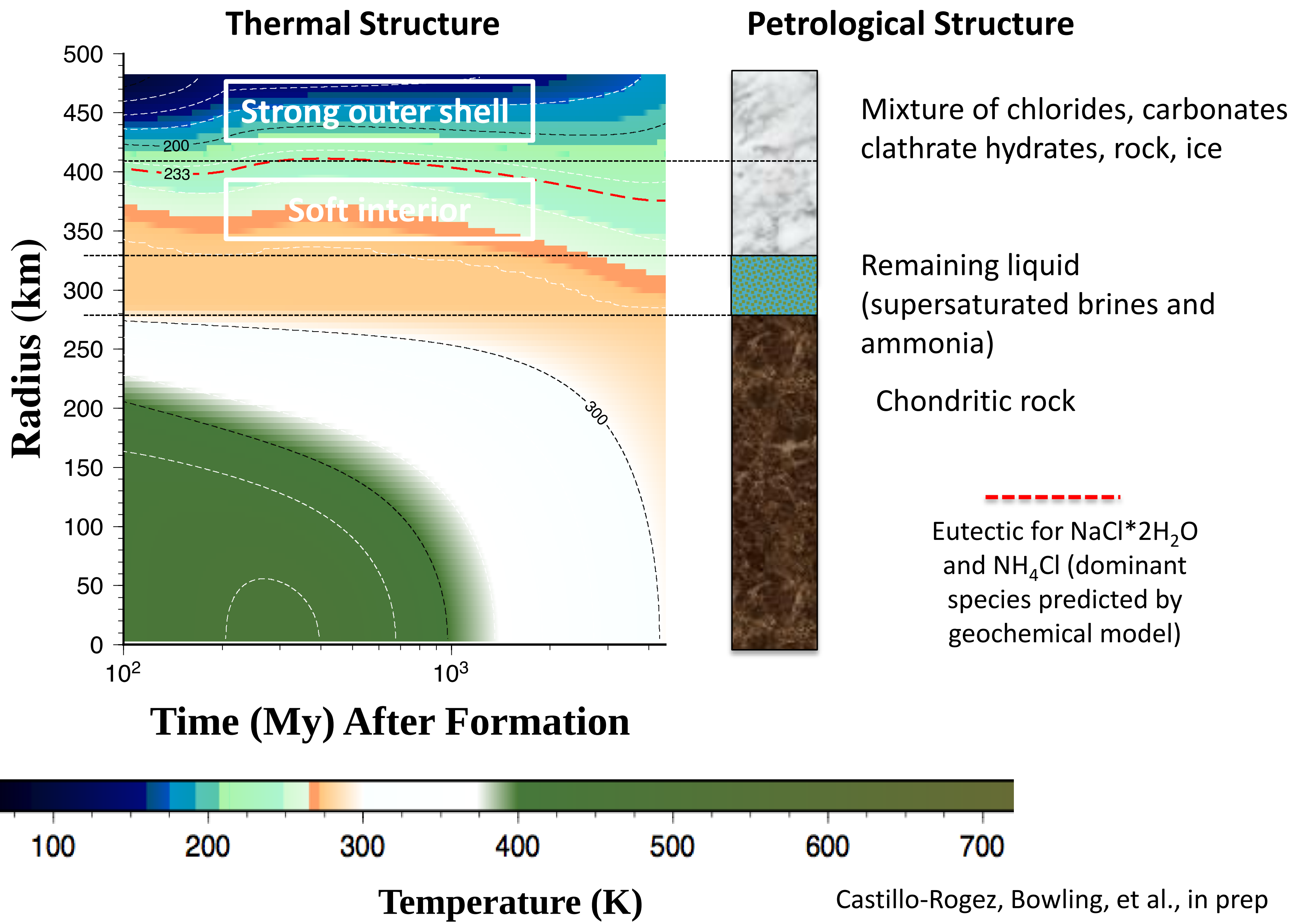
Ceres may have formed in the trans-Neptunian disk, before it was implanted into the main belt (e.g., McKinnon, 2012)



Or Ceres formed closer to its present position by accreting material that drifted inward from greater heliocentric distances (e.g. Mousis and Alibert, 2005, Johansen+2015)

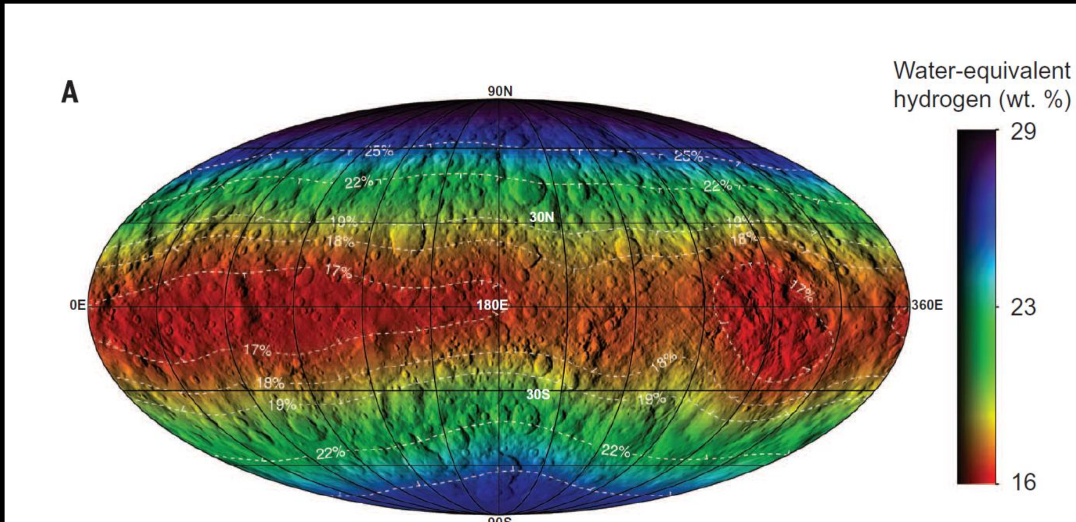
De Sanctis et al., Nature,2015, 10.1038/nature16172

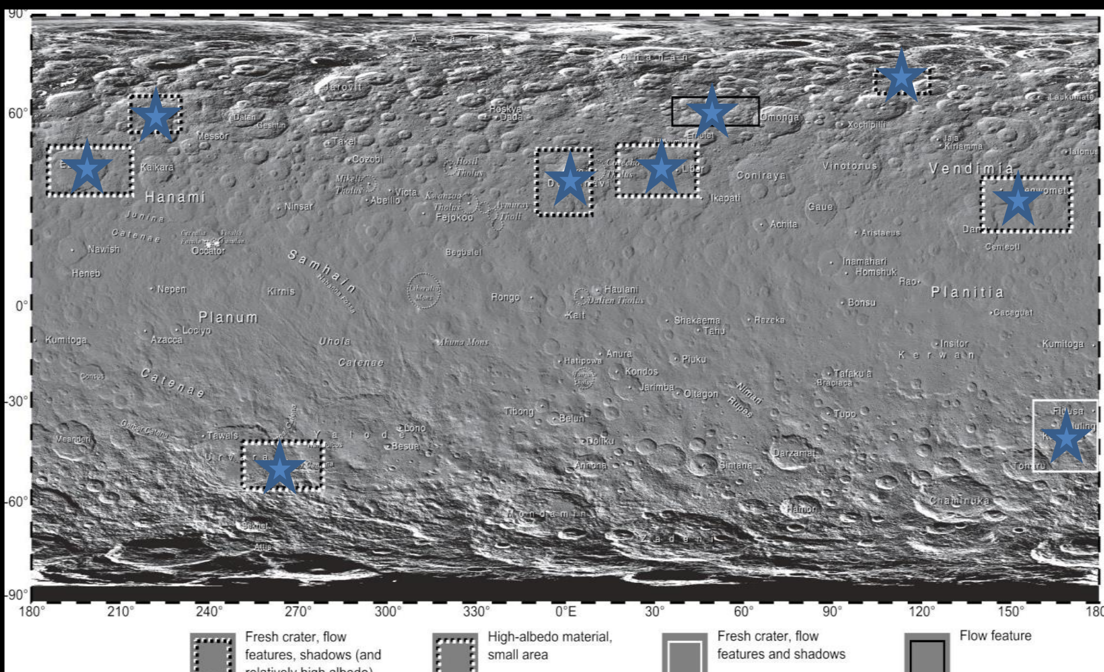
Ceres is chemical differentiated
A Shell of Ice/Clathrates/Salts/Clays Remains Warm Until Present



Castillo-Rogez, Bowling, et al., in prep

Water





- **Grand: distribution of water equivalent hydrogen**

- **Exposed H_2O ice detected on Ceres by VIR**

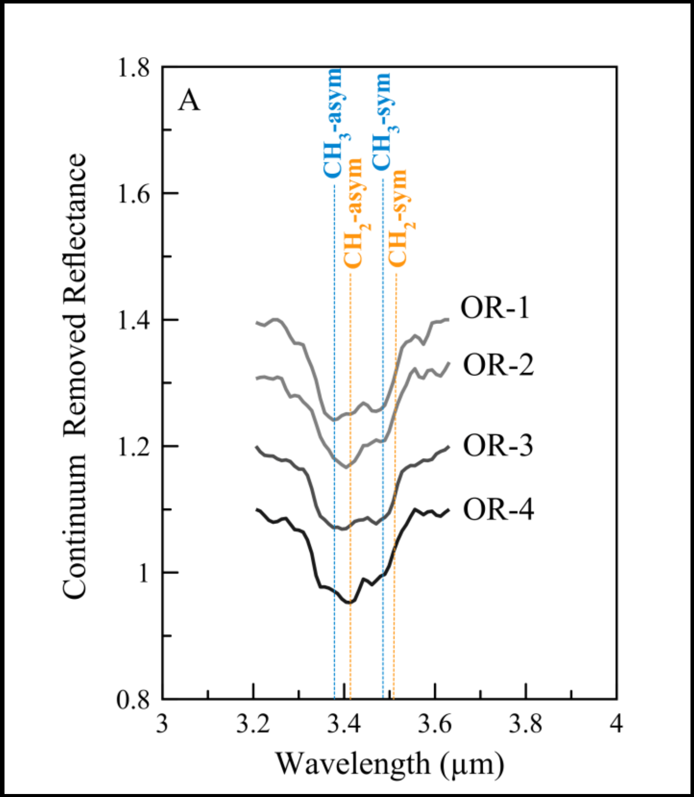
Can There be Meteorites from Ceres?

- The formation of a Ceres family of some kind seems nearly statistically inevitable, the lacking of family poses question on the nature of such family.
- Has been calculated that sublimation of an icy Ceres family would occur on timescales of hundreds of millions of years, much shorter than the history of the Solar System (Rivkin et al., 2014).
- Deep material sources by large impacts is salt- and likely volatile-rich
- Points to a depletion in silicate at depth, rather fragile material instead
- Meteorites from Ceres might not survive trip to Earth

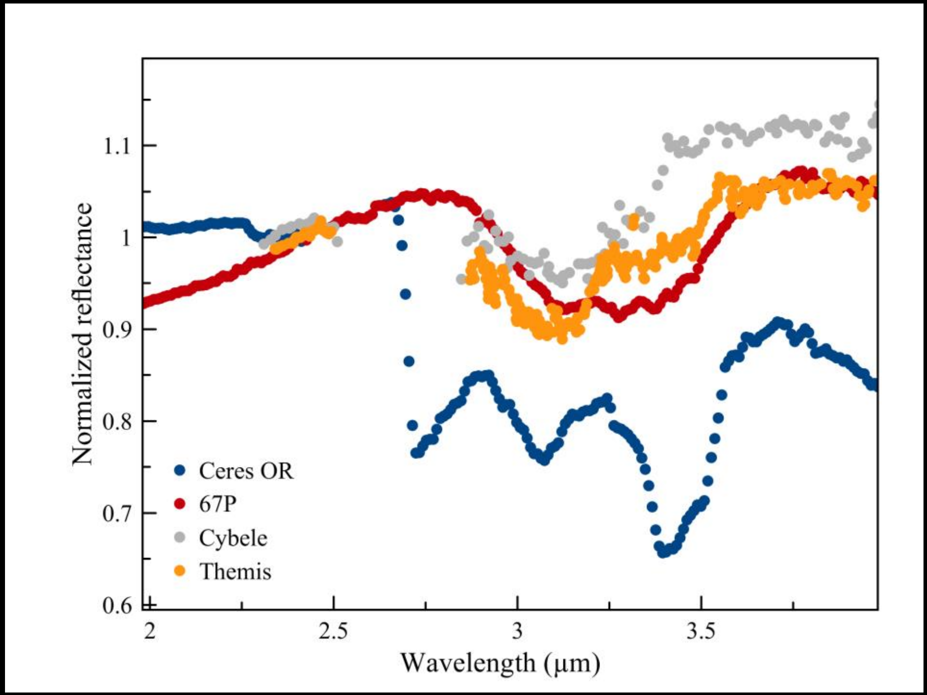
Astrobiological Ceres - Significance

- Potential analog for Europa, at least in terms of chemistry
- Playground for exobiological studies
- More definitive evidence is required to confirm Ceres as an ocean world
  - What is the extent of the ocean?
  - Does this ocean communicates with the surface?
- Assuming clues for a deep ocean are confirmed
  - Is the ocean a habitable environment (T, pH, redox)
  - Are the building blocks of life present (CHNOPS) - Yes
  - Is there an energy source available for life? - Yes
- Are biomaterials present?

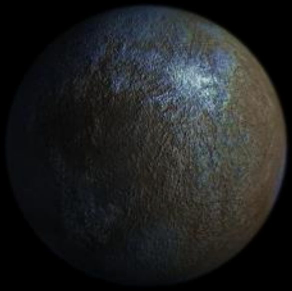
Organics on Ceres



- Clear signatures of aliphatic organics detected in a large region of Ceres (De Sanctis et al., Science, 2017)
- Compared with other solar system bodies, Ceres signature is extremely well defined

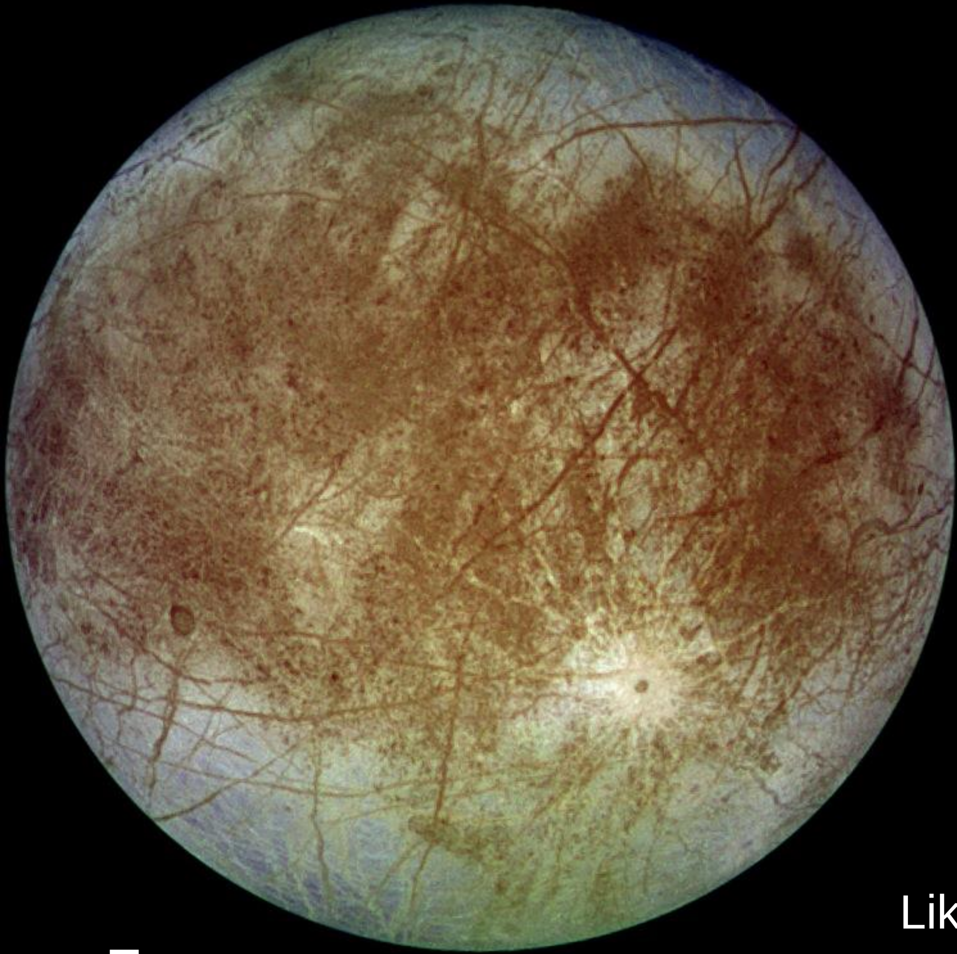


Ceres' Past and Current Habitability?



Ceres
Surface average temp: 130-160K
Energy source: radioisotopes

Enceladus
Surface temp: 94K
Energy source: tidal

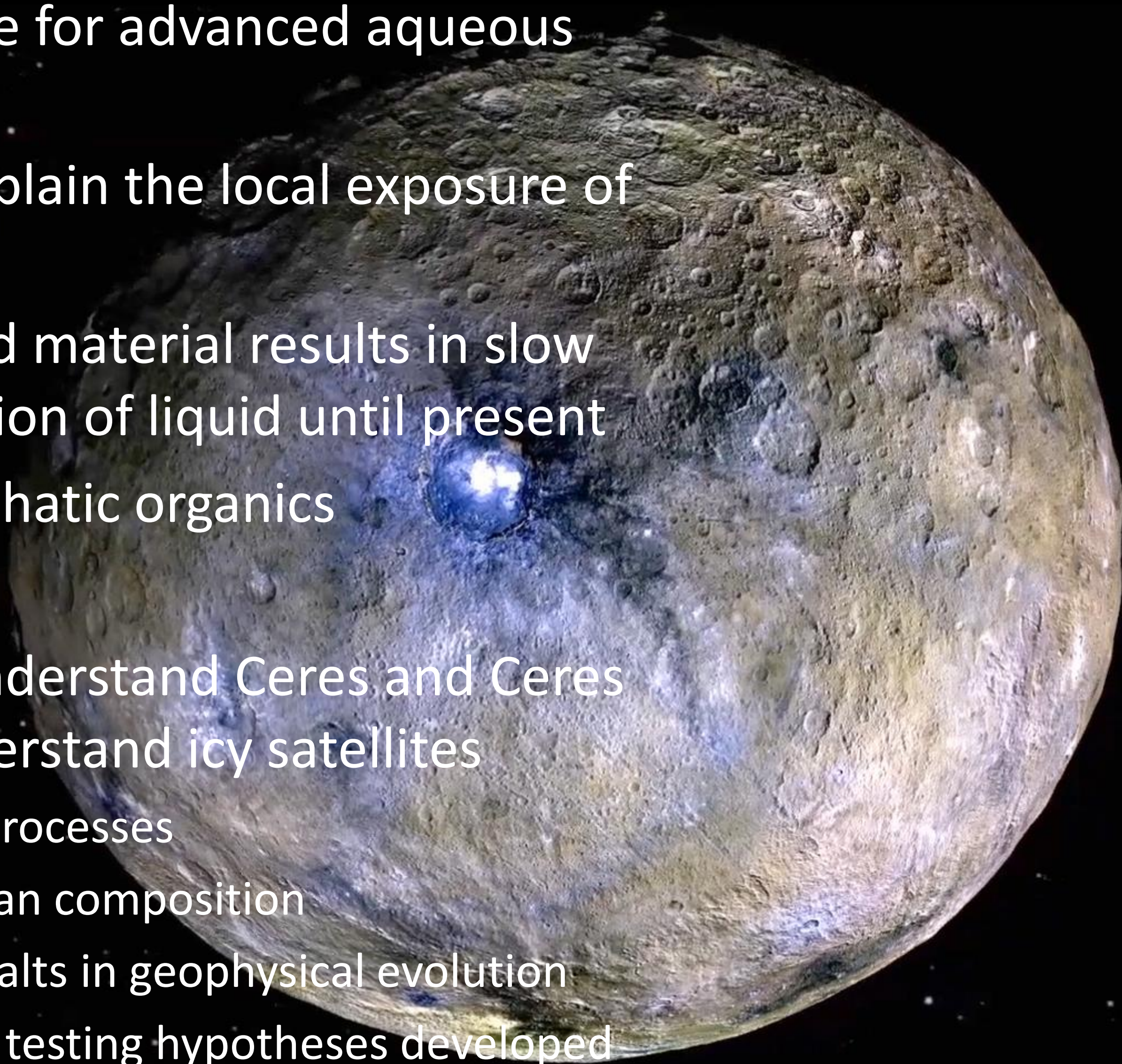


Europa
Surface temp: 102K
Energy source: tidal

Like Europa and Enceladus, during most of Ceres' evolution it had:

- Liquid water
- Essential chemical ingredients
- An energy source

Summary



- Ceres displays evidence for advanced aqueous alteraton
- Loss of ice shell can explain the local exposure of oceanic material
- Abundance of hydrated material results in slow freezing and preservation of liquid until present
- Clear signatures of aliphatic organics

- Icy satellites help to understand Ceres and Ceres will help to better understand icy satellites
  - Revisit differentiation processes
  - Constrain core and ocean composition
  - Emphasize the role of salts in geophysical evolution
  - Offers a playground for testing hypotheses developed for ocean worlds