Insights into Vesta and Ceres internal structures from their topography

AGU 2017 meeting
New Orleans, Louisiana,
12 December 2017.

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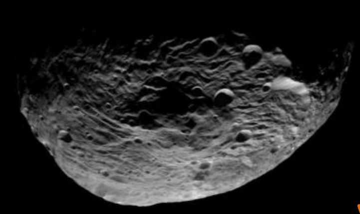
Goal of the talk:

- **Explain how the internal structures of Vesta and Ceres diverged by looking at the present-day topography (and gravity) measured by Dawn**

How we use shape data to study interiors?

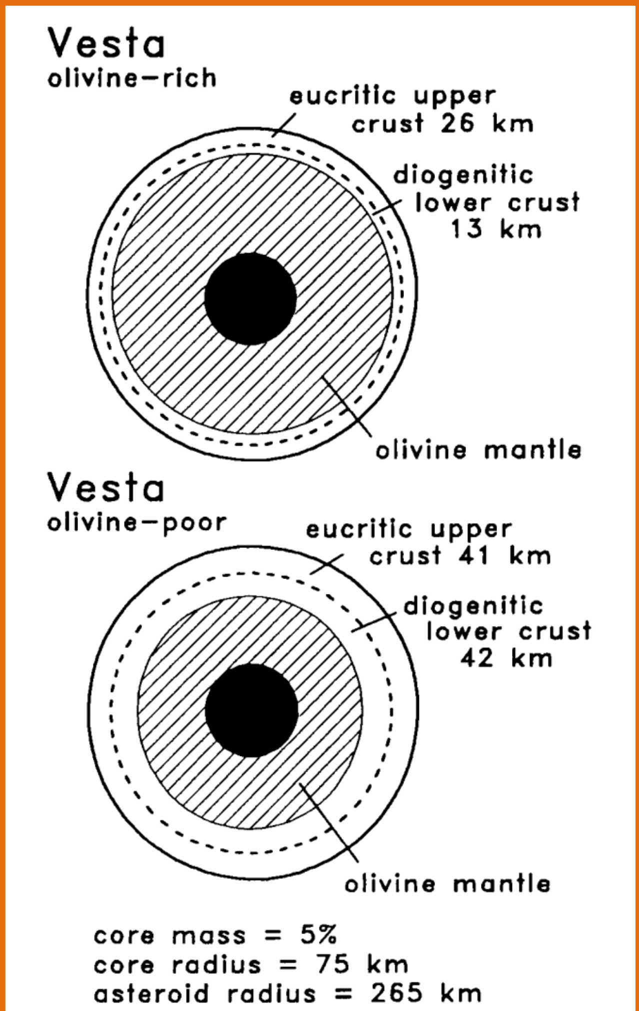
- Hydrostatic equilibrium
- Isostatic compensation
- Viscous relaxation

Ermakov et al., Vesta and Ceres topography, AGU 2017.



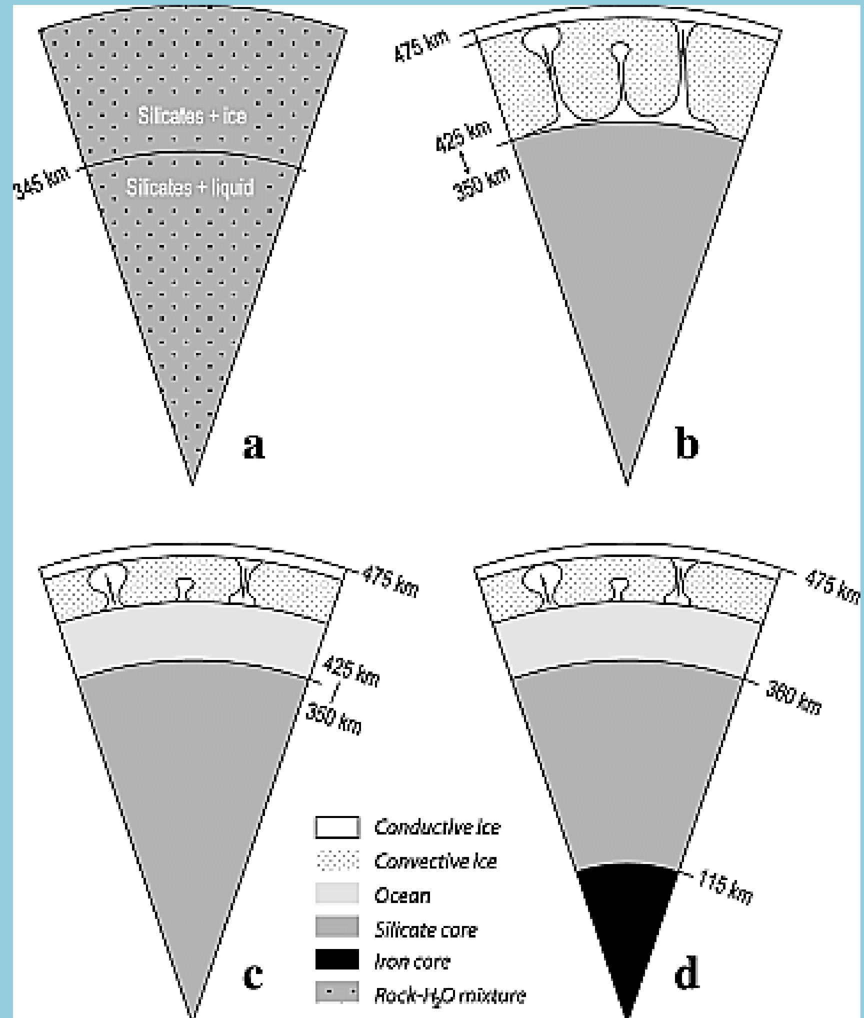
What did we know before Dawn?

Vesta



Ruzicka et al., 1997

Ceres



McCord and Sotin, 2005

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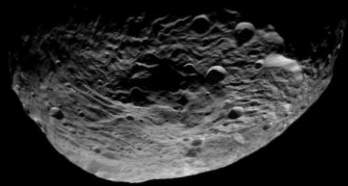

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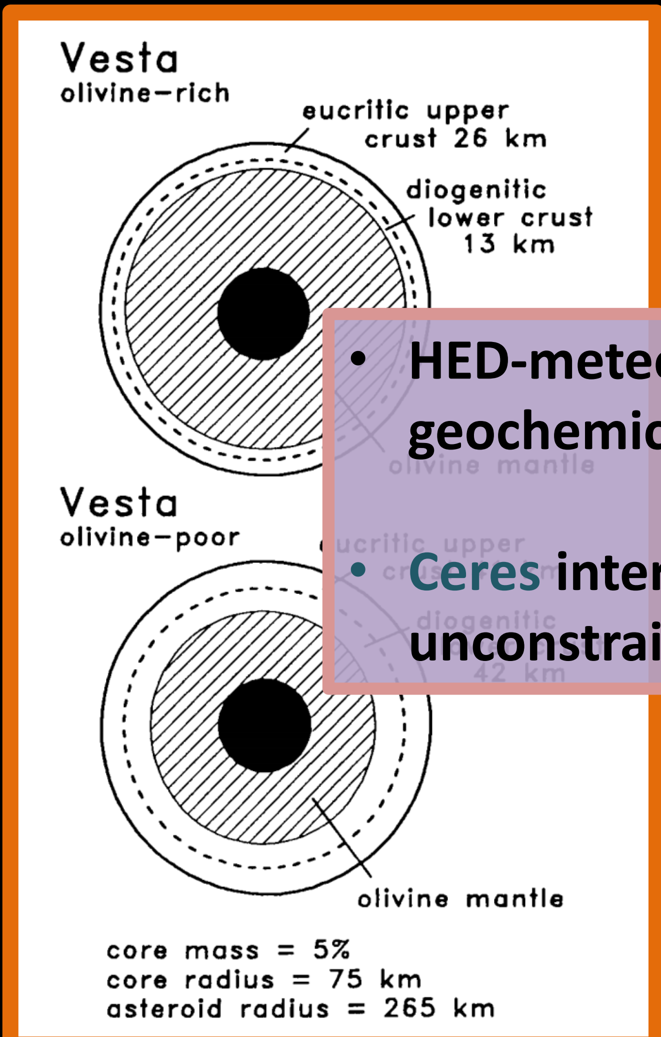

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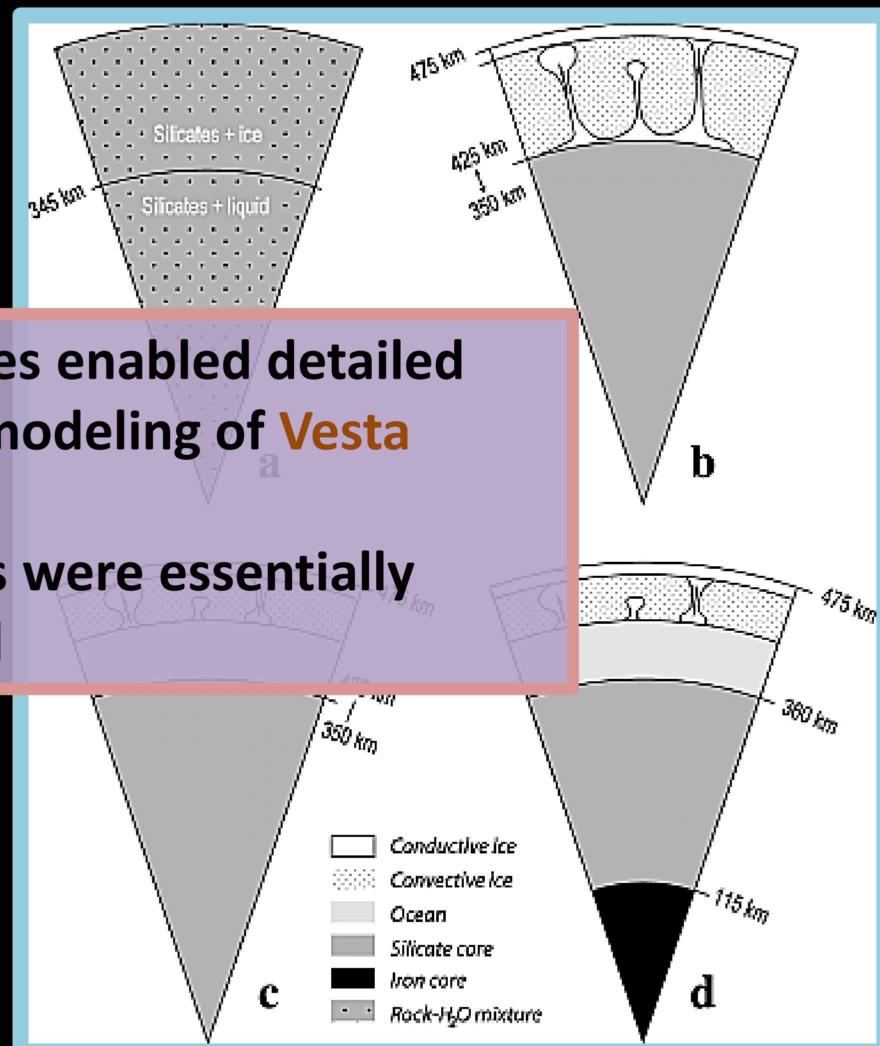
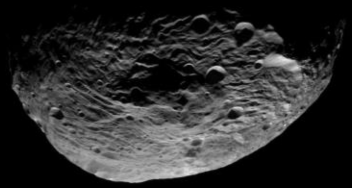


McCord and Sotin, 2005

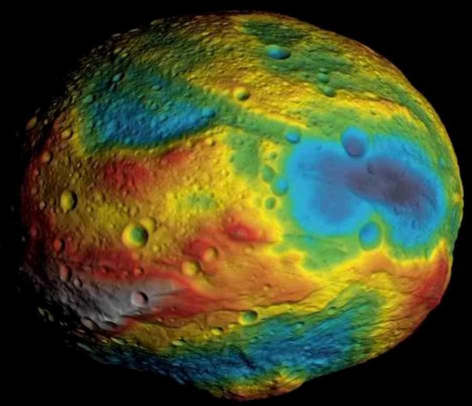
- HED-meteorites enabled detailed geochemical modeling of Vesta
- Ceres interiors were essentially unconstrained

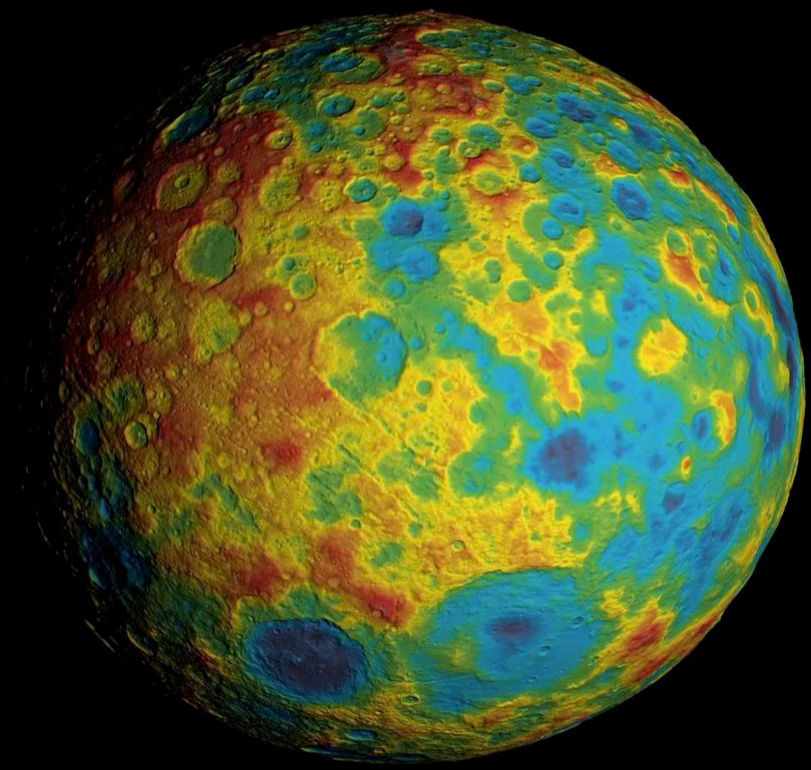


Input for our modeling

- **Shape model**
  - **Stereophotogrammetry (SPG)**
  - **Stereophotoclinometry (SPC)**
  - **Mutually consistent with the accuracy much better than the spatial resolution of gravity field**
- **Gravity field**
  - **Accurate up to *n* = 18 (λ=93 km) for Vesta (Konopliv et al., 2014)**
  - **Accurate up to *n* = 17 (λ=174 km) for Ceres (Konopliv et al., 2017)**
- **Assumptions we have to make:**
  - **Multilayer model with uniform density layers**
  - **Range of core densities for Vesta**
  - **Range of crustal densities from HEDs for Vesta**
  - **Can't really assume anything for Ceres**

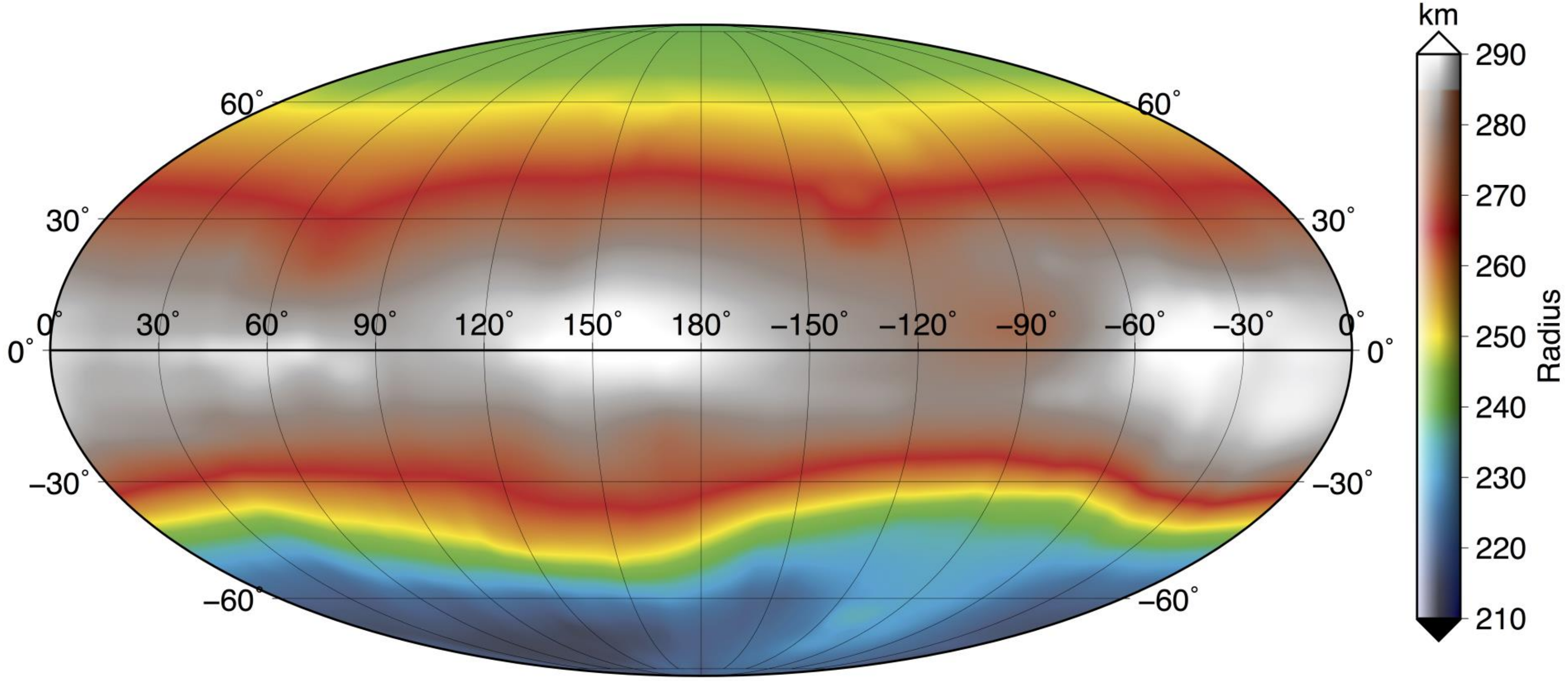
Vesta and Ceres





Ermakov et al., Vesta and Ceres topography, AGU 2017.

Vesta (Thomas et al, 1997)



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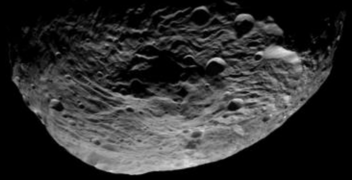
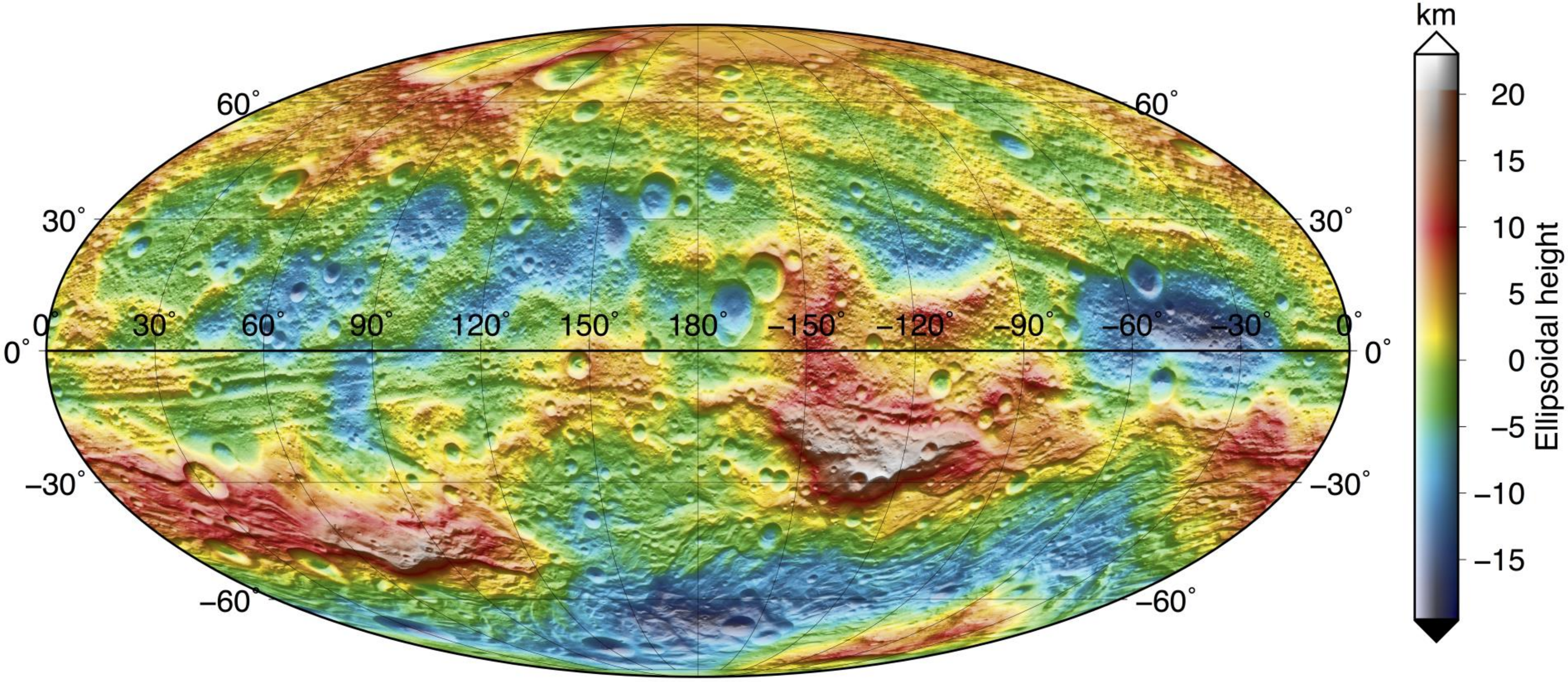


Vesta SPC



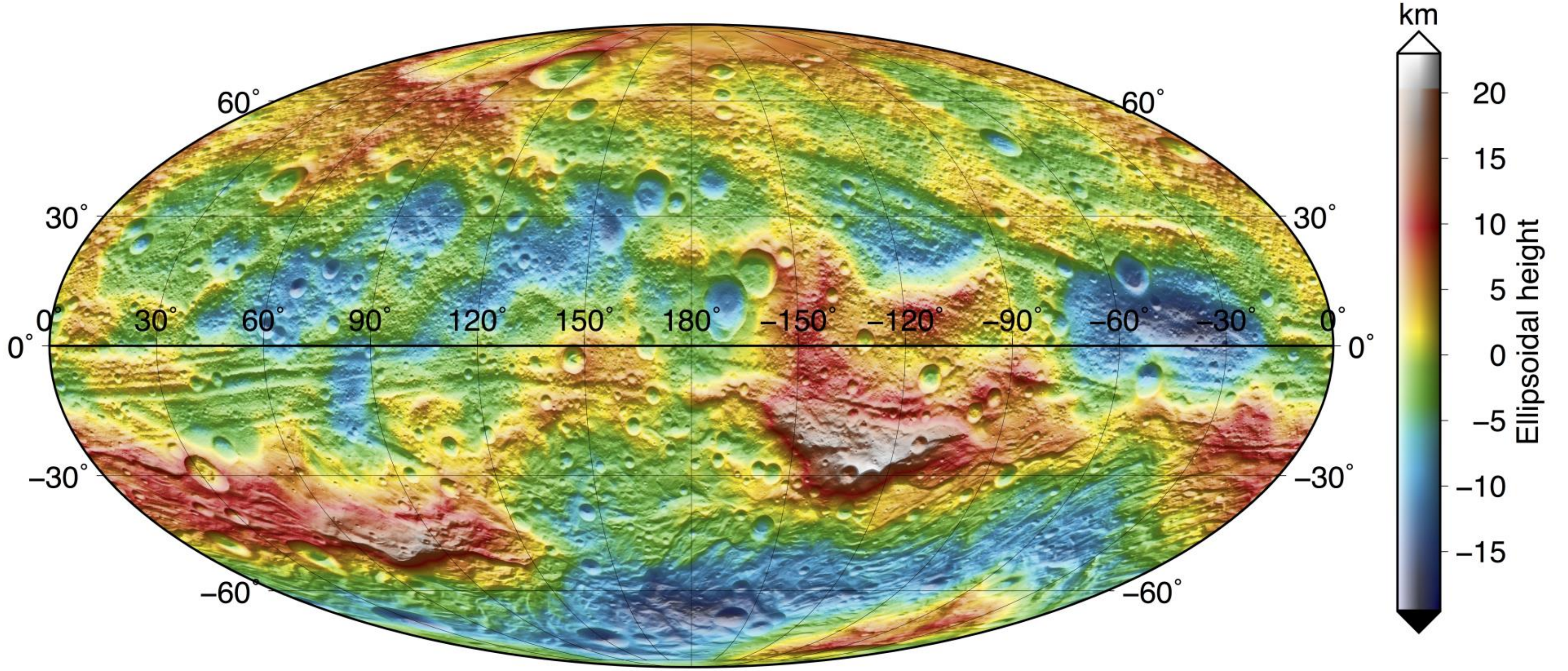
Reference ellipsoid:

a = 280.9 km

c = 226.2 km

Ermakov et al., Vesta and Ceres topography, AGU 2017.

Vesta SPG



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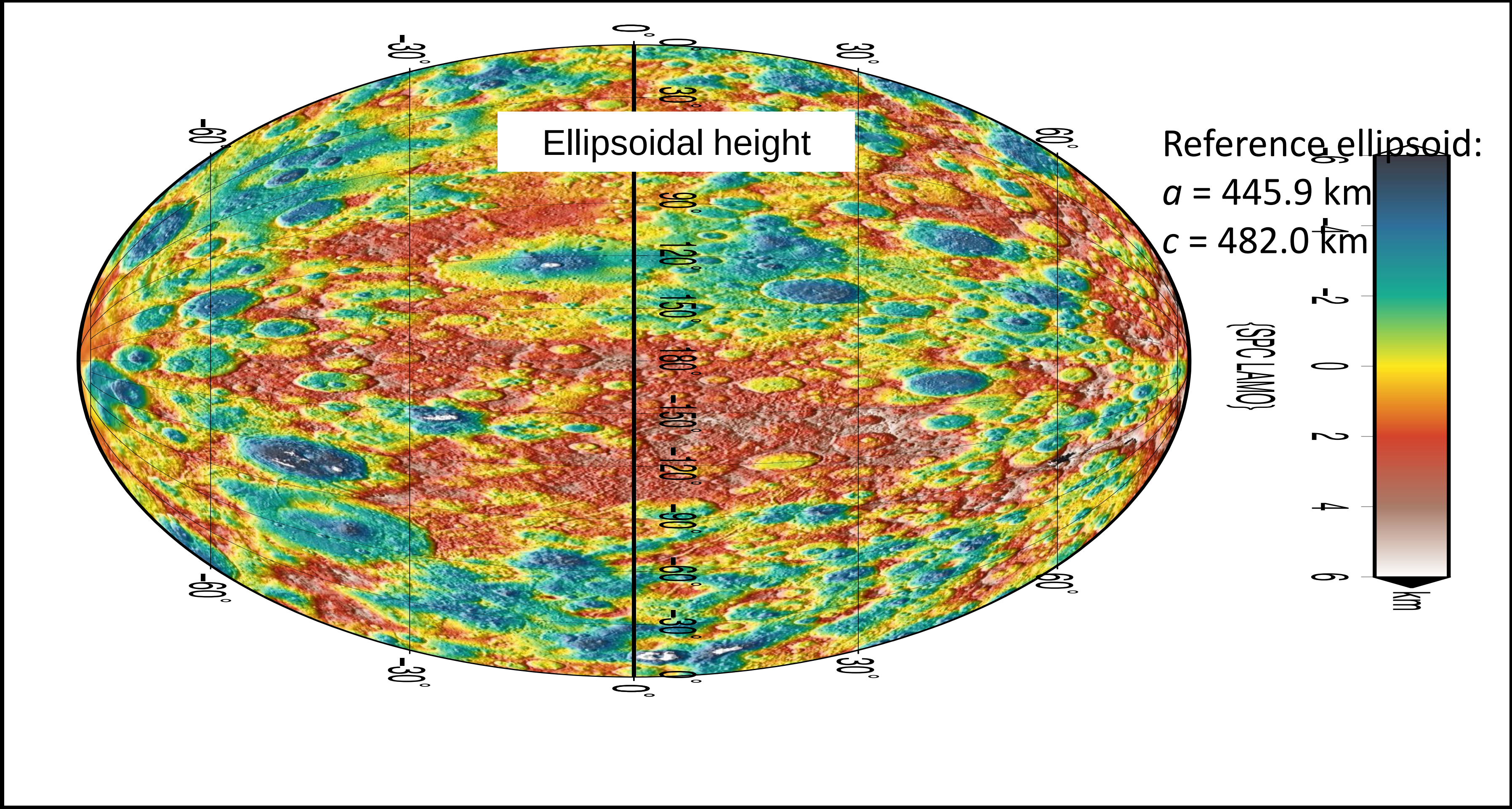
Ceres SPC



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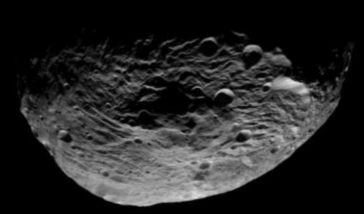
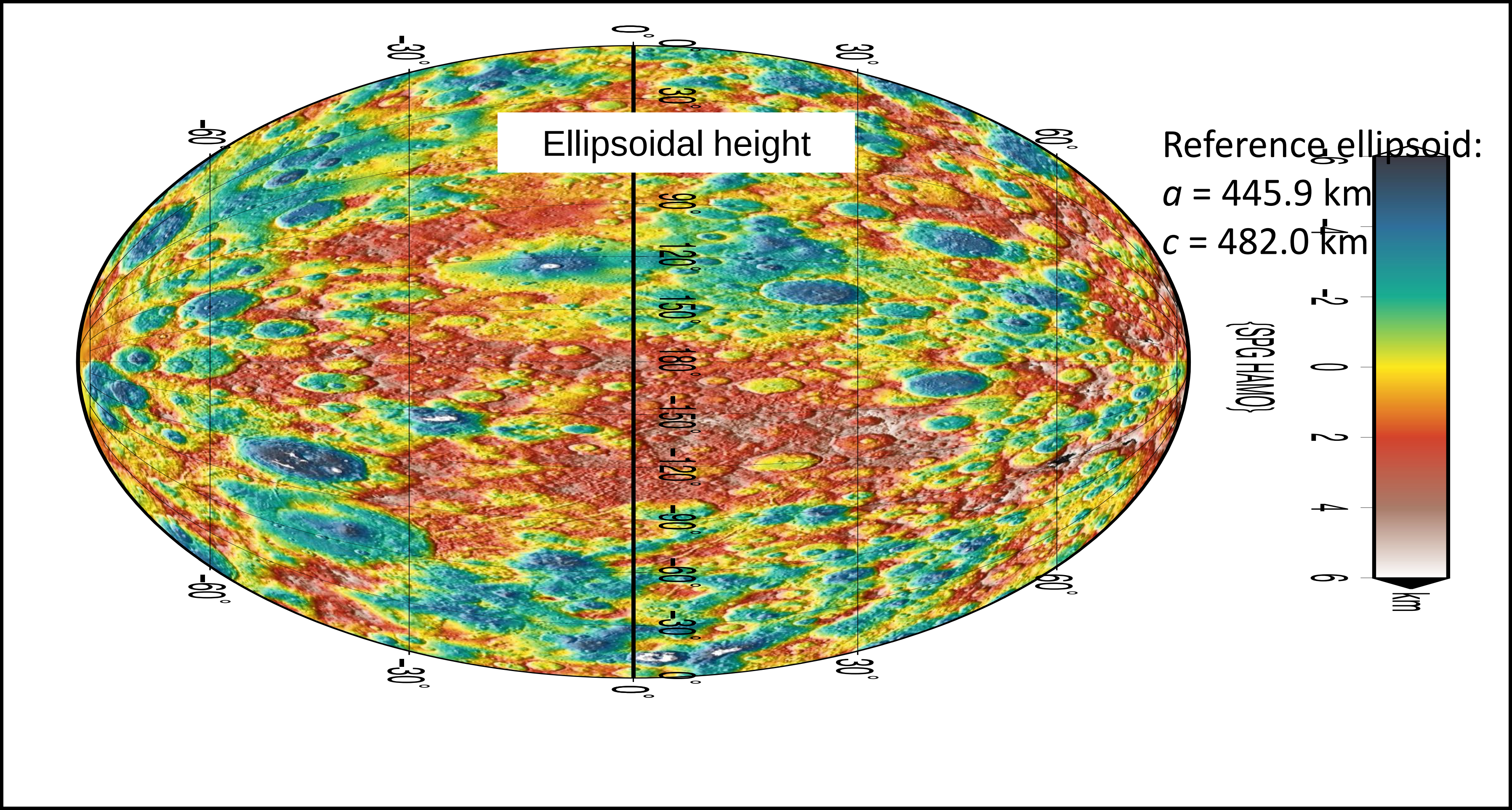


Ceres SPG



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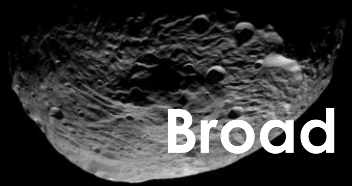
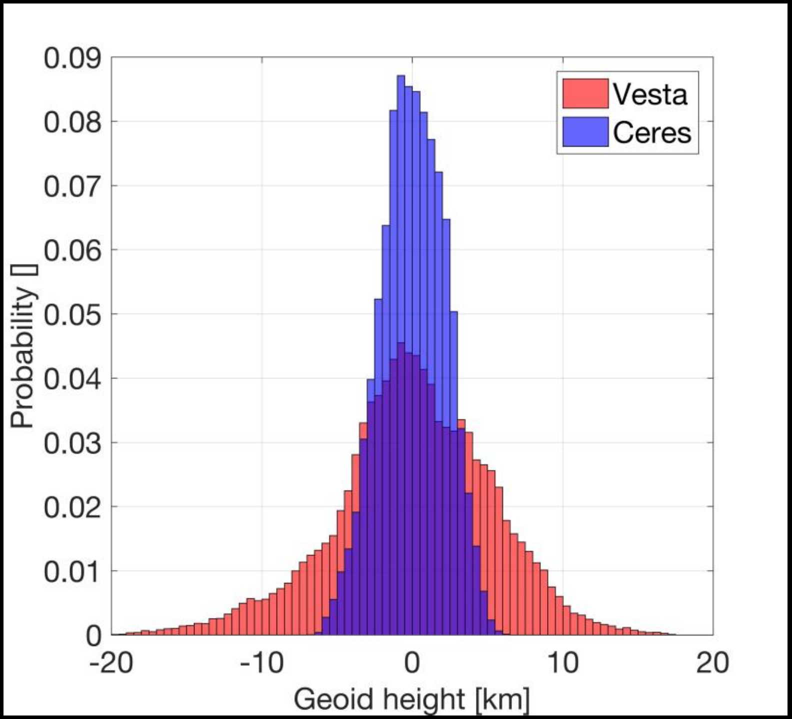


Broad characteristics of Vesta and Ceres topography

Parameter	Vesta	Ceres
Radius range (km)	80.1	44.5
Polar flattening	0.2038	0.0770
Equatorial flattening	0.0262	0.0043
Geoid height range (km)	37.9	13.2
Geoid height range RMS (km)	5.2	2.1

Hypsograms of Vesta and Ceres



Ermakov et al., Vesta and Ceres topography, AGU 2017.

How we use shape data?

- **Hydrostatic equilibrium**
- **Isostatic compensation**
- **Viscous relaxation**

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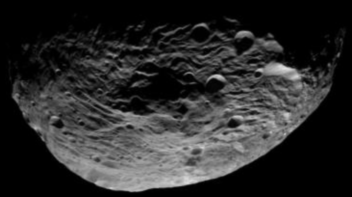
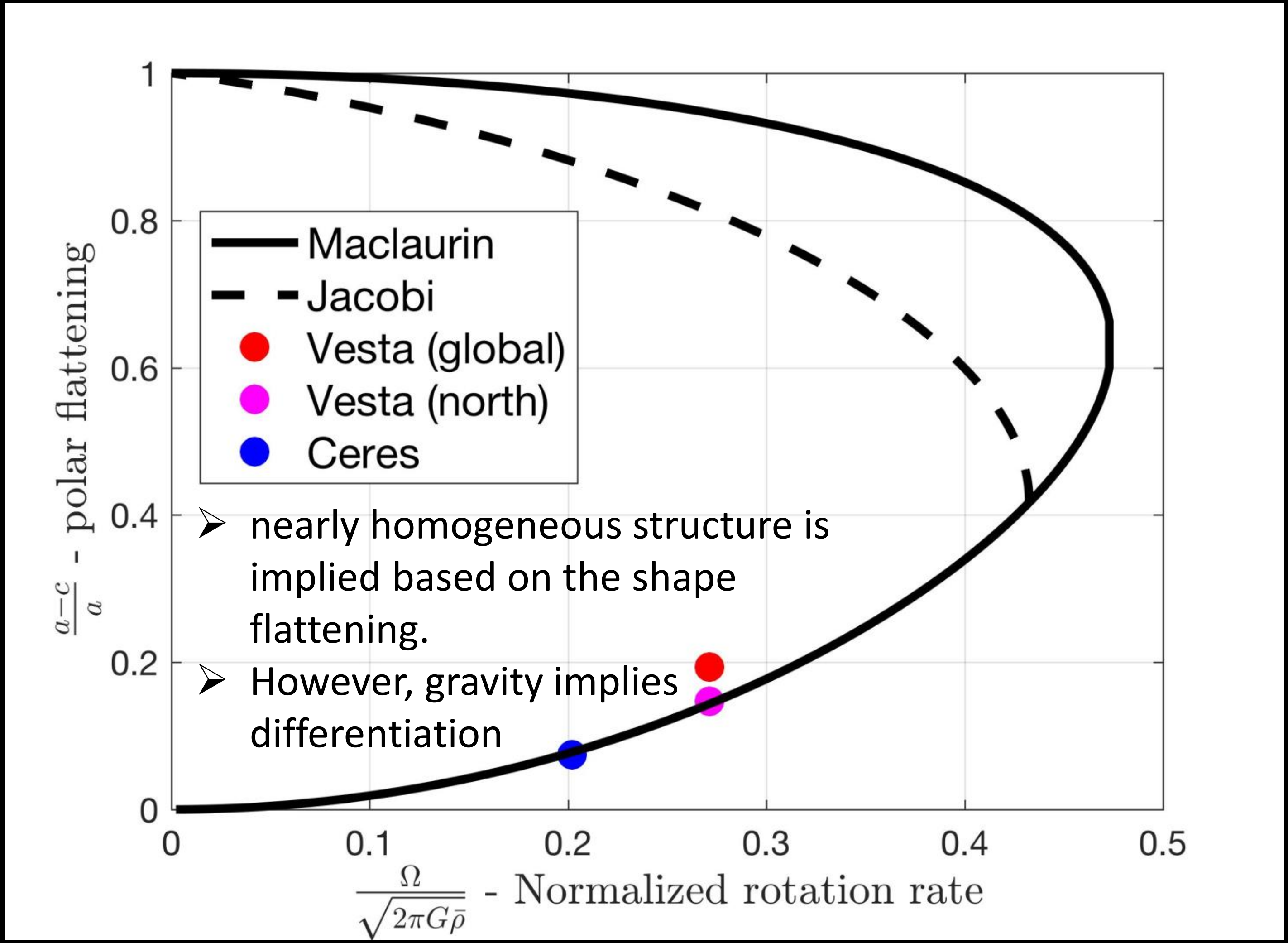
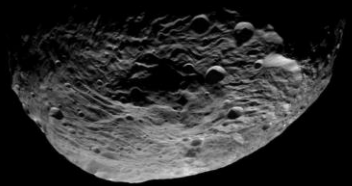


Hydrostatic equilibrium



- nearly homogeneous structure is implied based on the shape flattening.
- However, gravity implies differentiation

Ermakov et al., Vesta and Ceres topography, AGU 2017.



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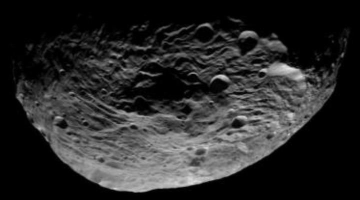
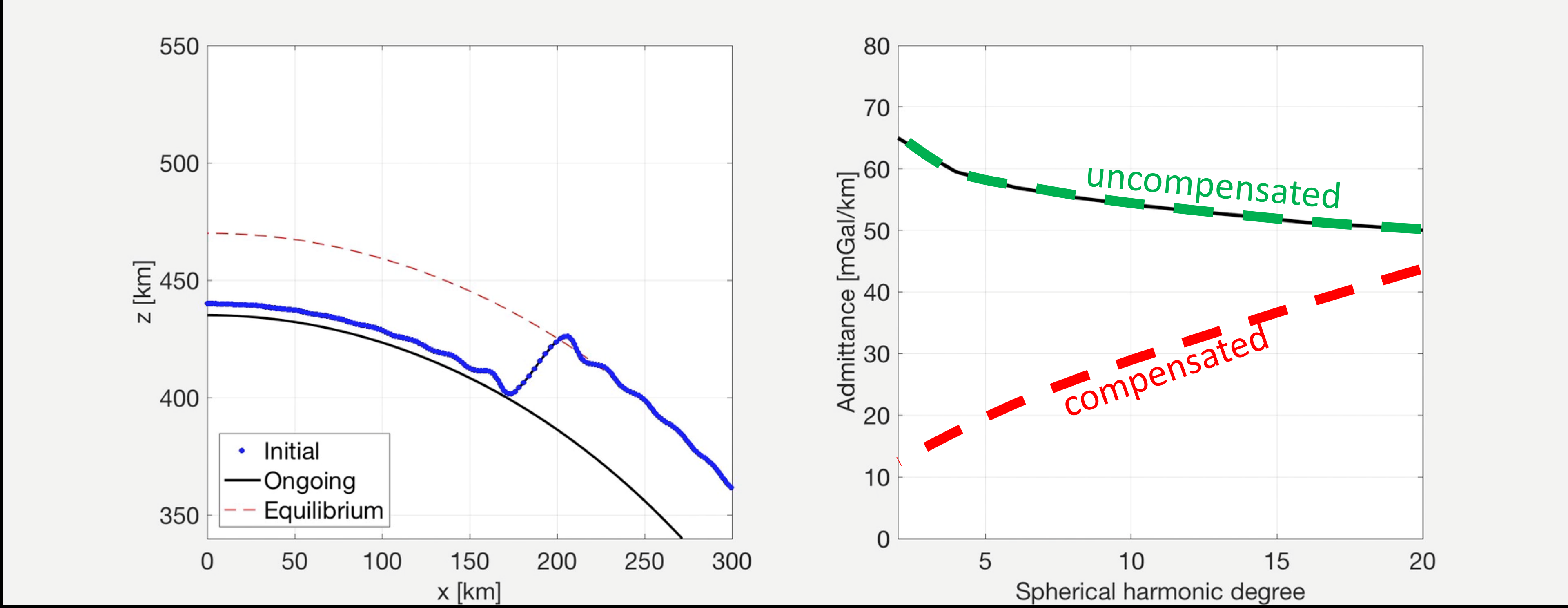


Isostatic compensation

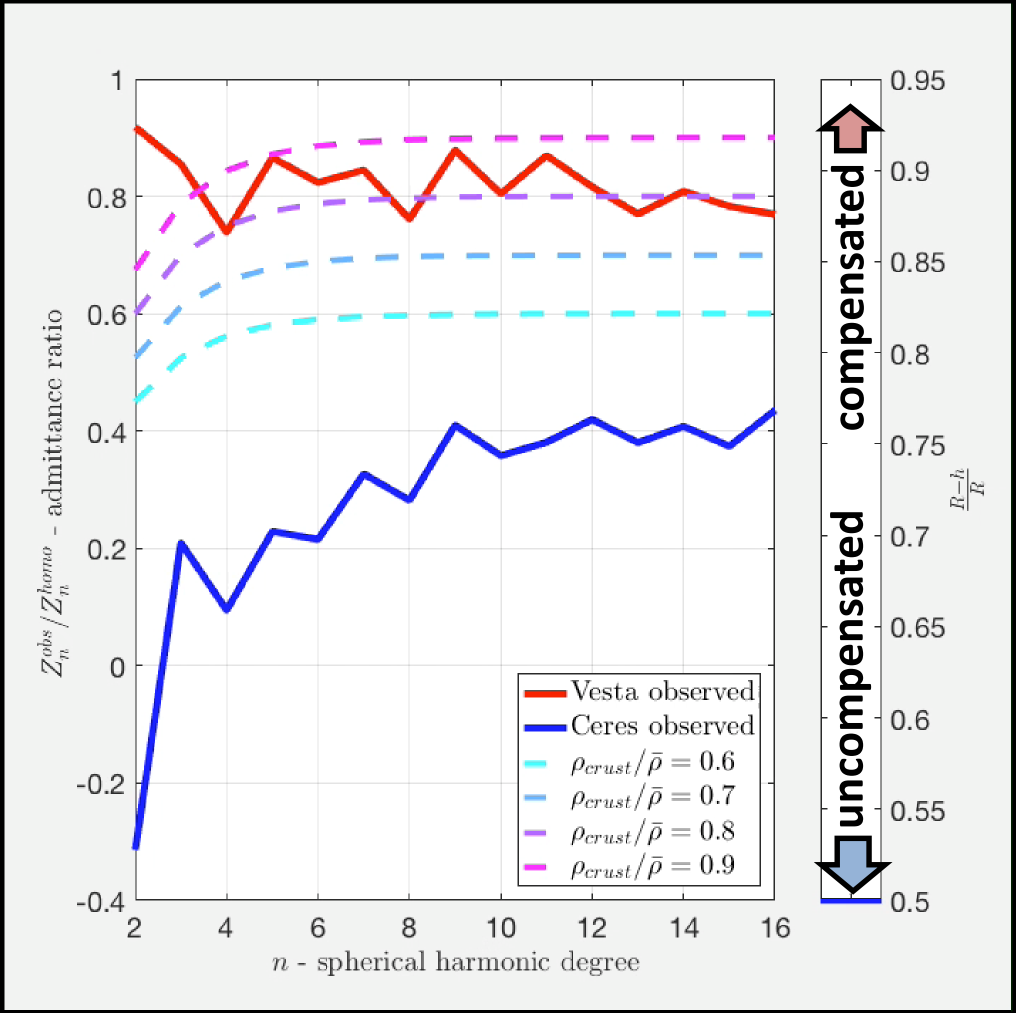
Example: viscous spherical cap relaxation



Ermakov et al., Vesta and Ceres topography, AGU 2017.

Isostatic compensation

- **Admittance (*Z*) is a ratio of gravity to topography.**
- **Compensated and uncompensated topography have difference admittances.**
- **Modeling of isostasy allows constraining the density and thickness of the compensated layer as well as the density contrast.**



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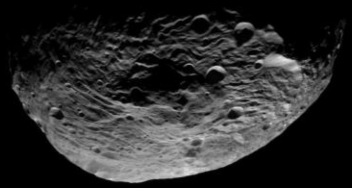
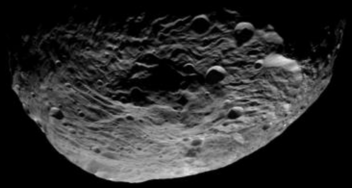


Compensation for Vesta and Ceres

- Vesta topography is <u>uncompensated</u>
- Vesta acquired most of its topography when the crust was already <u>cool and not-relaxing</u>

- Ceres topography is <u>compensated</u>
- Lower viscosities (compared to Vesta) enabled <u>relaxation</u> of topography to isostatic state

Ermakov et al., Vesta and Ceres topography, AGU 2017.



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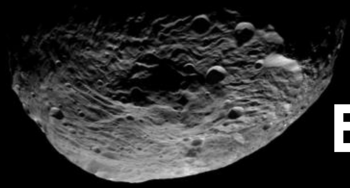
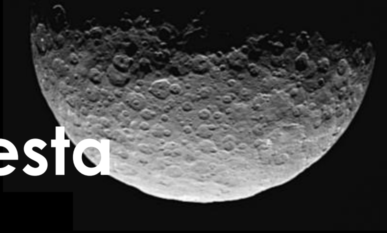
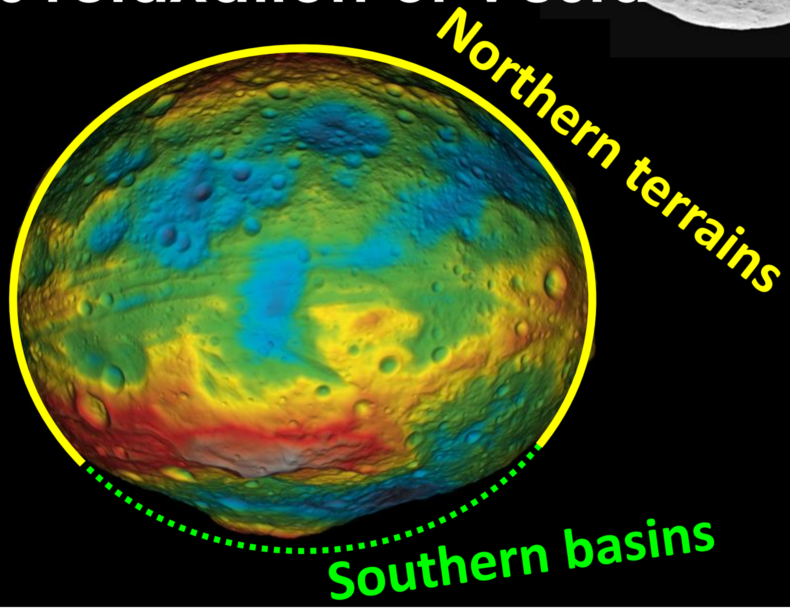
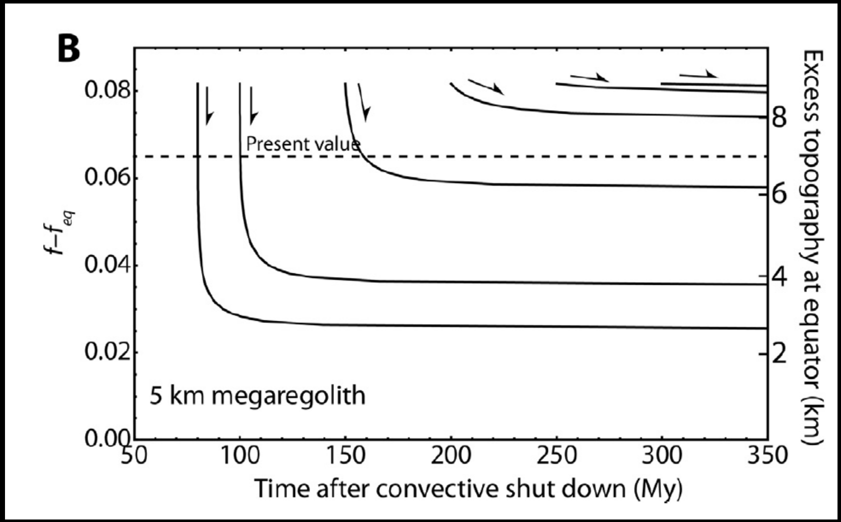




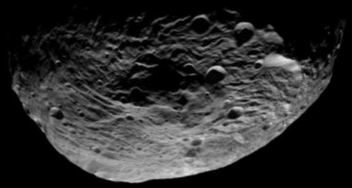
Early efficient viscous relaxation of Vesta

- Vesta was likely close to hydrostatic equilibrium in its early history (Fu et al., 2014)
- Vesta's northern terrains likely reflect its pre-impact equilibrium shape.
- Major impact occurred when Vesta was effectively non-relaxing leading to uncompensated Rheasilvia and Veneneia basins.



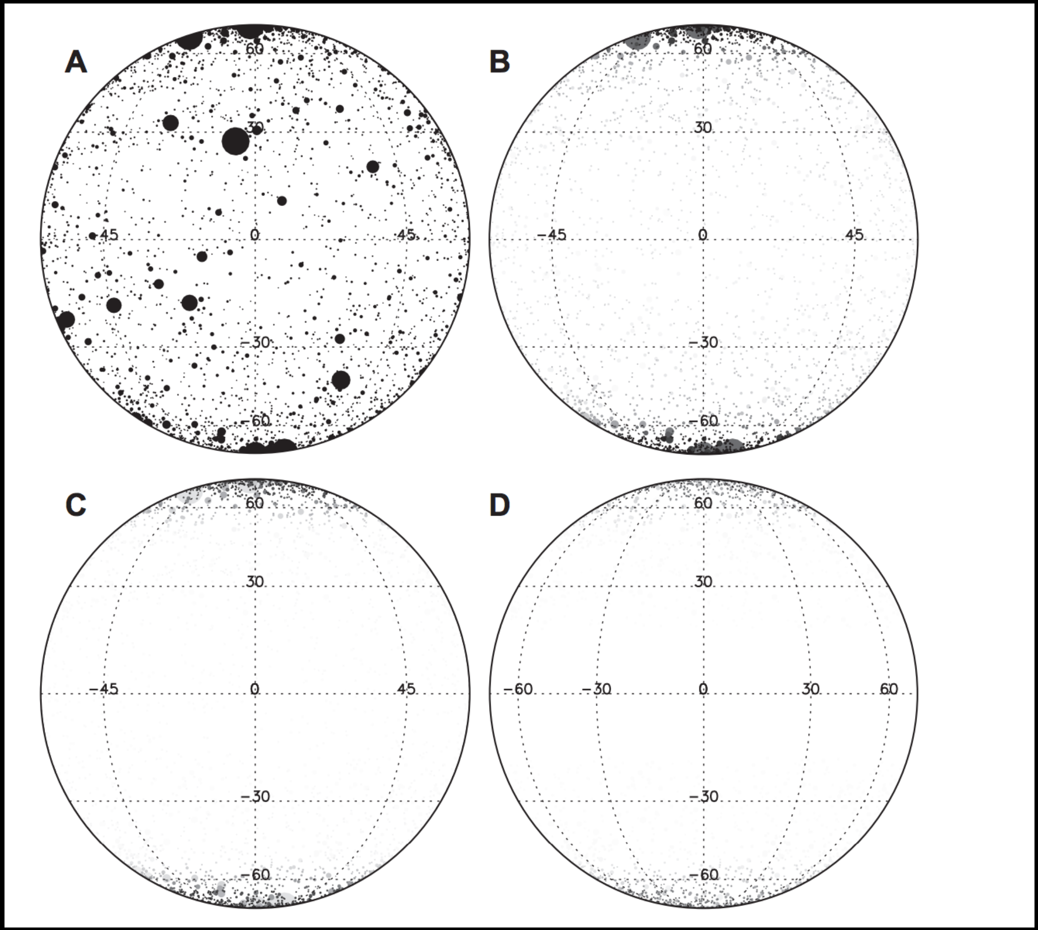


(Fu et al., 2014)



Viscous relaxation on Ceres (expectation)

- **Bland et al., 2013 predicted that craters on Ceres would quickly relax in an ice-dominated shell**
  - **Equatorial warmer craters would relax faster than colder polar craters**



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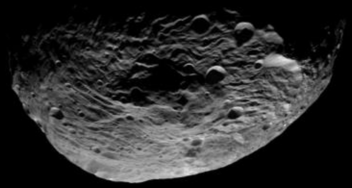
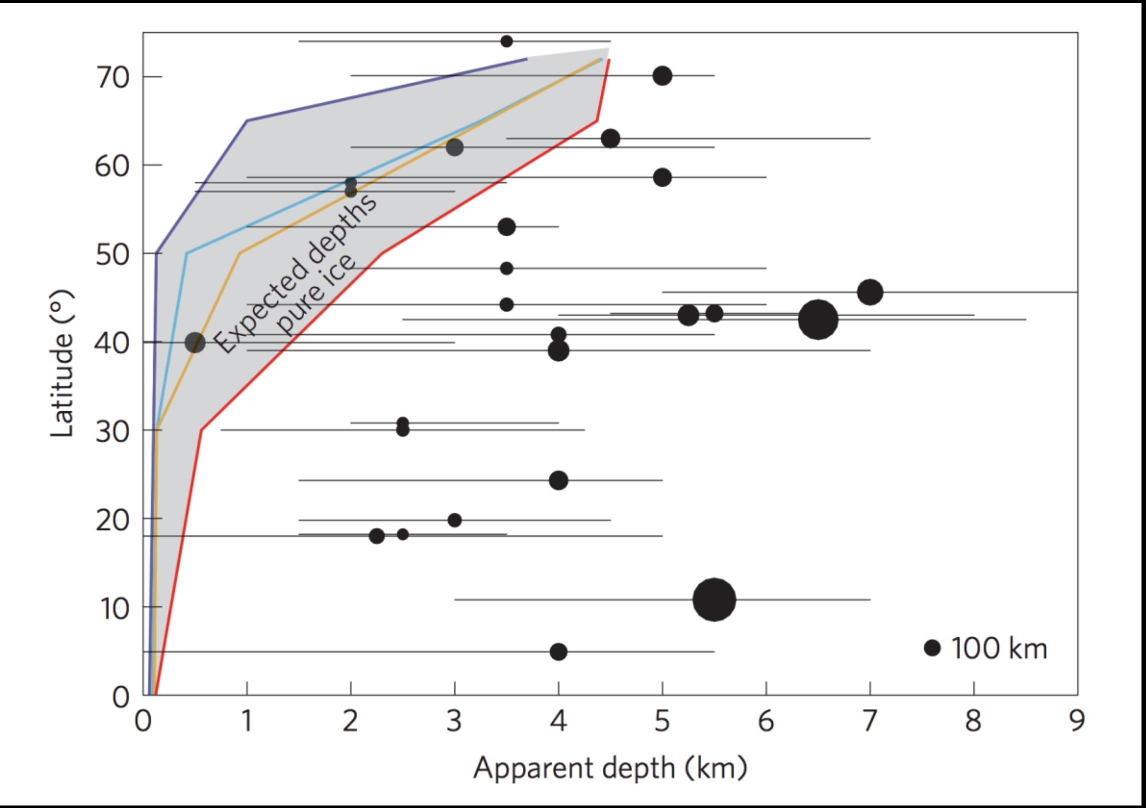


Viscous relaxation on Ceres (observation)

- **Bland et al., 2016 did not find that evidence for such relaxation pattern**
  - **No latitude dependence of crater depth**



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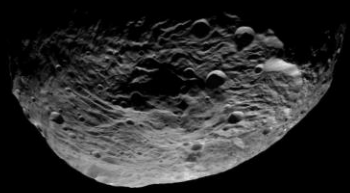
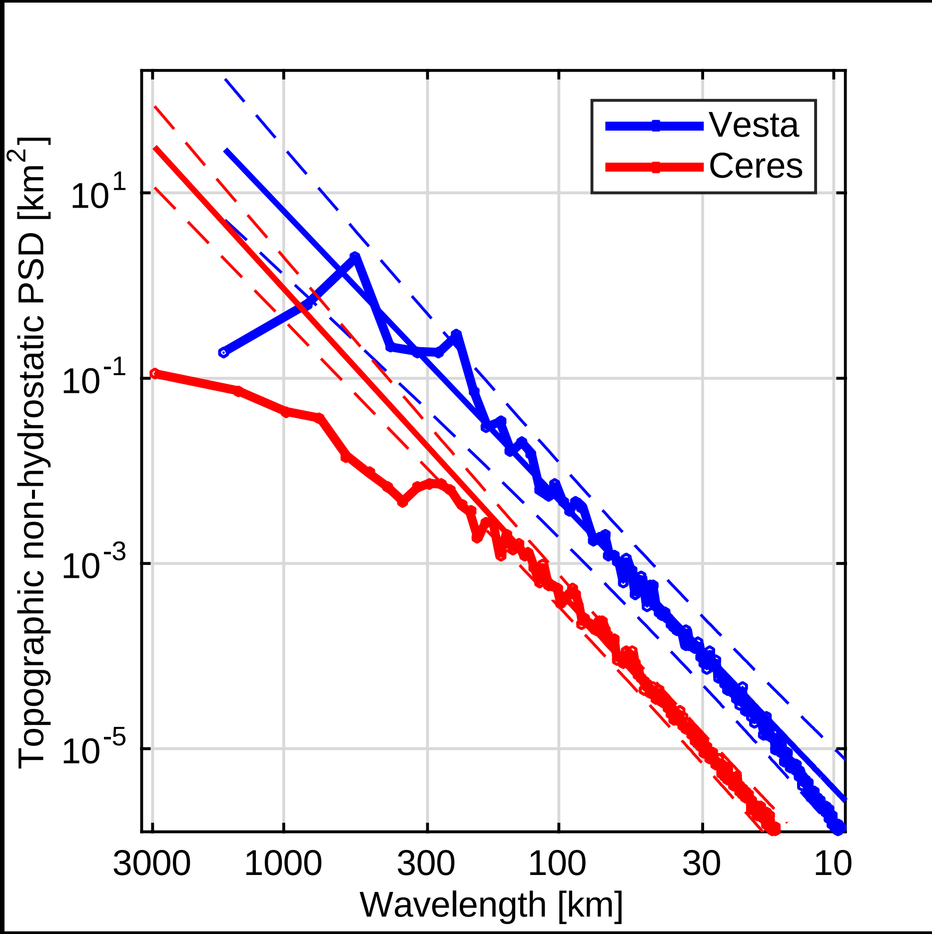


Evidence for viscous relaxation

- **More general approach: <u>study topography power spectrum</u>**
- Power spectra for Vesta closely fits with the power law to the lowest degrees (λ < 750 km)
- Ceres power spectrum deviates from the power law at λ > 270 km



Ermakov et al,. in prep

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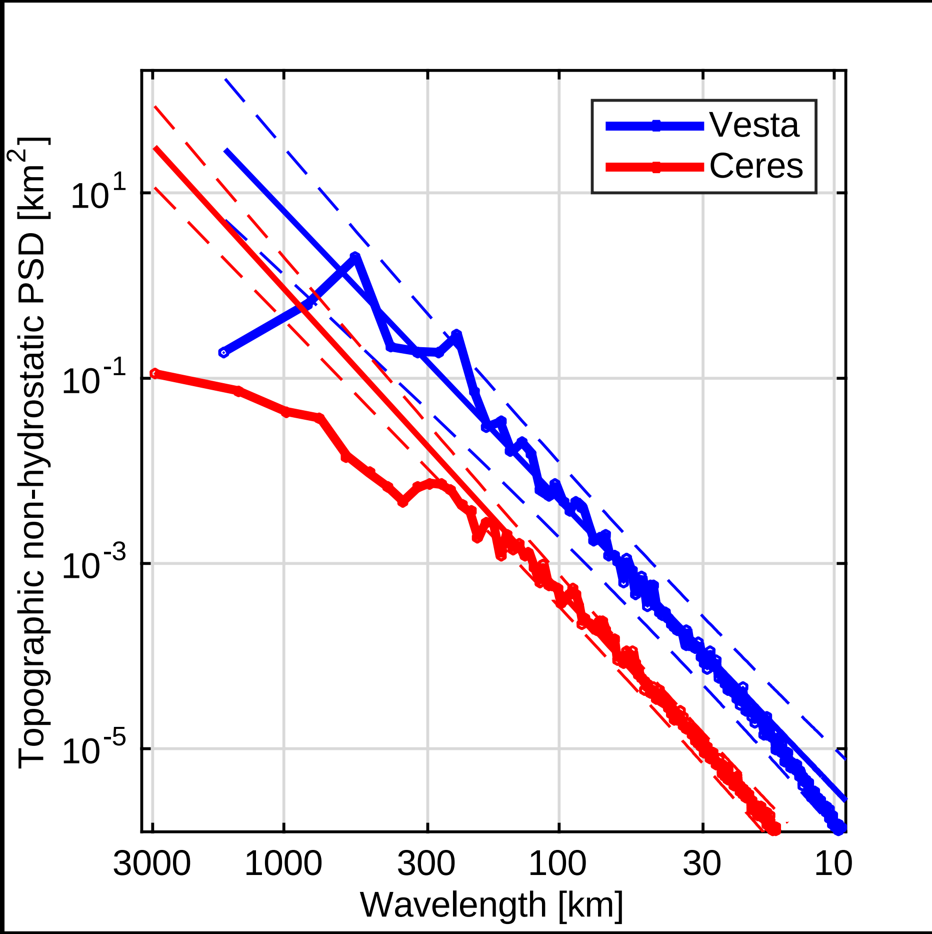

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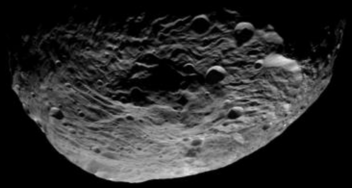

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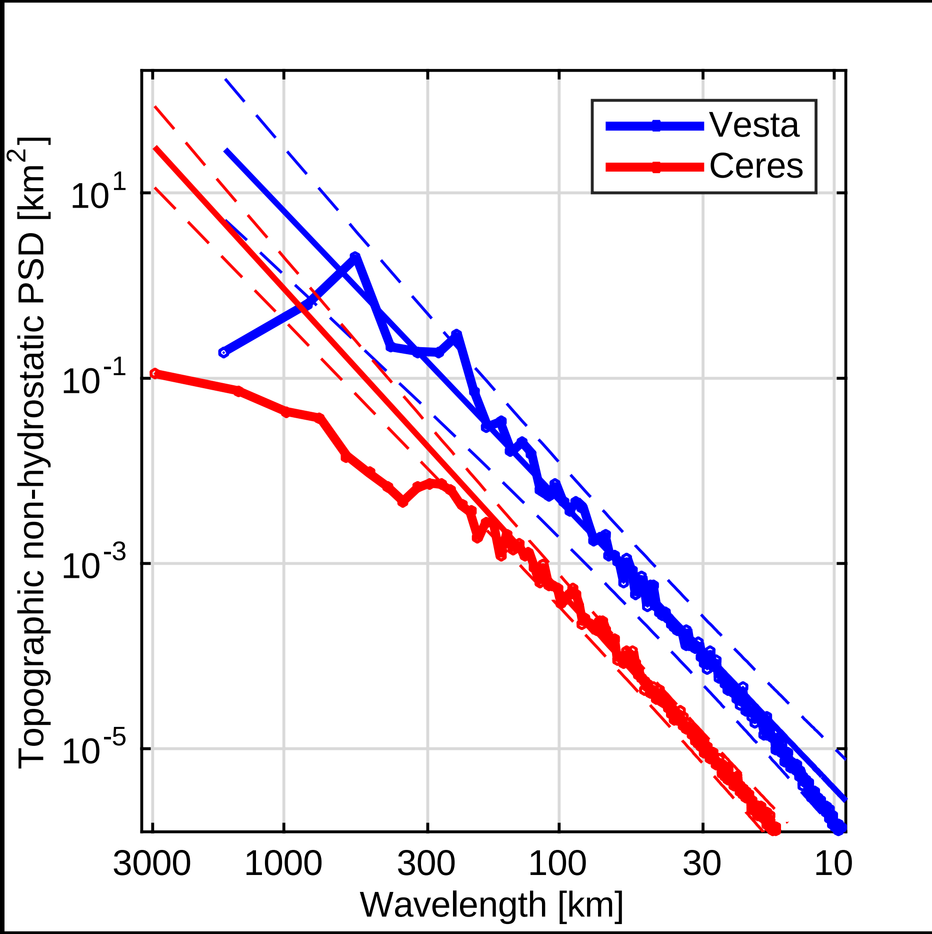

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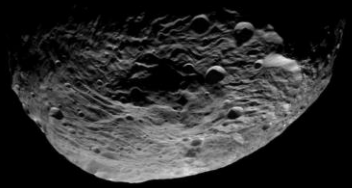
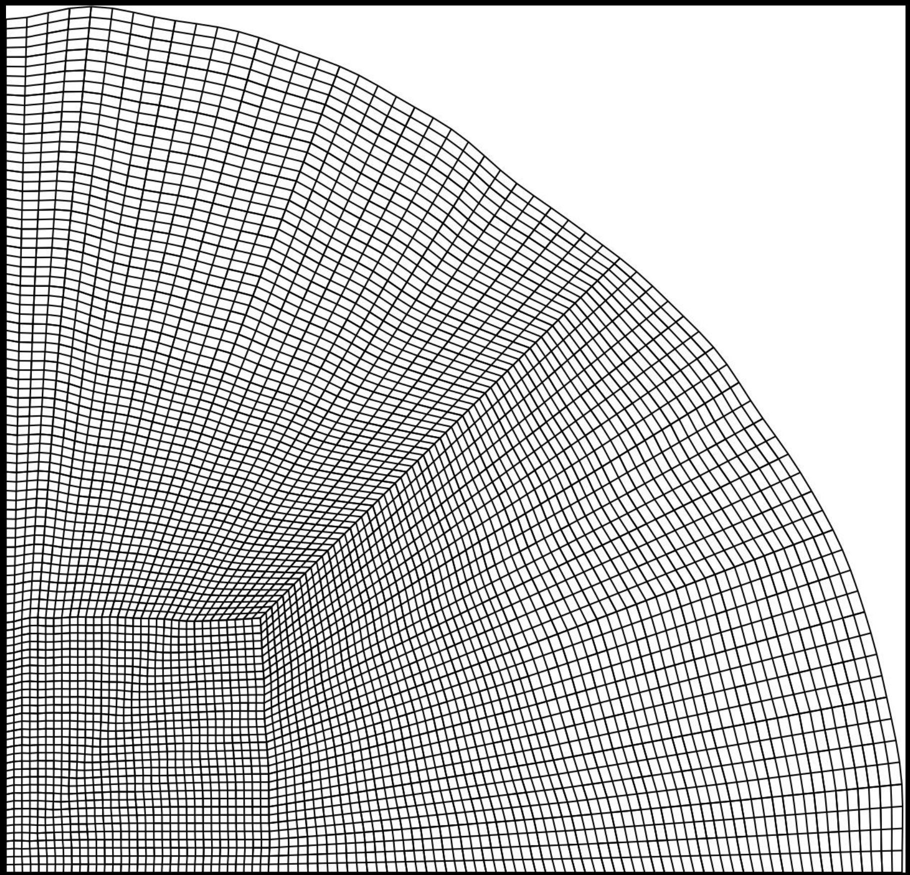


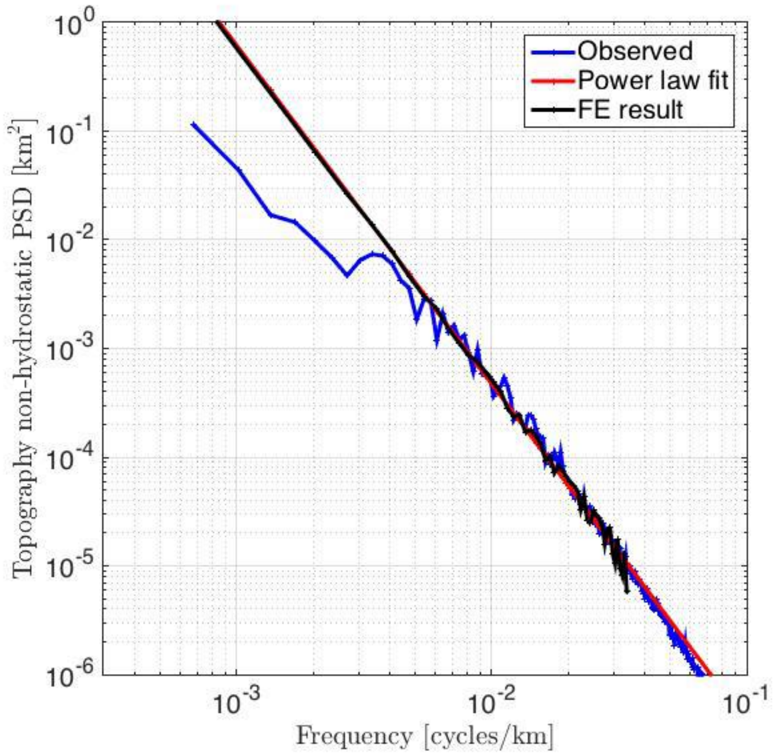
Finite element model

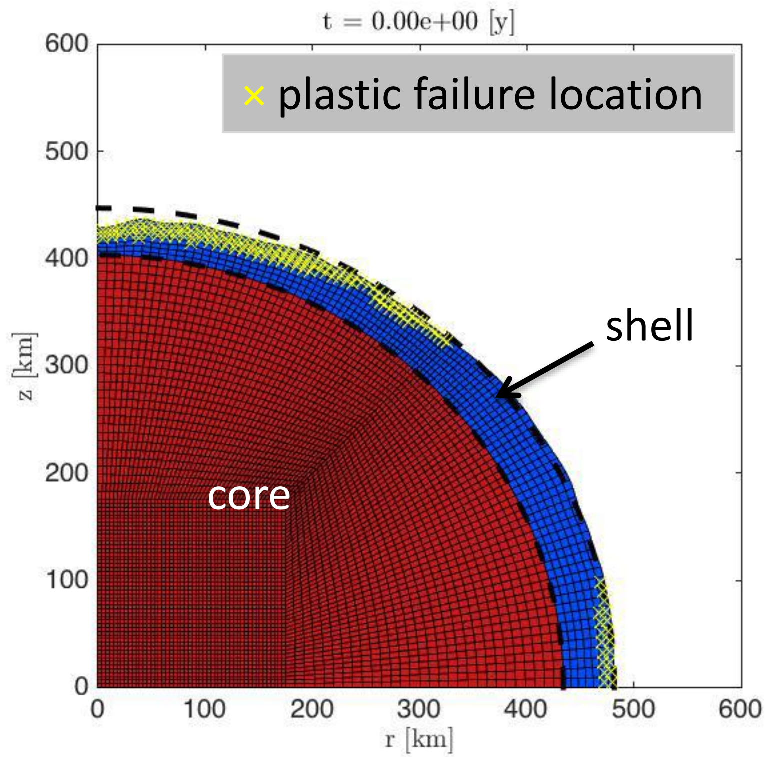


Fu et al., 2014; Fu et al, submitted to EPSL

- Assume a density and rheology structure
- Solve Stokes equation for an incompressible flow using deal.ii library
- Compute the evolution of the outer surface power spectrum

Example of a FE modeling run





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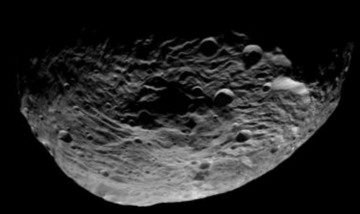
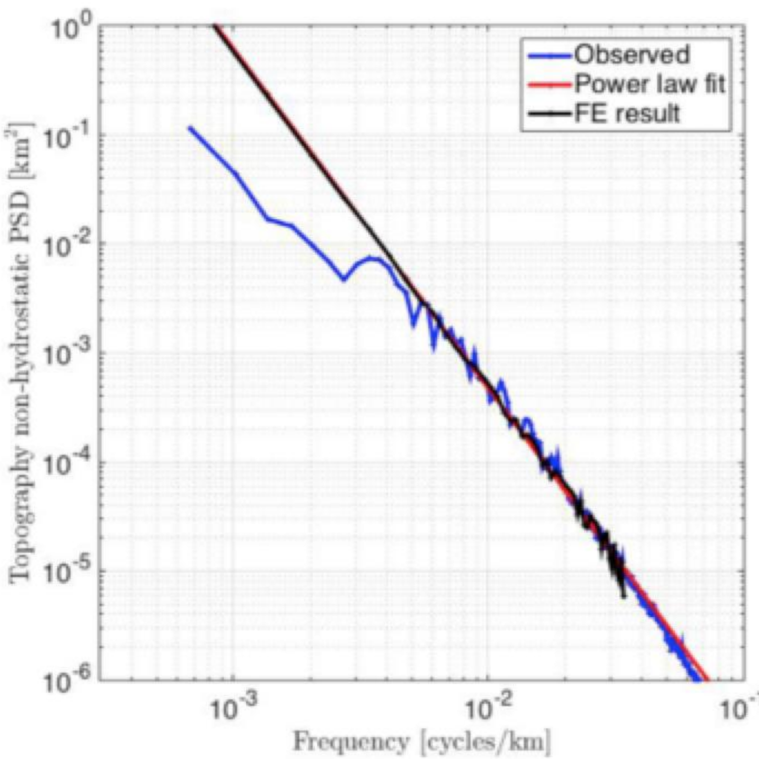
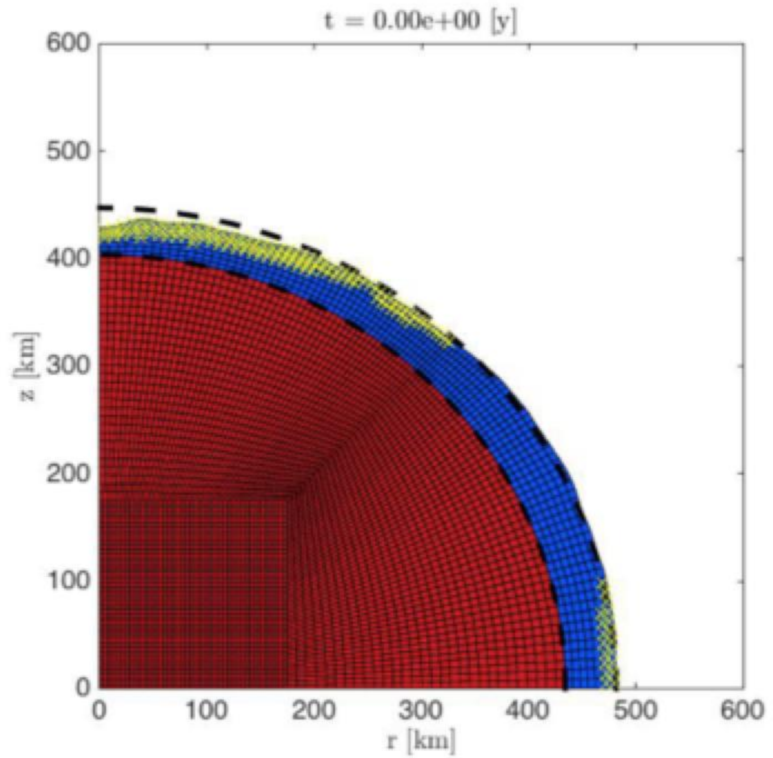


Finite element modeling results





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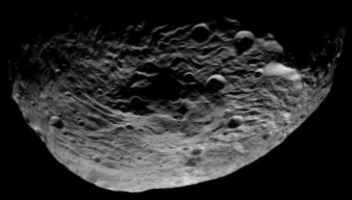

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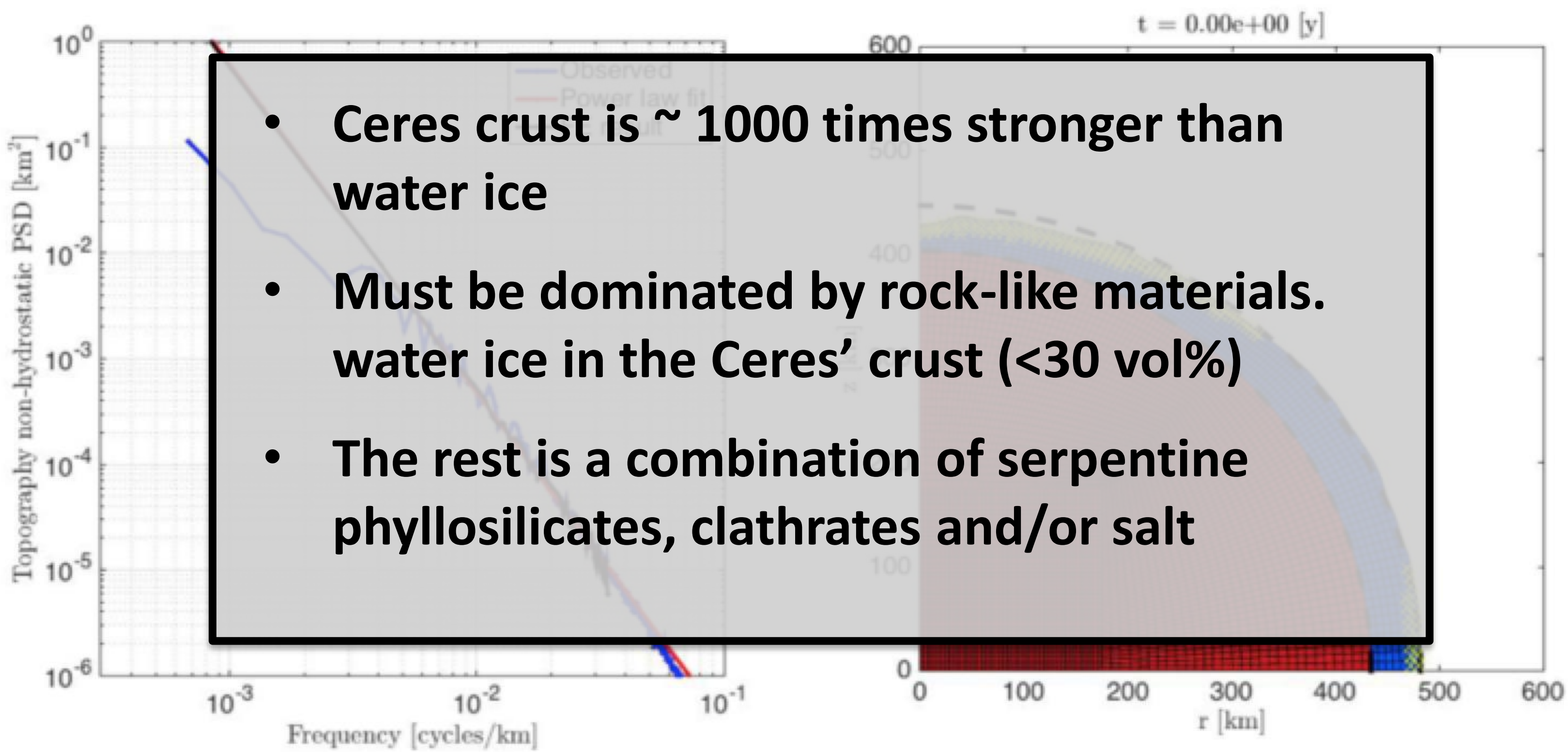
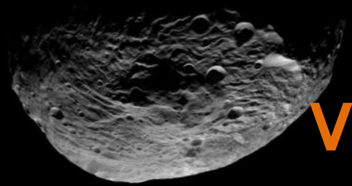
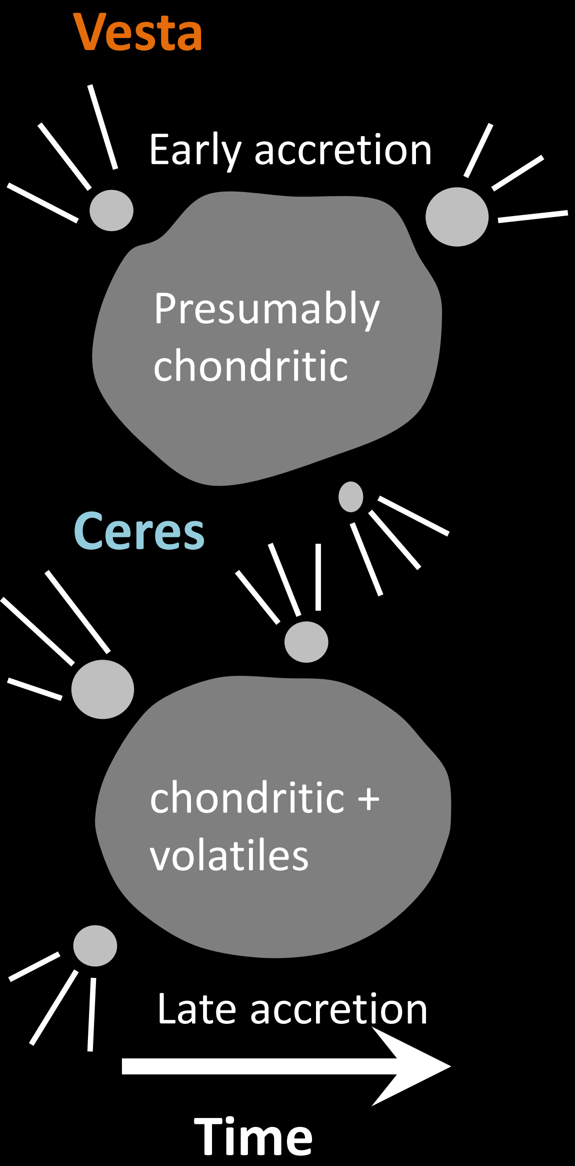


- Ceres crust is ~ 1000 times stronger than water ice
- Must be dominated by rock-like materials. water ice in the Ceres' crust (<30 vol%)
- The rest is a combination of serpentine phyllosilicates, clathrates and/or salt

Ermakov et al., Vesta and Ceres topography, AGU 2017.



Vesta and Ceres comparative evolution



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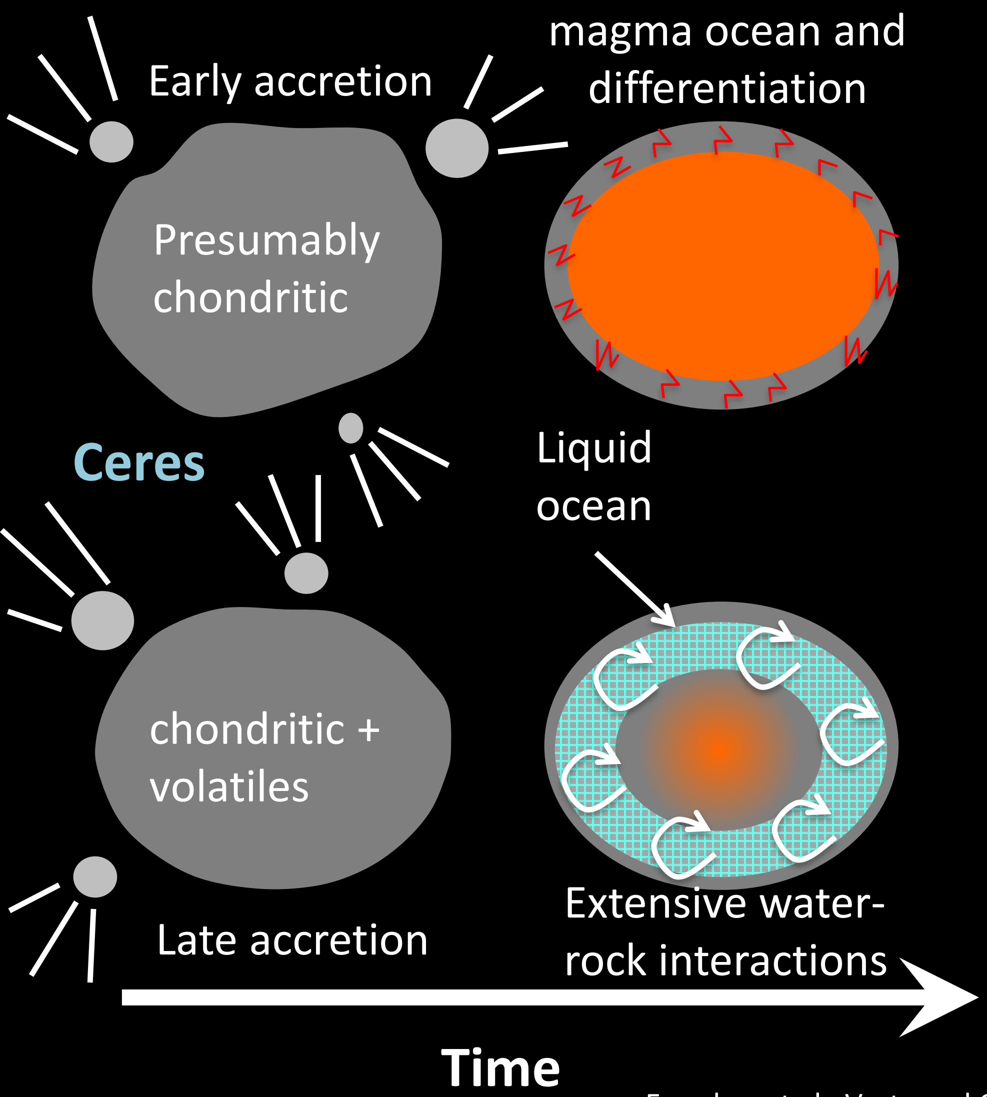

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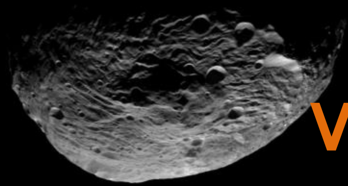

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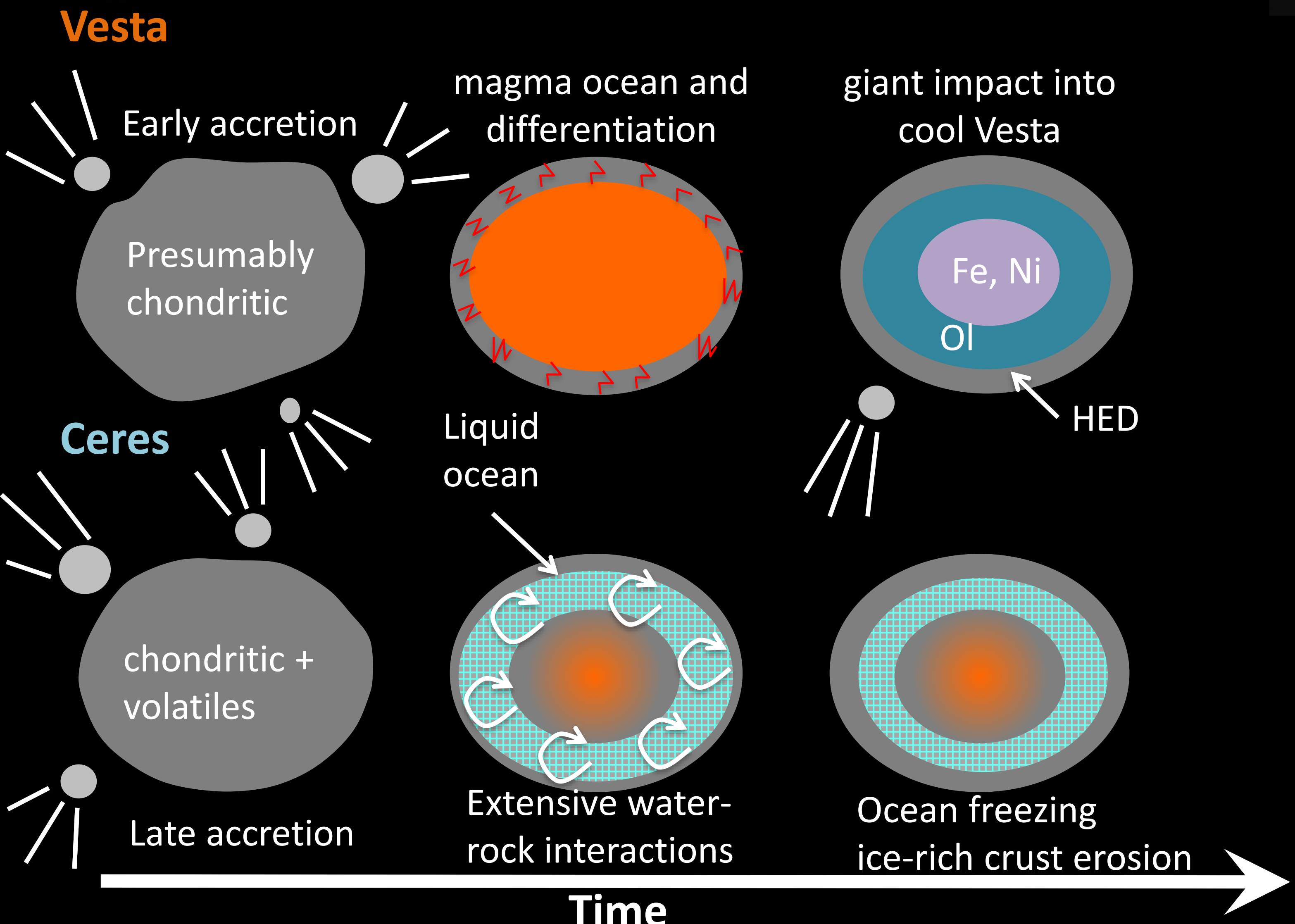

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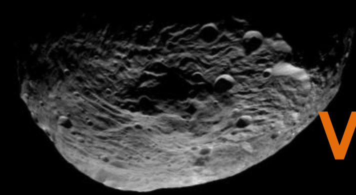

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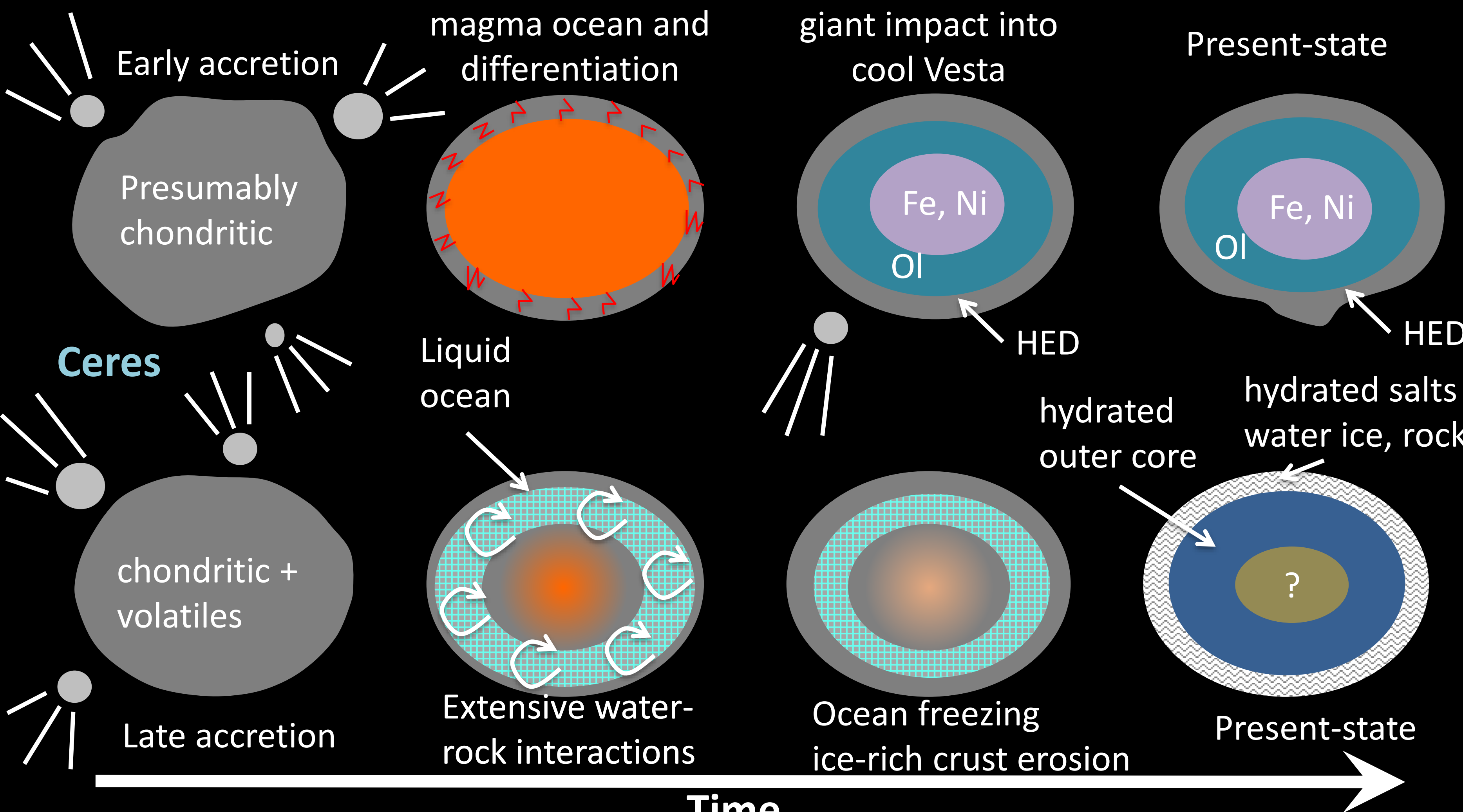

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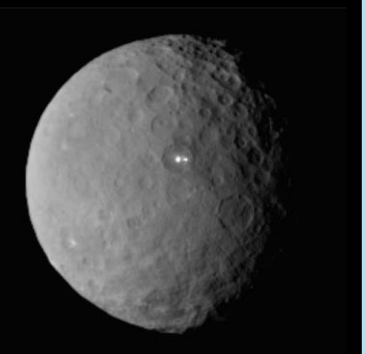
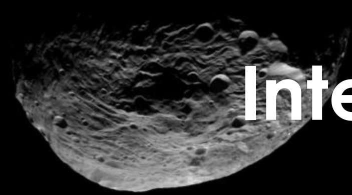
Summary

- Formed early (< 5 My after CAI)
- Once hot and hydrostatic, Vesta is no longer either
- Differentiated interior
- Most of topography acquired when Vesta was already cool => uncompensated topography
- Combination of gravity/topography data with meteoritic geochemistry data provides constraints on the internal structure



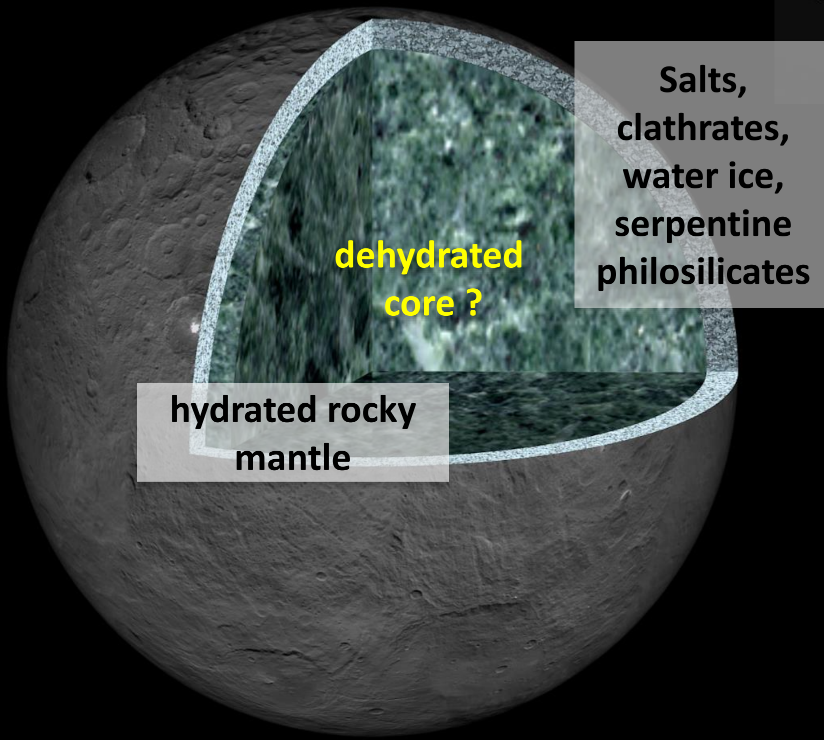
- Cooler history
  - late formation
  - and/or heat transfer due to hydrothermal circulation
- Partially differentiated interior
- Experienced viscous relaxation
- Much lower surface viscosities (compared to Vesta) allowed compensated topography
- Ceres' crust is light (based on admittance analysis) and strong (based on FE relaxation modeling)
- Not much water ice in Ceres crust (<30 vol%) now

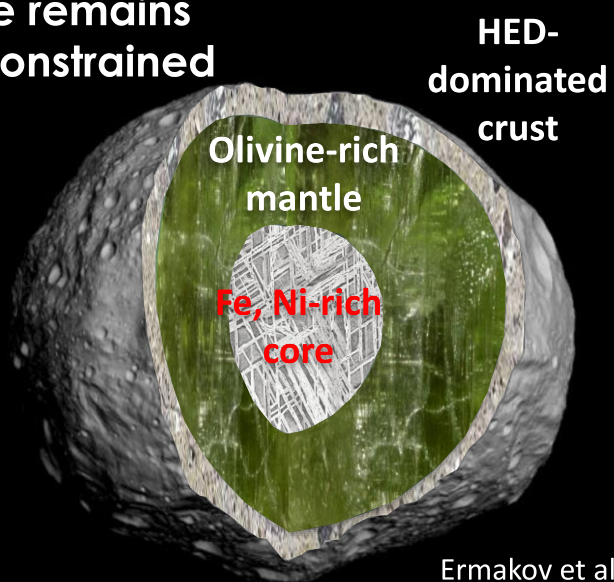


Internal structures of Vesta and Ceres

Ceres➔

- Crust is light (1.1-1.4 g/cc) and mechanically rock-like w
- Mantle density ~2.4 g/cc and unlithified at least to a depth of 100 km
- Possible dehydrated rocky core remains unconstrained

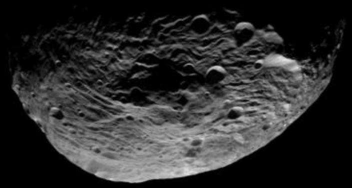




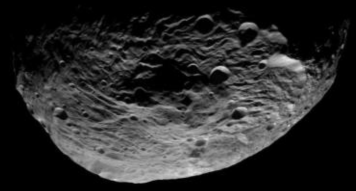
🡐Vesta

- Crustal density constrained by HEDs and admittance (2.8 g/cc)
- Assuming density of iron meteorites (5-8 g/cc), the core radius is 110 – 155 km

Ermakov et al., Vesta and Ceres topography, AGU 2017.

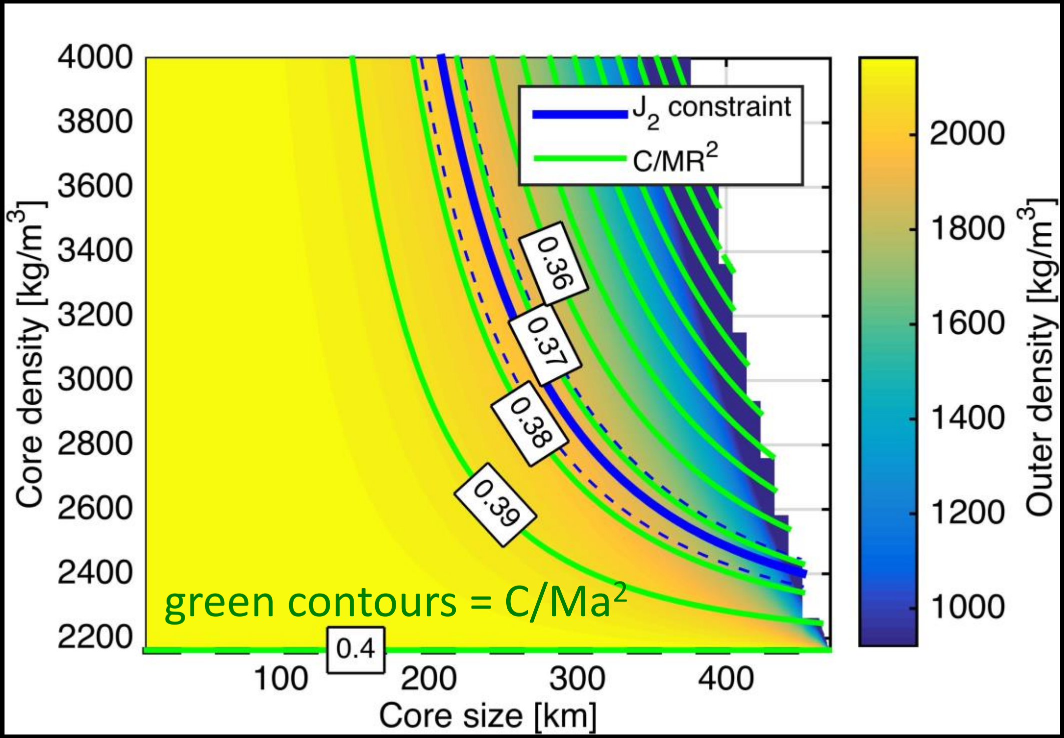


Backup slides



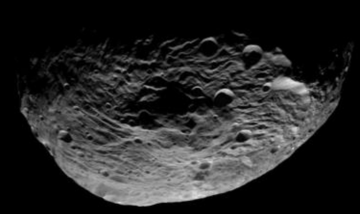
Two-layer model

- **Simplest model to interpret the gravity-topography data**
- **Only 5 parameters: two densities, two radii and rotation rate**
- **Yields $C/Ma^2 = 0.373$ $C/M(R_{vol})^2 = 0.392$**

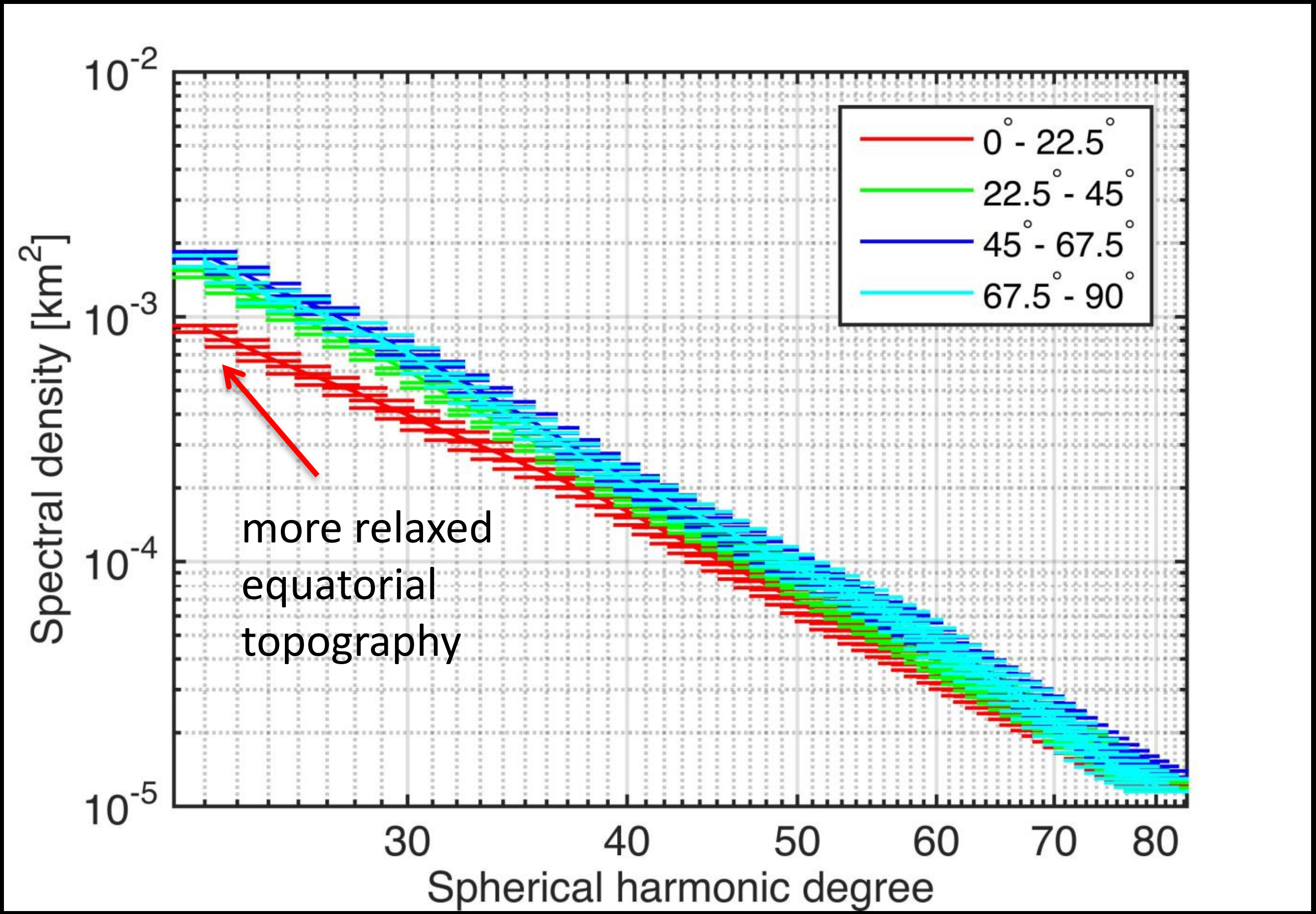


Using Tricarico 2014 for computing hydrostatic equilibrium

Ermakov et al., Vesta and Ceres topography, AGU 2017.



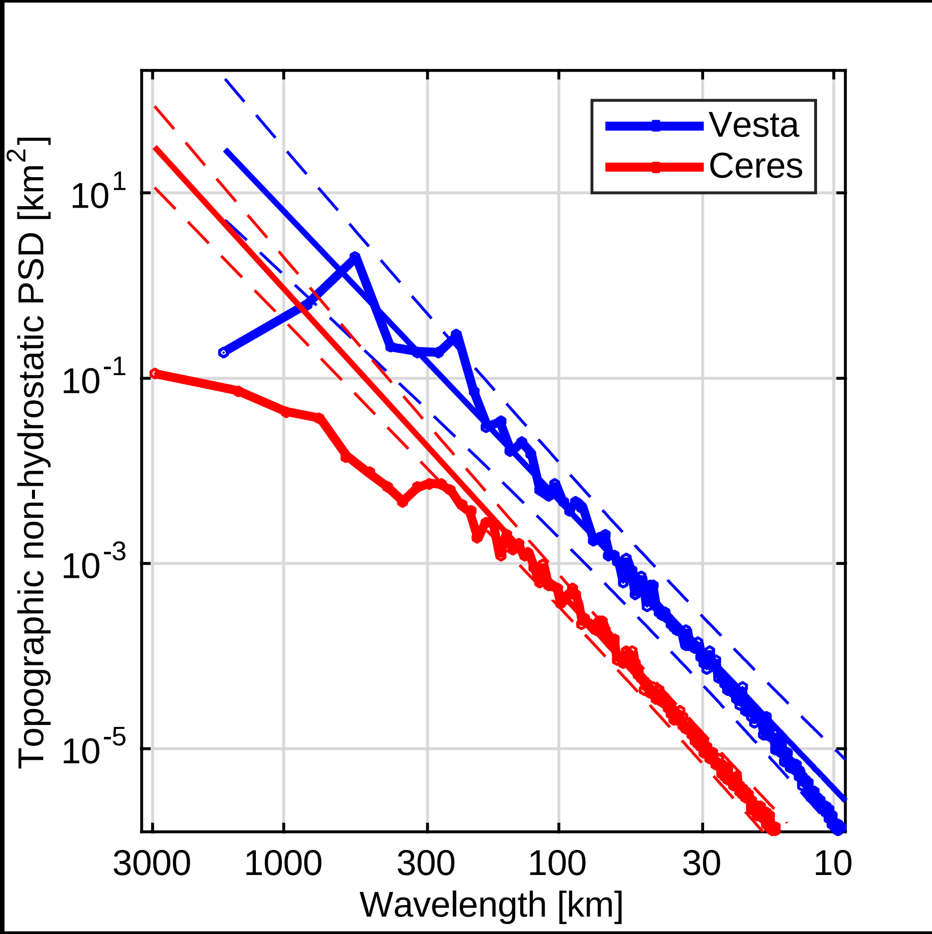
Latitude dependence of relaxation



Ermakov et al., in prep

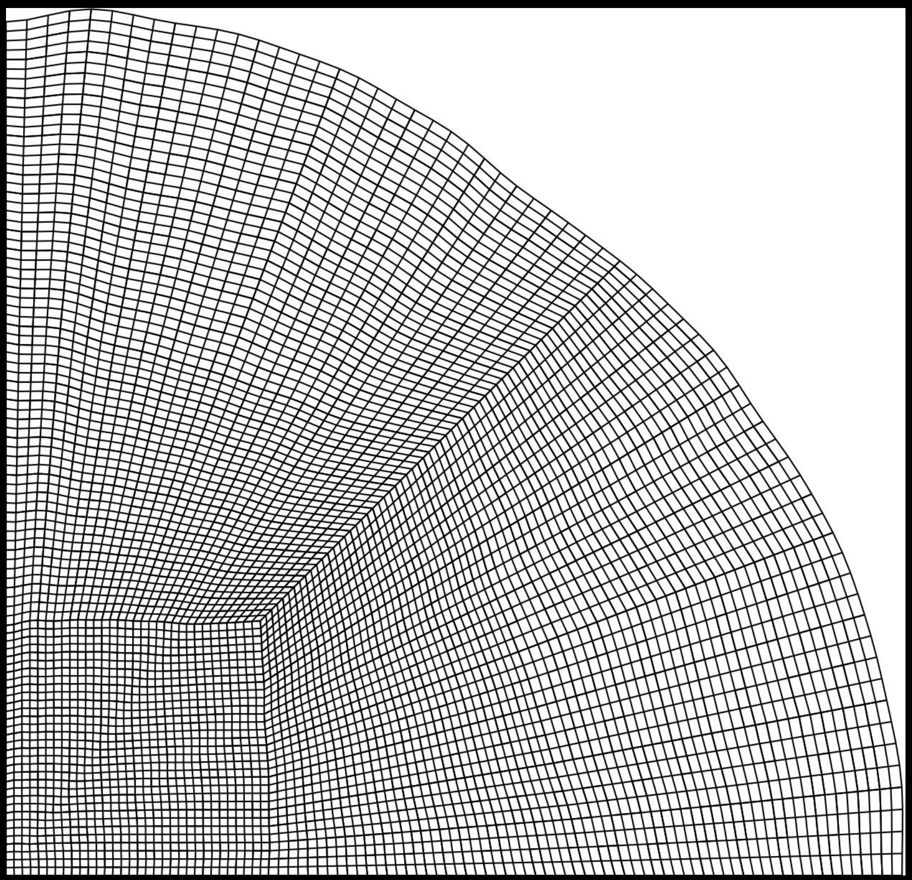
Evidence for viscous relaxation

- **More general approach: study topography power spectrum**
- **Power spectra for Vesta closely fits with the power law to the lowest degrees (λ < 750 km)**
- **Ceres power spectrum deviates from the power law at λ > 270 km**



Ermakov et al,. in prep

Finite element model



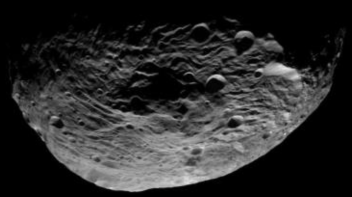
Fu et al., 2014; Fu et al, submitted to EPSL

- **Assume a density and rheology structure**
- **Solve Stokes equation for an incompressible flow using deal.ii library**

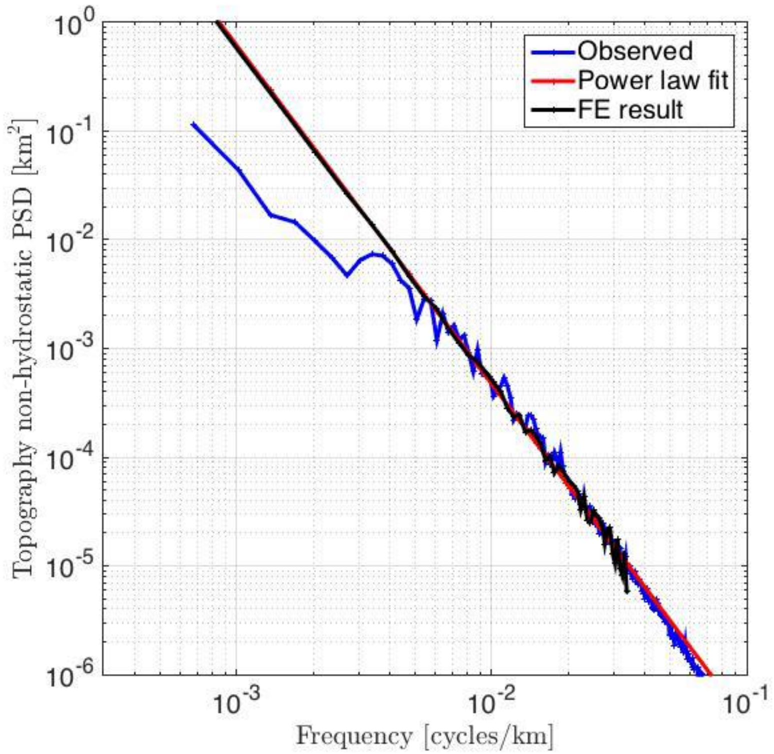
$$\partial_i(2\eta\dot{\varepsilon}_{ij}) - \partial_i p = -g_i\rho$$

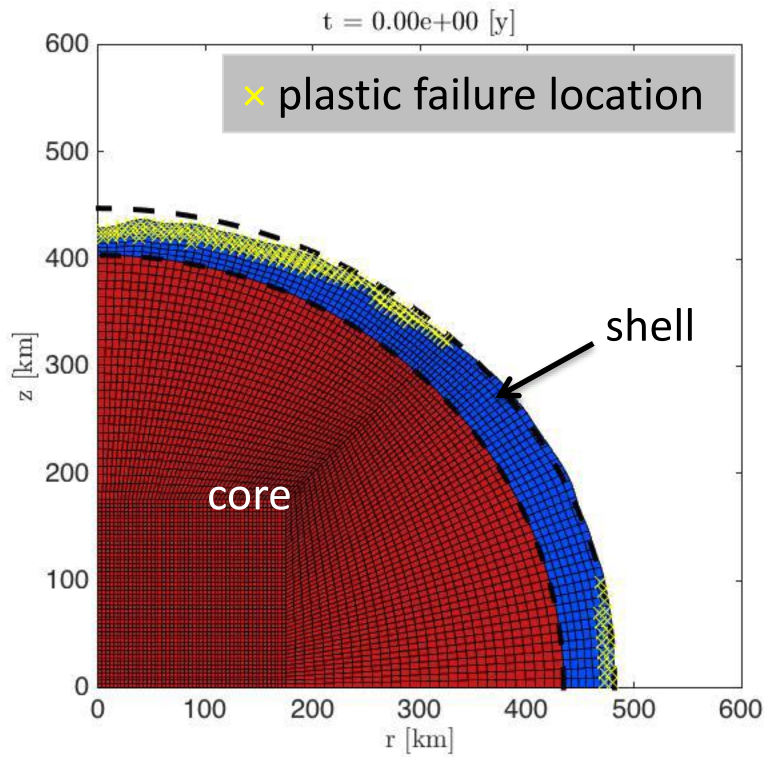
$$\P_i u_i = 0$$

- **Compute the evolution of the outer surface power spectrum**

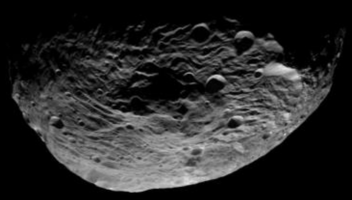


Example of a FE modeling run

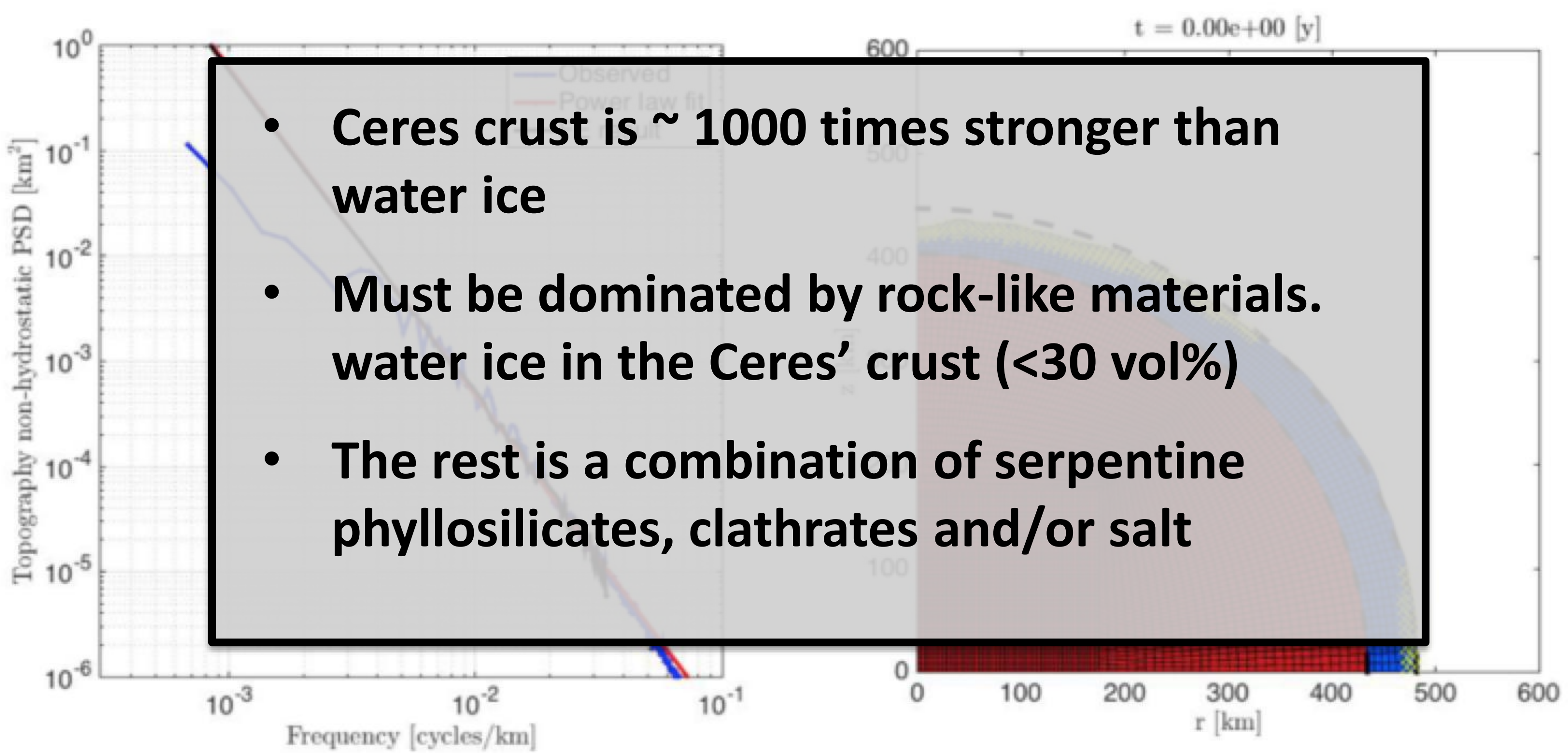




Ermakov et al., Vesta and Ceres topography, AGU 2017.

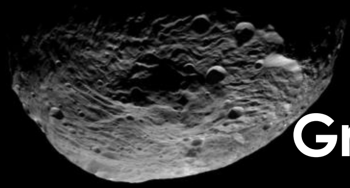


Finite element modeling results



- Ceres crust is ~ 1000 times stronger than water ice
- Must be dominated by rock-like materials. water ice in the Ceres’ crust (<30 vol%)
- The rest is a combination of serpentine phyllosilicates, clathrates and/or salt

Ermakov et al., Vesta and Ceres topography, AGU 2017.



Gravity and topography in spherical harmonics

- **Shape radius vector**

$$r(\varphi,\lambda)=R_0\left[\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(A_{nm}\cos(m\lambda)+B_{nm}\sin(m\lambda)\right)P_{nm}(\sin\varphi)\right]$$

- **Gravitational potential**

$$U(r,\varphi,\lambda)=\frac{GM}{R}\left[1+\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_0}{r}\right)^{n}\left(C_{nm}\cos(m\lambda)+S_{nm}\sin(m\lambda)\right)P_{nm}(\sin\varphi)\right]$$

- **Power Spectral Density**

$$S_n^{gg}=\sum_{m=0}^{n}\frac{C_{nm}^2+S_{nm}^2}{2n+1}$$

gravity

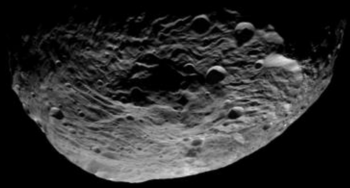
$$S_n^{tt}=\sum_{m=0}^{n}\frac{A_{nm}^2+B_{nm}^2}{2n+1}$$

topography

$$S_n^{gt}=\sum_{m=0}^{n}\frac{A_{nm}C_{nm}+B_{nm}S_{nm}}{2n+1}$$

gravity-topography cross power

Ermakov et al., Vesta and Ceres topography, AGU 2017.



Isostatic model

Z_n - gravity-topography admittance

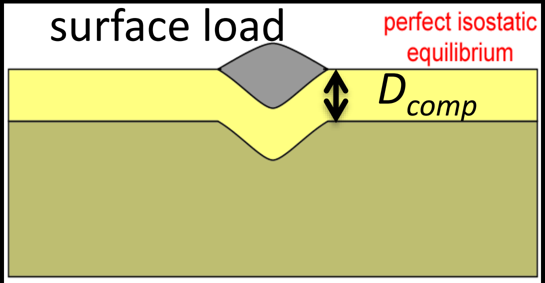
$$Z_n = \frac{S_{gt}}{S_{tt}}$$

- **Linear two-layer hydrostatic model**

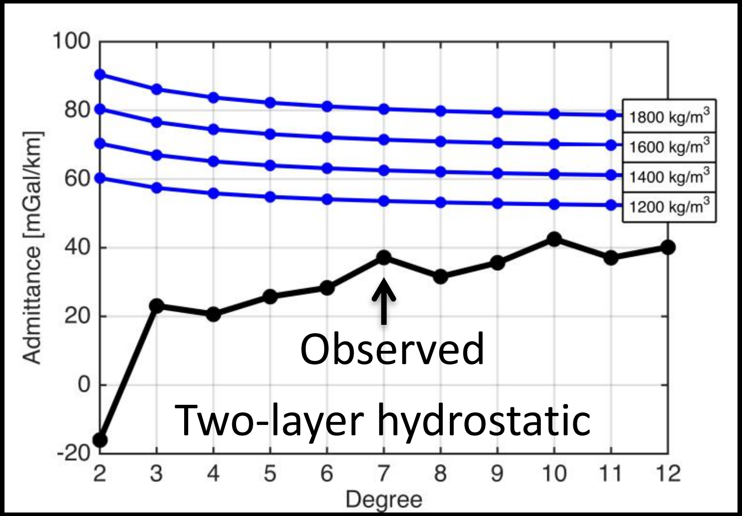
$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}$$

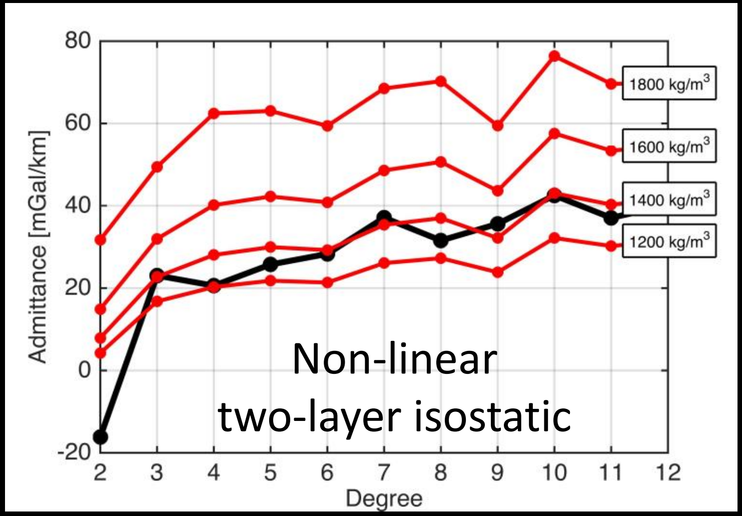
- **Linear isostatic model**

$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}\left[1-\left(1-\frac{D_{comp}}{R}\right)^n\right]$$

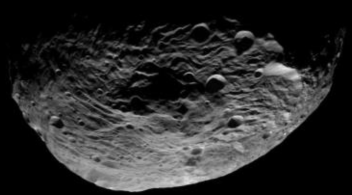


D_{comp}- depth of compensation



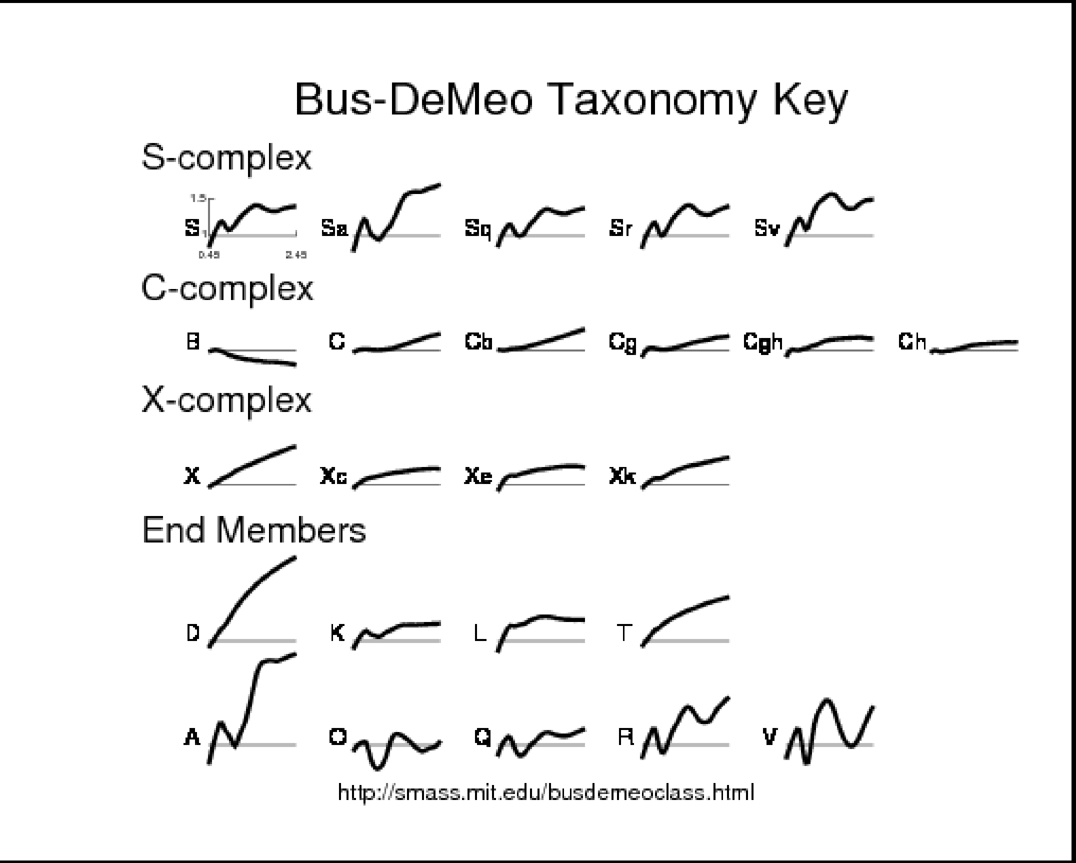


Ermakov et al., Vesta and Ceres topography, AGU 2017.

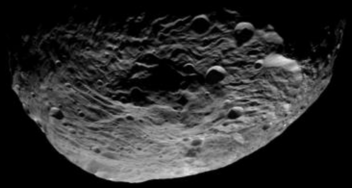


Why Vesta?

- **Unique basaltic spectrum**

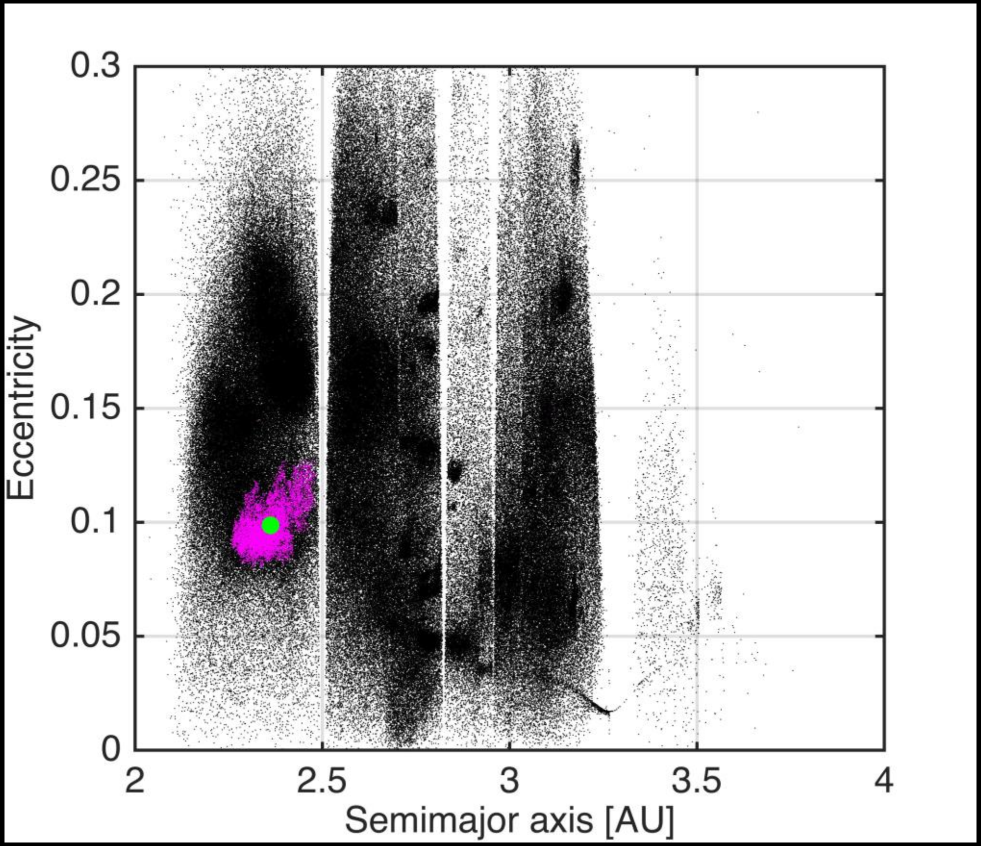


Ermakov et al., Vesta and Ceres topography, AGU 2017.

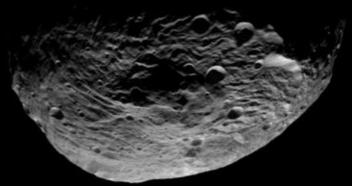


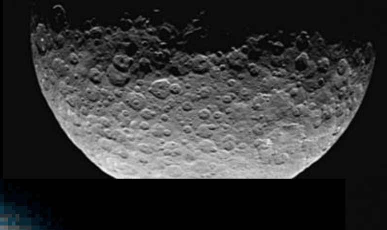
Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**



Ermakov et al., Vesta and Ceres topography, AGU 2017.





Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**
- **Large depression in the southern hemisphere of Vesta**

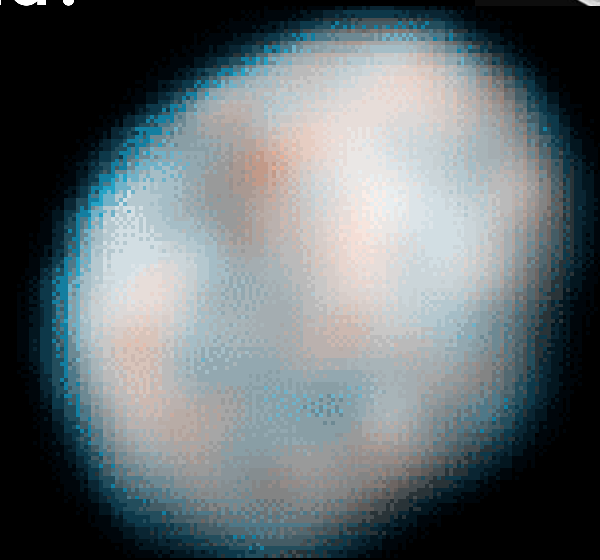
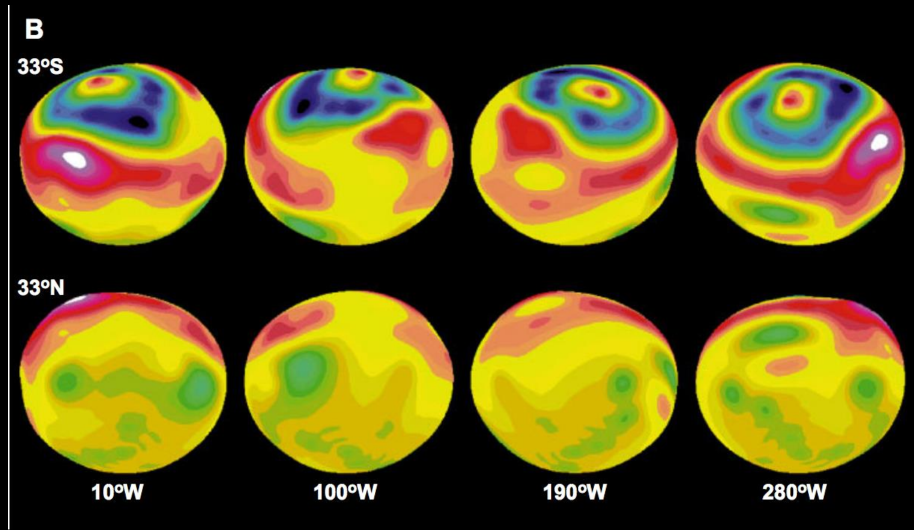
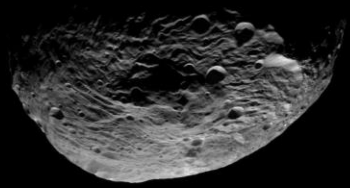


Image credit: NASA/HST



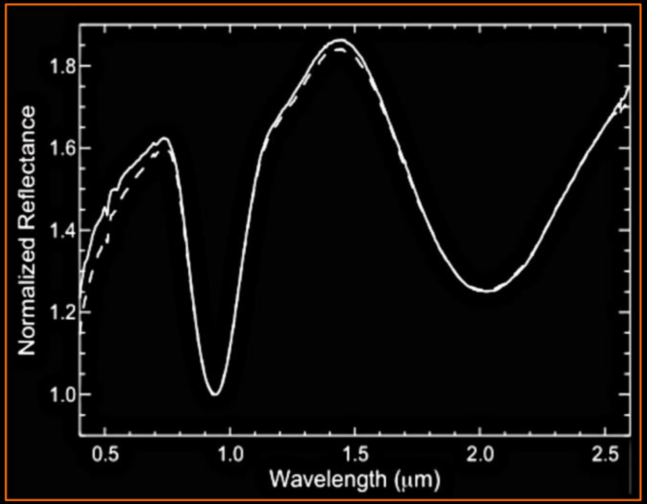
Thomas et al., 1997

Ermakov et al., Vesta and Ceres topography, AGU 2017.



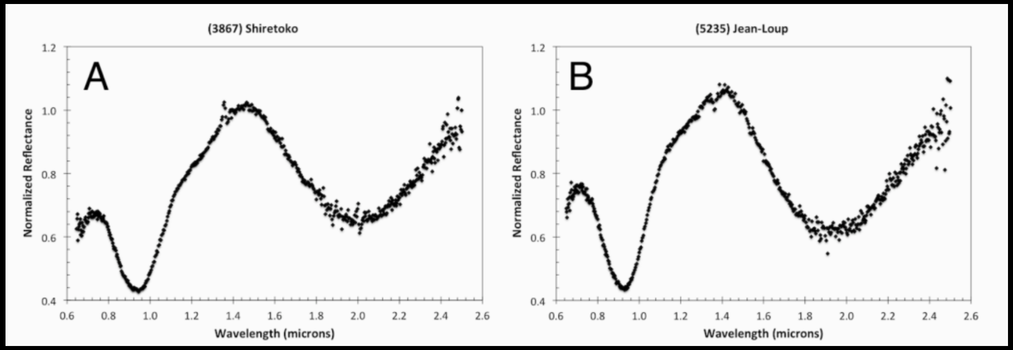
Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**
- **Large depression in the southern hemisphere of Vesta**
- **A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra**



↑ Reflectance spectra of eucrite Millbillillie from Wasson et al. (1998)

↓ V-type asteroids spectra from Hardensen et al., (2014)



Ermakov et al., Vesta and Ceres topography, AGU 2017.

Why Vesta?

- **Unique basaltic spectrum**
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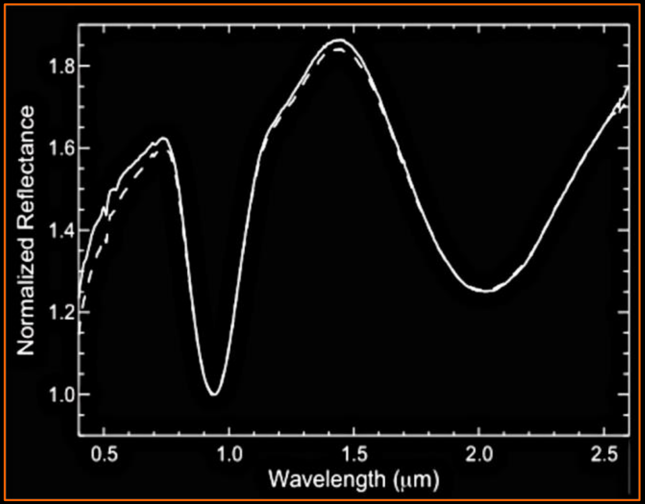
- **Large depression in the southern hemisphere of Vesta**
- **A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra**
- **Strongest connection between a class of meteorites and an asteroidal family**



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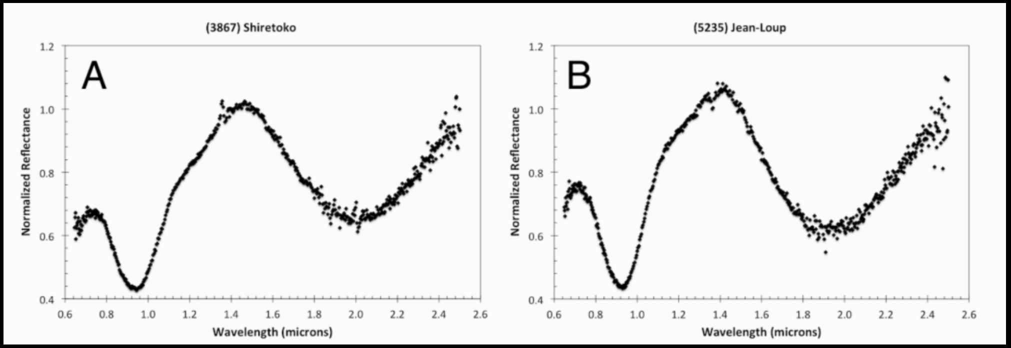
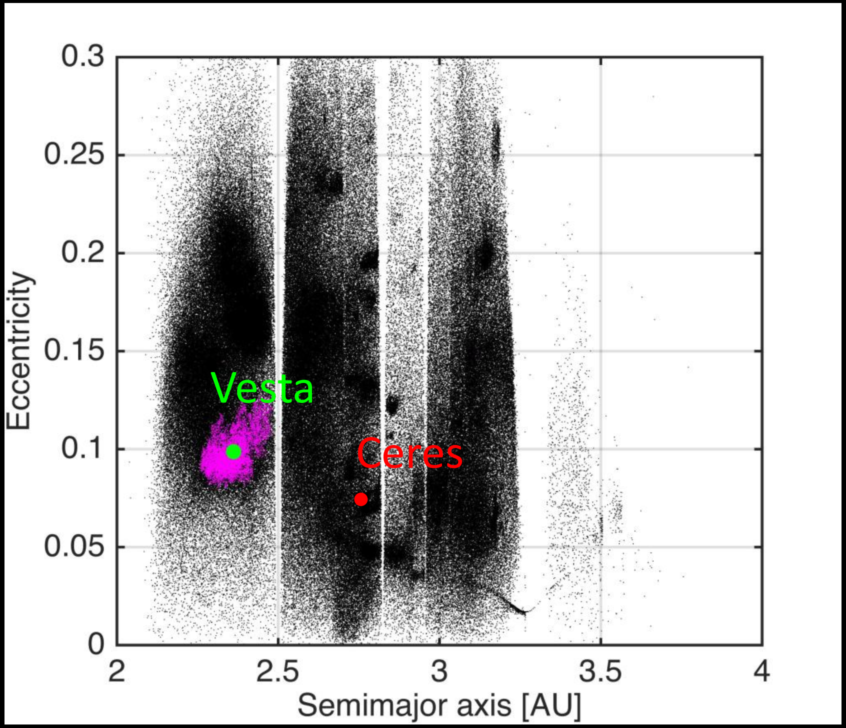


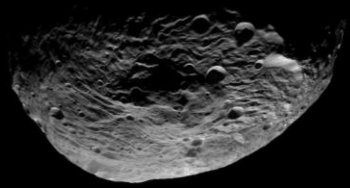
Ermakov et al., Vesta and Ceres topography, AGU 2017.

Why Ceres?

- Largest body in the asteroid belt
- Low density implies high volatile content
- Conditions for subsurface ocean
- Much easier to reach than other ocean worlds



Ermakov et al., Vesta and Ceres topography, AGU 2017.



What did we know before Dawn

- **Castillo-Rogez and McCord 2010**

  Ceres accreted as a mixture of ice and rock just a few My after the condensation of Calcium Aluminum-rich Inclusions (CAIs), and later differentiated into a water mantle and a mostly anhydrous silicate core.

- **Zolotov 2009**

  Ceres formed relatively late from planetesimals consisting of hydrated silicates.

- **Bland 2013**

  If Ceres *does* contain a water ice layer, its warm diurnally-averaged surface temperature ensures extensive viscous relaxation of even small impact craters especially near equator