Reorientation of Mini-Moons: Enceladus and Miranda

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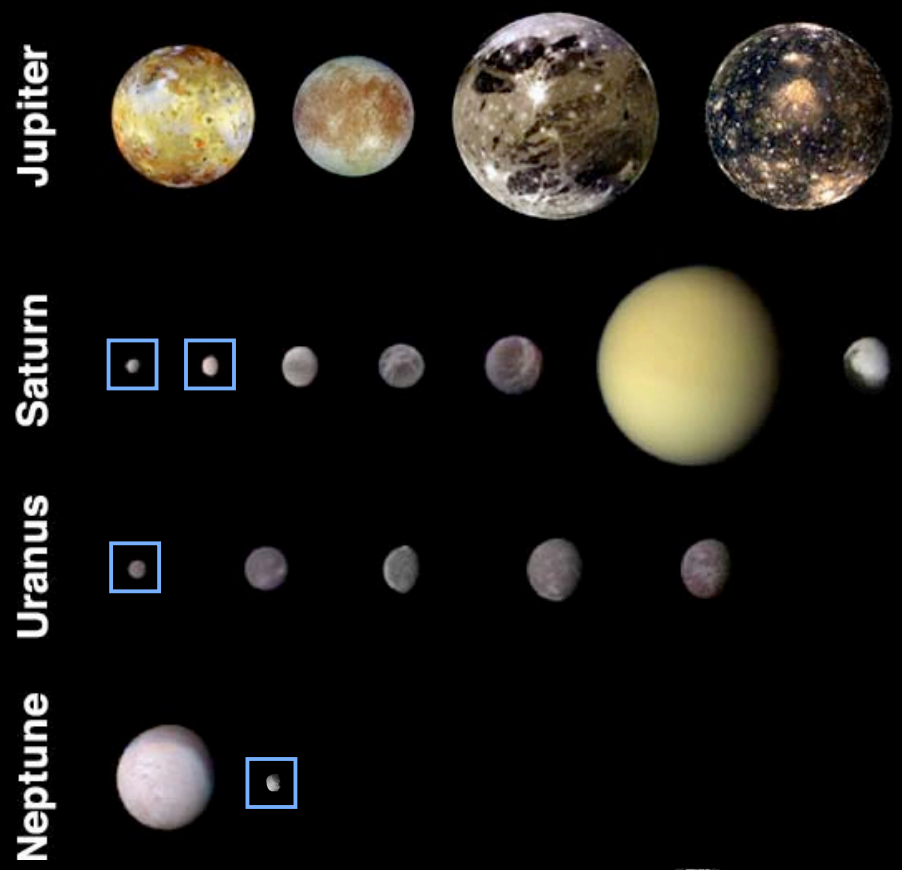
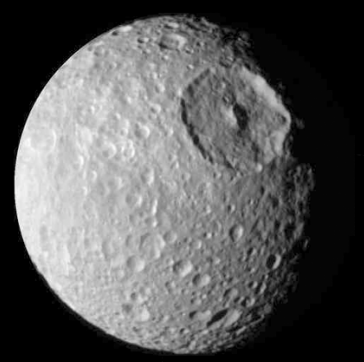
Reorientation of Mini-Moons

- Why is the hot spot of Enceladus centered on the south pole?
- What are the implications for Enceladus?
- What is the relationship to other planetary bodies, especially Miranda?

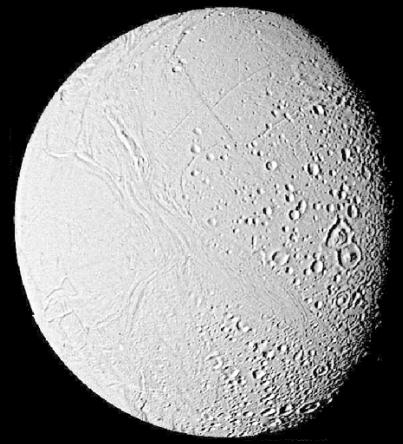
Mini-Moons



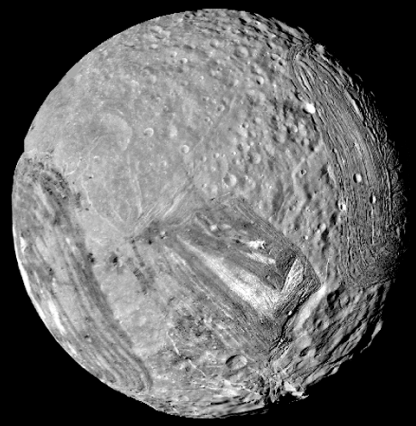
- Small radii (200-250 km).
- Tidally heated (Enceladus, Miranda), or cold & cratered (Mimas, Proteus).
- If heated, may have large diapiric plumes relative to radius, which could promote reorientation.
- Large craters on cold inactive moons can constrain models.



Mimas



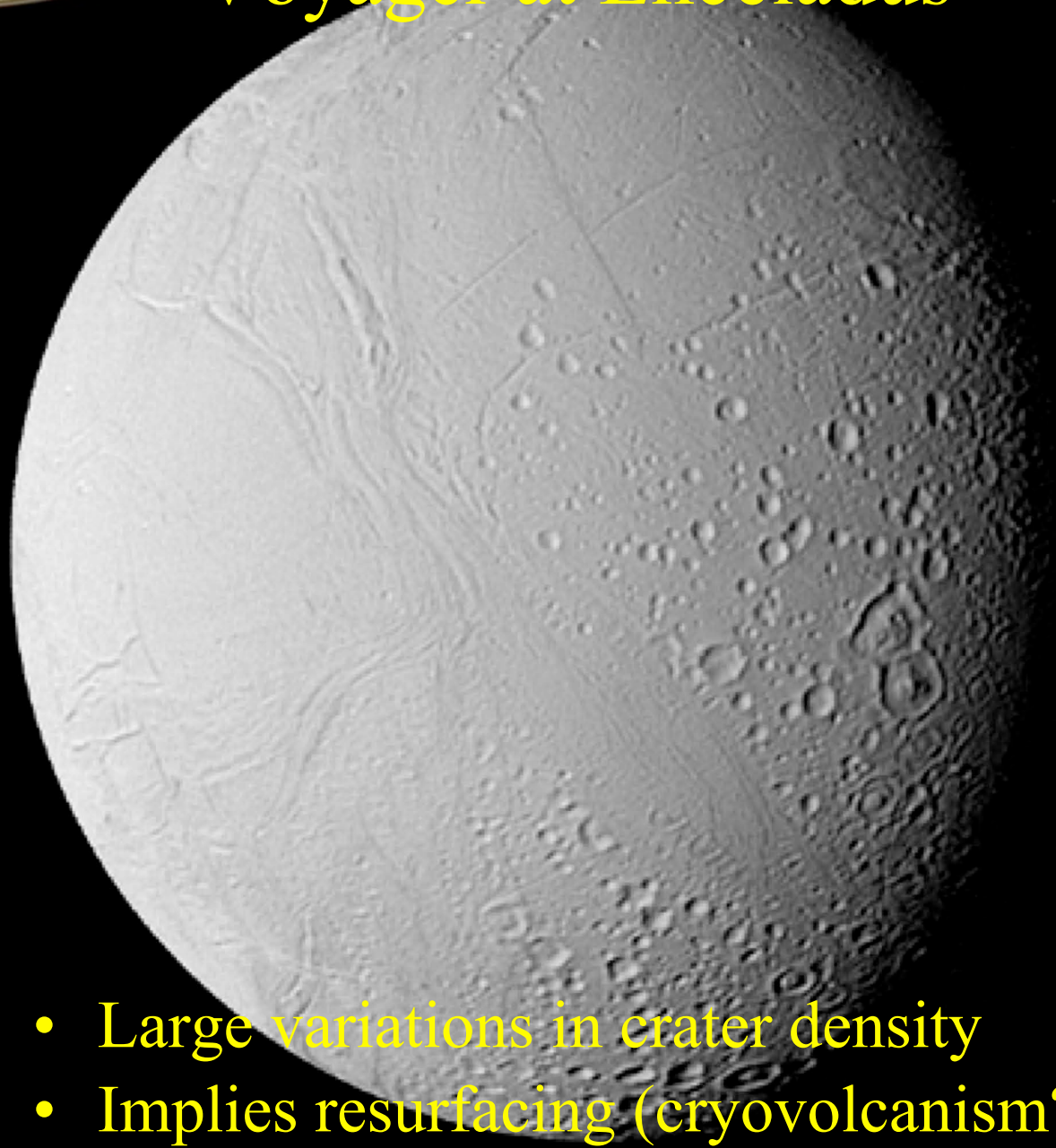
Enceladus



Miranda

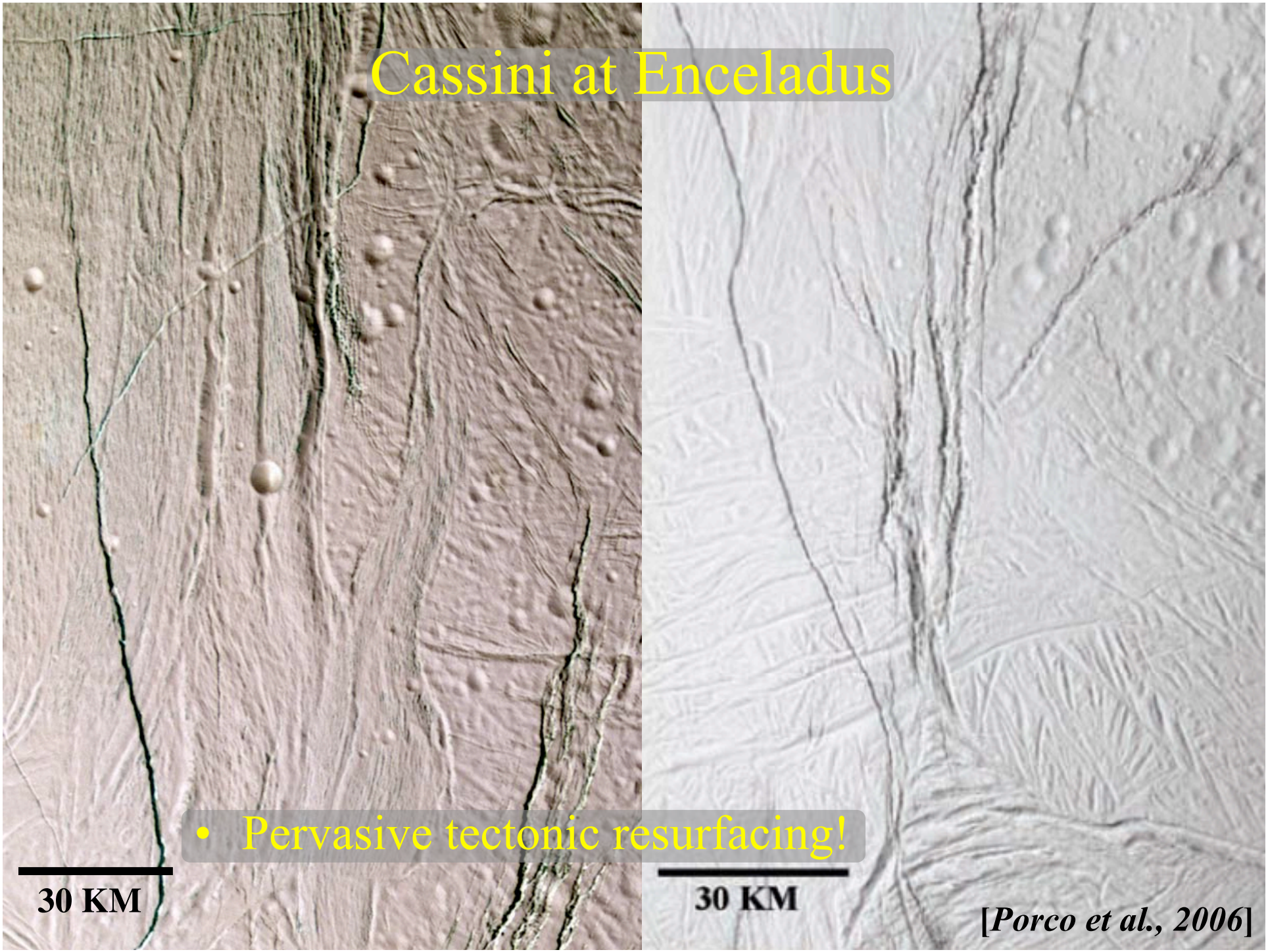
Proteus

Voyager at Enceladus



- Large variations in crater density
- Implies resurfacing (cryovolcanism?).

Cassini at Enceladus

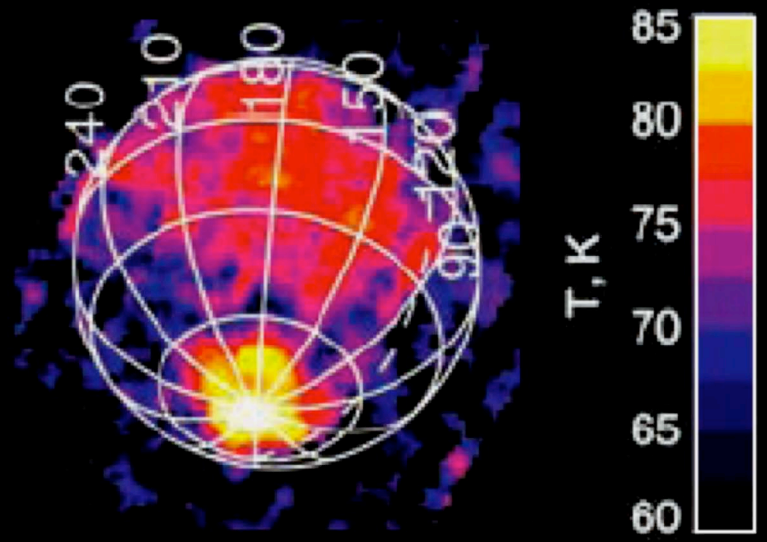


- Pervasive tectonic resurfacing!

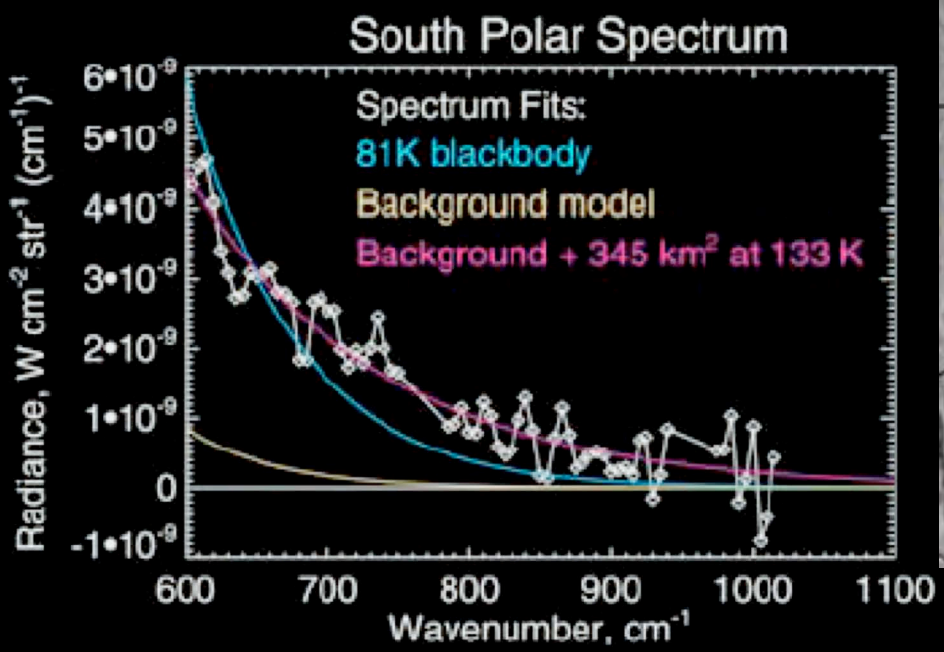
[*Porco et al., 2006*]

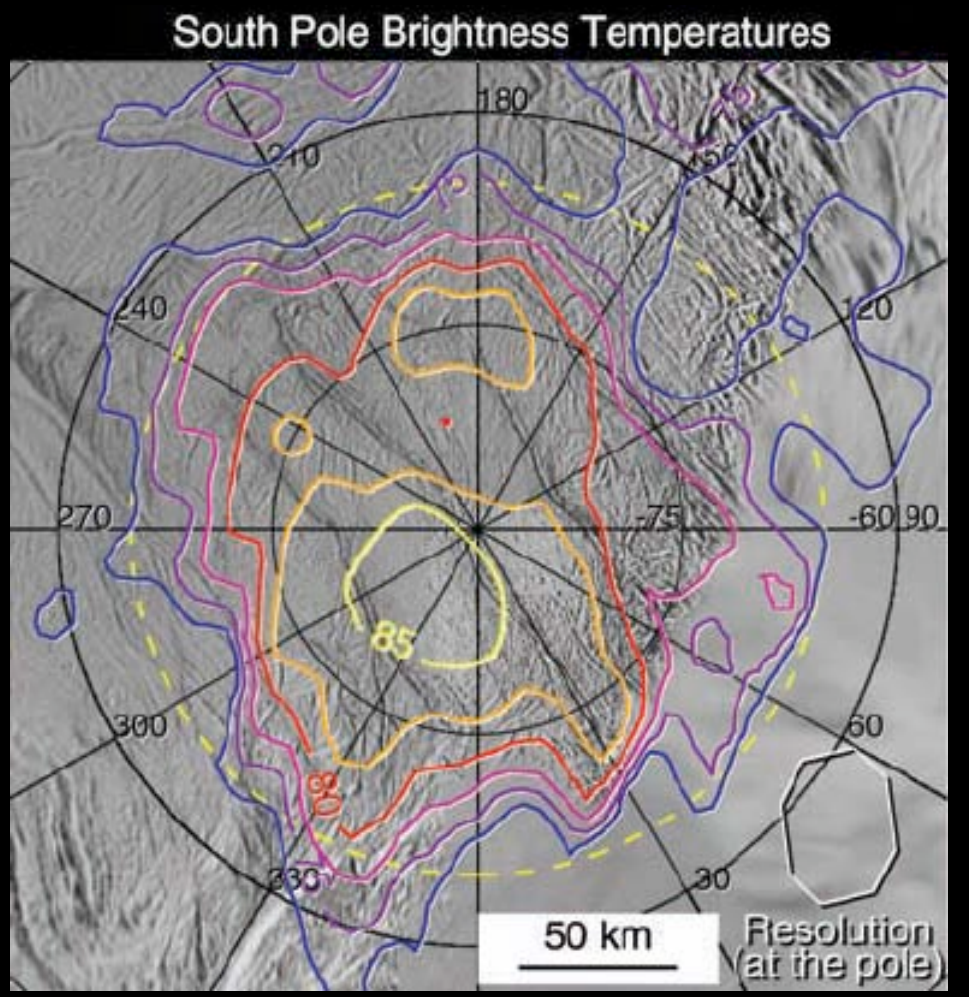
Enceladus: South Polar “Tiger Stripes”

South Polar Hot Spot



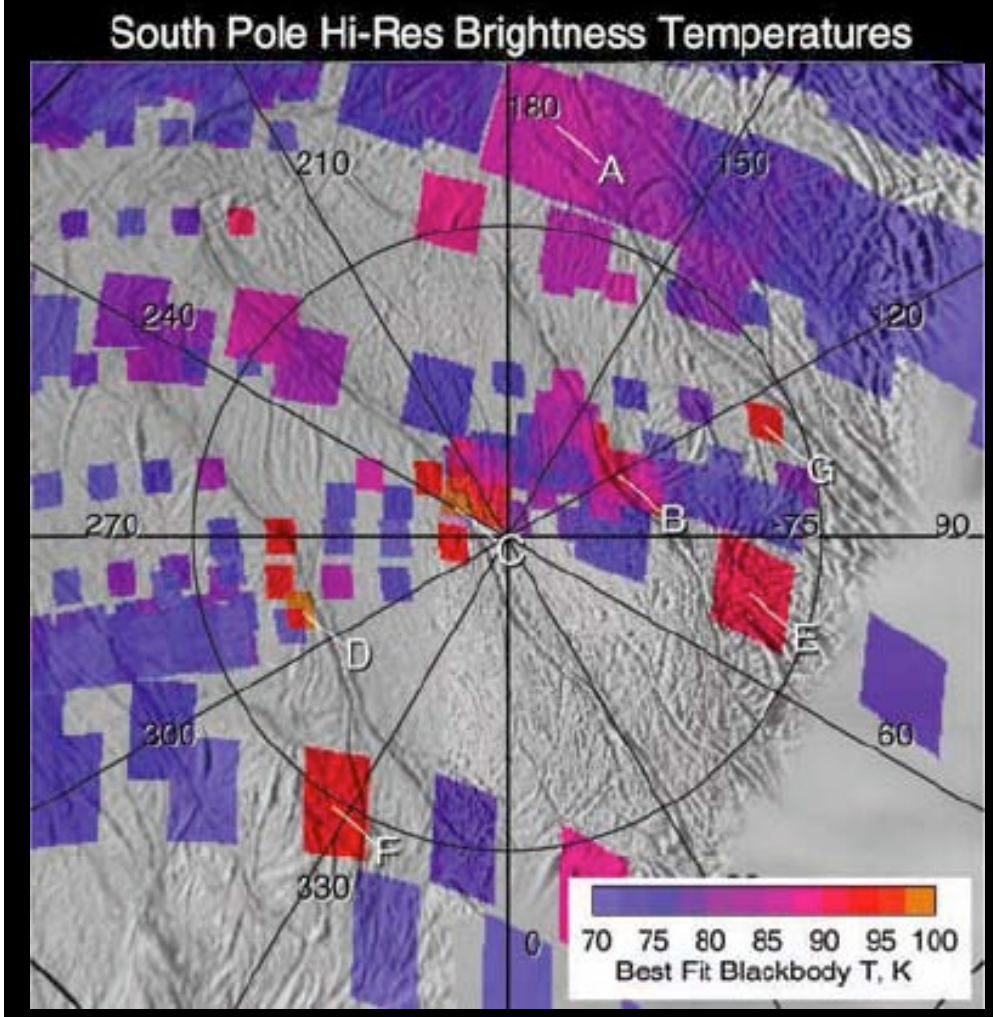
- Total power ~6 GW (~3% Io).

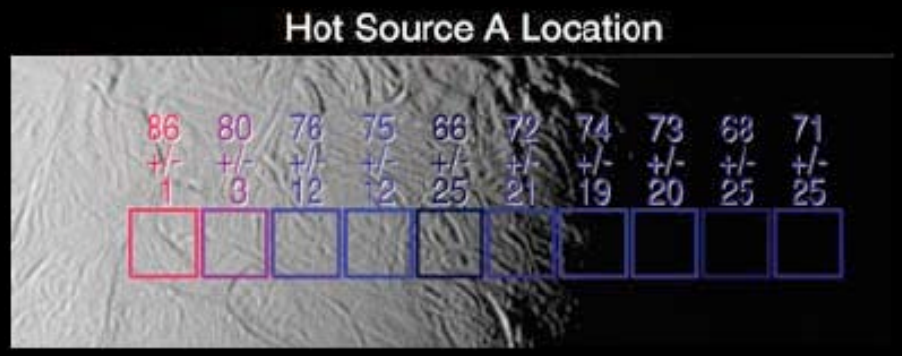


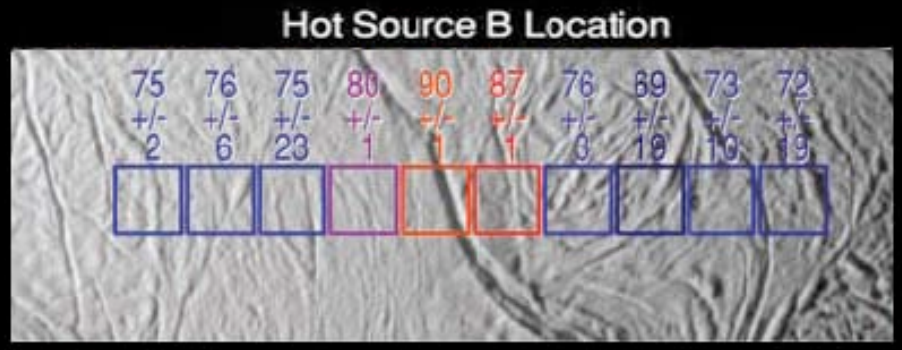


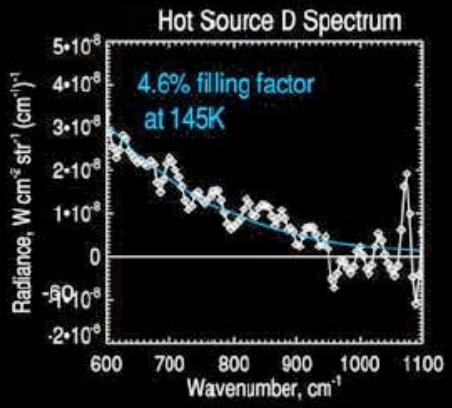
[*Spencer et al., 2006*]

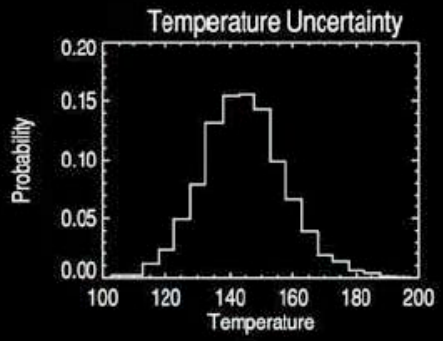
Hot Spots Correlate to "Tiger Stripes"



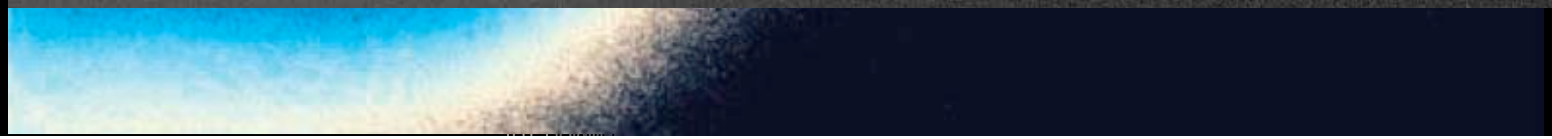




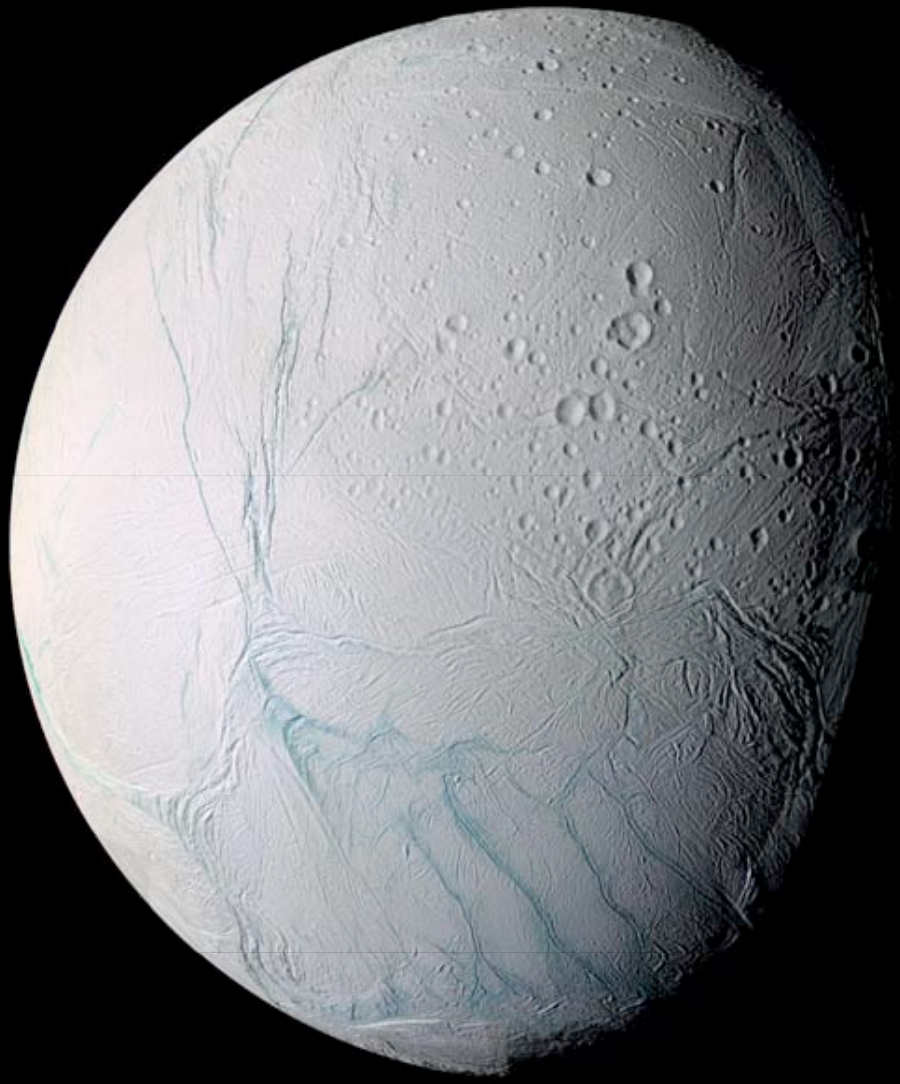


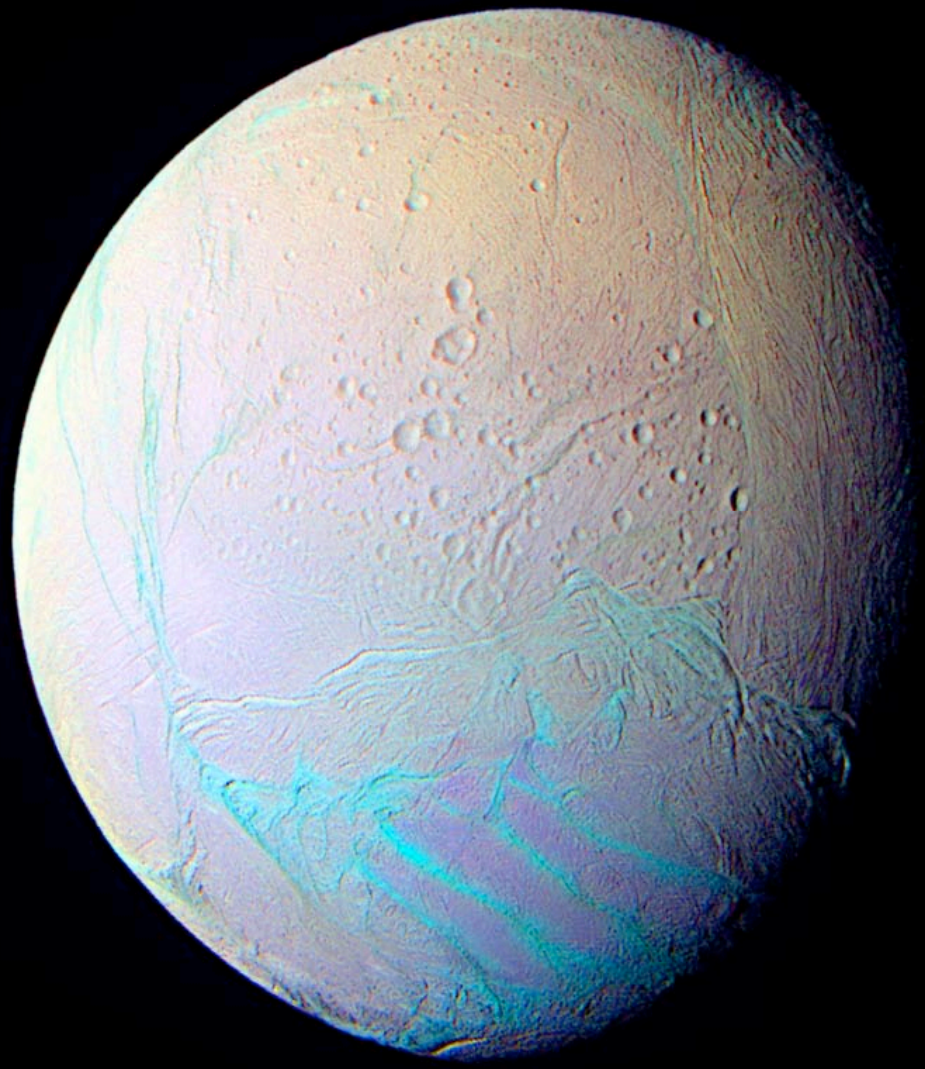


Active Plumes!

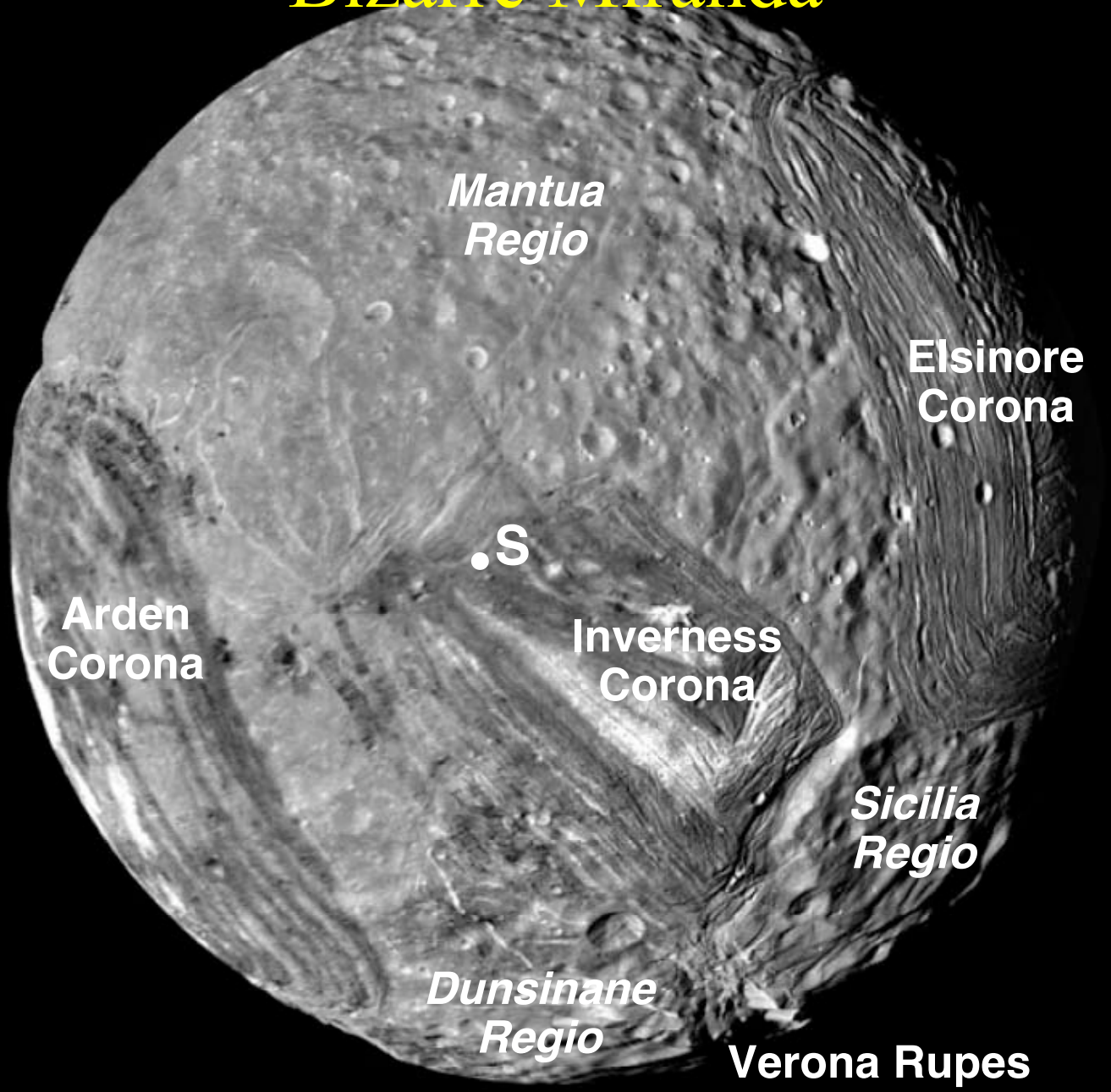


“Tiger Stripes”: Psychedelic Stretch



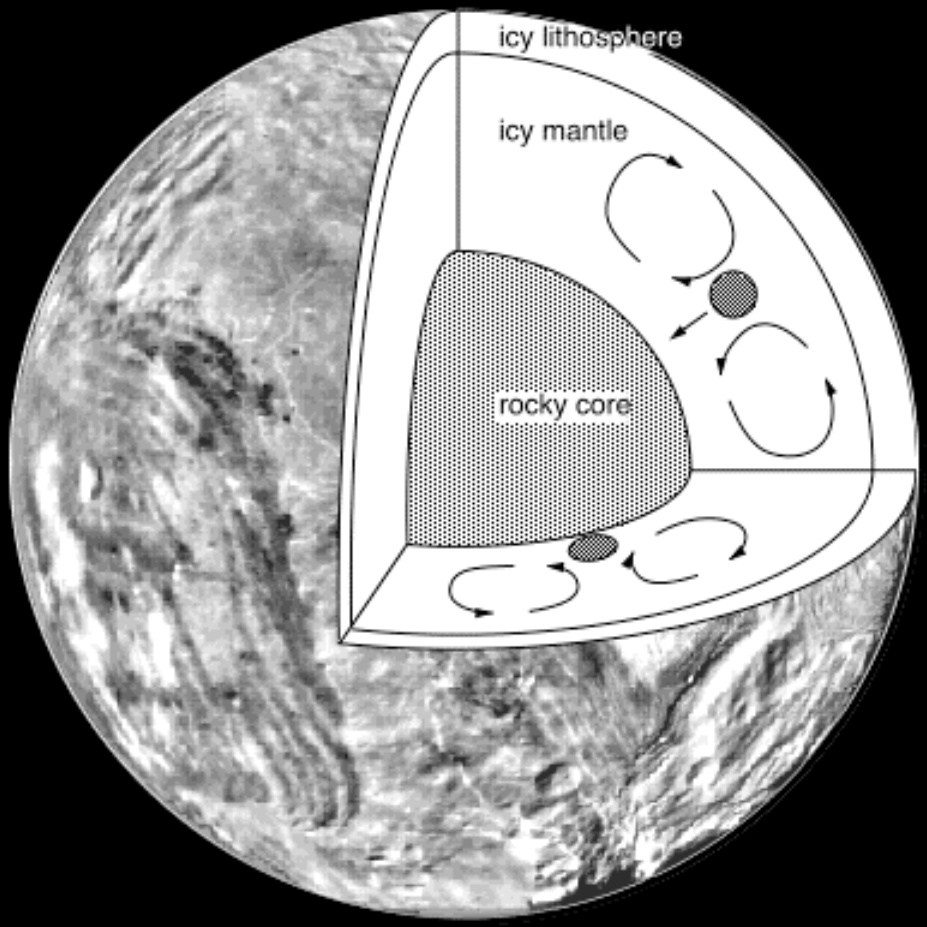


Bizarre Miranda

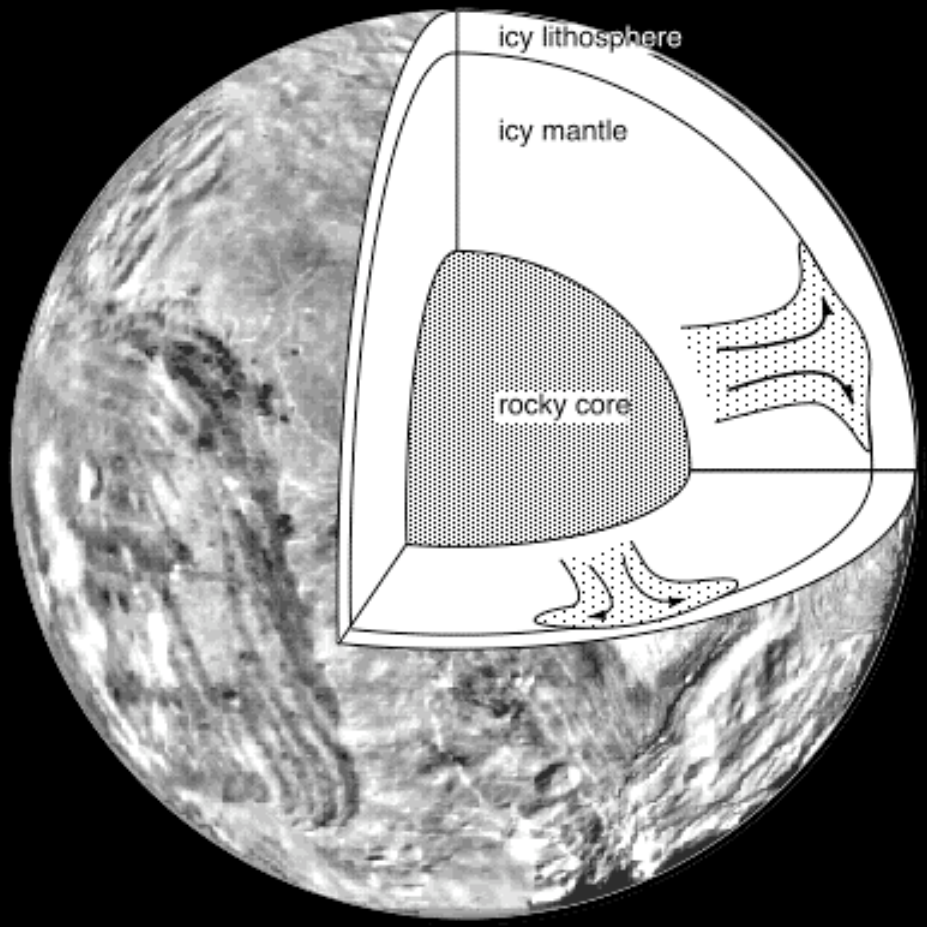


Miranda: Tempest Survivor?

Risers and Sinkers



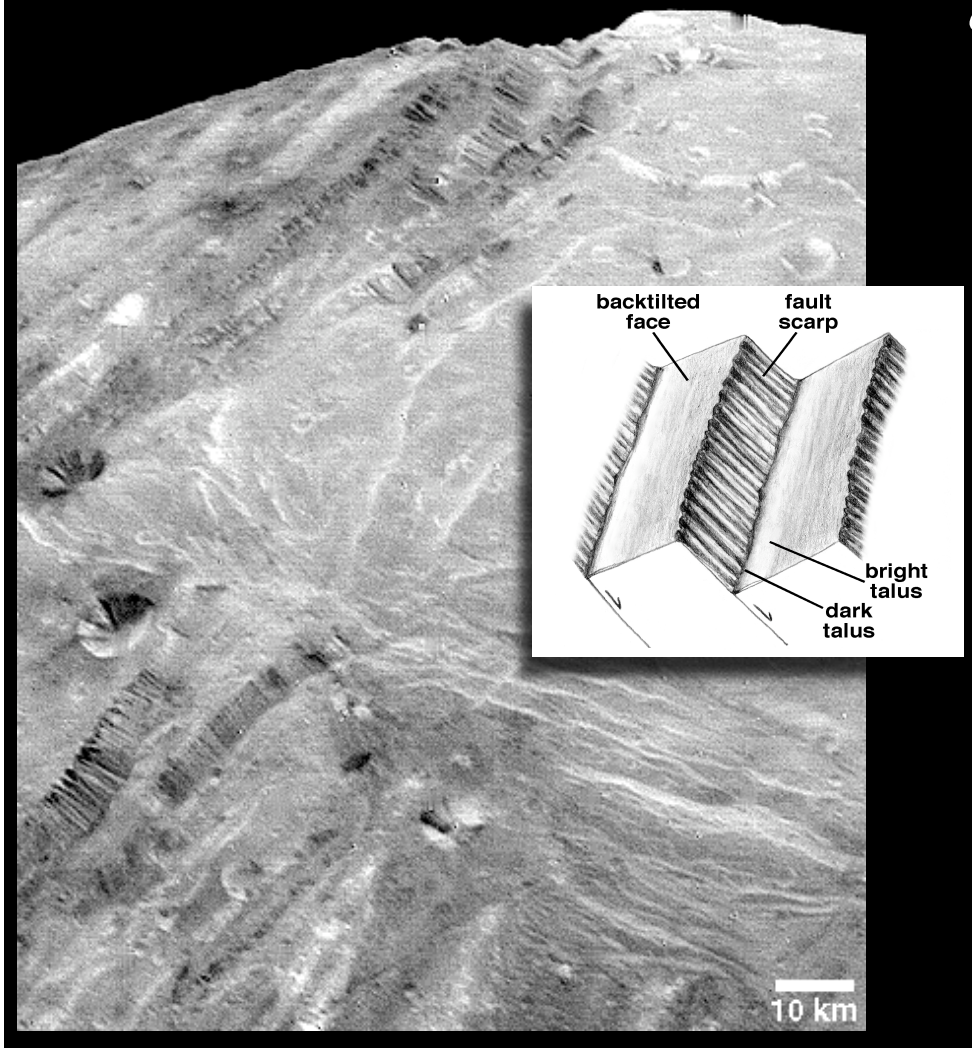
Sinker model
[*Janes & Melosh, 1988*]

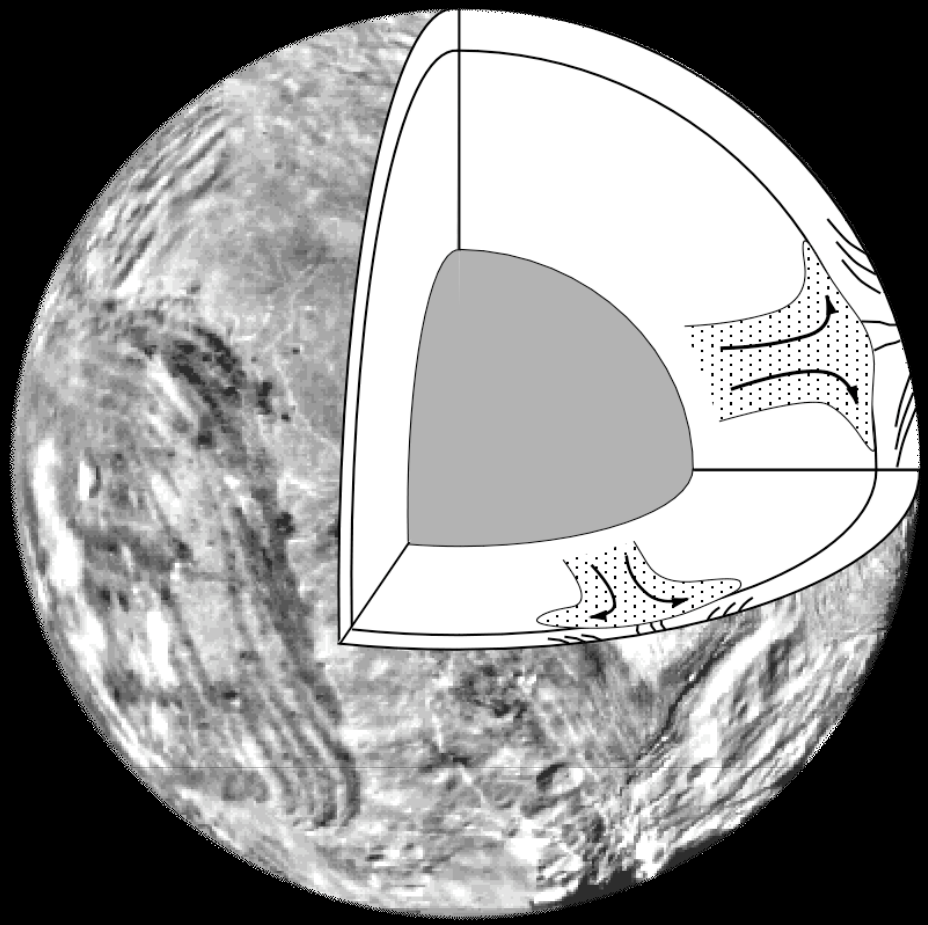


Riser model
[*Croft & Soderblom, 1991*]

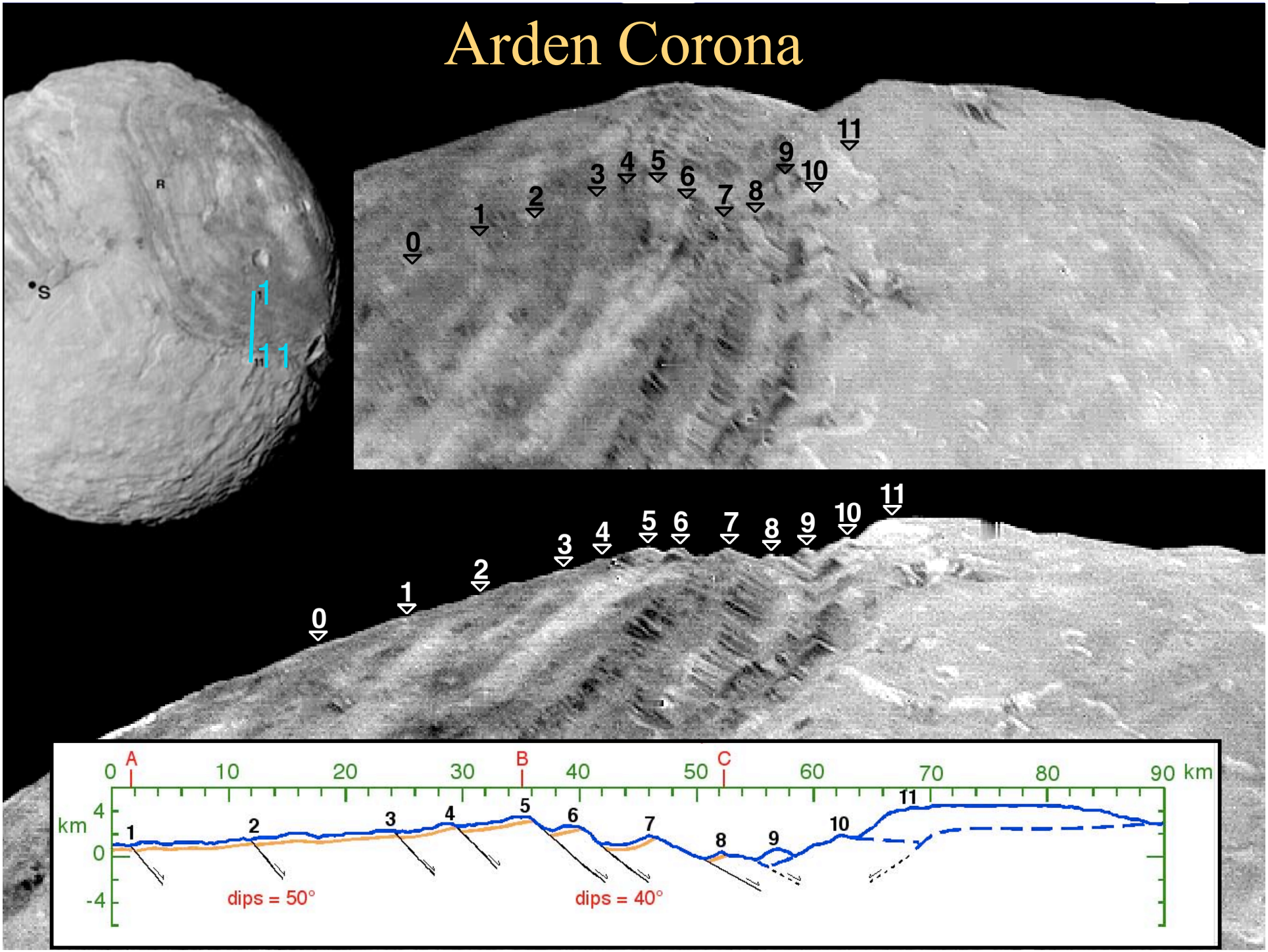
Miranda's Coronae: Origin above Diapirs

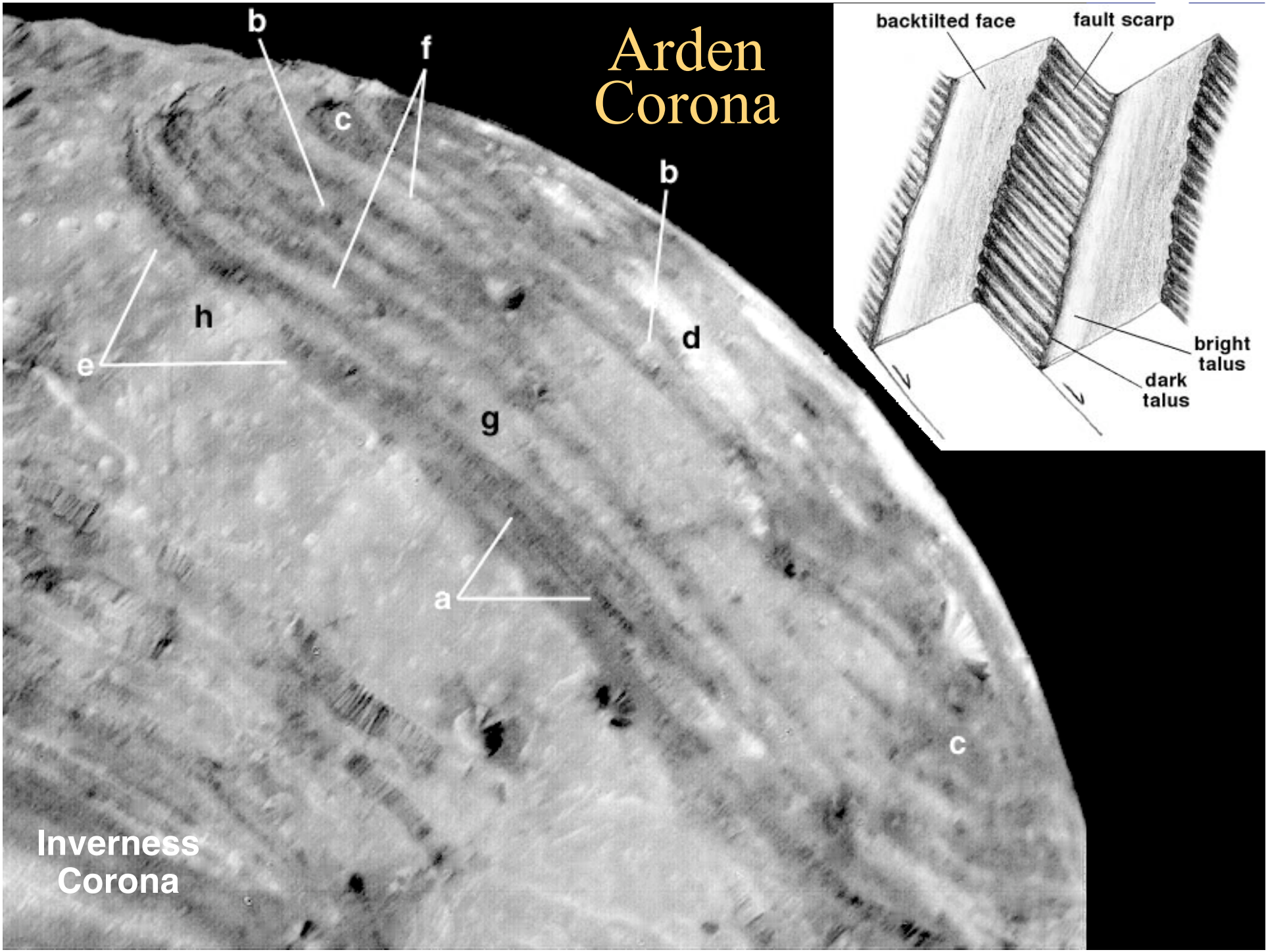
- Extensional structures and cryovolcanism suggest coronae formed above upwelling diapirs [*Johnson et al., 1987; Greenberg et al., 1991; Pappalardo et al., 1997*].

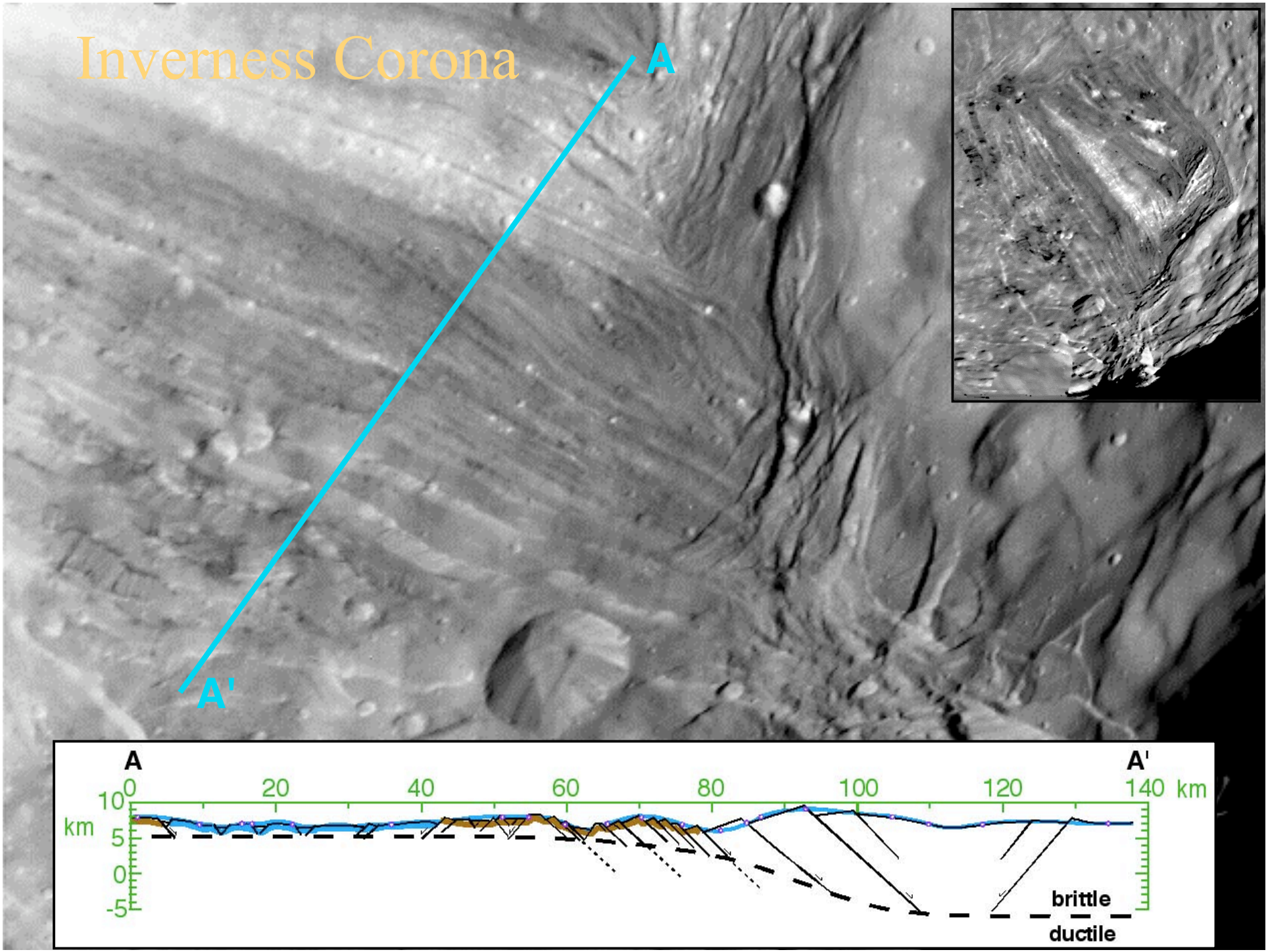


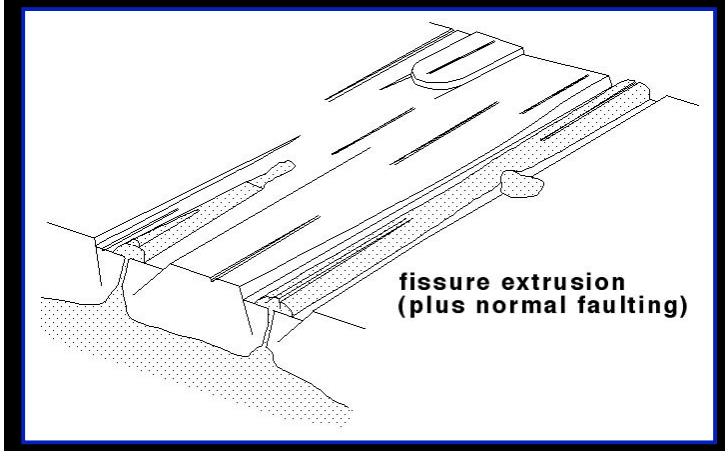


Arden Corona

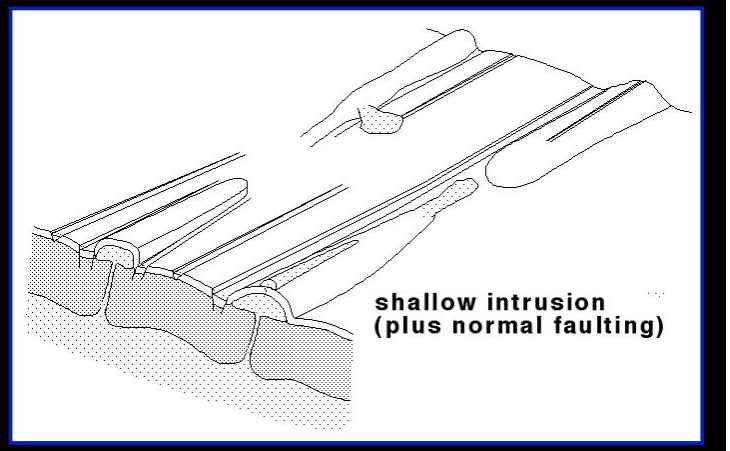


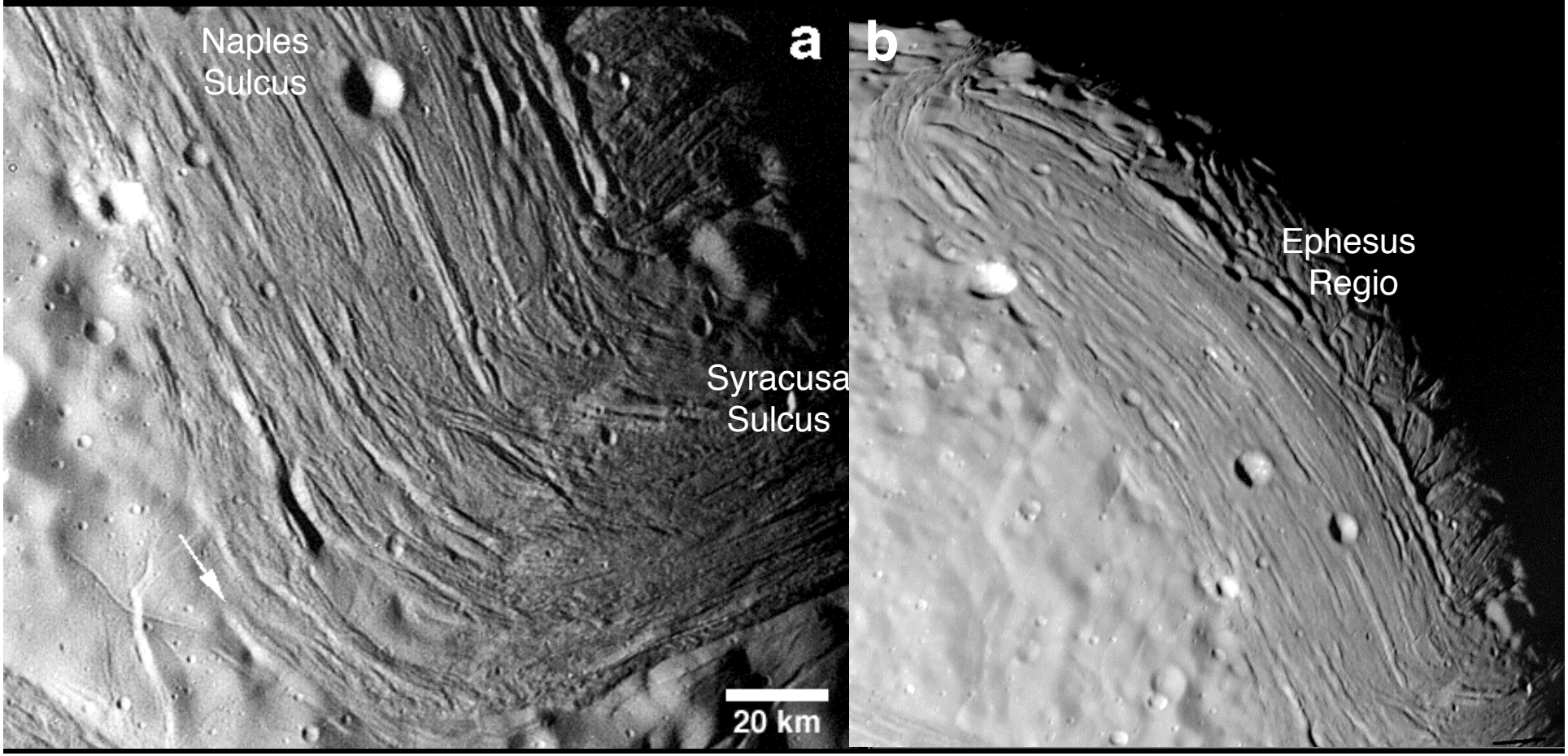

Arden Corona
b
f
c
b
h
e
d
g
a
c
Inverness Corona
backtilted face
fault scarp
bright talus
dark talus


Inverness Corona
A
A'
A
A'
0
20
40
60
80
100
120
140 km
10
km
5
0
-5
brittle
ductile



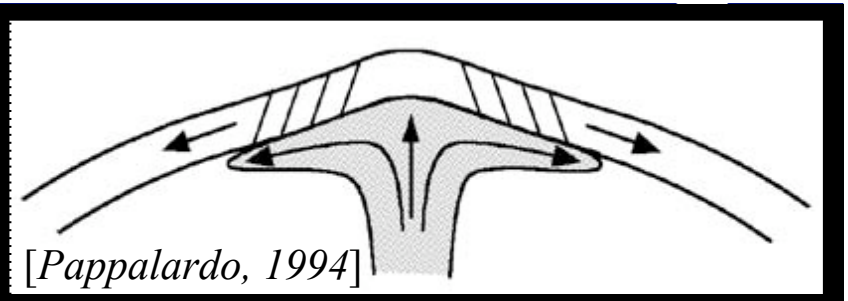
Elsinore Corona



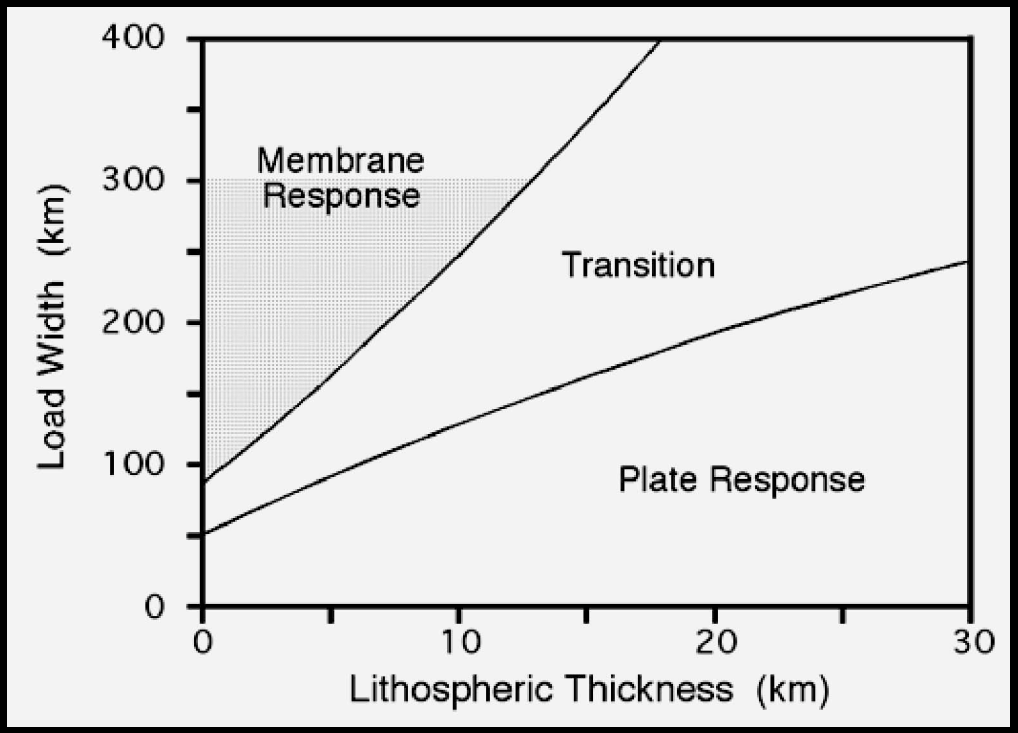


Loading Model

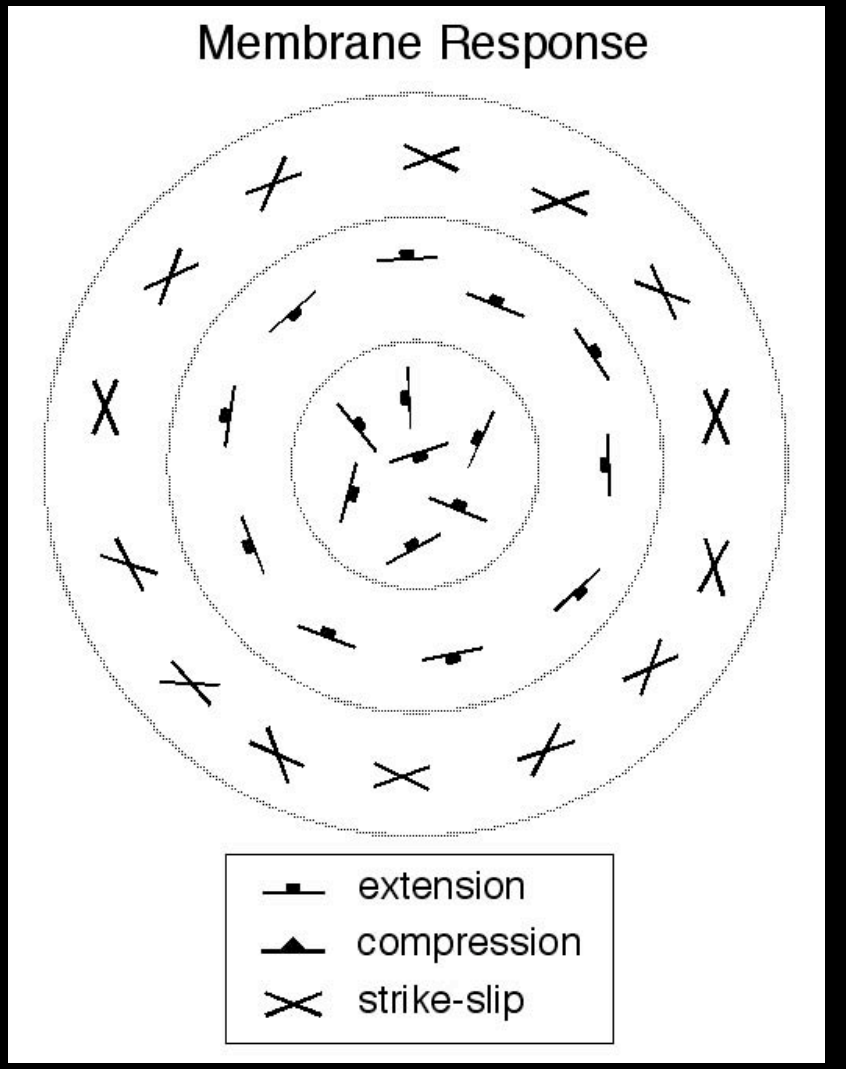
- Corona geology is a good match to upwelling predictions:
  - ◊ Outward facing normal faults.
  - ◊ Broad load on thin lithosphere.



[*Pappalardo, 1994*]

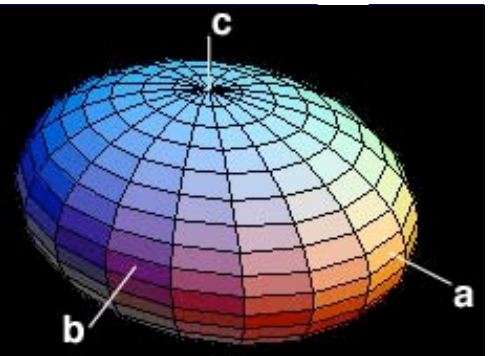


[*Pappalardo, 1994*]

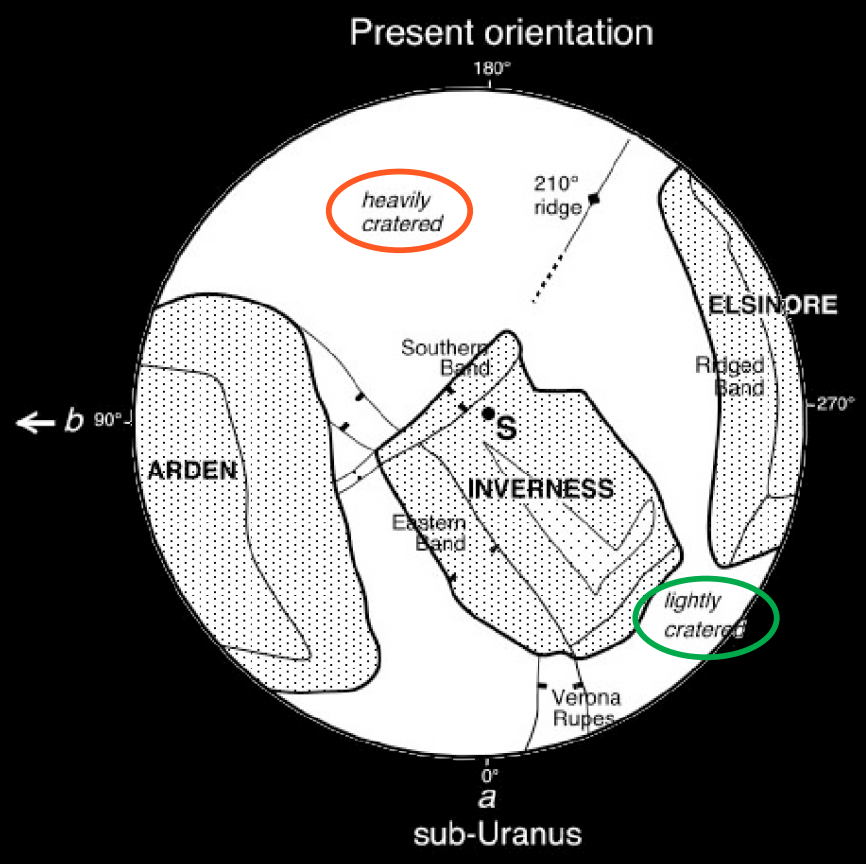


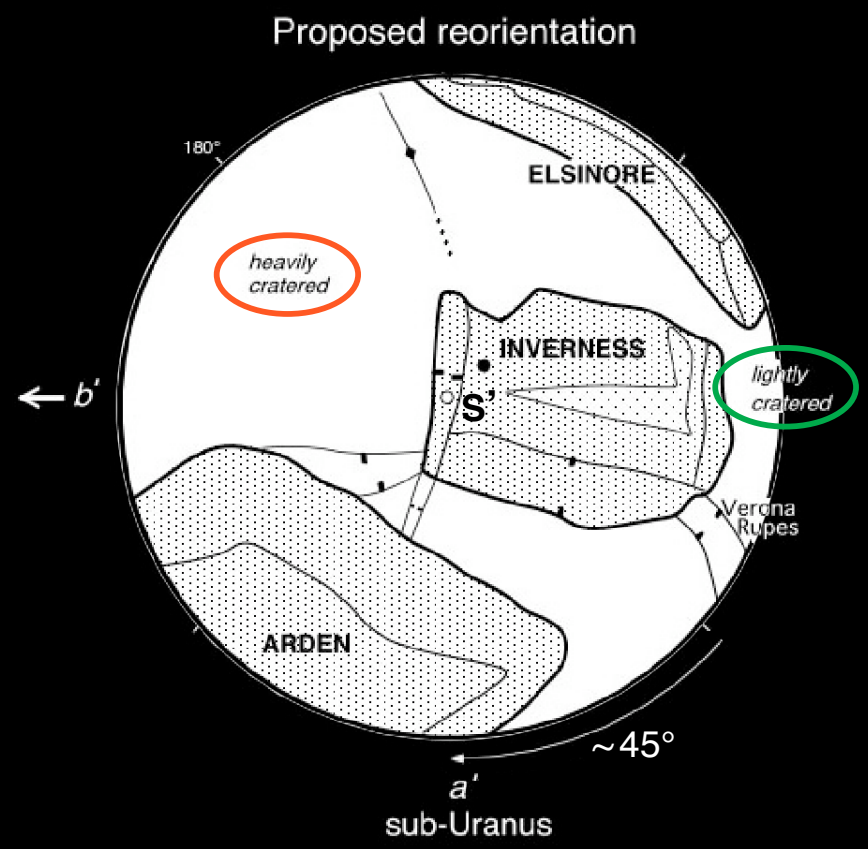
[after *Janes & Melosh, 1988*]

Reorientation of Miranda



- Coronae on greatest inertia axes (c, b) suggests reorientation to place mass deficiencies there [*Janes & Melosh, 1988; Greenberg et al., 1991*].
- Consistent with corona formation by low-density diapirs.
- Supported by craters and structures [*Plescia, 1988; Pappalardo, 1994*].

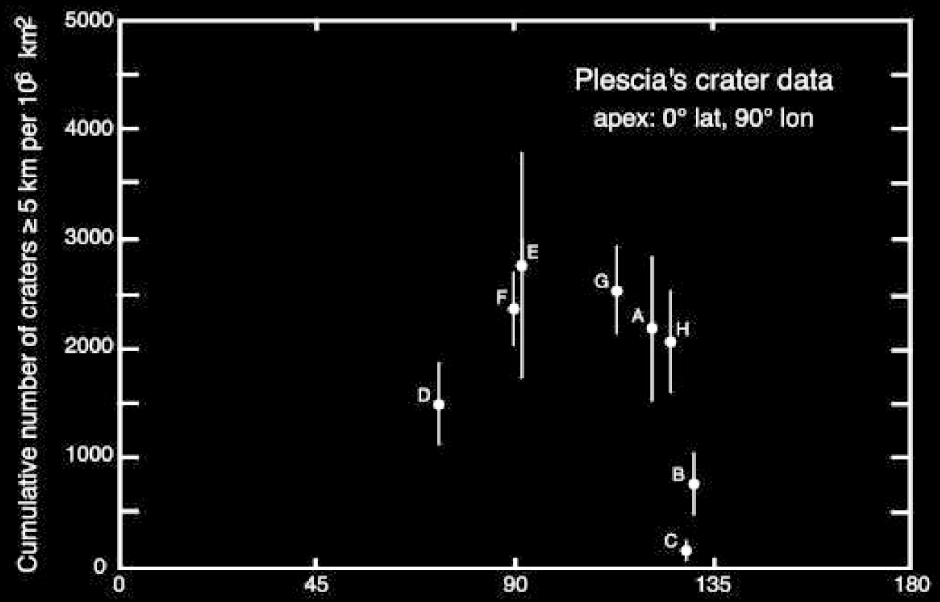


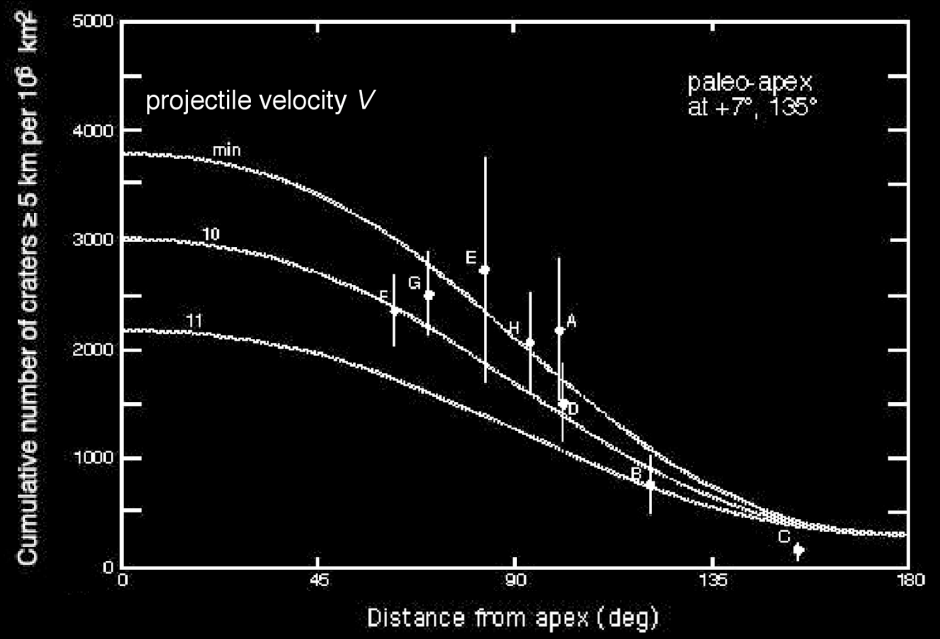


Reorientation of Miranda: Craters

- Miranda fresh crater distribution differs from expected leading-trailing asymmetry [Plescia, 1988].

- Asymmetry restored by reorientation about polar axis.

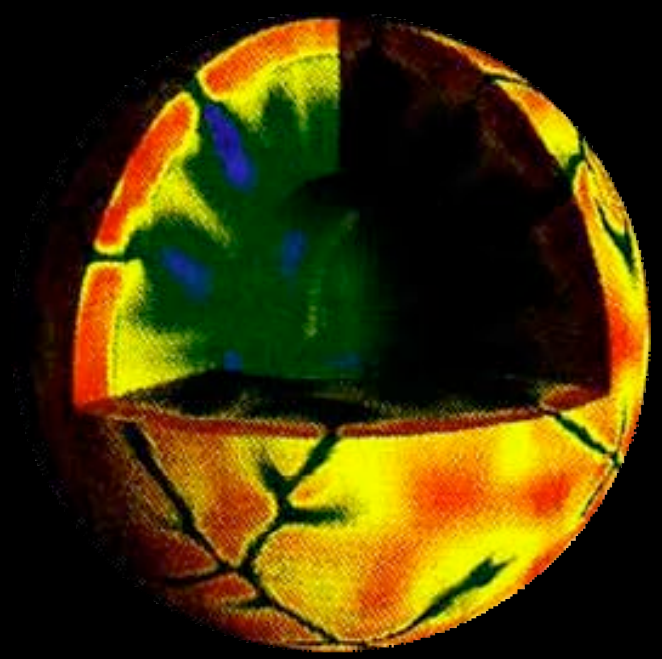




Planetary Reorientation

- *Earth:* Mantle convection can alter mass distribution to induce true polar wander (TPW), including inertial interchange events [*Richards et al., 1997, 1999*].

- *Mars:* Tharsis would reorient to equator [*Willemann, 1984; Bills and James, 1999; Sprenke et al., 2005; Matsuyama et al., 2006*], and dichotomy boundary to pole [*Roberts & Zhong, submitted*].

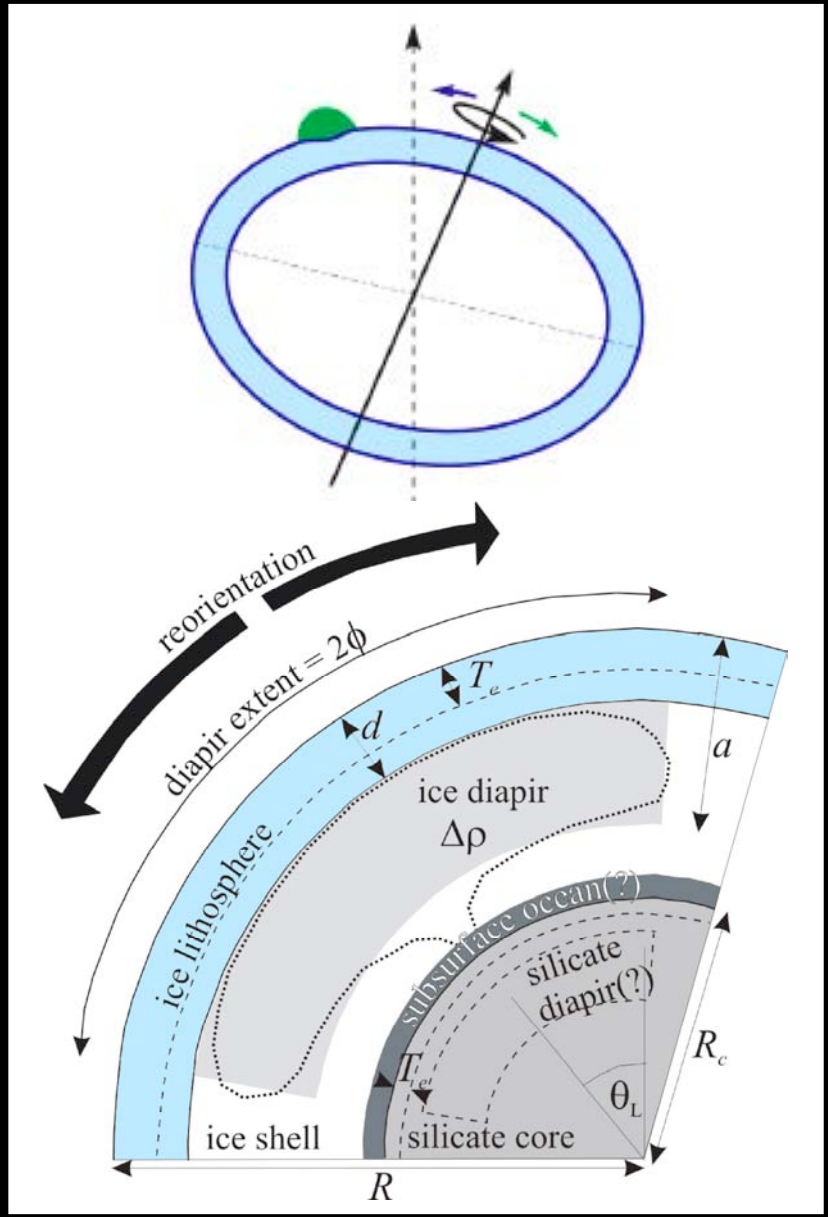


[*Richards et al., 1997*]

[*Roberts & Zhong, submitted*]

Icy Satellite Diapir-Induced Reorientation

- Adapt methods of *Matsuyama et al. (2006)*:
  - ◊ Balance between load-induced TPW and stabilization by fossil rotational **and tidal** bulges.
  - ◊ Lithospheric rigidity affects both fossil bulge size and load compensation *C*, thus TPW.
  - ◊ Uncompensated low-density diapir (*C*=0) is **negative** geoid anomaly: reorients **poleward**.
  - ◊ If compensated (*C*=1), upwarped topography is **positive** geoid anomaly: reorients **equatorward**.



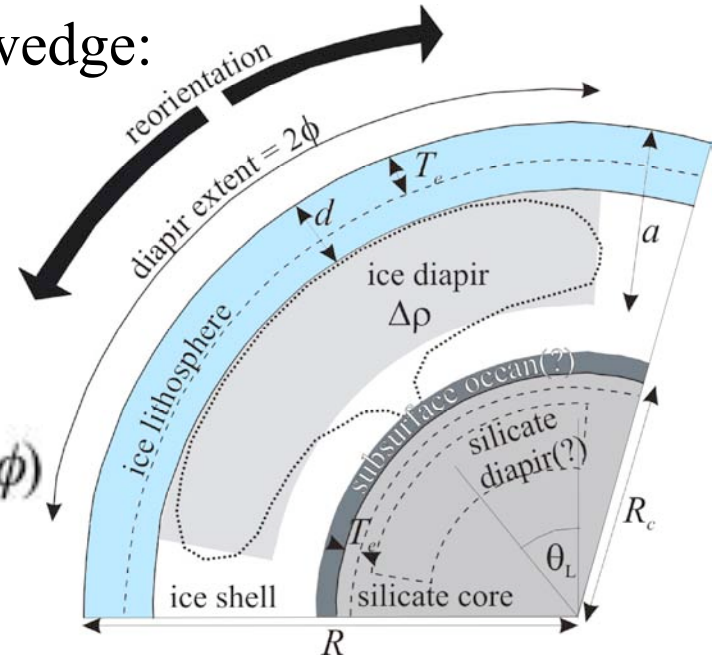
Modeling Diapir-Induced Reorientation

- Diapir modeled as low-density spherical wedge:

$$2\pi R_t^{\,2}\Delta\rho(a-d)(1-\cos\phi)\left\{1-\frac{a+d}{R_t}+\frac{e^2}{3R_t^{\,2}}\right\}$$

ϕ = angular radius of diapir

$e^2 = a^2 + ad + d^2$; assume $T_e = 0.4\,d$



- Mass excess at surface: $C2\pi\rho R_t^{\,2}h(1-\cos\phi)$

h = isostatic surface topography

C = degree of compensation ($0 < C < 1$)

- Angular reorientation due to load: $\boxed{\delta = \frac{1}{2}\tan^{-1}\left(\frac{Q^*\sin 2\theta_L}{n - Q^*\cos 2\theta_L}\right)}$

where $Q^* = \dfrac{3\sqrt{5}G_{20}}{R^2\Omega^2(k_2^f - k_2)}$; n=1 for b-axis, n=4 for a-axis

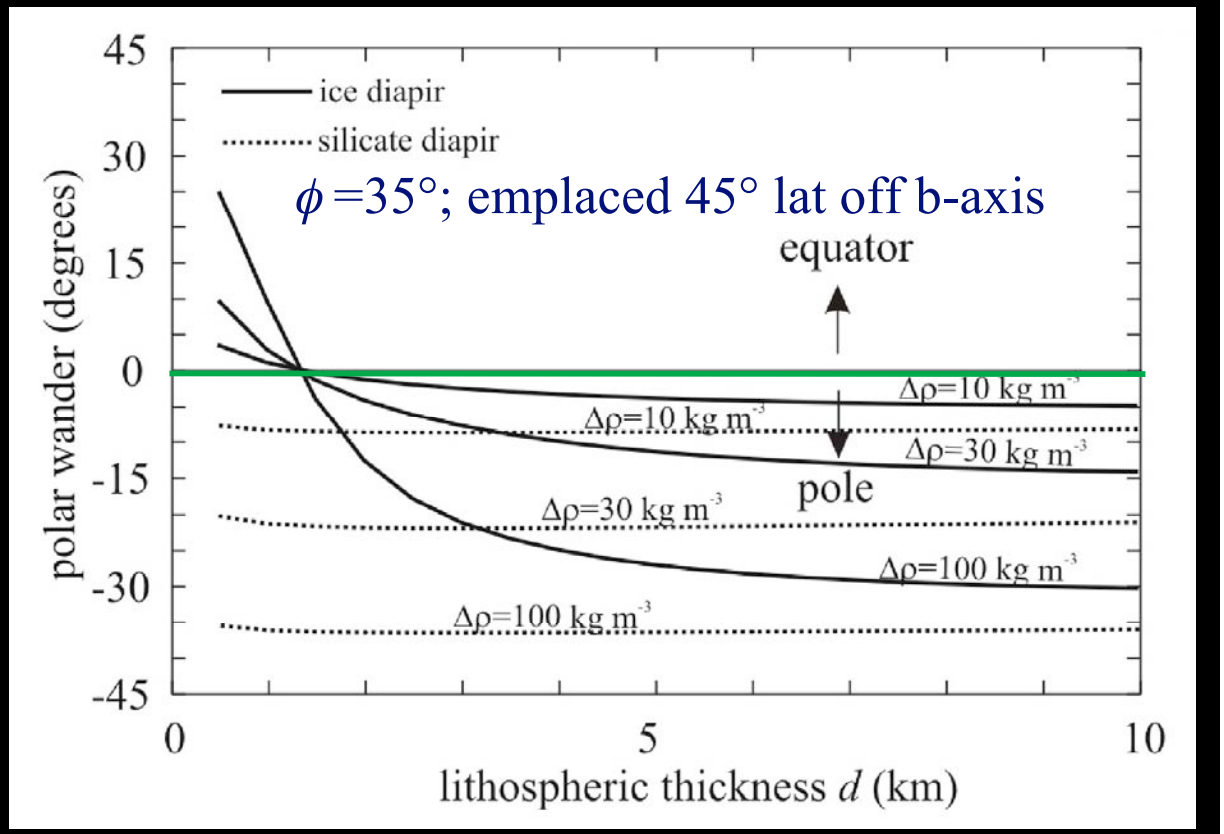
G_{20} = degree 2 component of gravitational potential due to diapir

k_2, k_2^f= Love numbers with and without an elastic lithosphere

Ω = angular rotation rate

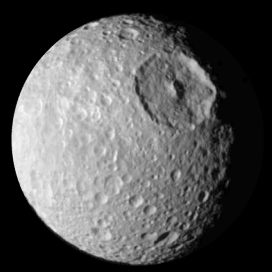
Diapir-Induced Reorientation: Results

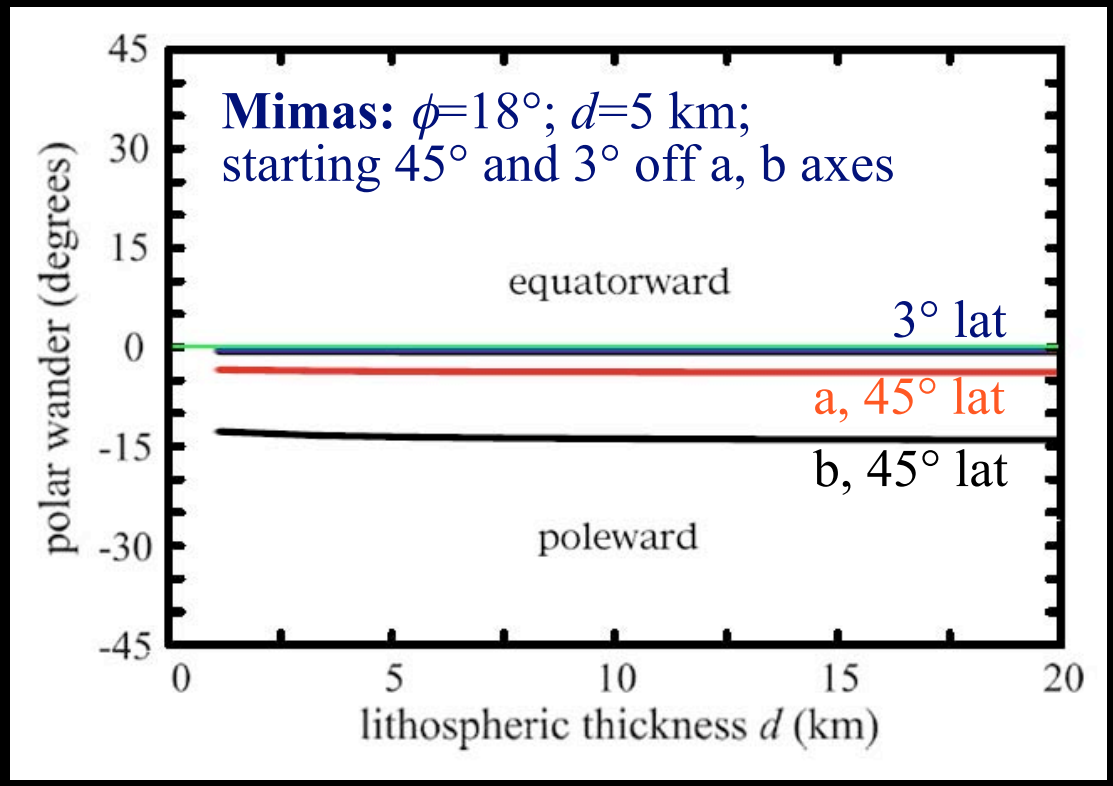
- For **ice diapir**, poleward reorientation up to ~30° for $d > 1.5$ km:
  - ◊ Large $\Delta\rho \approx 100$ kg m^3 ⇒ **thick ice and compositional diapirism**.
- For **silicate diapir**, similar reorientation amount ($C \approx 0$):
  - ◊ Coupling to ice ⇒ **no global ocean**.
- Reorientation is dependent on emplacement location.
- Results insensitive to k_2.
- Greater reorientation if silicate diapir triggers ice diapir.



Reorientation by Large Craters

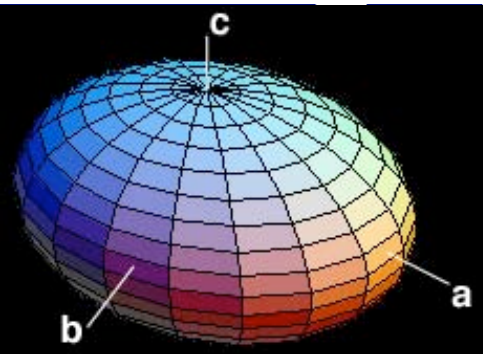
- Herschel-sized crater would reorient Mimas poleward:
  - ◊ Up to ~15° reorientation.
  - ◊ Location near equator suggests formation there, or mascon.
- Similar arguments apply to Pharos on Proteus:
  - ◊ But significant irregular topography complicates the issue.

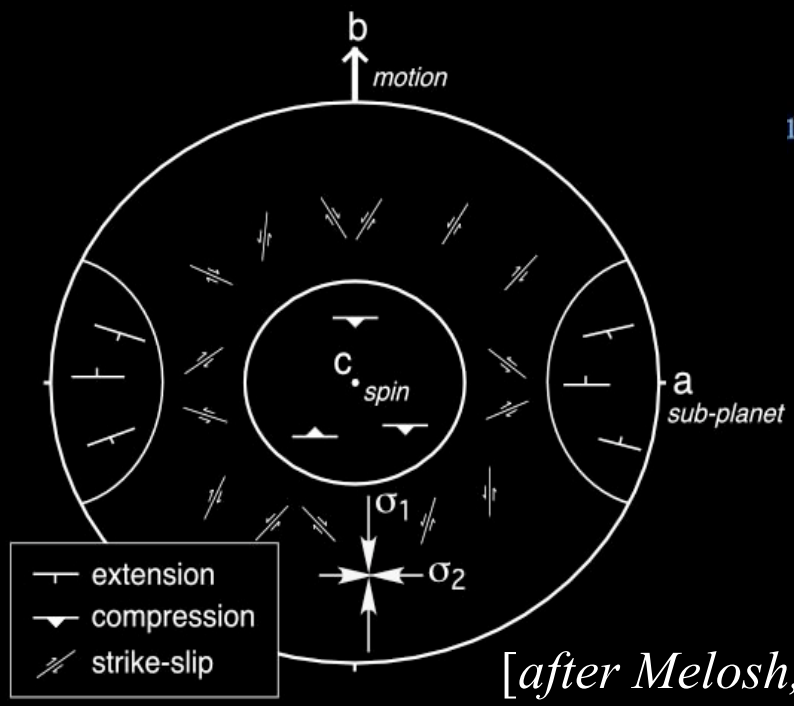




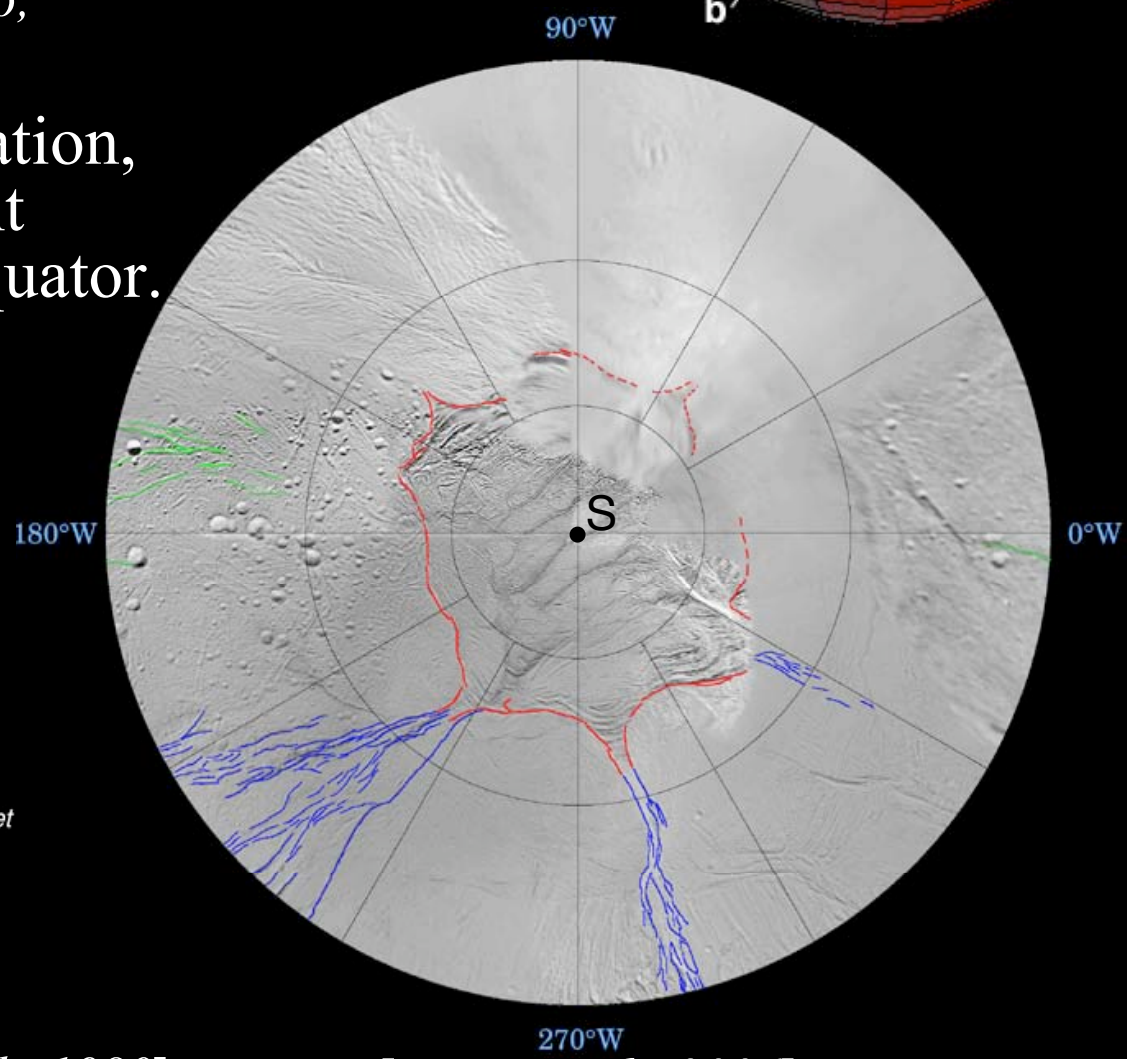
Reorientation Tectonics

- Tectonics suggest spin axis flattening [*Porco et al., 2006; Helfenstein et al., 2006*].
- Consistent with reorientation, which "squashes" current spin axis and expands equator.
- Stresses ~10 MPa.





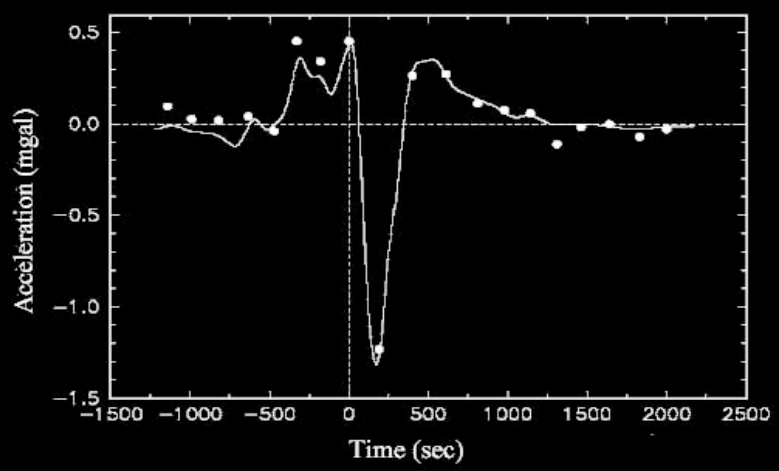
[*after Melosh, 1980*]

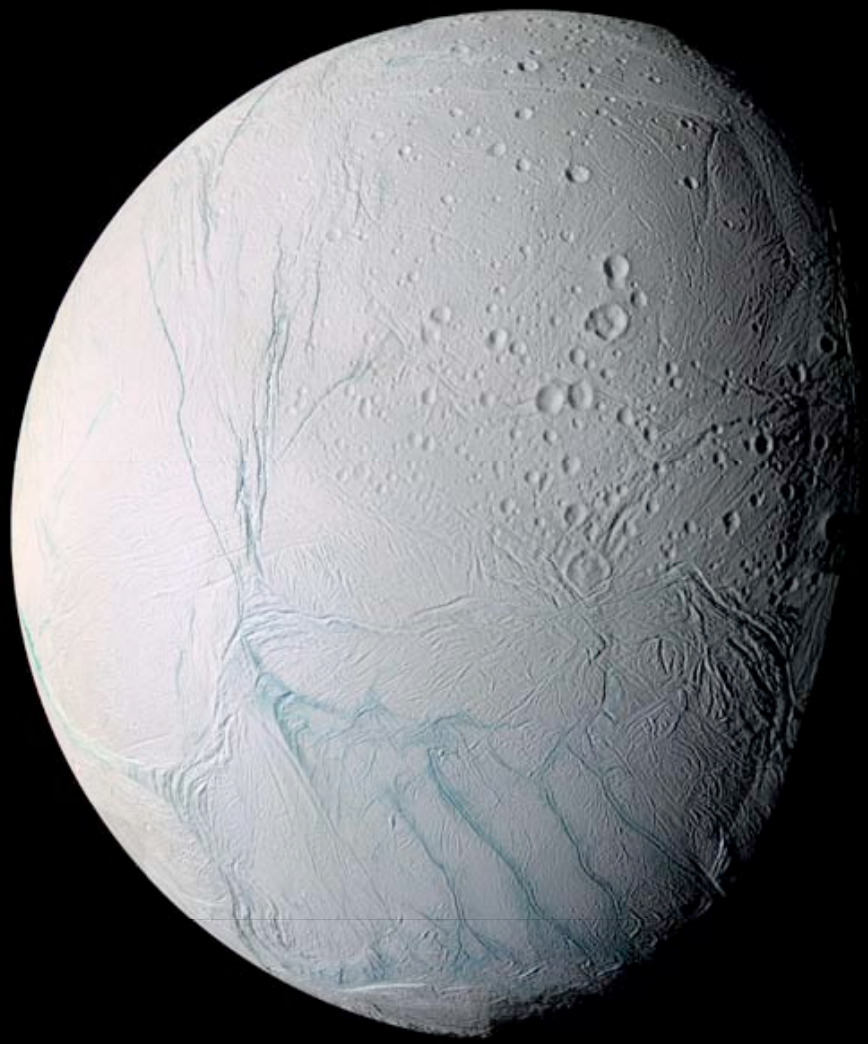


[*Porco et al., 2006*]

Additional Tests of Reorientation Model

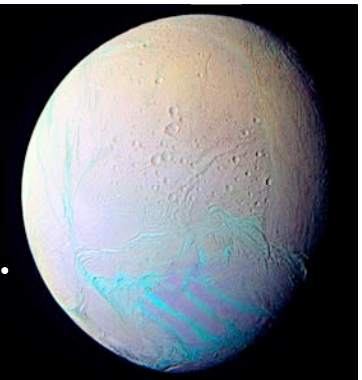
- Reorientation should affect crater distribution by affecting leading-trailing asymmetry:
  - ◊ Decipherable from imaging.
- Gravity anomaly should be associated with diapir:
  - ◊ A few mGal from 200 km.
  - ◊ Similar anomalies detected at Ganymede by Galileo.



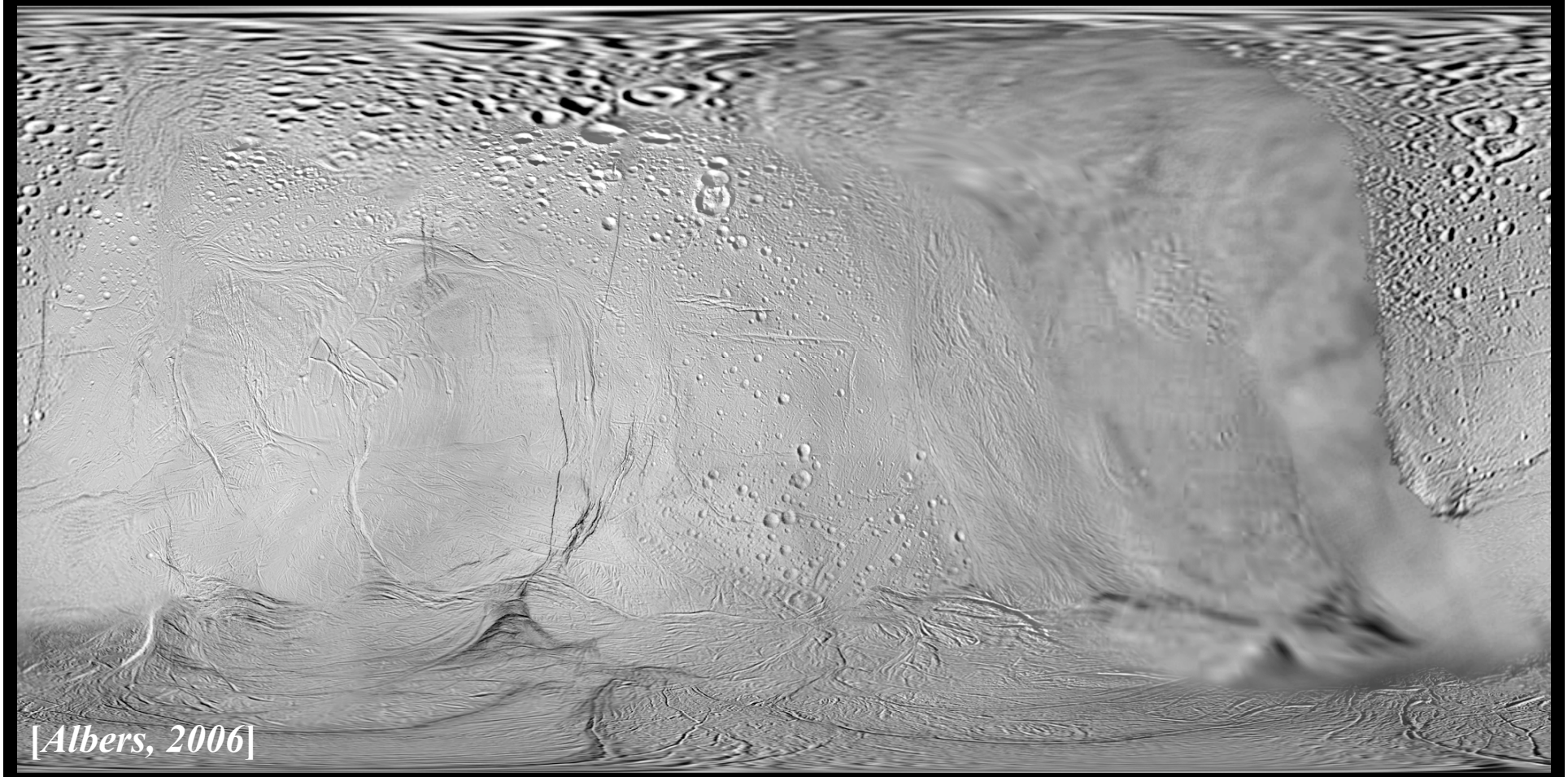


[*Palguta et al., 2006*]

Enceladus Global Map

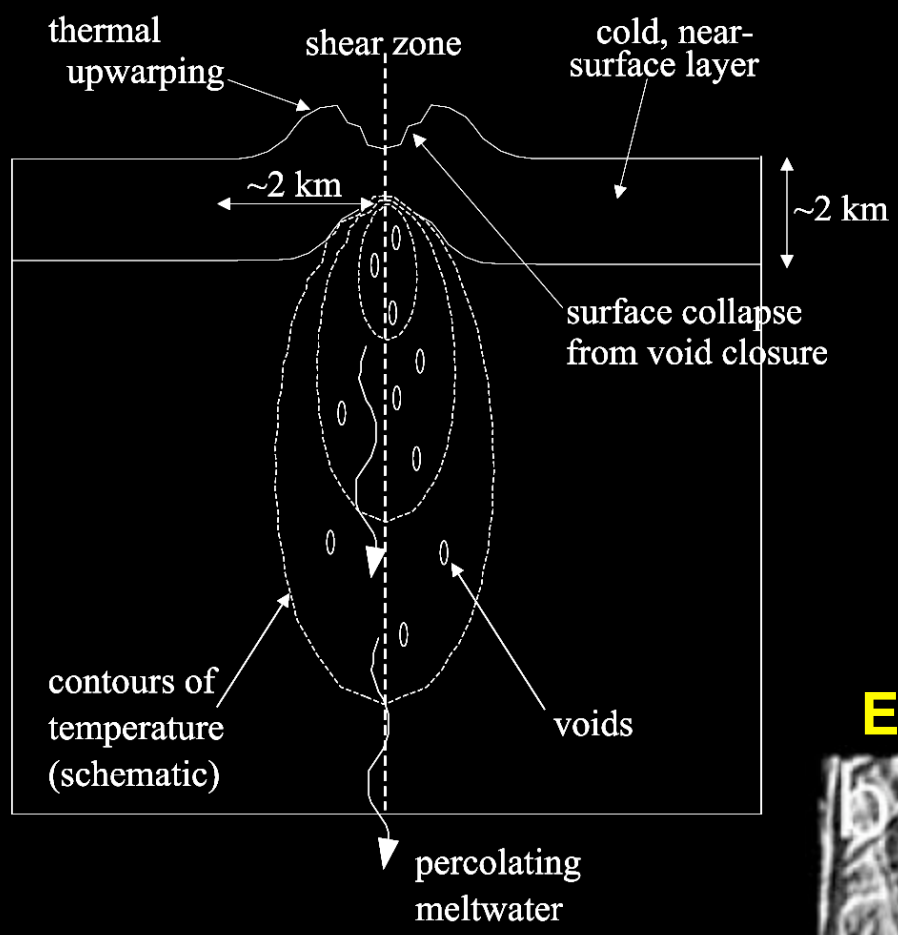


- Geologically active areas along leading & trailing points...
- Multiple diapiric and reorientation events?



360° trailing hemisphere 180° leading hemisphere 0°

Tidal Heating on Enceladus

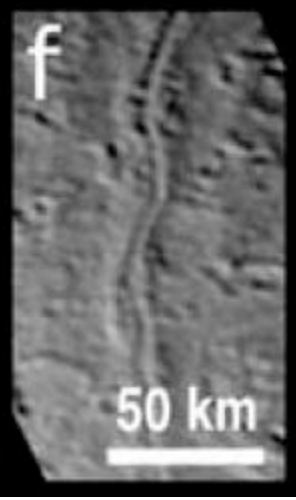


[*Nimmo & Gaidos, 2002*]

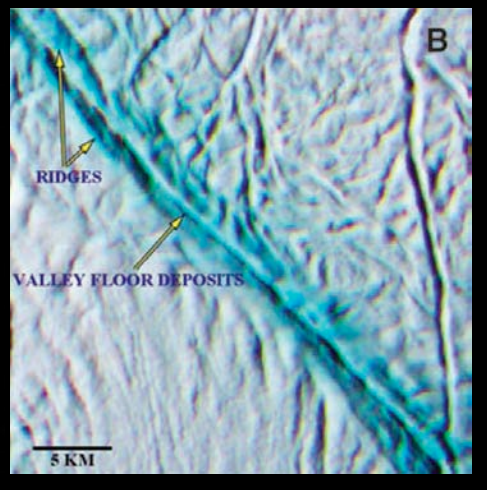
- Presumed tidal heat source [*Ross & Schubert, 1989; Matson et al., 2006*].
- Tidal heating would concentrate in warm diapir.
- Shear heating in lithosphere may explain warm tiger stripes [cf. *Nimmo & Gaidos, 2002*].

Europa

Triton

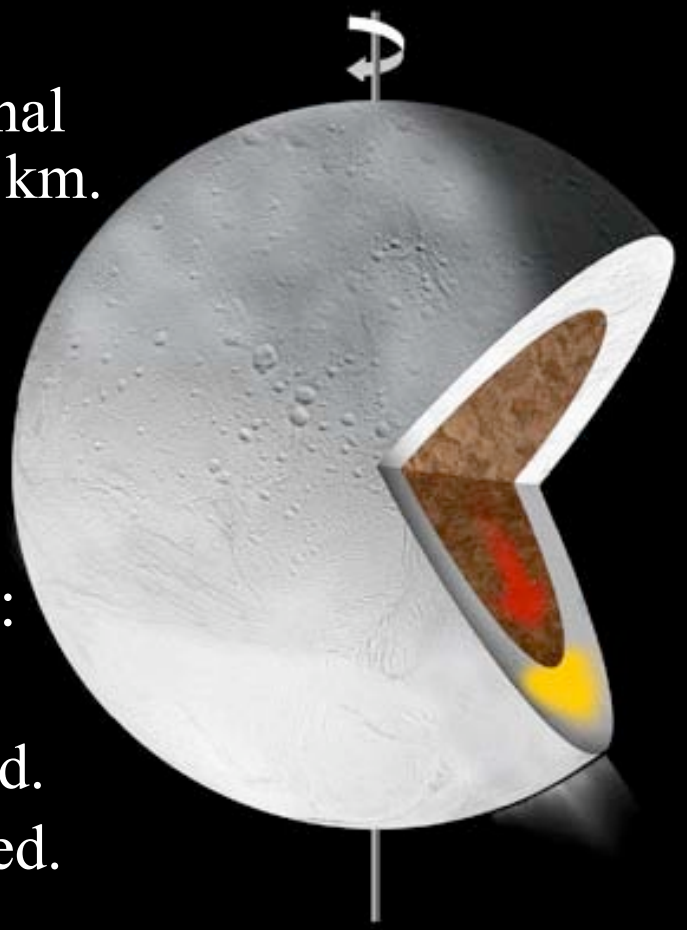


Enceladus



Reorientation of Mini-Moons: Conclusions

- Large diapir within Enceladus can reorient active region to south pole:
  - ◊ Ice diapir ⇒ thick shell, compositional buoyancy, rigid lithosphere $T_e > 0.5$ km.
  - ◊ Silicate diapir ⇒ no global ocean.
  - ◊ These may combine.
  - ◊ But Enceladus cannot have both a thin ice shell and a global ocean.
- Tests of diapir-induced reorientation:
  - ◊ Tectonic record: polar flattening!
  - ◊ Cratering record: asymmetry affected.
  - ◊ Gravity: detectable anomaly predicted.



Diapir-Induced Reorientation: Future Work

- Origin and nature of large diapirs.
- Relative timing of diapir rise, lithosphere thickness, tidal heating, and reorientation.
- Multiple heating-diapir episodes?
- Effect of emplacement position.
- Miranda's apparent a→b-axis reorientation, and timing of corona formation.
- Consideration of other mid-sized icy satellites (including Mimas).
- Future Cassini tests for Enceladus and other satellites.