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.
Voyager at Enceladus

- Large variations in crater density
- Implies resurfacing (cryovolcanism?).
• Pervasive tectonic resurfacing!

[Cassini at Enceladus]

[Porco et al., 2006]
Enceladus: South Polar “Tiger Stripes”
South Polar Hot Spot

- Total power $\sim 6$ GW ($\sim 3\%$ Io).

[Spencer et al., 2006]
Hot Spots Correlate to “Tiger Stripes”
Active Plumes!
“Tiger Stripes”: Psychedelic Stretch
Miranda: Tempest Survivor?

John William Waterhouse
Risers and Sinkers

Sinker model
[Janes & Melosh, 1988]

Riser model
[Croft & Soderblom, 1991]
Miranda’s Coroanes: Origin above Diapirs

- Extensional structures and cryovolcanism suggest coroanes formed above upwellling diapirs [Johnson et al., 1987; Greenberg et al., 1991; Pappalardo et al., 1997].
Elsinore Corona

fissure extrusion (plus normal faulting)

shallow intrusion (plus normal faulting)

Naples Sulcus

Syracusa Sulcus

Ephesus Regio

20 km
Loading Model

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

[after Janes & Melosh, 1988]

[Pappalardo, 1994]

[Pappalardo, 1994]
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].
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:
  \[
  2\pi R_i^2 \Delta \rho (a - d)(1 - \cos \phi) \left\{ 1 - \frac{a + d}{R_i} + \frac{e^2}{3R_i^2} \right\}
  \]

  \( \phi \) = angular radius of diapir
  \( e^2 = a^2 + ad + d^2; \) assume \( T_e = 0.4 \ d \)

- Mass excess at surface: \( C 2\pi \rho R_i^2 h(1-\cos \phi) \)
  \( h \) = isostatic surface topography
  \( C \) = degree of compensation (0 < \( C < 1 \))

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

  where \( Q^* = \frac{3\sqrt{5}G_{20}}{R^2 \Omega^2 (k_2^f - k_2)} \); \( n=1 \) 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
  \( \Omega \) = 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\(^3\) \(\Rightarrow\) **thick ice and compositional diapirism**.
- For **silicate diapir**, similar reorientation amount \((C \approx 0)\):
  - Coupling to ice \(\Rightarrow\) **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 \([\text{Porco et al., 2006; Helfenstein et al., 2006}]\).

• Consistent with reorientation, which “squashes” current spin axis and expands equator.

• Stresses \(\sim 10\ \text{MPa.}\)
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?

[Albers, 2006]
Tidal Heating on Enceladus

- Presumed tidal heat source \cite{Ross_Schubert_1989, Matson_et_al_2006}.
- Tidal heating would concentrate in warm diapir.
- Shear heating in lithosphere may explain warm tiger stripes \cite[cf. Nimmo & Gaidos, 2002]{Nimmo_Gaidos_2002}.

[Diagram showing thermal upwarping, shear zone, cold near-surface layer, surface collapse from void closure, contours of temperature (schematic), voids, percolating meltwater, Europa, Triton, Enceladus]
Reorientation of Mini-Moons: Conclusions

• Large diapir within Enceladus can reorient active region to south pole:
  ◦ Ice diapir $\Rightarrow$ thick shell, compositional buoyancy, rigid lithosphere $T_e > 0.5$ km.
  ◦ Silicate diapir $\Rightarrow$ 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 $a \rightarrow b$-axis reorientation, and timing of corona formation.
- Consideration of other mid-sized icy satellites (including Mimas).
- Future Cassini tests for Enceladus and other satellites.