Partially Molten Magma Oceans on Io and Europa

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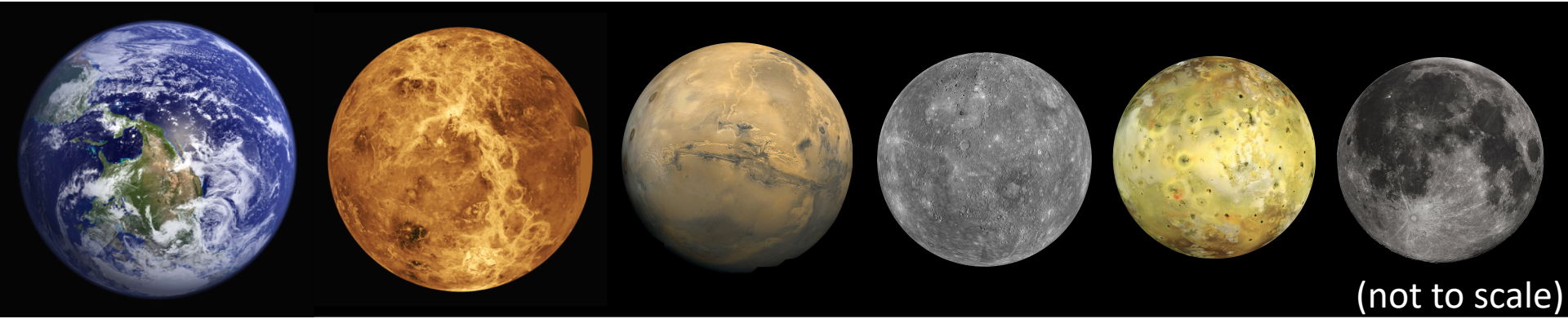
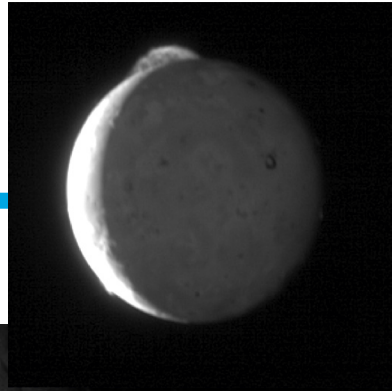
Partial melting and planetary heat loss



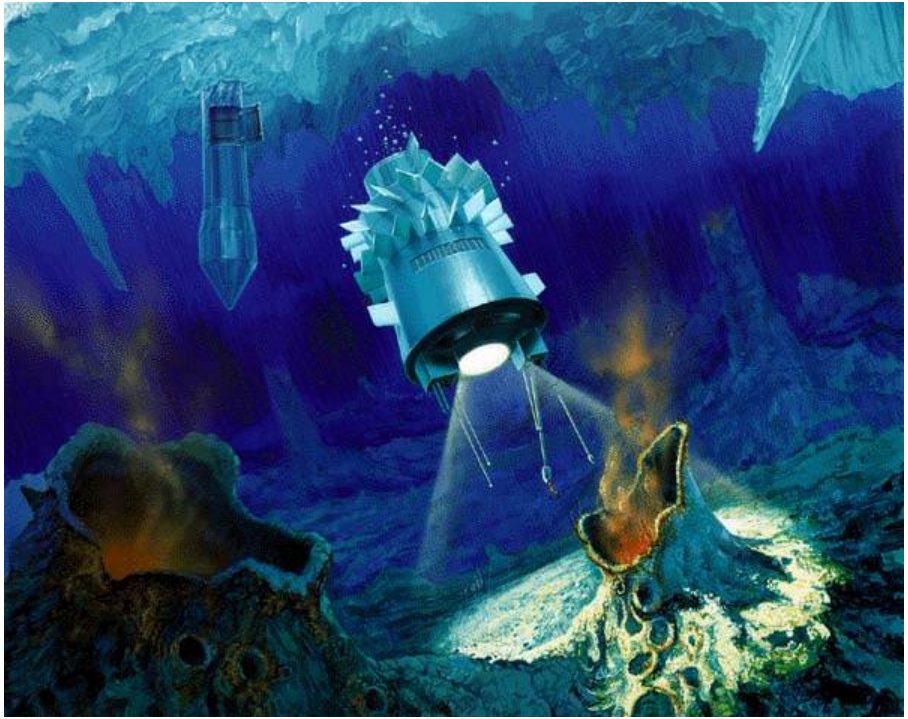
- Are Earth-sized planets Earth-like?
  - Or Venus-like? Io-like? Mars-like?
- Plate tectonics, stagnant lid, heat pipe

Heat Pipes on Io

- Extensive volcanism (>0.7 mm/yr)
- High surface heat flux (~30x Earth's)
- No signs of plate tectonics
- Tall mountains suggesting a thick lithosphere

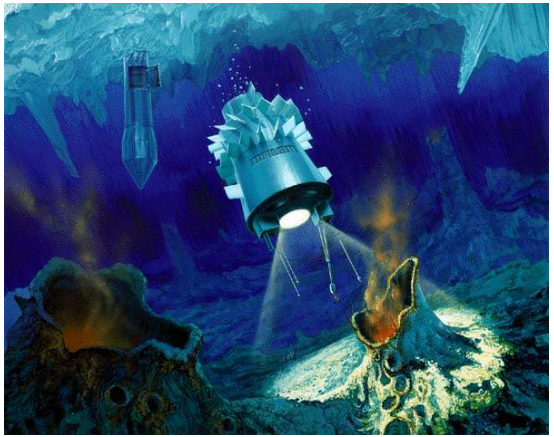


Why study Europa's silicate mantle?



Artist's depiction of a hypothetical Europa mission.
Credit: NASA

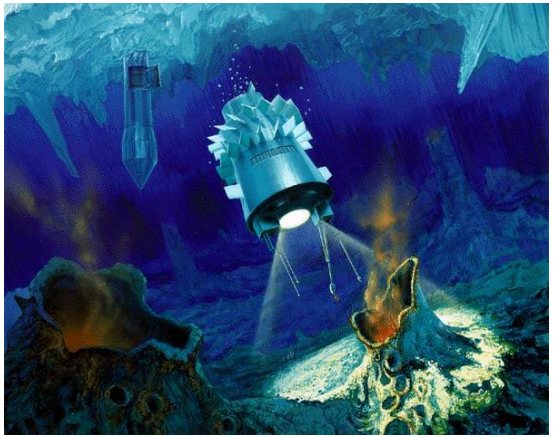
Why study the silicate mantle?



Artist's depiction of a hypothetical Europa mission. Credit: NASA

- Multiple metabolic pathways and biogeochemical cycles *if new rock is delivered to the seafloor* (Zolotov and Shock, 2004)
- "Thermodynamics-driven extinction" / "Specter of entropic death" (Gaidos et al., 1999; Chyba and Hand, 2001)

Why study the silicate mantle?



Artist's depiction of a hypothetical Europa mission. Credit: NASA

Is there volcanic activity at the seafloor today?

- Multiple metabolic pathways and biogeochemical cycles *if new rock is delivered to the seafloor* (Zolotov and Shock, 2004)
- "Thermodynamics-driven extinction" / "Specter of entropic death" (Gaidos et al., 1999; Chyba and Hand, 2001)

Previous work

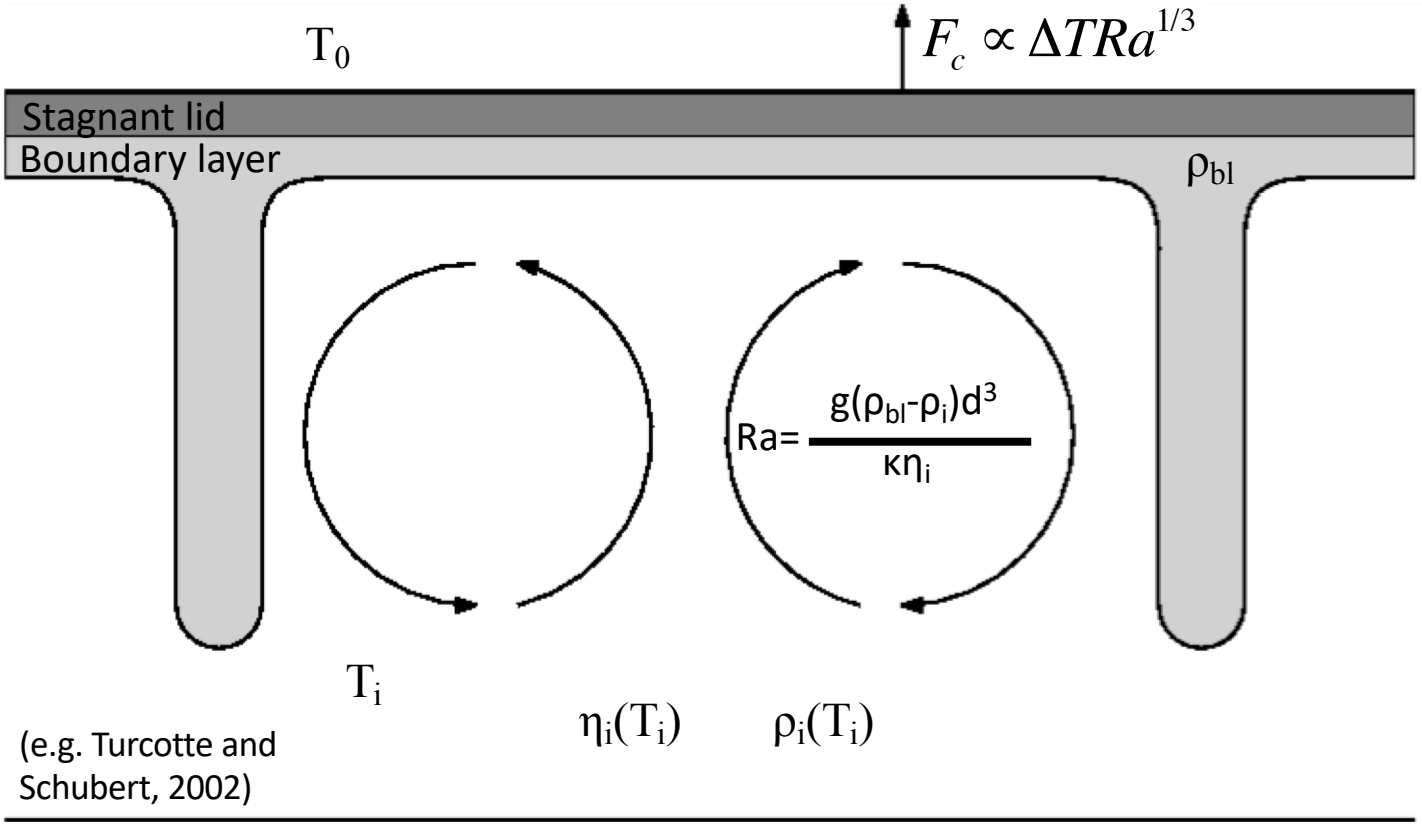
- Io convection: Ojakangas and Stevenson (1986), Fischer and Spohn (1990), Tackley *et al.* (2001), Tackley (2001), and Moore (2003)
- Io melt migration: Moore, 2001
- Europa: Moore and Hussmann (2009)

Mantle convection and melt migration are coupled processes and both contribute to heat loss.

This work

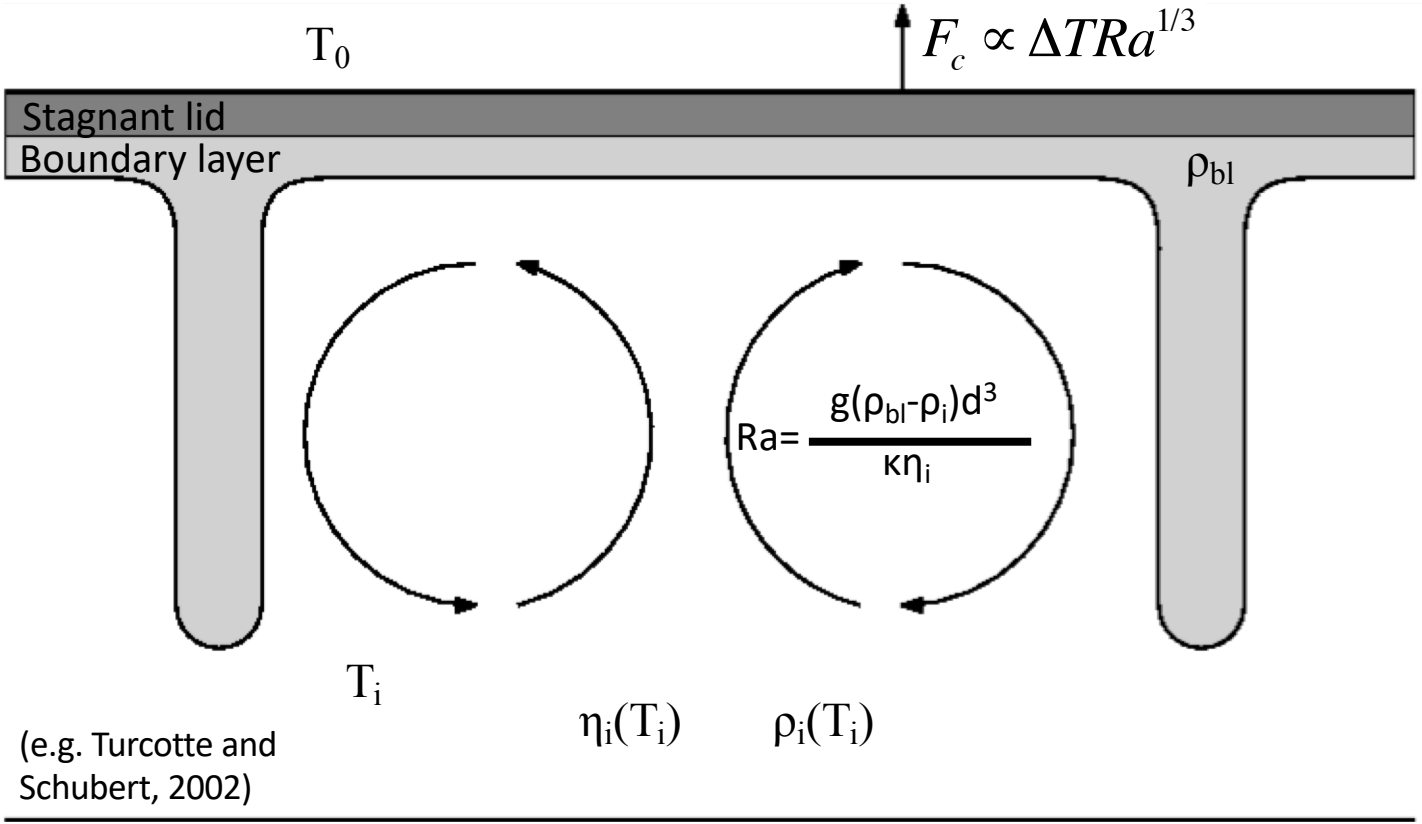
- Derive convective scaling laws that include the effects of partial melting and couple with a 1D melt migration model

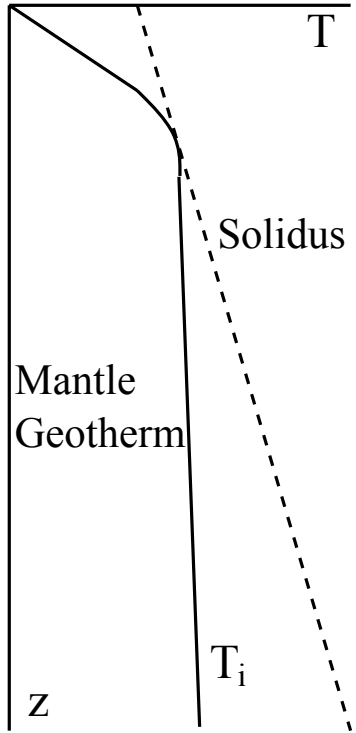
Scaling laws for convection



(e.g. Turcotte and Schubert, 2002)

Scaling laws for convection





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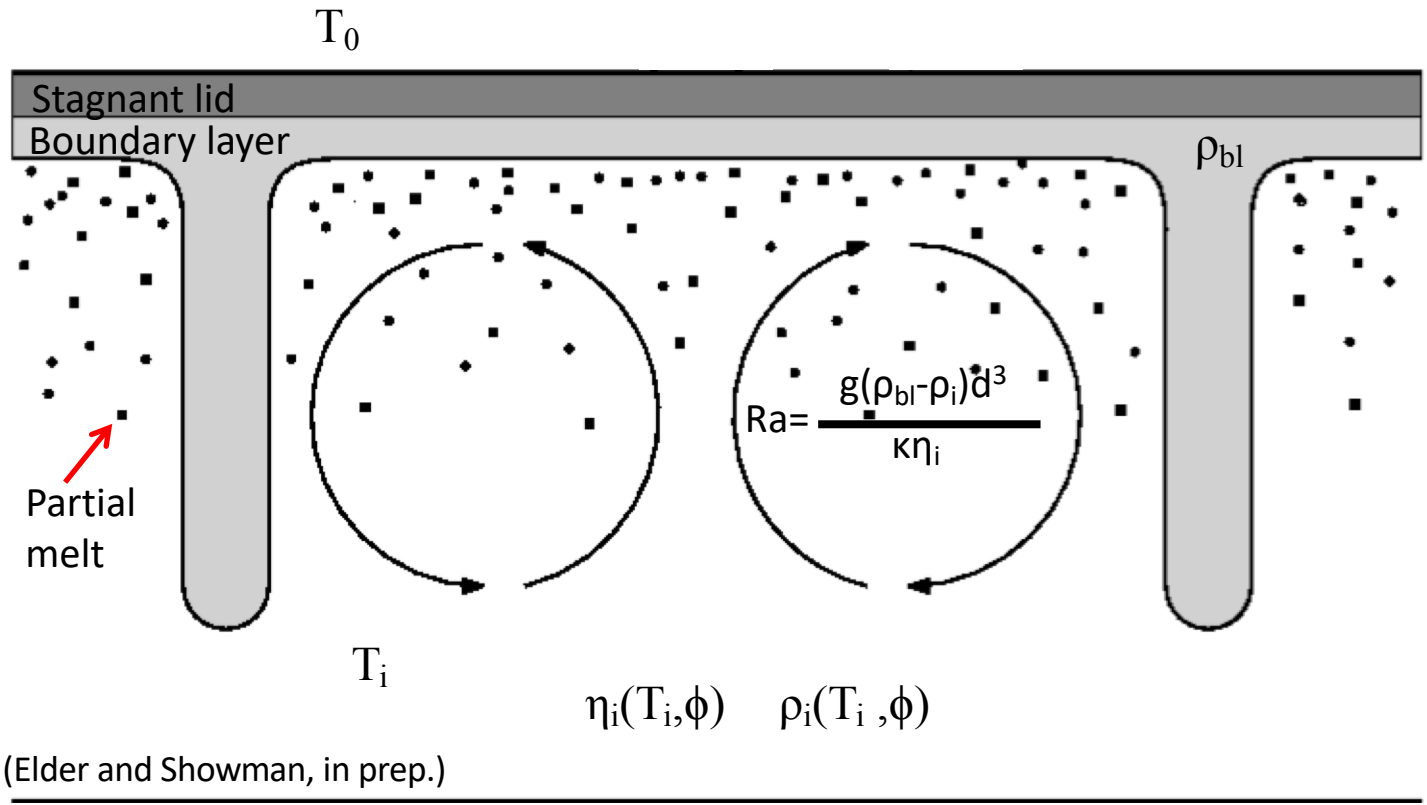
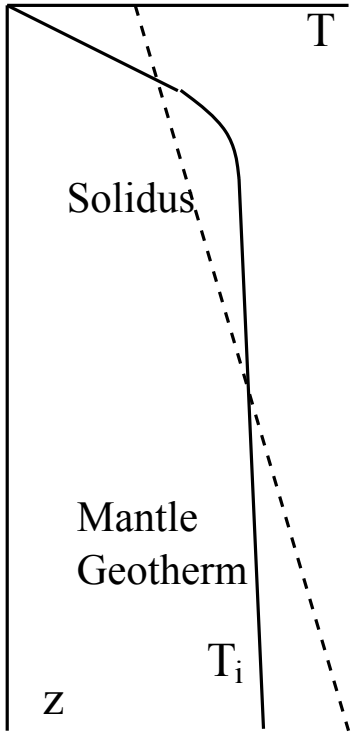


(Elder and Showman, in prep.)



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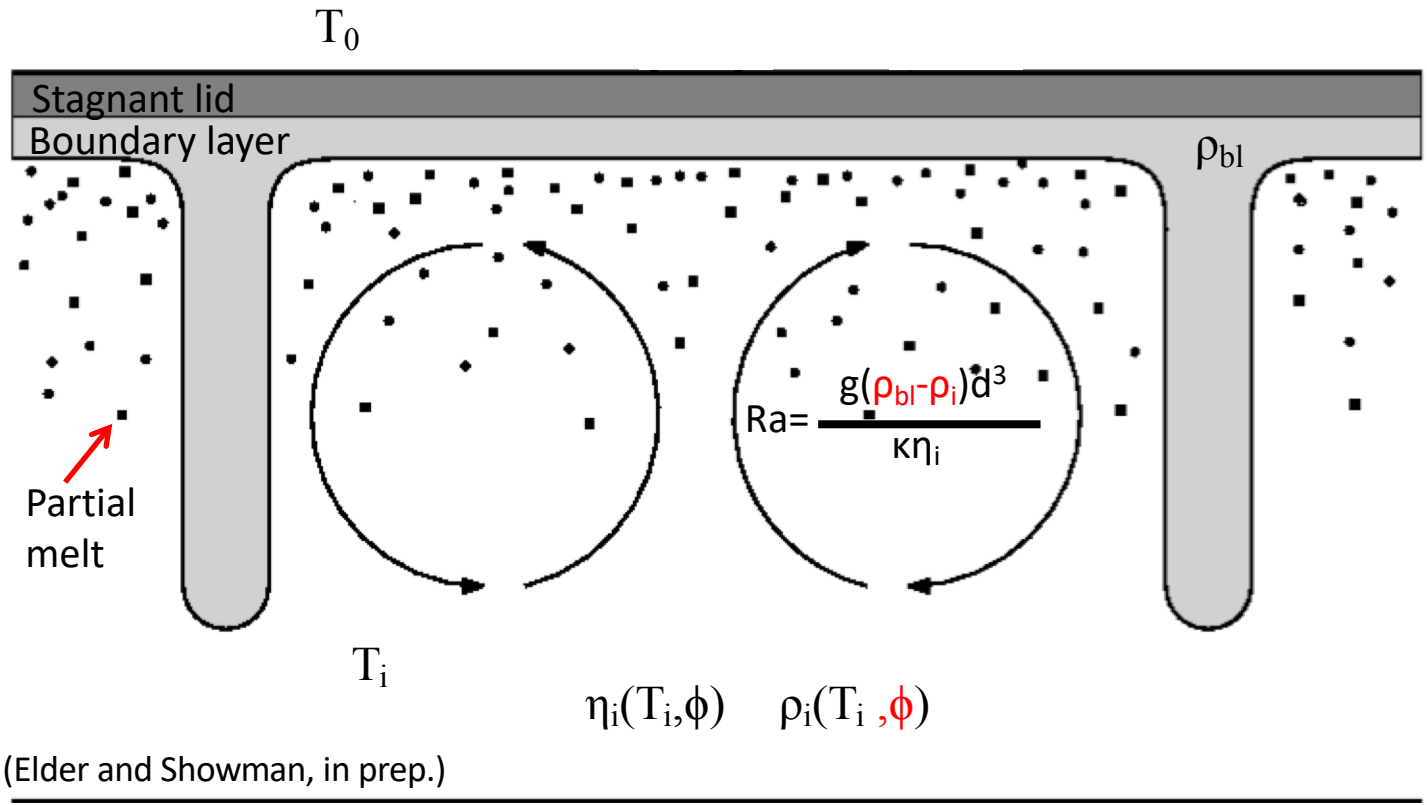

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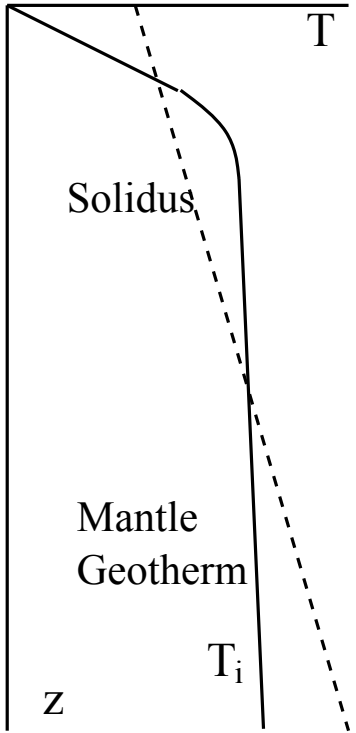

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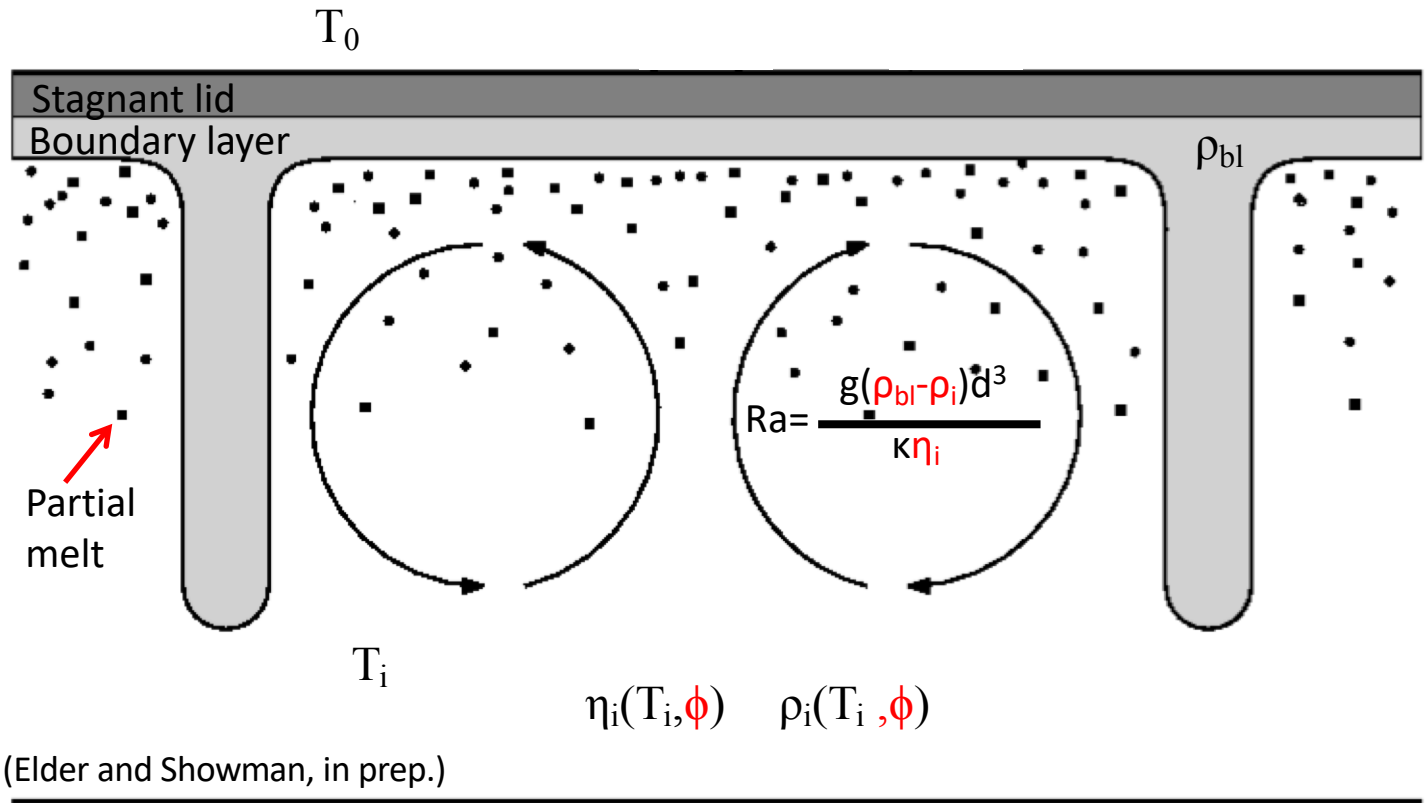

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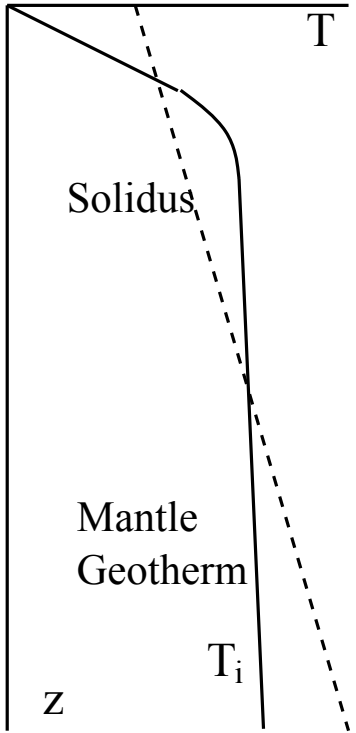

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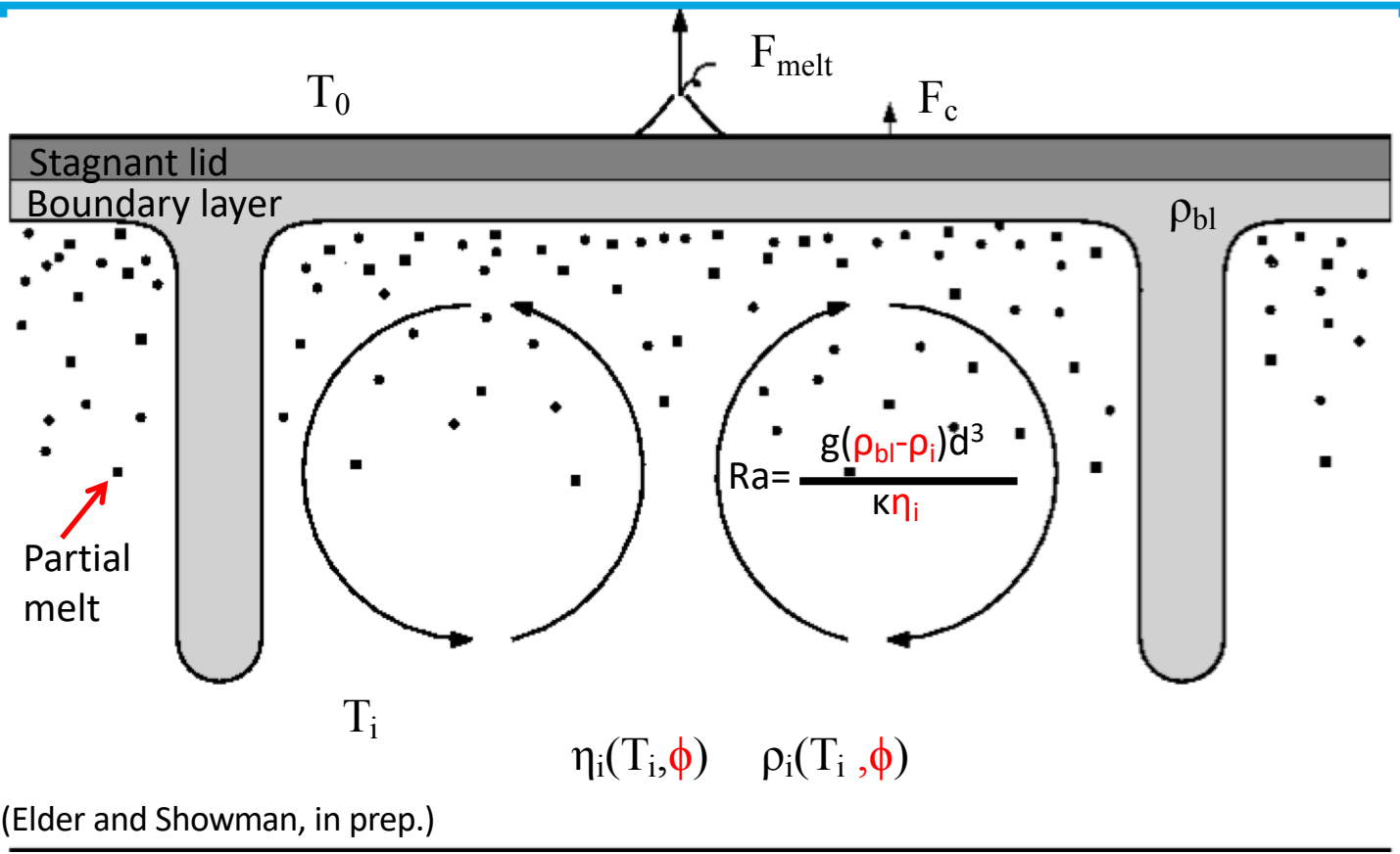

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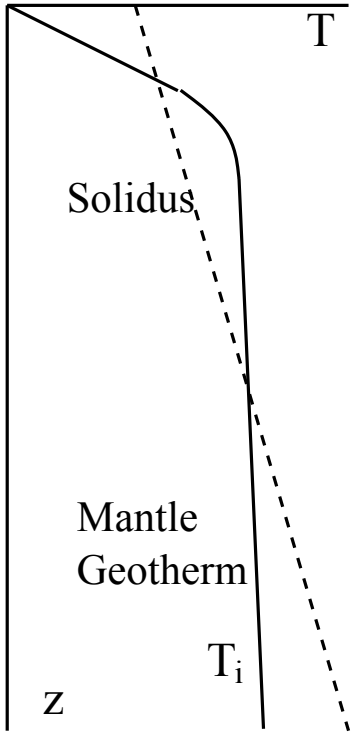

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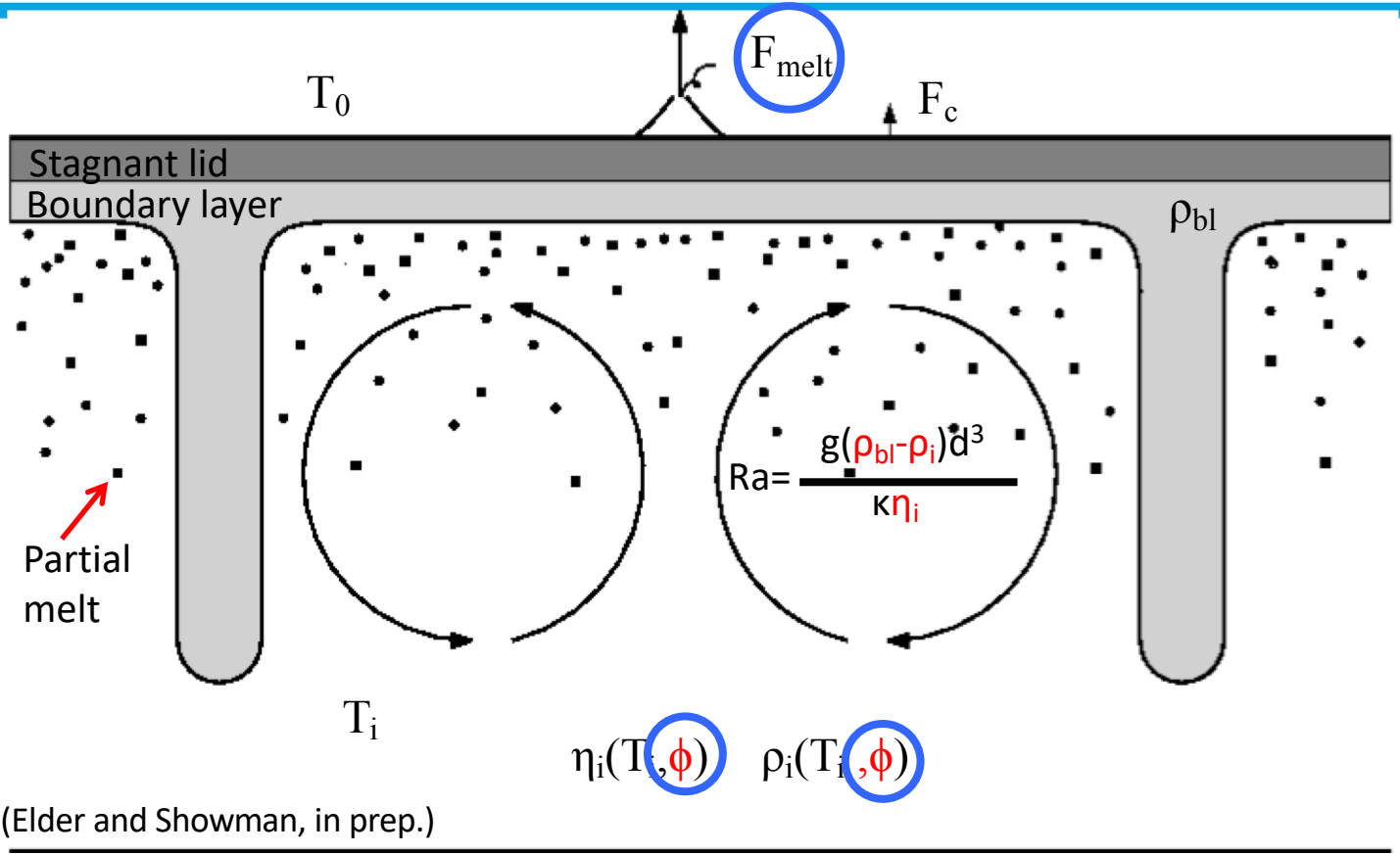

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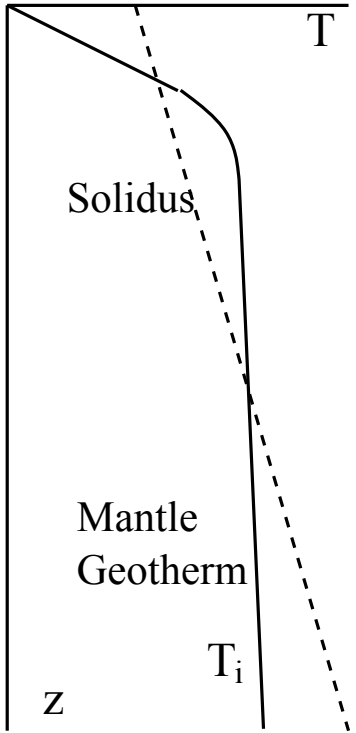
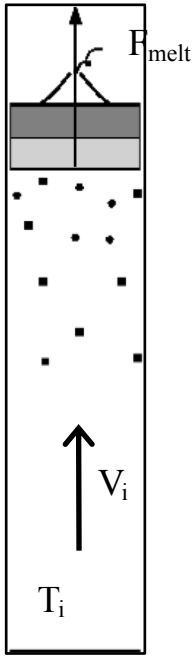
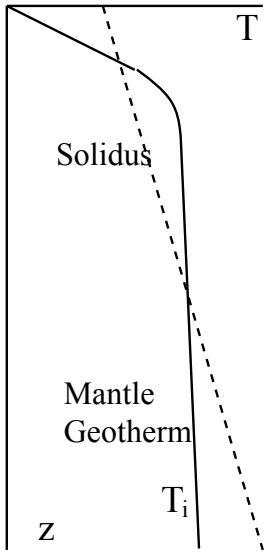


Melt migration





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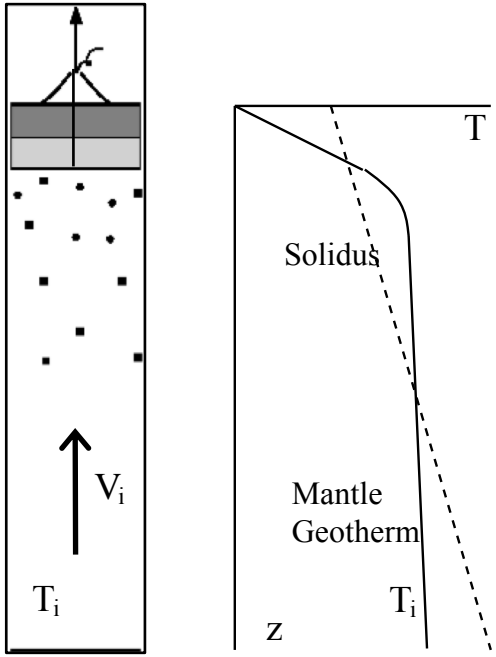
Melt migration

- 1D model of melt generation and migration (Hewitt and Fowler, 2008)
- Conserve mass, momentum and energy, and use Darcy's law to solve for the melt velocity relative to the solid
- Add internal heating term to account for tidal heating (Elder and Showman, in prep.)



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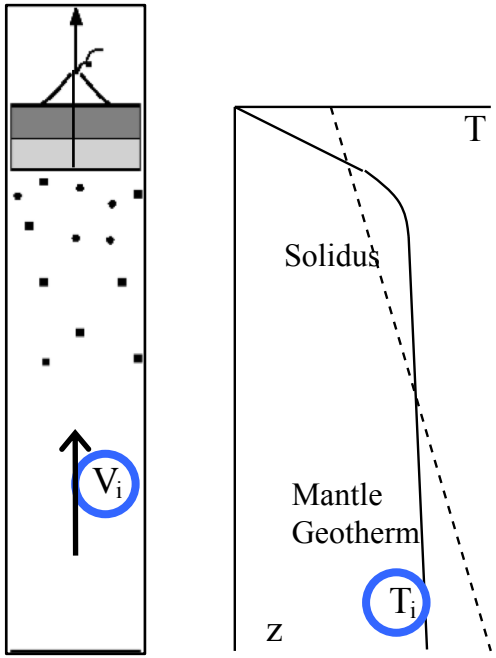

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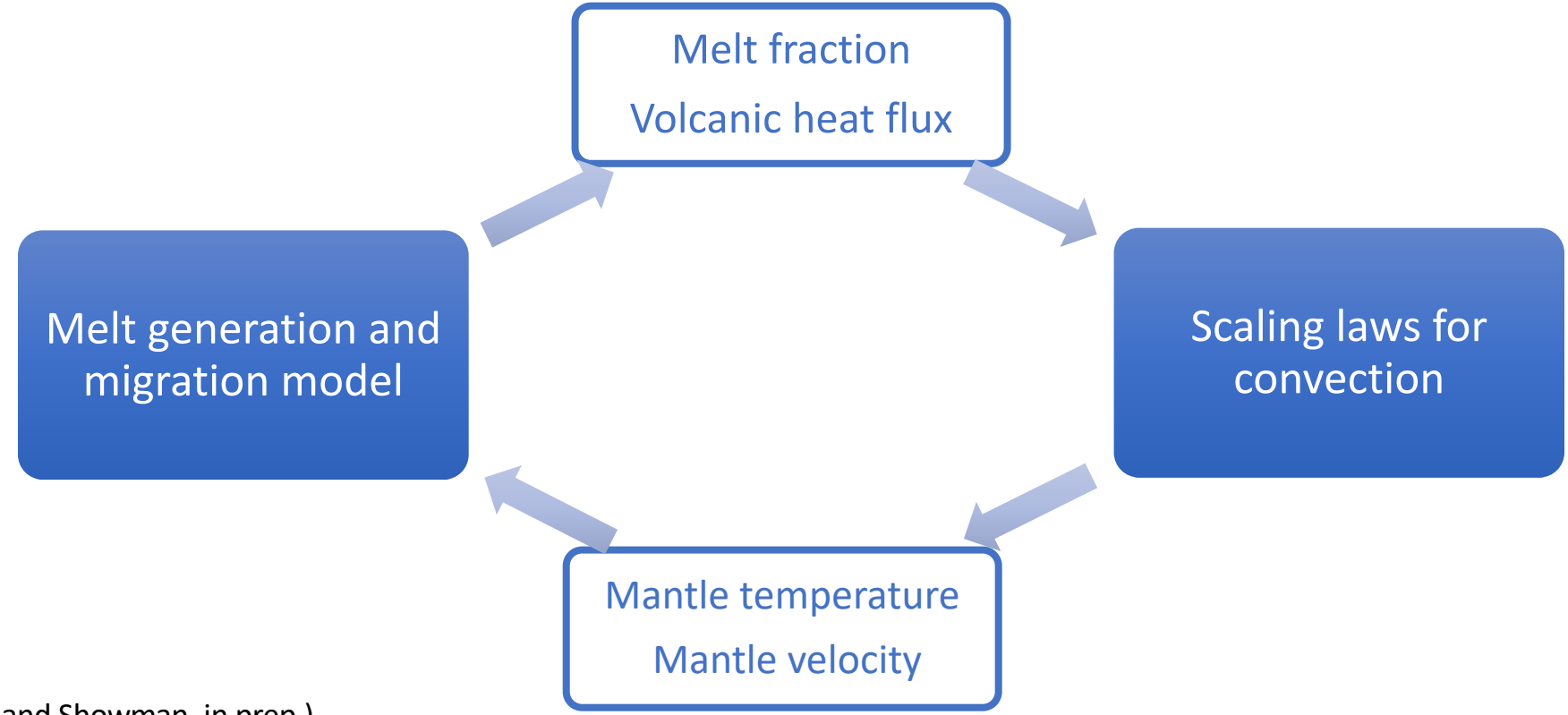
Convection and partial melting



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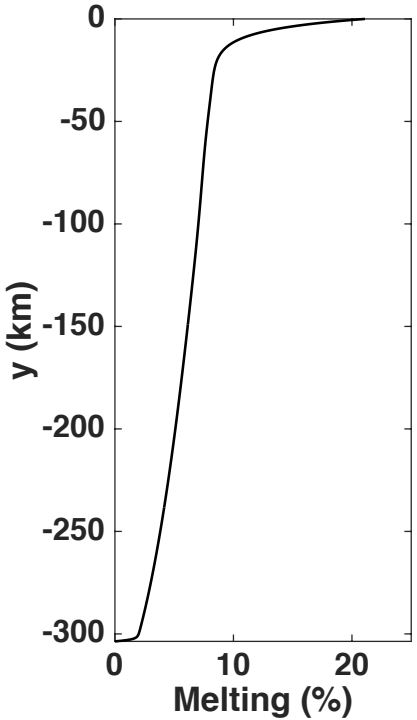
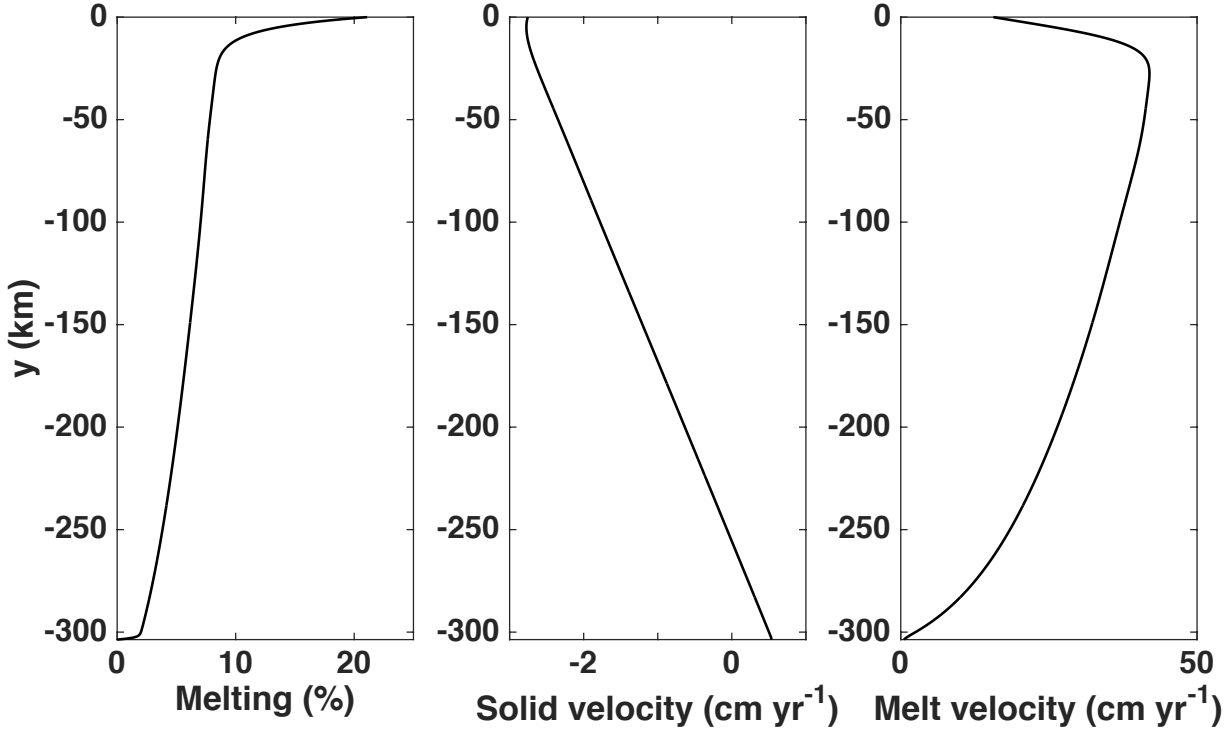
Io results



T_i = 1575 K, V_i = 0.5 cm yr $^{-1}$, F_{conv}= 0.005 F_{melt}

Io results

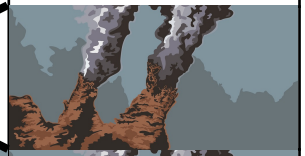
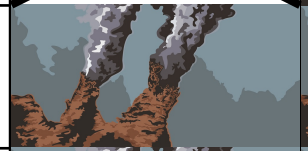
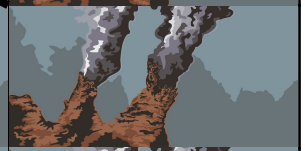
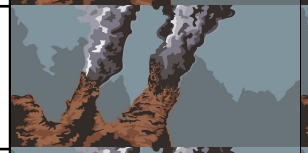
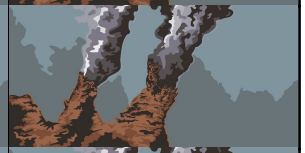
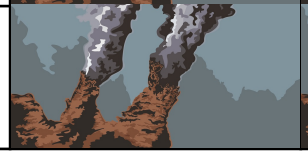
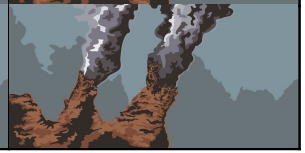


T_i = 1575 K, V_i = 0.5 cm yr $^{-1}$, F_{conv}= 0.005 F_{melt}

Europa

- Very poorly constrained…
- Internal heating rate
  - Radiogenic heating 1.1-1.9x10^{11} W (chondritic)
  - Tidal dissipation <5x10^{13} -1.7x10^{14} W (Io)
  - Tidal dissipation in Europa's silicate mantle is expected to be lower than radiogenic (Tobie et al., 2003) unless it's partially molten then dissipation increases (Moore and Hussman, 2009)
  - Test 10^{11}-10^{14} W
- Mantle rheology
  - 'Wet' – water-saturated, lower viscosity
  - 'Dry' – water free

Europa Results

	H (W)	Wet rheology	Dry rheology
Radiogenic	10^{11}		
Tidal	10^{12}		
Tidal	10^{13}		
Tidal	10^{14}		

Thickness of partially molten zone and fraction molten

	H (W)	Wet rheology	Dry rheology
Radiogenic	10^{11}	0 km, 0 %	7 km, 0.6%
Tidal	10^{12}	9 km, 0.5%	49 km, 2.1%
Tidal	10^{13}	49 km, 1.3%	98 km, 5.8%
Tidal	10^{14}	93 km, 4.3 %	188 km, 16.7%

Europa Results

	H (W)	Wet rheology	Dry rheology
Radiogenic	10^{11}	~~	?
Tidal	10^{12}	?	
Tidal	10^{13}		
Tidal	10^{14}		

Future work

- Sensitivity testing

Discussion and Conclusion

- If radiogenic heating is the only heat source and Europa's mantle is hydrated, volcanic activity will not occur
- If earlier volcanic activity dehydrated the mantle, magma will be produced even with just radiogenic heating, but perhaps not enough to erupt?
- If tidal heating can produce at least 10^{12} W of heating, magma will form in the mantle dry or wet
- More work is necessary to evaluate fraction of melt that can erupt
  - Earth 5 times more intrusion than eruption
  - Shallow intrusion could still cause hydrothermal vents