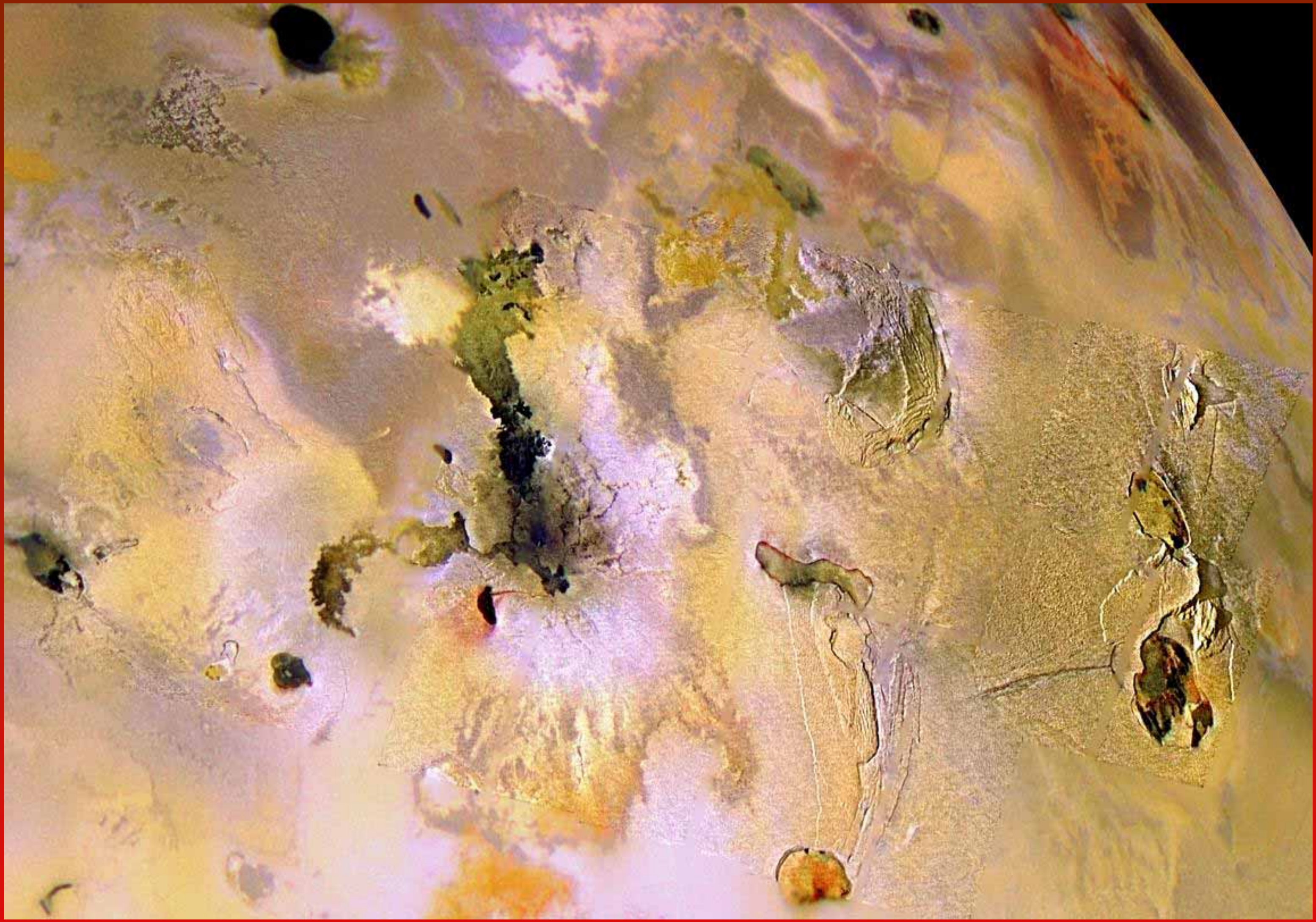
A Model for Patera Formation on Io

Jani Radebaugh
University of Arizona

Many thanks to Alfred McEwen, Jay Melosh, Zibi Turtle,
David Kring, and Adam Showman

Outline

- Patera morphologies as motivation
- Model:
  - Application of analytical treatments of magma convection and transport
  - Convection in asthenosphere
  - Magma rise through lithosphere via diapirs or dikes
  - Collapse over high-level magma chamber to form patera
  - Evolution of patera



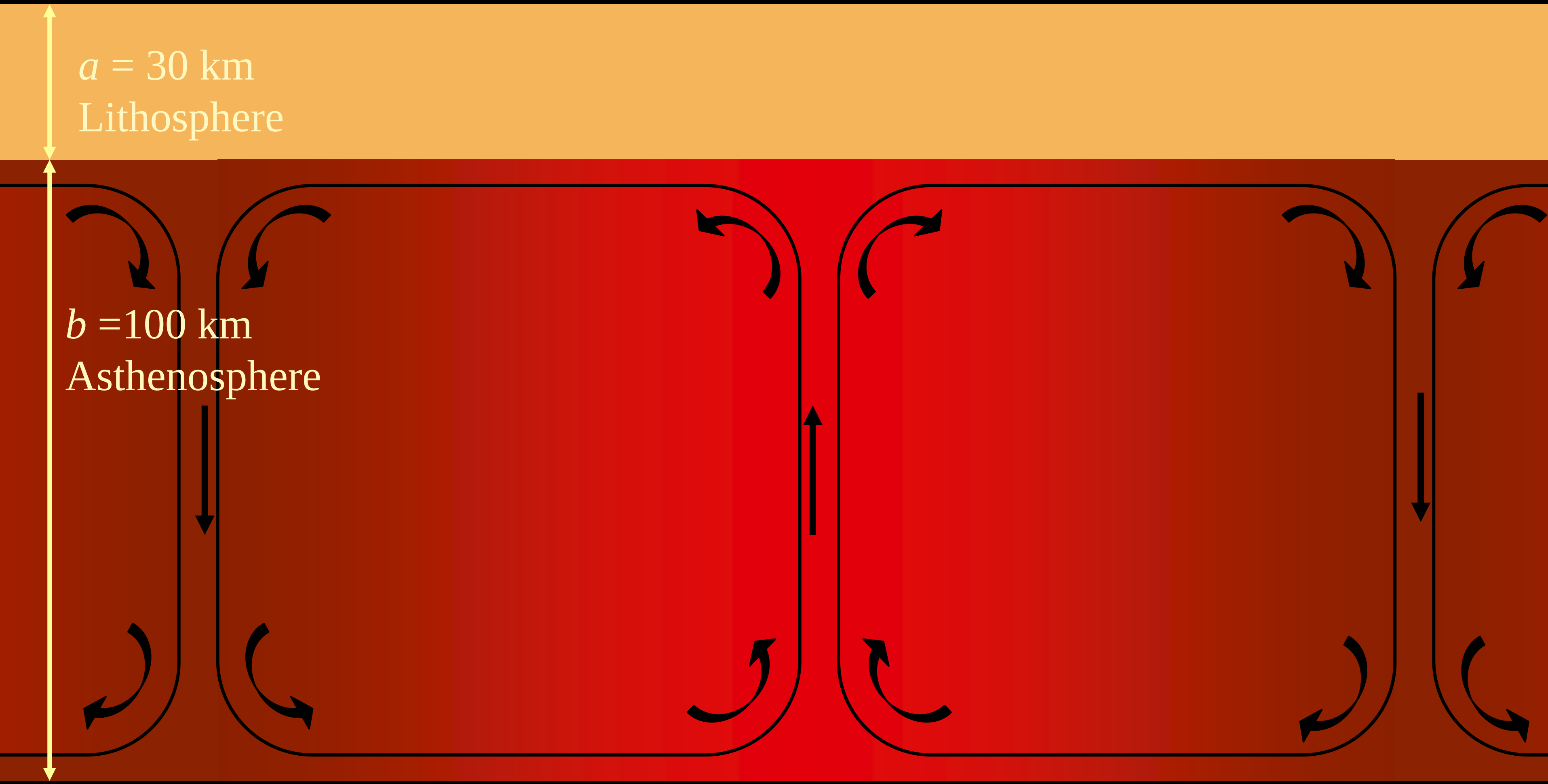
* Formation process must lead to the morphologies we observe

I. Heating and convection in the asthenosphere lead to transport of hot material to the base of the lithosphere.

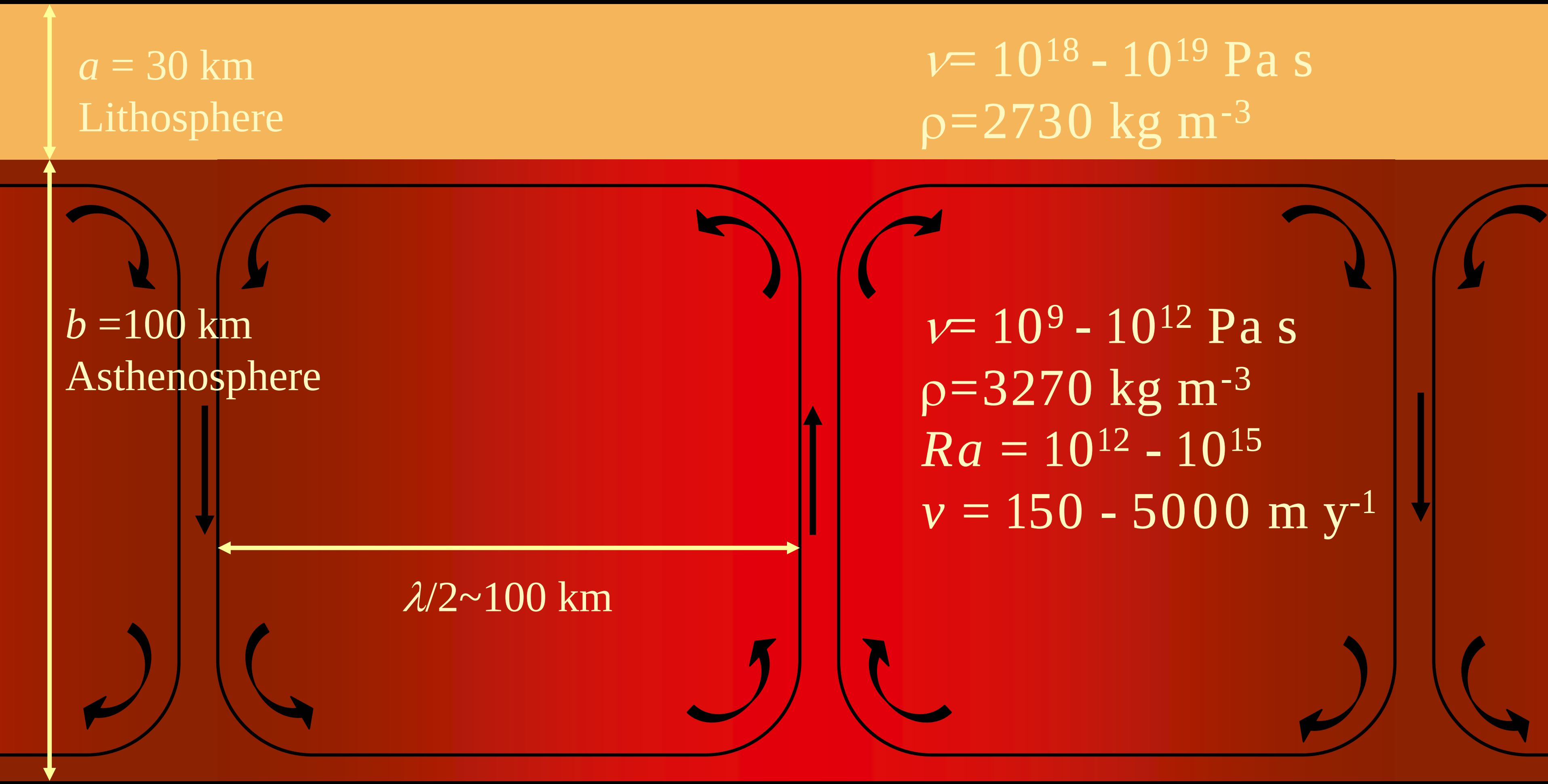
- Asthenosphere: Dense, partially molten region above mantle
- Patera distribution[1] fit by model results[2] for asthenospheric heating and convection

[1]Lopes et al. 1999; Schenk et al 2001; Radebaugh et al. 2001

[2]Tackley et al. 2001; Tackley 2001



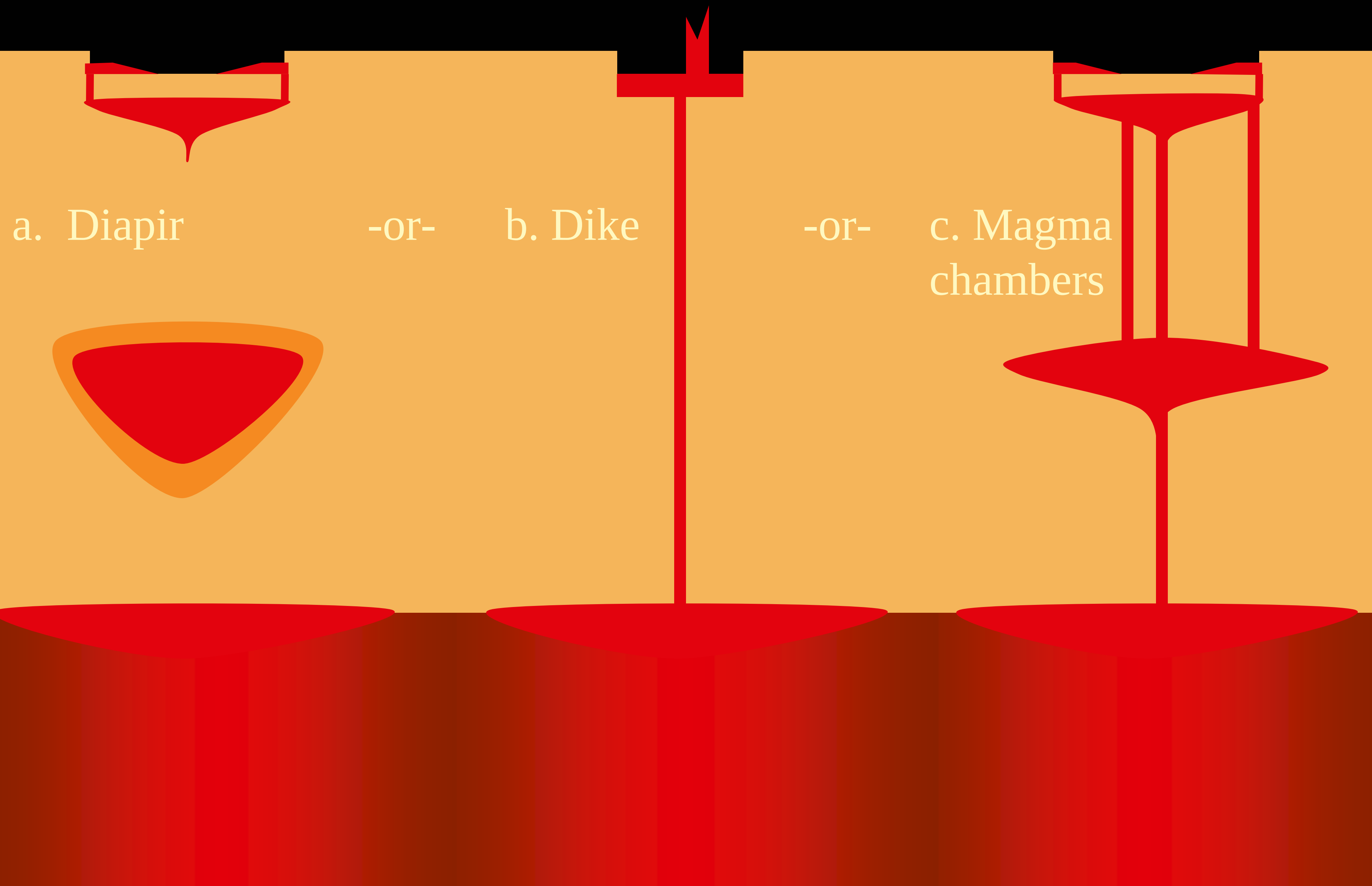
Turcotte and Schubert, 2002

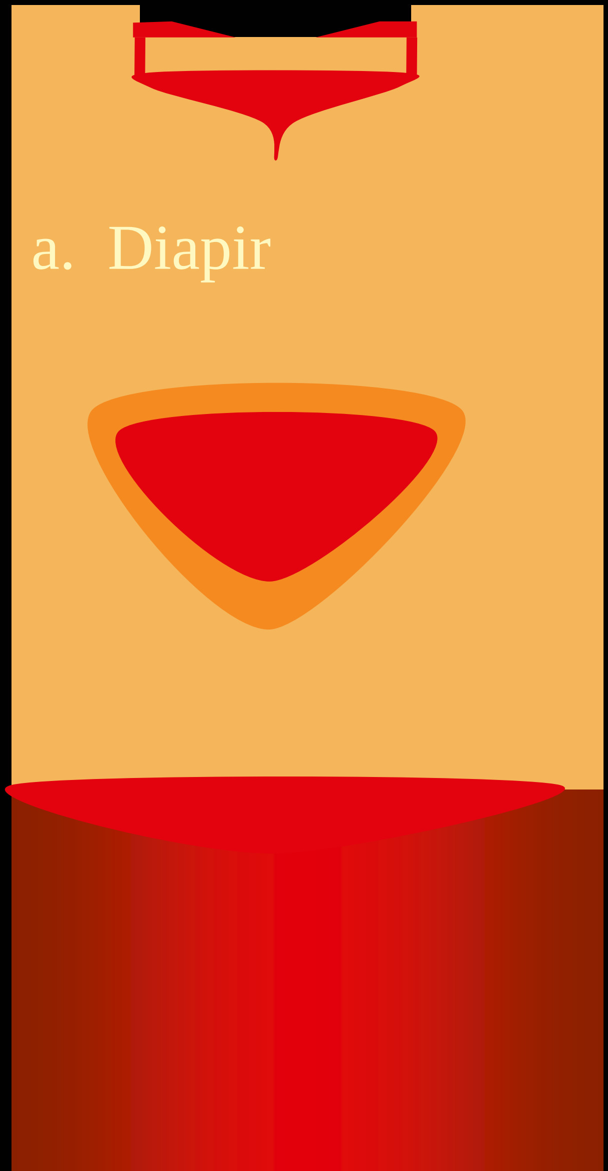


Turcotte and Schubert, 2002

Velocities consistent with those from numerical models by Tackley et al. 2001; Tackley 2001

II. Magma rises through the lithosphere

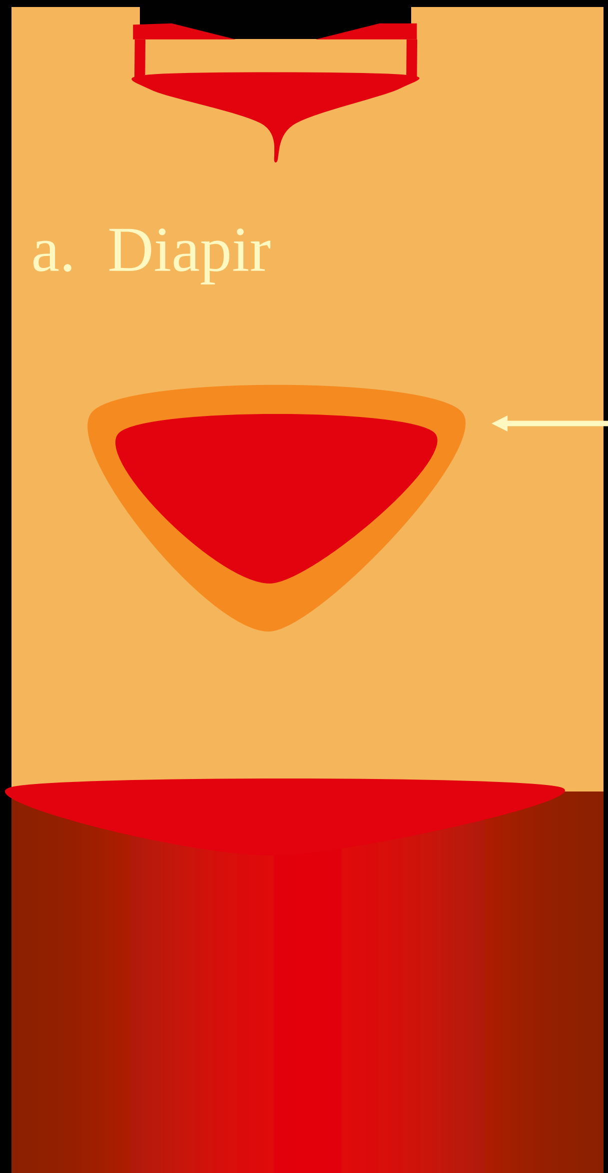




Diapiric Rise

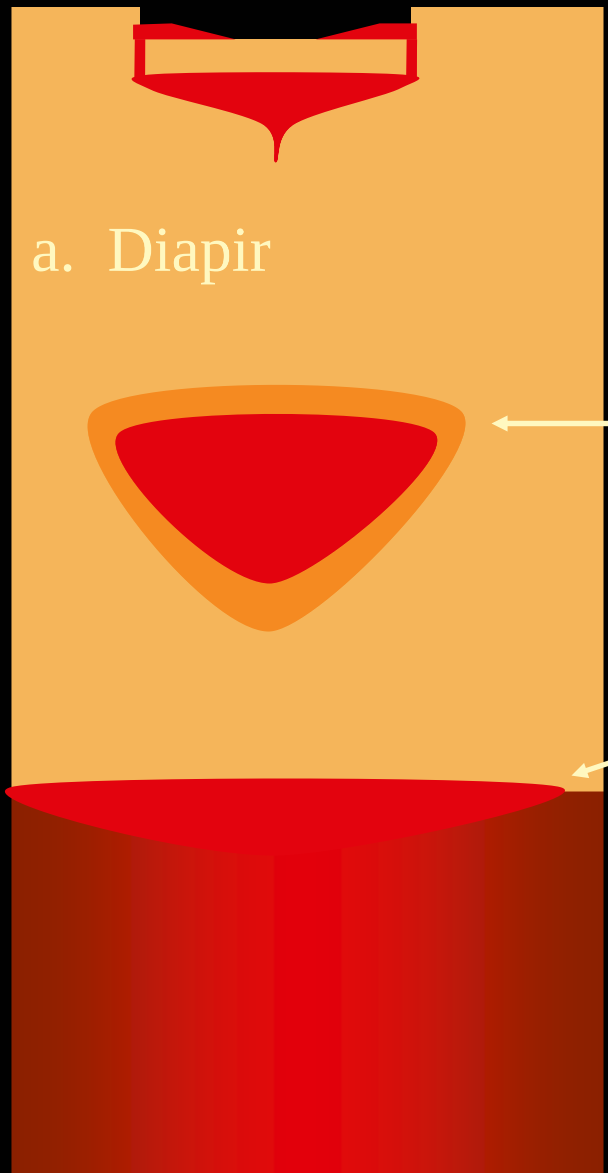
- Stokes' flow of buoyant fluid
  - Modified to include thermal considerations via the Peclét number (measure of heat transfer)

Diapiric Rise



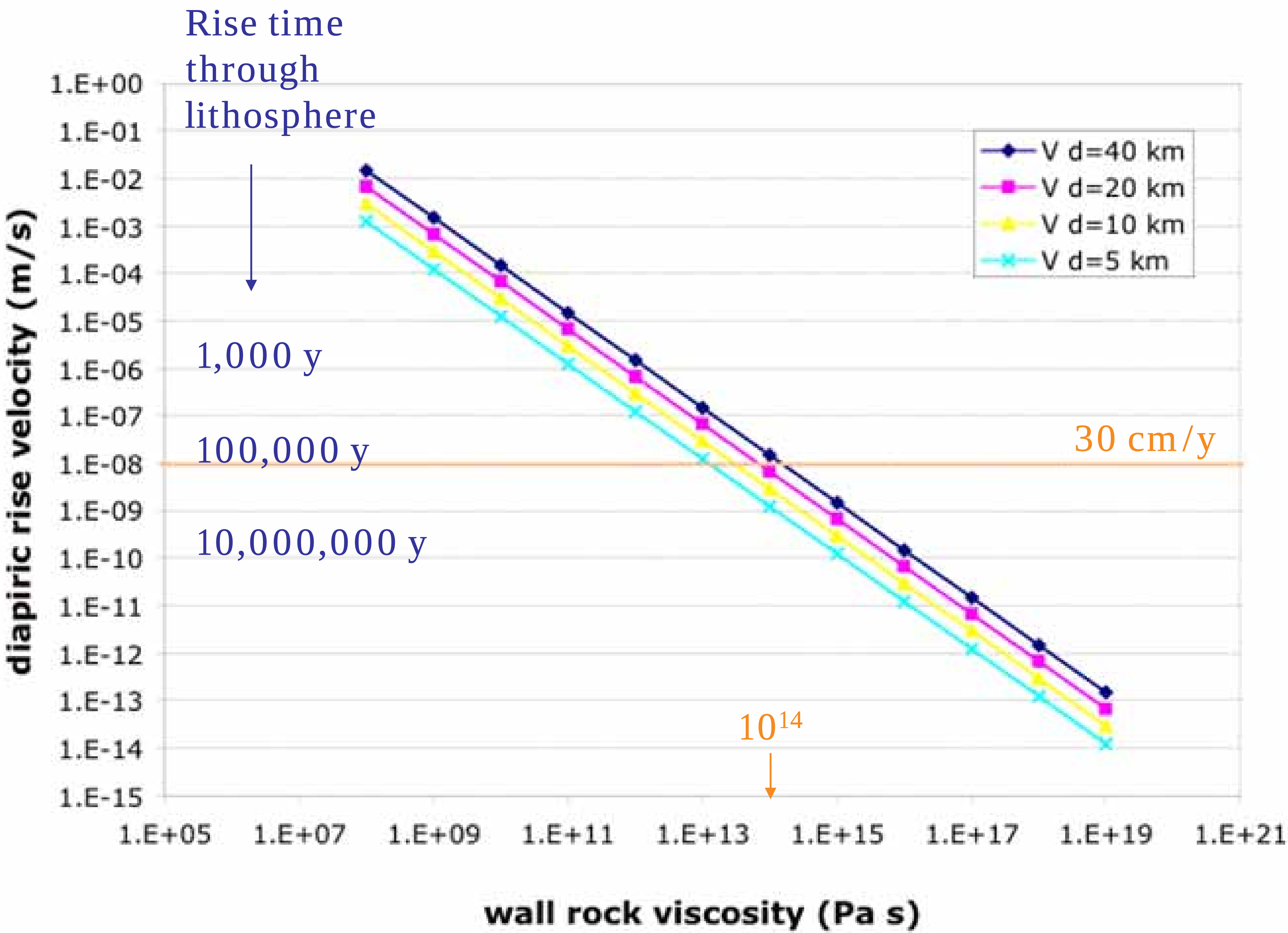
- Stokes' flow of buoyant fluid
  - Modified to include thermal considerations via the Peclet number (measure of heat transfer)
  - Assume thermally softened layer around diapir
    - Reduces effective viscosity

Diapiric Rise

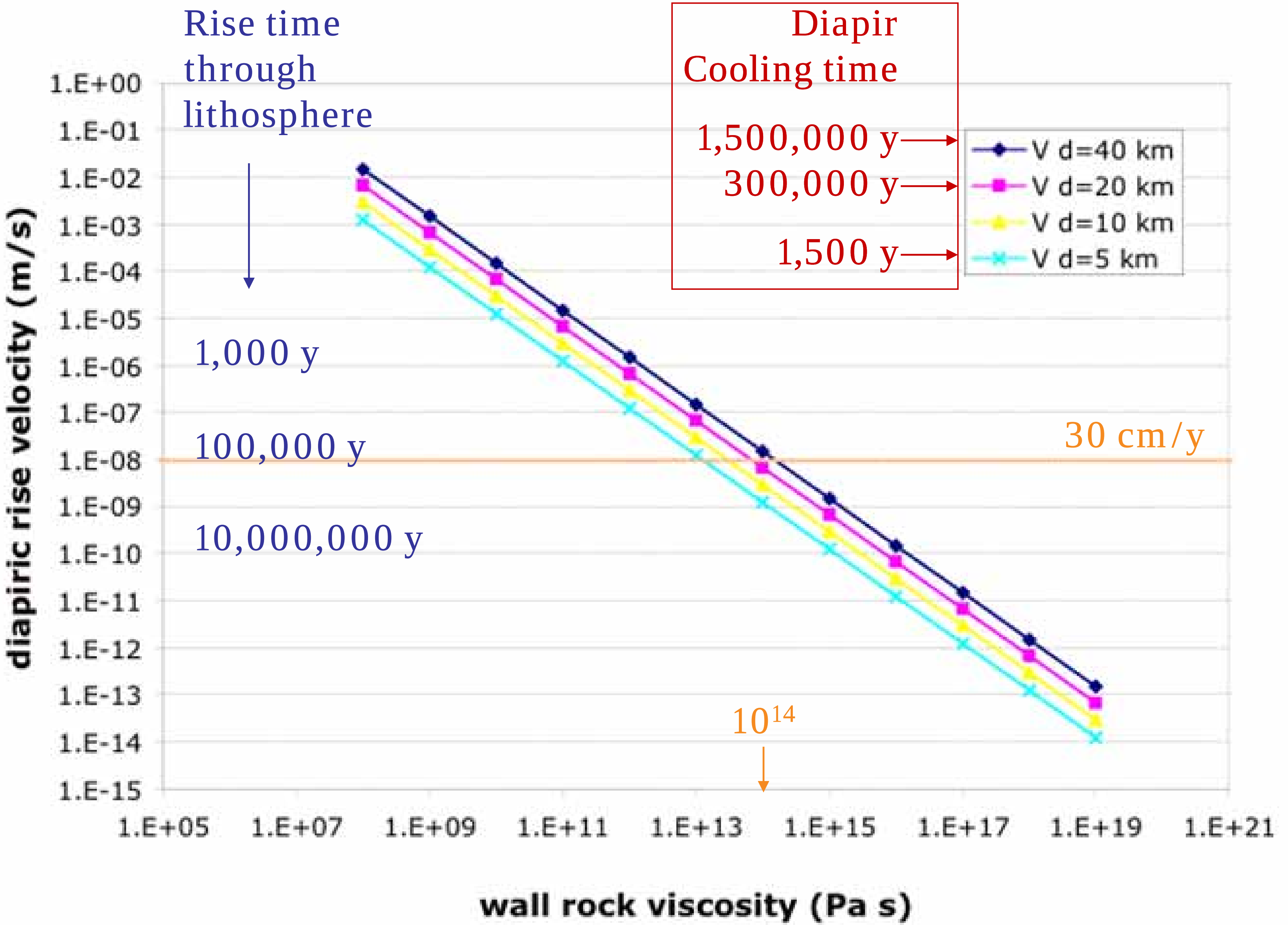


Stokes' flow of buoyant fluid

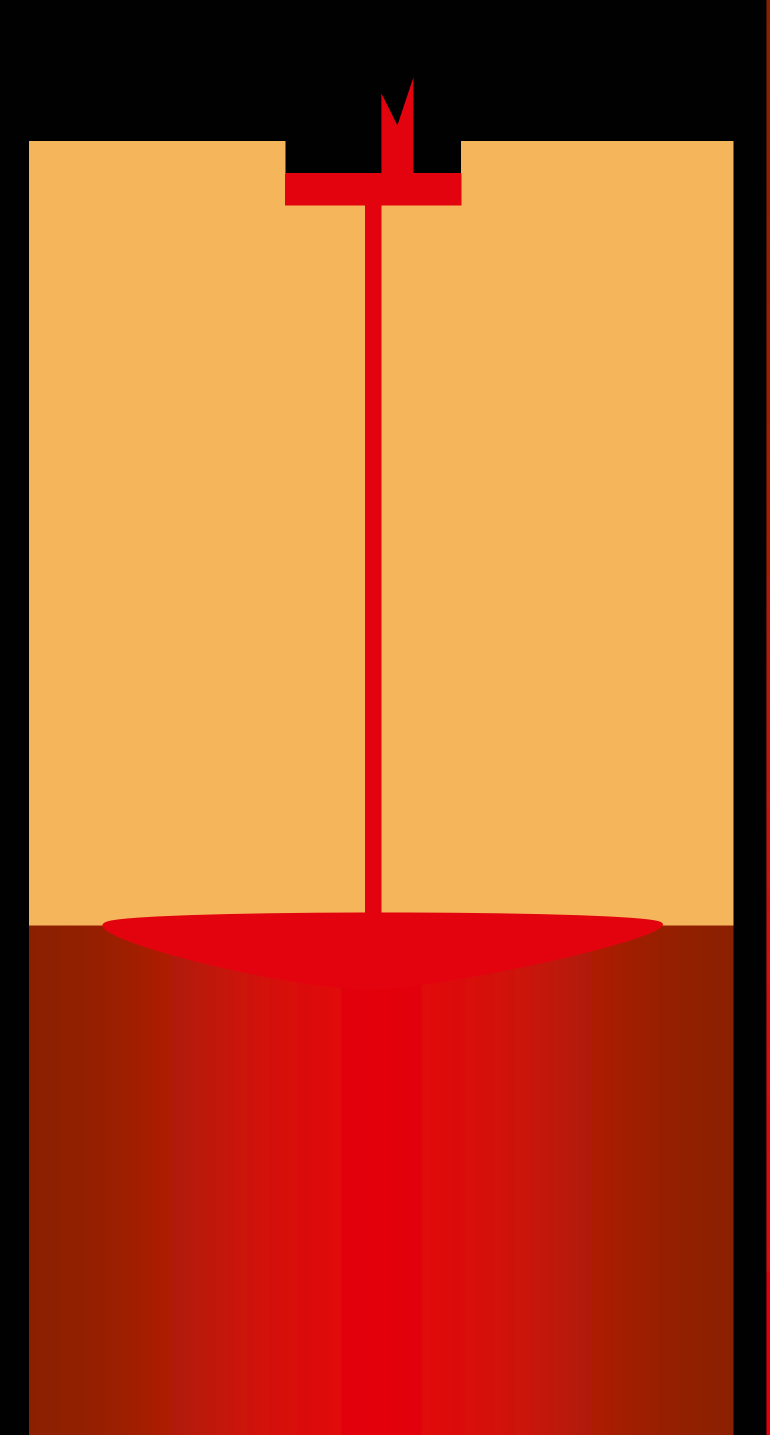
- Modified to include thermal considerations via the Peclet number (measure of heat transfer)
- Assume thermally softened layer around diapir
  - Reduces effective viscosity
- Obtain magma (40% partial melt) from lens at base of lithosphere ~ 0.5 km - 2 km thick for diapir diameter d = 5 km - 40 km



Rise time through lithosphere
1,000 y
100,000 y
10,000,000 y
30 cm/y
10^{14}
V d=40 km
V d=20 km
V d=10 km
V d=5 km
diapiric rise velocity (m/s)
wall rock viscosity (Pa s)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
1.E-15
1.E+05
1.E+07
1.E+09
1.E+11
1.E+13
1.E+15
1.E+17
1.E+19
1.E+21

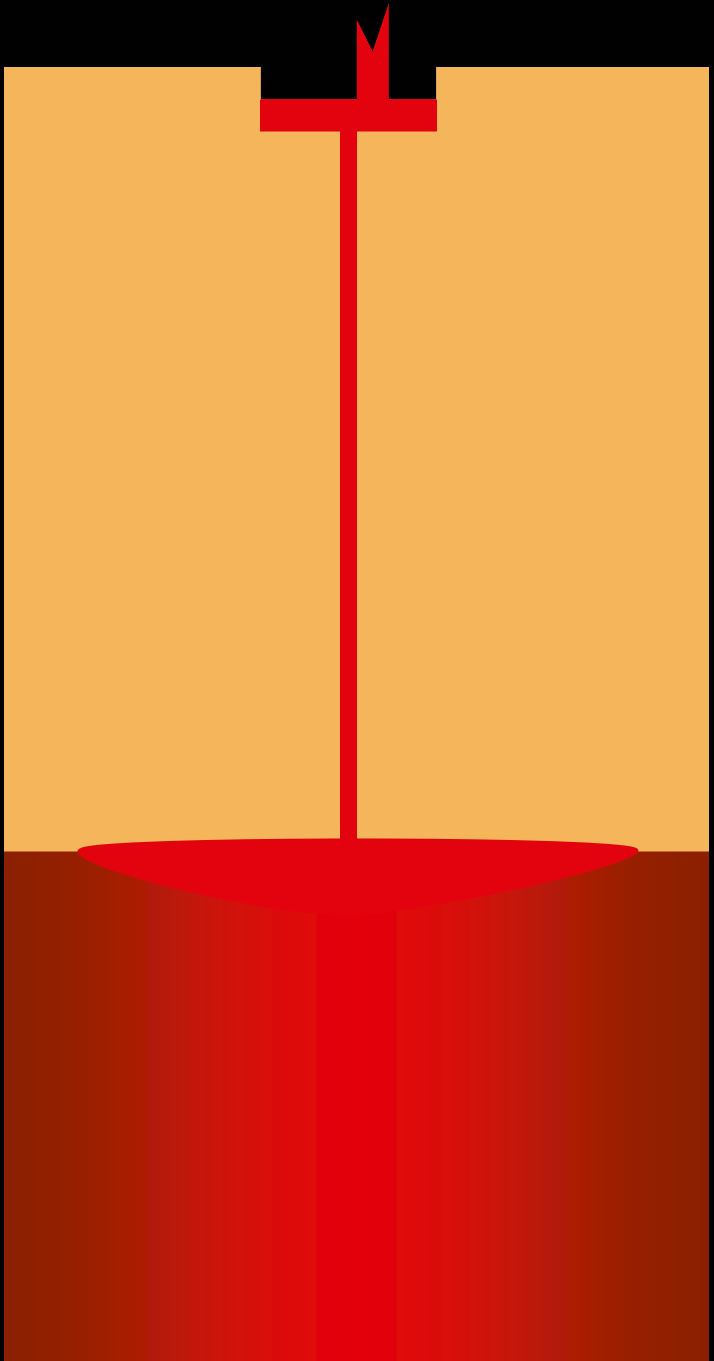


Rise time through lithosphere
Diapir Cooling time
1,500,000 y
300,000 y
1,500 y
V d=40 km
V d=20 km
V d=10 km
V d=5 km
1,000 y
100,000 y
10,000,000 y
30 cm/y
10^14
diapiric rise velocity (m/s)
wall rock viscosity (Pa s)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
1.E-15
1.E+05
1.E+07
1.E+09
1.E+11
1.E+13
1.E+15
1.E+17
1.E+19
1.E+21



Rise via Dikes

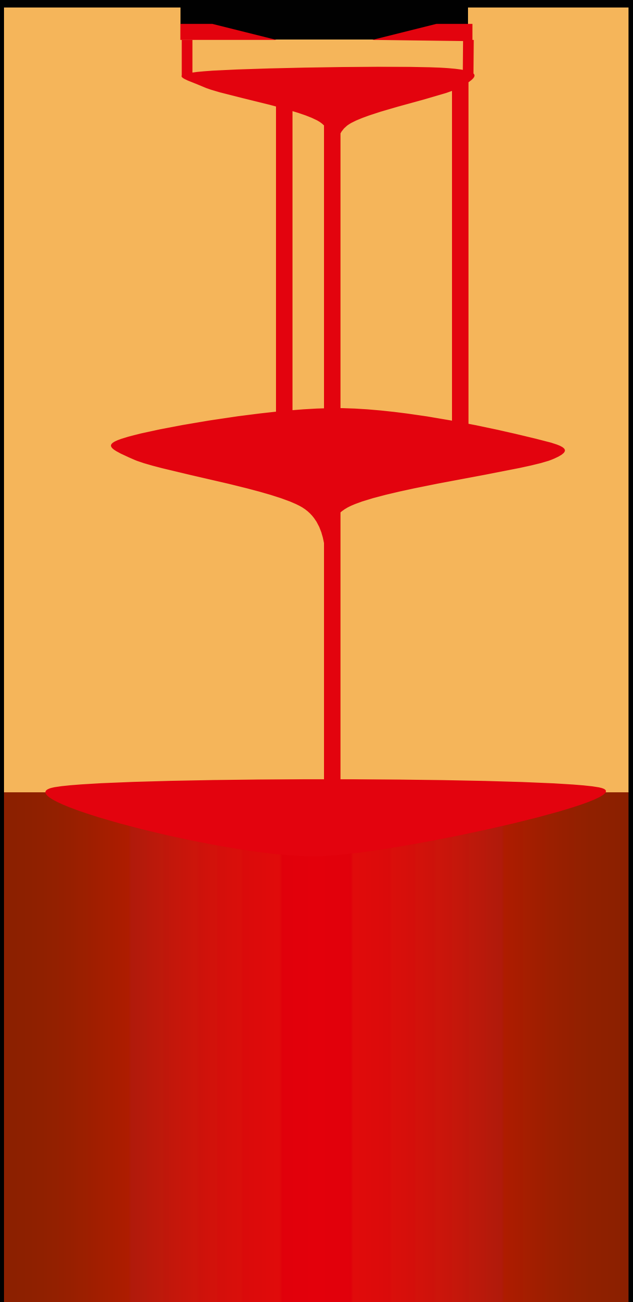
- Mafic to ultramafic, low-viscosity material typically rises in dikes (sheet-like injection through brittle crust)



Rise via Dikes

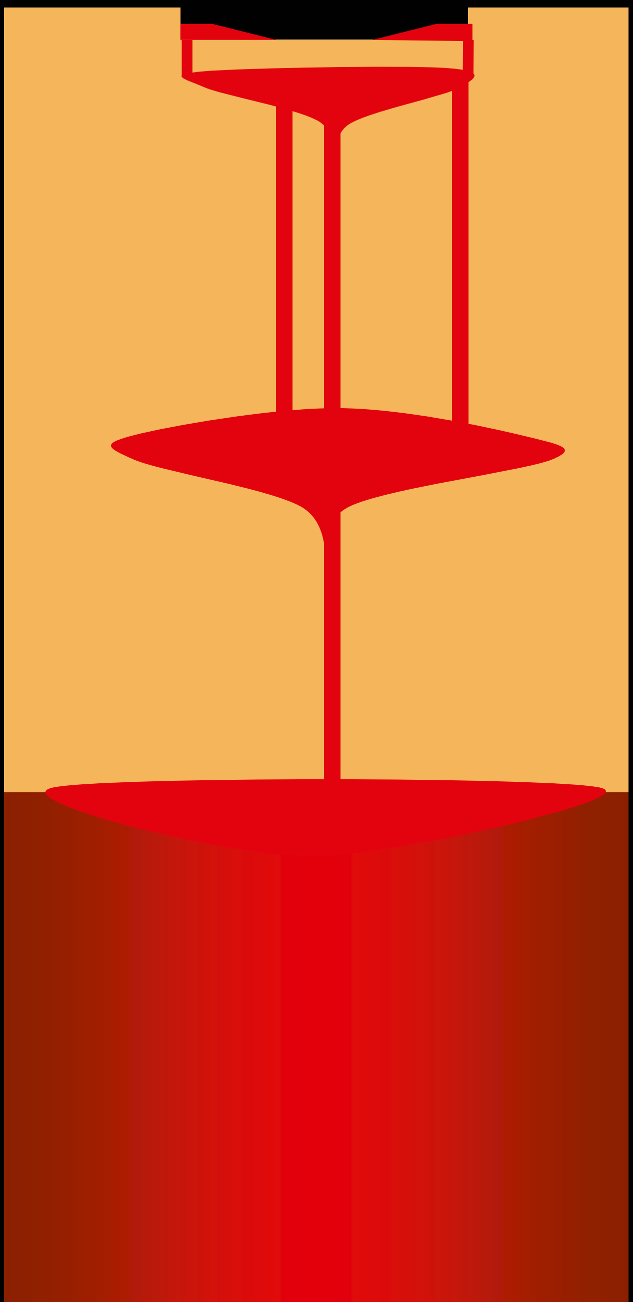
- Mafic to ultramafic, low-viscosity material typically rises in dikes (sheet-like injection through brittle crust)
- Dike can extend height of Io's lithosphere (~30 km)
- Rise speeds high: Tvashtar fissure eruption ascent velocity $v = 2 – 6\ m\ s^{-1}$

Wilson and Head, 2001



Series of Magma Chambers

- Neutral buoyancy zone at 12 km depth for 40% melt diapir
  - For lithosphere 75% silicates, 15% SO_2 frost, 10% void space (Leone and Wilson 2001)
  - Depth reduced for smaller void space/ SO_2 frost percentage OR more partial melt



Series of Magma Chambers

- Neutral buoyancy zone at 12 km depth for 40% melt diapir
  - For lithosphere 75% silicates, 15% SO_2 frost, 10% void space (Leone and Wilson 2001)
  - Depth reduced for smaller void space/ SO_2 frost percentage OR more partial melt
- Connection to source ensures replenishment of magma chambers

III. Magma finds a high-level zone of neutral buoyancy. Then it:

a) Spreads laterally to form a chamber of 5-40 km in diameter, a few kilometers below the surface.

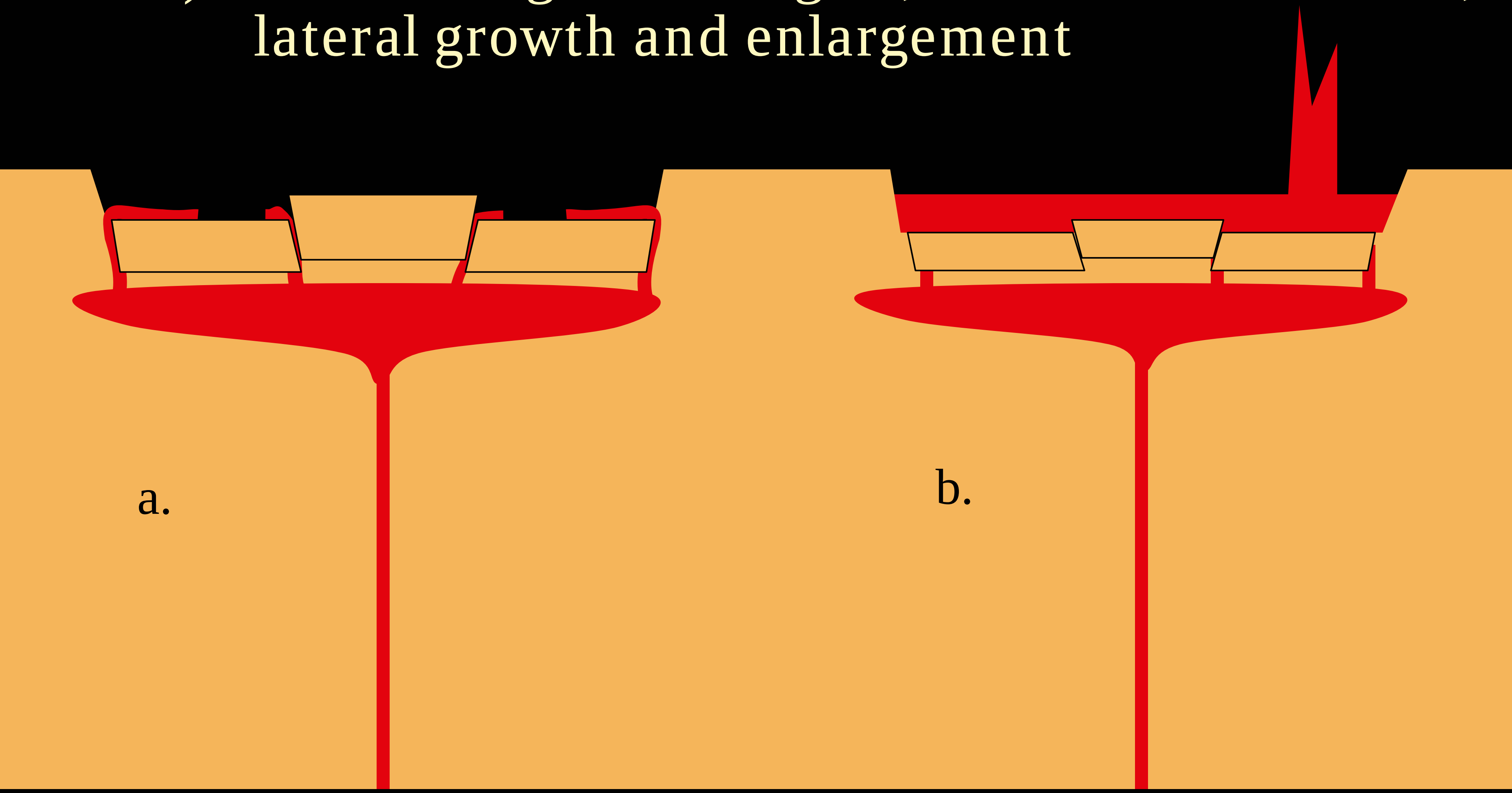
b) Erupts in a lava flow field.

IV. The overlying crust, thermally weakened by the underlying magma chamber, collapses.

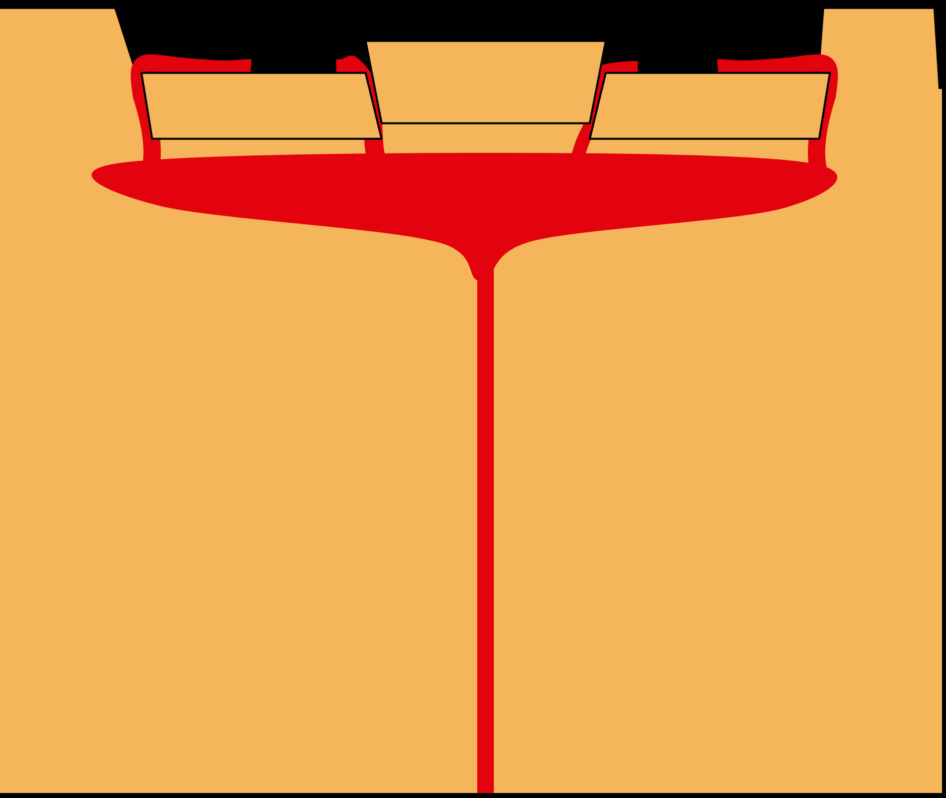
- Often happens when there is an associated eruption

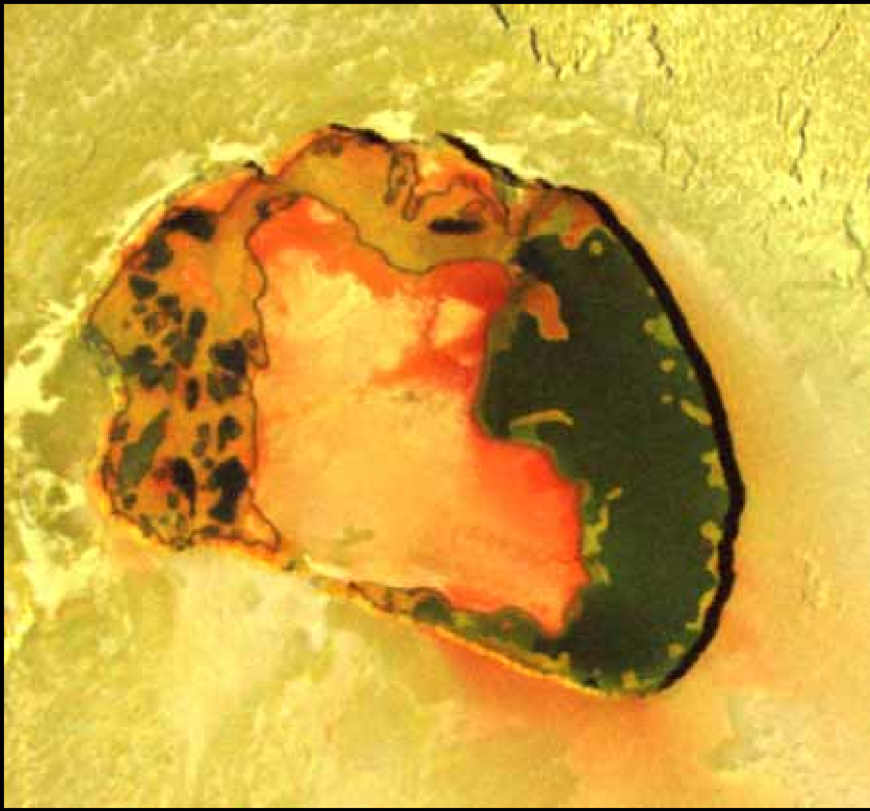
V. Patera evolution:

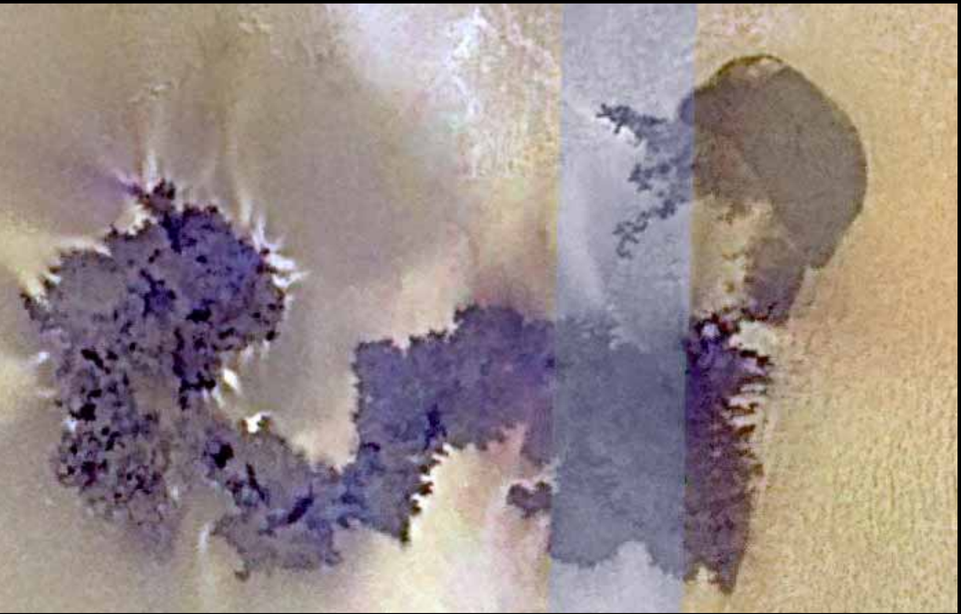
a) Lava emerges at margins, flows across its floor, lateral growth and enlargement

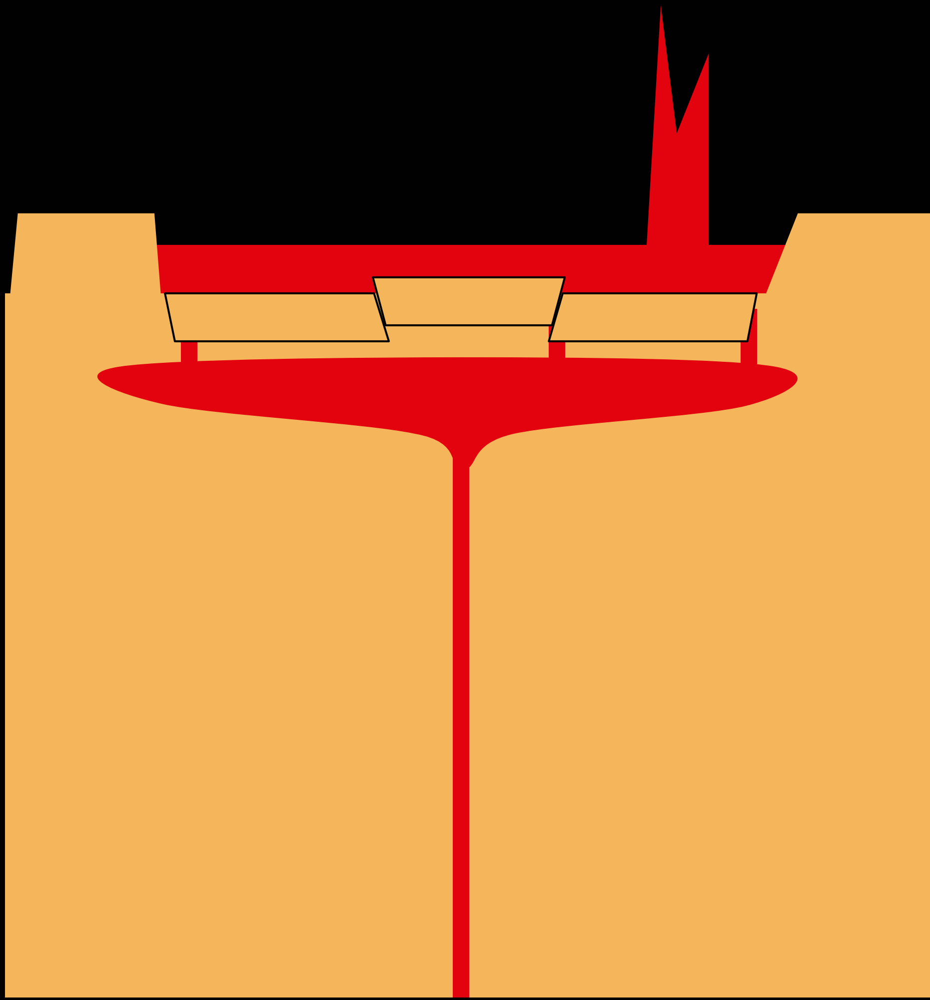


b) Lava fills the patera, erupts as a lava lake









Conclusions

- Heating and rapid convection (V = 150 – 5000 m y^{-1}) in asthenosphere leads to magma rise through lithosphere
  - Diapiric rise can occur for sufficiently large diapirs (d = 20 - 40 km) and thermal softening of wall rock (effective $\nu = 10^{14}$ Pa s)
  - Dikes can extend height of lithosphere; rapid magma rise (v = 2 – 6 m s^{-1}) brings asthenospheric material up with little differentiation
  - Based on resurfacing rates and diapiric d and v, only 10% of magma flux from diapirs
- High-level magma chambers form if high melt percentages and dense lithosphere
- Collapse over chamber, subsequent filling and lateral evolution leads to patera morphologies

Extra slides

Properties of Io's Asthenosphere and Lithosphere

Parameter	Symbol	Value	Units
Asthenosphere:			
Thickness	*b*	100	km
Density	ρ	3260	kg m^{-3}
Viscosity	ν_{asth}	$10^{9} – 10^{12}$	Pa s
Lithosphere:			
Thickness	*a*	30	km
Density (subsurface, 10% void, 15% SO2)	ρ	2730	kg m^{-3}
Viscosity	ν_{lith}	$10^{18} – 10^{19}$	Pa s
Gravitational acceleration	*g*	1.8	m s^{-2}

Segatz et al. 1988; Ross et al. 1990; Tackley et al. 2001; Leone and Wilson 2001; Jaeger et al. 2003

Resurfacing Rates

- Global heat flow can be related to resurfacing rate (Reynolds et al. 1980).
- Current estimate of heat flow ~ 2 W/m^2 leads to resurfacing rate of 1.06 - 0.55 cm/y (McEwen et al. Jupiter book) so 4.16×10^{11} m^3/y on Io's surface
- Single diapir d = 40 km rising v = 50 cm/y provides 6.3×10^8 m^3/y
- ~100 volcanic centers: 6.3×10^{10} m^3/y
  - Still one order of magnitude short
- ~500 volcanic centers: 3.1×10^{11} m^3/y

Magma supply

- Tvashtar fire fountain eruption estimated at $2 \times 10^4 - 2 \times 10^5\ m^3\ s^{-1}$ (Wilson and Head 2001)
  - Single diapir *d* = 40 km, *h* = 5 - 15 km can feed this eruption for 1 - 30 years
  - Magma chamber *d* = 5 km, *h* = 1 km for less than 5 days
- Pele mass eruption rate estimated at $248 - 341\ m^3\ s^{-1}$ (Davies et al. 2001)
  - Diapir *d* = 20 km *h* = 5 km, feeds this for 150 years
  - Diapir *d* = 5 km, *h* = 1 km, for 2 years

Asthenospheric convection

- Steady-state boundary layer theory (Turcotte and Schubert, 2002) to a fluid layer heated from within (due to friction, related to tidal forces) and cooled from above. Very large Prandtl number: ignore inertia terms in momentum equation

More parameters

Thermal diffusivity	κ	10^{-6}	$m^2\ s^{-1}$
Thermal expansivity	α	$3x10^{-5}$	K^{-1}
Heat capacity	c_p	1200	$J\ kg^{-1}\ K^{-1}$
Average tidal dissipation	Q	$1.4023x10^{-9}$	$W\ kg^{-1}$
Latent heat of fusion	L	400	$kJ\ kg^{-1}$