SLAB DYNAMICS IN 3D MANTLE MODELS

The applicability of Stokes Law to a "Perfect Plate" model

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INTRODUCTION

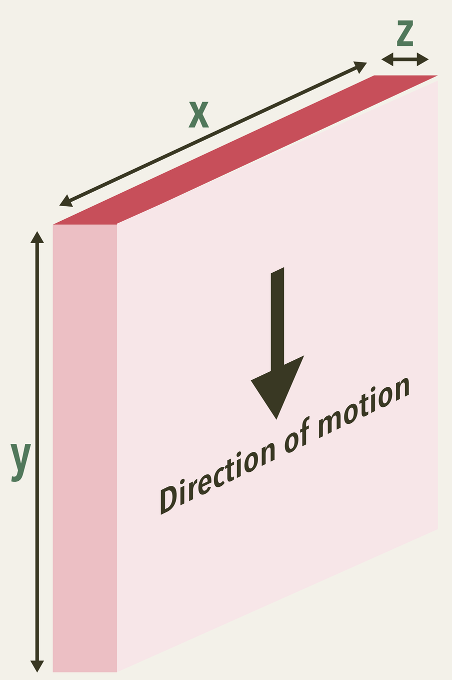
- Numerous studies have sought to understand slab sinking dynamics
- 3D spherical models driven by 'perfect' plate at the surface used to understand relationship between slab properties & dynamics
- Aim to relate slab sinking to Stokes Law & how this can be used to tune geodynamic models

STOKES LAW

Stokes Law describes drag force of particle sinking through sphere[1]:

$$F_D = 3\pi\mu V d_n K_n$$

μ = viscosity, V = velocity, d_n = diameter of sphere with same projected surface area as slab normal to direction of motion, and shape factor K_n[2]:



$$K_n = 1/(0.197+0.627\psi+0.24d_v/d_n-0.029d_{max}/d_n)$$

d_v = diameter of sphere with same volume as object, d_{max} = max dimension of the object along principal axis and ψ = :

$$\psi = \frac{d_v}{\text{surface area of the object}}$$

Simplify slabs to 3D sheet descending vertically, x = trench length, y = depth of slab in mantle, z = thickness of the slab.

METHODS

Generate plate motion reconstruction in GPlates[3]

Specify latitude & longitude values of subduction trench & spreading ridge, joined by transform faults along line of latitude

Export velocities to TERRA[4] grid

Assign tracking particles to moving plate

Vary simulation parameters

VISCOSITY	PLATE GEOMETRY	VELOCITY
Isoviscous 10^{22}-10^{25} Pa s	Lat & long varies between ± 5° to ± 80°	1-8 cm/yr at surface

Repeat for simulations initiated with plate motion history at the surface, then left to develop with free slip boundary condition

REFERENCE MODEL PARAMETERS

- Rayleigh Number = ~ 10^7
- Ref. Viscosity = 10^{23} Pa s
- Model Duration = 500 Myr
- Surface Plate Velocity = 4 cm/yr
- Plate geometry = ± 35° x ± 35°

VISCOSITY

PLATE DRIVEN: Visc ≈ 10^{21} DRIP TECTONICS

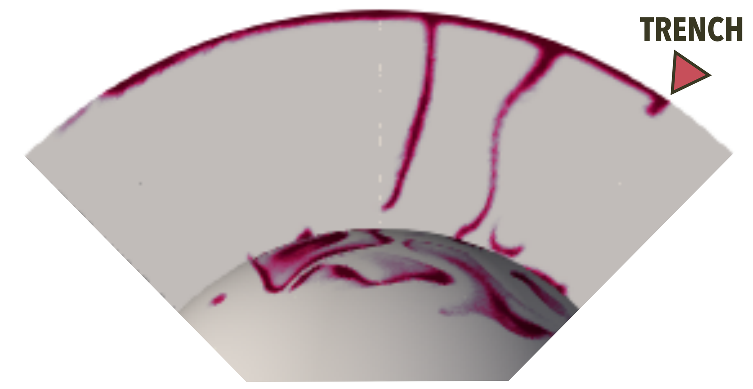
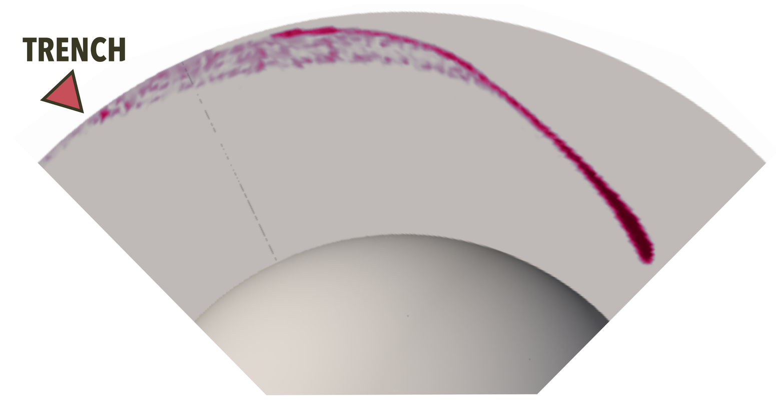


PLATE DRIVEN: Visc ≈ 10^{25} SHALLOW SLAB SINKING



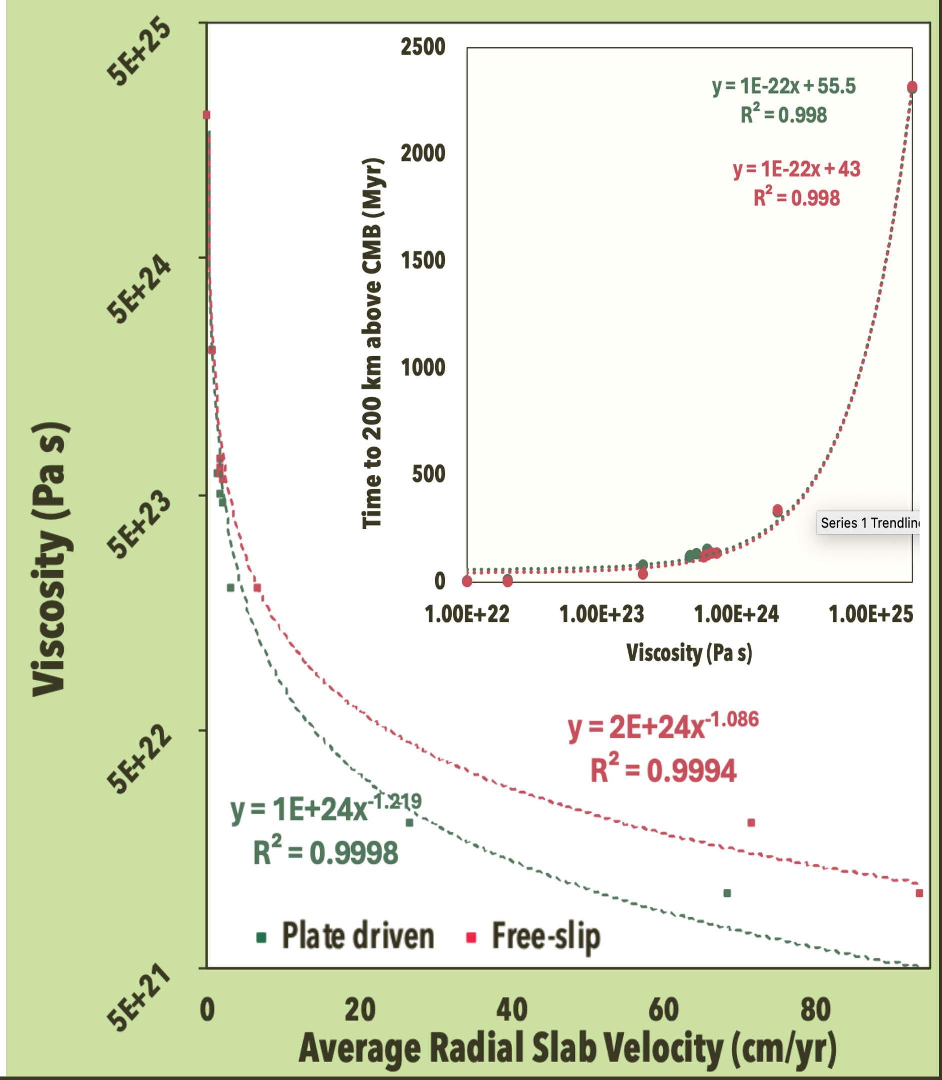
At low viscosities, slabs descend vertically from beneath plate

At high viscosities, slab descends shallowly & thicken in the near surface

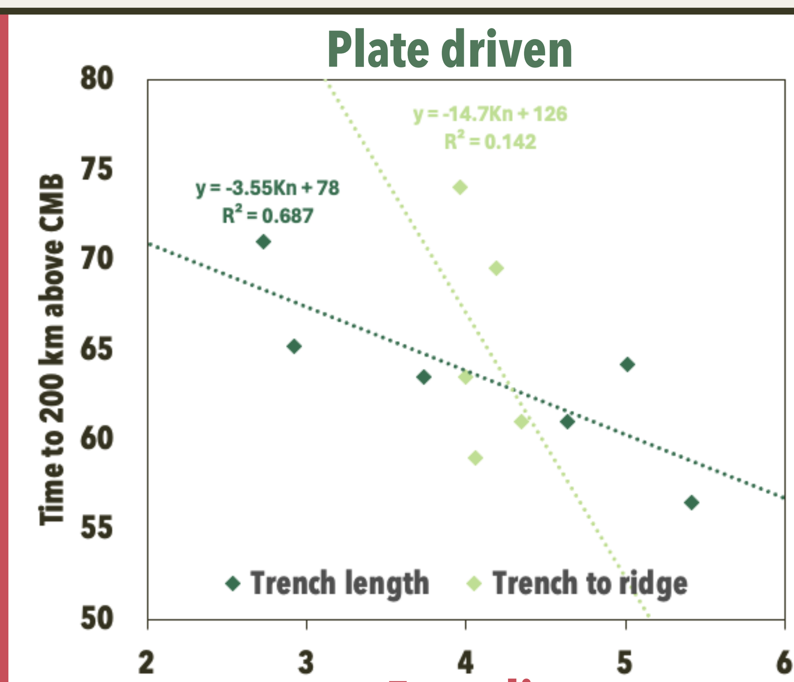
Power law relationship between viscosity & velocity

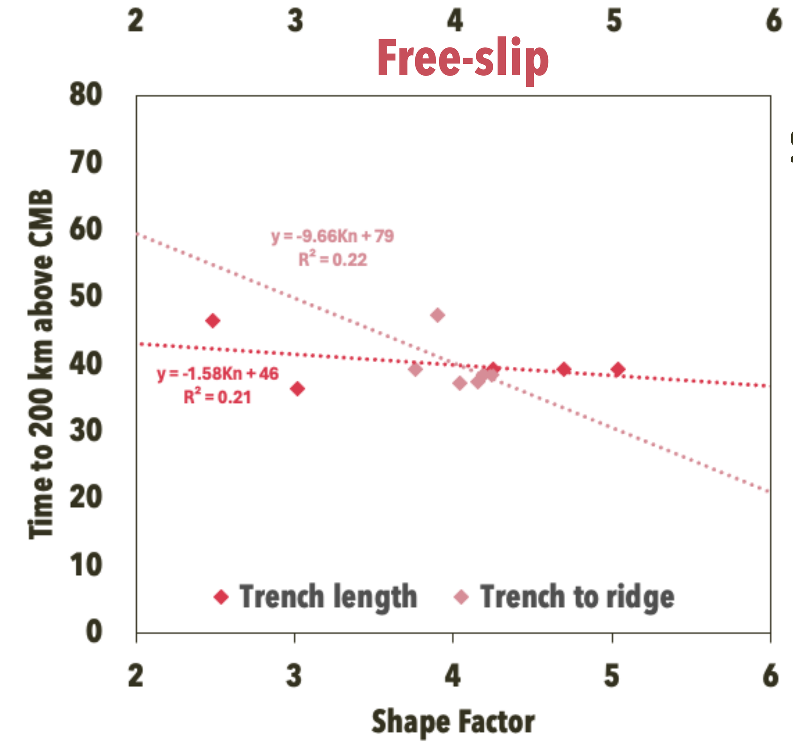
Linear relationship between viscosity and slab sinking time

Strong correlation between slab sinking time and viscosity



SHAPE FACTOR





Correlation between trench length and slab sinking time for plate driven slabs

Weak correlation between trench to ridge distance and slab sinking time

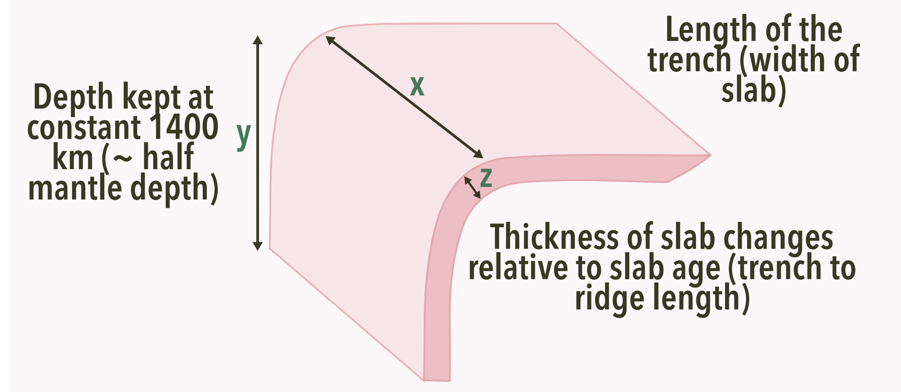
Weak correlation between shape factor and sinking times for all free-slip models

Shape factor does change slab geometry

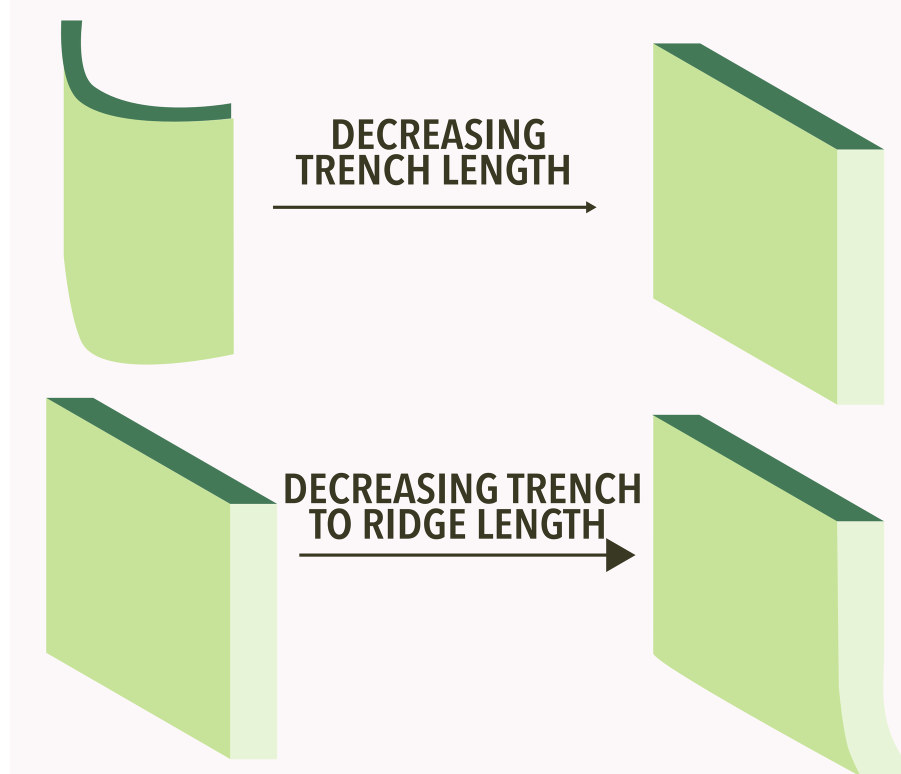
As trench length increases, slab becomes arcuate

For plate-driven models, slab geometry at depth changes with trench to ridge length

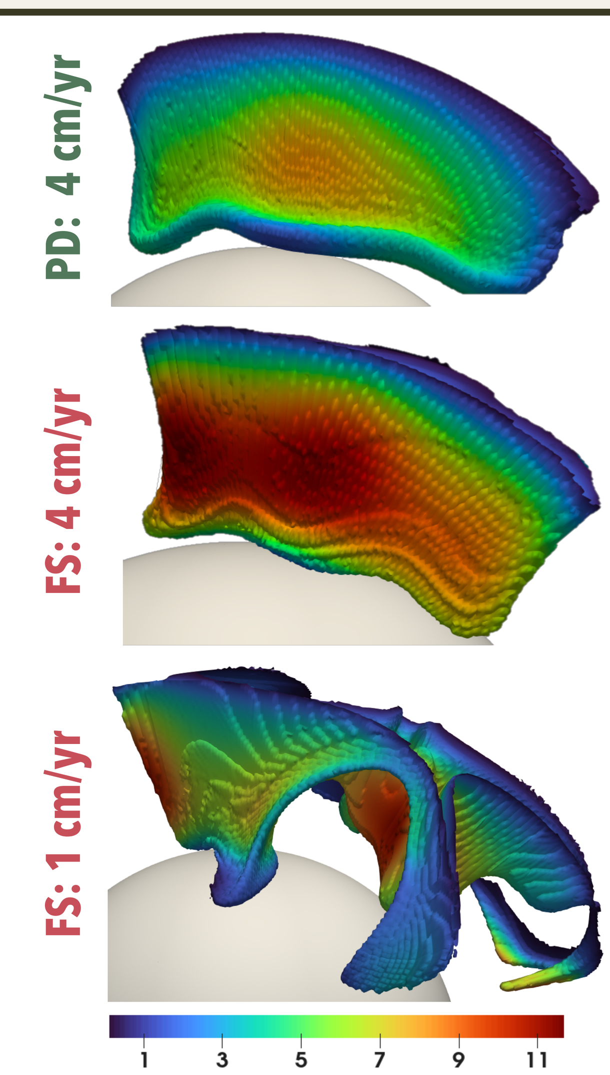
CALCULATING SHAPE FACTOR



SLAB GEOMETRY WITH SHAPE FACTOR



SURFACE VELOCITY



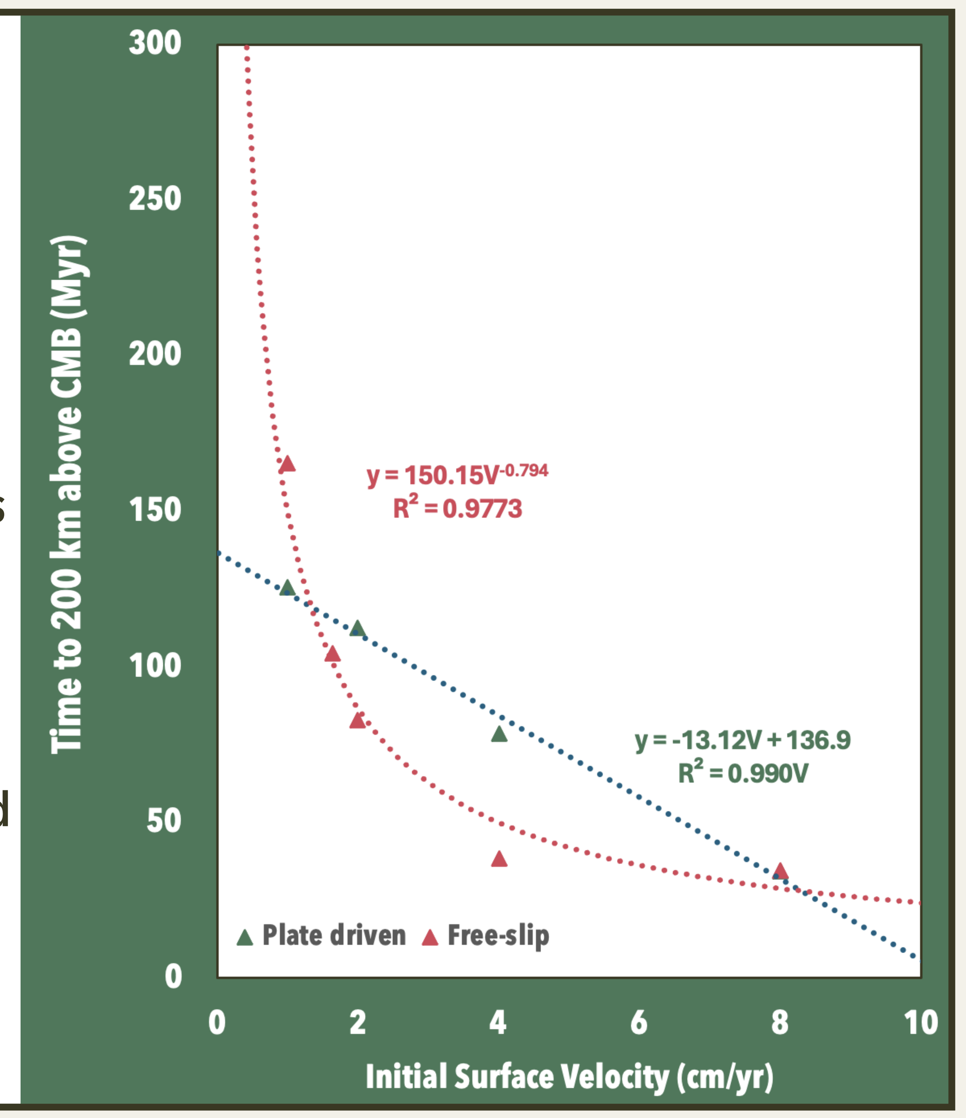
Free-slip (FS): power law relationship between velocity & sinking time

Plate driven (PD): linear relationship between velocity and sinking time

Difference between PD & FS models determined by interplay between slab dip & thickness

If surface velocities = 4 cm/yr, PD models sink at angle & maintain thickness, FS slabs thin and descend vertically

At low velocities, FS subduction zone deforms, slabs take longer to reach the CMB than PD slabs



EXAMPLE APPLICATION: Tuning Models to 100 Myr

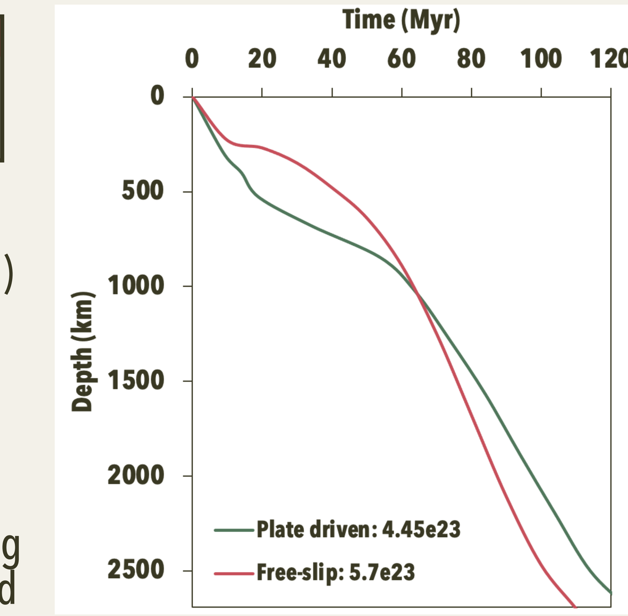
VISCOSITY

PLATE DRIVEN	FREE-SLIP
100 = 1 x 10^{-22}μ +55.5 μ = 4.45 x 10^{23}	100 = 1 x 10^{-22}μ +43 μ = 5.7 x 10^{23}

Plate driven slabs sink in 122 Myr (needs additional tuning to better constrain equation)

Free-slip slabs sink in 108 Myr

We suggest these equations are a good starting point from which further tuning can be applied



SHAPE FACTOR

Lower shape factors sink slower

Shape factor = 1 represents a sphere, cannot be lower than 0

Future work can increase slab thickness using viscosity, though this would require a more complex viscosity profile and is beyond the scope of this study

VELOCITY

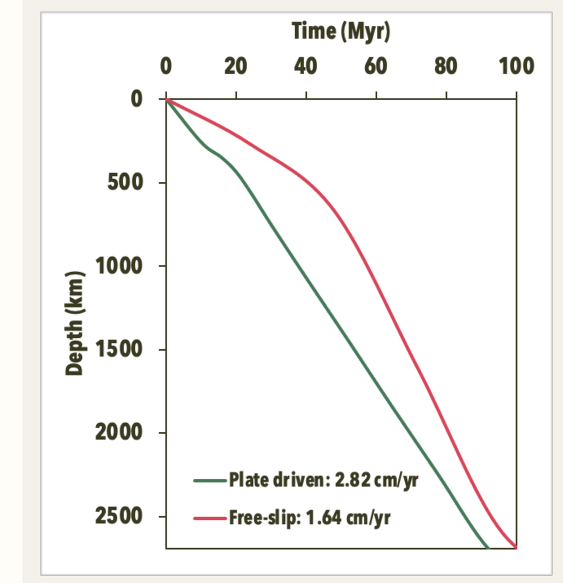


PLATE DRIVEN	FREE-SLIP
100 =-13.12V + 137 V = 2.82 cm/yr	100 = 148.03$V^{-0.787}$ V = 1.64 cm/yr

Plate driven slabs sink in 93 Myr

Free-slip slabs sink in 104 Myr, validating this model within a reasonable error

CONCLUSIONS

Stokes Law can be applied to slabs in mantle

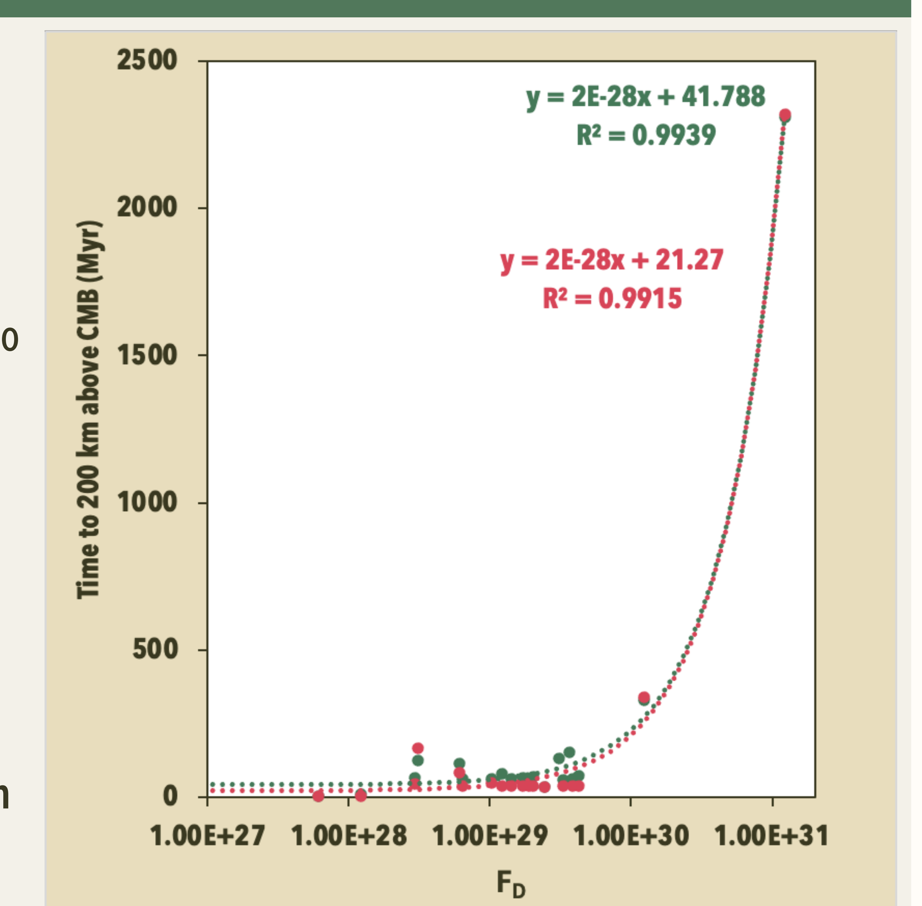
Drag force (F_D) has linear correlation with sinking time

Can tune geodynamic models to ideal sinking rates

Constituent equations can be used to constrain Stokes Law parameters separately

Applicable to models with PD and FS boundary conditions

Additional work to test this in Earth-like simulations, with multiple slabs & complex viscosity profiles.



ACKNOWLEDGEMENTS & REFERENCES

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[2] Johnson, D.L., 1985. Drag force on orthotropic aerosol particles (Doctoral dissertation, Ph. D. Dissertation, University of North Carolina at Chapel Hill).
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