Dangling Slab Dynamics

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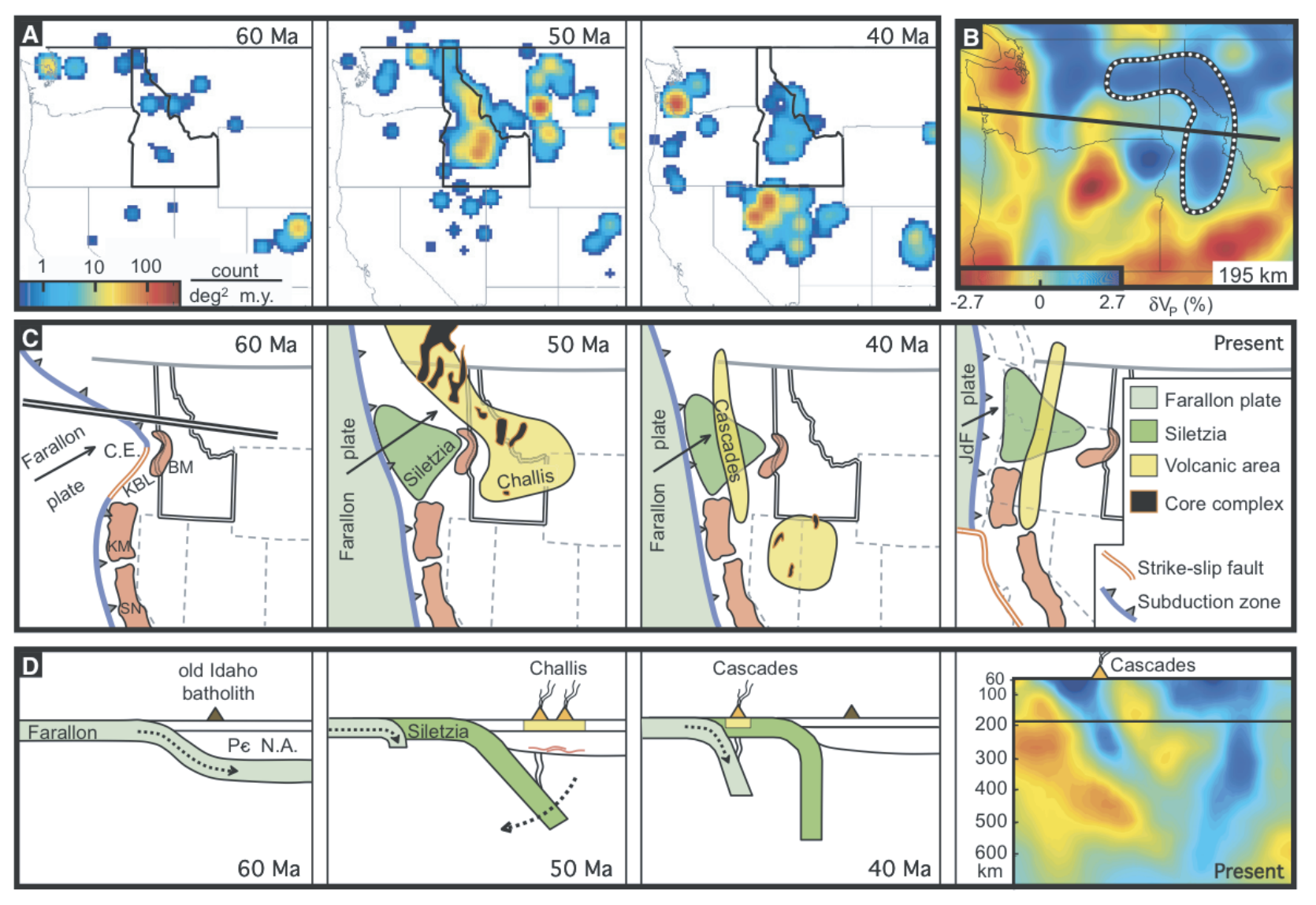
I. Introduction

Motivation: Recent seismic imaging of the mantle beneath western North America reveals complexities interpreted to include structures ranging from plumes to drips and dangling slab fragments. Schmandt and Humphreys (2011)[1] propose a model that interprets a high-velocity 'curtain' to be a remnant of subducted Farallon plate that may have been dangling within the upper mantle for 50 My while subduction continued nearby. Such observations and models provide motivation for better understanding the rheologic, dynamic, and buoyancy conditions under which a slab fragment might persist in the upper mantle, either in the presence or absence of nearby subduction.



Schmandt and Humphreys (2011)

We use 2D numerical models to explore: effects of slab and mantle rheology, buoyancy, and geometries on the dynamics of subducting and dangling slabs.

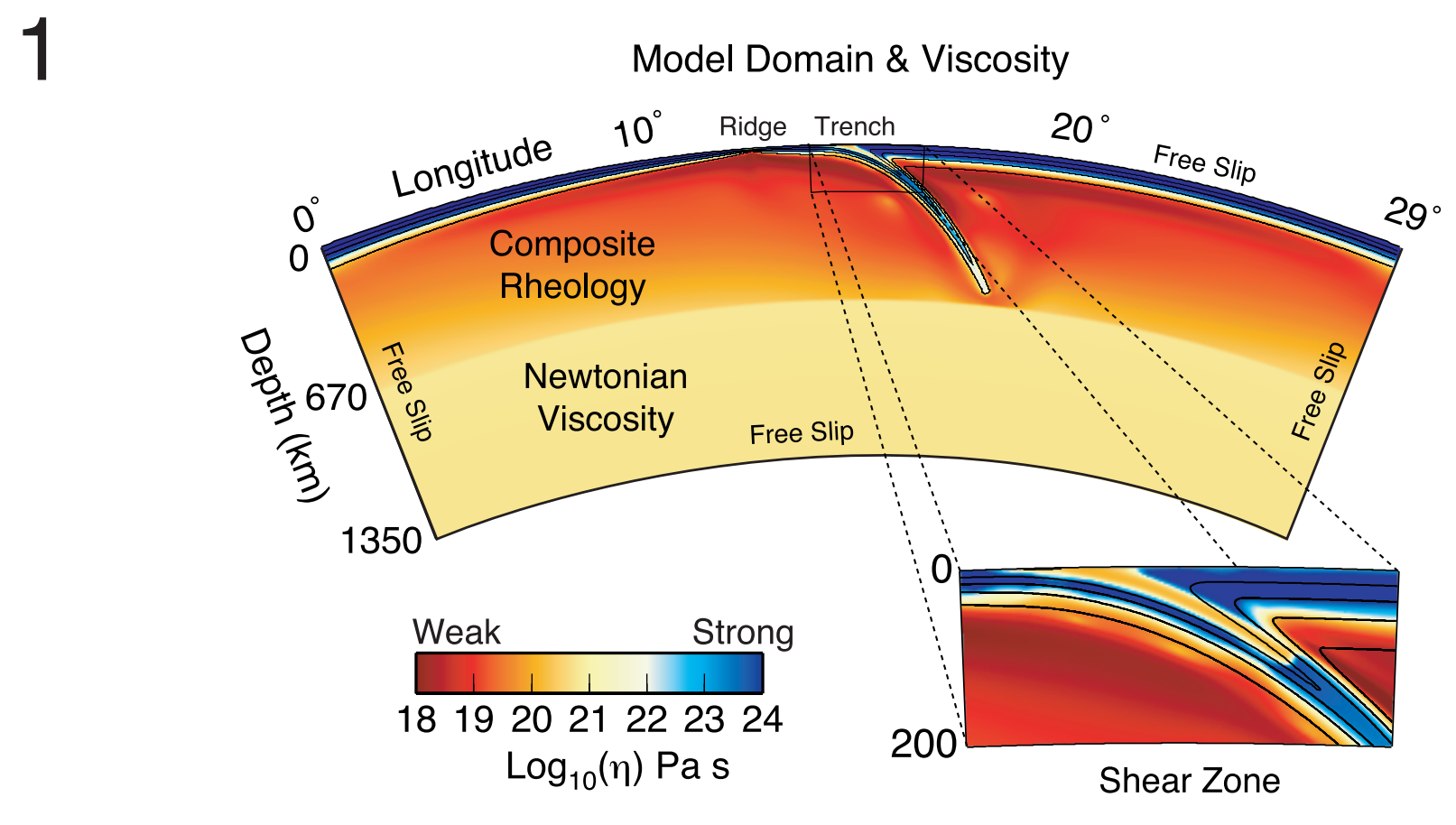
II. Model Setup

We use the 3D numerical finite element code CitcomS* which solves the standard equations for incompressible viscous flow (conservation of mass, momentum, and energy).

*Zhong et al. (2000) and Tan et al. (2006), with weak zone and composite viscosity modifications by Magali I. Billen

Boundary Conditions

Domain Size
Longitude: 0° to 29°
Depth: 0 (surface) to 1350 km depth
Resolution: 1.4x1.5 km (highest resolution in wedge) to 14x10 km (bottom side boundaries)
Boundaries: Free slip



Viscosity Structure

Upper Mantle: Composite Viscosity (Newt. & non-Newt.)
Lower Mantle: Newtonian

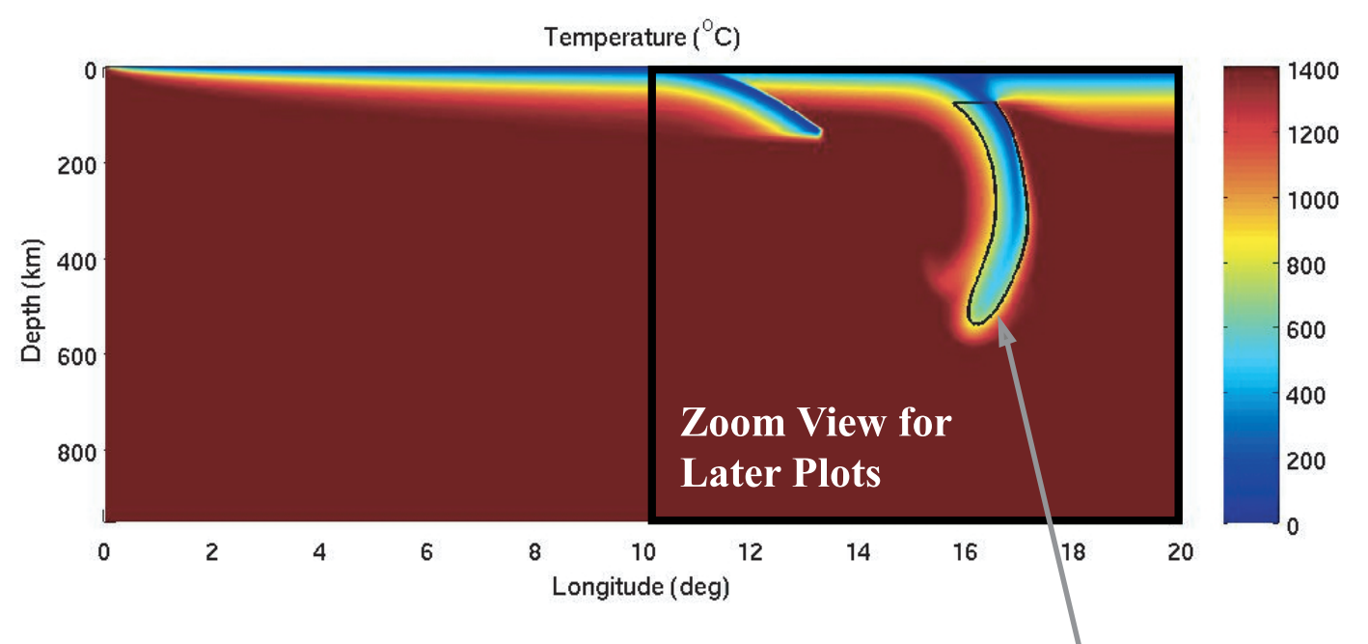
Olivine flow law parameters from Hirth and Kohlstedt (2003)[4].

$$\eta_{df,ds} = \left(\frac{d^p}{AC^r_{OH}}\right)^{\frac{1}{n}} \dot{\epsilon}_E^{\frac{1-n}{n}} \exp\left[\frac{E+P_{lc}V}{nRT}\right] \qquad n=3.0$$

Yield Stress, σ_y: σ_{ymax} = 500 or 1000 MPa (constraints[5])

Temperature Initial Condition

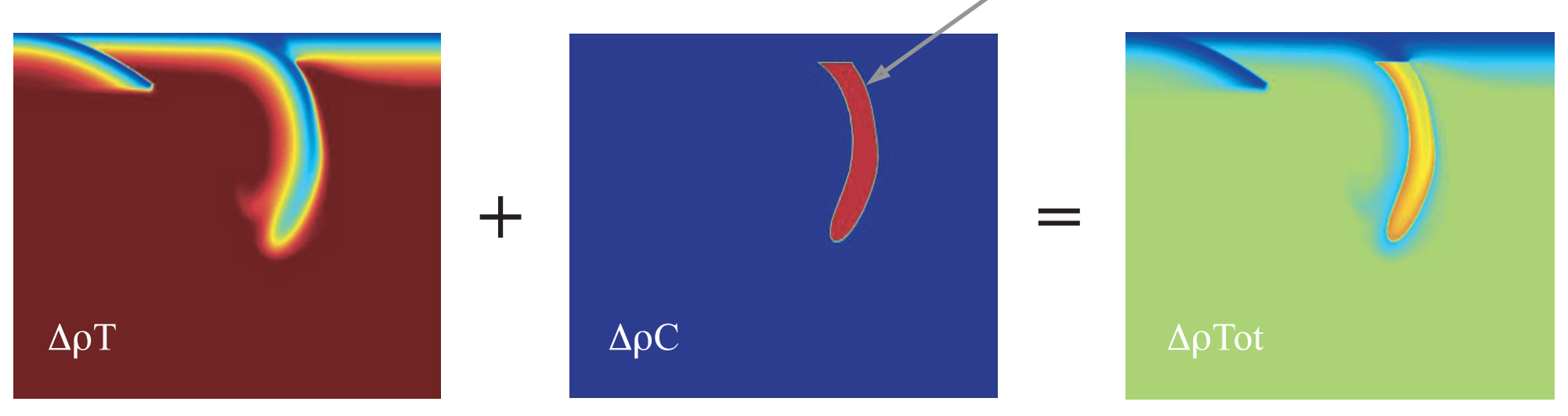
Surface plates: generated according to half-space cooling model
Initial subducted slab: short prescribed intial profile based on trench age (200 km deep to start dynamic subduction)
Initial stalled ("dangling") slab: generated dynamically



Overriding plate age: intitially 50 My (66 km deep to 1000°C)
Subducted plate: 0 (ridge 1000 km outboard) to 50 My at trench
Temperature range: 0 to 1400°C

Density/Buoyancy Initial Condition

800°C slab contour containing tracers defines chemical density anomaly (lighter than background density 3300 kg/m³)



Density differences due to thermal anomalies

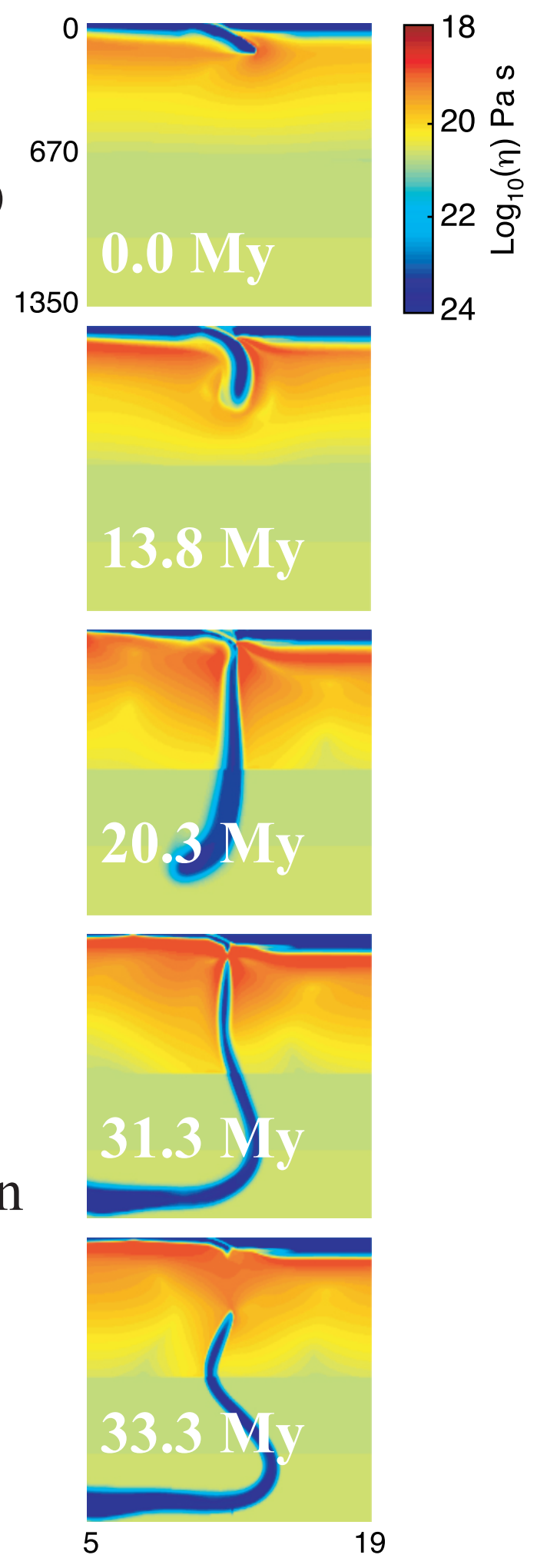
Prescribed 'chemical' density anomaly: 0, 30, or 90 kg/m³

Total effective density anomaly, ΔρTot = ΔρT + ΔρC

III. Model Results

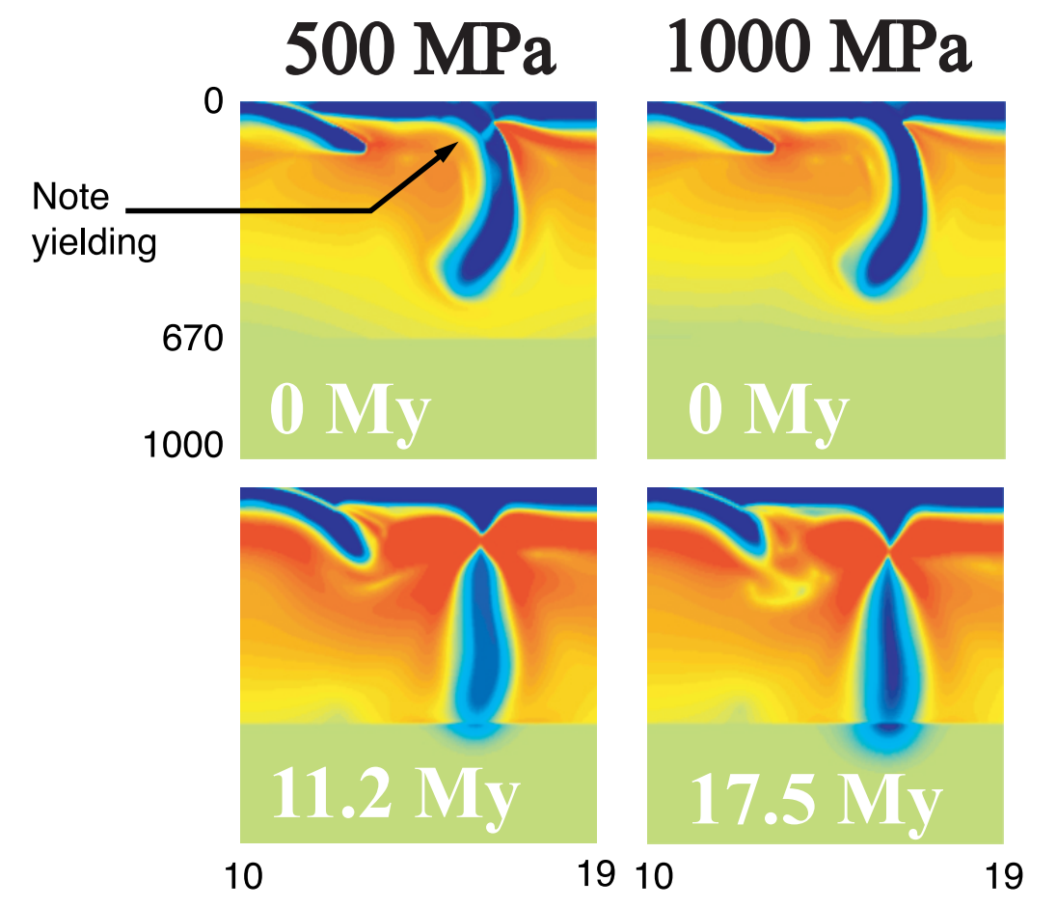
Subduction Without Stalled Slab

Model 1



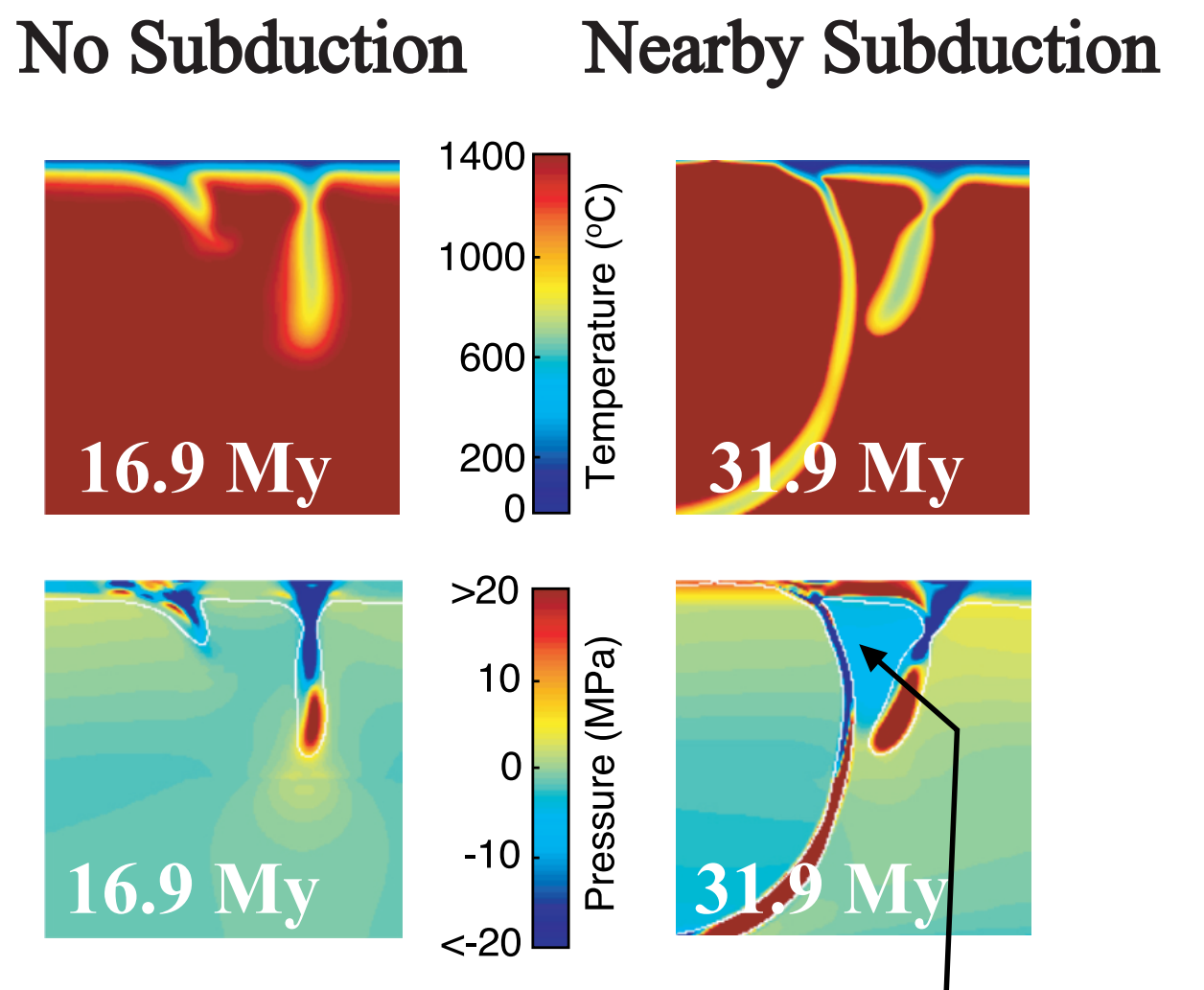
- ∗ Continuous subduction
- ∗ vertical slab sinking
- ∗ no slab dip shallowing
- ∗ detachment upon ridge-trench collision (ridge abandonment 430 km outboard)

Higher Yield Strength Delays Detachment of Stalled Slab



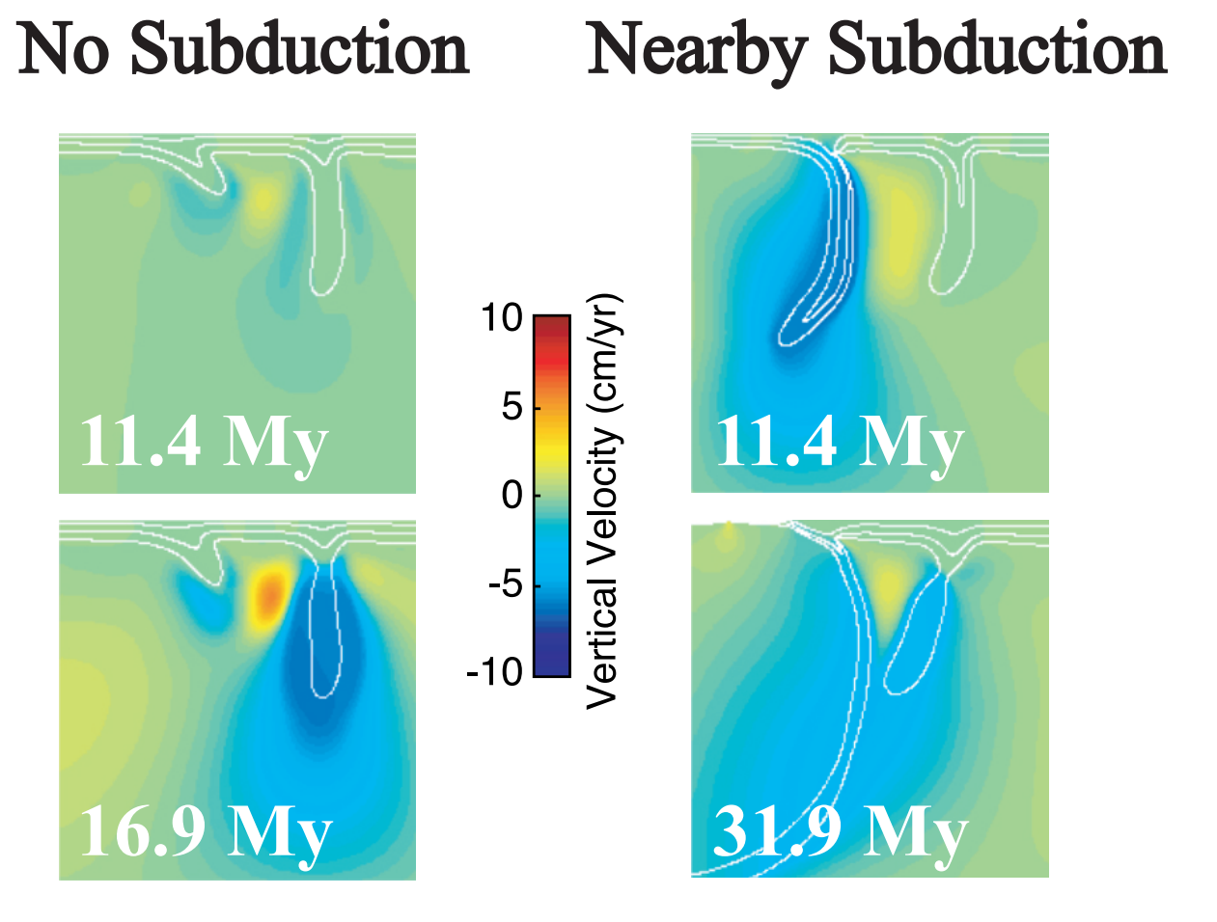
- ∗ No Subduction (strong shear zone)
- ∗ vertical profile and detachment of stalled slab within 20 My (quicker for lower maximum yield strength)
- ∗Dangling stalled slab detaches by yielding (see Andrews and Billen (2009) for details of stalled slab detachment dynamics)

Dynamics of Subduction Interaction with Stalled Slab



No subduction, flow pressures dominated by hanging slab (slow sinking until detachment) and small instabilities

Suction (negative) pressures in wedge during subduction pull stalled slab toward subduction zone

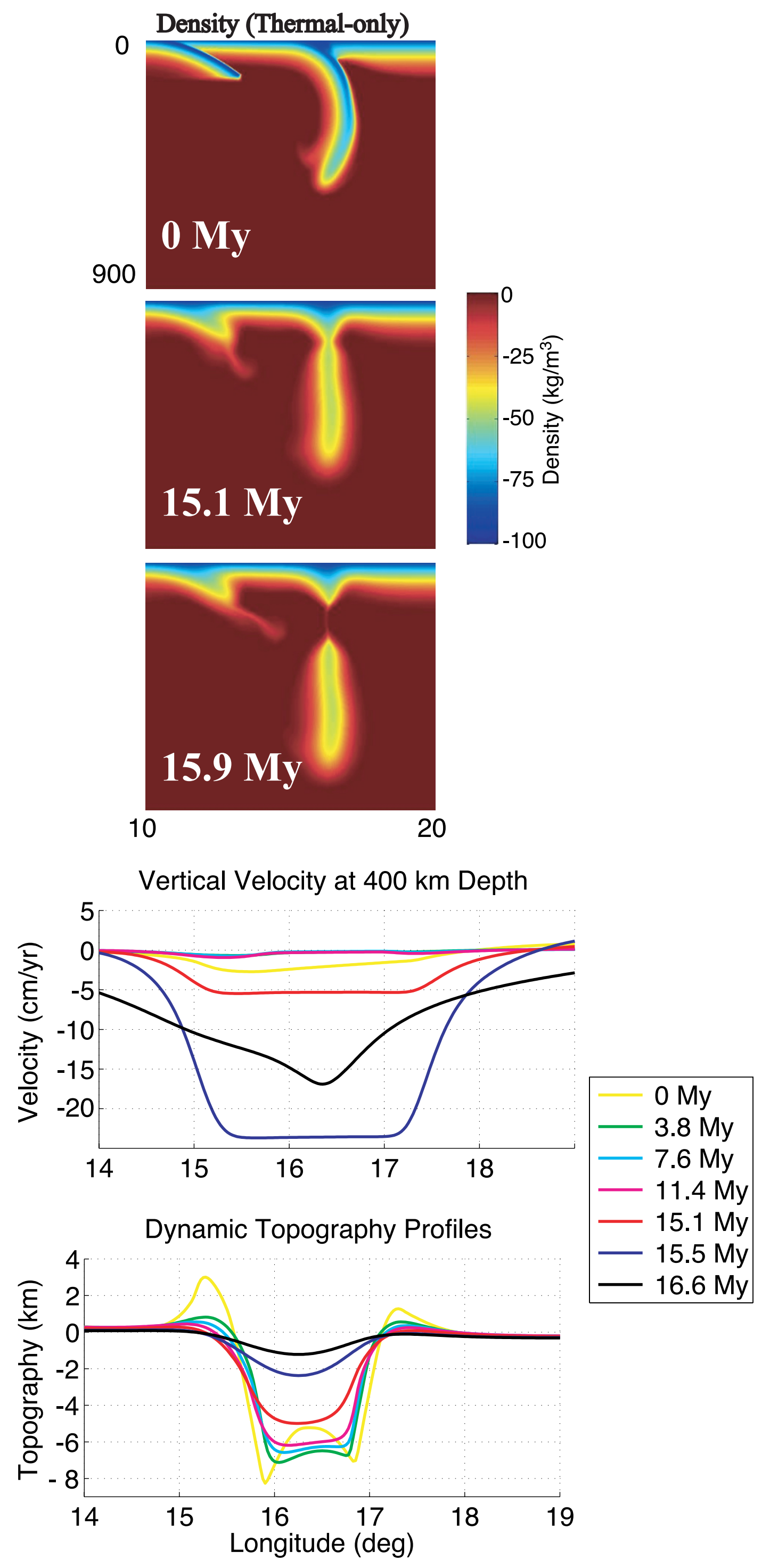


Without subduction-dominated flow, velocities localize in response to downward sinking, detaching of stalled slab

Subduction creates upward return flow pattern, which helps viscously support dangling slab and hence delay detachment

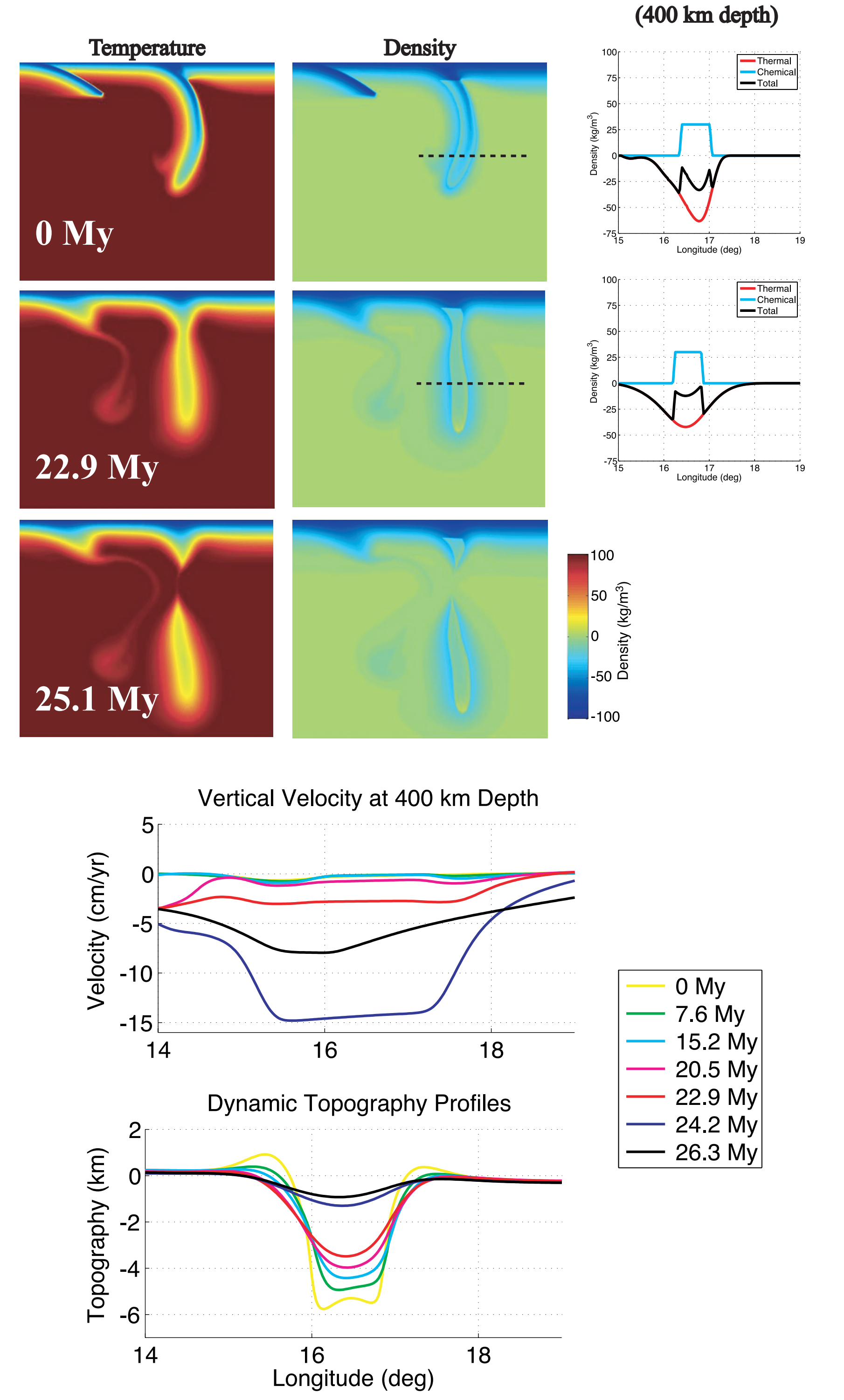
Effects of Adding Slab Chemical Buoyancy to Thermal (Negative) Buoyancy

Model 2: ΔρC = 0 kg/m³



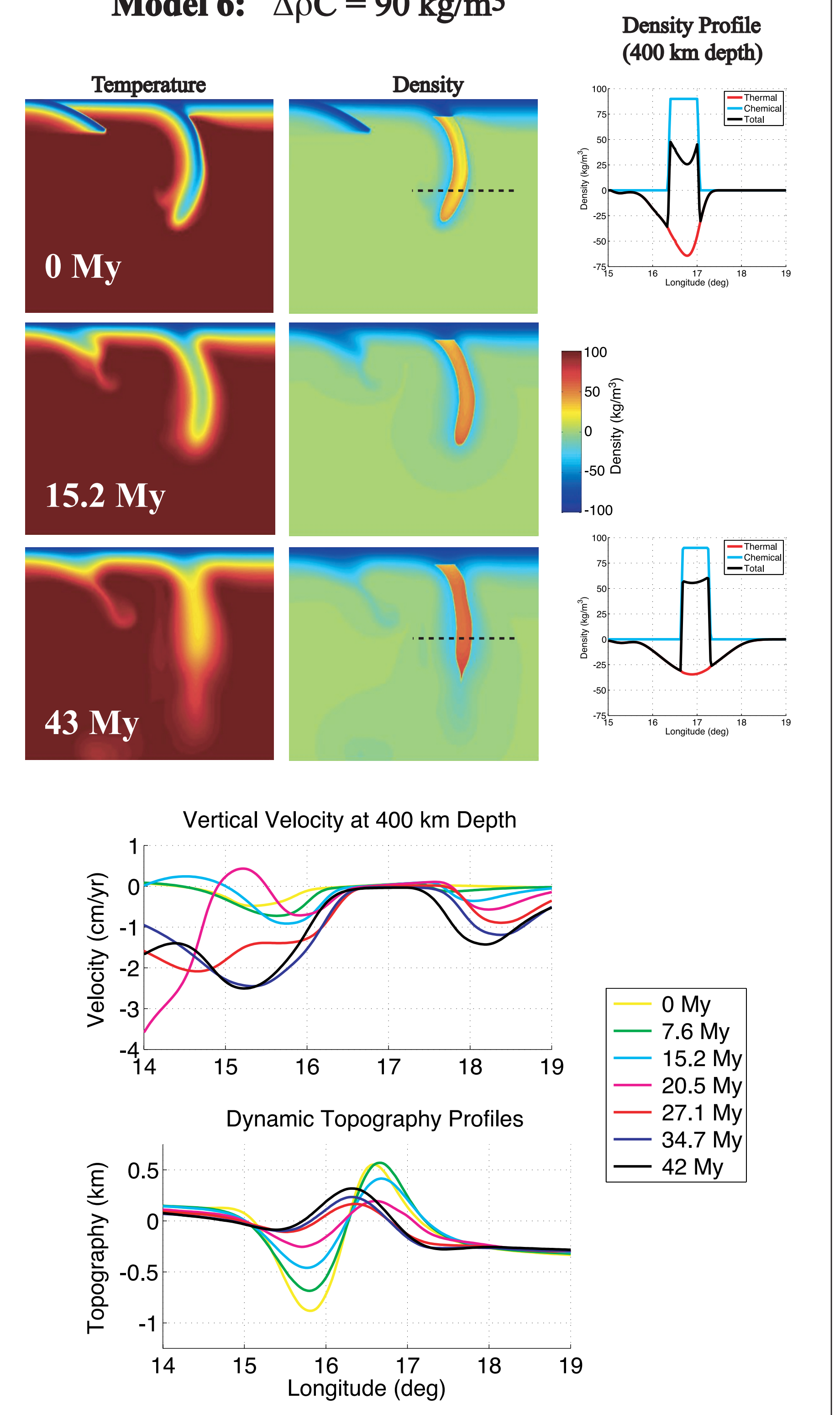
Negative slab thermal buoyancy leads to detachment (within ~15 My) and uplift

Model 5: ΔρC = 30 kg/m³



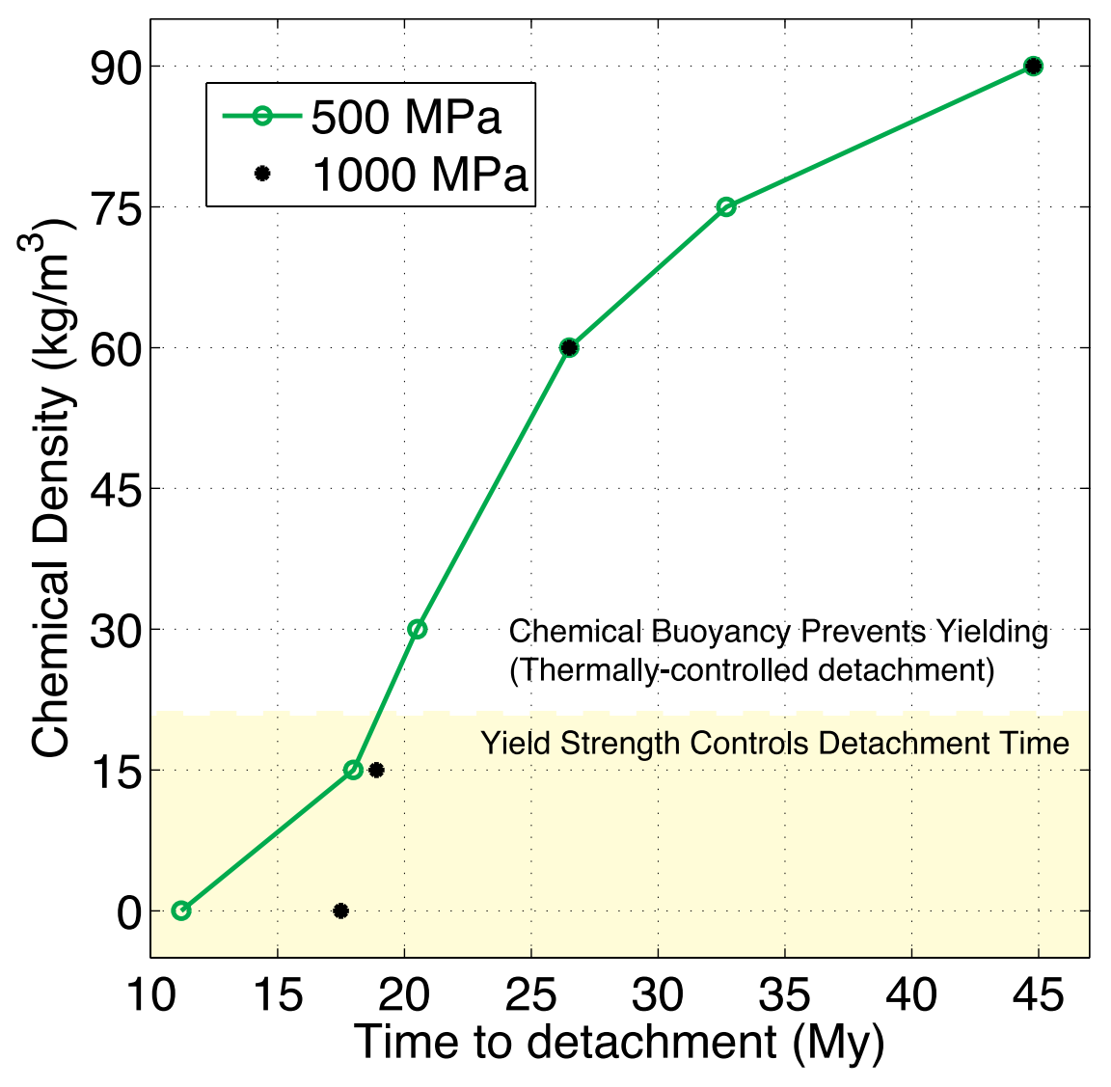
30 kg/m3 of chemical buoyancy slows sinking and delays detachment ~10 My, although thermal buoyancy 'wins'

Model 6: ΔρC = 90 kg/m³



>90 kg/m3 of chemical buoyancy is necessary to overcome thermal negative buoyancy and lead to a stagnant slab

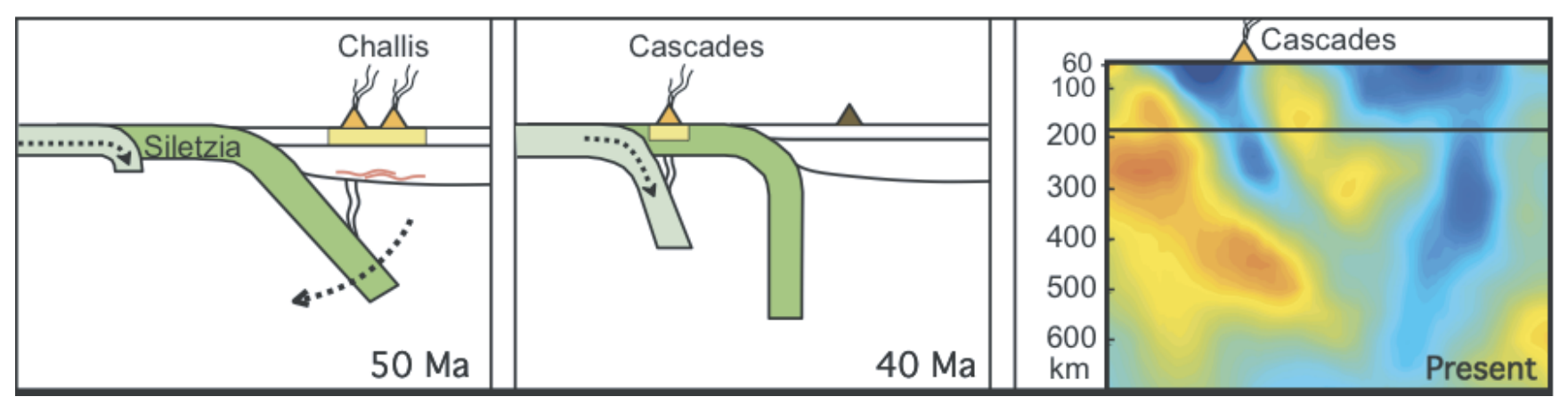
Buoyancy &Yield Strength Effects on Dangling Slab Residence Time



Chemical counteracts thermal buoyancy; delays but doesn't ultimately prevent detachment (cases without nearby subduction summarized above).

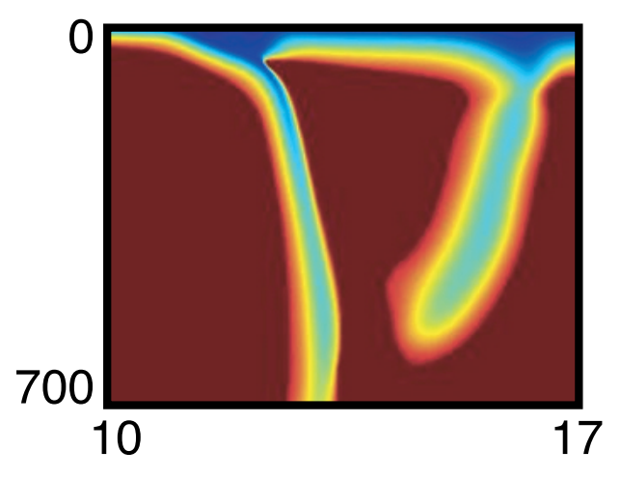
-Viscous support by flow from nearby subduction might allow further delay

Comparison with Observations



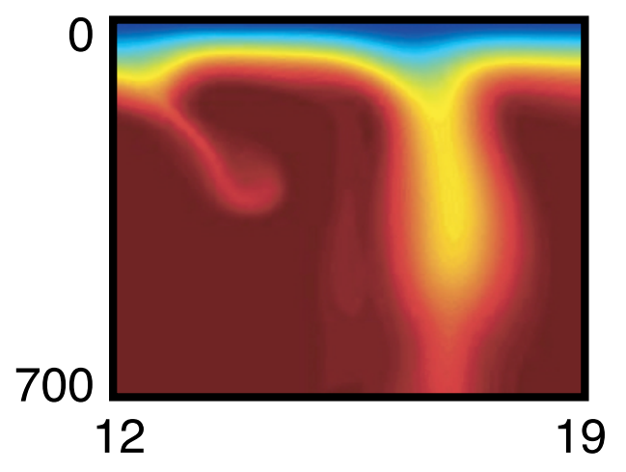
∗ The apparent westward deflection of observed high velocity 'curtain' with depth may be consistent with response to flow toward subduction zone

Model 3



∗ A positive chemical slab buoyancy (90 km/m³ density anomaly) may allow slab to remain dangling within the mantle for >40 My whereas thermal buoyancy alone predicts detachment within 10-20 My

Model 6



IV. Summary/Conclusions

(1) Subduction in close proximity (~450 km) to a stalled 'dangling' slab can lead to:
(a) deflection of the dangling slab toward the subduction zone and the sinking slab
(b) and a delay in detachment time due to viscous support by return flow toward wedge from nearby subducting slab

(2) Detachment occurs within ~10-20 My for dangling slabs whose buoyancy is solely thermally controlled

(3) Additional positive buoyancy from a slab density decrease of at least 90 kg/m³ would be necessary to overcome negative thermal buoyancy and allow the slab to 'dangle' for more than 40 My (in absence of subduction flow effects)

References

1. Schmandt, B., and E. D. Humphreys, Seismically imaged relict slab from the 55 Ma Siletzia accretion to Northwest USA, Geology, 39(2), 175-178, doi: 10.1130/G31558, 2011. 2. Zhong, S., M.T. Zuber, L.N. Moresi, and M. Gurnis, The role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection. J. Geophys. Res., 105, 11,063-11,082, 2000. 3. Tan, E., E. Choi, P. Thoutireddy, M. Gurnis, and M. Aivazis, GeoFramework: Coupling multiple models of mantle convection within a computational framework, Geochem., Geophys., Geosyst. 7, Q06001, doi:10.1029/2005GC001155, 2006. 4. Hirth, G., and D. Kohlstedt, Rheology of the upper mantle and the mantle wedge: a view from the experimentalists, in Inside the Subduction Factory, edited by J. Eiler, AGU, Washington D.C., 2003. 5. Goetze, C., and Brian Evans, Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics, Geophys. J. R. astr. Soc., 59, 463-478, 1979. 6. Andrews (Burkett), Erin R., and Magali I. Billen. Rheologic controls on the dynamics of slab detachment. Tectonophysics, 464, 60-69, doi:10.1016/j.tecto.2007.09.004, 2009. 7. Burkett, Erin R., and Magali I. Billen. Dynamics and Implications of Slab Detachment Due to Ridge-Trench Collision. J. Geophys. Res., 114, B12402, doi:10.1029/2009JB006402, 2009. 8. Burkett, Erin R., and Magali I. Billen. Three-dimensionality of slab detachment due to ridge-trench collision: Laterally simultaneous boudinage versus tear propagation. Geochemistry Geophysics Geosystems, Vol. 11, Q11012, 21 PP., doi:10.1029/2010GC003286, 2010.