Absolute asthenosphere viscosity from Caribbean dynamic topography, mantle structure and magmatism

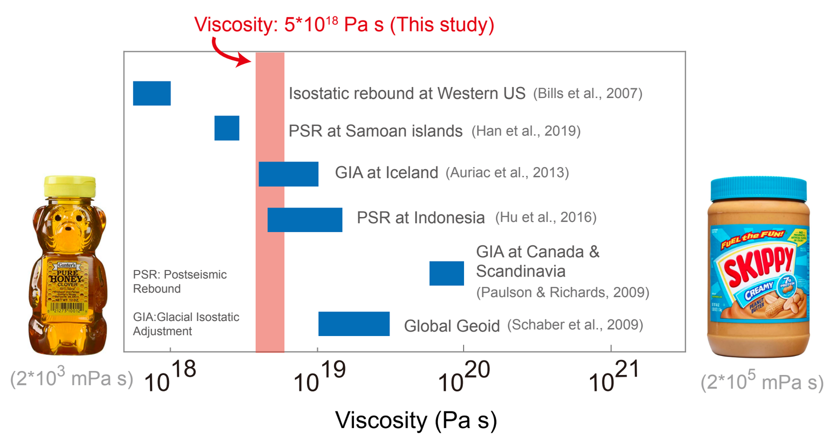
Yi-Wei Chen[1] (yiweichen.tw@gmail.com), Lorenzo Colli[1], Dale E. Bird[1], Jonny Wu[1] and Hejun Zhu[2]
[1]Dept. of Earth and Atmospheric Science, University of Houston
[2]Dept. of Geoscience, University of Texas at Dallas

CENTER FOR TECTONICS AND TOMOGRAPHY

① A Honey Sandwich or a Peanut Butter Sandwich?

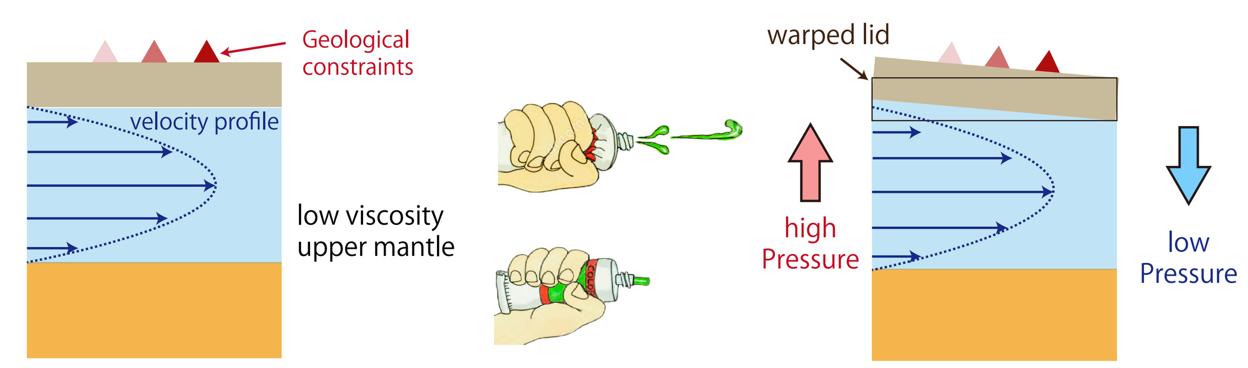
The concept of a weak asthenosphere sandwiched between mobile tectonic plates and mechanically strong sub-asthenospheric mantle is fundamental to understand plate tectonics and mantle convection. However, the quantitative estimation of absolute asthenospheric viscosity is highly uncertain and it varies by 1 to 3 orders of magnitude (see①). Wide-range viscosity estimations come mainly from two reasons: (1) Most observations can be satisfied with proper viscosity contrasts –instead of the absolute viscosity– between asthenosphere and sub-asthenospheric mantle. (2) The viscosity contrast trades off with the thickness of the asthenospheric layer.

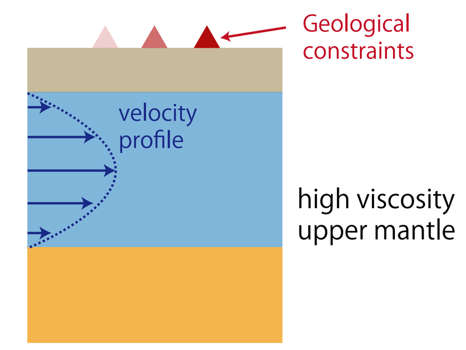
Here, we estimate absolute viscosity of asthenosphere for the first time from the pressure gradient and the asthenospheric flow velocity at the Caribbean, using the well-established analytical solution (see⑧). Funnelled by subduction zones and continental lithospheric roots (see③), the Caribbean region provides a unique tectonic setting reminiscent of a plane channel (see②) that closely approximates the conditions of the analytical solution. The asthenesphric flow at Caribbean from the Pacific towards the Atlantic has been a long-standing hypothesis. We inferred the flow velocity from regional magmatism (see⑨) and tomographic imaging with the onset time of the flow at ~8.5 Ma constrained by the opening of Panama slab window (see ⑩). This flow is mainly pressure-driven (i.e. Poiseuille flow), since the Caribbean has been fixed in mantle reference frame since Eocene. The pressure gradient (see⑦) is calculated from the dynamic topography (see③) across the Caribbean, obtained by removing the isostatic effect of sediments (see⑤) and crust (see⑥). Independent constraint of asthenosphere thickness of ~200km is suggested by tomography (see⑨).



The importance and improvement of this study are three folded. First, we provided a better quantified pressure gradient based on a proper isostatic correction and uncertainty estimations. With reasonable assumptions, we are the first study that use the stain rate (i.e. flow velocity) directly from the asthenosphere, instead of an average strain rate of the upper mantle from surface constraints. Finally, we show for the first time an on-site estimation of the viscosity where the asthenosphere thickness is independently constrained. Our results suggest the viscosity of the asthenosphere at the Caribbean is ~5*10^18 Pa s, which is in line with estimates for non-cratonic and oceanic regions, but is significantly lower than post-glacial rebound estimates for cratonic regions. This further supports the notion that the stronger asthenosphere estimates are relatively limited to cratonic regions.

② Flow velocity varies with different viscosities

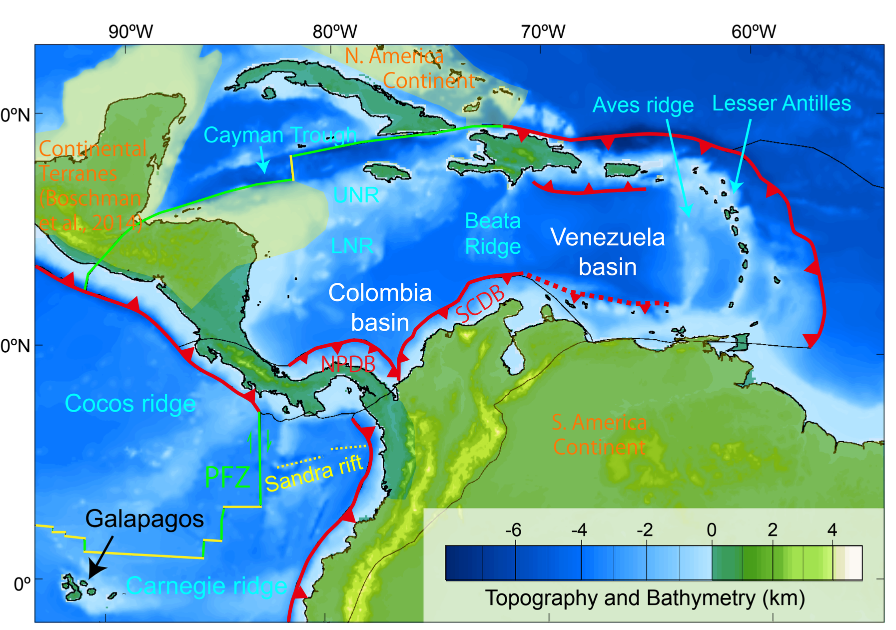


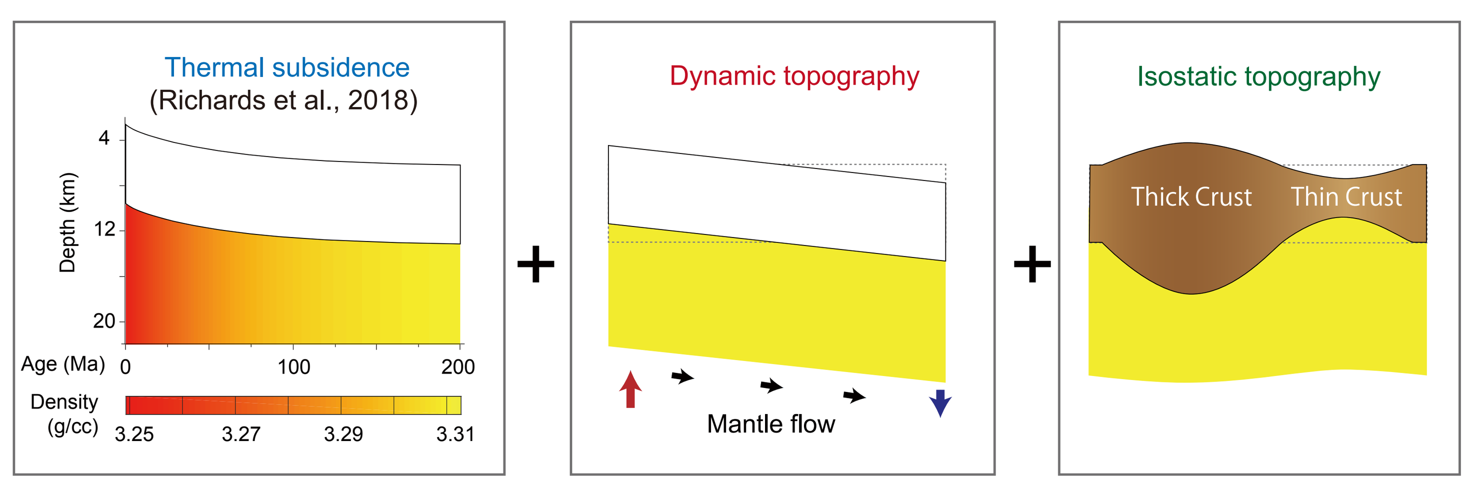


Strategy:

1. Quantify the dynamic topography across the Caribbean region.
2. Convert it to an average pressure gradient.
3. Calculate flow velocities with different viscosity values.
4. Compare to independent velocity constraints from geology.

③ Topography = Thermal subsidence + Dynamic topography + Isostatic topography

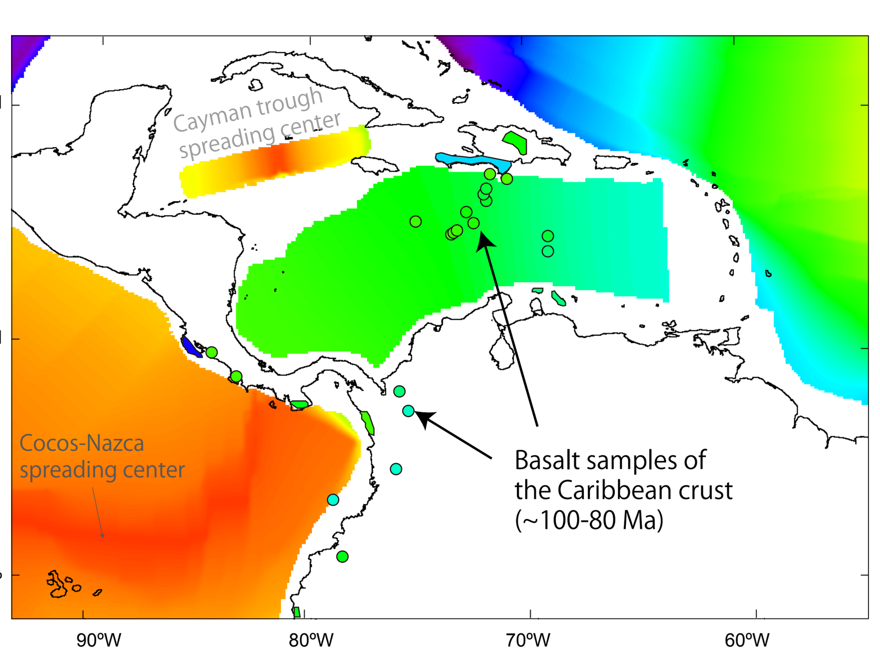




← To obtain dynamic topography, we subtract the total topography from thermal subsidence and isostatic topography. Thermal subsidence is obtained from the plate cooling model of Richards et al. (2018) using the age model from Müller et al. (2008) (see ④). Isostatic effect was corrected using seismic-constrained sedimentary thickness (see ⑤) and gravity constrained Moho (see ⑥). The residual topography (see ⑦) is generated by mantle flow and is our best-estimate for dynamic topography.

←The Caribbean is bounded by subduction zones and continental terrains (transparent yellow polygons); therefore, the subducted slabs and the continental roots hinder the asthenosphere to flow freely, but confine the flow within a narrow gateway beneath the Caribbean, a scenario similar to the simplified 2D model shown in ②.

④ Lithospheric age of the Caribbean

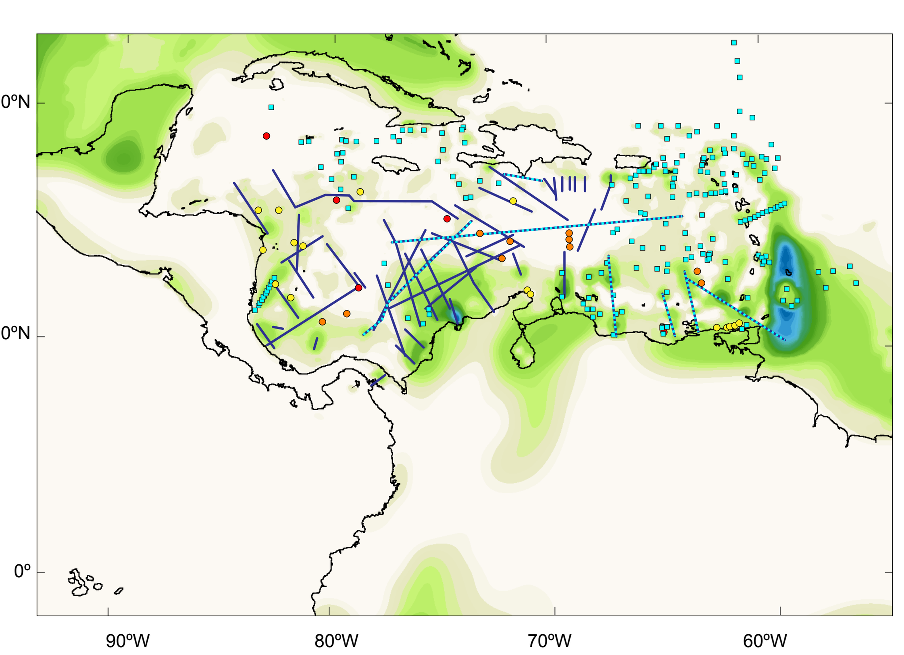


The thermal age of the Caribbean lithosphere was was rescaled from 100 Ma to 80 Ma based on the basalts.

Age (Ma) (from Muller et al., 2008)

References:
1. Müller et al. (2008) Geochemistry, Geophysics, Geosystems 9.4.
2. Weismüller et al. (2015) Geophysical Research Letters 42.18: 7429-7435.
3. Magnani et al., (2009) Journal of Geophysical Research: Solid Earth 114.B2
4. Paulson and Richards. (2009) Geophysical Journal International 179.3: 1516-1526.
5. Schaber et al. (2009) Geochemistry, Geophysics, Geosystems 10.11.
6. Boschman et al. (2014) Earth-Science Reviews 138: 102-136.
7. Gazel et al. (2011) Lithos 121.1-4: 117-134.
8. Hoggard et al. (2016) Nature Geoscience 9.6: 456.
9. Hu et al. (2016) Nature 538.7625: 368.
10. Sandwell et al. (2014) Science 346.6205: 65-67.

⑤ Sedimentary Thickness (This study)

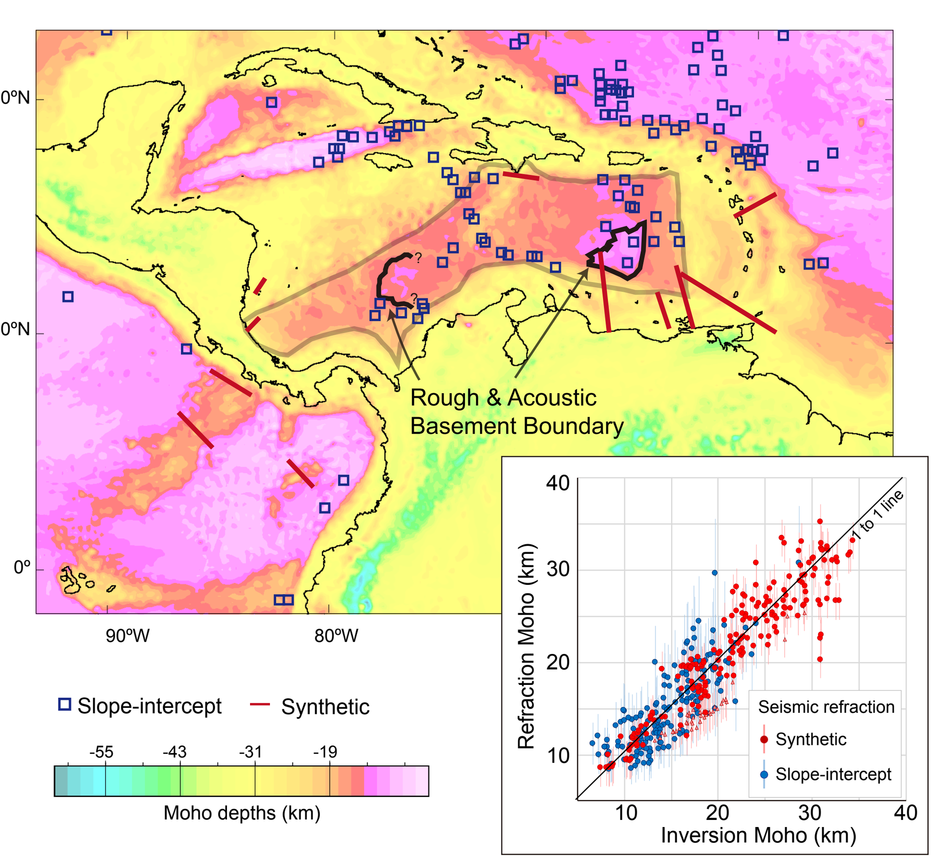


wells · DSDP · IODP · seismic refraction · seismic reflection · reflection + refraction

Sediment Thickness (km)

We used seismic refraction, reflection and borehole data to build the velocity model of the upper most crust as a function of depth. The velocity model and the 2-way travel time from seismic reflection help us constrain the sediment thickness. Subtracting the sediment thickness from the bathymetry, the basement depth is obtained.

⑥ Moho Depth (This study)

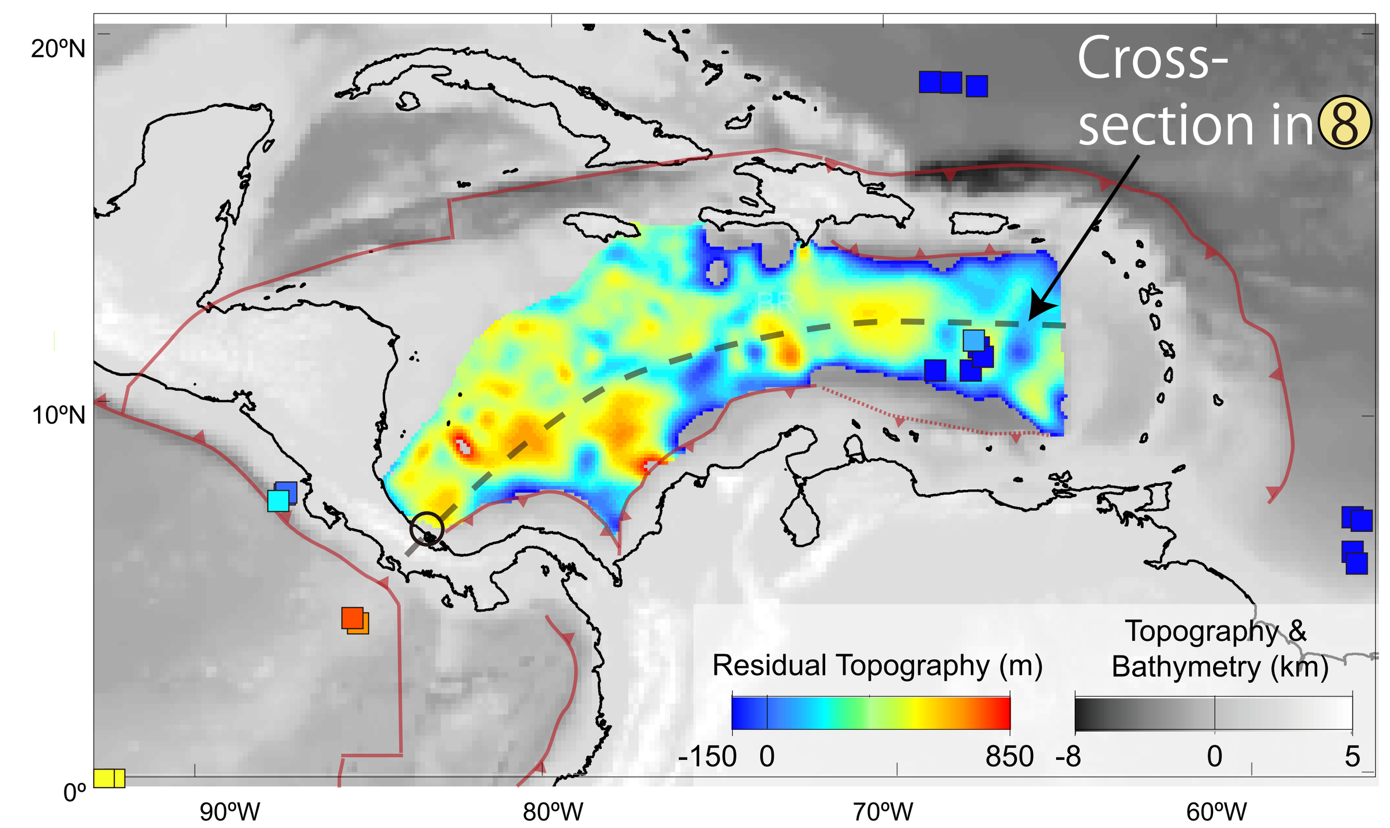


Slope-intercept · Synthetic

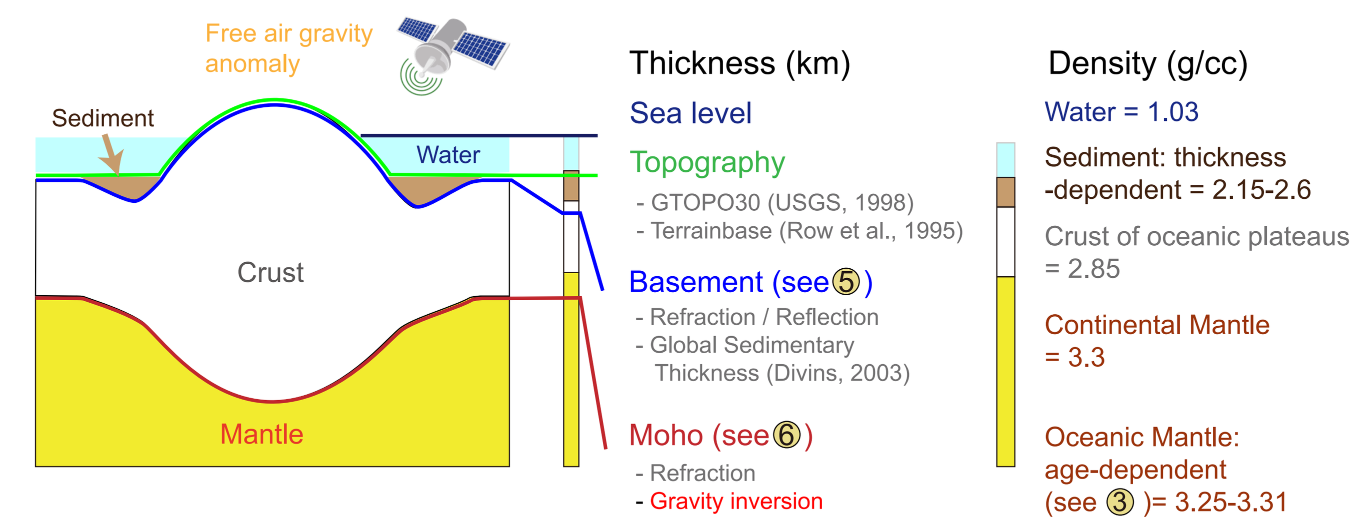
Moho depths (km)

Due to the limited refraction constraints of the Moho (red lines and blue open boxes), we used free air gravity anomaly to constrain the Moho. Our regional gravity-constrained Moho model fits local Moho depth estimates from refraction studies (see inset).

⑦ Residual Topography (i.e. Dynamic topography)

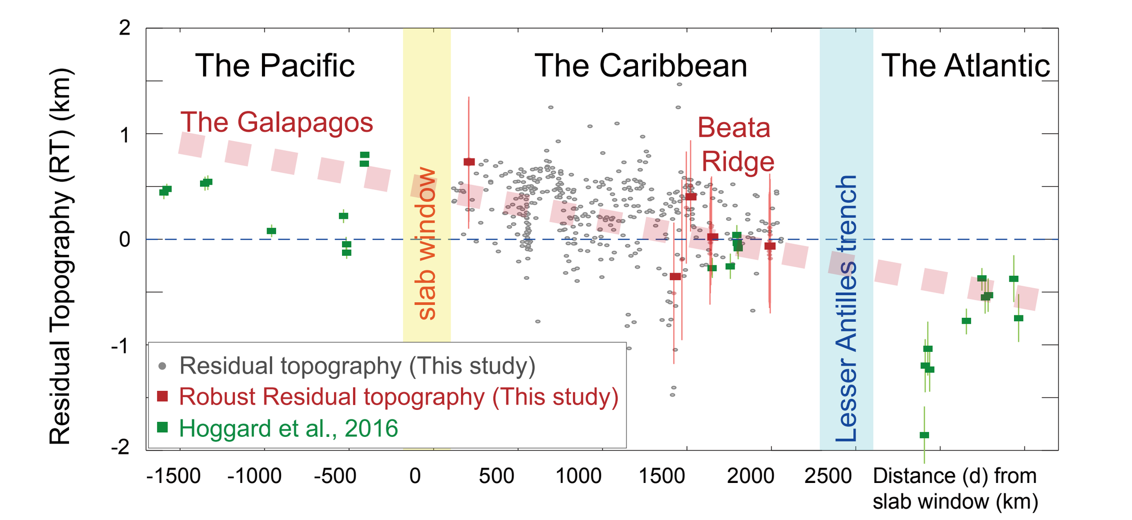


A gravity-constrained crustal model (using Oasis Montaj)



Free air gravity anomaly ⟷ Gravity ⟵ ΣMass = Σ (Thickness x Density)

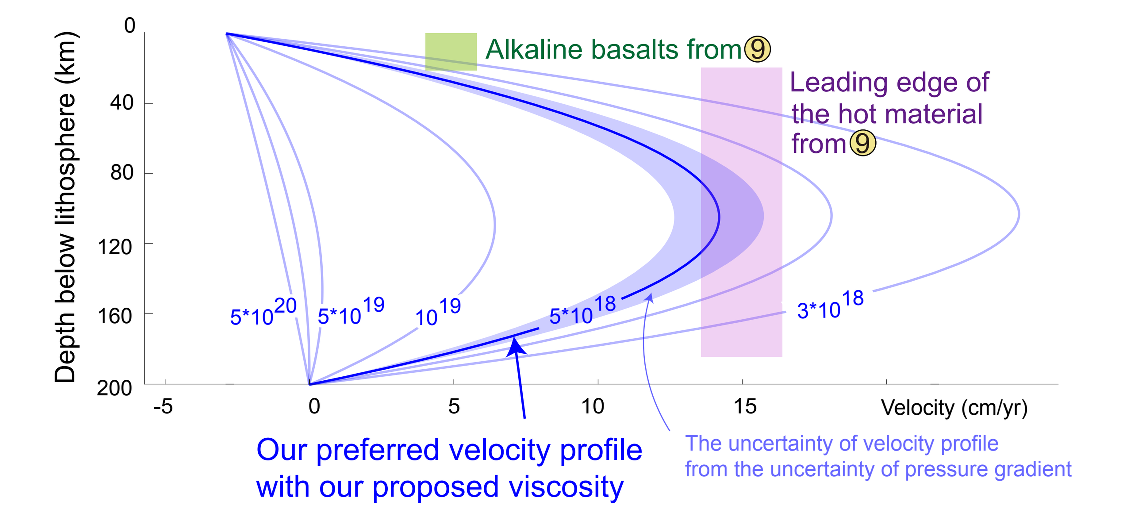
⑧ Pressure Difference & Velocity Profile



Best-fit regression line: $RT = \alpha + \beta * d$

$\alpha = 0.476 \pm 0.012$

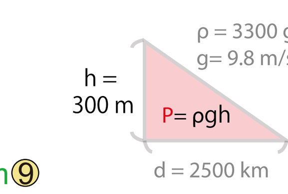
$\beta = 1.4*10^{-4} \pm 9*10^{-6}$



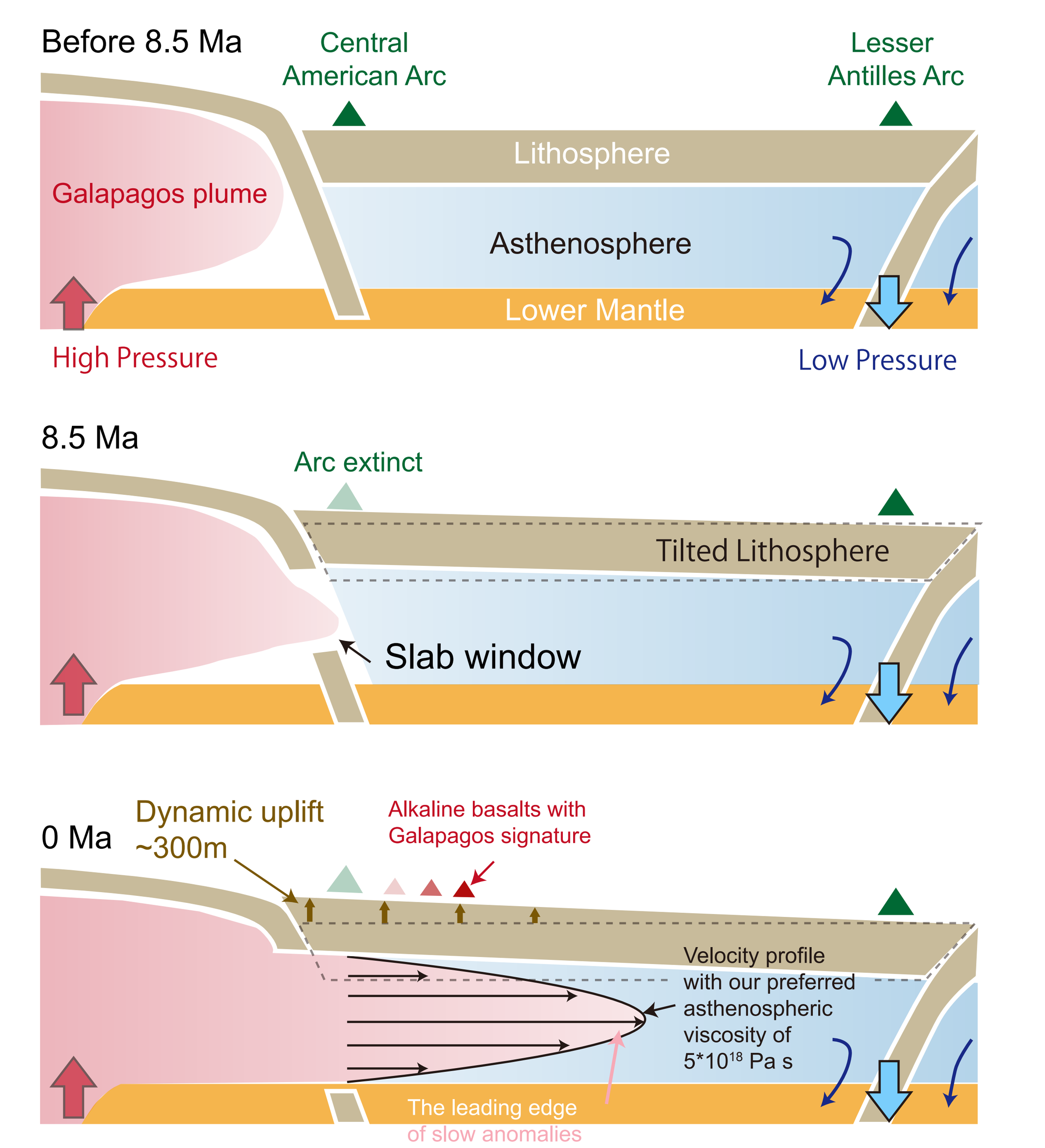
Velocity as a function of depth

$$v(y) = \rho g \beta * \frac{1}{2\eta} * y * (y - H) + u * \frac{y}{H}$$

Pressure gradient ($\rho g \beta$); Viscosity values from① (η); Thickness from⑨ (H)

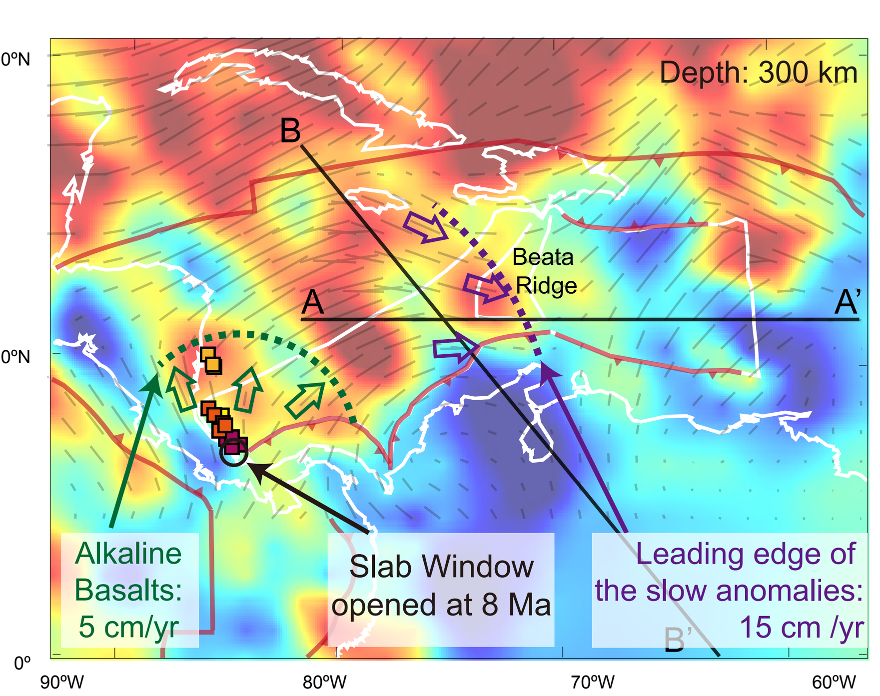


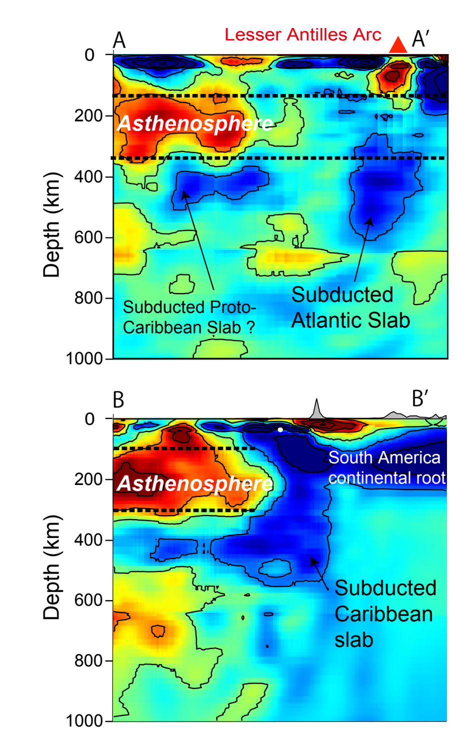
⑩ Conceptual evolution



The dynamic topography across the Caribbean region constrains the pressure gradient that drives Galapagos hot mantle material flowing eastward through the slab window. Given the driving pressure gradient and the thickness of the asthenosphere, flow speeds depend only on the viscosity of the asthenosphere. A value of ~5*10^18 Pa s best fits the propagation rates of the back-arc basalts and the imaged seismic structure.

⑨ Independent constraints





Alkaline basalts (Gazel et al., 2011)

- Tortuguero <<0.1 Ma?
- Pearl Lagoon/Cukra Hill: <0.7 Ma
- Guayacan/Azules: 4.5-2 Ma
- Victoria dikes: 6.5 Ma

Azimuthal anisotropy, proxy for flow direction

δln Vs (%)

Independent constraints come from (1) back arc magmatism which shows clear Galapagos isotopic signatures, initiating at ~6.5 Ma near the slab window (black circle) which opened at ~8 Ma and propagating at a rate of 5 cm/yr northward. (2) Full waveform tomography shows a slow velocity anomaly in the western Caribbean (west of Beata Ridge). If we assume the anomaly is hot mantle material flowing through the slab window, the propagation rate is ~15 cm/yr. The two cross sections suggest that the asthenosphere is ~200 km thick.