Three-dimensional mantle flow pattern near the flat-slab section of the Mexican subduction zone

Juan Carlos Rosas[1], Felipe Cruz Pimentel[1], Claire Currie[1], Jiangheng He[2]

Introduction

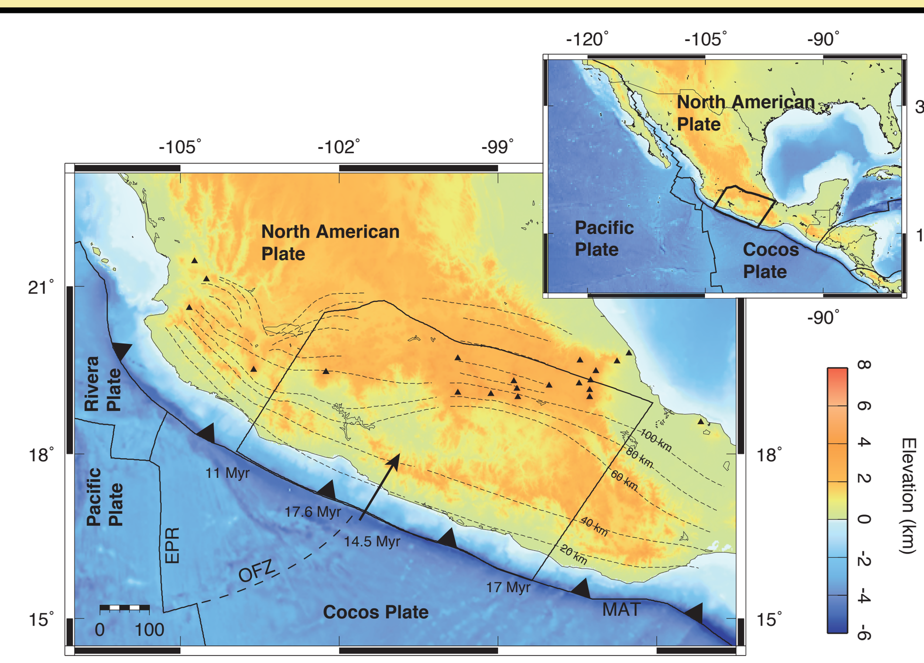
Temperature is a primary control on key processes at subduction zones, such as slab metamorphism and dehydration, arc volcanism and the rupture width of megathrust earthquakes. The thermal state is partially controlled by the three-dimensional (3D) flow pattern of the overlying mantle wedge, which is driven by pressure gradients created by the downward motion of the slab, as well as by along-strike changes in its geometry [Kneller and van Keken (2008), Bengston and van Keken (2012), Wada et al., (2015), Rosas et al., (2015, submitted)]. The flow results in a temperature distribution that deviates from the more-classical 2D corner flow model.

For this study, we report the first three-dimensional (3D), finite-element thermal model of the Mexican subduction zone. Evidence of along-strike flow in this region comes from seismic anisotropy studies, which revealed fast-direction axis for olivine that are not perpendicular to the trench. A common interpretation for this flow is the presence of gaps within the Cocos plate that induce a mantle toroidal flow around the slab edges. However, given the geometry of the Cocos plate in this region (flat-slab section at a depth of 50 km in Central Mexico, and a slab that dips at 40-45° further west), it is possible for this flow to be generated by along-strike pressure gradients as well. The purpose of this study is to investigate the 3D mantle wedge flow pattern, as driven by plate geometry variations, and to compare it with the observed seismic anisotropy pattern.

Model Description

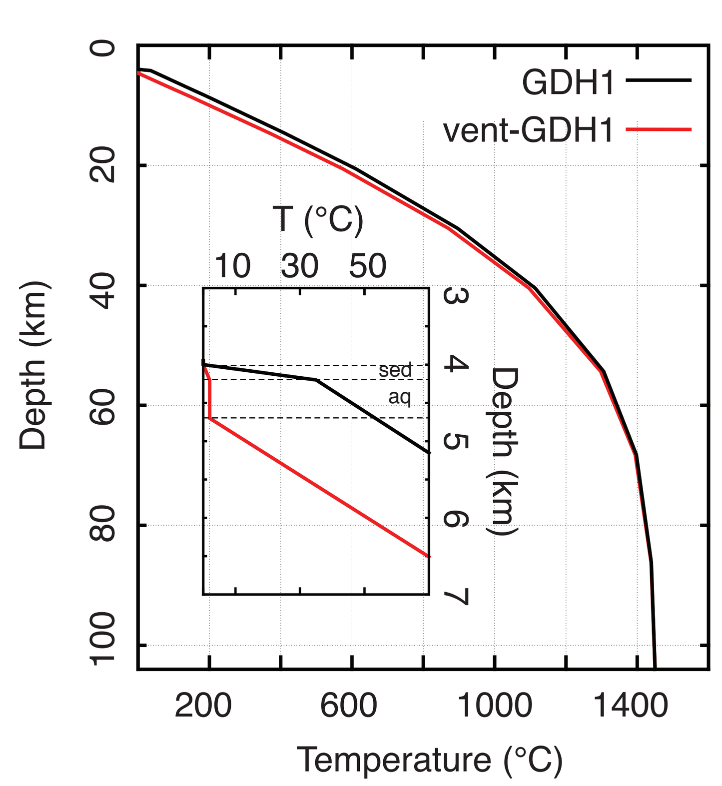
Subduction Zone of Mexico:

- Subduction of Cocos plate beneath North American plate
- Flat-slab section in central Mexico extends 250 km from trench
- Slab dips at 45-50° westward from flat-slab section
- Age variation along the trench from 11-17 Myr
- Hydrothermal circulation (possibly) in subducting crustal aquifer

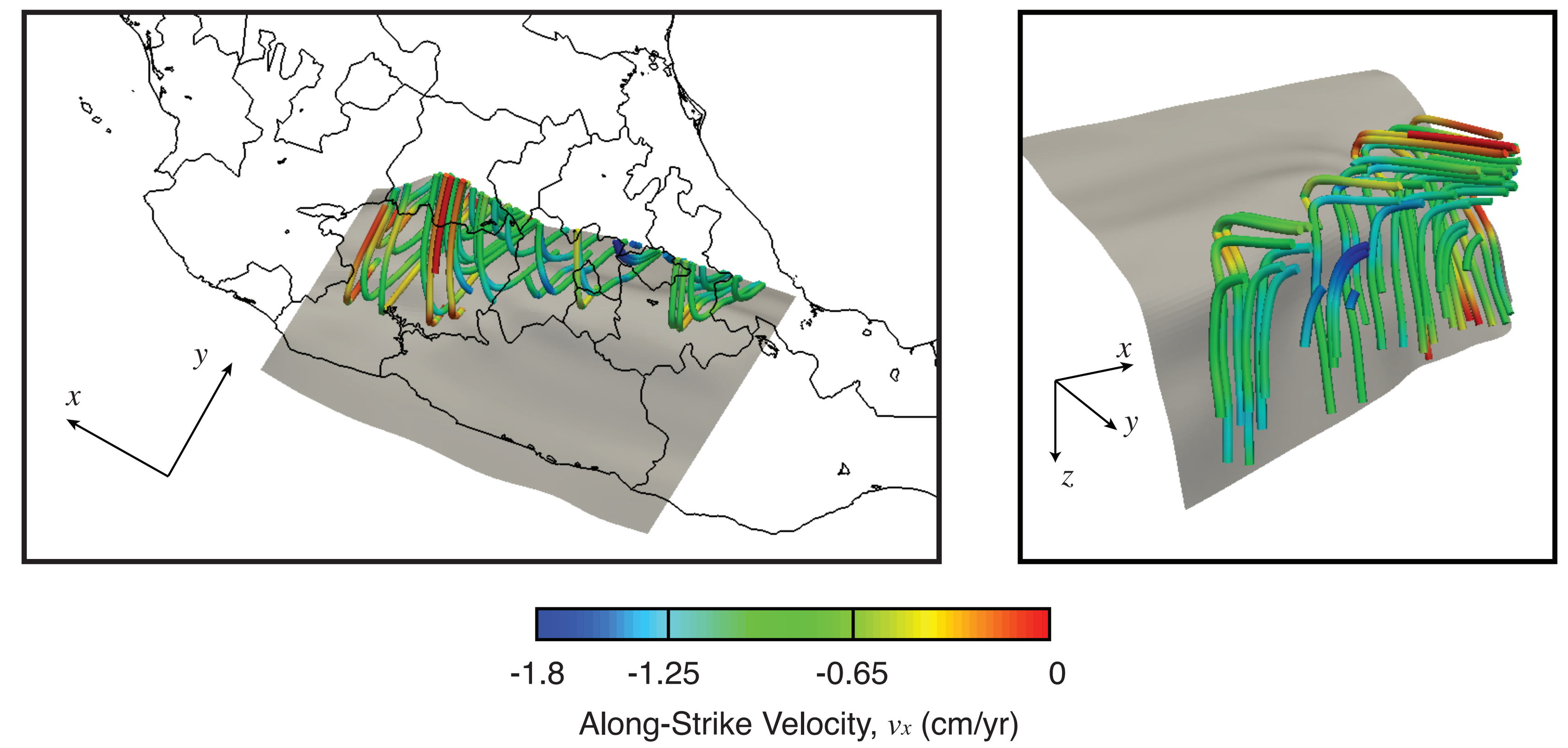


Model setup

- Numerical code: PGCtherm3D
- Isoviscous wedge (10^{21} Pa s)
- 642 km along-strike width
- Maximum depth of 300km
- 2D GDH1 oceanic geotherm with age variations (normal and ventilated)
- Temperatures of 0° C and 1450° C for the surface and bottom of the model
- Convergence rate of 6 cm/yr
- Sediment layer: 200 m thick
- Aquifer: 500 m thick



Mantle Wedge Flow



Flow characteristics:

- Along-strike mantle flow throughout entire model domain.
- Direction is predominantly in the negative x-axis (eastward). This is in agreement with previous studies, which show mantle flowing from steeply-dipping region to a shallow-dipping region.
- With an isoviscous (10^{21} Pa s) rheology, maximum along-strike flow component (v_x) of 1.8 cm/yr. This represents 30% of the slab convergence rate (6 cm/yr).

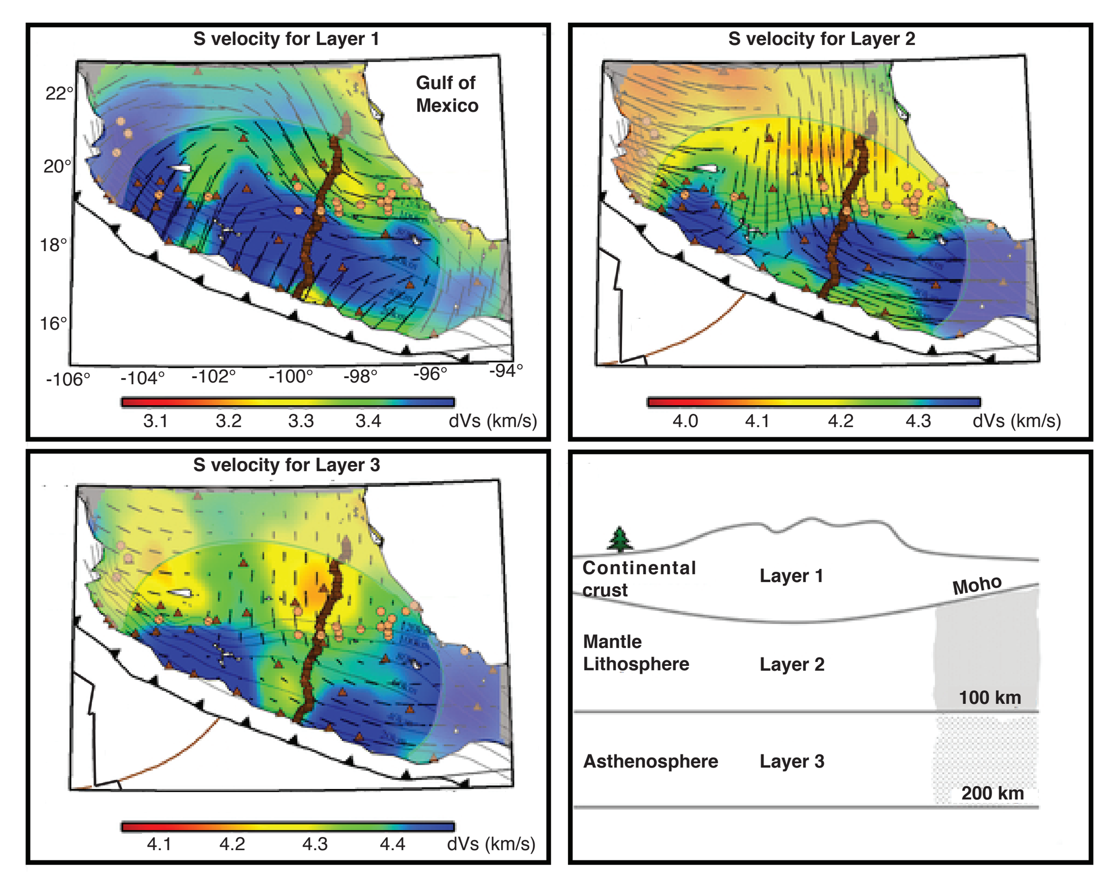
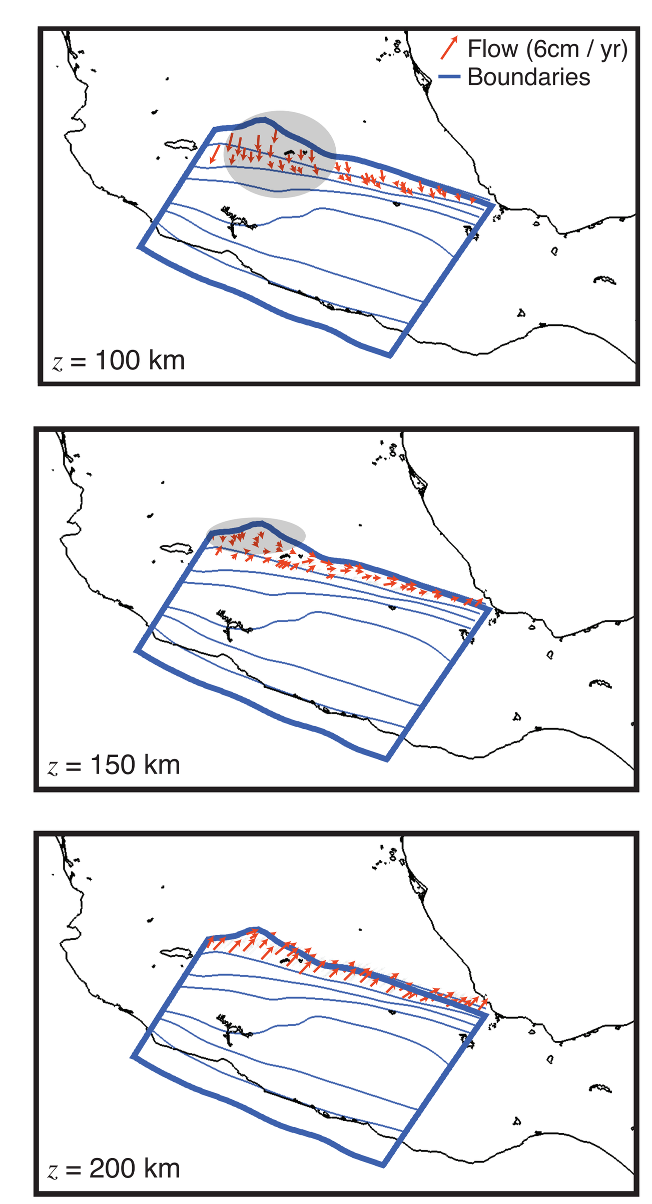


Figure modified from Stubailo et al., (2012)



3D model of mantle flow at depths of 100, 150 and 200 km

Seimic Anisotropy at a depth between 100 km and 200 km [Stubailo et al., (2012)]:

- Indicates mantle flow curves follows the same trend as 3D model.
- Flow direction (red arrows) roughly aligned with fast direction axis (black lines in from figure above) at depths less than 200 km.
- For depths ≥ 200 km, anisotropy pattern is harder to reconcile with flow from 3D model.

Slab Surface Temperatures

Possible effect of hydrothermal circulation along the Mexican trench

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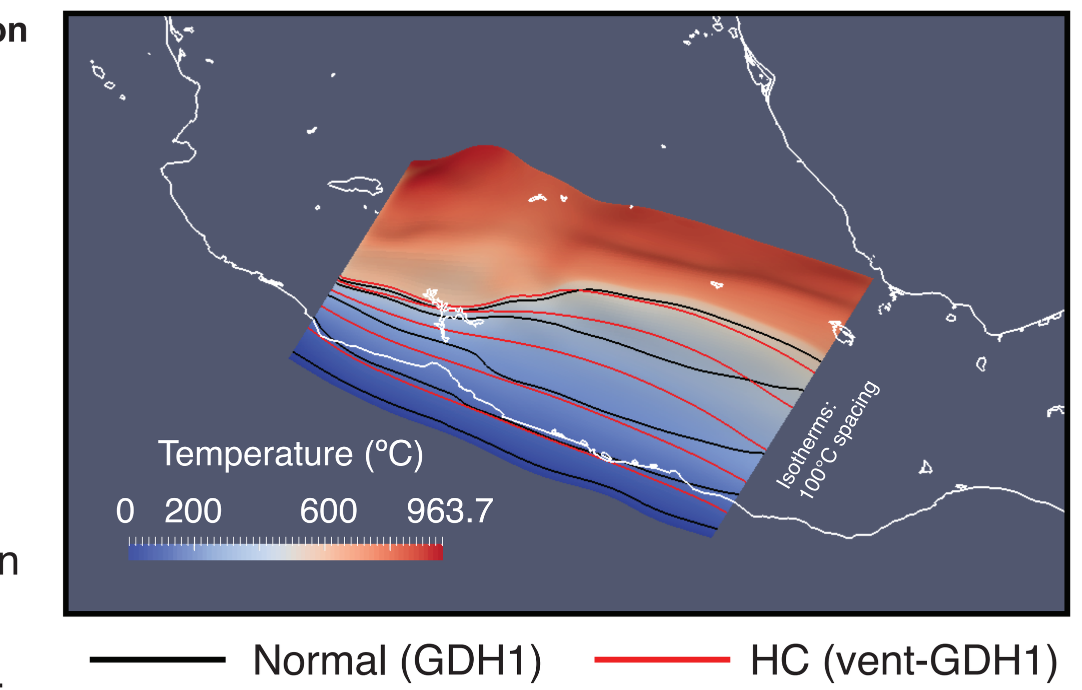
Two types of oceanic boundary conditions:

1) GDH1: age variations along the trench
2) vent-GDH1: age variations + effect of hydrothermal circulation



Nusselt thermal conductivity: increase k for aquifer in shallowest 30 km of the slab, in order to simulate vigorous convective heat transport

$$k' = k\,Nu = 1500 \text{ W / m K}$$

Hydrothermal circulation significantly reduces slab temperatures. The decrease can be as much as 100°C

Future Work

- **Slab metamorphism and dehydration:** effect of hydrothermal circulation could alter the depth of metamorphic reactions.
- **Surface heat flow:** hydrothermal circulation is known to alter surface heat flux. This can serve as a constraint on the real effect of hydrothermal circulation, and thus slab temperatures.
- **Megathrust seismogenic zone:** between 100-150°C and 350-400°C.
- **Mantle rheology:** implement stress-temperature dependent rheology (dislocation creep) for the mantle wedge. This will affect temperatures (likely increase it) and the flow pattern of the mantle wedge.

$$\eta = \left(A C_{OH}^{\,r}\right)^{-\frac{1}{n}} \dot{\epsilon}^{\frac{1-n}{n}} \exp\left(\frac{E}{nRT}\right)$$

References:

- *Bengston and van Keken: Three-dimensional thermal structure of subduction zones: effects of obliquity and curvature. Solid Earth (2012)*
- *Kneller, et al: Effect of three-dimensional slab geometry on deformation in the mantle wedge: Implications for shear wave anisotropy. G3 (2008)*
- *Rosas et al: Three-Dimensional Thermal Model of the Costa Rica-Nicaragua Subduction Zone. PAAG (2015, submitted)*
- *Stubailo et al: Structure and anisotropy of the Mexico subduction zone based on Rayleigh-wave analysis and implications for the geometry of the Trans-Mexican Volcanic Belt. Journal of Geophysical Research (2012)*
- *Wada et al: Mantle wedge flow pattern and thermal structure in Northeast Japan: Effects of oblique subduction and 3-D slab geometry. EPSL (2015)*

[1] Department of Physics, University of Alberta Edmonton, AB, Canada
[2] Pacific Geosciences Centre, Canadian Geological Survey Sidney, BC, Canada

Email addresses:
J.C Rosas: jrosas@ualberta.ca
F. C Pimentel: cruzpime@ualberta.ca
C. Currie: claire.currie@ualberta.ca
J. He: jiangheng.he@nrcan-rncan.gc.ca