Overriding plate thickness control on subducting slab curvature

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1. SUMMARY

Subducting plate (SP) curvature exerts a key control on the amount of bending dissipation associated with subduction, and the magnitude of the subduction resisting bending force. However, the factors controlling the development of slab curvature at subduction zones are not well understood. We use numerical models to quantify the role of SP rheology on the minimum radius of curvature, R_{min}. We find that R_{min} depends strongly on the SP thickness when the rheology is viscous. This dependence is substantially reduced when the SP behaves plastically, in line with the absence of a correlation on Earth. Plasticity also promotes a strong positive correlation between R_{min} and the thickness of the overriding plate (OP). Using an analysis of R_{min} vs. OP thickness, we show that there is such a positive correlation on Earth, and so suggest that OP structure, in conjunction with SP plasticity, is crucial in generating the curvature systematics on Earth.

2. MODEL SETUP

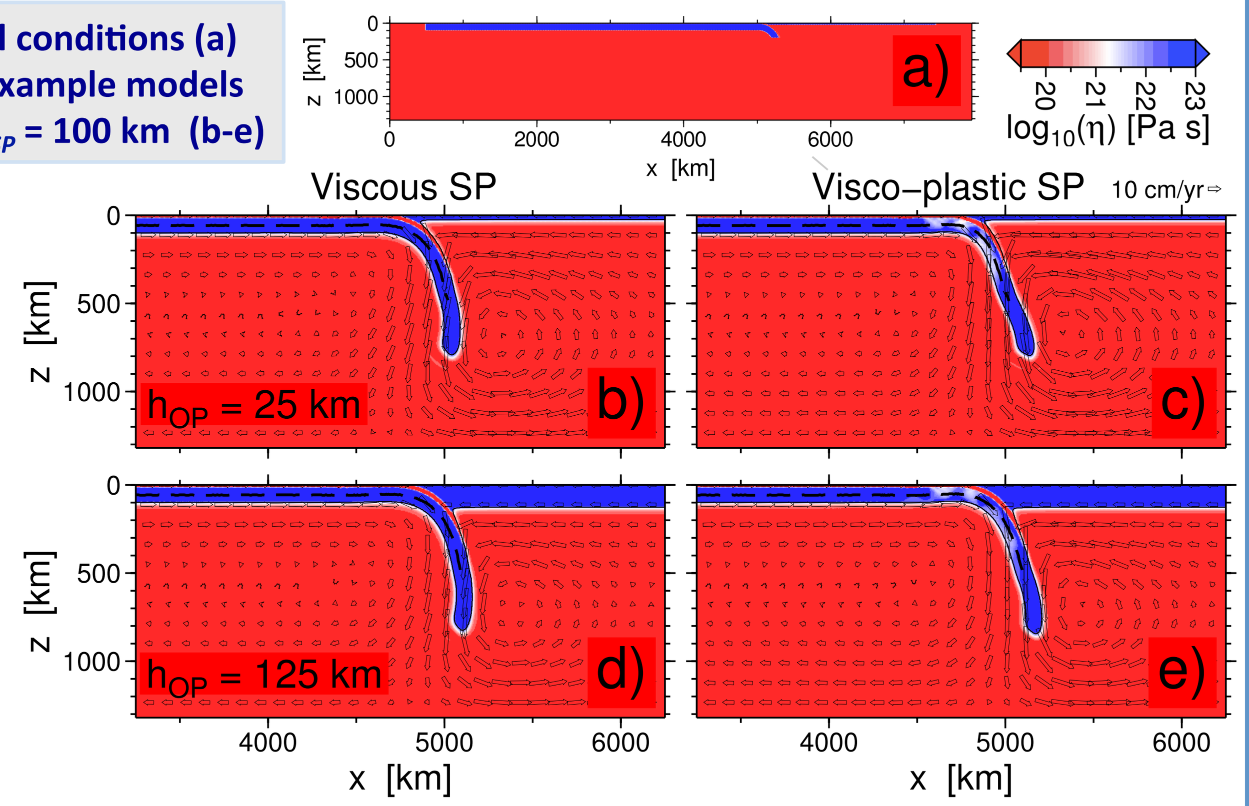
2-D visco-plastic models used to investigate dependence of subducting plate curvature (R_{min}) on overriding and subducting plate thickness, h_{OP} and h_{SP}. Modelling carried out with ***CitcomCU*** (Moresi & Gurnis, 1996; Zhong, 2006), and weak, isoviscous crust used to decouple two plates.

Temperature dependence of viscosity given by a Frank-Kamenetskii relationship with high E and viscosity cut-off:

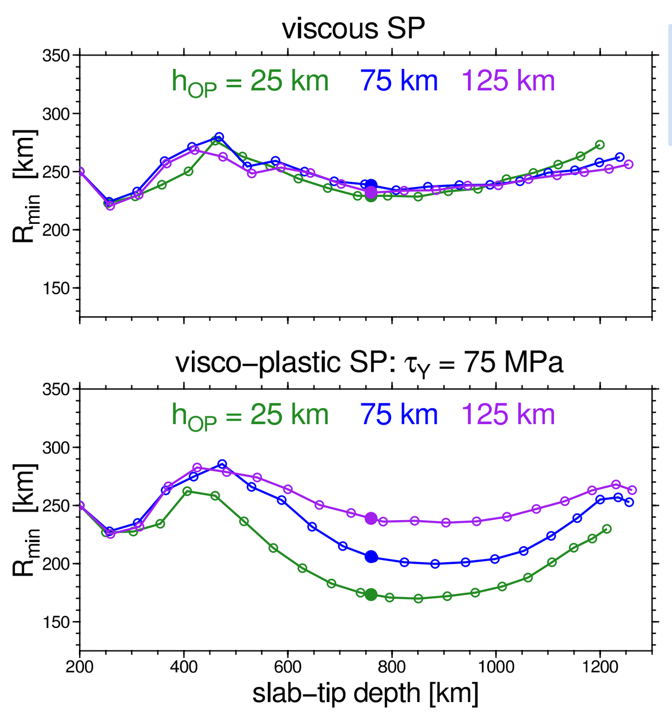
$$\eta_N = \eta_0 \exp(E(1-T')) \quad where\ \eta_{max} = 500\eta_0\ and\ E = 9.9$$

For visco-plastic models, the plastic viscosity is computed using a constant yield stress, and the effective viscosity is taken as the minimum of the viscous and plastic components: $\eta_Y = \frac{\tau_Y}{2\dot{\varepsilon}_{II}}$ $\quad \eta_{eff} = \min(\eta_N, \eta_Y)$

Initial conditions (a) and example models with h_{SP} = 100 km (b-e)



5. TIME-DEPENDENT *R* EVOLUTION



Temporal evolution of R_{min} for variable h_{OP}

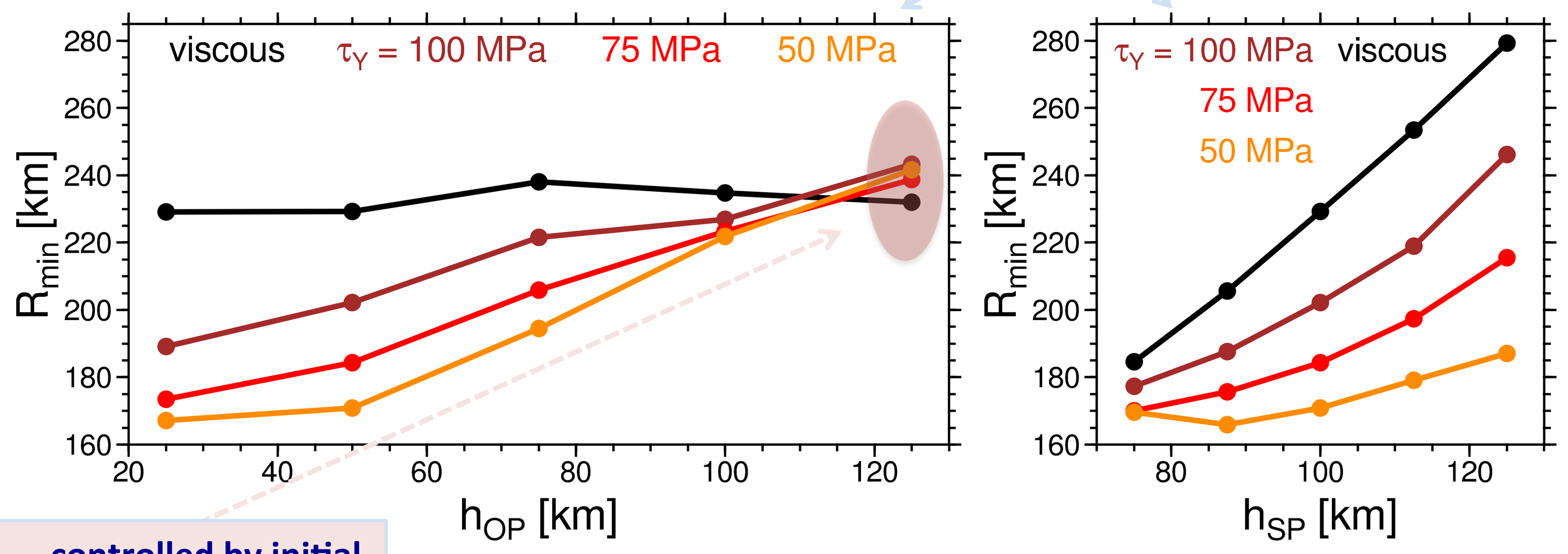
While R_{min} is strongly time-dependent, only during the initial period (200 km < slab depth < 500 km) are the h_{OP} - R_{min} trends poorly developed. We therefore consider the trends shown in Box 3 to be representative of the model runs.

Symbol	Explanation	Value
Geometry:		
H	domain height	1320 km
W	domain width	7920 km
n_H	no. of nodes (height)	256
n_W	no. of nodes (width)	769
R_0	initial radius	300 km
Z_0	initial notch depth	200 km
Constants:		
$\Delta\rho$	density contrast	50 kg/m^3
Ra	Rayleigh Number	11.3 x 10^6
Rheology:		
E	Frank–Kamenetskii param.	9.9
σ_Y	yield stress	50, 75, 100 MPa
η_0	reference viscosity	1 x 10^{20} Pa s
η_{crust}	crust viscosity	5 x 10^{19} Pa s

3. MODEL SYSTEMATICS

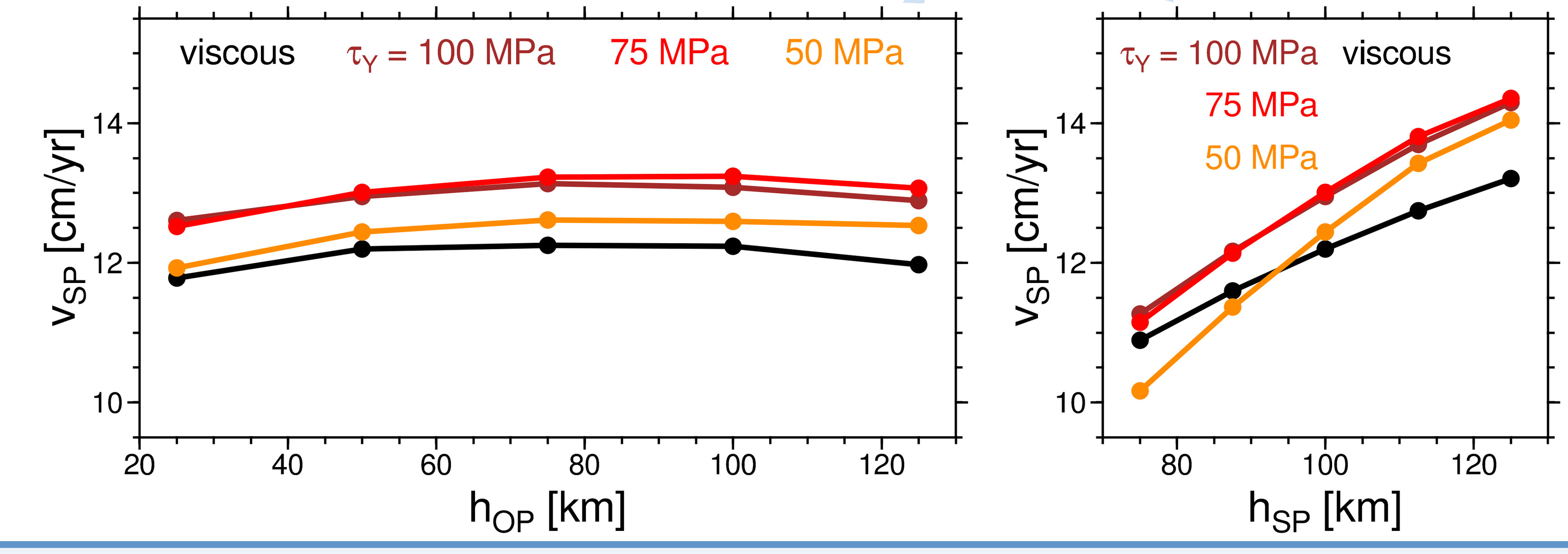
Plots show minimum radius of curvature (R_{min}) and subducting plate velocity (v_{SP}) extracted at equivalent, mid-box slab depths

Curvature as $f(h_{OP}, h_{SP})$



R_{min} controlled by initial (R_{init}) geometry for thickest OPs

Plate velocity as $f(h_{OP}, h_{SP})$



Subducting plate thickness (h_{SP})

We observe a linear dependence of R_{min} on h_{SP} for viscous SPs. Assuming proportionality between buoyancy flux and thin sheet dissipation gives,

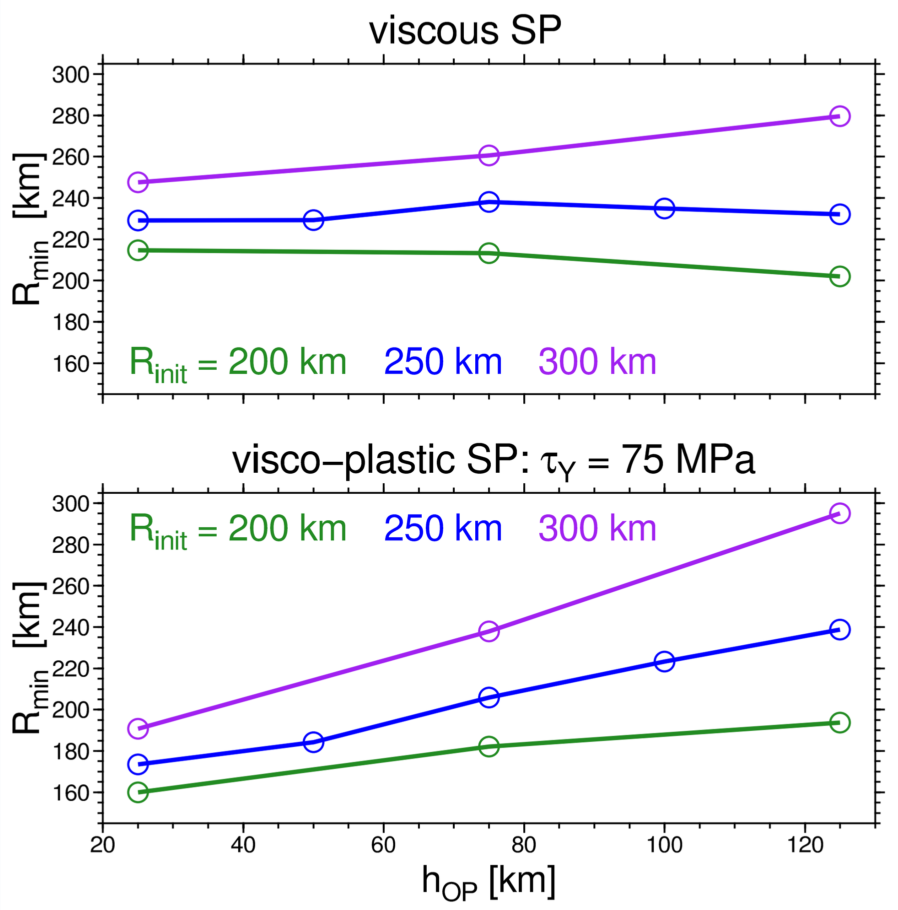
$$\Delta\rho g h_{SP} D v_{SP} \propto \left(\frac{h_{SP}}{R_{min}}\right)^3 \eta' v_{SP}^2,$$

Rearranging for R and assuming v_{SP} increases linearly with h_{SP} (bottom right figure panel), such a linear R_{min}- h_{SP} dependence is expected. However, this is not observed on Earth (Buffett & Heuret, 2011). The addition of plasticity reduces the dependence of *Rmin* on h_{SP}, and the dependence deviates from a linear trend

Overriding plate thickness (h_{OP})

Conversely, R_{min} has no dependence on h_{OP} for viscous subducting plates, with a constant R_{min} of 225-235 km observed. However, the addition of plasticity gives rise to a strong positive scaling. As the yield stress is reduced (i.e. the area of yielding increases), the strength of this dependence increases

4. DEPENDENCE ON INITIAL GEOMETRY



Models with variable initial radius of curvature

The initial radius of curvature exerts a control on the strength of the dependence of R_{min} on h_{OP}, by controlling R_{min} for thick OPs. While these tests highlight the control of pre-existing OP structure on these systematics, the strength of the positive trend is always greater for visco-plastic slabs. Thus, this is a robust feature (for reasonable Earth R_{init}),

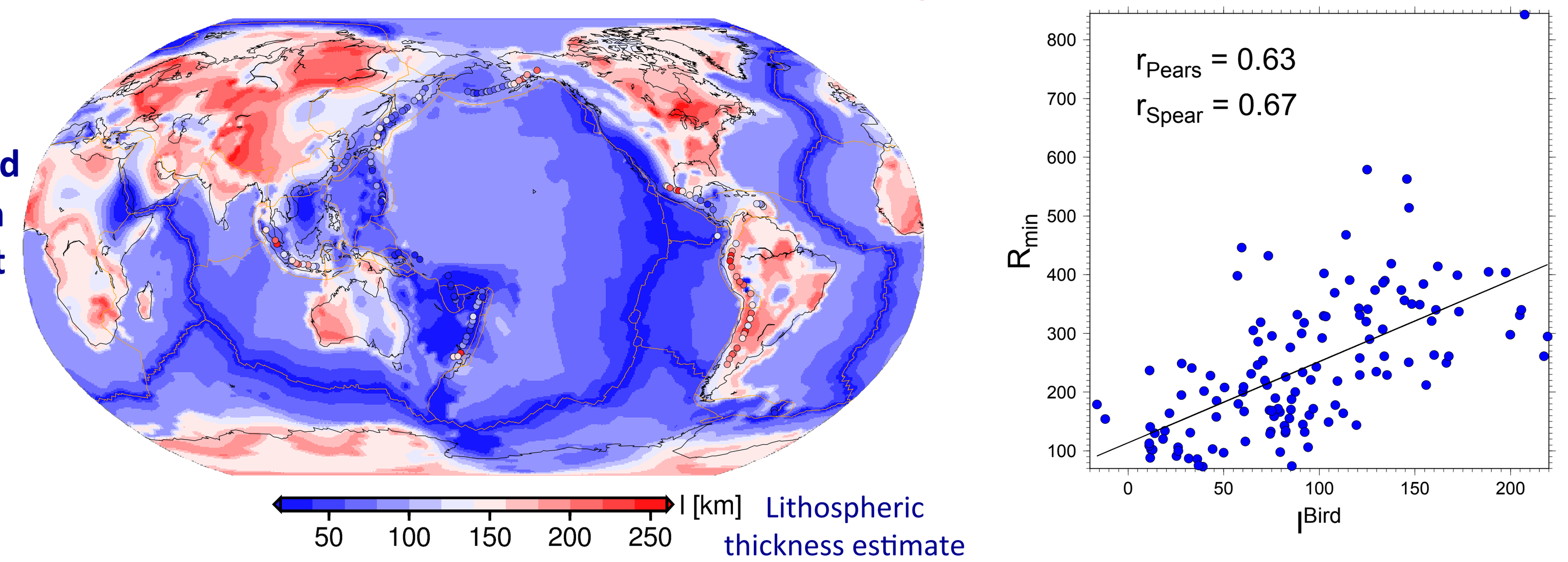
7. CONCLUSIONS

1) Plasticity reduces the dependence of slab curvature (R) on subducting plate thickness, in line with the apparent lack of correlation of those parameters on Earth.
2) Plasticity introduces a positive scaling between R and overriding plate thickness (h_{OP}).
3) Such a positive correlation between R and h_{OP} appears to be present on Earth.

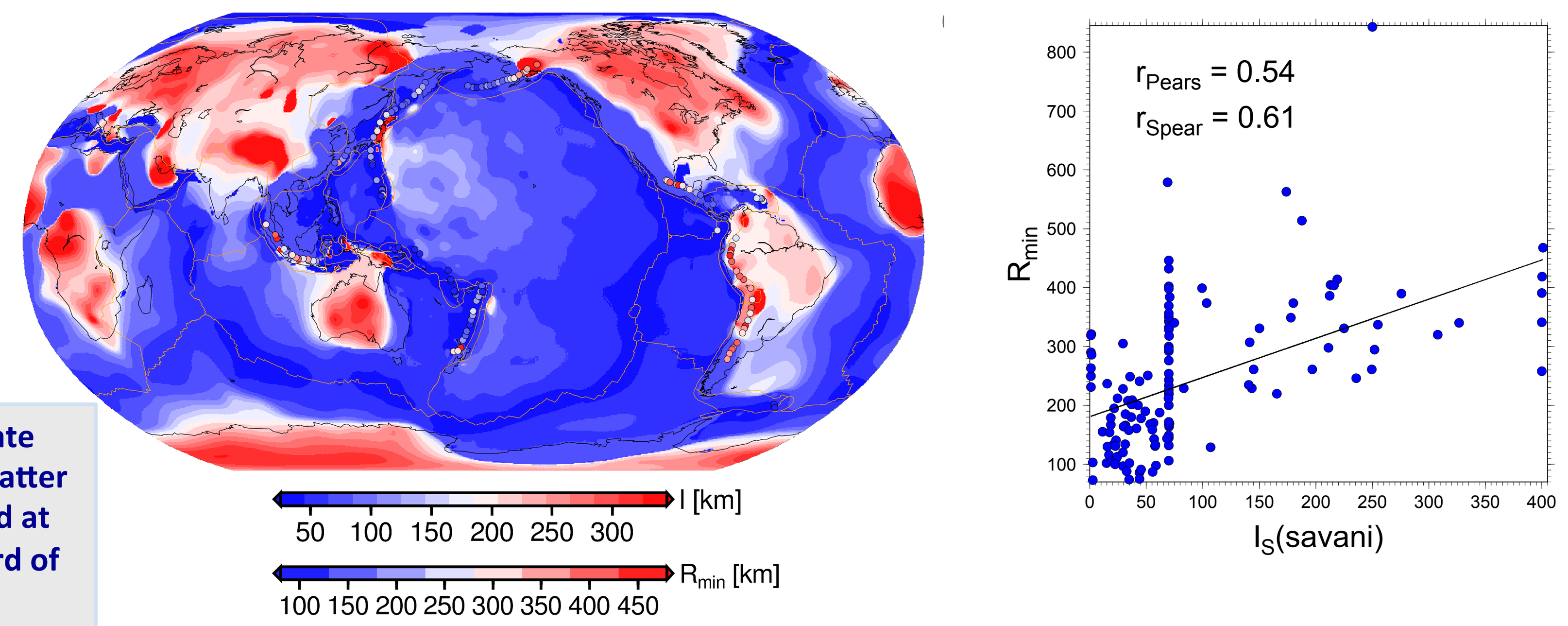
Plasticity, in conjuction with overriding plate structure, plays a crucial role in dictating subducting plate curvature.

6. OBSERVED CORRELATION BETWEEN *R* AND h_{op} ESTIMATES

Lithospheric thickness estimate of **Bird (2008) overlain by R_{min} (Buffett and Heuret, 2011)**



Lithospheric thickness estimate of **B. Steinberger** from ***Savani*** **(Auer et al., 2014)**



Overriding plate thickness (for scatter plots) extracted at 500 km on-board of trench

Auer et al., 2014. *Savani*: A variable resolution whole-mantle model of anisotropic shear velocity variations based on multiple data sets. JGR
Bird et al., 2008. Stresses that drive plates from below: Definitions, computational paths, model optimization, and error analysis, JGR.
Buffett, B. A., 2006. Plate force due to bending at subduction zones, JGR.
Buffett, B. A. & A. Heuret, 2011. Curvature of subducted lithosphere from earthquake locations in the Wadati-Benioff zone, G^3.
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Rodriguez-Gonzalez et al., 2012. The role of the overriding plate thermal state on slab dip variability and on the occurrence of flat subduction, G^3.
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