The influence of far-field mantle density anomalies on subduction dynamics

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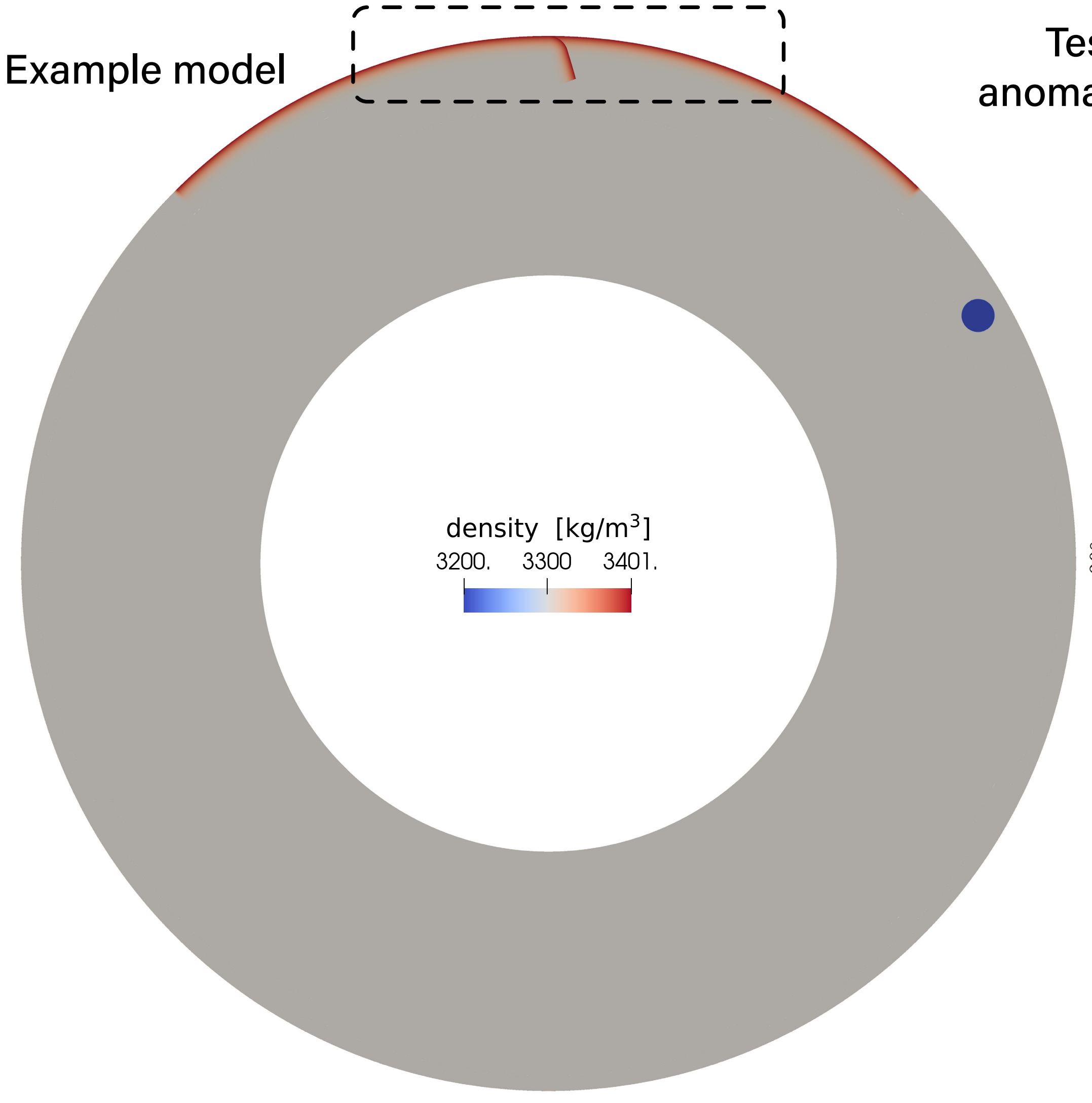
1. Summary

The forces exerted on subduction zones, and so subduction properties like convergence rate, can be affected by mantle density anomalies via the mantle flow that such anomalies induce[1,2]. However, most numerical subduction modeling studies limit subduction to within a regional box and so neglect these effects[e.g. 3].

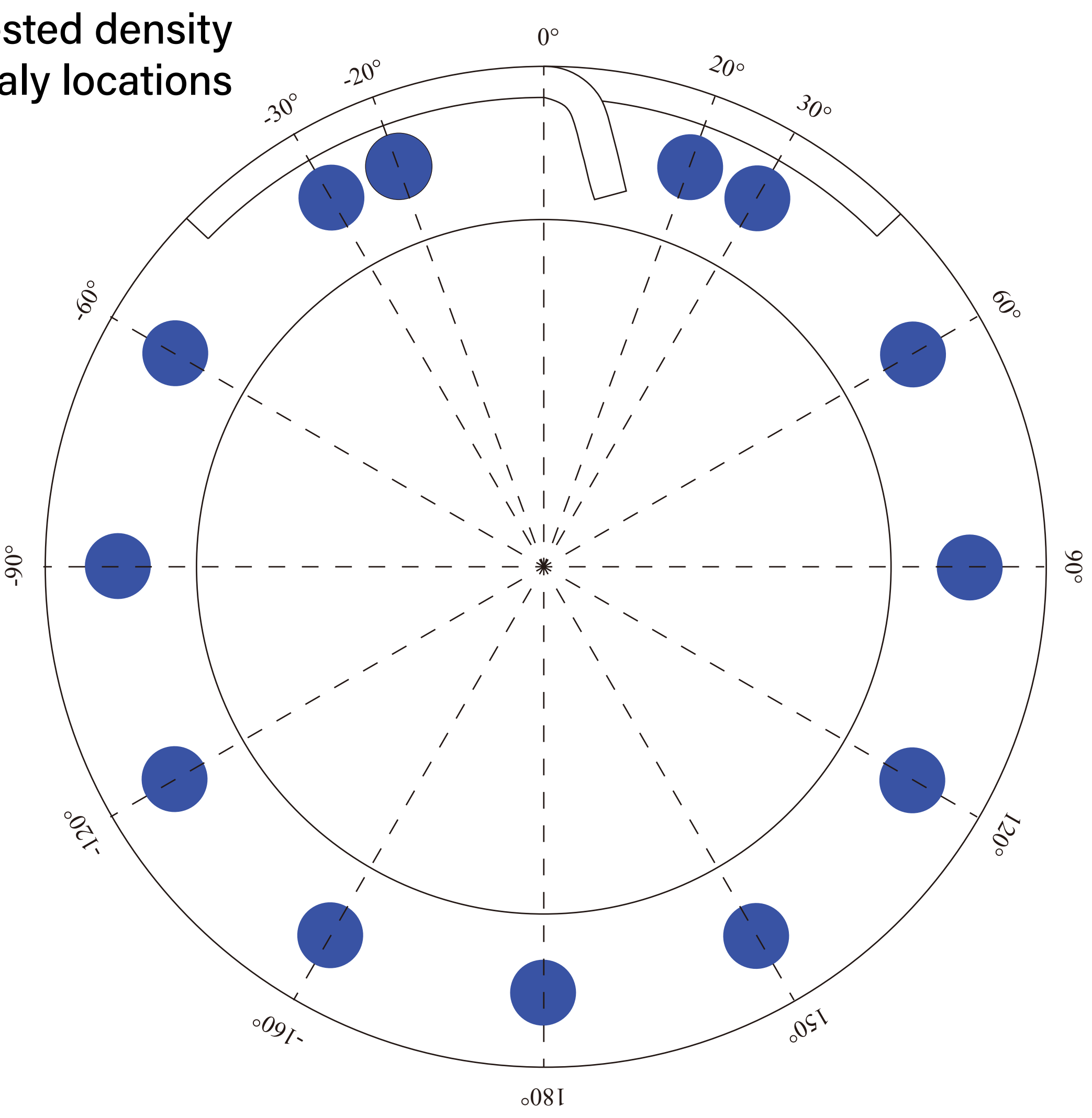
In this project, we address this by quantifying how subduction dynamics is affected by distant mantle anomalies by investigating the influence of density anomaly location, size, and amplitude on subduction within idealized global models. These 2-D, near-instantaneous models were developed using the ASPECT finite element code[4,5]. We initially focus our analysis on subduction zone convergence rate and near-slab mantle flow field. Ultimately, we aim to develop quantitative rules for the effects of far-field mantle density anomalies on various subduction zone properties.

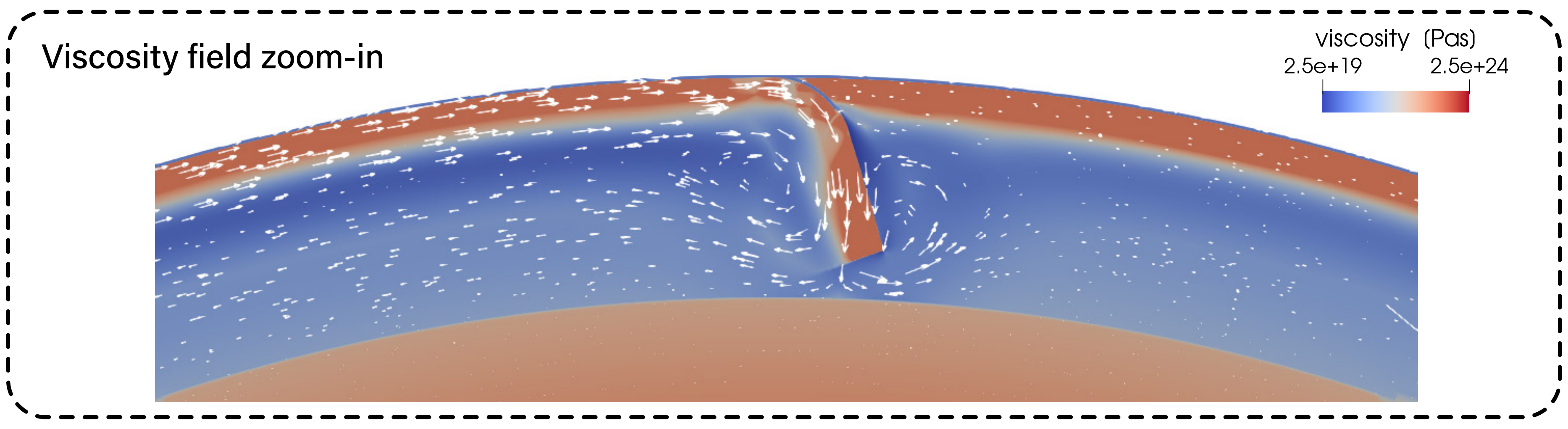
2. Methodology

Example model



Tested density anomaly locations





Ultimate goal: To develop quantitative expressions for the effect of density anomalies, at different global locations, on subduction dynamics.

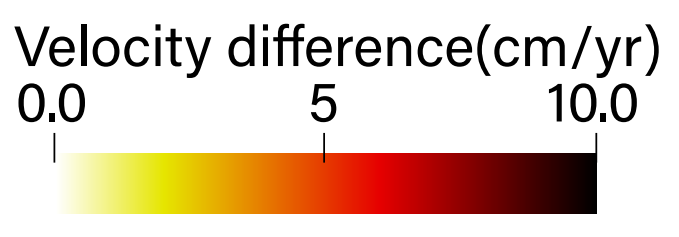
Overall approach: The ASPECT finite element code[4,5] was used to develop near-instantaneous subduction models within a 2D spherical annulus. ASPECT's adaptive mesh refinement enables us to highly resolve the slab and subduction interface (0.6 km-sized finite elements).

Rheology: Composite viscosity with diffusion creep (entire domain), dislocation creep (upper mantle), pseudo-plastic yielding (lithosphere) and a factor of ~15 viscosity jump at 660km.

Density anomalies: We place circular anomalies of different radii (100 km, 150 km, 200 km) and densities (+100 kg/m^3 or 100 kg/m^3 relative to 3300 kg/m^3 mantle) at a constant depth of 380km.

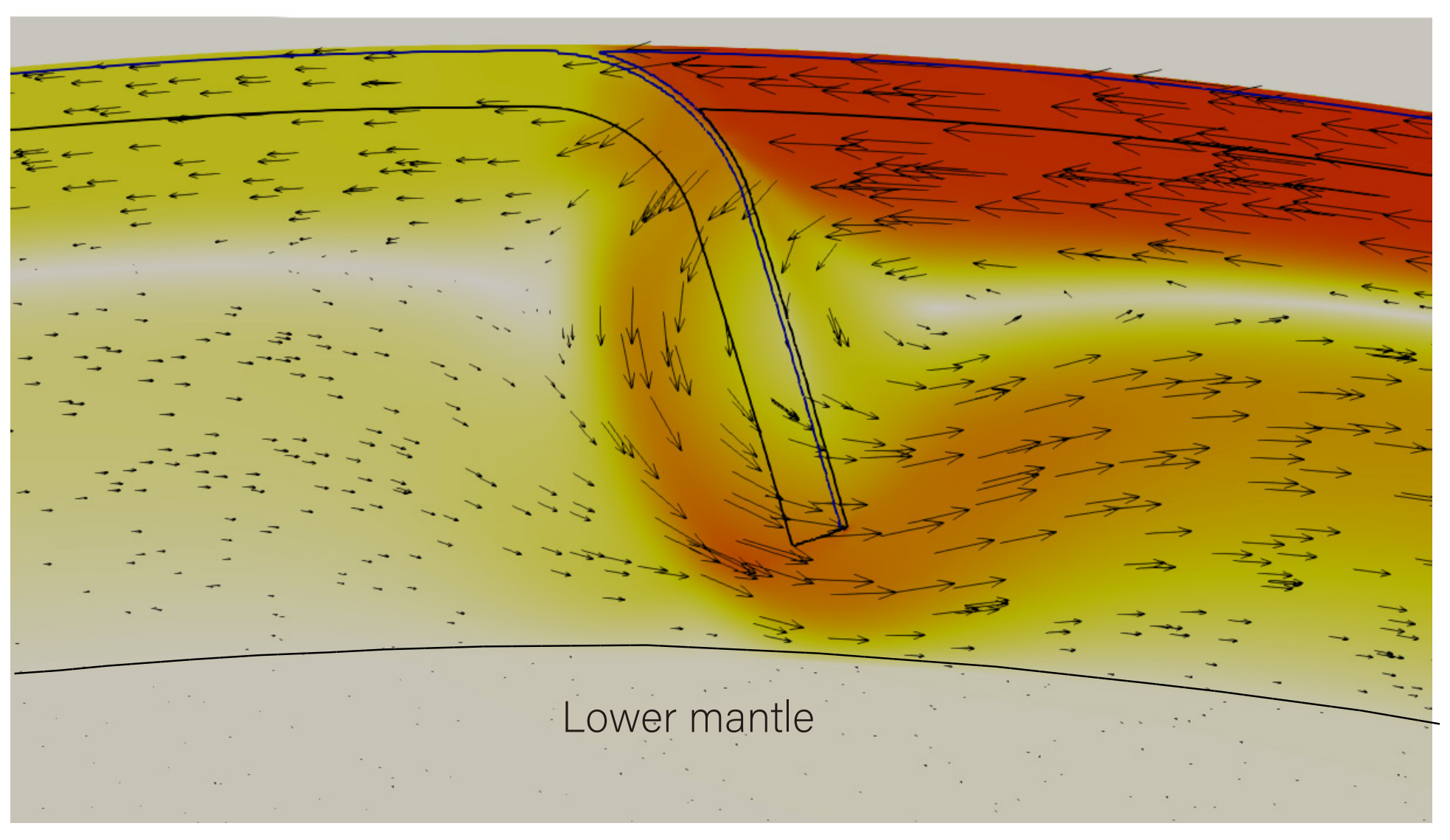
3. Effect of anomaly on mantle flow

The figures below show the difference between mantle flow fields within the reference model and models with variable density anomaly locations and densities. (All anomalies have a 200 km radius.)



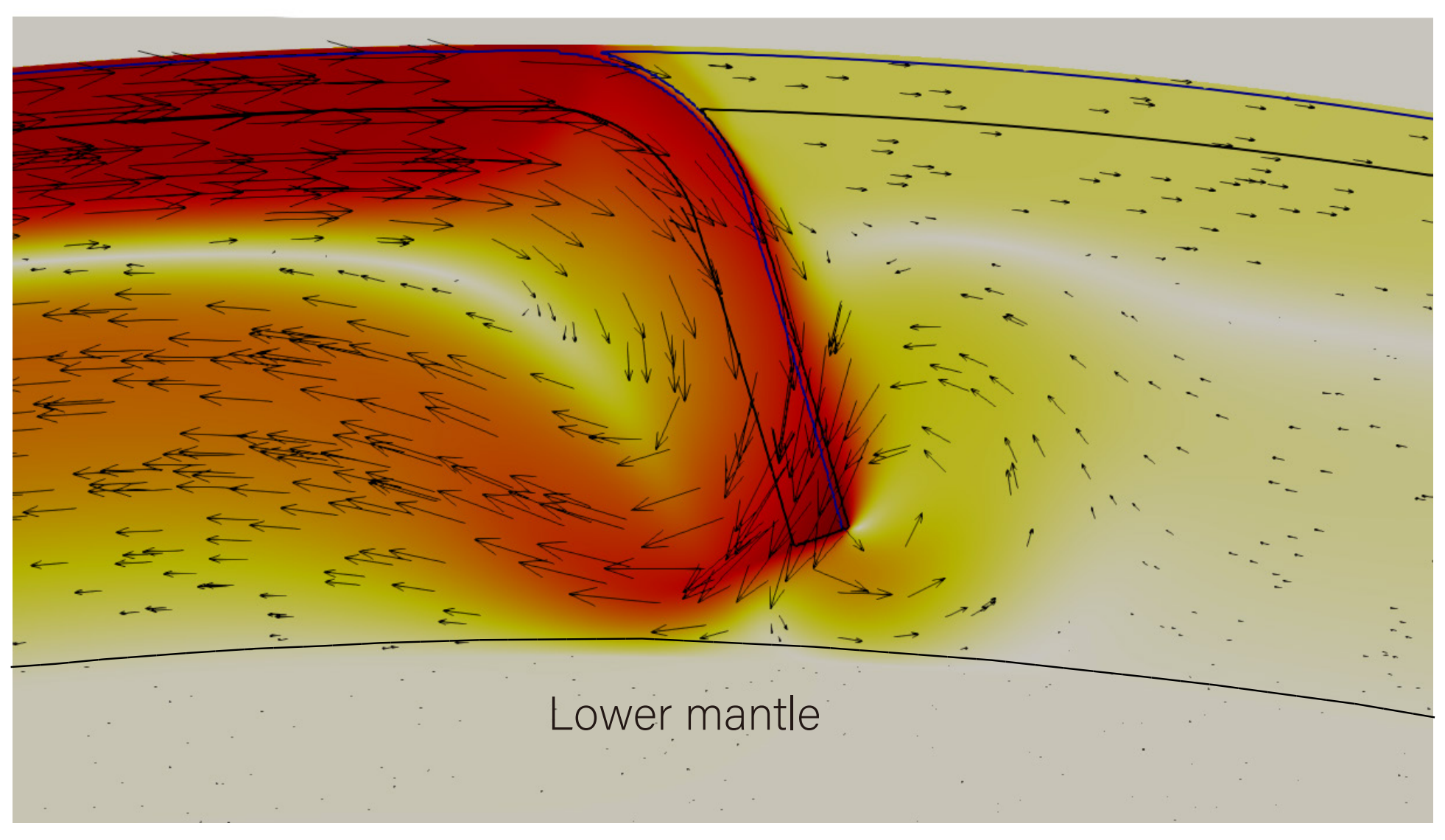
Light anomaly
(3200kg/m^3)
Beneath OP
(azimuth = 30°)

Flow driven by a rising (light) anomaly under the overriding plate (OP) rapidly pushes the OP, and also exerts a net push on the entire system.



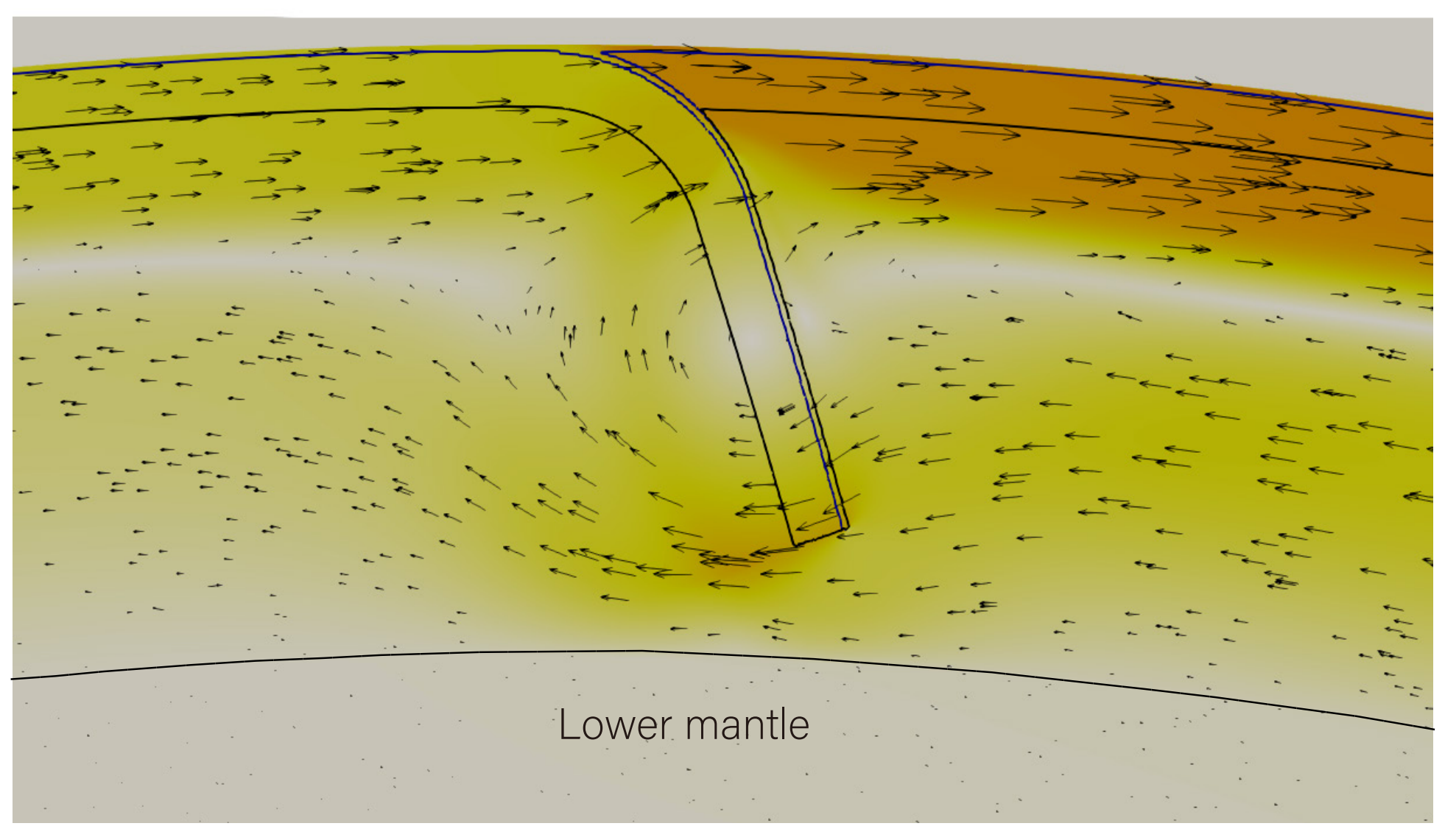
Light anomaly
(3200kg/m^3)
Beneath SP
(azimuth = -30°)

Flow driven by a rising anomaly under the SP (subducting plate) rapidly pushes the SP towards the trench, and has a small effect on the OP.



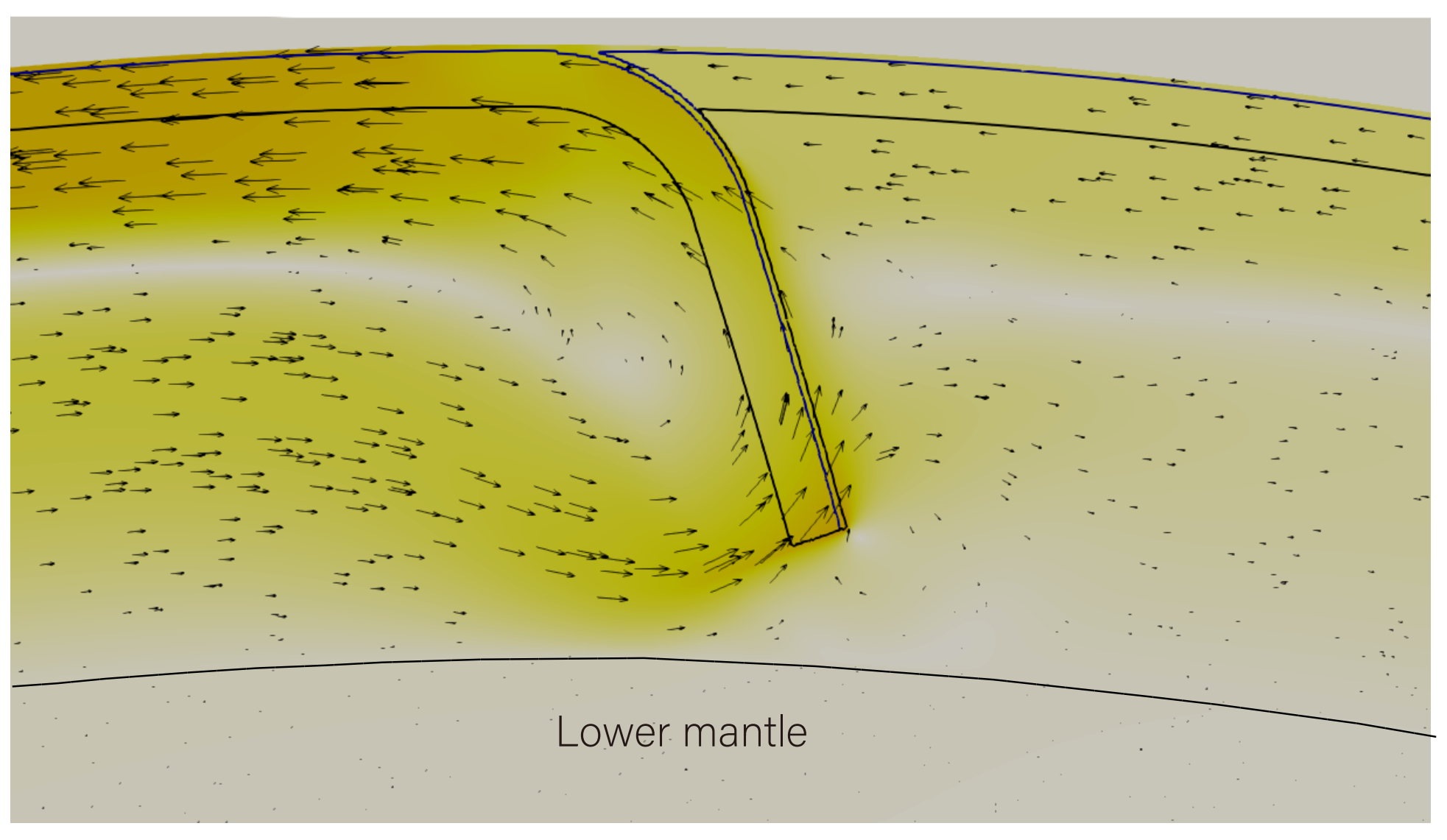
Heavy anomaly
(3400kg/m^3)
Beneath OP
(azimuth = 30°)

Flow driven by a sinking (heavy) anomaly has a smaller effect on plate velocities/mantle flow. When beneath the OP, it drags the OP away from the trench.



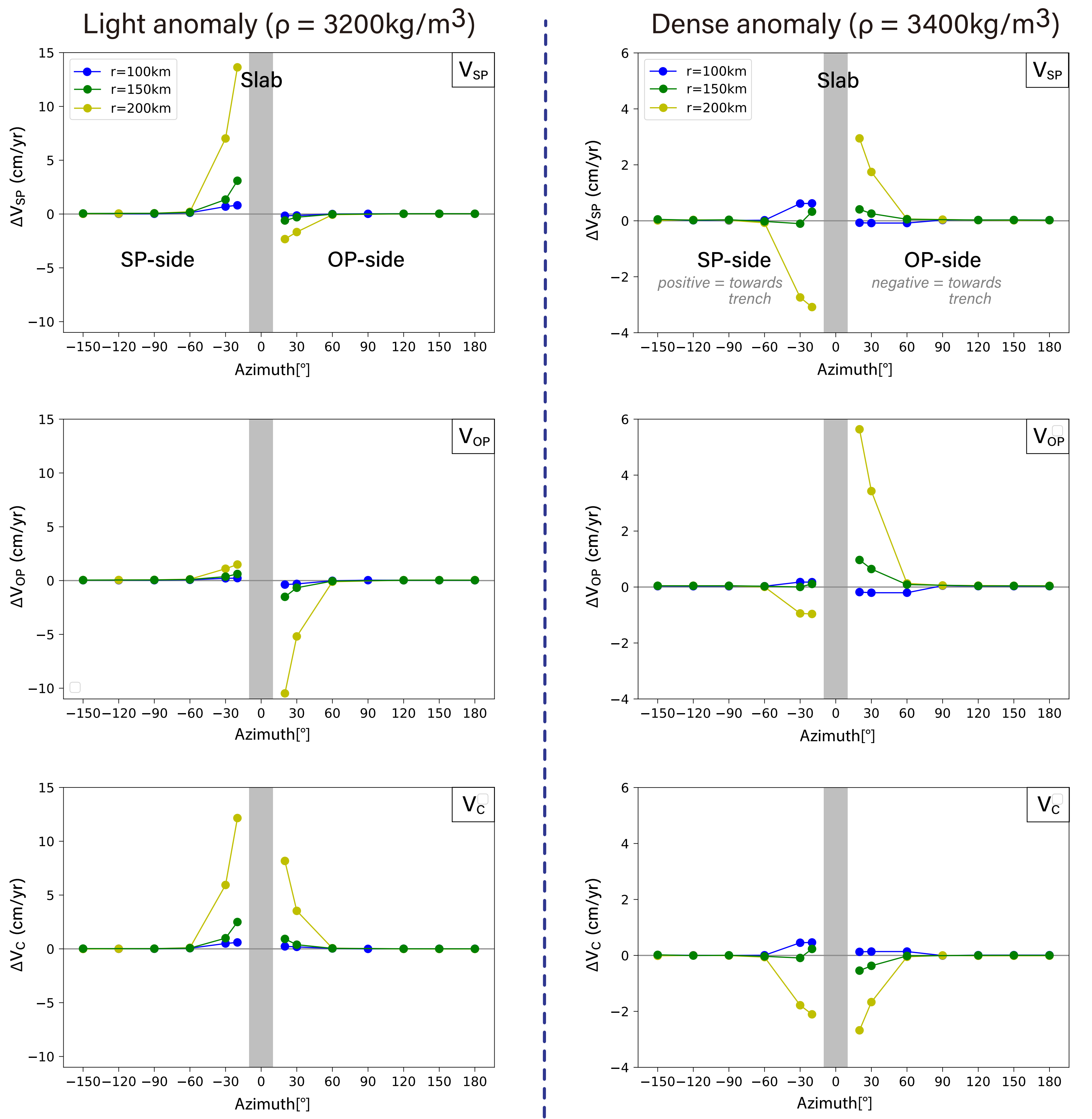
Heavy anomaly
(3400kg/m^3)
Beneath SP
(azimuth = -30°)

When the denser anomaly is under the SP, it instead drags the SP away from the trench.



4. Effect of anomaly on plate velocity

The figures below show the difference between plate velocities within the reference model and models with density anomalies of variable locations, radius, and signs (i.e., heavy or light). A positive ΔV corresponds to plates moving faster in the model with an anomaly. We analyze subducting plate velocity (V_{SP}), overriding plate velocity (V_{OP}), and convergence rate (V_C)



- A lighter anomaly beneath the SP causes a large speed-up in V_{SP}, a small reduction in trench-ward V_{OP}, and so a significant V_C increase.
- A lighter anomaly beneath the OP causes a large speed-up in trench-ward V_{OP}, a small reduction in trench-ward V_{SP}, and so, again, a V_C increase.
- The magnitude of this effect increases with anomaly radius and anomaly closeness to the slab.

- A large (r = 200 km) and dense anomaly always reduces V_C. When it's beneath the SP, this is mainly because of a large reduction in V_{SP}. When beneath the OP, this is mainly because of a large reduction in trench-wards V_{OP}.
- A small (r = 100 km) and dense anomaly causes a small increase in V_C when placed benath the SP. This is mainly due to a small increase in V_{SP}. When placed beneath the OP, the V_C increase is even smaller (<< 0.25 cm/yr).
- As for the lighter anomalies, the magnitude of this effect also increases with closeness to the slab.

5. Preliminary Conclusions

1) The larger the anomaly, or the closer it is to the slab, the larger the impact of the anomaly on subduction zone convergence rate.
2) A lighter anomaly (e.g., a plume) increases the convergence rate irrespective of whether it is on the OP or SP side of the subduction zone.
3) A heavy anomaly (e.g., a slab fragment) has more complex effects: A large anomaly (r = 200 km) decreaes the convergence rate; Smaller anomalies (r = 100 km) can decrease the convergence rate slightly.
4) An example: a 200 km sized anomaly with 100 kg/m3 greater density than the mantle decreases convergence rates by at least 3 cm/yr for anomalies within 30° of the slab.

6. Next steps

1) More detailed analysis of the subduction zone dynamics (e.g., mantle density anomaly effects on the pressure forces acting on slabs). This well help us to develop generalized expressions for the effects of mantle density anomalies.
2) Extension of these simplified models to 3-D. This will enable us to consider flow, and forces, in the 3rd dimension (i.e., the trench-parallel direction).
3) Implementation of "realistically"-shaped slabs and mantle density anomalies (based on seismic tomography). This will enable us to relate our models to observations at select subduction zones (e.g., South America).

References

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