Check for updates

AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099286

Plume-Slab Interactions Can Shut Off Subduction

Erin Heilman[1,2] and **Thorsten W. Becker**[1,2,3]

[1]Institute for Geophysics, Jackson School of Geosciences, The University of Texas, Austin, TX, USA, [2]Department of Geological Sciences, Jackson School of Geosciences, The University of Texas, Austin, TX, USA, [3]Oden Institute for Computational Sciences, The University of Texas, Austin, TX, USA

Key Points:

- Mantle plumes are capable of terminating subduction in weakened, young subducting slabs
- Plume-slab 'talk back' may be seen in tomographic models of present-day subduction zones, shown here for South America
- Plume-slab interactions may explain links between Large Igneous Province eruptions and flat slab episodes for example, for a supercontinental breakup

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

E. Heilman,
erin.heilman@utexas.edu

Citation:

Heilman, E., & Becker, T. W. (2022). Plume-slab interactions can shut off subduction. *Geophysical Research Letters*, *49*, e2022GL099286. https://doi.org/10.1029/2022GL099286

Received 28 APR 2022
Accepted 20 JUN 2022

Author Contributions:

Data curation: Erin Heilman
Formal analysis: Erin Heilman
Funding acquisition: Thorsten W. Becker
Investigation: Erin Heilman
Methodology: Erin Heilman
Project Administration: Thorsten W. Becker
Supervision: Thorsten W. Becker
Visualization: Erin Heilman
Writing – original draft: Erin Heilman, Thorsten W. Becker
Writing – review & editing: Erin Heilman, Thorsten W. Becker

© 2022. American Geophysical Union. All Rights Reserved.

Abstract

Mantle plumes are typically considered secondary features of mantle convection, yet their surface effects over Earth's evolution may have been significant. We use 2-D convection models to show that mantle plumes can in fact cause the termination of a subduction zone. This extreme case of plume-slab interaction is found when the slab is readily weakened, for example, by damage-type rheology, and the subducting slab is young. We posit that this mechanism may be relevant, particularly for the early Earth, and a subdued version of these plume-slab interactions may remain relevant for modern subduction zones. Such core-mantle boundary–surface interactions may be behind some of the complexity of tomographically imaged mantle structures, for example, in South America. More generally, plume "talk back" to subduction zones may make plate tectonics more episodic.

Plain Language Summary

The main driving force of mantle convection is the subduction of cold, lithospheric slabs. Mantle plumes that rise from the bottom of the mantle are typically not considered as important to plate tectonics, even though they have been suggested to initiate subduction, for example, here, we use 2-D computer models of mantle convection, with the particular addition of a deformation memory for rocks. We show that mantle plumes can actually stop subduction if certain criteria are met. The weakening behavior of the subducting slab and the overall slab thickness/age are the main criteria for deciding if a plume can stop subduction. We compare our findings to present-day subduction zones that show indications of possible plume-slab interactions. One such case is South America, and we consider how this mechanism may play out in a more complicated system. Our findings have implications for early Earth plate tectonics and perhaps present-day subduction.

1. Introduction

Plate tectonics is the expression of the cold thermal boundary layer of mantle convection, that is, the lithosphere (Oxburgh & Turcotte, 1976). The recycling of the lithosphere back into the mantle in subduction zones represents the major plate driving force at present, and subduction serves to organize the scales of mantle flow. However, any bottom-heated convective system will exhibit localized, hot upwellings from thermal instabilities at its base. Such mantle plumes from the core-mantle boundary (CMB) may be linked to hotspot volcanism (Morgan, 1971; Wilson, 1963), and these plumes represent an important, secondary scale of mantle convection (e.g., Koppers et al., 2021).

How important plumes are in mantle convection depends primarily on the balance between internal and basal heating (e.g., Zhong, 2006). The degree of bottom heating is relatively uncertain, with more recent estimates favoring higher core heat flux than traditionally thought (e.g., Lay et al., 2008). While plumes do not typically represent a major plate driving force, they have likely played a supporting role in plate tectonics over Earth's history. Possible plume effects include the formation of buoyant early crust which may help initiate subduction indirectly (Rey et al., 2014), more direct subduction initiation (Gerya et al., 2015; van Hinsbergen et al., 2021; Ueda et al., 2008), and disruption of plate coherence and motion rates (Cande & Stegman, 2011; Foley & Becker, 2009; Rodriguez et al., 2021).

Mantle convection is a nonlinear, coupled system, meaning that specific components cannot be comprehensively analyzed in isolation. Plume-slab interactions are one important example of the connections between the top and bottom boundary layers of the mantle. Subducting slabs modulate the dynamics of a thermo-chemical core-mantle boundary layer and can trigger thinner (cavity) plumes and more significant (diapiric) upwellings (Lenardic & Jellinek, 2009; Tan et al., 2002). Vice versa, once plumes arrive at the surface, they may affect trench motions and subduction rates (Betts et al., 2012; Mériaux et al., 2015), they can be deflected by slabs (Druken et al., 2014; Kincaid et al., 2013), and possibly disrupt them (Liu & Stegman, 2012). When the complexity of temperature-dependent viscosity is introduced, relatively strong slabs generally dominate the effects of plumes, meaning the tectonic importance of mantle plumes is dependent on mantle rheology (Arnould et al., 2020; Fletcher & Wyman, 2015).

While there are some imaging trade-offs (Bezada et al., 2016), plume anomalies have been suggested to explain seismic tomography features, for example, in the vicinity of morphologically complex slabs for the western US (Obrebski et al., 2010; Xue & Allen, 2007), South America (Portner et al., 2017), and China (Tang et al., 2014). Such improved observational constraints partially motivate a renewed interest in plume-slab interactions. While hot mantle anomalies close to slabs have been suggested to affect subduction for a number of upper mantle settings, the origin of these anomalies has received less attention and has sometimes been treated more or less ad hoc (Morishige et al., 2010).

Here, we show results from high-resolution, 2-D cylindrical mantle convection computations which illustrate a causal relationship between subduction, plume triggering at the core-mantle boundary, and modification of subduction and plate dynamics at the surface. For convective regimes that are episodic, such as might be expected for early Earth type convection, these interactions can be quite dramatic and direct. Plumes that were triggered at the core-mantle boundary by subducted material anchored in a higher viscosity lower mantle can rise along the contorted slab, reach the lithosphere, and shut off subduction. Such plume "talk back" is most dramatic when rock weakening behavior is accounted for by means of damage rheologies (cf. Gerya et al., 2021), and slabs are hence more prone to segmentation.

2. Model Setup

We utilize the open-source mantle finite-elements code *ASPECT* (Fraters et al., 2019; Heister et al., 2017; Kronbichler et al., 2012) to solve the convection equations of conservation of mass,

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

momentum,

$$-\nabla \cdot \left[\eta\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)\right] + \nabla p = \rho_0 g \alpha \left(T - T_0\right), \tag{2}$$

and energy

$$\left(\frac{\delta T}{\delta t} + \mathbf{u} \cdot \nabla T\right) - \kappa \nabla^2 \mathbf{T} = H \tag{3}$$

for an incompressible, Boussinesq fluid in the laminar, infinite Prandtl number regime. Here, $\mathbf{u}$ is velocity, T temperature, α thermal expansivity, ρ_0 and T_0 reference density and temperature, respectively, η viscosity, p pressure, ρ density, κ thermal diffusivity, and H the internal heat production. We show results from experiments with pure bottom heating with $H = 0$ to understand the effects of mantle plumes on subduction dynamics as an end-member case. We briefly discuss models with internal heat production included as a comparison to the end-member case (cf. Figures S1 and S2 in Supporting Information S1).

We use *ASPECT*'s adaptive mesh refinement to increase the resolution of the mesh in areas with large gradients in temperature or viscosity to capture these contrasts across several smaller cells. For our models, the finest resolution is ~7 km and the coarsest resolution is ~88 km at typical degrees of freedom of 10^5.

We employ a temperature-dependent Arrhenius-type viscosity law for our models that is based on a diffusion creep deformation mechanism affected by temperature that incorporates an activation energy (E_v), activation volume (V), and dimensional temperature (T), bounded by a minimum and maximum viscosity,

$$\eta_{eff} = 0.5\left(\frac{1}{A_v}\right)\dot{\varepsilon}_{II}\exp\left(\frac{E_v + PV}{RT}\right). \tag{4}$$

Here, A_v is the prefactor for diffusion creep, $\dot{\varepsilon}_{II}$ the second invariant of the strain rate tensor, P pressure, and R the gas constant. This viscosity law allows us to capture simplified temperature and depth dependence of viscosity with six orders of magnitude. We implement a viscosity jump at ∼660 km depth by varying the activation energies, volumes, and prefactors for diffusion creep (Table S1 in Supporting Information S1).

Coupled with the temperature-dependent viscosity, we incorporate viscoplasticity and simplified, viscous damage rheology following Fuchs and Becker (2019). *ASPECT* uses Drucker-Prager plasticity (e.g., Glerum et al., 2018) for the calculation of yield stress in 2D where the stress is set equal to the Mohr-Coulomb criterion, the local effective viscosity is rescaled following Equation 5 if the stress exceeds the yield stress σ_y (e.g., Enns et al., 2005; Moresi & Solomatov, 1998).

$$\eta_{eff} = \frac{\sigma_y}{2\dot{\varepsilon}_{II}} \tag{5}$$

We consider a strain-based damage variable, γ, which is treated as a field variable, that is, a compositional field that is advected and can evolve. The combination of plasticity and evolving, damage-type rheology can approximate more realistic weakening processes such as inferred from grain-size-dependent rheologies (Fuchs & Becker, 2021). Damage evolves according to a discretized evolution law

$$d\gamma = \dot{\varepsilon}_{II}\,dt - \gamma\left(A_d \cdot \exp\left(E_d\left(T - T_0\right)\right)\right)dt \tag{6}$$

where $d\gamma$ is the change in accumulated damage, $\dot{\varepsilon}_{II}$ is the second invariant of the strain-rate tensor, A_d is a timescale for strain-healing, E_d is non-dimensional activation energy, following temperature-dependent strain healing (Fuchs & Becker, 2019). This formulation allows for damage to accumulate and advect in the cold lithosphere but in the hot mantle, the damage will heal according to a specified rate with temperature (Table S1 in Supporting Information S1). For the strain-weakening component of the damage rheology, we set the parameters such that the yield stress can be reduced by 75%, to minimum yield stress of ∼15 MPa, as a linear function of damage, up to critical damage of 5.

Computations are for a 2-D quarter annulus with periodic side boundaries to approximate Earth's sphericity in a computationally efficient manner. Models are run to dimensional times of 15 Ga to reach steady-state to evaluate the time dependency of the model after initial transients. Surface velocities in the models are of the order of 1–10 cm/year, meaning the scaled model time is relevant to nature.

For a given temperature-dependent viscosity, the vigor of convection is tied to the convective regime of the model, and without plastic yielding, stagnant lid convection results in contrasts above ∼1,000 (Solomatov & Moresi, 1997). With damage rheology choices similar to Fuchs and Becker (2019); Fuchs and Becker (2021) for the strain-weakening and strain-healing, we adjust our models to be on the edge between episodic and mobile regimes. In particular, we show results from two models which yielded an episodic case (Model 1, yield stress 65 MPa) and a more mobile case (Model 2, yield stress 60 MPa) both with a Rayleigh number of $\sim 2.3 \cdot 10^7$. We also discuss results from models run without damage as a comparison to the models with damage highlighted here. Results from Models 1 and 2 demonstrate the sensitivity of convection as a transition from episodic to mobile occurs with a 5 MPa decrease in yield stress (cf. Foley & Becker, 2009). This becomes evident in Model 2 as the change in convection style from episodic to mobile was not seen in the model until the model run exceeded ∼10 Ga when there was enough accumulated damage. As in prior work, the yield stress of the lithosphere is comparatively weak compared to expectations from dry Byerlee yielding, as this is necessary to achieve plate-like deformation (van Heck & Tackley, 2008; Foley & Becker, 2009; Moresi & Solomatov, 1998).

3. Results

Here we discuss the main results of our modeling, mantle plume-driven subduction zone interactions, and termination. An example of both termination and non-terminating interaction is shown in Figure 1. In Figure 1a, a mantle plume is triggered next to subducted material i.e., piling up at the CMB. The plume is deflected by the sinking slab, but once the plume reaches the surface, it spreads laterally, impinging on the subduction zone, and shutting off subduction.

The dynamics and style of this termination mechanism differ in some of the cases. Usually, the mantle plume head will reach the top, cold boundary layer and spread, deflecting underneath the lithosphere to a subduction zone which then causes its termination. We see this occurring with plumes striking the surface both behind and in front of the subduction zone. In at least one case, two plumes rise on either side of the subduction zone and

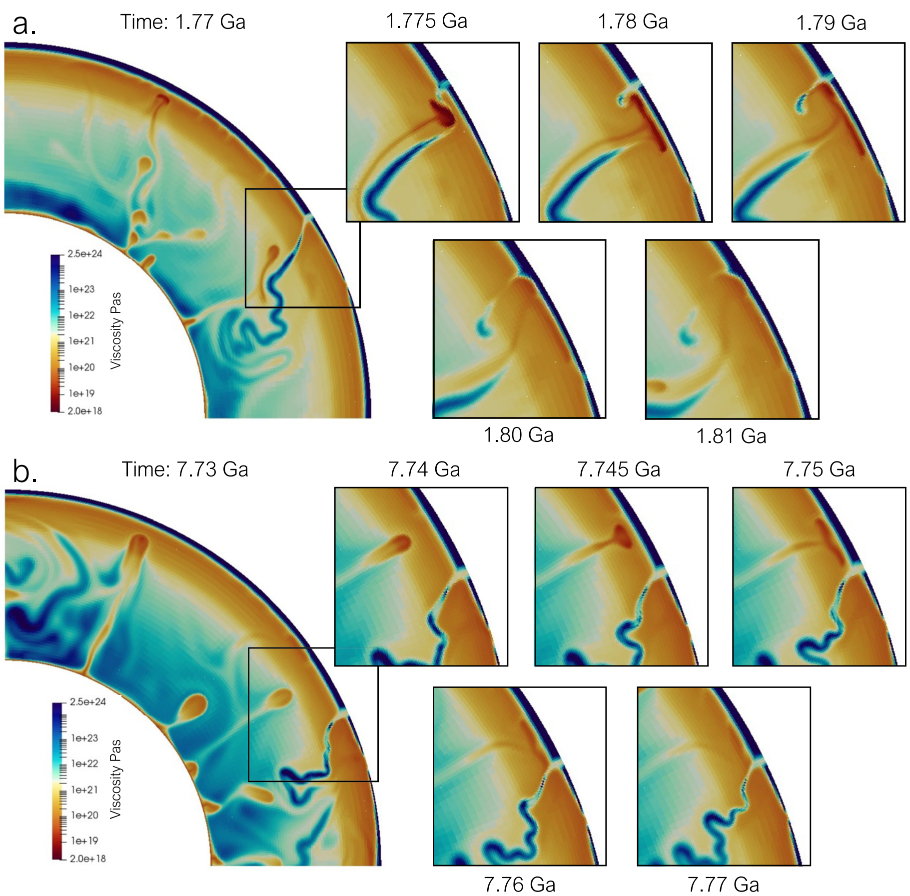

Figure 1. Comparison of plume-slab termination and interaction. (a) Instance of plume-driven subduction termination. The mantle plume deflects around the descending slab, cuts through it, and hits the lithosphere near the subduction zone, terminating subduction. (b) Instance of plume-subduction zone interaction where a plume hits the lithosphere near the subduction zone and interacts with the slab but subduction is not terminated.

pinch out the descending slab, terminating subduction. In another instance, the plume hits the surface directly at the subduction zone, transecting the subducting slab and terminating it, this style of shut off occurs less often. The average timescale for plume subduction termination is of the order of ∼40–60 Myr from initial contact of the mantle plume with the underside of the lithosphere at/near the subduction zone to complete termination of subduction.

There are cases in both Model 1 and 2 where a plume will interact with a subduction zone but not terminate subduction. In these instances for both models, we do not see long-lived, stationary plumes. On average a mantle plume will interact with the subduction zone for ∼20 Ma, starting from initial contact, before diffusing to ambient mantle temperature. However, we do see these interactions affecting slab morphology, changing the subduction speed, direction, or dip angle.

One such case of interaction without termination is shown in Figure 1b, where the plume hits the top boundary layer, the plume head spreads and the edge of the plume slides underneath the subducting slab similar to the subduction terminating cases. In these interactions, plumes will mainly strike on either side of the subduction zone, and rarely directly underneath, as expected statistically. The sizes of the plume heads vary in these interactions as well as how close the rising plumes are to the subduction zone when they first contact the top boundary layer.

This plume-driven slab termination mechanism occurs 8 times per 15 Ga in Model 1 (every $\sim 1-2$ Ga), in which there are several different styles of plume-subduction termination, and 10 times per 15 Ga in Model 2 (every ∼1.5 Ga). Figure 2 illustrates the instances of plume-driven termination as dashed lines compared to surface

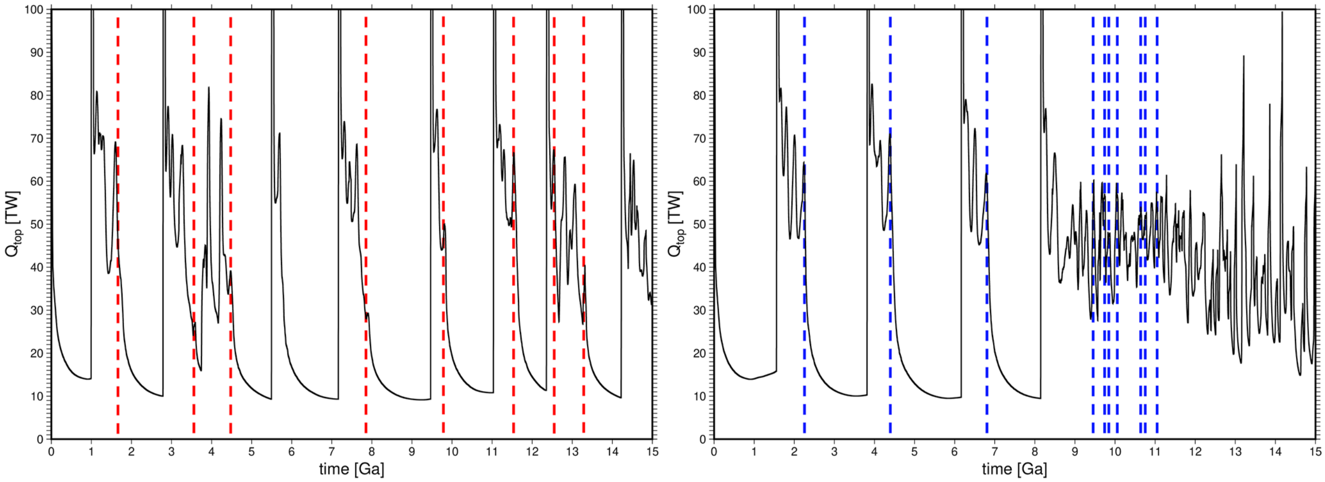

Figure 2. Surface heat flow (scaled up from 2D to global values) over time for Model 1 (left) and Model 2 (right). Vertical, red dashed lines denote when termination occurs. Spikes in heat flow represent onset of plate tectonic-like convection after a period of stagnant lid. Plume-driven subduction termination leads to periods of stagnant lid in episodic models. Similar terminations occur in Model 2 while remaining mobile.

heat flow. In Model 1 (Figure 2 left), after a termination occurs the model switches to stagnant lid convection, and thus the heat flow decreases as the top surface is no longer mobile. In Model 1 (higher yield stress), when plume-driven subduction termination occurs, it can shut off subduction in the entire model domain as there is only a single subduction zone and the convective regime transitions to a stagnant lid.

The right plot in Figure 2 shows Model 2, where the model experiences a few episodic overturns at the beginning of the run time and then transitions to a more mobile convection style, perhaps reminiscent of the transition from the stagnant lid of early Earth to modern day plate tectonic mobile convection. In this lower yield stress model, when multiple subduction zones are present, termination occurs on a single subduction zone while other subduction zones remain active. The instances of plume-driven subduction termination are less pronounced in the heat flow record in this case as the surface is mobile with multiple subduction zones. There is a slight drop in heat flow at each occurrence but the plume talk back is less dramatic than in Model 1. Regarding the instances of plume-slab interaction without termination, those occur once every ∼1 Ga for Model 1, and once every ∼0.5 Ga for Model 2.

The control on whether a slab will be terminated or not is overall slab strength. This is a combination of the weakness of the slab in terms of damage and the slab thickness/age that is inferred here from the internal temperature of the slab according to the half-space cooling of the surface thermal boundary layer. An example of plume-driven slab termination showing these factors is seen in Figure 3. Weakened subducting slabs are a prerequisite to slab termination, we see in terminating and non-terminating cases that the descending slab has been fully damaged such that the yield stress is at its minimum. Once a slab is fully weakened (in Model 1–16 MPa and in Model 2–15 MPa), the age and thickness of the slab become the controlling factor of termination. In instances of non-terminating interactions, the internal temperature of the descending slab is ∼350 K colder than during termination. This indicates that older, colder, and thicker slabs are less likely to undergo subduction termination than hotter, thinner, and younger slabs.

4. Discussion

We find that plume-driven subduction termination recurs every 1-2 Ga in Model 1, and in Model 2 every 2 Ga during the initial episodic overturns, and 7 times in 2 Ga when the model is mobile. The main control of this plume-driven subduction termination is the subducting slab strength as a function of its age. The deformation in the subducting slab is from plastic yielding and the damage rheology, while in plumes it is controlled by the temperature contrast of the surrounding mantle (e.g., Druken et al., 2014; Fletcher & Wyman, 2015). We observe many plume-slab interactions that do not terminate subduction and find that the slab ages, as inferred through internal slab temperature, are greater than cases with termination, which are generally warmer and thinner. Not all

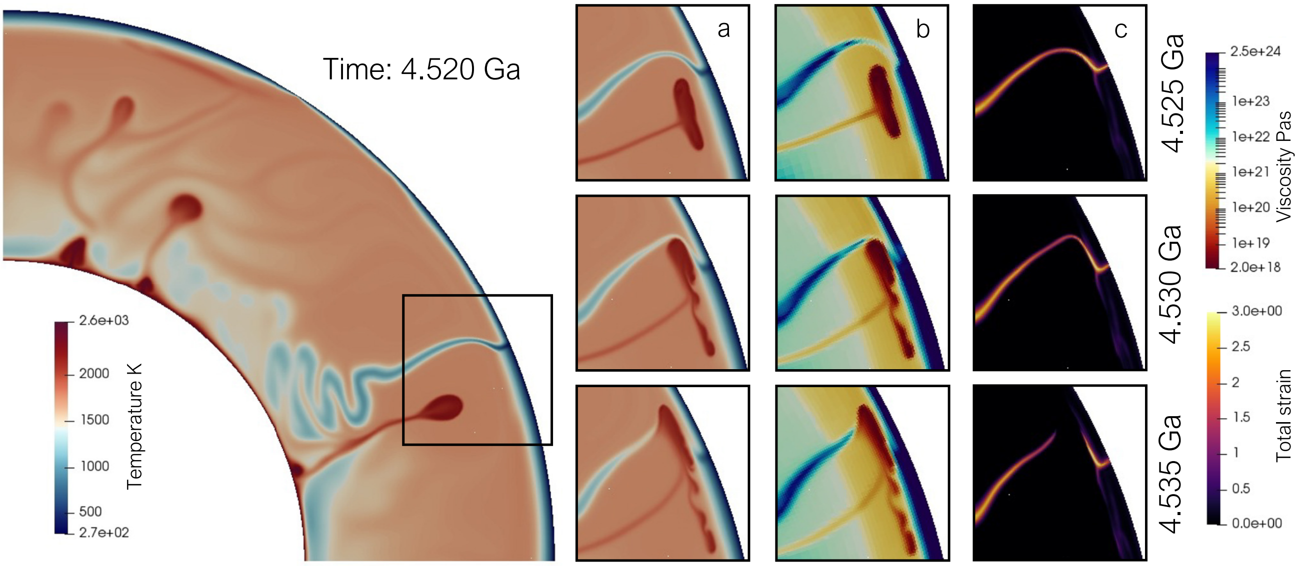

Figure 3. Instance of plume-driven termination from Model 1. Columns a, b, and c, show temperature, viscosity, and total accumulated strain, respectively. The subducting slab thickness before plume interaction is ~60 km. The slab is fully weakened and damaged as shown by column c and has an internal slab temperature of ~900 K as seen in column (a).

plume-subduction zone interactions end in termination and it is 2-3 times as likely in our models that the plume will interact with the slab but not cause termination. Nonetheless, slab morphologies are still affected when interacting with mantle plumes.

In circumstances where the subduction zone is weakened and the slab is sufficiently warm, the temperature increase from the rising mantle plume can be the catalyst to shut off the subduction zone. We also considered the case where plumes affect subduction for a mixture of bottom and internal heating (roughly at equal contribution to surface heat flux) to compare to our cases of pure bottom heating. Those cases also show numerous instances of significant plume-slab interactions that impact but do not shut off subduction (Figure S1 in Supporting Information S1). In those instances, there is often a decrease in subduction speed and vigor after plume interaction. For mixed heating, the temperature contrast between the plume and slab is reduced due to the addition of internal heating, which affects the inferred slab temperature criteria for termination, but plume-driven termination does still occur.

Damage rheology plays an important role in our models as the weakness of the descending slab is the other determining factor for possible subduction termination (Gerya et al., 2021). The weakest point in the subduction zone coincides with the area with the greatest buildup of accumulated strain, see Figure 3. As employed, the damaged memory allows accumulated strain in the lithosphere to last longer than damage within the mantle due to the temperature-dependence of the strain healing and lower temperature in the lithosphere (Fuchs & Becker, 2019, 2021). Weakened slabs have been shown to be more easily deformed or torn by mantle plumes in other modeling scenarios (Baes et al., 2020; Betts et al., 2012). In a comparable non-damage rheology case, we see fewer instances of plume subduction termination due to the stronger, undeformed lithosphere in contrast with the damage rheology case. The non-damage rheology case, for example, has ~one plume-driven subduction termination per ~3 Ga (Figure S2 in Supporting Information S1) compared to the episodic damage case's one every ~0.5 Ga and the mobile damage case's one every ~0.7 Ga. This reinforces the importance of the damage rheology in weakening the slabs and leads to twice as many plume-slab terminations as the non-damage rheology case. The instances of termination in the non-damage rheology case arise primarily from the descending slabs being warm and young enough to facilitate termination.

Our models have several important simplifications, for example, their homogeneous composition, and they are 2-D. Allowing for 3-D flow may likewise work in favor of subduction continuation, as the hot plume anomaly may be able to flow around the slab, rather than pinch it off, as well as the influence of lateral flow effects.

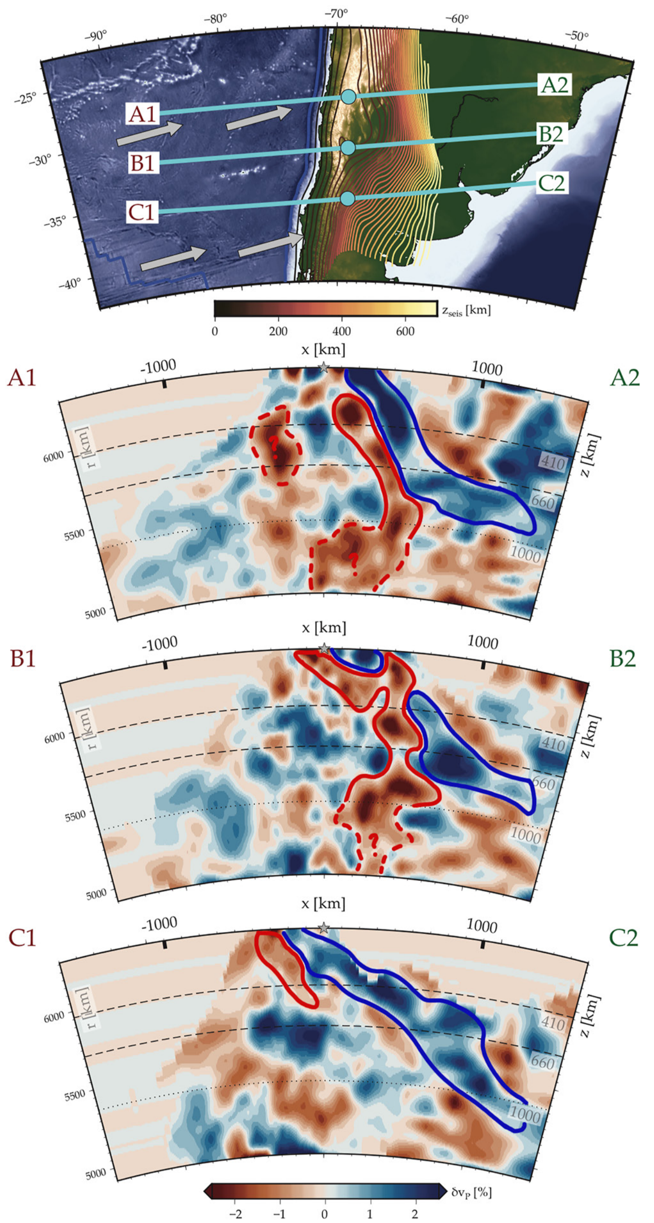

Figure 4. Slices through the tomographic model of Portner et al. (2020) for the South American subduction zone, reinterpreted (contours) but generally following the scenario of Portner et al. (2017); Portner et al. (2020). A-C are profiles perpendicular to the trench with added interpretation. A1-A2 shows the subducting slab underlay by a slow anomaly interpreted to be a plume, and possible smaller plume west of the trench. Further south, B1-B2 shows the plume rising through a hole in the descending slab resulting in the flattening of the slab dip angle (Portner et al., 2017). C1-C2 shows the remnant of the plume head to the south and the end of the plume-slab interaction.

4.1. Relation to Geologic Settings

Fletcher and Wyman (2015) explore the interaction of 18 plumes located within 1,000 km of subduction in the past 60 Ma alone. It is thus likely that plume-slab interaction remains significant in the Cenozoic, and possible that plumes have shut off subduction at some point in the past. For example, mantle plumes have been suggested to be capable of exploiting and creating slab tears or slab windows in subducting plates (e.g., Betts et al., 2012; Obrebski et al., 2010; Portner et al., 2017). Seismic tomography revealed several slab tears, for example, for Farallon, Nazca, and Japan (Ismail-Zadeh et al., 2013; Liu & Stegman, 2012; Obrebski et al., 2010; Portner et al., 2017). The presence of slab tears, some of which are the result of thermal mantle anomaly interaction, indicates that mantle plumes may be able to deform subduction zones significantly.

Figure 4 suggests a possible scenario of present-day plume-slab interactions in the South America subduction zone where a slab window may interact with the Juan Fernández associated plume (Portner et al., 2017, 2020). A transition from slab tear to subduction shut off may then occur similarly to that of the process in Figure 1 as the rising plume creates a tear in the slab and then terminates subduction. However, it is unclear what the effect of these plume-slab interactions would be in a 3-D setting. The deflection of the warm thermal anomaly structure in Figure 4 by the descending slab could modify the temperature of the slab such that over time the temperature of the slab would be warm enough to cause eventual termination.

Another geological example of plume-slab interaction is in the Gondwanide orogeny, where a rising mantle plume in the Early Jurassic (∼200 Ma) has been inferred to have impinged on the subducting slab to create flat slab subduction, subsequently breaking through the slab, causing the Karoo-Ferrar Large Igneous Province (∼182 Ma), resulting in eventual slab break off (Dalziel et al., 2000, 2013). A similar scenario of a rising plume creating flat slab subduction and eventual termination is indeed seen in Figure 3.

Fletcher and Wyman (2015) find that in the last 60 Ma at least four documented mantle plumes have interacted with subduction zones, but typically do not interact for very long or survive the interaction. We find this replicated in our models where both plumes that cause termination and plumes that do not, aren't long-lived after interacting with a subduction zone. This contrasts with what is inferred for relatively stable plumes away from subduction zones associated with hotspots such as the Hawaii-Emperor Island chain plume that has been sustained for at least ∼80 Myr (e.g., Doubrovine et al., 2012). With as many recent plume-subduction zone interactions, we can assume at least as many interactions occurred in the past and that plumes with a deep mantle/CMB source can directly affect surface tectonics. We show that while mantle plumes indeed do not survive this trench interaction, the subduction zone itself may not either, resulting in the termination of the subduction zone and plume.

5. Conclusions

The study of plume-slab interactions has mainly focused on subduction initiation, but we propose that mantle plumes also have the capability to shut off subduction. Exploring subduction with damage rheology, which can lead to increased weakening and slab segmentation, we find that mantle plumes are able to terminate subduction for young oceanic lithosphere. This plume talk back is found in episodic and mobile plate style convection models with bottom heating, and plume-slab interactions are significant in general. Several present-day subduction zones show evidence of slab tears possibly due to interactions with plumes. In nature, the effects of plume modulated subduction complexity may be less stark than termination but still important to affect plate tectonics over geologic history. Our findings suggest a sustained role of plumes in shaping our planet's surface via top-down-bottom-up feedback. We suggest that plume-slab interaction and subduction termination may be a relevant mechanism for plate reorganizations and that mantle tomography images are less dramatic instances of CMB-surface communication.

Data Availability Statement

ASPECT is an open-source mantle convection code hosted by the Computational Infrastructure for Geodynamics, all features used are available in ASPECT version 2.4.0-pre at (https://aspect.geodynamics.org/). The necessary data to replicate models can be found at https://doi.org/10.5281/zenodo.6484525.

Acknowledgments
This project was funded by the National Science Foundation under award EAR-1853856. We thank the developers and Computational Infrastructure for Geodynamics (geodynamics.org) which is funded by the National Science Foundation under award EAR-0949446 and EAR-1550901 for supporting the development of ASPECT, and the reviewers for their helpful comments.

References

Arnould, M., Coltice, N., Flament, N., & Mallard, C. (2020). Plate tectonics and mantle controls on plume dynamics. *Earth and Planetary Science Letters*, *547*, 116439. https://doi.org/10.1016/j.epsl.2020.116439

Baes, M., Sobolev, S., Gerya, T., & Brune, S. (2020). Plume-induced subduction initiation: Single-slab or multi-slab subduction? *Geochemistry, Geophysics, Geosystems*, *21*(2), e2019GC008663. https://doi.org/10.1029/2019gc008663

Betts, P. G., Mason, W. G., & Moresi, L. (2012). The influence of a mantle plume head on the dynamics of a retreating subduction zone. *Geology*, *40*(8), 739–742. https://doi.org/10.1130/g32909.1

Bezada, M., Faccenda, M., & Toomey, D. (2016). Representing anisotropic subduction zones with isotropic velocity models: A characterization of the problem and some steps on a possible path forward. *Geochemistry, Geophysics, Geosystems*, *17*(8), 3164–3189. https://doi.org/10.1002/2016gc006507

Cande, S. C., & Stegman, D. R. (2011). Indian and African plate motions driven by the push force of the Réunion plume head. *Nature*, *475*, 47–52. https://doi.org/10.1038/nature10174

Dalziel, I. W., Lawver, L., & Murphy, J. (2000). Plumes, orogenesis, and supercontinental fragmentation. *Earth and Planetary Science Letters*, *178*(1–2), 1–11. https://doi.org/10.1016/s0012-821x(00)00061-3

Dalziel, I. W., Lawver, L. A., Norton, I. O., & Gahagan, L. M. (2013). The scotia arc: Genesis, evolution, global significance. *Annual Review of Earth and Planetary Sciences*, *41*, 767–793. https://doi.org/10.1146/annurev-earth-050212-124155

Doubrovine, P. V., Steinberger, B., & Torsvik, T. H. (2012). Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. *Journal of Geophysical Research*, *117*(B09101). https://doi.org/10.1029/2011JB009072

Druken, K., Kincaid, C., Griffiths, R., Stegman, D., & Hart, S. (2014). Plume–slab interaction: The Samoa–Tonga system. *Physics of the Earth and Planetary Interiors*, *232*, 1–14. https://doi.org/10.1016/j.pepi.2014.03.003

Enns, A., Becker, T. W., & Schmeling, H. (2005). The dynamics of subduction and trench migration for viscosity stratification. *Geophysical Journal International*, *160*, 761–775. https://doi.org/10.1111/j.1365-246x.2005.02519.x

Fletcher, M., & Wyman, D. A. (2015). Mantle plume-subduction zone interactions over the past 60 Ma. *Lithos*, *233*, 162–173. https://doi.org/10.1016/j.lithos.2015.06.026

Foley, B., & Becker, T. W. (2009). Generation of plate tectonics and mantle heterogeneity from a spherical, visco-plastic convection model. *Geochemistry, Geophysics, Geosystems*, *10*(Q08001). https://doi.org/10.1029/2009GC002378

Fraters, M. R. T., Bangerth, W., Thieulot, C., Glerum, A. C., & Spakman, W. (2019). Efficient and practical Newton solvers for nonlinear Stokes systems in geodynamics problems. *Geophysical Journal International*, *218*, 873–894. https://doi.org/10.1093/gji/ggz183

Fuchs, L., & Becker, T. W. (2019). Role of strain-dependent weakening memory on the style of mantle convection and plate boundary stability. *Geophysical Journal International*, *218*, 601–618. https://doi.org/10.1093/gji/ggz167

Fuchs, L., & Becker, T. W. (2021). Deformation memory in the lithosphere: A comparison of damage-dependent weakening and grain-size sensitive rheologies. *Journal of Geophysical Research*, *126*, e2020JB020335. https://doi.org/10.1029/2020jb020335

Gerya, T. V., Bercovici, D., & Becker, T. (2021). Dynamic slab segmentation due to brittle-ductile damage in the outer rise. *Nature*, *599*, 245–250. https://doi.org/10.1038/s41586-021-03937-x

Gerya, T. V., Stern, R. J., Baes, M., Sobolev, S. V., & Whattam, S. A. (2015). Plate tectonics on the Earth triggered by plume-induced subduction initiation. *Nature*, *527*(7577), 221–225. https://doi.org/10.1038/nature15752

Glerum, A., Thieulot, C., Fraters, M., Blom, C., & Spakman, W. (2018). Nonlinear viscoplasticity in ASPECT: Benchmarking and applications to subduction. *Solid Earth*, *9*, 267–294. https://doi.org/10.5194/se-9-267-2018

Heister, T., Dannberg, J., Gassmöller, R., & Bangerth, W. (2017). High accuracy mantle convection simulation through modern numerical methods – II: Realistic models and problems. *Geophysical Journal International*, *210*, 833–851. https://doi.org/10.1093/gji/ggx195

Ismail-Zadeh, A., Honda, S., & Tsepelev, I. (2013). Linking mantle upwelling with the lithosphere descent and the Japan sea evolution: A hypothesis. *Scientific Reports*, *3*, 1–8. https://doi.org/10.1038/srep01137

Kincaid, C., Druken, K., Griffiths, R. W., & Stegman, D. R. (2013). Bifurcation of the Yellowstone plume driven by subduction-induced mantle flow. *Nature Geosciences*, *6*, 395–399. https://doi.org/10.1038/ngeo1774

Koppers, A. A., Becker, T. W., Jackson, M. G., Konrad, K., Müller, R. D., Romanowicz, B., et al. (2021). Mantle plumes and their role in Earth processes. *Nature Reviews of Earth & Environment*, *2*, 382–401. https://doi.org/10.1038/s43017-021-00168-6

Kronbichler, M., Heister, T., & Bangerth, W. (2012). High accuracy mantle convection simulation through modern numerical methods. *Geophysical Journal International*, *191*, 12–29. https://doi.org/10.1111/j.1365-246x.2012.05609.x

Lay, T., Hernlund, J., & Buffett, B. (2008). Core-mantle boundary heat flow. *Nature Geosciences*, *1*, 25–32. https://doi.org/10.1038/ngeo.2007.44

Lenardic, A., & Jellinek, A. (2009). Tails of two plume types in one mantle. *Geology*, *37*, 127–130. https://doi.org/10.1130/g25229a.1

Liu, L., & Stegman, D. R. (2012). Origin of Columbia River flood basalt controlled by propagating rupture of the Farallon slab. *Nature*, *482*, 386–389. https://doi.org/10.1038/nature10749

Mériaux, C., Duarte, J. C., Schellart, W. P., & Mériaux, A.-S. (2015). A two-way interaction between the Hainan plume and the Manila subduction zone. *Geophysical Research Letters*, *42*, 5796–5802. https://doi.org/10.1002/2015GL064313

Moresi, L. N., & Solomatov, V. (1998). Mantle convection with a brittle lithosphere: Thoughts on the global tectonic styles of the Earth and Venus. *Geophysical Journal International*, *133*, 669–682. https://doi.org/10.1046/j.1365-246x.1998.00521.x

Morgan, J. P. (1971). Convection plumes in the lower mantle. *Nature*, *230*, 42–43. https://doi.org/10.1038/230042a0

Morishige, M., Honda, S., & Yoshida, M. (2010). Possibility of hot anomaly in the sub-slab mantle as an origin of low seismic velocity anomaly under the subducting Pacific plate. *Physics of the Earth and Planetary Interiors*, *183*, 353–365. https://doi.org/10.1016/j.pepi.2010.04.002

Obrebski, M., Allen, R. M., Xue, M., & Hung, S.-H. (2010). Slab-plume interaction beneath the Pacific Northwest. *Geophysical Research Letters*, *37*(L14305). https://doi.org/10.1029/2010GL043489

Oxburgh, E. R., & Turcotte, D. L. (1976). The physico-chemical behaviour of the descending lithosphere. *Tectonophysics*, *32*, 107–128. https://doi.org/10.1016/0040-1951(76)90088-3

Portner, D. E., Beck, S., Zandt, G., & Scire, A. (2017). The nature of subslab slow velocity anomalies beneath south America. *Geophysical Research Letters*, *44*(10), 4747–4755. https://doi.org/10.1002/2017gl073106

Portner, D. E., Rodríguez, E. E., Beck, S., Zandt, G., Scire, A., Rocha, M. P., et al. (2020). Detailed structure of the subducted nazca slab into the lower mantle derived from continent-scale teleseismic p wave tomography. *Journal of Geophysical Research: Solid Earth*, *125*(5), e2019JB017884. https://doi.org/10.1029/2019jb017884

Rey, P. F., Coltice, N., & Flament, N. (2014). Spreading continents kick-started plate tectonics. *Nature*, *513*, 405–408. https://doi.org/10.1038/nature13728

Rodriguez, M., Arnould, M., Coltice, N., & Soret, M. (2021). Long-term evolution of a plume-induced subduction in the neotethys realm. *Earth and Planetary Science Letters*, *561*, 116798. https://doi.org/10.1016/j.epsl.2021.116798

Solomatov, V. S., & Moresi, L. N. (1997). Three regimes of mantle convection with non-Newtonian viscosity and stagnant lid convection on the terrestrial planets. *Geophysical Research Letters*, *24*, 1907–1910. https://doi.org/10.1029/97gl01682

Tan, E., Gurnis, M., & Han, L. (2002). Slabs in the lower mantle and their modulation of plume formation. *Geochemistry, Geophysics, Geosystems*, *3*(1067). https://doi.org/10.1029/2001GC000238

Tang, Y., Obayashi, M., Niu, F., Grand, S. P., Chen, Y. J., Kawakatsu, H., et al. (2014). Changbaishan volcanism in northeast China linked to subduction-induced mantle upwelling., *7*, 470–475. https://doi.org/10.1038/ngeo2166

Ueda, K., Gerya, T., & Sobolev, S. V. (2008). Subduction initiation by thermal–chemical plumes: Numerical studies. *Physics of the Earth and Planetary Interiors*, *171*, 296–312. https://doi.org/10.1016/j.pepi.2008.06.032

van Heck, H., & Tackley, P. J. (2008). Planforms of self-consistently generated plate tectonics in 3-D spherical geometry. *Geophysical Research Letters*, *35*(L19312). https://doi.org/10.1029/2008GL035190

van Hinsbergen, D. J., Steinberger, B., Guilmette, C., Maffione, M., Gürer, D., Peters, K., et al. (2021). A record of plume-induced plate rotation triggering subduction initiation. *Nature*, *14*, 626–630. https://doi.org/10.1038/s41561-021-00780-7

Wilson, J. T. (1963). A possible origin of the Hawaiian Islands. *Canadian Journal of Physics*, *41*, 863–870. https://doi.org/10.1139/p63-094

Xue, M., & Allen, R. M. (2007). The fate of the juan de Fuca plate: Implications for a Yellowstone plume head. *Earth and Planetary Science Letters*, *264*, 266–276. https://doi.org/10.1016/j.epsl.2007.09.047

Zhong, S. (2006). Constraints on thermochemical convection of the mantle from plume heat flux, plume excess temperature and upper mantle temperature. *Journal of Geophysical Research*, *111*. https://doi.org/10.1029/2005JB003972