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Effect of Buoyant Sediment Overlying Subducting Plates on Trench Geometry: 3D Viscoelastic Free Subduction Modeling

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Abstract Buoyant trench sediment generates an isostatic restoring force that opposes the slab pull of subducting plates; however, the influence of this force on subduction dynamics is poorly understood. Here, we performed three-dimensional free subduction simulations adopting a variety of sediment distributions along a trench to investigate the correlation between trench motions and heterogeneous buoyant forces. Two endmembers, sediment-rich and sediment-starved centers, induced convex and concave trenches, respectively. The trench curvatures obtained from the natural subduction zones are well constrained by our models over wide magnitudes (1–9 km) and wavelengths (100–400 km) of deficient and excess sediments. Conversely, a uniform sediment distribution leads to an extremely narrow range of trench curvatures. These results imply that trench sediment contributes significantly to deviated curvatures along trench strikes. Finally, we observed stress localization at shallow slab hinges that lie beneath abundant sediments, clarifying the relationship between sediment thickness and subduction earthquakes.

Plain Language Summary The role of trench sediment in subduction dynamics as a lubricant or restoring force against denser oceanic crust remains controversial. Buoyant sediment induces a restoring force and variations in sediment thickness may lead to laterally complicated force balances. However, the effect of variations in sediment distribution along strikes on subduction dynamics is underexplored. We conducted three-dimensional free subduction modeling to analyze the factors that affect trench morphology and stress states within the subducting slab. Our results show that trench motion is strongly affected by differences in local isostatic restoring forces associated with sediment thickness variations. Locally thin trench sediment leads to a more rapid trench retreat and vice versa. The resultant differential trench motion along strike yields complicated trench shapes which exhibit a wide range of curvatures. By comparing the trench curvatures derived from our models to those obtained from natural subduction zones, we confirmed that the models with differential sediment distribution explained the patterns observed in major subduction zones. In contrast, models with uniform sediment thickness did not reflect natural trench curvature. Our study provides a fresh perspective on the trench shape of subduction zones (e.g., the Tonga-Kermadec) with highly variable along-strike sediment thickness.

1. Introduction

Trench curvatures in modern subduction zones are highly variable, indicating that the direction and velocity of trench motions are irregular along strikes. A global compilation of trench curvatures derived from hundreds of trench segments showed that the proportions of concave and convex trenches are approximately 70% and 30%, respectively (Schellart & Rawlinson, 2013). Based on hotspot reference frames (O’Neill et al., 2005) and geodetic studies (Chamot-Rooke & Le Pichon, 1999; Zellmer & Taylor, 2001), the rate of local trench retreat or advance deviates significantly from the overall average rate. To explain this variation in trench motion related to subduction dynamics, the various tectonic mechanisms, such as mantle toroidal flow (Schellart et al., 2007), the presence of oceanic plateau (Mason et al., 2010) or ridge (Martinod et al., 2005), plume impingement (Betts et al., 2012), age-dependent negative buoyancy and geometric stiffening due to the Earth’s sphericity (Mahadevan et al., 2010) have been suggested. However, the effects of sediment on trench motion are still poorly understood.
Previous studies have mainly focused on the capacity of trench sediment to act as a lubricant owing to the presence of pore water (Lamb & Davis, 2003), which can accelerate subduction rates (Behr & Becker, 2018), and increase b-values along the subduction interface (Schlaphorst et al., 2016). By contrast, the statistical correlation between subduction velocity and sediment thickness is slightly negative (Duarte et al., 2015). Other studies found that thick trench sediment with high and homogeneous friction properties promotes giant earthquakes (Olsen et al., 2020; Ruff, 1989) and decreases slab dip, thereby increasing the width of seismogenic zones (Brizzi et al., 2020). These discrepancies in understanding the rheological effects (i.e., frictional weakening vs. strengthening) of trench sediment highlight the need to consider another inherent property of buoyant sediment: Its relatively low density.

The sediment covering the subducting plates is characterized by the low density (i.e., 2,400–2,600 kg/m³; Malatesta et al., 2013), low mechanical strength (i.e., <1 MPa; Ikari & Kopf, 2011), and high pore-pressure (Meridith et al., 2017), which may promote the decoupling of the sediment from the subducting slab. However, geochemical (Chen et al., 2017) studies on intraplate volcanoes in East Asia have suggested that trench sediment can descend to the mantle transition zone (i.e., >410 km). Furthermore, geodynamic simulations (Currie et al., 2007) have shown that the trench sediment can be transported to a depth of 150 km by the subducting slab. Thus, the effects of sediment should be investigated at depths of at least several kilometers to elucidate subduction dynamics. The low density of sediment causes an isostatic restoring force that opposes the sinking of subducting plates (Buiter et al., 1998). Previous free subduction models applied an isostatic force to generate sequential plate descent from a trench by overcoming the bending moment of the oceanic lithosphere (Capitanio et al., 2007; Fourel et al., 2014; Funiciello et al., 2003). However, the effect of this differential isostatic restoring force along trench strike is difficult to analyze because the models employed did not account for the three-dimensional (3D) nature of the system. In this study, we performed 3D thermo-mechanical subduction modeling, adopting various sediment distributions. To quantify the effect of sediment on the trench shape, we compared the trench curvatures derived from our models and geophysical slab-geometry models (i.e., Slab 1.0 and 2.0; Hayes et al., 2012, 2018) with those measured at natural subduction zones.

2. Numerical Methods

We developed 3D viscoelastic free subduction models solely driven by a gravitational body force using a commercial finite element package, COMSOL Multiphysics®, to explore the differential buoyancy effect of variable sediment distribution on trench motion. The size of the subducting plate was 3,500 × 2,000 × 80 km in the X, Y, and Z directions, respectively (Figure 1). The meshes in the vicinity of the trench center (Y = 1,000 km) were refined to precisely measure the trench curvature. We assigned 25,000 linear hexahedron elements with different volumes, corresponding to approximately 1.5 million degrees of freedom around the trench center (70 × 13.3 × 10 km) and its edges (70 × 66.6 × 10 km). We solved a fully coupled system of momentum (Equation 1) and energy conservations (Equation 2) to obtain displacement and temperature, as follows:

\[
\frac{\partial \sigma_{ij}}{\partial x_j} = -\Delta \rho g, \text{ where } \Delta \rho = \left( \rho_L - \rho_m \right) \cdot \left( 1 - \alpha \left( T - T_0 \right) \right),
\]

\[
\frac{DT}{Dt} = \kappa \left( \frac{\partial^2 T}{\partial x_i \partial x_j} \right)
\]

where \(\sigma_{ij}, x_i, g, \) and \(T\) are the Cauchy’s stress tensor, spatial coordinate in the \(i\)th direction, gravity acceleration, and temperature, respectively; \(\rho_L\) and \(\rho_m\) are the reference densities of the oceanic lithosphere and mantle, respectively; \(\alpha\) is the thermal expansion coefficient; \(T_0\) is the reference temperature; \(t, \kappa,\) and \(D / Dt\) indicate the time, thermal diffusivity, and material time derivative, respectively. Detailed descriptions of the symbols and values are provided in Table S1. The constitutive relation for Maxwell viscoelastic material (e.g., So & Capitanio, 2017) is defined as follows:
The total deviatoric strain-rate tensor ($\dot{\varepsilon}_{ij}$) is the sum of the deviatoric elastic ($\dot{\varepsilon}^{\text{ela}}_{ij}$) and viscous ($\dot{\varepsilon}^{\text{vis}}_{ij}$) strain-rate tensors. $\tau_{ij}$, $G$, and $\eta_{\text{eff}}$ are the deviatoric stress tensor, shear modulus, and effective viscosity, respectively. The isostatic restoring force ($s_R = (\rho_m - \rho_s) g z$) was determined using the Winkler foundation, which consists of a parallel combination of Hookean springs at the top surface (Wu, 2004). The stiffness of the foundation is $K = (\rho_m - \rho_s) g$, where $\rho_m - \rho_s$ is the difference in density between the mantle and sediment. $s_R$ acts upward when the vertical displacement $z < H_i$ (Fourel et al., 2014). Previous two-dimensional free subduction models have widely adopted the Winkler foundation owing to its convenient parameterization of the isostatic restoring force (Capitanio et al., 2007; Funiciello et al., 2003).

We tested a total of 105 models, considering seven uniform sediment distributions, 49 sediment-starved center (SSC) conditions, and 49 sediment-rich center (SRC) conditions. The dashpot elements representing a viscous mantle of $10^{21}$ Pa s were attached to all boundaries. When the subducting plate reached a depth of 660 km, the viscosity of the dashpot increased by 100-fold owing to the mantle phase transition. Subduction initiation was implemented by imposing a downward force up to 150 km to overcome the bending moment of the oceanic lithosphere, after which the subduction system became self-sustaining.

We applied a composite rheological model with brittle strength, diffusion creep, and dislocation creep (e.g., Běhounková & Čížková, 2008). The effective viscosity ($\eta_{\text{eff}}$) was calculated using the minimum values of viscosity $\eta_b$, $\eta_{\text{diff}}$, and $\eta_{\text{disl}}$ (Equation 4). We set the viscosity threshold to $10^{18}$ Pa s to prevent unrealistic deformation.

$$\eta_{\text{eff}} = \min\left(\eta_b, \eta_{\text{diff}}, \eta_{\text{disl}}\right).$$

where $\eta_b = \frac{p \cdot \tan \phi + C}{2\varepsilon_{\text{ref}}} \cdot \eta_{\text{diff}} = \frac{1}{2A_{\text{diff}}} \cdot \exp\left(\frac{E_{\text{diff}} + pV_{\text{diff}}}{RT}\right)$, and

$$\eta_{\text{disl}} = \frac{1}{2A_{\text{disl}}} \cdot \tau_{\text{disl}}^{(1-n)} \cdot \exp\left(\frac{E_{\text{disl}} + pV_{\text{disl}}}{RT}\right).$$

Figure 1. Three-dimensional thermo-mechanical model setup. (a) Initial thermal structure of the half-space cooling model with 100 Ma and boundary conditions for modeling. $X = 3,500$ km and $X = 0$ km indicate 0 and 100 Ma, respectively. The black springs attached to the top surface indicate the boundary condition of the isostatic restoring force due to buoyant sediment. Viscous mantle drag exerted on all boundaries is represented by viscous dashpot elements. The red arrows indicate the imposed force, which acts over up to 150 km to initiate subduction. The boundary surface of $X = 3,500$ km is fixed in the $z$-direction. (b) Temperature profiles (dashed lines) and strength envelopes (solid lines) of the model correspond to $X$-coordinates of 500–3,000 km.
\( \tau_\text{II} \) and \( \dot{\varepsilon}_\text{ref} \) denote the second invariant of the deviatoric stress and the reference strain rate, respectively. The other parameters are listed in Table S1. The initial thermal structure of the oceanic lithosphere was based on a half-space cooling model of 100 Ma (Turcotte & Schubert, 2002). The mantle geothermal gradient was applied to the top and bottom boundary surfaces (Figure 1).

### 3. Results

Figure 2 shows the spatial distribution of \( \sigma_v \) (von Mises stress) for the three different sediment distribution scenarios. Figures 2a–2d show the evolution of the stress and morphology of the subducting slab under a uniform sediment distribution. Figures 2e–2h and 2i–2l depict the SSC and SRC scenarios, respectively. In all models, a stagnant slab formed over the lower mantle due to the viscosity jump at the phase boundary (660 km depth). In the uniform sediment scenario, we set the sediment to a thickness of 5 km based on the global marine sediment thickness (Straume et al., 2019). While oceanic lithosphere with uniform sediment thickness sinks into the viscous mantle, the viscous drag is weaker at the center of the trench than that at the two lateral edges, leading to a lateral difference in the amount of trench retreat and a weakly concave trench shape. The interaction between the negative slab buoyancy and sedimentary isostatic restoring force generates a bending stress concentration of 180 MPa in the upper hinge of the subducting slab. Viscous resistance...
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from the lower mantle led to the localization of bending stress (105 MPa). Figure 2e shows the SSC scenario, which has a 9 km difference in sediment thickness between the center and edge (i.e., \( \Delta s_H \)) and a wavelength of 400 km (i.e., \( W \)). The value of \( \sigma_v \) in the trench center (145 MPa) is lower than that at the trench edges (200 MPa), because the isostatic restoring force (\( s_R \)) affects materials to a shallower depth (1 km) in the center of the trench than it does at the edges (10 km). This indicates that the distribution of the trench sediment strongly affected the stress zonation within the subducting slab. In the SRC scenario with \( \Delta s_H \) = 9 km and \( W \) = 400 km, \( s_R \) is exerted to a deep depth (10 km) because of the thick sediment at the trench center, resulting in high bending stress at the center (see Figure 2j). The \( \sigma_v \) values at the center and edges were 191 and 136 MPa, respectively. Under greater along-strike differences in sediment thickness between the sediment-rich and -starved regions, stronger stress concentrations appeared. This intensive stress localization within the subducting slabs results from a highly differential along-strike restoring force.

To analyze the effects of \( \Delta H_r \) (3, 5, 7, and 9 km) and \( W \) (100, 200, 300, and 400 km) on trench shapes in both the SSC (solid lines in Figure 3) and SRC (dotted lines in Figure 3) scenarios, we measured the amount of trench retreat at time = 17.8 Myrs. We determined the convexity (solid lines in Figure 3) and concavity (dotted lines, in Figure 3) of trenches based on the subduction direction. All experiments in Figure 3 show highly variable extents of trench retreat depending on the sediment distribution characteristics. Centrally located convex and concave trenches clearly appeared in the SRC and SSC scenarios, respectively. Figure 3a shows the extent of trench retreat with different \( \Delta H_r \) values and \( W = 400 \) km. For convex trenches (solid lines in Figure 3a), the local minimum in the trench retreat occurs at the center, because \( R_s \) works to a deeper depth at the trench center compared to the edges. For example, the extent of trench retreat at the center is 2,370 km (solid purple line in Figure 3a) and 2,554 km (solid blue line in Figure 3a) when \( \Delta H_r \) = 9 and 3 km, respectively, while thin sediment cover at the trench center leads to a local maximum of trench retreat. In both the SRC and SSC scenarios, trenches were more strongly convex and concave with increasing \( \Delta H_r \) values (Figure 3a). We also tested the effect of heterogeneous sediment wavelengths (\( W \)) on the trench

Figure 3. Amount of trench retreat with different wavelengths (i.e., \( W = 100–400 \) km) and degree of sediment heterogeneity (\( \Delta s_H = 3–9 \) km) in the sediment-rich center (SRC) and sediment-starved center (SSC) scenarios at time = 17.8 Myrs. Red arrows indicate the subduction direction. (a) The extent of trench retreat with fixed \( W = 400 \) km and different \( \Delta H_r \) values in the SRC (solid lines in Figure 3b) and SSC (dashed lines in Figure 3c) scenarios. (d) Trench retreat with fixed \( \Delta H_r \) = 9 km and different \( W \) in SRC (solid lines in Figure 3e) and SSC (dashed lines in Figure 3f) scenarios.
geometry (Figure 3d). We varied $W$ between 100 and 400 km with a fixed $\Delta H$, value of 9 km for the SRC and SSC scenarios. In the SRC scenarios (Figure 3e), the central trench retreat decreased with increasing $W$ (solid lines in Figure 3d). While in the SSC scenarios, larger $W$ values were associated with a greater amount of trench retreat in the center. These results indicate that a lateral differential in the sediment thickness induces variable trench motion along strike.

Moreover, the along-strike differences between local maximum and minimum trench retreats (i.e., tens to hundreds of kilometers) are similar to those found by studies that applied widely accepted mechanisms (i.e., age-differential negative buoyancy, toroidal flow, oceanic plateau, ridge, and plume impingement). Furthermore, we quantitatively evaluated the effect of age-dependent negative buoyancy and buoyant sediment on trench motion using sensitivity tests (Figures S3–S8). We confirmed that the effect of the lithospheric age along the strike was weaker than that of the buoyant sediment. This means that along-strike sediments variation should be considered when modeling trench morphology.

Parametric calculations were performed over a wide range of $\Delta H$, and $W$ values to measure the trench curvature ($T_c$) at the center (see Figures 4a and 4b). $T_c$ values were evaluated using a simple differential geometry (Equation S1). Positive and negative $T_c$ values indicate convex and concave trenches, respectively. To compare the magnitude of $T_c$ between concave (Figure 4a) and convex (Figure 4b) trenches, we plotted $|T_c|$ at time $= 17.8$ Myrs on a map, using each of the 49 numerical models from the SRC and SSC scenarios. In both the scenarios, the $|T_c|$ pattern showed a positive correlation with the $\Delta H$, and $W$ values. This correlation indicates that greater variations in sediment thickness (i.e., larger $\Delta H$, and larger wavelengths (i.e., larger $W$) along trench strike induce more prominent surface expressions. The solid contours in Figures 4a and 4b denote the total area covered by the trench-filling sediment, which is an integrated value of sediment thickness along strike. Even when identical total amounts of trench sediment are present, the trench shapes represented by $|T_c|$ are diverse and reflect local differences in sediment distribution (compare insets in Figures 4a and 4b).

$|T_c|$ values of the nine major subduction zones were determined using the Slab 1.0 (Hayes et al., 2012) and 2.0 models (Hayes et al., 2018) (Figure 4c). To precisely calculate the trench curvature, we excluded subduction zones with widths $< 500$ km due to the small number of data points from these types of subduction zones. Trench traces were rotated to fix the subduction direction along the positive vertical axis (black arrow in Figure 4c). We then plotted the $|T_c|$ values from the modern subduction zones in Figure 4d. The red shaded area refers to the range of $|T_c|$ ($-1.8 \times 10^{-3}$ to $2.12 \times 10^{-3}$ km$^{-1}$) values calculated from 105 numerical runs, including homogeneous sediment scenarios with thicknesses of 3–9 km. Most trench shapes in modern subduction zones are broadly concave due to Earth’s sphericity (Frank, 1968). However, we confirmed that the trench curvatures derived from natural subduction zones repeatedly show local concavity and convexity, which is also supported by a global compilation study indicating the similar frequencies of convex (~30%) and concave (~70%) trenches (Schellart & Rawlinson, 2013). We also found that the $|T_c|$ values derived from our models included the local maximum and minimum $|T_c|$ values of modern subduction zones. The narrow blue-shaded area demonstrates nearly flat trenches and indicates the range of $|T_c|$ values ($-0.13 \times 10^{-3}$ to $-0.24 \times 10^{-3}$ km$^{-1}$), calculated from numerical models with a uniform sediment thickness (3–9 km; see Figure S2). The narrow range of $|T_c|$ under this scenario poorly explains the wide range of modern trench curvatures ($-1.86 \times 10^{-3}$ to $1.76 \times 10^{-3}$ km$^{-1}$).

4. Discussion

Our 3D models with uniform trench sediment thickness (3–9 km) consistently yielded nearly flat trenches with low curvatures. We found that the differential isostatic restoring force due to strike-dependent trench-sediment distribution amplified trench curvature, which implies that detailed sediment distributions should be considered to constrain the highly variable trench motion of natural subduction zones. However, most 3D free subduction models considered only uniform trench sediment distribution (e.g., Li et al., 2013; Malatesta et al., 2013), even though geophysical surveys have revealed that sediment thickness varies in mature and incipient subduction trenches (Straume et al., 2019). It has been proposed that buoyant local tectonic structures in the oceanic lithosphere strongly affect trench kinematics and morphology (Martinod et al., 2005; Mason et al., 2010). However, our numerical simulation showed that sediment, which is more fundamental and com-
than other short-wavelength features (e.g., oceanic ridges and plateaus), can modulate the buoyancy of natural subduction systems. Furthermore, we found that the contributions from the mechanisms previously proposed to modulate trench motion are similar to or even weaker than those of our models that contain differential buoyant sediment. Thus, we suggest that buoyant anomalies at various spatial scales (both short and long wavelengths) should be jointly considered in the analyses of trench motion.

Our study demonstrates a strong correlation between stress levels and sediment-rich regions, which has implications for seismicity in subduction zones. Typical faulting in subduction zones is attributed to bending stress (Herman & Govers, 2020), which can be controlled by the buoyancy of the sediment. Our results are also supported by a statistical analysis using massive geophysical data (Schellart & Rawlinson, 2013), suggesting a positive correlation between trench sediment thickness and earthquake magnitude (i.e., a

Figure 4. The calculated $|T_c|$ (absolute trench curvature) values at the center of concave (a) and convex (b) trenches, respectively, from each of the 49 runs of the SSC and SRC models with a wide range of $W$ and $\Delta H_s$ values. The free subduction models shown in the insets correspond to the rectangular symbols indicating the same amount of sediment. The black lines in the insets indicate trench traces. (c) Trench traces extracted from Slab 1.0 and 2.0 models of nine major subduction zones (see inset); Al—Aleutians, Ca—Cascadia, IBM—Izu-Bonin-Mariana, Ke—Kermadec, Ku—Kuril, MA—Middle-America, PC—Peru-Chile, Ry—Ryukyu, and Su—Sumatra. (d) Comparison between trench curvature derived from our models (red shaded area) and those obtained from natural subduction zones (colored lines). Positive and negative $|T_c|$ values indicate convex and concave shapes, respectively. The narrow blue-shaded area in the inset represents $|T_c|$ values derived from numerical models with uniform sediment distribution.
proxy of plate interface strength). A highly differential stress level along a trench, attributable to differential sediment distribution, may change the pressure within a slab. The bending stress and subsequent extensional regime along the upper hinge of the subducting slab are thought to generate tectonic underpressure (Gerya, 2015; So & Yuen, 2015), which causes volatile fluid to percolate into a subducting slab (Faccenda et al., 2009). A detailed simulation using our model and a given sediment distribution could estimate the spatial distribution of tectonic under/overpressure, thus providing insight into the locations of intermediate earthquakes and volcanoes in the arc and back-arc systems.

Whether the lubrication or buoyancy of the trench sediment plays a dominant role at the plate interface remains unresolved. Abundant sediment lubrication along the subduction interface increases the plate velocity (Behr & Becker, 2018) by reducing friction. Furthermore, Brizzi et al. (2020) recently showed that interfaces that are well lubricated by thicker trench sediment experienced faster trench retreat rates. In contrast, our models that focused on buoyant trench sediment indicated that thicker sediment leads to slower trench retreat. It is well known that the trench motion of the Tonga-Kermadec subduction zone is controlled by complicated mechanisms, such as a slab dragging (van de Lagemaat et al., 2018) and the strongly coupled interplay between the oceanic plateau, subducting slab, and mantle plume (Chang et al., 2016). However, previous models for the Tonga-Kermadec subduction zone did not consider a widespread buoyant feature (i.e., sediment). The sediment distribution along the Tong-Kermadec trench is highly variable between the sediment-starved northern (~16°S) and the sediment-rich southern (~34°S) regions, which is supported by global marine sediment data (Straume et al., 2019). The trench retreat velocity of the Tonga-Kermadec subduction zone dramatically decreases from the northern (15.8 cm/yr) to southern (0.9 cm/yr) regions (Schellart et al., 2007). We propose that the apparent negative correlation between trench retreat and sediment thickness in our numerical results could aid the understanding of the trench motion in the Tonga-Kermadec subduction system. Therefore, validating the effect of sediment buoyancy on trench motion requires consideration of this interaction and a four-dimensional free subduction model that includes time-dependent information such as plate reconstruction and paleo-sediment deposition systems.

5. Conclusions

We modeled 3D free subduction with various trench-sediment distributions to analyze the effect of the isostatic restoring force on the trench shape and internal deformation. Thin and thick trench sediment generated relatively low and high effective isostatic restoring forces, respectively, leading to large and small amounts of trench retreat. Consequently, the differential sediment thickness along strike caused different trench shapes (i.e., concave and convex). We confirmed that the range of trench curvature (~2 × 10\(^{-3}\) to 2 × 10\(^{-3}\) km\(^{-1}\)) obtained from our numerical simulations adopting heterogeneous sediment distribution was consistent with that of natural trench curvatures. We also found that numerical models with uniform sediment thickness yielded very low trench curvatures compared to those measured in modern subduction zones. Thus, we propose that local variations in sediment distribution affect the trench shape. Because the location and intensity of stress concentration within the subducting slab are determined by the distribution and magnitude of the effective isostatic restoring force, we argue that the role of trench sediment in subduction dynamics should be considered in terms of not only lubrication but also buoyancy.

Data Availability Statement

Model inputs and visualized outputs in our numerical simulation are available for download through the following link: https://zenodo.org/record/4299319. The authors adopted Paraview for 3D visualization of the data on numerical simulation (https://paraview.org/).

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