Impact of decreasing trench depth during aseismic ridge subduction on the forearc stress state: Insights from analytical and finite-element force-balance models

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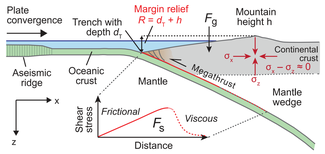
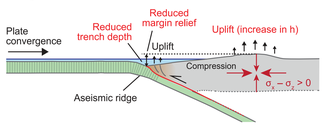
Introduction

Undisturbed subduction



F_s	Megathrust shear force	h	Mountain height
F_g	Gravitational force	d_T	Trench depth
σ_x	Horizontal stress	R	Margin relief
σ_z	Vertical stress		

Ridge subduction



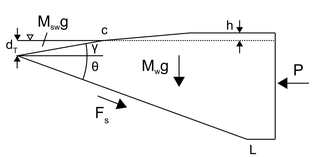
- The subduction of aseismic oceanic ridges at convergent plate margins causes a reduction in submarine relief, which alters the balance of topographic and tectonic stresses
- This stress change increases the compression of the upper plate and may hence be relevant for understanding surface uplift and mountain building in response to ridge subduction (e.g., Zeumann & Hampel, 2015)
- We use analytical force-balance (Dielforder et al., 2020) and 2-D finite-element models (Dielforder & Hampel 2021) to quantify stress changes in the upper plate due to ridge subduction
- Based on the parameter study, we investigate the effects of ridge subduction and submarine relief changes on mountain building in Costa Rica (Central America)

Highlights

- **We model stress changes due to a decrease in trench depth during ridge subduction**
- **The stress changes promote surface uplift in the upper plate of 10^2 – 10^3 m**
- **We apply our results to the subduction of the Cocos Ridge beneath Costa Rica**
- **Trench-depth reduction caused considerable uplift and shortening in Costa Rica**

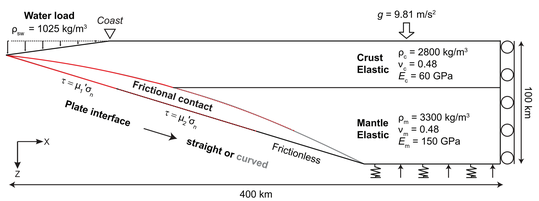
Methods

Analytical force-balance model



- A decrease in trench depth alters the weight of the wedge (M_wg) and the weight of seawater ($M_{sw}g$), which causes an adjustment in force balance
- The adjustment in force balance involves a stress change $\Delta\sigma_x$, which can be quantified with the anlytical model assuming that the shear force F_s remains constant

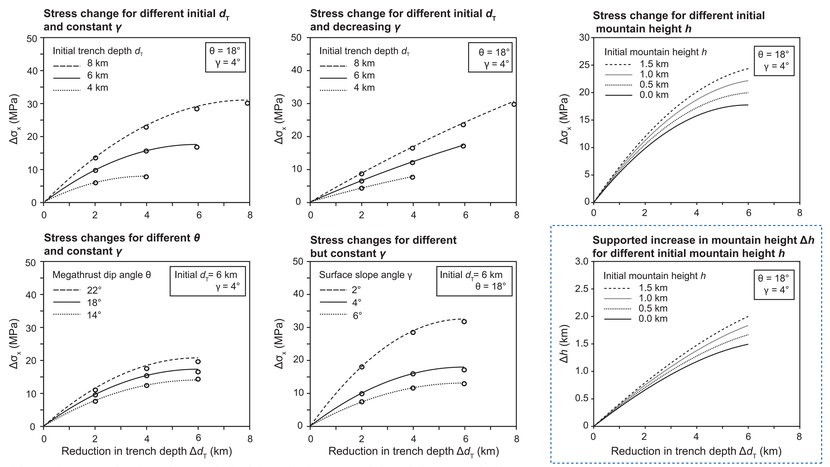
Numerical force-balance model



- The numerical model yields the total stresses in the forearc resulting from the applied forces and boundary conditions
- The numerical model comprises an elastic upper plate and a straight or curved rigid lower plate
- The numerical model is created with the commercial finite-elelment software ABAQUS (version 2023)

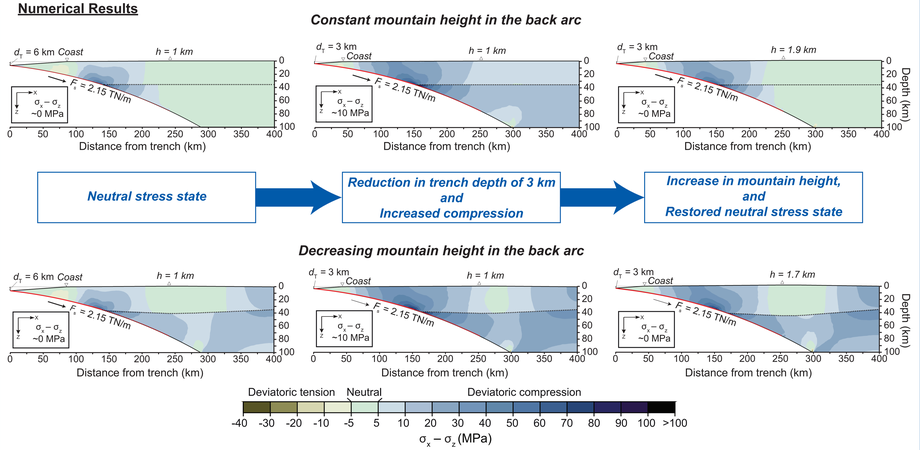
Results: General Models

Analytical Results



▲ *Lines show results from the analytical force-balance models, while open circles represent results from numerical models designed to match the boundary conditions and geometry of the analytical models. Overall, the analytical and numerical results are in good agreement.*

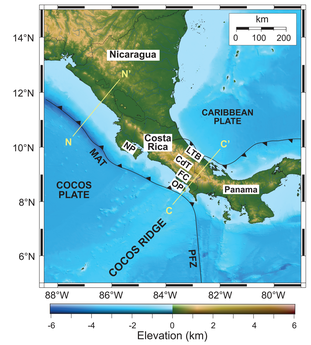
Numerical Results



▲ ***The numerical models enable investigation of parameters not captured by the analytical model, including a more complex upper plate structure and a curved plate interface. The results indicate the stress σ_x- σ_z in the upper plate resulting from a 3 km reduction in trench depth, as well as the corresponding increase in mountain height for two different model configurations***

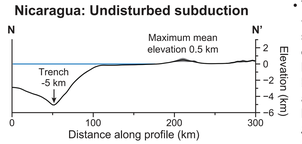
Results: Central America

Tectono-topographic setting of Central America



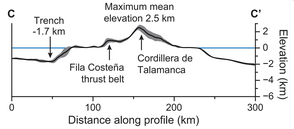
▲ *OP - Osa Peninsula, FC - Fila Costeña thrust belt, CdT - Codillera de Talamanca, LTB - Limón thrust belt, NP - Nicoya Peninsula. Topography from the SRTM 15+ digital elevation model (Tozer et al., 2019)*

yellow line N-N'



- The aseismic Cocos Ridge rises ~2 km above the surrounding seafloor and has a thickened oceanic crust of ~15–20 km (Sallarès et al., 2003). It subducts beneath the Caribbean Plate at a rate of ~91 mm/yr, apprimxately perpendicular to the Middle American trench (DeMets et al., 1994)

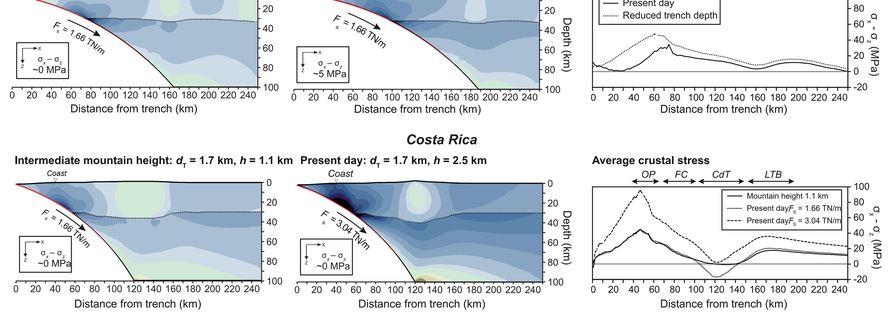
yellow line C-C'



- Subduction of the Cocos Ridge leads to significant surface uplift and deformation in the overriding plate, particularly in the Cordillera de Talamanca (Gräfe et al., 2002; Morell et al, 2012).

▲ *Mean elevation (solid black line) ± one standard deviation (grey shading) calculated from the ETOPO1 global relief model using TopoToolbox for MATLAB (Schwanghart and Scherler, 2014)*

Numerical model results for Nicaragua and Costa Rica



▲ *Share the same color scale as the left panels*

▲ *The slab geometry is approximated by fitting an arc with constant curvature through the upper 60 km of the Slab2 model (Hayes et al., 2018).*

- The model results indicate that a megathrust shear force of 1.66 TN/m, as constrained for Nicaragua, together with a reduction in trench depth of ~3.3 km due to Cocos Ridge subduction, can support a maximum mean elevation of 1.1 km in Costa Rica, corresponding to an uplift of ~600 m
- For a megathrust shear force of 1.66 TN/m, the crust beneath the Cordillera de Talamanca would experience deviatoric tension of ~17 MPa and tend to extend. Supporting the Cordillera at a maximum mean elevation of 2.5 km requires an increase in the megathrust shear force to 3.04 TN/m
- Taken together, the decrease in trench depth explains about one third of the inferred uplift in Costa Rica. The remaining uplift may be attributed to uplift directly above the indenting ridge (Zeumann and Hampel, 2017) and/or an increase in shear stress along the plate interface during ridge subduction

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