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Supporting Information for

Downgoing plate-buoyancy driven retreat of North Sulawesi Trench: transition of a passive margin into a subduction zone

Miao Dong[1,2]*, Tianyao Hao[1, 2]*, Chuanchuan Lü[3], Jian Zhang[2]

1 Key Laboratory of Petroleum Resource Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029

2 University of Chinese Academy of Sciences, Beijing, 100049

3 Bullard Labs, Department of Earth Sciences, University of Cambridge, Cambridge CB3 0EZ UK

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Introduction

Text S1 summarizes basic equations of the numerical simulations and initial model domain and thermal configurations.

Tables S1 list parameters used in the numerical simulations.

Figure S1 shows how to simplified the 3-D situation to 2-D model.

Text S1.

We use the Advanced Solver for Problems in Earth's Convection (ASPECT)(Bangerth et al., 2020; Heister et al., 2017; Kronbichler et al., 2012), which is a highly scalable open-source code, to develop a 2D numerical geodynamic model. The model solves the momentum, mass conservation and heat conservation equations:

$$-\nabla \cdot 2\eta\dot{\varepsilon} + \nabla P = \rho g, \quad (1)$$

$$\nabla \cdot v = 0, \quad (2)$$

$$\rho C_P \left(\frac{\partial T}{\partial t} + v \cdot \nabla T\right) - k\nabla^2 T = H, \quad (3)$$

where η is the effective viscosity (see equations (4)–(6)), $\dot{\varepsilon}$ is the deviatoric strain rate tensor, which is given by $\frac{1}{2}\left(\nabla v + (\nabla v)^T\right)$, P is the pressure, ρ is the density, which is defined as $\rho = \rho_0\left(1 - \alpha(T - T_0)\right)$ with T_0 being the reference temperature, g is the gravitational acceleration, v is the velocity, C_P is the specific heat capacity, T is the temperature, t is time, k is the thermal conductivity, and H is the volumetric heat source term that includes radiogenic heat, shear heating, and adiabatic heating.

We use the Drucker–Prager yield criterion and a visco-plastic rheology(Glerum et al., 2018) with dislocation and diffusion creep, which are incorporated into ASPECT in 2D via the following equations:

$$\eta_{comp} = \left(\frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}}\right)^{-1}, \qquad (4)$$

$$\eta_{diff} = \frac{1}{2}A^{-1}d^{m}\exp\left(\frac{E_{diff}+PV_{diff}}{RT}\right), \qquad (5)$$

$$\eta_{disl} = \frac{1}{2}A^{\frac{1}{n}}\left(\dot{\varepsilon}_{II}\right)^{\frac{1-n}{n}}\exp\left(\frac{E_{disl}+PV_{disl}}{nRT}\right), \qquad (6)$$

where η_{comp} is the composite viscosity, η_{diff} is the diffusion creep, η_{disl} is the dislocation creep, A is the pre-exponential factor, n and m are stress and grain size exponents, $\dot{\varepsilon}_{II}$ is the second invariant of the strain rate tensor, which is defined as $\dot{\varepsilon}_{II} = \left(0.5\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}\right)^{0.5}$, E is the activation energy, V is the activation volume, R is the gas constant. These parameters are determined from the flow law experiments (Table S1).

Frictional-plastic deformation is responsible for faulting and follows a pressure-dependent Drucker–Prager yield criterion:

$$\sigma_{yeild} = C_0\cos\varphi + P\sin\varphi, \qquad (7)$$

$$\eta_{Drucker-Prager} = \begin{cases} \eta_{comp}, & 2\eta_{comp}\dot{\varepsilon}_{II} < \sigma_{yeild} \\ \frac{\sigma_{yeild}}{2\dot{\varepsilon}_{II}}, & 2\eta_{comp}\dot{\varepsilon}_{II} > \sigma_{yeild} \end{cases}, \qquad (8)$$

where σ_{yield} is the yield stress, C_0 is the cohesion, and φ is the angle of internal friction. The final effective viscosity, $\eta_{Drucker-Prager}$, is capped by minimum and maximum viscosities. Table S1 shows the parameters that we use.

The initial 2D model domain is 2,000 km by 670 km (Figure. 2a), with adaptive mesh refinement for finite elements with large gradients in the viscosity, temperature, and composition. The adaptive mesh refinement parameters in our reference model produce a maximum level of refinement corresponding to 1-km-wide finite element dimensions (in the lithosphere layer) and a minimum level of refinement corresponding to 64-km finite elements (in the lowermost mantle).

An initial internal free surface is simulated with a layer of sticky air on the top of the model and is 10 km thick. The overriding plate is simulated as a continental plate with an upper continental crust, lower continental crust, and an underlying lithospheric mantle with thicknesses of 30, 35, 40, 45, and 50 km, respectively. The subducted plate incorporates oceanic crust, which is 10 km thick, and the oceanic lithosphere, which has a thickness that is determined by the half-space cooling model (Turcotte and Schubert, 2014). The model is initiated with a weak zone between the subducted and overriding plates, which represents the pre-existing subduction interface. The angle between subducted and overriding plates is set to 15°, 30°, 45° and 60°, respectively.

The thermal structure of the initial model is as follows: the oceanic lithosphere geotherm corresponds to a half-space cooling model for a seafloor age of 40 Ma, the continental lithosphere varies from 0 to 1300 °C, which is calculated by solving the steady state heat conduction equation. The temperature gradient in the asthenospheric mantle is about 0.5 °C/km, and the upper and lower thermal boundaries are fixed.

Table S1. Physical properties of materials used in the numerical experiments (Hirth and Kohlstedt, 2003; Rutter and Brodie, 2004; Rybacki et al., 2006). Density values of asthenosphere and continental lithospheric mantle (ρ) are set according to the model.

Parameters	Units	Asthenosphere	Air	Upper continental crust	Lower continental crust	continental Lithospheric mantle	Upper Oceanic crust	Lower Oceanic crust	Weak zone
thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$	3.3	82.5	2.5	2.5	3.3	2.5	2.5	3.3
specific heat capacity	$J\cdot kg^{-1}\cdot K^{-1}$	1000	1000	1000	1000	1000	1000	1000	1000
Density	$kg\cdot m^{-3}$	3300	1	2700	2838	ρ	3000~3450	3000~3450	3300
Thermal expansivity	K^{-1}	2×10^{-5}	0	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}
Rheological Flow	-	Dry olivine		Wet quartzite	Wet anorthite	Dry olivine	Gabbro	Gabbro	Wet olivine
pre-exponential factor	$Pa^{-n}\cdot m^{-p}\cdot s^{-1}$	2.37×10^{-15} 6.52×10^{-16}	1×10^{-50} 5×10^{-19}	1×10^{-50} 8.57×10^{-28}	1×10^{-50} 7.13×10^{-18}	2.37×10^{-15} 6.52×10^{-16}	1×10^{-50} 2.2553×10^{-17}	1×10^{-50} 1.3725×10^{-25}	1×10^{-50} 2.03×10^{-15}
Stress exponents	-	1 3.5	1 1	1 4.0	1 3	1 3.5	1 2.3	1 4.7	1 3.5
activation energy	$J\cdot mol^{-1}$	375×10^{3} 530×10^{3}	0 0	0 223×10^{3}	0 345×10^{3}	375×10^{3} 530×10^{3}	0 154×10^{3}	335×10^{3} 485×10^{3}	0 497×10^{3}
activation volume	$m^{3}\cdot mol^{-1}$	4×10^{-6} 13×10^{-6}	0 0	0 0	0 0	4×10^{-6} 18×10^{-6}	0 0	4×10^{-6} 0	4×10^{-6} 18×10^{-6}
grain size exponents	-	3	0	1	1	3	0	0	1

Figure S1. Slab2 model for Celebes Sea and Sangihe slab