

*[Frontiers in Earth Science]*

Supporting Information for

**Overriding lithospheric strength affects continental collisional mode selection and subduction transference: Implications for Greater India-Asia convergent system**

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**Introduction**

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Figure S2 shows the time-dependent evolution of the averaged overriding crustal thickness during collision for 55 Myrs, with variable plastic friction coefficient of overriding lithospheric mantle.

Text S1.

The numerical models are conducted using the code I2VIS, which combines the 2D finite-difference and the marker-in-cell methods (Gerya, 2010). The basic equations of the numerical model are briefly described here; and please refer to Li et al. (2019) for details.

**1 Governing equations**

The fundamental equations of the numerical model include conservation equations of mass, momentum and energy, as well as the constitutive relationships.

**1.1 Stokes equation**

(i, j = 1, 2) (1)

Where is the deviatoric stress tensor, the spatial coordinate, and *g* the gravitational acceleration. The density *ρ* depends on composition *C*, dynamic pressure *P* and temperature *T*. The density for a specific rock type is set to be:

(2)

Where is the density under the reference condition with =0.1 MPa and =298 K. and are the thermal expansion coefficient and the compressibility coefficient, respectively.

**1.2 Conservation of mass**

The mass conservation is approximated by the incompressible continuity equation:

(3)

**1.3 Energy equation**

(4)

(5)

(6)

(7)

Where is the effective isobaric heat capacity, *DT/Dt* the substantive time derivative of temperature, *q* the thermal heat flux; and *k* is the thermal conductivity, dependent on composition *C*, pressure *P* and temperature *T*. *H* represents all the sources of heat generations, including radioactive heat production (*Hr*), adiabatic heating (*Ha*) and shear heating (*Hs*).

**2 Constitutive relationships**

In the numerical model, the constitutive relationship is combined with visco-plastic-Peierls flow laws (Li et al., 2019).

**2.1 Viscous flow law**

Two different flow laws are applied for the crustal (Ranalli, 1995) and mantle rocks (Karato and Wu, 1993), respectively.

For the crustal rocks (the continental and oceanic crust) follow the flow laws of Ranalli (1995):

(8)

Where is the pre-exponential factor, the second invariant of the strain rate tensor, *E* the activation energy, *V* activation volume, *R* the gas constant and *n* the creep exponent.

For mantle rocks, the viscosity is defined according to Karato and Wu (1993), integrating both diffusion and dislocation creeps:

(9)

Where is the pre-exponential factor, *u* the shear modulus (*u* = 80 GPa), *d* the grain size (*d* = 1 mm), *b* the length of Burgers vector (*b* = 0.5 nm), *m* the grain size exponent, *E* the activation energy, *V* the activation volume and *n* the creep exponent.

**2.2 Plastic rheology**

The extended Drucker-Prager yield criterion (e.g., Ranallli, 1995) is applied as follows:

(10)

(11)

Where is the yield stress, *P* the dynamic pressure, the residual rock strength at *P* = 0; and is the effective internal friction coefficient, which includes the possible fluid effects that control the brittle strength of fluid containing porous or fractured media (e.g., Gerya and Meilick, 2011; Li et al., 2016). Strain weakening effect is included in the plastic rheology in some of the numerical models.

**2.3 Peierls mechanism**

The Peierls mechanism is also implemented to the model by (e.g., Kameyama et al., 1999; Karato et al., 2001):

(12)

Where is the second invariant of stress tensor, the limitation of stress on the material; and , *p* and *q* are experimentally derived material constants.

**2.4 Effective viscosity**

The integrated viscosity of ductile, plastic and Peierls is the minimum value of them (Ranalli, 1995).

(13)

**3. Dehydration and water migration**

Water plays significant roles in the subduction processes, which is thus included in the current numerical models in the forms of both connate water and mineral water. The connate water, present in sediment and oceanic upper crustal basalt, makes up to 1.0 wt% at the surface and decreases to zero at 25 km (Connolly, 2005; Gerya and Meilick, 2011):

(14)

Where is the depth below the surface (0-25 km); and is the connate water content at the surface (1.0 wt%). For the other rock types, e.g., oceanic lower crust, continental crust and mantle, the connate water content is assumed to be negligible.

For the mineral water, the water capacity is computed with Perple\_X (Connolly, 2005, 2009) for four typical rock types in the subduction models, i.e. sediment, basalt (oceanic upper crust), gabbro (oceanic lower crust) and hydrated mantle. The *P-T* range for the water capacity of sediment is *Pmax* = 7 GPa and *Tmax* = 1500 °C, since the sediment generally cannot be subducted to deeper mantle. In contrast, the water capacities in oceanic crust (basalt, gabbro) and mantle are computed with pressures up to 30 GPa, i.e. a depth in the lower mantle, which thus allow the simulation of water activity in the whole upper mantle including the MTZ, and even to the topmost lower mantle (Li et al*.*, 2019).

Expelled water is stored in newly generated water tracers that move independently, with the velocity calculated as:

(15)

Where is the fluid velocity, the local velocity of solid rock, *A* a water percolation constant with a presumed standard value of = 10 cm/yr (e.g., Peacock, 1990; Gorczyk et al., 2007); and = 9.81 m/s2 is the vertical gravitational acceleration component. When a moving water tracer meets a lithology capable of absorbing water by hydration or partial melting reactions at given *P-T* conditions and rock composition, the water will be consumed.

**4 Phase transition and density structure**

The phase transitions at 410 km and 660 km discontinuities are included in the numerical models with detailed implementation strategies shown in Li et al. (2019).

The phase transitions modify the mantle density structure with the gradual pressure and temperature dependence (Equation 2). In the current study, these phase transitions are only affecting the density, whereas the related variations of latent heat and possible viscosity change are not considered (Li et al., 2019). The resulting density structure of the mantle is consistent with the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981). The Clapeyron slopes of 3.0 MPa/K and -1.0 MPa/K are applied for the 410 km and 660 km discontinuities, respectively. Two additional phase transitions are also included, i.e. the oceanic crustal eclogitization (Ito and Kennedy, 1971, 2013) and the metastable olivine in the MTZ (Rubie and Ross, 1994), which could both influence the density structure of the subducting slab and are thus included following Li et al. (2019).

**Table S1.** Viscous flow laws used in the numerical experiments

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ID symbol | Flow laws |  |  | n |  | m |  |
| A | Wet quartzite | 154 | 8 | 2.3 |  | - | - |
| B | Plagioclase | 238 | 8 | 3.2 |  | - | - |
| C | Mafic granulite | 445 | 12 | 4.2 |  | - | - |
| D | Dislocation creep of dry olivine | 540 | 13 | 3.5 | - | 0.0 |  |
| E | Diffusion creep of dry olivine | 300 | 4 | 1.0 | - | 2.5 |  |
| F | Dislocation creep of wet olivine | 430 | 10 | 3.0 | - | 0.0 |  |
| G | Diffusion creep of wet olivine | 240 | 4 | 1.0 | - | 2.5 |  |

References: Kirby, 1983; Kirby and Kronenberg, 1987; Ranalli and Murphy, 1987; Ji and Zhao, 1993; Ranalli, 1995; Karato and Wu, 1993.

**Table S2.** Material properties used in the numerical experiments

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Section |  |  | |  |  |  | (μW) | Viscous Flow | | Plastic  (Mpa) | | Plastic |
| All plates | Sticky air (1) | 1 | 0 | | 0 | 200 | 0 |  | 0 | | - | |
| Sticky water (2) | 1000 | 0 | | 0 | 200 | 0 |  | 0 | | - | |
| Sediments (3, 4) | 2600 |  | |  |  | 2 | A | 10 | | 0.1-0.05 | |
| Weak zone mantle (15) | 3300 |  | |  |  | 0.022 | F + G | 1 | | 0.1 | |
| Asthenosphere (14) | 3300 |  | |  |  | 0.022 | D + E | 10 | | 0.6-0.1 | |
| Oceanic Plate | Upper crust (7) | 3000 |  | |  |  | 0.25 | A | 10 | | 0.1-0.05 | |
| Lower crust (8) | 3000 |  | |  |  | 0.25 | B | 10 | | 0.6-0.1 | |
| Lithospheric mantle (12) | 3300 |  | |  |  | 0.022 | D + E | 10 | | 0.6-0.1 | |
| Drifting continental plate | Upper crust (5) | 2700 |  | |  |  | 1 | A | 10 | | 0.1-0.05 | |
| Lower crust (6) | 2900 |  | |  |  | 1 | C | 10 | | 0.1-0.05 | |
| Lithospheric mantle (11) | 3275 |  | |  |  | 0.022 | D + E | 10 | | 0.6-0.1 | |
| Overriding continental plate | Upper crust (9) | 2700 |  | |  |  | 1 | A | 10 | | 0.1-0.05 | |
| Lower crust (10) | 2900 |  | |  |  | 1 | B | 10 | | 0.1-0.05 | |
| Lithospheric mantle (13) | 3300 |  | |  |  | 0.022 | F + G | 10 | |  | |
|  | - | 1, 2 | 4 | | 4 | 3 | 1 | 4 | 5 | | 5 | |

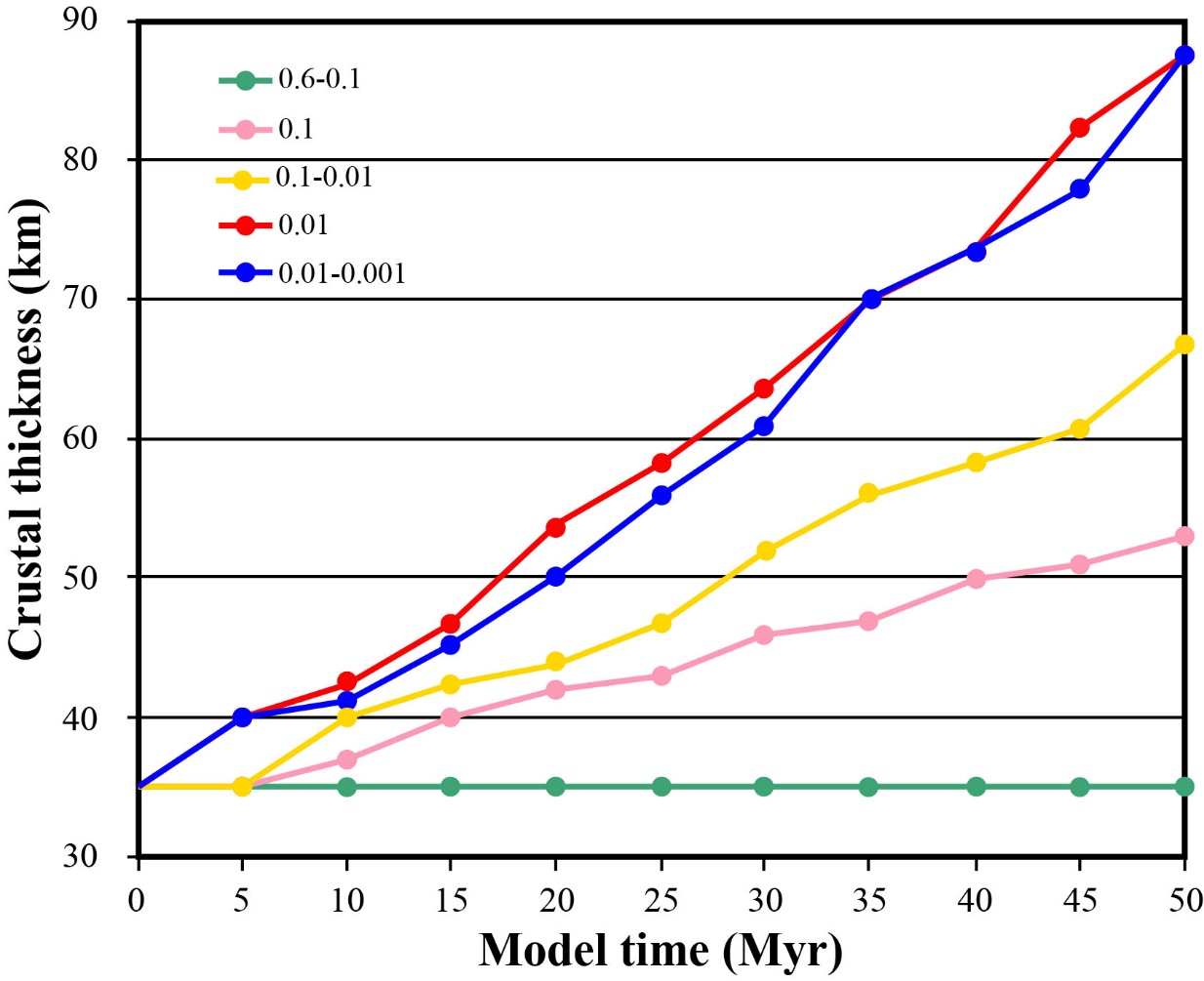
a Numbers of materials corresponding to Figure 2.

b; ; .

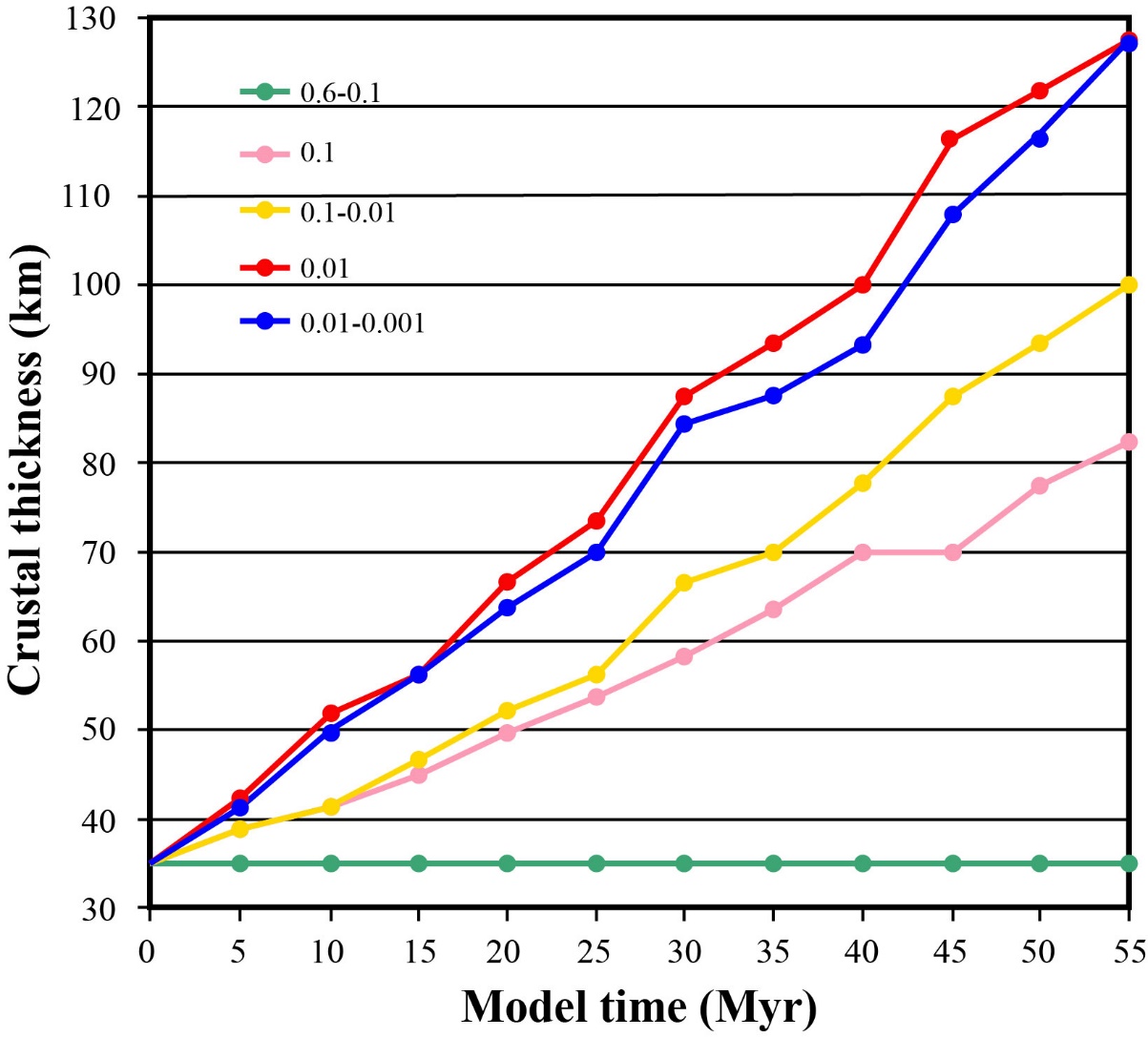
c Parameters of viscous flow laws are shown in Table S1

d The plastic yielding strength of overriding lithospheric mantle is varied in this study.

e Reference: 1. Turcotte and Schubert, 2002; 2. Bittner and Schmeling, 1995; 3. Clauser and Huenges, 1995; 4. Ranalli, 1995; 5. Li et al., 2019.



**Figure S1.** Time-dependent evolution of the averaged overriding crustal thickness for the first group of models with continental collision for ~50 Myrs. The colored lines represent the models with different plastic friction coefficients of overriding lithospheric mantle as shown in the figure.



**Figure S2.** Time-dependent evolution of the averaged overriding crustal thickness for the second group of models with continental collision for ~55 Myrs. The colored lines represent the models with different plastic friction coefficients of overriding lithospheric mantle as shown in the figure.

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