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Continental underplating after slab break-off

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ABSTRACT

We present three-dimensional numerical models to investigate the dynamics of continental collision, and in particular what happens to the subducted continental lithosphere after oceanic slab break-off. We find that in some scenarios the subducting continental lithosphere underthrusts the overriding plate not immediately after it enters the trench, but after oceanic slab break-off. In this case, the continental plate first subducts with a steep angle and then, after the slab breaks off at depth, it rises back towards the surface and flattens below the overriding plate, forming a thick horizontal layer of continental crust that extends for about 200 km beyond the suture. This type of behaviour depends on the width of the oceanic plate marginal to the collision zone: wide oceanic margins promote continental underplating and marginal back-arc basins; narrow margins do not show such underplating unless a far field force is applied. Our models show that, as the subducted continental lithosphere rises, the mantle wedge progressively migrates away from the suture and the continental crust heats up, reaching temperatures >900 °C. This heating might lead to crustal melting, and resultant magmatism. We observe a sharp peak in the overriding plate rock uplift right after the occurrence of slab break-off. Afterwards, during underplating, the maximum rock uplift is smaller, but the affected area is much wider (up to 350 km). These results can be used to explain the dynamics that led to the present-day crustal configuration of the India–Eurasia collision zone and its consequences for the regional tectonic and magmatic evolution.

1. Introduction

The dynamics of continental collision are complex due to the many forces acting in the system at the same time and the many factors that can affect them. Different scenarios are possible when a continent reaches the subduction zone trench. For instance, in the Apennines and the Carpathians many studies suggested that delamination of the lithospheric mantle from the continental crust occurred, leaving a thin layer of crust as the lithospheric mantle keeps subducting (e.g. Bird, 1979; Cloos, 1993; Brun and Faccenna, 2008; Göğüş et al., 2011). In other cases (e.g. Zagros, Himalayas) slab break-off occurs as a result of the high tensile stresses caused by the oceanic slab pull at depth and the buoyant continental crust that resists subduction at the surface (e.g. Davies and von Blanckenburg, 1995; Wong A Ton and Wortel, 1997; Replumaz et al., 2010). Seismic studies that focused more on the architecture of the Himalayan area, however, showed that the Indian continental lithosphere lies sub-horizontally underneath Eurasia for about 200 km north of the suture zone (Nábělek et al., 2009; Chen et al., 2010). This configuration has also been suggested to be present in ancient orogenies (e.g. the Slave Province in Canada, Helmstaedt, 2009; the Variscan orogeny in France, Averbuch and Piromallo, 2012). It is still unclear how the underthrusting of the subducting continental lithosphere and slab break-off coexist in the same system. In particular, it is poorly known how underthrusting evolves during continental collision, the dynamics of this process, and the factors that control its occurrence.

The long-term history of the plates prior to collision is one of the key factors that can affect the evolution of the continental collision itself. Old and cold continents, such as cratons, are stronger than younger continents, which are usually characterised by a weak, "jelly sandwich"-style ductile lower crust (Burov, 2011), and favours the decoupling between upper crust and lithospheric mantle needed for delamination to occur (Bajolet et al., 2012; Magni et al., 2013). Moreover, the dynamics of collision might also be affected by the interaction with mantle convection caused by features like mantle plumes, or the formation of slab windows, or the presence of other subduction zones nearby. This is, for instance, the case for the India–Eurasia collision, in which the

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presence of an external force has been argued for to explain the sustained convergence between the plates (Chemenda et al., 2000; Becker and Faccenna, 2011; Cande and Stegman, 2011).

In the last decade many 2D and 3D numerical and analogue experiments on slab break-off allowed us to have a much better understanding of the break-off process and its consequences on the evolution of topography, stress field and magmatism (Wong A Ton and Wortel, 1997; Gerya et al., 2004; Duretz et al., 2011; van Hunen and Allen, 2011; Pusok and Kaus, 2015). However, less work has been done in studying what happens to the subducted lithosphere after slab break-off. Several numerical studies have found the process of eduction to be geodynamically plausible, where subducted continental lithosphere coherently exhumes through the suture zone after slab detachment (Duretz et al., 2012; Bottrill et al., 2014). In this study we use 3D numerical models of continental collision to investigate what controls the occurrence of underplating, and discuss the possible applications of our model to the India–Eurasia collision system.

2. Methodology

We investigate the dynamics of continental collision with 3D numerical models of subduction using the finite element code CITCOM that solves the conservation of mass, momentum, thermal energy, and composition in a Cartesian geometry (Moresi and Gurnis, 1996) (see Magni et al. (2012) and Table 1 for used values of default parameters). Our models simulate the collision of a 2000 km wide continental block with a continental overriding plate after an initial stage of oceanic subduction (Fig. 1). Oceanic lithosphere of variable width flanks the continental block, to take into account the complexity of natural subduction systems, where often oceanic and continental subduction happen simultaneously along the trench, and to better understand how they interact with each other. We vary the width of the oceanic margin and the density of the continental crust to investigate what controls the occurrence of underplating and its dynamics. Moreover, we also run an additional model with an imposed continuous convergence between the plates.

Table 1
Symbols, units and default model parameters.

Parameters	Symbols	Value and unit
Rheological pre-exponent	A	6.52×10^6 [Pa^n s]
Activation energy	E^*	360 [kJ/mol]
Gravitational acceleration	g	9.8 [m/s^2]
Rheological power law exponent	n	1 (diff. c.), 3.5 (disl. c.) [–]
Lithostatic pressure	p_0	[Pa]
Gas constant	R	8.3 [J/K/mol]
Absolute temperature	T_{abs}	[K]
Reference temperature	T_m	1350 [°C]
Compositional density contrast	$\Delta\rho_c$	500 (300) [kg/m^3]
Strain rate	$\dot{\varepsilon}_{ij}$	[s^{-1}]
Second invariant of the strain rate	$\dot{\varepsilon}_{II}$	[s^{-1}]
Effective viscosity	η	[Pa s]
Reference viscosity	η_m	10^{20} [Pa s]
Maximum lithosphere viscosity	$\eta_{\max}$	10^{24} [Pa s]
Friction coefficient	μ	0.1 [–]
Reference density	ρ	3300 [kg/m^3]
Yield stress	τ_y	[MPa]
Surface yield stress	τ_0	40 [MPa]
Maximum yield stress	$\tau_{\max}$	400 [MPa]
Model geometry		
Domain depth	h	660 [km]
Domain length	l	3300 [km]
Domain width	w	1848 (2180–3690) [km]
Mesh resolution		from $8 \times 8 \times 8$ to $20 \times 20 \times 20$ [km^3]
Continental block half-width	–	1000 [km]
Oceanic side width	–	200 (500–2000) [km]
Continental crust thickness	Hc	40 (30) [km]

To reduce computational costs, we exploit the system's symmetry along the plane through the centre of the continental block perpendicular to the trench (x–z plane). Therefore, in the y-direction we model only half of the domain. The reference model (which has a computational domain size of 3300 × 2180 × 660 km) has a 500-km wide oceanic part within the subducting lithosphere (Fig. 1). Other model calculations have different oceanic plate widths (200–2000 km), and in those models the computational domain size in y-direction is adjusted accordingly (1850–3960 km). The initial position of the trench is imposed (at $x = 1850$ km), but during the model evolution the trench is free to move in response to the system dynamics (Magni et al., 2012). Subduction is facilitated by imposing an initial oceanic slab that extends to 200 km depth. The initial temperature field for the oceanic lithosphere is calculated following a half-space cooling solution for an 80-Myr old plate (Turcotte and Schubert, 2002). In the reference model, the continental lithosphere is modelled with a 40-km thick layer of positively buoyant crust ($\Delta\rho_c = 500$ kg/m^3 or $\rho_c = 2.8$ g/cm^3) and its temperature extends linearly from 0 °C at the surface to $T = T_m$ at 150 km depth. To allow possible mantle flow around the edge of the slab and avoid artefacts due to the lateral boundary condition the computational domain is wider than the subducting plate. This is modelled by imposing a transform fault with a 20 km wide low viscosity zone at $y = 660$ km. For simplicity, we assume the two plates to have the same width.

Thermal boundary conditions are: $T = 0$ °C at the top, $T = T_m$ at the bottom and left boundary (at $x = 0$), and insulating conditions along the rest of the boundaries. Mechanical boundary conditions are free-slip everywhere except the bottom boundary where

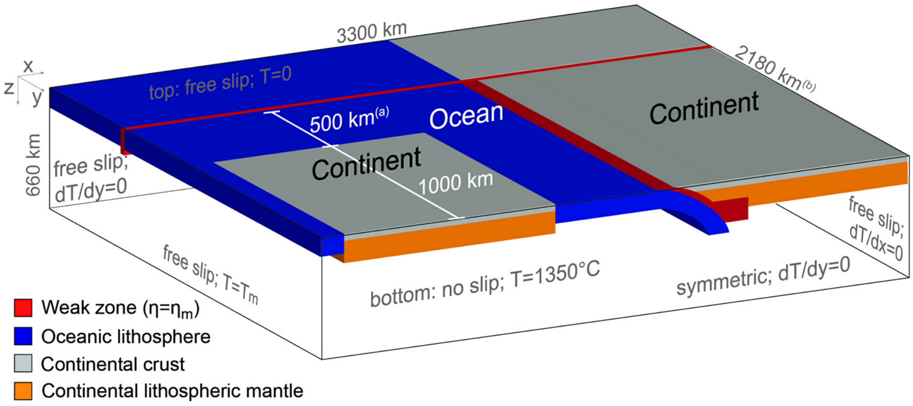

Fig. 1. Initial setup and boundary conditions of the reference model. (a) The width of the oceanic side is 500 km in the reference model, but is varied in the other models: 200 or 2000 km, and accordingly (b) the width of the domain is varied: 1850 or 3960 km.