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Flat versus steep subduction: Contrasting modes for the formation and exhumation of high- to ultrahigh-pressure rocks in continental collision zones

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ABSTRACT

Flat and steep subduction are end-member modes of oceanic subduction zones with flat subduction occurring at about 10% of the modern convergent margins and mainly around the Pacific. Continental (margin) subduction normally follows oceanic subduction with the remarkable event of formation and exhumation of high- to ultrahigh-pressure (HP–UHP) metamorphic rocks in the continental subduction/collision zones. We used 2D thermo-mechanical numerical models to study the contrasting subduction/collision styles as well as the formation and exhumation of HP–UHP rocks in both flat and steep subduction modes. In the reference flat subduction model, the two plates are highly coupled and only HP metamorphic rocks are formed and exhumed. In contrast, the two plates are less coupled and UHP rocks are formed and exhumed in the reference steep subduction model. In addition, faster convergence of the reference flat subduction model produces extrusion of UHP rocks. Slower convergence of the reference flat subduction model results in two-sided subduction/collision. The higher/lower convergence velocities of the reference steep subduction model can both produce exhumation of UHP rocks. A comparison of our numerical results with the Himalayan collisional belt suggests two possible scenarios: (1) A spatially differential subduction/collision model, which indicates that steep subduction dominates in the western Himalaya, while flat subduction dominates in the extensional central Himalaya; and (2) A temporally differential subduction/collision model, which favors earlier continental plate (flat) subduction with high convergence velocity in the western Himalaya, and later (flat) subduction with relatively low convergence velocity in the central Himalaya.

1. Introduction

Oceanic subduction zones can be classified into normal-to-steep (high-angle) and flat (low-angle) subduction styles. Steep (normal) subduction usually has a dip angle of $\geq 30°$at the top of the upper mantle (e.g., Turcotte and Schubert, 2002), whereas flat subduction is characterized by shallow dip angle and a high degree of coupling between the converging plates. In nature, flat subduction occurs at about 10% of the modern convergent margins and mainly around the Pacific, with the best known present-day examples located beneath western South America, in Peru and central Chile/NW Argentina (e.g., Gutscher et al., 2000a,b; Lallemand et al., 2005). It has been proposed that flat subduction may have been widespread during the early stages in the Earth's history and contributed to the processes of continental growth in the Proterozoic and Archean (Abbott et al., 1994; Vlaar, 1983, 1985). However, the cause of flat subduction is the subject of an active discussion with several possible mechanisms having been proposed, e.g. the subduction of buoyant anomalies (such as bathymetric highs, aseismic ridges, or oceanic plateaus), rapid absolute motion of the overriding plate, interplate hydrostatic suction, a delay in the basalt to eclogite transition, the curvature of the margin, etc. (e.g. Gutscher et al., 2000b). In addition, several analogue (e.g., Chemenda et al., 2000; Espurt et al., 2008; Martinod et al., 2005) and numerical models (e.g., van Hunen et al., 2002a,b, 2004) have explored the conditions permitting the appearance of flat subduction zones as well as their consequences on overriding plate deformation. As discussed by van Hunen et al. (2004), flat subduction does not necessarily imply buoyant slabs. Other factors, such as overriding plate velocity and slab strength, may also play significant roles in controlling this process.

Continental (margin) subduction normally follows oceanic subduction under the convergent forces of lateral "ridge push" and/or oceanic "slab pull". The remarkable event during early continental collision is the formation and exhumation of high- to ultrahigh-pressure (HP–UHP) metamorphic rocks. Occurrences of UHP terranes around the world have been increasingly recognized with more than 20 UHP terranes documented (e.g., Liou et al., 2004), which have repeatedly invigorated the concepts of deep subduction (>100 km) and exhumation of crustal

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materials. Continental subduction/collision and exhumation of HP–UHP rocks are widely investigated with analogue (e.g., Boutelier et al., 2004; Chemenda et al., 1995, 1996) and numerical modeling method (e.g., Beaumont et al., 2001, 2009; Burg and Gerya, 2005; Burov et al., 2001; Gerya et al., 2008; Li and Gerya, 2009; Toussaint et al., 2004b; Warren et al., 2008a,b; Yamato et al., 2007, 2008). The tectonic styles of continental subduction can be either "one-sided" (overriding plate does not subduct) or "two-sided" (both plates subduct together) (Faccenda et al., 2008; Pope and Willett, 1998; Tao and O'Connell, 1992; Warren et al., 2008a), as well as several other possibilities, e.g. thickening, slab break-off, slab drips etc. (e.g., Toussaint et al., 2004a,b). Models of HP–UHP rocks exhumation can be summarized into the following groups: (1) syn-collisional exhumation of a coherent and buoyant crustal slab, with formation of a weak zone at the entrance of the subduction channel (Chemenda et al., 1995, 1996; Li and Gerya, 2009; Toussaint et al., 2004b); (2) episodic ductile extrusion of HP–UHP rocks from the subduction channel to the surface or crustal depths (Beaumont et al., 2001; Warren et al., 2008a); and (3) continuous material circulation in the rheologically weak subduction channel stabilized at the plate interface, with materials exhumed from different depths (Burov et al., 2001; Gerya et al., 2002; Stöckhert and Gerya, 2005; Warren et al., 2008a; Yamato et al., 2007).

The previously-mentioned analogue and numerical models for continental subduction/collision associated with burial and exhumation of crustal rocks are mostly based on the steep (normal) subduction mode. It is unknown therefore what the characteristics of HP–UHP metamorphism and exhumation would be in the flat subduction mode. In order to address this issue, we used 2D thermo-mechanical numerical modeling to study the contrasting subduction/collision styles as well as the formation and exhumation of HP–UHP metamorphic rocks in both the flat and steep subduction modes. In addition, we investigated the sensitivities of the model predictions to the convergence velocity. The numerical model results are compared to the western and central Himalayas as this large, young continental collisional belt shows intriguing contrasts in subduction geometry and exhumation patterns along strike.

2. Numerical model design

The numerical simulations are conducted with the 2D code "I2VIS" (Gerya and Yuen, 2003a) based on finite differences and marker-in-cell techniques (see Appendix A.1 for details of the numerical methodology). Large scale models (4000 × 670 km, Fig. 1) are designed for studying the dynamic processes from oceanic subduction to continental collision associated with the formation and exhumation of HP–UHP rocks. The non-uniform 699 × 134 rectangular grid is designed with a resolution varying from 2 × 2 km in the studied collision zone to 30 × 30 km far away from it. The lithological structure of the model is represented by a dense grid of ~7 million active Lagrangian markers used for advecting various material properties and temperature (Gerya et al., 2008; Li et al., 2010).

The velocity boundary conditions (Fig. 1) are free slip at all boundaries except the open lower boundary along which an infinity-like mass-conservative condition is imposed (e.g., Gerya et al., 2008; Li et al., 2010). Infinity-like external free slip conditions along the lower boundary imply free slip condition to be satisfied at ~1000 km below the base of the model (external lower boundary). As for the usual free slip condition, external free slip allows global conservation of mass in the computational domain and is implemented by using the following limitation for velocity components at the lower boundary: $\partial v_x/\partial z = 0$, $\partial v_z/\partial z = -v_z/\Delta z_{external}$, where $\Delta z_{external}$ is the vertical distance from the lower boundary to the external boundary where free slip ($\partial v_x/\partial z = 0$, $v_z = 0$) is satisfied. The subducting plate is pushed rightward by prescribing a constant convergence velocity (Vx) in a small internal domain that remains fixed with respect to the Eulerian coordinate (Fig. 1).

In the numerical models, the driving mechanism of subduction is a combination of "plate push" (prescribed rightward convergence velocity) and increasing "slab pull" (temperature-induced density contrast between the subducted lithosphere and surrounding mantle). This type of boundary condition is commonly used in numerical models of subduction and collision (e.g., Burg and Gerya, 2005; Currie et al., 2007; Toussaint et al., 2004b; Warren et al., 2008b; Yamato et al., 2007) and assumes that in the globally confined three-dimensional system of plates, local "external forcing" coming either from different slabs or from different sections of the same laterally non-uniform slab can be significant. As discussed in detail by Li and Gerya (2009), although slab pull is considered the most significant global 3-D driving force in subduction, eliminating the lateral push from 2-D models is not necessarily the most realistic option since in this case the plate will be driven only by the local negative buoyancy generated in exactly the same 2-D section. In contrast, 3-D plate motion is driven by the global negative buoyancy of the plates (e.g. Labrosse and Jaupart, 2007).

Following previous numerical studies for similar geodynamic settings (e.g., Li and Gerya, 2009; Warren et al., 2008a), our numerical models are

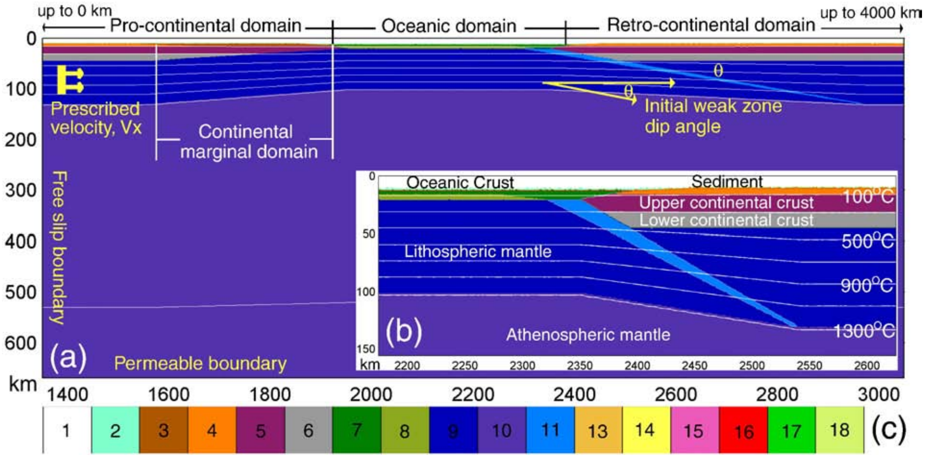

Fig. 1. Initial model configuration and boundary conditions. a) Enlargement (1700 × 670 km) of the numerical box (4000 × 670 km). Boundary conditions are indicated in yellow. b) The zoomed domain of the subduction zone. White lines are isotherms measured in °C. c) The colorgrid for different rock types, with: 1—air; 2—water; 3,4—sediment; 5—upper continental crust; 6—lower continental crust; 7—upper oceanic crust; 8—lower oceanic crust; 9—lithospheric mantle; 10—athenospheric mantle; 11—weak zone mantle; 13 and 14—partially molten sediment (3 and 4); 15 and 16—partially molten continental crust (5 and 6); 17 and 18—partially molten oceanic crust (7 and 8). The partially molten crustal rocks (13, 14, 15, 16, 17 and 18) are not shown in Figure 1, but will appear during the evolution of the model (e.g., Figs. 3 and 4). In the numerical models, the medium-scale layering usually shares the same physical properties, with different colors used only for visualizing slab deformation and structural development. Detailed properties of different rock types are shown in Tables S2 and S3.