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Continental collision with a sandwiched accreted terrane: Insights into Himalayan–Tibetan lithospheric mantle tectonics?

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ABSTRACT

Many collisional orogens contain exotic terranes that were accreted to either the subducting or overriding plate prior to terminal continent–continent collision. The ways in which the physical properties of these terranes influence collision remain poorly understood. We use 2D thermomechanical finite element models to examine the effects of prior 'soft' terrane accretion to a continental upper plate (retro-lithosphere) on the ensuing continent–continent collision. The experiments explore how the style of collision changes in response to variations in the density and viscosity of the accreted terrane lithospheric mantle, as well as the density of the pro-lithospheric mantle, which determines its propensity to subduct or compress the accreted terrane and retro-lithosphere. The models evolve self-consistently through several emergent phases: breakoff of subducted oceanic lithosphere; pro-continent subduction; shortening of the retro-lithosphere accreted terrane, sometimes accompanied by lithospheric delamination; and, terminal underthrusting of pro-lithospheric mantle beneath the accreted terrane crust or mantle. The modeled variations in the properties of the accreted terrane lithospheric mantle can be interpreted to reflect metasomatism during earlier oceanic subduction beneath the terrane. Strongly metasomatized (i.e., dense and weak) mantle is easily removed by delamination or entrainment by the subducting pro-lithosphere, and facilitates later flat-slab underthrusting. The models are a prototype representation of the Himalayan–Tibetan orogeny in which there is only one accreted terrane, representing the Lhasa terrane, but they nonetheless exhibit processes like those inferred for the more complex Himalayan–Tibetan system. Present-day underthrusting of the Tibetan Plateau crust by Indian mantle lithosphere requires that the Lhasa terrane lithospheric mantle has been removed. Some of the model results support previous conceptual interpretations that Tibetan lithospheric mantle was removed by convective coupling to the pro-lithosphere. They can also be interpreted to suggest that delamination beneath Tibet was facilitated by densification and weakening of the plateau lithosphere, perhaps owing to long-lived pre- to syn-collisional subduction-related metasomatism beneath the Asian margin.

1. Introduction: orogenesis involving accreted terranes

Continent–continent collisional orogenesis is commonly preceded by the accretion of one or more terranes to one or both of the continents as part of the Wilson Cycle (Wilson, 1966; Dewey, 1969). Accretion ranges from that seen in accretionary orogens (Cawood et al., 2009), comprising mainly stacked fragments derived from the subducting ocean, to small and large accreted terranes, either 'rootless' or attached to their lithospheric mantle. Accreted terranes may be small (Williams and Hatcher, 1982; Van Staal et al., 1998) or large, e.g., those comprising the Tibetan Plateau (Dewey et al., 1988; Yin and Harrison, 2000). Accretion to the continent may be 'soft' or 'hard', the former involving 'docking' but limited tectonic shortening, overthrusting and metamorphism, and the latter involving structural emplacement of the allochthonous terrane, major tectonic thickening of crust and possibly mantle lithosphere, and metamorphism, leading to orogenesis within the accreted terrane itself. The terranes themselves include oceanic arcs, large igneous provinces, distal rifted margins, and ribbon and micro-continents (Roberts, 2003; Cawood et al., 2009; Tetreault and Buiter, 2014; Moresi et al., 2014). Moreover, they may be accreted while hot or cold, giving them a range of strengths depending on their prior history.

Here we present numerical models motivated by the question, 'What effect does prior terrane accretion have on subsequent continent–continent collision?' The case investigated is simple (Fig. 1)—that of a medium-sized continental lithospheric terrane which has undergone soft accretion to the upper plate ('retro'-side)

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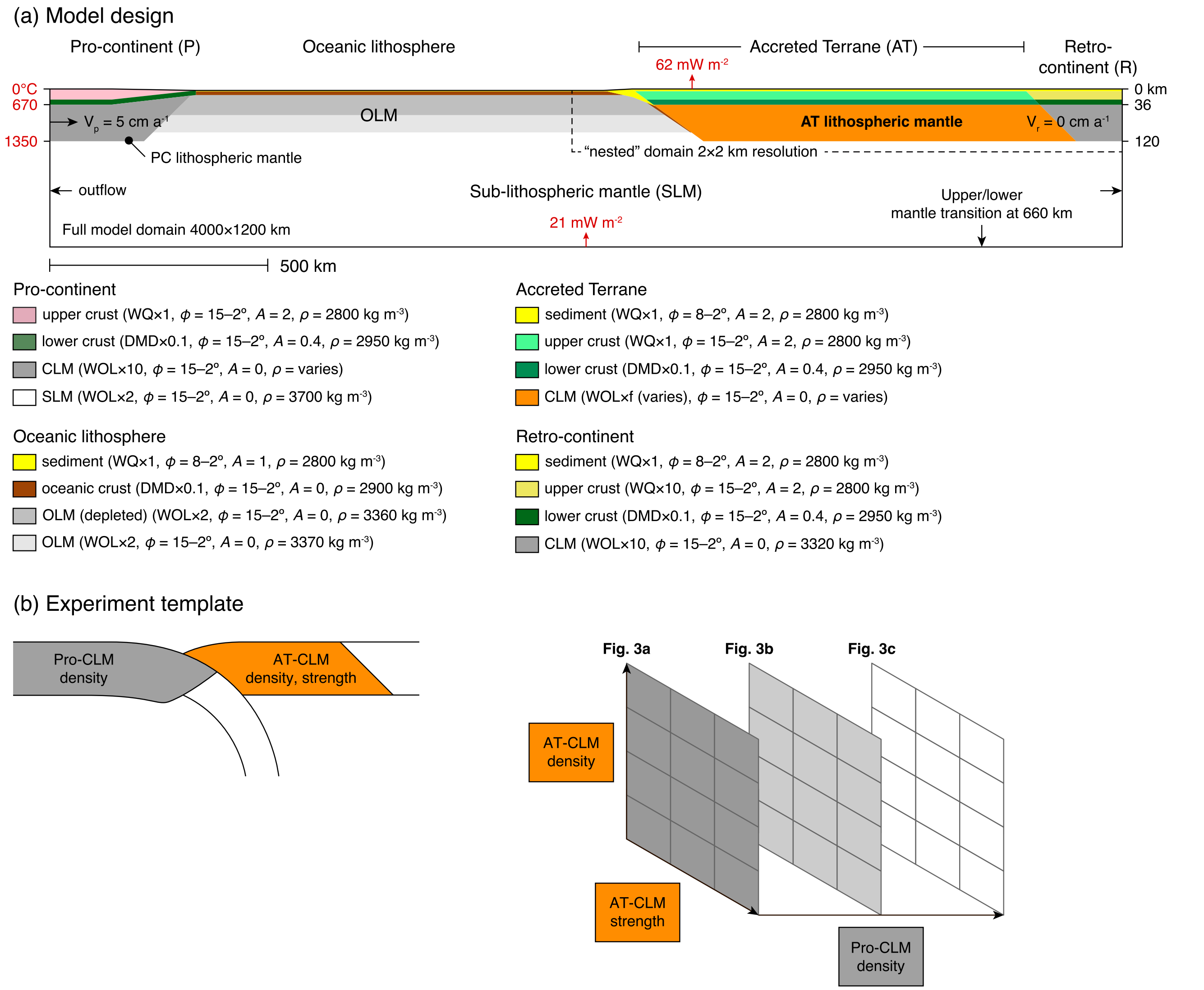

Fig. 1. (a) Design of two-dimensional models (see Section 2 and Appendix A.1 for details). The full model 4000×1200 km domain is represented by a coarse computational grid with a maximum resolution of 10×2 km. A higher-resolution, 'nested' computational grid (dashed line) is embedded within the coarse mesh in the vicinity of the subduction zone and retro-lithosphere, and has a maximum resolution of 2×2 km. AT = accreted terrane, CLM = continental lithospheric mantle, OLM = oceanic lithospheric mantle, SLM = sublithospheric mantle. Black arrows show velocity boundary conditions in schematic form. Red shows thermal boundary conditions (basal heat flux) and resulting surface heat flux and continental temperatures. P = pro-continent lithosphere, R = retro-continent lithosphere. WQ = wet quartzite, DMD = dry Maryland diabase, WOL = wet olivine. ϕ = range of effective angle of internal friction (ϕ_{eff}) owing to pore-fluid pressure and frictional-plastic strain-softening; A = radiogenic heat production ($\mu\mathrm{W\,m^{-3}}$) (A_R in text); ρ = density (Table 1). (b) Schematic illustration of experimental parameter space (see Section 4). Panels in 3-dimensional grid correspond to Figs. 3a–c. Each panel represents a set of models with a different pro-continent CLM density. Within each panel, models vary by AT-CLM density and AT-CLM strength (viscosity scaling factor f).

of the system. Using 2D thermomechanical finite element model experiments we explore how the style of orogenesis varies with the properties of the pro-continental and accreted terrane lithospheric mantles. In particular, models are designed to assess:

1. how oceanic slab break-off influences the subsequent subduction of the pro-continent mantle;
2. under what circumstances subduction of pro-continent mantle under the accreted terrane leads to advancing subduction and shortening of the accreted terrane;
3. how tectonic shortening of the accreted terrane is accommodated by its lithospheric mantle; and,
4. the influences of crustal thickening and lithospheric mantle deformation/delamination on the topographic and thermal evolution of the orogen.

Even with a simple model design (Fig. 1), many variables could be considered. We purposely confine our investigation to factors we consider first-order in regard the behavior of the lithospheric mantle, namely the density of the pro-continent mantle and the density and viscous strength of the accreted terrane lithospheric mantle. We justify this choice by appealing to the Archimedes number for the mantle lithosphere which determines its propensity to deform and/or subduct (Appendix A.2).

While the model design is intended to be a generic prototype for similar natural systems, the results reveal emergent behaviors similar to those previously diagnosed for the more complex Himalayan–Tibetan (H-T) orogen. We therefore conclude with a discussion of the applicability of our results to the H-T system, focusing on the controversial problem of how India–Asia convergence was accommodated at the lithospheric scale (e.g., Argand, 1924; Dewey et al., 1988; Le Pichon et al., 1992; Molnar et al., 1993; Willett and Beaumont, 1994; Owens and Zandt, 1997; Shen et al., 2001; Tapponnier et al., 2001; Johnson, 2002; Royden et al., 2008; van Hinsbergen et al., 2011a).