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A mid-crustal strain-transfer model for continental deformation: A new perspective from high-resolution deep seismic-reflection profiling across NE Tibet

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ABSTRACT

Understanding why continental deformation departs from the theory of plate tectonics requires a detailed knowledge of three-dimensional structures at a lithospheric scale. In Tibet, the end-member models of continental deformation make distinctively different predictions on strain distribution and contrasting structural geometry as a function of depth. Specifically, the thin-viscous-sheet model predicts vertically coherent deformation while channel-flow and continental-subduction models predict the presence of sub-horizontal detachment zones within or at the base of the Tibetan crust during the Cenozoic deformation. To differentiate the above models, we conducted a high-resolution seismic-reflection survey across the active left-slip Kunlun fault and its nearby contractional structures. The results of this work show that the actively deforming middle Tibetan crust is dominated by discrete sub-horizontal simple-shear zones that terminate the sub-vertical, left-slip Kunlun fault above and mantle-cutting thrusts below. The flat shear zones appear to act as roof and floor thrusts of large duplex structures that transfer shortening strain from locally deformed and coupled lower crust and mantle lithosphere below to the high-strain domains of the upper crust above. The middle-crustal strain-transfer model proposed here implies that the weak Tibetan middle crust may not be active everywhere during the Indo-Asian collision. It also predicts that the kinematics of the activated portions of the middle crust, whether being deformed by simple shear or channel-flow deformation, may vary from place to place, depending strongly on the lateral variation of mechanical strength at different depths of the lithosphere. Our approach of establishing the kinematics of middle-crust deformation departs significantly from the early work that emphasizes exclusively the role of vertically varying rheology in controlling the mode of continental deformation.

1. Introduction

Although the inability of the plate-tectonics theory to explain diffuse continental deformation has long been related to continuum flow (Molnar and Tapponnier, 1975), how such a mode of deformation operates in three dimensions during collisional orogenesis remains hotly debated (e.g., Harrison, 2006; Klemperer, 2006; Webb et al., 2007; Yin, 2006) (Fig. 1). Three end-member models have been proposed to resolve this issue: (1) the thin-viscous-sheet model (Bird and Piper, 1980; England and Houseman, 1986; England and McKenzie, 1982; Flesch et al., 2005), (2) the continental subduction model and its special case invoking strike-slip assisted oblique subduction (Argand, 1924; Meyer et al., 1998; Tapponnier et al., 2001), and (3) the middle- or lower-crustal channel flow model (Bird, 1991; Clark and Royden, 2000; Royden et al., 1997, 2008) (Fig. 1). The three models make distinctively different predictions on strain distribution in the map and cross section views, leading to different lithospheric geometry via different deformation paths. The thin-viscous-sheet model requires vertically coherent deformation and thus no major sub-horizontal detachment zones are allowed during continental deformation (Fig. 1A and B). In addition, as deformation is distributed via flow in map view, the predicted faults are closely spaced and have similar slip magnitudes. Finally, as the entire

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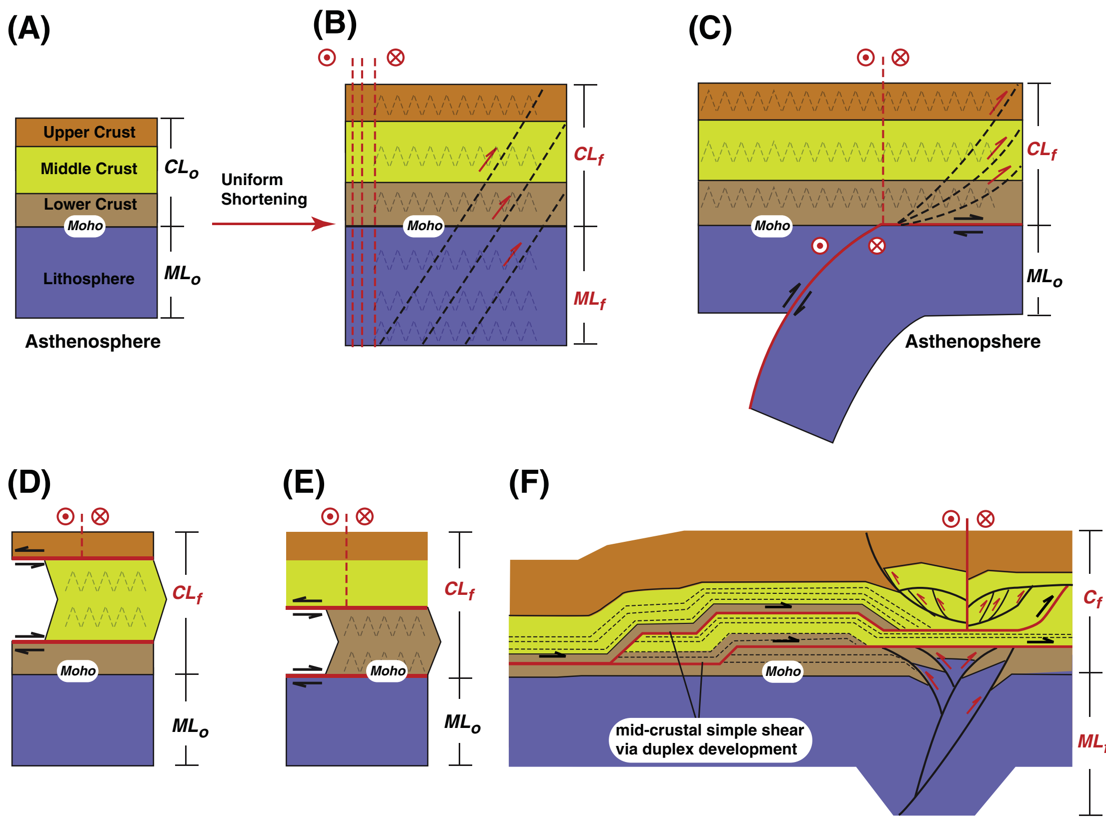

Fig. 1. Schematic diagrams illustrating competing models for continental deformation. Thick horizontal red lines indicate the locations of the predicted decoupling zones and the arrows show their sense of shear. CL_o and ML_o represent the original and CL_f and ML_f represent the final thickness of the crust and mantle lithosphere before and after continental deformation. The vertical straight red lines indicate predicted strike-slip faults in a deforming lithosphere; a circle with a dot indicates motion towards the reader while a circle with a cross indicates motion away from the reader. (A) Continental lithosphere before deformation. (B) The thin-viscous-sheet model predicts vertically uniform strain and the absence of decoupling zone. Faults should be lithospheric and closely-spaced. (C) The oblique continental-subduction model predicts decoupling of the deformed crust from mantle lithosphere. Strike-slip faults root into the subduction zone, allowing continental lithosphere to move laterally. (D) and (E) The channel-flow model predicts lateral extrusion of the ductile middle and/or lower crust. The channel thickness may expand or contract vertically during ductile flow in the channel. The model requires two sub-horizontal decoupling zones with opposite senses of shear and faults in the crust do not penetrate into the mantle. (F) Simplified cross section based on this study. Two detachment zones are revealed, both having the same transport direction. Also, the mantle lithosphere and lowermost crust experienced significant shortening.

lithosphere is deforming coherently, the predicted faults by the thin-viscous-sheet model must cut across the entire lithosphere. The continental-subduction model differs from the thin-viscous-sheet model in that it requires the presence of a major detachment zone at the base of the continental crust; the detachment zone allows decoupling of the pervasively deformed crust above from the subducting mantle lithosphere below (Fig. 1C). The mantle-subduction zones in this model may be linked with large strike-slip faults, allowing the continental lithosphere to translate horizontally (i.e., lateral extrusion) during continental subduction (Fig. 1C). In contrast to the above two models, the channel-flow hypothesis predicts little deformation above and below the flow channel and that deformation of the upper crust and the mantle is decoupled (Fig. 1D and E).

Due to the emphasis of different deformation paths, the above models also predict very different structural fabrics in the crust and the upper mantle. As no sub-horizontal detachment zones are required in the thin-viscous-sheet model, there should be no sub-horizontal fabrics developed during continental deformation. Although the oblique continental-subduction model of Tapponnier et al. (2001) and the middle-crustal channel flow model of Clark and Royden (2000) both predict the presence of sub-horizontal detachment zones and thus the development of sub-horizontal fabrics during continental deformation, the position and kinematics of the required shear zones differ sharply between the two. In the continental-subduction model, the detachment zone has a unidirectional sense of shear and lies at the base of the crust. In contrast, the channel-flow model requires the presence of two sub-horizontal shear zones opposite senses of shear bounding the channel in the middle or lower crust (Fig. 1). As channel flow is laminar, one would expect continuous sub-horizontal shear foliation in the middle and/or lower crust.

In this study, we test the above models by determining the vertical distribution of strain and fabrics using high-resolution reflection-seismology across the active left-slip Kunlun fault in northeastern Tibet (Fig. 2). The survey transect consists of two nearly orthogonal survey lines allowing the establishment of a three-dimensional view of the lithospheric structures, Our results indicate that the Kunlun fault zone terminates downward at a large thrust duplex system in the middle crust. The same duplex system also bounds the mantle-cutting thrusts that offset the Moho (Fig. 2F). This structural relationship requires the middle-crustal duplex system to have served as a transfer zone linking deformation in the upper crust and the coupled lower crust and the mantle lithosphere.

2. Geologic setting

Our seismic profile crosses the active left-slip Kunlun fault, which is ~1000-km long and was inferred to merge downward with a continental subduction zone (Tapponnier et al., 2001). The fault was