# Himalayan hinterland-verging superstructure folds related to foreland-directed infrastructure ductile flow: Insights from centrifuge analogue modelling

Laurent Godin[1], Chris Yakymchuk[1,2], Lyal B. Harris[3]

[1] Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada, godin@geol.queensu.ca
[2] Now at Department of Geology, University of Maryland, College Park, MD, 20742-4211, USA
[3] Institut national de la recherche scientifique, centre - Eau Terre Environnement, 490 de la Couronne, Quebec City, Quebec G1K 9A9, Canada

The orogenic superstructure (SS) and infrastructure (IS) constitute two levels of a mountain belt with contrasting structural styles. In several Himalayan transects, N-verging back folds, which oppose the orogenic vergence, dominate the SS. Competing explanations for these folds are tested using scaled centrifuge analogue models employing new materials and computed tomodensitometry (CT scanning) (Fig. 1) (Godin et al., 2011; Yakymchuk et al., in press). This technique provides insight into the progressive three-dimensional formation of mechanically active, buckle and kink folds of a stratified sedimentary sequence upon migmatitic gneisses in a large hot orogen.

Analogue materials with properties scaled to represent both the layered Tethyan sedimentary sequence (the SS) and the underlying lower-viscosity Greater Himalayan sequence (the IS) are used. Polydimethylsiloxane (PDMS), a low viscosity polymer simulating migmatites and melt pooling in the upper part of the IS, is incorporated on half the SS-IS interface to investigate its effects on superstructure fold geometry and superstructure-infrastructure decoupling efficiency.

Modelling suggests that SS folding occurs during bulk shortening accompanied by IS thickening before IS flow. Focused erosion then instigates IS lateral flow and stretching, decoupling of the SS, and transposition of the lower SS into a detachment zone. Decoupling at the IS-SS interface separates a SS dominated by older folds and an IS characterised by younger horizontal transposition and stretching of early folds. Extrusive ductile flow of the IS locally modifies fold vergence in the SS. The fold asymmetry is thus controlled by the efficiency of coupling between IS and SS; a low viscosity at the IS-SS interface favours complete decoupling and hinders modification of fold vergence, whereas a higher viscosity IS-SS interface favours fold vergence modification. Modelling supports a tectonic scenario in which Himalayan hinterland-verging folds are the product of early shortening of the SS followed by local modification of fold geometry when the IS subsequently stretches and flows during focused erosion and melt-enhanced IS weakening (e.g. Larson et al., 2010).

Models without PDMS, akin to localities without significant melts near the South Tibetan detachment, may also provide insight into the structural evolution of debated units such as the Haimanta Group in the Sutlej valley, NW India. The basal part of the Haimanta Group is similar to the Everest Series in eastern Nepal and to the Annapurna-Yellow Formation in central Nepal (as proposed by Gleeson and Godin, 2006) as well as the Chekha Group in eastern Himalaya (Kellett et al., 2010). In contrast, however, it displays minor differences in metamorphic grade with the uppermost Greater Himalayan sequence, despite being separated from it by a top-to-the-northeast shear zone. The Haimanta Group also distinguishes itself from the Greater Himalayan sequence by a distinct structural style, and a marked difference in exhumation path (Chambers et al., 2009). Our modelling suggests that without a weak layer (pooled crustal melts), the detachment is distributed over a broader zone, and can isolate part of the infrastructure in its hanging wall (Fig. 2). As such, the Haimanta Group may have initially evolved as part of the IS, but later became incorporated in the superstructure as the lower part of the infrastructure underwent later horizontal stretching flow.

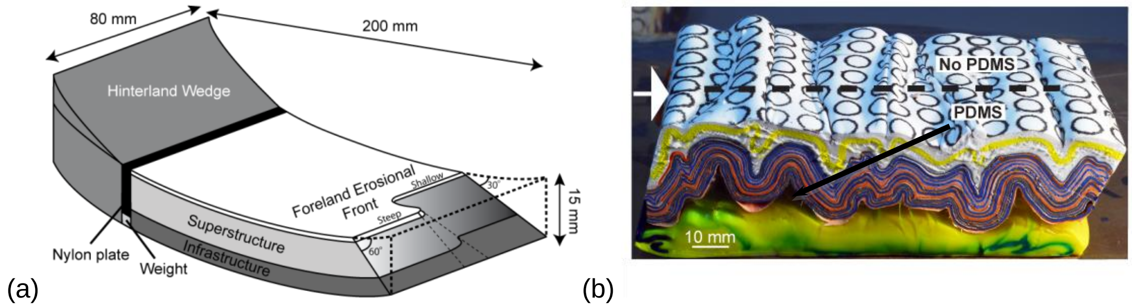


**Figure 1.** (a) Model set-up showing the collapsing wedge in the hinterland that activates layer-parallel shortening. Models consist of a 10 mm thick brittle-ductile superstructure overlying a 5 mm thick ductile infrastructure. The portrayed irregular erosion front was created on some models, while others contained an extra layer of polydimethylsiloxane (PDMS), a clear, low density and viscosity polymer, at the infrastructure-superstructure interface that simulates the presence of crustal melts. (b) Example of a model containing one half of clear PDMS at the interface between the layered sequence and ductile substrate and the other half with no PDMS along this interface.

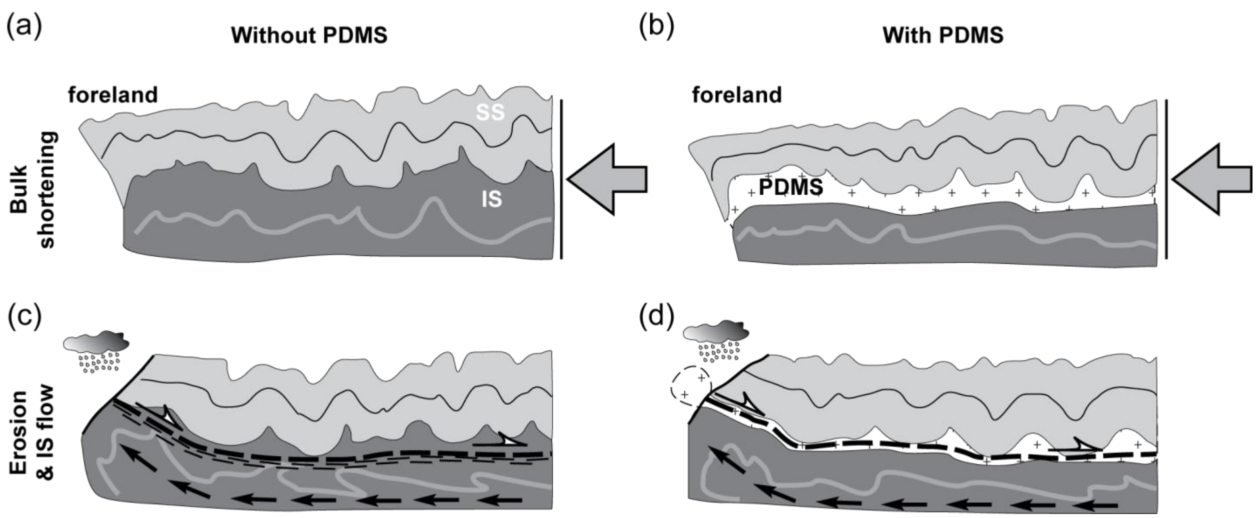


**Figure 2.** Sketches depicting deformation features developed in the models. (a) Without polydimethylsiloxane (PDMS) at the superstructure (SS) – infrastructure (IS) interface, initial shortening of the model develops buckle folds in the SS, while the IS material infills the SS anticlinal cores. (b) SS anticlines are cored by PDMS during early shortening, while the IS remains planar and horizontal, yet vertically thickens. (c) Once horizontal IS flow is triggered by focused foreland erosion (depicted by raining clouds), the IS-SS decoupling zone is localised in the upper part of the IS, and isolates the uppermost IS in the hanging wall of the detachment. (d) When PDMS is present, the detachment is localised within it; the entire IS is then confined to the footwall of the detachment, with only part of the PDMS isolated in the hanging wall.

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