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The structural styles of underthrusting-dominated non-cohesive tectonic wedges

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Underthrusting is a typical process at compressive margins responsible for nappe stacking and sediment subduction. Despite being essential for orogenesis, and the subduction cycle, the mechanics of underthrusting is still incompletely understood. The critical taper theory predicts that underthrusting occurs only in the limit where $\mu' = \mu'_b$, with μ' and μ'_b the inner and basal effective coefficient of friction, respectively. Paradoxically, in nature, underthrusting is associated with weak faults. For instance, at erosive subduction margins, sediments are dragged in subduction, while normal faulting in the middle prism suggests the plate boundary is weak. Wang et al., (2010) have proposed that dynamic fault strength variations during the earthquake cycle can reconcile these observations. In their model, underthrusting occurs during earthquakes when the fault is strong and normal faulting occurs in the prism during the interseismic period when the fault is weak. However, recent evidence (Gao and Wang, 2016) suggests that plate boundaries are relatively weak also during earthquakes.

In this contribution, we investigate the control of permanent fault weakening on the dynamics of a strong-based ($\mu' = \mu'_b$) non-cohesive tectonic wedge. We control the wedge material strength by a spatially constant fluid overpressure factor (λ_{ov}), and fault strength by a strain weakening factor (χ). We investigated the problem in two steps. First, we used the critical taper theory to determine a mechanical mode diagram that predicts structural styles. This diagram is deduced from the function $\Delta\alpha(\beta, \chi, \lambda_{ov})$ which is the difference in taper angle at a given β, between the compressively critical taper of a strong-based wedge and the extensionally critical taper of a weak-based wedge ($\mu'_b = (1 - \chi)\mu'$). Then, we performed numerical simulations of accretionary wedge formation to establish the characteristics of these structural styles regarding wedge and fault geometry. We determined there is a continuum of structural styles with three end-members occurring at the theoretically determined mechanical mode transitions.

- Style 1 is characterized by thin tectonic slices and little to no underthrusting. Surface angles are bimodal with a peak corresponding to the strong-based wedge stability, and another corresponding to the compressively critical taper of a weak-based wedge.
- Style 2 is characterized by thick slices and nappe stacking. Surface angles are multimodal and vary cyclically within the stability of the weak-based wedge; with part of the wedge being asymptotic to the strong-based stability line.
- Style 3 is characterized by the complete underthrusting of the incoming sediments. Sediments are exhumed when they reach the backstop to form a weak upper wedge whose base is the paleosurface of the incoming sediments. Surface angles are asymptotic to the stability line of a fully weakened wedge ($\mu' = \mu'_b = (1 - \chi)\mu'_0$, with μ'_0 a reference friction coefficient).

The model gives a mechanical explanation that reconciles underthrusting with weak faults. In agreement with observations, the model predicts the occurrence of style 2 in strong-based sandbox experiment ($\mu = 0.6$, $\lambda_{ov} = 0$, $\chi = 0.1 - 0.2$). Finally, we argue that style 3 is triggered by any mechanism, such as material weakening, erosion or sedimentation, that limits the surface angle such that the incoming material is always significantly under-critical.