Extension During Active Collision in Thin-skinned Wedges: Insights from Laboratory Experiments

Supplemental – Additional Description of Modeling Technique

For the experiments described in the main text (Figure 1), we have taken a series of images using a camera attached to a rigid tower atop the sandbox. This tower moves with the pushing back wall, keeping the camera fixed with respect to the model foreland. At regular intervals of back wall motion the image-processing software then determines the coordinates of a grid of passive marker dots on the surface. From those coordinates, the software then calculates surface displacement fields (e.g. Figure DR1a).

Figure DR1 shows an example of this quantitative analysis in an analog model from a part of a complex convergent margin. The five panels in Figure DR1 show (a) the velocity field determined from a pair of images using the marker grids, (b) the 2-D principal strain rate field determined from the velocity field shown overlain on the corresponding image for the interval, where red indicates contractional and blue indicates extensional strain rate, (c) the idealized focal mechanisms, in which the strikes of the two nodal planes correspond to the two no-length change directions that have been determined from the 2-dimensional deformation tensor field using the method of Haines and Holt (1993), (d) the contoured rotation field and (e) the contoured shear field from the deformation tensor.
For each image a set of indexed coordinates is determined from the set of marker points. While many dots may be lost, in these convergent experiments there is a net increase in the number of marker points as additional grid points enter the image frame (700 to ~1000). The position of the coordinates can be determined to a resolution of 70 microns. This precision is achieved by correcting for rigid body motions due to small changes in camera’s position and for lens distortion but is also a function of the camera’s resolution and size of the region being imaged. With the automation of our code we can determine the coordinate and displacements for a spatially dense deformation field at small intervals of back wall motion (Figure DR1) for an unlimited number of image pairs.

We have carefully chosen our granular material, subrounded carbonate sand, to ensure that it has a small dilatancy in shear, as this has been shown to be an important parameter for frictional analog material [Lohrmann et al., 2003]. As discussed in the main text, it is important to choose materials with the appropriate time and length scaling of rheology [Hubbert, 1959]. We want the ductile layer to be comparable in strength to the frictional lid above it during the main phase of deformation, rather than being vastly weaker than it. Accounting for boundary effects related to the finite width of the box is a particularly significant challenge in executing these models. Spurious boundary effects are minimized by reducing the sidewall drag by the direct application of a lubricating compound (e.g., RainX®) and through the use of a relatively wide box (61 cm). The experiments in Figures 2 and 3 in the main text are geometrically simple, so
we are able to exclude disturbed regions by the sidewalls and consider only a large central portion of the model in which our quantitative analysis has verified that there is no measurable side-wall drag-related curvature of the deformation front or rotations in the velocity field. Neither of these effects should occur in simple margin-normal convergence as dictated by the initial boundary conditions. In our analysis, roughly 7 cm on either side of the experiment is ignored because of the propagation of such side-wall drag, leaving 47 cm along strike within which we calculate the margin-normal profiles of average displacement.

Figure DR2: Representative images of the development of a normally converging frictional experiment (corresponding to Figure 2 in the main text). As the experiment develops there is the characteristic development of the pro-wedge and a maximum-taper inner and minimum taper outer retro-wedge. To the left is the foreland and right is the hinterland of the model wedge. Note the pin line (red) to the right and the red arrows indicating the deformation fronts. The dashed line near the center of the image indicates the location of the backstop edge.
In Figures 2 to 4 in the main text the smoothed profiles are calculated from velocities along the width of the experiments, parallel to the strike of the model, along the entire transect. Velocities are normalized to the increment of back wall displacement, allowing us to see variations in the strain rate profiles that are associated with evolution of deformation as shown in DR2 and DR3.

Figure DR3: Representative images of the development of a normally converging experiment with a layered rheology corresponding to Figure 2 in the main text (i.e., friction over Newtonian viscous). As the experiment matures there is the characteristic development of the pro-wedge but also a broad inner plateau and minimum taper outer retro-wedge. The foreland is to the right. Note the pin line (red) to the right and the red arrows indicating the deformation fronts. The dashed line near the center of the image indicates the location of the backstop edge. The taper of the pro-wedge is much smaller and spacing of its thrusts much large than the pure frictional model as would be expected when there is a weak basal layer (e.g., Davis and Engelder, 1985).
Figures 2 and 3 in the main text show strain rate for a late interval of convergence of the respective experiments and a representative series of images are shown in Figures DR2 and DR3. Additionally, the Videos DR4 and DR5 correspond to the two experiments in Figure 2 (and DR2), and to Figure 3 (and DR3). These videos show how strain rate and cumulative strain evolve as the model orogens develop. In Video DR4, a time series of analyzed profiles for the frictional experiment, the locus of the maximum rate of change in length (dark blue contractional regions) migrates with the deformation fronts of the pro and retro wedges as they develop. The frictional experiment in Video DR4 never demonstrates any extensional strain rate. In Video DR5, a similar series for the layered experiment (friction/viscous), there is a similar development of the pro and retro wedge fronts but there is also a small amount of extensional deformation (dark blue region above the line) that occurs only after large gradients in topography have developed. Figure DR6 shows a layered experiment in which the ductile layer was initially thinner than in the Figure 3 experiment. When this second layered experiment was run at similar displacement rates as for the experiment in Figure 3, our analysis shows a component of margin-normal extension only when back wall motion was stopped. While the ductile layer was present it was sufficiently strong (due to higher strain rates) during active convergence that it did not to allow margin-normal extension to occur. Such extension occurred with this thinner layer only after active convergence (wall motion) stopped.
**DR4 Video: Analysis of frictional experiment.** Series of velocity, strain rate, and cumulative strain profile plots for all intervals of the experiment.

**DR5 Video: Analysis of layered experiment.** Series of velocity, strain rate, and cumulative strain profile plots for all intervals of the experiment.

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**Figure DR6 (a-e): Experiment with an oblique dual rheology wedge in which the frictional lid predominates (11 mm sand over 3 mm gel, vs. 9 mm sand over 4 mm gel in the first layered experiment).** Plan-view image-(a) is taken shortly before (b), but well after the end of wall-driven ‘plate motion’ ends: the difference between them shows post-tectonic relaxation during that interval. In (c), two measured topographic profiles are overlain to show the collapse of topography (before – black; after – red). The collapse is primarily located near the topographic high but a small amount of displacement propagates down-slope into the fore- and hinterlands, shown in (d). While the co-tectonic deformation has a large margin parallel component (profile not shown), the ‘post-tectonic’ deformation is dominated by almost pure margin normal extension at high altitude (e), extending parallel to the largest topographic gradients.
Supplemental References
