# Cyclical behavior of thrust wedges: Insights from high basal friction sandbox experiments

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## ABSTRACT

**Scaled sandbox experiments with high basal friction, simulating the growth of accretionary wedges, display cycles alternating between frontal imbricate thrusting and underthrusting of long, undeformed sheets. By contrast, low basal friction experiments with otherwise similar and constant, initial conditions produce a classic frontal imbricate fan through repeated failure along frontal thrusts. The cyclical behavior observed in high basal friction experiments is expressed by three quantities: (1) the average spacing between frontal thrusts, (2) the advance and retreat of the deformation front, and (3) the frontal slope ($\alpha$) of the actively deforming wedge. As a long sheet is underthrust, the front is steepened through slumping until the maximum critical angle is reached. Then frontal thrusting resumes and the accretion of imbricate slices builds the wedge forward, thereby lowering the taper to the minimum critical angle. At shallow tapers, a long unit is underthrust and subsequently uplifts, shortens, and steepens the overlying wedge through backthrust deformation, thus completing the cycle. Underthrusting of long units offers a simple mechanism for underplating overlying units. It also provides a possible explanation for temporally and spatially varying wedge geometries in nature, when basal frictions attain 80%–90% of the internal friction.**

## INTRODUCTION

The tectonic evolution of active thrust wedges cannot be observed directly because of the time scales involved. Thus, the structures viewed in depth (from seismic profiles) or the surface morphology (topography or bathymetry) represent a snapshot in time. The kinematic history must be reconstructed using structural geological principals and techniques (e.g., section balancing) or can be forward modeled through analog modeling. Lateral variations in wedge morphology in a single trench-accretionary wedge system (Moore et al., 1990) and wide variations in the length of thrust slices (Bangs et al., 1990) raise suspicions that accretionary processes may not be steady state. In order to test this hypothesis, a series of more than 20 sandbox experiments were performed with a wide range of initial conditions. In all accretionary high basal friction experiments, cyclical behavior was observed, alternating between frontal accretion of imbricate thrust slices and underthrusting of long, undeformed sheets.

Scaled sandbox modeling has been applied by numerous investigators to model the growth of accretionary prisms and fold-and-thrust belts (Davis et al., 1983; Malavieille, 1984; Mulugeta, 1988; Liu et al., 1992; Lallemand et al., 1994). Sand is a good choice for an analog material because it has low cohesion and obeys a Coulomb failure criterion, most appropropriate for modeling deformation in the brittle uppermost 10–15 km of convergent margins. The reproduction of numerous fold-and-thrust structures (e.g., fault-propagation fold, conjugate fore- and backthrust sets, imbricate thrust fans) has confirmed the validity of this approach. Good agreement has been demonstrated between predictions made by Mohr-Coulomb wedge theory and observed wedge geometries for low-basal-friction experiments (Davis et al., 1983; Dahlen, 1984). Some investigations have suggested a positive dependence of basal friction and fault spacing (Mulugeta, 1988; Liu et al., 1992); mechanical analysis (Platt, 1988) predicts the same. First investigations with a deformable backstop and subducted material leaving the system (Kukowski et al., 1994) have demonstrated that frontal accretion and erosion at the base of the backstop can occur simultaneously.

Modeling of accretionary processes occurring over several million years requires experiments with large convergence (representing 100+ km in nature). This allows observation of any deviation from an initial stable wedge configuration. By contrast, analog experiments with small convergence (5–10 times layer thickness) and without an initial wedge shape (Coletta et al., 1991; Mulugeta and Koyi, 1992) are well suited to model the initiation and deformation of individual thrust faults, but are less appropriate for studies of convergent margins because equilibrium (critical taper) is barely attained before the experiment is terminated. The results presented here are from the first large convergence (~70 times layer thickness) experiments, with constant, accretionary conditions.

## EXPERIMENT

The experimental apparatus consists of a 240-cm-long, 30-cm-wide, glass-sided box (Fig. 1). Well-sorted eolian quartz sand, 300–500 $\mu$m in diameter, with $\rho$ = 1600 kg/m$^3$, an internal coefficient of friction of $\mu$ = 0.6, and low cohesion ($C_0$ = 20 Pa) is sprinkled on a polyvinyl chloride (PVC) plate. Untreated, the PVC plate has a low basal friction of $\mu_b$ = 0.35, and applying

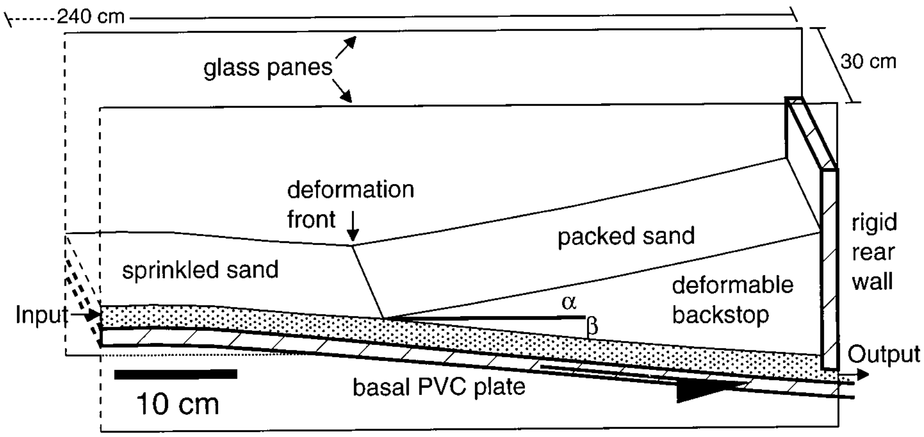

**Figure 1. Perspective view of experimental apparatus: basal polyvinyl chloride (PVC) plate can be treated to produce different basal frictions (e.g., double-sided adhesive tape = high).**

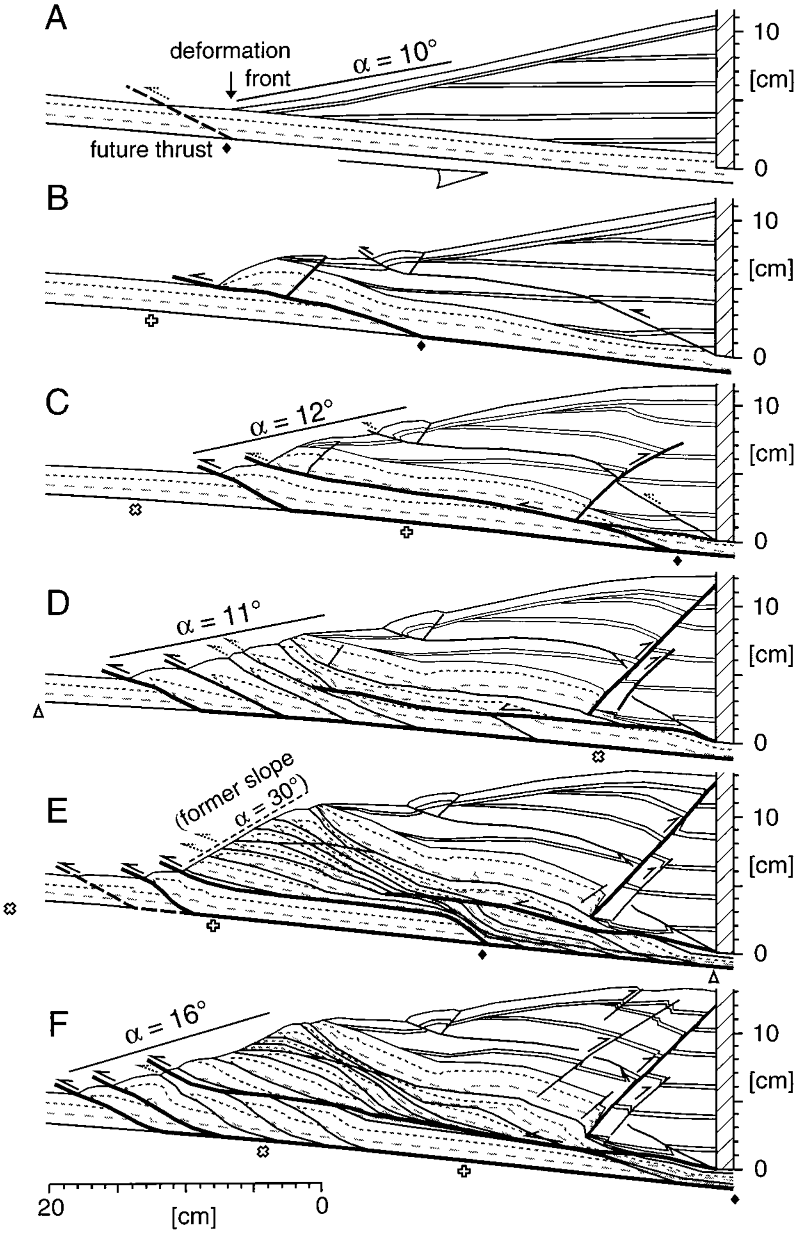

**Figure 2. Evolution of high basal friction experiment with increasing convergence. A: 0 cm—initial stage; B: 15 cm; C: 35 cm; D: 75 cm; E: 120 cm; F: 140 cm—final stage. Thick solid lines = active faults; arrows show sense of motion (dotted arrows represent initiating or reduced motion); thinner single lines = inactive faults; light dashed and dotted lines are passive markers indicating deformation. Some frontal slope measurements are shown. Note markers—e.g., diamonds and crosses—indicating progressive advance of polyvinyl chloride plate. Initial conditions: input = 2 cm, output = 1 cm, α = 10°, β = 6°, backstop is packed sand.**

double-sided adhesive tape produces a high basal friction of $\mu_b = 0.5$. The sand thickness is termed "input." The rigid rear wall can be raised or lowered to the desired aperture, allowing a fixed amount of material to leave the system (termed output) (Kukowski et al., 1994). A wedge of deformable material (packed sand, $C_0$ ~100 Pa) is placed against the rear wall, overlying the sprinkled sand, and represents a neo-prism (i.e., the initial wedge configuration at a hypothetical convergent margin). For the scaling factor of $10^{-5}$, 1 cm in the box represents ~1 km in nature. Thus the model sediment and backstop cohesion scale to 2 and 20 MPa, respectively, which are reasonable values for unconsolidated and lithified sediments (Hoshino et al., 1972). One typical high basal friction experiment is presented here with a constant 2 cm input (representing sediments on subducting oceanic lithosphere) and a constant 1 cm output (measured on the PVC plate after exiting the system). The cyclical behavior described here was observed in seven other high basal friction experiments with outputs ranging from 0% to 50% of the input thickness.

A frontal thrust develops immediately at the apex of the initial wedge (Fig. 2A). The roof thrust remains active as this first unit is underthrust beneath the sand wedge, with very little internal deformation (Fig. 2B). Between 30 and 35 cm of convergence, the roof thrust blocks, a major backthrust develops, deforming the overlying "backstop," and then a new basal thrust propagates forward, initiating a new frontal thrust (Fig. 2C). Seven imbricate slices accrete during the frontal accretion phase of the cycle and the wedge grows forward rapidly. Shearing of the lower portions of the imbricate slices occurs along a mid-level detachment (Fig. 2D). During the ensuing underthrusting phase of the cycle, the wedge deforms internally and is pushed up and back. The deformation front retreats as the front is oversteepened and eroded by slumping. Then the roof thrust bounding the top of the underthrusting unit jams once again. A new basal thrust propagates forward, emerging at the toe, and frontal thrusting resumes (Fig. 2E). The imbricate slices formed at the front are entrained into a subduction channel along a mid-level detachment (Fig. 2F). A total of 13 frontal thrusts formed in 140 cm of convergence, 12 of them during two episodes of frontal accretion.

The dramatic difference in tectonic style between high- and low-basal-friction experiments is seen when comparing the internal section of high-basal-friction experiment A ($\mu_b = 0.5$) (Fig. 3A) with the internal section of low basal friction experiment B ($\mu_b = 0.35$) (Fig. 3B). Both have the same constant 2 cm input and the same, constant 1 cm output and similar β and convergence. Internal sections of the experiment, made by moistening and cutting the final stage, provide a clearer view of the detailed structures, because there is no diffusion of the passive sand markers against the sidewalls. These differences can be quantified when considering (1) variation in frontal slope, (2) fault spacing, and (3) advance of the deformation front.

The frontal slope (α) is plotted as a function of convergence (Fig. 4A) along with the initiation of each frontal thrust. For high basal friction, the surface slope is shown to vary cyclically, decreasing during the imbricate thrusting phase of the cycle as the wedge builds out forward and increasing during the underthrusting phase of the cycle as the front is oversteepened by erosion along the emerging roof (or out of sequence) thrust. Low basal friction produces continuous frontal imbricate thrusting at fairly regular intervals of ~6 cm, and α maintains a nearly constant value, barely increasing, from 6° to 7°. A total of 24 frontal thrust slices form during 150 cm convergence, building a classic leading imbricate fan (Fig. 3B).

The position of the deformation front vs. convergence is also plotted for both experiments (Fig. 4B). For high basal friction there are periods of rapid retreat associated with underthrusting and pulselike advances when frontal thrusting builds the wedge forward. For low basal friction there is a more steady advance, though here too a modulation caused by the formation of individual thrusts is observed, similar to that reported in a previous study (Mulugeta and Koyi, 1992).

## SIMPLE MECHANISM FOR UNDERPLATING

The advance of long underthrust sheets provides a simple mechanism for underplating overlying units. The mechanism demonstrated in high basal friction experiment A is illustrated schematically (Fig. 5). At first, imbricate thrust slices build at the front, and the lower parts are sheared at a mid-level detachment. These entrained duplexes are then uplifted over the ramp at the tip of a long underthrusting sheet. Next, displacement occurs along a major backthrust, and a new basal thrust propagates forward, emerging at the toe as a frontal thrust. The units above the now inactive roof thrust are truly underplated, i.e., they are no longer displaced toward the arc and have become part of the overriding plate. The internal structure of experiment A (Fig. 3A) resembles this underplated duplex configuration (Fig. 5). Compare the advance of the underthrusting sheet (position of asterisk in Fig. 5, A–C) to the progress of the diamond markers in experiment A (Fig. 2, E and F), where two full accretionary cycles are observed.

## DISCUSSION

The cyclical behavior observed in high-basal-friction sandbox experiments produces wide variations in wedge geometry, despite constant experimental conditions and material parameters. Underthrusting of long sheets is associated with an oversteepening of the frontal part of the wedge and an arcward retreat of the deformation front. Frontal accretion builds the wedge rapidly forward and lowers the surface slope. These tectonic processes offer a model to be tested by direct observations of submarine accretionary prisms.

Most research on accretionary wedges has

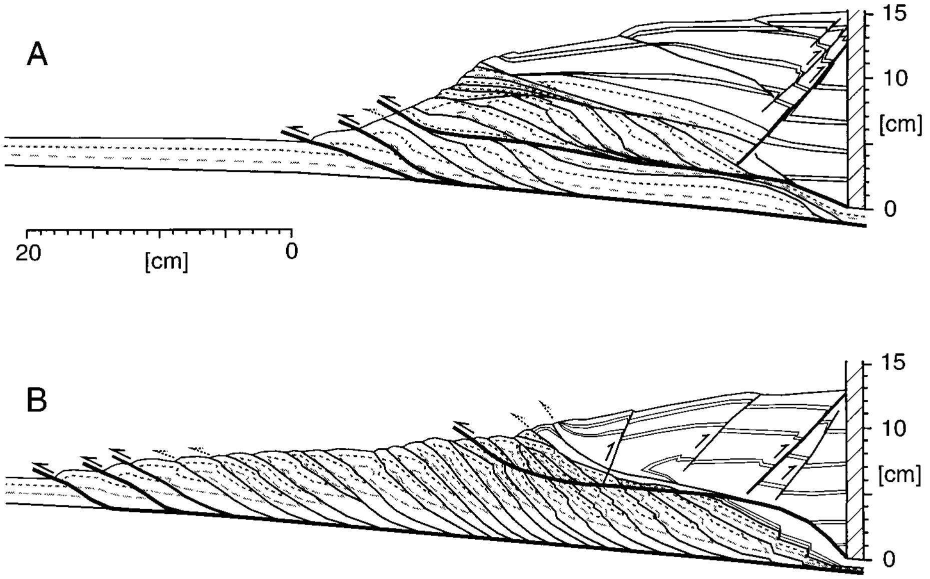

**Figure 3. A: High basal friction experiment A ($\mu_b = 0.5$), internal section of final stage (140 cm). B: Low basal friction experiment B ($\mu_b = 0.35$), internal section of final stage (150 cm). Lines and arrows as in Figure 2. Initial conditions: input = 2 cm, output = 1 cm, α = 6°, β = 4°, backstop is packed sand.**

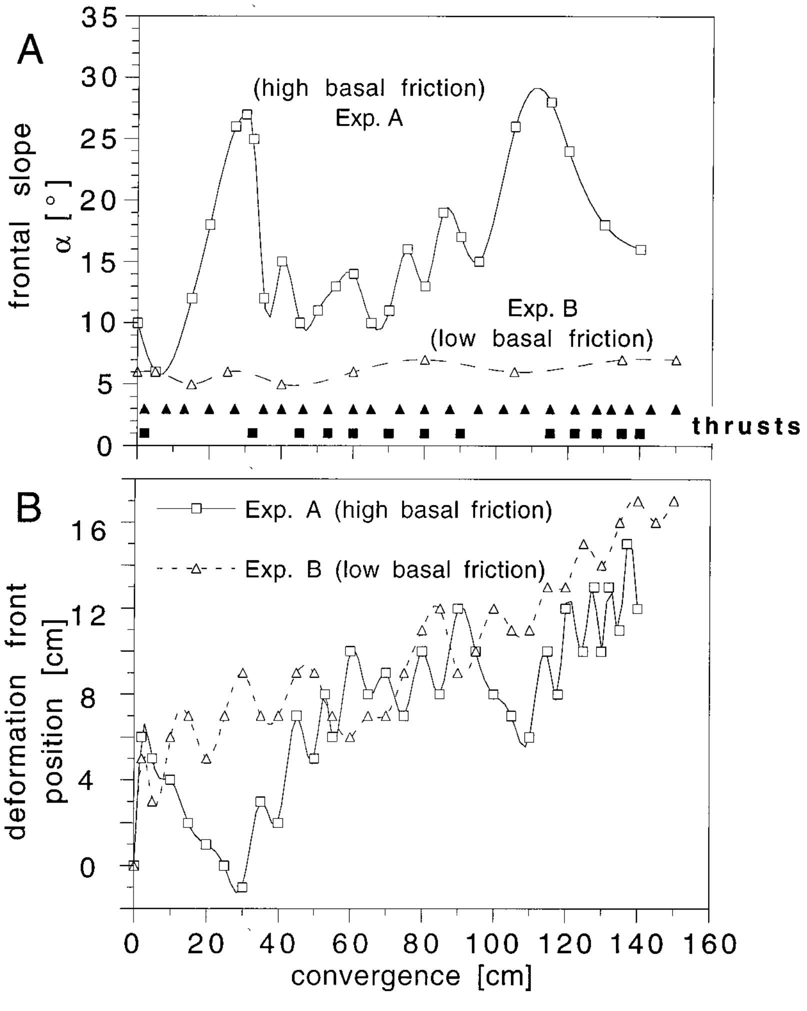

**Figure 4. A: Frontal slope (α) vs. convergence for high basal friction experiment A (squares) and low basal friction experiment B (triangles), including initiation of each new frontal thrust. B: Position of deformation front vs. convergence.**

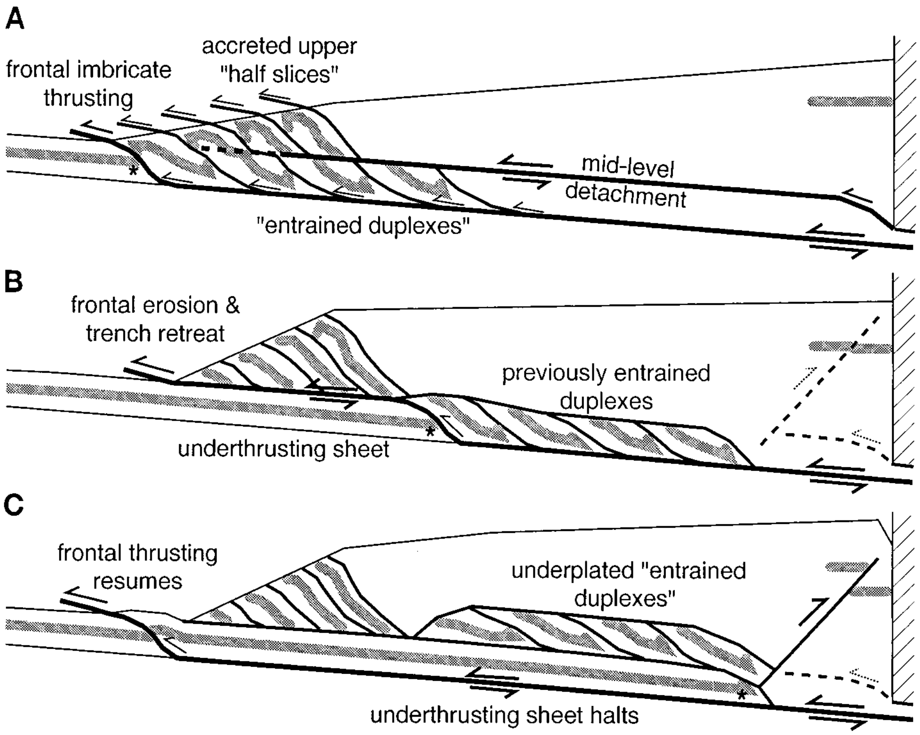

**Figure 5. A: Frontal accretion and shearing of imbricate slices. B: Early underthrusting with steepening of the frontal slope. C: Underplating of entrained duplexes with resumption of frontal thrusting. Note asterisk at tip of advancing unit.**

focused on models where the basal friction is very low due to elevated fluid pressure along the decollement (Bangs et al., 1990; Davis and von Huene, 1987; Byrne and Fisher, 1990; Platt, 1990). However, depending on the rate of plate convergence, sediment deposition, compaction, and fluid expulsion, and the presence of permeable or impermeable horizons, a wide range of fluid pressures and material parameters is possible, including cases with high basal friction. Where the basal friction of the accretionary prism is high (80%–90% of the internal friction), one could expect to find a cyclical deformation mechanism similar to that described here.

Future work will include a mechanical analysis of the forces and work involved in both modes of accretion reported here, as well as interpretation of depth-migrated seismic reflection profiles. Published data from the Nankai and Eastern Aleutian prisms (Moore et al., 1990, 1991) image a variety of accretionary structures (frontal imbricate slices, long sequences of underthrust sediment, and out of sequence thrusts) comparable to those observed in these analog experiments. Field studies of underplated units in an exposed, Cretaceous accretionary complex on Kodiak Island, Alaska (Sample and Fischer, 1986; Fisher and Byrne, 1987), reveal flat, out-of-sequence thrusts cutting imbricate structures, as shown in Figures 3A and 5C. Thus there is ample evidence suggesting that similar mechanisms may operate in currently active thrust wedges.

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