Development of slip partitioning within wet kaolin and dry sand oblique-convergence experiments

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Abstract

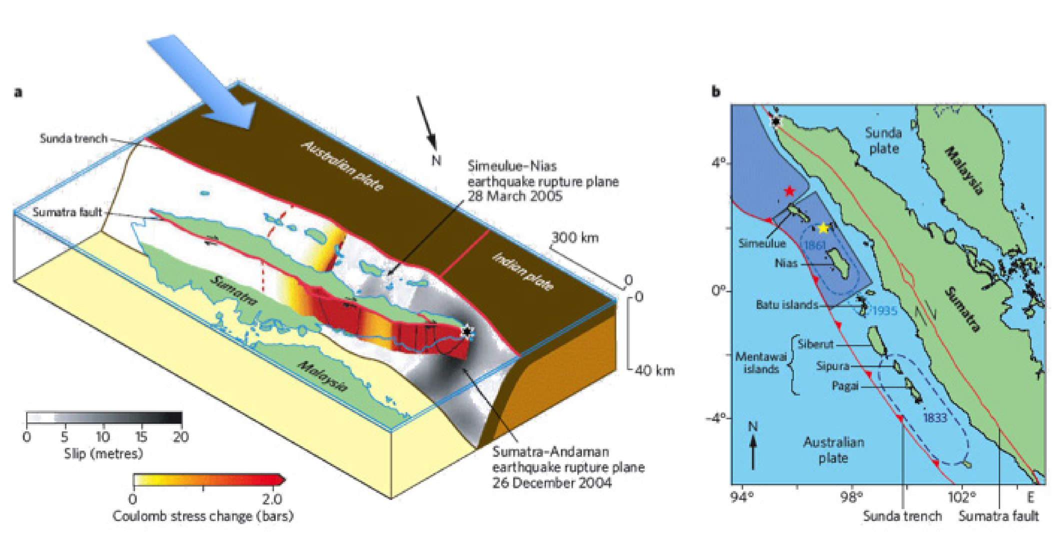
Slip partitioned systems can accommodate oblique convergence with different slip rake on two or more faults and are well documented; however, the evolution of slip partitioned crustal systems is unconstrained. Carefully scaled physical experiments in crustal analogs inform our understanding of fault evolution because we can control the loading and directly observe the ensuing deformation. Using experiments in both dry sand and wet kaolin clay we explore how slip partitioning evolves under different convergence angles. Previous cohesionless dry sand experiments documented that convergence angle and fault strength control slip partitioning. In contrast to dry sand, the non-zero cohesion of wet kaolin produces long-lived fault structures that easily reactivate. Scaled experiments using both dry sand and wet kaolin with identical boundary conditions provide insights on the role of material properties in slip partitioning. We use motorized movement of rigid blocks overlaid by a layer of dry sand or wet kaolin clay to approximate crustal deformation due to oblique subduction zone convergence. Digital image correlation combined with stereovision techniques provides evolution of horizontal strain and uplift that constrain fault geometry and slip vectors along the faults. Additionally, force gauges record the evolution of fault-normal forces throughout slip partitioning, such as stress drops associated with fault growth. Within the dry sand, an oblique-slip forethrust-backthrust pair forms first followed by a late stage through-going strike-slip fault. In contrast, at shallow convergence angles within the clay, the strike-slip fault forms first and a backthrust never develops. As convergence accumulates in the clay, a forethrust forms dipping toward the underlying discontinuity. The lack of cohesion in dry sand may prevent the concentration of mode III stresses that leads to the early vertical strike-slip fault growth observed in the clay. The cohesion of the clay, which is similar to crustal rock strength, may facilitate the maintenance of slip partitioned fault systems.

Slip Partitioning in the Crust

Slip partitioning can occur at multiple scales within the crust and ranges from local convergence within restraining bends (e.g., the Transverse Ranges of the southern San Andreas Fault) to thousands of kilometers across along subduction zones such as the Great Sumatra Fault (right) or median tectonic line in Japan (e.g., Bowman et al., 2003; Jones & Wesnousky, 1992; Fitch, 1972).

At the subduction zone scale, slip partitioning occurs along two margin parallel faults with a characteristic geometry: a dipping oblique slip fault along the trench and a continental vertical strike-slip fault (Fitch, 1972).

Due to their crustal scale, these faults are capable of producing some of the largest magnitude earthquakes in recorded history including the devastating Sumatra-Andaman earthquake of 2004 and the more recent 2011 Tohoku Oki earthquake in Japan.



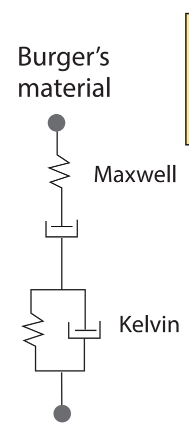
Above, a three-dimensional schematic of the Sumatra subduction zone depicts the oblique-thrust fault along the Sunda trench where the Australian and Indian plates subduct beneath the Sunda plate. Map view shows the parallel trending strike-slip fault bisecting Sumatra. *Modified from Nature 435,756-757 (9 June 2005).*

Experimental Design

Three plastic blocks with abutting 30° contacts drive a 2.5 cm overlying layer of dry sand (320 µm) or wet kaolin. The blocks are positioned on two plates: one fixed and the other moved along the x- and y-axis by two stepper motors.

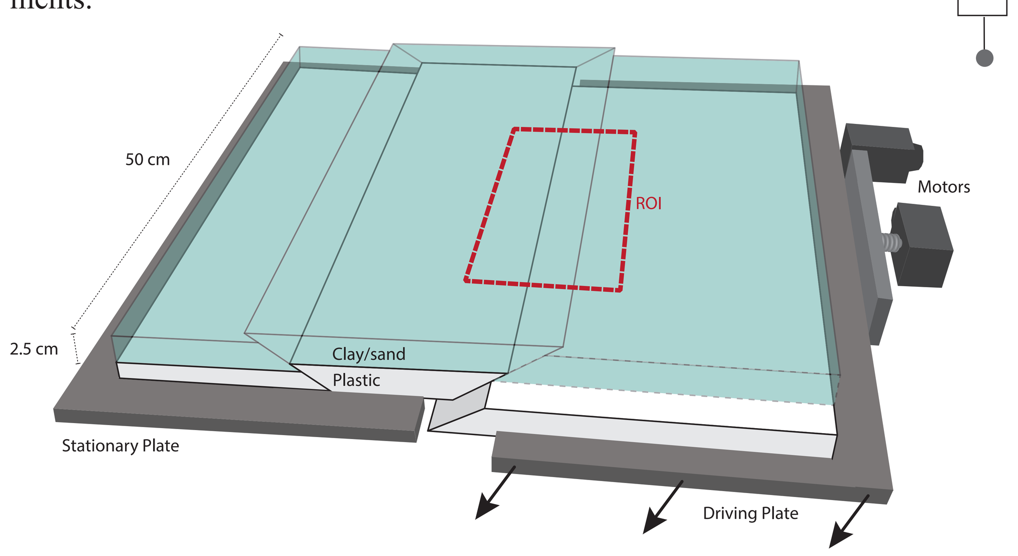
A calibrated stereo camera system mounted above the model captures high-resolution images of the region of interest (ROI). A force sensor embedded in the clay, or attached to the plate for sand models, records the variations in fault normal stresses throughout the experiments.

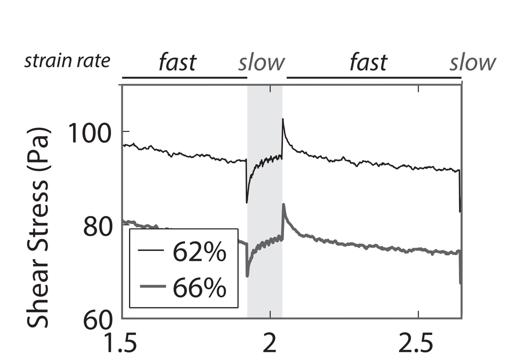
LENGTH SCALING[3,4]
Dry Sand: 1 cm = 5 km crust
Wet Kaolin: 1 cm = 0.75 - 1.4 km



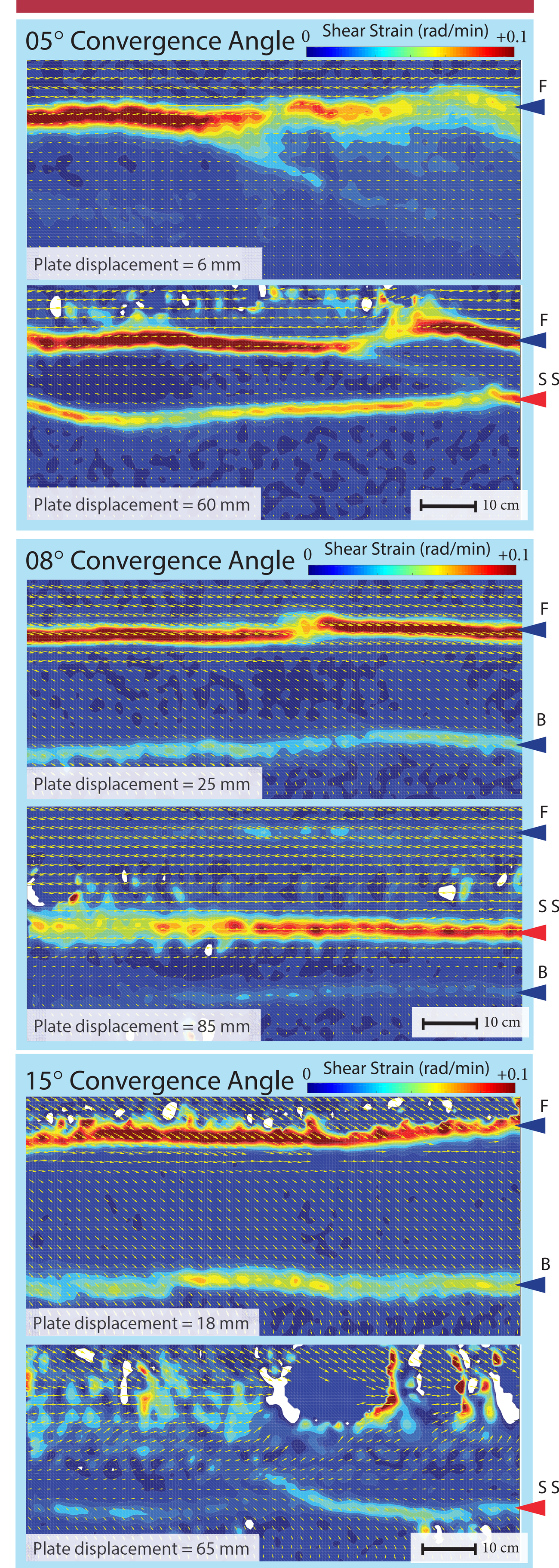
We measure the clay's shear strength by fall cone method and adjust to 90-115 Pa by varying the water content (70% by weight).

Wet Kaolin clay deforms as a bi-viscous Burger's material exhibiting rate and state behavior at failure[5] (below).





Dry Sand

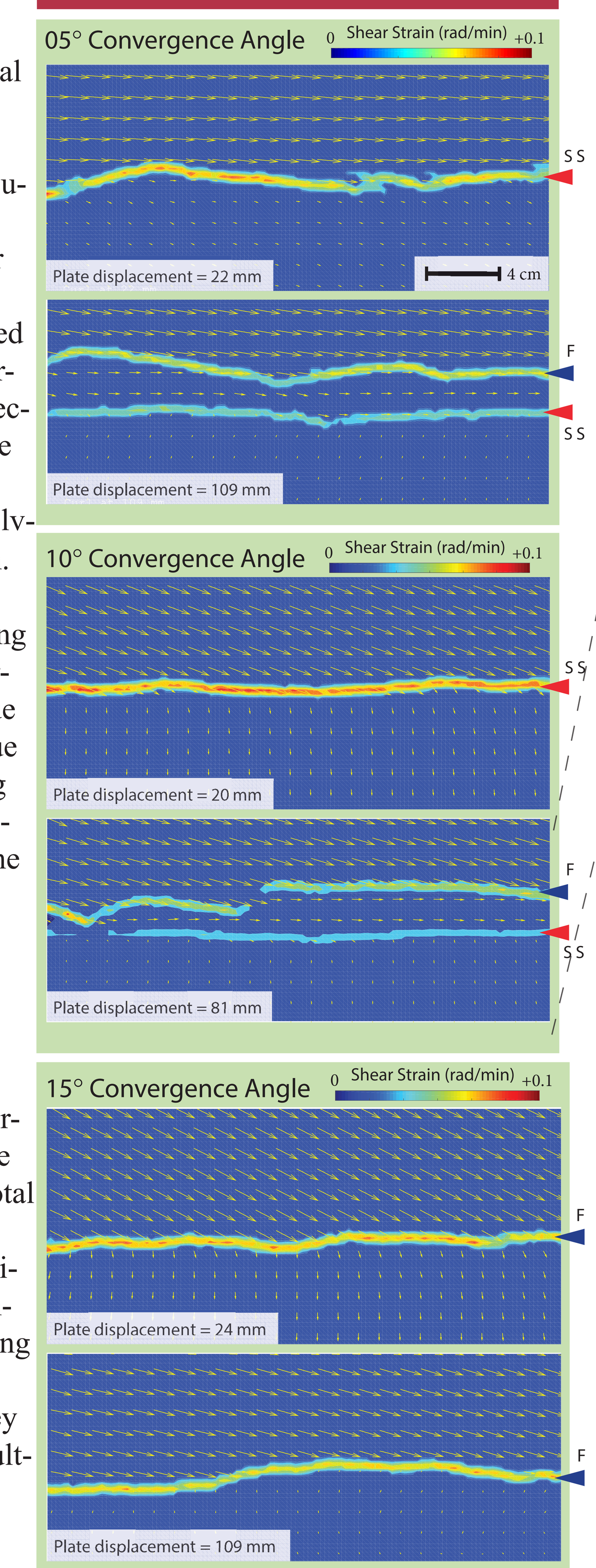


Incremental shear strain maps overlaid by horizontal displacements for experiments in dry sand and wet kaolin. Shear strain is calculated using the curl of displacement. A critical shear value for faulting is determined emperically and used to create a fault map. Overlaying the displacement vectors from PIV on top of the fault maps reveals the slip style of faulting in the evolving slip partitioned system.

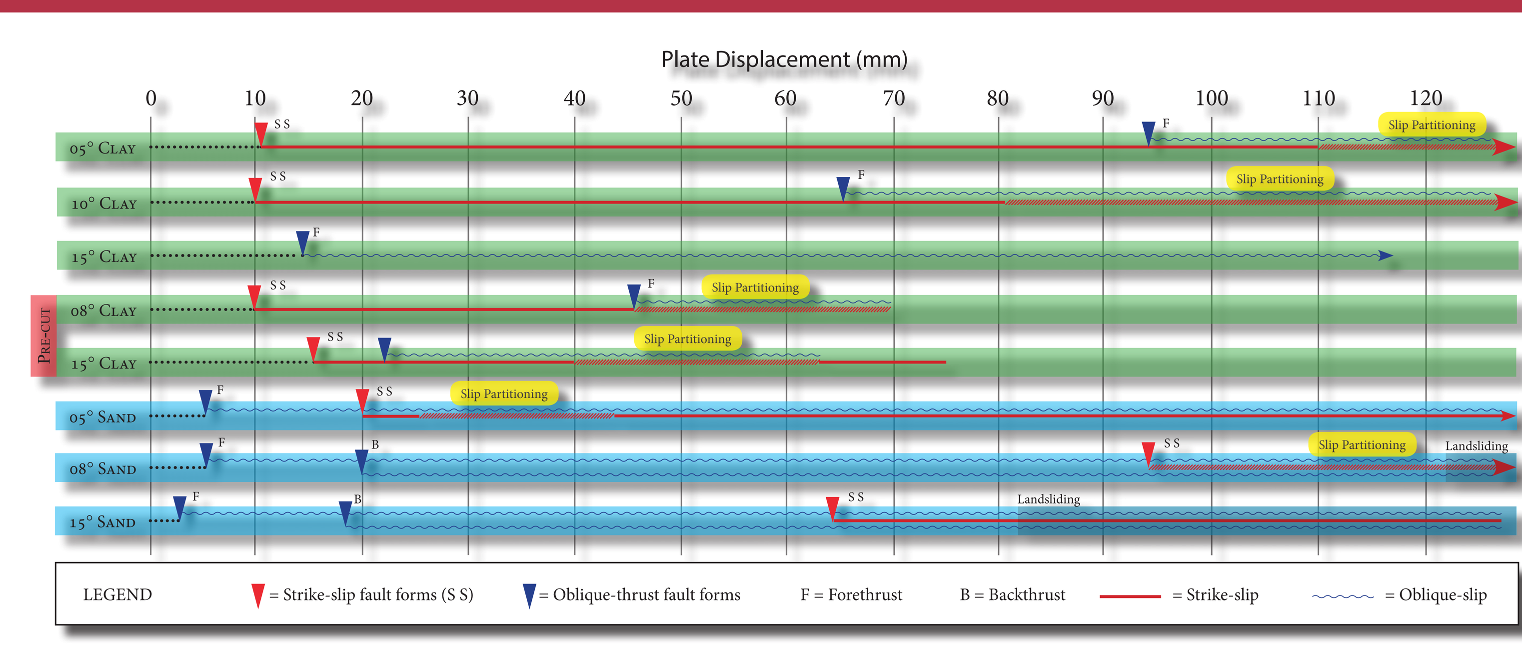
Note early slip partitioning (85 mm) in the sand experiments along active oblique fore- and back-thrusts (blue arrows) and through-going strike-slip fault. Slip partitioning develops later in the 05° clay experiment (109 mm) as an oblique forethrust (F) and strike-slip fault (red arrows-SS).

Slip partitioning fails to develop in either 15° experiment over the tested range of total strain. At higher total strain (>65 mm plate displacement) the sand experiments begin to develop unstable slopes and landsliding obscures detailed analysis of fault activity (e.g. noisey vectors in the 15° sand fault-map on bottom left).

Wet Kaolin

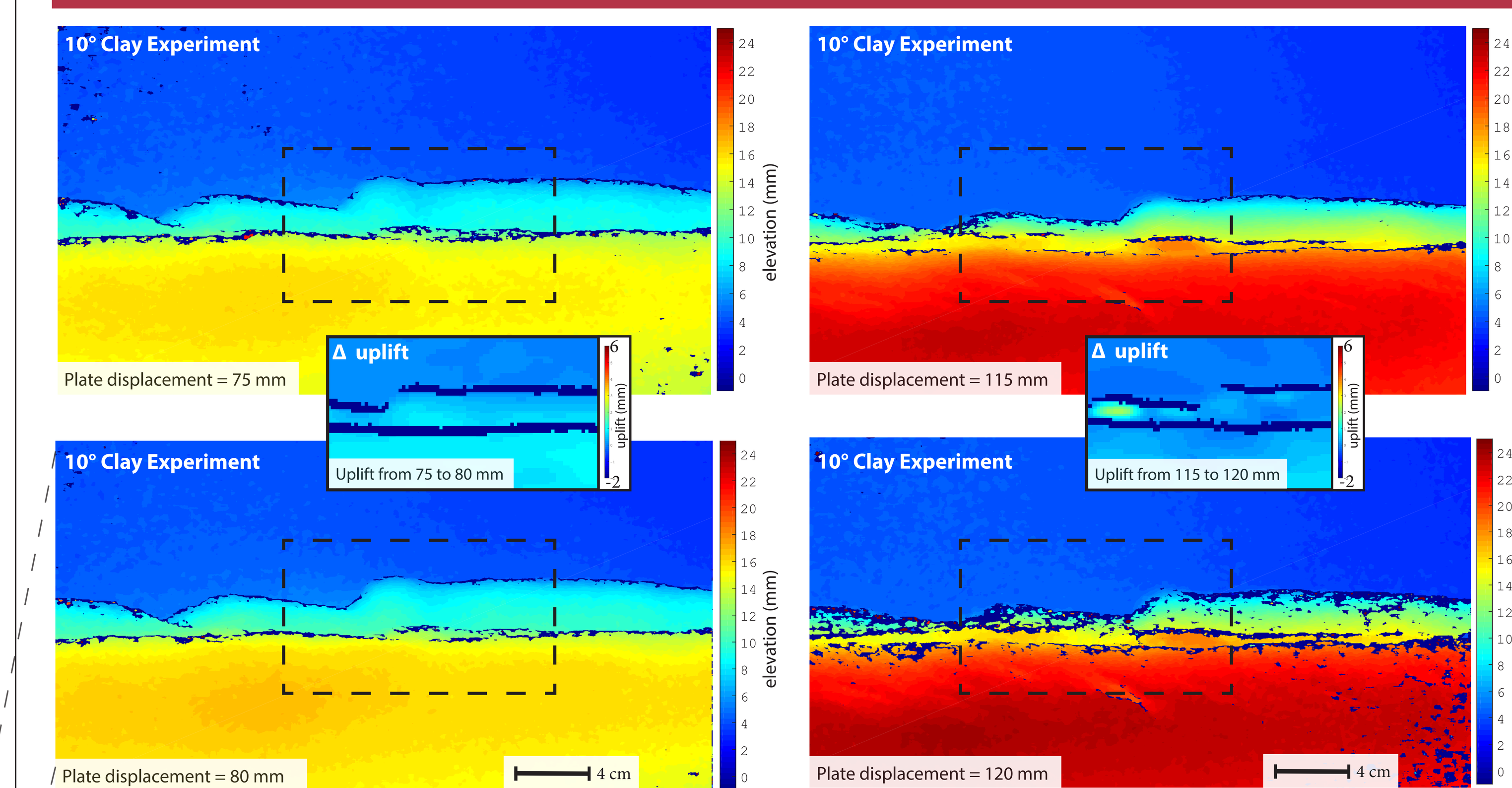


Timeline of Slip Partitioning Evolution



Summary of fault timing reveals how convergence angle, analog material, and the presence of a pre-existing weakness (pre-cutting a vertical fault) affect the development and maintenance of slip partitioning. The wet kaolin experiments form a strike-slip fault (red arrowheads) early before the oblique-thrust (blue arrowheads). In contrast, the sand experiments form an oblique-slip forethrust (F) backthrust (B) pair before a through-going strike-slip fault facilitates slip partitioning. Only the pre-cut clay 15° develops slip partitioning, the other 15° experiments only form a single oblique slip fault. The onset of slip partitioning in the clay is later for lower convergence angles (opposite for sand) and earlier in pre-cut clay experiments than uncut.

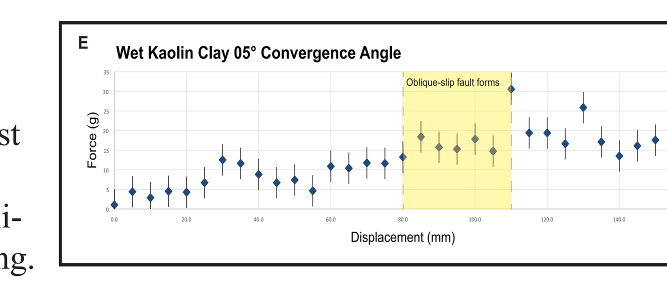
Uplift From Stereovision

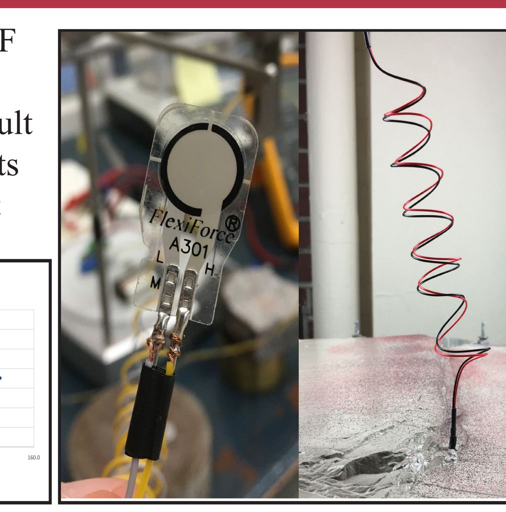


Stereovision records the 3D topography throughout the experiments providing the incremental uplift. Uplift maps show where vertical strain accumulates between faults in addition to providing uplift rates across the faults, which can be converted to dip slip rates with knowledge of fault dip. Insets of incremental uplift show how the pattern of uplift rate between the strike-slip and oblique-thrust faults varies as slip partitioning begins to subside.

Measuring Stress Changes with Pressure Transducers

A Tekscan® FlexiForce A301 (0-1 lb) force sensor and Tekscan® ELF handle record pressure changes in the clay at 8 Hz. The force sensors are oriented with the sensing area parallel to the vertical strike-slip fault plane to maximize the signal from fault normal stress changes as faults initiate. Results from the 05° clay experiment (below) show a distinct increase in force immediately preceding the formation of the oblique-slip fore-thrust suggesting an "unclamping" effect facilitates strike-slip faulting.





Discussion/ Conclusions

1. Dry sand: an oblique-slip forethrust-backthrust pair forms first followed by a late stage through-going strike-slip fault
2. Wet Kaolin clay: the strike-slip fault forms first and a backthrust never develops, a forethrust forms dipping toward the underlying discontinuity
3. The lack of cohesion in dry sand may prevent the concentration of mode III stresses that leads to the early vertical strike-slip fault growth observed in the clay.
4. The cohesion of the clay, which is similar to crustal rock strength, may facilitate the maintenance of slip partitioned fault systems.
5. Pre-existing crustal weaknesses, such as from back-arc volcanism along a subduction zone, play an important role in the timing of slip partitioning.
6. Due to the high obliquity of the tested convergence angles, these experiments however, likely more appropriately model smaller scale transpressional systems such as the West Spitsbergen fold-and-thrust belt or Transverse Ranges of the San Andreas Fault system rather than larger scale subduction zones.

Acknowledgements

[3]Leever, K. A., Gabrielsen, R. H., Sokoutis, D. and Willingshofer E., 2011. The effect of convergence angle on the kinematic evolution of strain partitioning in transpressional brittle wedges: Insight from analog modeling and high-resolution digital image analysis. Tectonics, 30, 1–25.

[4]Hatem, A. E., Cooke, M. L., Madden, E. H. (2015). Evolving efficiency of restraining bends within wet kaolin analog experiments. J. of Geophys. Res. Solid Earth, 120.

[5]Cooke & Van der Elst, 2010, etc. Cooke, Michele L and Nicholas J. van der Elst, 2012. Rheologic testing of wet kaolin reveals frictional and bi-viscous behavior typical of crustal materials, Geophysical Research Letters, vol. 39, L01308.

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