Physical modeling of locked-to-creeping behavior transition along a strike-slip fault

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ABSTRACT

Physical modeling provides an opportunity to explore the formation and evolution of strike-slip systems where individual parameters are varied across different experiments. Previous experimental studies of strike-slip systems have explored such parameters as restraining and releasing bend geometry, shear distribution, and seismic cycles. This study examines deformation in a strike-slip fault system at a transition point, defined as the point where slip behavior changes from locked-to-creeping. I use a physical model to investigate the effects on off-fault deformation at varied creep rates.

Experiments use either a single layer of silicone, to help visualize patterns of deformation, or two layers: wet kaolin on top, to mimic the upper-crust, and silicone below, to mimic the mid-crust. I vary the strain rate in the experiments in four ways: (1) slow creep rate (0.2 cm/s) for a relatively long period, (2) slow creep rate (0.2 cm/s) for a relatively short period, (3) fast creep rate (varied by force applied), and (4) fast creep rate (again varied by force applied) preceded by a period of relatively slower creeping.

The vector patterns of average velocity fields obtained from particle image velocimetry did not differ significantly across the different strain rate experiments. Every experiment developed a zone of contraction on one side of the fault and a zone of extension on the other, as is mechanically expected. This suggests that the average velocity fields due to creep at a transition from locked-to-creeping slip behavior are independent of creep rate. However, the patterns of deformation within the wet kaolin layers revealed significant differences in structures that formed at varying creep rates. At slow rates, the wet kaolin behaved as a "brittle" material, while at fast rates, the wet kaolin behaved as a "ductile" material. These physical modeling results may have implications for the development of structures within and adjacent to actively creeping faults, such as the San Andreas and Hayward faults.

Keywords: Physical models, slip rates, velocity analysis, deformation, creeping
INTRODUCTION

Physical modeling is a widely-used technique that purposefully simplifies nature so that the evolution of geologic processes can be analyzed on a manageable scale, both temporally and physically, and then compared to real world settings. Strike-slip fault systems are an example to which physical modeling can be applied in order to form a better understanding of complex and varied structures observed. This study utilizes physical modeling to explore the transition of slip behavior from locked-to-creeping, a specific characteristic observed along various strike-slip faults such as the San Andreas and Hayward faults in California. The previous physical modeling work done for intraplate, strike-slip tectonics includes the evolution of fault formation and the effects of shear distribution, fault geometry, and strain accumulation on fault systems, which this project expands upon (e.g., Riedel, 1929; Naylor et al., 1986; Dooley and Schreurs, 2012; Caniven et al., 2015; Hatem et al., 2015).

Previous Physical Modeling Studies

There are two basic experimental set-ups used to study strike-slip systems. Riedel experiments, the first and most fundamental strike-slip model set-up, explore the transfer of deformation from a straight, vertical basement fault that experiences pure, strike-slip to the surface of the overlying material beginning from an undeformed state (Riedel, 1929). Riedel experiments done in either sand or clay each have distinct advantages. Clay (kaolin) models, such as those presented by Tchlenko (1970), Wilcox and others (1973), and Atamaoui and others (2006), best show two-dimensional structures on the surface of the model. The shears that form include R, P, Y and R' shears; en echelon R shears form
first at a ~12° strike from the basement fault (Fig. 1A). Then, as displacement continues, those shears rotate parallel to the basement fault and connect into a principal displacement zone, the Y shear zone (Fig. 1A). Finally, a through-going fault parallel to the basement fault accommodates the majority of shear (Fig. 1A). Dry sand models do not show the structural variance and detail of surface shears that clay models do. However, they allow for three-dimensional geometry to be analyzed. On the surface, Riedel shears begin forming at a slightly higher strike (17° to 20° from parallel to the basement fault) than in clay models (Naylor et al., 1986). Naylor and others (1986) and Richard and others (1995) showed that each Reidel shear has a three-dimensional helicoidal geometry, more commonly referred to as a wrench or flower structure, where the shear changes its dip direction midway above the basement fault affecting principal stress orientations (Fig. 1B).

The second type of experimental set-up used to study strike-slip systems are distributed strike-slip shear experiments. This experimental set-up helps to rectify some of the differences that are seen between the narrow band of deformation seen in pure, strike-slip Riedel experiments and the wide zones of deformation seen in Earth’s lithosphere. In these experiments, the shear is distributed by a ductile layer below a brittle overlying material (Mandl, 1988; Schreurs, 2003). En echelon R shears form at 17° to 24° from parallel to shear direction and eventually coalesce into master faults with overall 15° strikes to parallel to shear direction (Mandl, 1988; Schreurs, 2003). Schreurs (2003) outlines how the results from his and similar experiments may be applied directly to identify strike-slip faults with distributed shear characteristics.

Once the experimental set-up is established, parameters, such as fault geometry
Figure 1. (A) Riedel experiment in wet clay. Adapted from Naylor et al. (1986) and Tachlenko (1970). (B) Cross-sectional geometry schematic of Riedel R shears in dry sand from actual physical model experiment. Adapted from Mandl (1988). (C) Top-down view of the evolution (I–V) of a pull-apart basin over a releasing stepover in a physical model composed of an underlying layer of silicone and an overlying layer of packed sand. Adapted from Dooley and Schuers (2012). (D) Top-down view of a model showing the evolution (I–V) of a pop-up structure over a restraining stepover. Adapted from Dooley et al. (1999).
and strain orientation, can be altered beyond a simple straight fault to study their effects on the system. One example is the effects of transpression and transtension on Riedel and distributed shear experiments (e.g. Naylor et al., 1986; Scheurs and Coletta, 1998). Naylor and others (1986) demonstrated both transpression and transtension in a sand, pure strike-slip, Riedel experiment. Transtension results in a narrower deformation zone because initial shears form close to parallel to the basement fault and require little displacement to form a through-going fault. Transpression produces more complex shear patterns and a more pronounced helicoidal geometry. This is because initial shears form at high angles with respect to the basement fault that are followed by the formation of shears between those initial, high-angle shears that are more parallel to the basement fault. In contrast, Scheurs and Colletta (1998) modeled distributed shear zones with transpression and transtension. They found that the angle of obliquity of shear governs the types of faults that accommodate shear: at a low obliquity, for both transpression and transtension, shear was initially taken up by strike-slip motion, while, at high obliquity (> 18˚) initially transpressive and transtensive shear was accommodated by thrust and normal faults, respectively. For all distributed shear experiments, after ample displacement, shear was taken up as oblique slip on favorably oriented faults.

The experiments reviewed above describe regional strike-slip tectonics. Step-over physical models, which model restraining and releasing bends, explore the deformation that results from local fault geometry when master faults are segmented as often observed in the real world (e.g. Dooley, 1994; Rahe et al., 1998; Dooley and Schreurs, 2012; Cooke et al., 2013; Hatem et al., 2015). Releasing bends are localized extensions known as pull-apart basins, while restraining bends are localized shortening that are often
referred to as pop-up uplifts (Fig. 1C and 1D). Parameters, such as the angle of offset, the separation distance between master faults, the presence of a viscous sublayer, and transpressive or transtensive elements, can be altered to produce differences in deformation between experiments (e.g. Dooley et al., 2004; Wu et al., 2009). From these various experiments, studies extrapolate a general evolutionary pattern for these structures (Dooley and Schreurs, 2012). Pull-apart basins begin with strike- and oblique-slip shears that propagate and link preferentially in the offset region eventually forming a sidewall-fault system, which outlines the limits of the structure, along with cross-basin fault systems (Fig. 1C; Rahe et al., 1998; McClay and Dooley, 1995; Dooley, 1994). Generally, these basins have a rhombic geometry, and, as Rahe and others (1998) demonstrate with cross-sections of sand models, they exhibit graben or half-graben vertical geometries depending on the symmetry of the basin (Fig. 1C). Pop-up structures are also lozenge to rhomboidal in shape, however a broad uplift zone forms first in the offset region followed by oblique-reverse faults that accommodate rotation of the central block (Fig. 1D; Hatem et al., 2015; Cooke et al., 2013; Dooley et al., 2009; McClay and Bonoro, 2001; Richard et al., 1995). Cross-sections of these models reveal a flower structure characterized by thrust faults at the limits of the pop-up or pull-apart structure that are shallow and flatten towards the surface (McClay and Bonoro, 2001; Dooley et al., 1999).

In addition to the formation and evolution of strike-slip systems, strain field and stress distribution due to seismic cycles—including interseismic, coseismic, and postseismic periods—on strike-slip faults are also of great interest to us because of their implications for earthquake studies (e.g. Bilham and King, 1989; Caniven et al., 2015). A
majority of studies done on this subject do not use physical models but instead use numerical models. Bilham and King (1989), for example, studied the spatial distribution of strain around a strike-slip fault and argue that both geometrically induced strain fields and spatial distribution of slip influence the morphology of the fault zone. They alter the geometry and slip rates along a theoretical fault and are able to attain results that are consistent with observed secondary deformation features on portions of the San Andreas fault. Among the few physical models that investigate strain and stress fields, Caniven and others (2015) use a two layer, visco-elasto-plastic physical model to study the mechanisms that control surface and deep crustal deformation during a full seismic cycle. They characterize interseismic, coseismic, and postseismic displacement, strain, and stress fields, slip distribution and profiles at the surface and at depth, and seismic cycle behavior to better understand how long-term stress-loading influences short-term stress-evolution during a cycle.

Current Physical Modeling Study

In order to expand on the various effects of different periods of the seismic cycle on strike-slip systems, this study explores the consequences of varying aseismic creep rate during an interseismic period, or the strain-accumulating period, at a transition point from locked-to-creeping slip behavior. Ross (2017), also prompted by the lack of physical models that evaluate deformation due to seismic cycles, developed a physical model of a locked-to-creeping transition along a strike-slip fault. She looks specifically at the off-fault deformation and velocity and strain fields that result from the continuous creeping of one portion of the fault while another portion is locked. This study builds
onto her work by exploring the effects of varying slip rate at the transition point on off-fault deformation adjacent to the fault. I use qualitative experimental results to evaluate the off-fault deformational structures that result from varying slip rates and particle tracking to compare velocity fields and displacement fields between experiments. The results from this study reveal a more complex picture than may be expected; while some results point to similar velocity fields between experimental types, the off-fault deformation observed that develops over the course of each experiment differed by experimental type. These differences may have implications for other studies’ field observations of off-fault deformation and interpretations of slip-rates at transition points along a strike-slip fault.

**METHODS**

**Analog Materials**

To simulate crustal rocks, I use two types of commonly applied geologic analog materials: silicone (PDMS SGM-36 by Dow Corning) and wet kaolin (Minnesota #6 tile clay). Numerous studies describe both materials’ physical properties and use these materials in various physical modeling experiments to simulate and compare results to crustal systems (Dooley and Schreurs, 2012; Cooke and Van Der Elst, 2012; Reber et al., 2014; Hatem et al., 2015). Silicone exhibits almost perfect Newtonian viscous behavior, thus shear rate and shear stress increase proportionally (Weijermars, 1985). Experimental viscosities of PDMS SGM-36 by Dow Corning range from 2 × 10^4 Pa·s to 5 × 10^4 Pa·s, and it has a density of 0.965 g/cm³ (Dooley and Schreurs, 2012). Silicone is widely favored among physical modelers and was chosen for this project as an analog for the
lower crust and upper mantle because of its viscoelastic qualities.

Wet kaolin is a good analog for studying deformation in the upper crust. When deformed, wet kaolin has been shown to develop clear and distinct faults that can be easily reactivated along with distributed deformation (Henza et al., 2009; Cooke and van der Elst, 2012; Hatem et al., 2015). Wet kaolin deforms as a viscoelastic Burger’s material, like the crust (Cooke and van der Elst, 2012). A Burger’s material can be described as a circuit containing springs, to represent elastic behavior, and dash-pots, to represent viscous behavior. Half of the circuit behaves like a Kelvin material in which the spring and dash-pot are in parallel such that deformation is fully-recovered, while the other half behaves as a Maxwell material where the spring and dash-pot are in series and, thus, not all of the deformation is recovered (Cooke and van der Elst, 2012).

For this study, the features of kaolin described above allow for a detailed observation of off-fault deformation and fault evolution. Furthermore, the cohesion of wet kaolin can be systematically reduced by increasing water content. The wet kaolin used in this project has a 40% water content by mass. Henza and others (2009), whose wet kaolin had a 40% water content, found that wet kaolin has a similar coefficient of friction, ~ 0.6, to crustal materials. The #6 tile clay specifically also exhibits a relatively low plasticity index and low viscoelasticity, which are appropriate for scaling to crustal strength (Cooke and van der Elst, 2012).

Using a viscometer, I measured the viscosity of the wet kaolin mixture used from 0.2 to 3.0 rotations per second (Fig. 2). The viscosity curve generated shows that wet kaolin exhibits a strain rate dependent viscosity, where slow deformation leads to high viscosity and fast deformation leads to low viscosity.
Figure 2. Viscosity curve of the experimental wet kaolin mixture. The y-axis describes the viscosity in Pa·s versus the shear rate in s⁻¹ on the x-axis. The shear rate corresponds to the rotation of the parallel plate used on the viscometer. This plot displays a single viscosity measurement of the 40% water content wet kaolin mixture used in experiments. The viscometer takes ten measurements as the rotation of plate increases from 0.0 rotations per second (start) to 3.0 rotations per seconds and back to 0.0 rotations per second (finish). The wet kaolin has a higher viscosity at slow shear rates and lower viscosity at fast shear rates. The viscosity curve also exhibits the hysteresis effect, wherein the behavior of the material depends both on its current state and on its past history.
The model in this study utilizes materials chosen because of their similarity to the rheology of earth materials: silicone mimics that of the ductile lower crust and upper mantle and wet kaolin imitates that of the brittle upper crust. However, the model does not have a scaling factor and therefore cannot be exactly extrapolated to real systems. Despite this limitation, the general behaviors and patterns that we can infer from this physical model are still valuable and worth examining. Paola and others (2009) describe this phenomenon as the unreasonable effectiveness of experimental systems. They echo the sentiment that experimental physical models are not exact dynamic models of field systems but are instead a good insight into the scale independence and dependence of systems. The results of this study reflect this idea for the particular experimental materials described above.

**Experimental Model Technical Details**

To simulate the transition from locked-to-creeping behavior of a strike-slip system, I configured a physical model using Iowa State University’s shear table (Fig. 3). One side of the plexiglass table is stationary while the other side moves left-laterally, pulled at a constant rate by a stepping motor. The line where the two sides meet simulates a "basement fault." A plexiglass box (30 cm by 28 cm) that holds the experimental materials is cut in half to allow the separate sides of the experiment to slip in opposite directions. This cut is centered over the "basement fault" and clamped to the table (Fig. 3). I used two different combinations of materials: (1) either a single 3 cm thick layer of silicone, to help visualize patterns of deformation, or (2) a 1.5 cm thick layer of wet kaolin, to mimic the upper-crust, over top a 3 cm thick layer of silicone, to mimic the mid-crust.
Figure 3. Shear table apparatus (above) and schematic diagram of experimental model containing silicone and wet kaolin layers.
To simulate locked-to-creeping behavior, I use a paring knife to make a 10 cm cut through the experimental materials along the basement fault starting from the right edge of the box (Fig. 3). The cut is lubricated with detergent so that the fault will slip throughout the experiment. Along the rest of the experimental "basement fault," the materials are left unaltered to mimic locked behavior during an interseismic period. Each experiment is videotaped for qualitative and quantitative measurements of deformation from above and from the side. Sand grains are sprinkled on the surface of the model for quantitative analysis of off-fault deformation via particle image tracking software described below using videos taken from directly above the model. Oblique side-view videos show topographic changes such as basin and fold development over the course of an experiment (e.g. Fig 7C).

The experiments are run at a variety of rates to simulate slow and fast deformation (Fig. 4). Slow deformation is achieved by moving the table at a constant rate of 0.2 mm/s. Ross (2017) found that a slower rate of 0.025 mm/s would scale up better to the upper and lower crust but would not produce topography because of the viscous nature of the silicone. She found 0.2 mm/s to be the most efficient velocity to develop topography. In order to achieve fast deformation, the table is held stationary by obstructing its movement with a metal rod—in this case, a screwdriver is used—while the motor stretches the spring. Once the maximum force (95 N, 105 N, 115 N, 125 N, or 135 N) accumulates, the metal rod is pulled out allowing the spring to pull the table forward quickly. The force and displacement during each experiment is recorded at 10 Hz by a force gauge and a cable transducer, respectively (Fig. 5).
Figure 4. Experimental types overview diagram. Beginning from the left of the diagram, the type names are denoted as Type I, II, III, or IV. The next column to the right describes the model type (i.e., either Silicone Only or Kaolin and Silicone). To the right, the following portion of the diagram indicates two varieties of experimental steps: (1) the amount of slow rate (0.2 mm/s) displacement, in cm, the experiments underwent and/or (2) the various amounts of force applied to the experiments are all listed for each type.
Figure 5. Force/displacement versus time plot of experiments. Each experiment is recorded at 10 Hz by a force gauge and a cable transducer; software outputs force in N (red) and displacement in cm (green) versus time in seconds. (A) This force/displacement versus time plot represents Type I experiments, for which the table is displacement at a constant force. (B) This plot represents Type III experiments during which a screwdriver is placed in front of the table to prevent movement while the force builds. Once the force reaches the desired amount, the screwdriver is removed (dashed line). (C) The first half of this plot, which ends when the screwdriver is placed (first dashed line on the left), represents Type II experiments. The second half of the plot (starting at the first dashed line) represents Type IV experiments.
Computing Velocity Fields

In order to produce velocity fields for each experiment, I use particle image velocimetry, a commonly used technique for non-intrusive, quantitative and qualitative flow visualization (e.g. Fig. 9). The software I use is a package developed in MatLab called PIVlab (Thielicke and Stamhuis, 2014). The motion of materials on the surface of the model is visualized and tracked by tracer particles; in this study, I use contrasting colored sand grains spread on top of the model surface.

The software uses a series of photos taken during the experiment to produce the velocity field. However, the displacement of a particle between photos may only be as large as half the size of the particle, in pixels. Since fast deformation rate experiments move very rapidly, the experiments were videotaped and frames were extracted for detailed analysis. I used a Nikon D5200 camera with an AF-S Nikkor 18-55 mm f/3.5-5.6 lens placed 40 cm above the surface of the model. Natural light was coupled with two stand-alone lights for all experiments. The camera recorded the experiments at 50 frames per second with a high ISO (between 1000 and 2000) depending on lighting, although only 25 frames per second are necessary for PIV analysis for the fast rates of deformation. The slow deformation experiments only required one frame per second for analysis.

The PIV software uses the direct Fourier transform correlation algorithm that preforms multiple passes of the data (Thielicke and Stamhuis, 2014). The first pass is a larger interrogation area that produces low vector resolution, and subsequent passes narrow the size of the interrogation window by 50% and produce higher vector resolution. The initial pass for analysis of this data used an interrogation area of 64 pixels
with a 32 pixel (50%) step, while the second pass used an interrogation area of 32 pixels with a 16 pixel (50%) step. To calibrate the software for each experiment, a calibration step using a calibration image taken from a frame of a video, to keep photo quality consistent, is performed. The PIV analysis for slow slip rate experiments is conducted with a series of 200 frames, corresponding to 200 seconds in real time. Analysis for the fast slip rate experiments uses a series of 100 frames beginning from the moment the table begins moving, which corresponds to 4 seconds in real time.

Once the series of frames is analyzed, all frames are averaged to produce an average velocity field for each experiment (e.g. Fig. 9). The velocity field vector component most relevant to these experiments is the vertical component, or the \( v \)-component, because the \( v \)-component is a measurement of fault-perpendicular motion of material, or the extent to which a particle is rotated, and correlates to off-fault deformation. The magnitudes of the average \( v \)-component of the velocity fields are represented by colors in the background of the velocity fields. Finally, the velocity fields are also processed such that motion of either side of the fault is held relative to the opposite side, as would be done with GPS velocity data analyzed relative to two plates on either side of a real-world strike-slip fault. This is achieved by subtracting the horizontal motion along the fault relative to each plate and stitching the resulting velocity fields from above and below the fault together into a single velocity field.

**Analyzing Velocity Fields**

*Displacement Contour Plots*

I generate displacement field contour plots in order to observe material movement
patterns of each experiment at varying slip rates (e.g. Fig. 8). The txt file is processed manually. Each v-component, expressed in m/s, is multiplied by the amount of time, determined using force/displacement versus time plots generated for each experiment, necessary for the model to slip 2 cm. The displacement field contour plots are then created in RStudio. The R-code, written by Joshua R. Davis, employs the akima package. The code first makes a grid which is then filled with interpolated values from the txt file. It takes the prepared grid and values to produce a contour plot of the v-component.

_V-component Velocity Cross-Sections_

To better quantify the velocities for comparison and analysis, I used the polyline extraction function in the PIVLab software. This function essentially produces a cross-section of the component of interest from the velocity field, which, for this study, is the v-component velocity (e.g. Fig. 10). I take a cross-section normal to the fault starting from the top of the frame through the regions of highest fault-perpendicular motion, i.e. the zones of contraction and extension on either side of the transition point from locked to creeping.

_Qualitative Analysis Methods_

I also conduct a qualitative analysis of the deformation that evolves over the course of an experiment. Both silicone-only and kaolin and silicone models were analyzed. Silicone-only experiments were run with a 2 cm by 2 cm grid pressed into the top of the silicone (e.g. Fig. 7A). A series of frames over the course of the experiment were selected and traced for comparison. For the kaolin and silicone model, the structures
Figure 6. Vertical component velocity reproducibility results from PIVlab. The vertical component velocity is measured along a fault-perpendicular transect of three separate experiments in each plot. (A) Slow slip rate experiments in Silicone Only models. (B) Slow slip rate experiments in Kaolin and Silicone models. (C) Fast slip rate experiments in Silicone Only models. (D) Fast slip rate experiments in Kaolin and Silicone models.
of interest that develop in the kaolin layer are fractures, openings, cracks, fault propagation, and various faults (e.g. Fig. 7B). I log the time of their development over the course of an experiment by observing frames and videos for the structures that developed in a series of frames from each experiment.

**Reproducibility**

Multiple experimental runs for each experimental type were run to determine the consistency of PIV results between tests. Figure 6 shows the velocity cross-sectional data from fast and slow slip rate experiments done in either silicone-only or kaolin and silicone. For simplicity, only one of the five maximum forces was chosen to represent the reproducibility of all five possible maximum forces. Comparing the magnitude of the v-component velocity across the fault along a fault-perpendicular transect, the results show a high level of reproducibility within types of experiments. The results from fast slip rate experiments run to a maximum force of 135 N are unreliable however because, at the slip rate produced by this magnitude of force, the model begins to dysfunction.

**RESULTS**

*Type I & II - slow rate experiments*

Type I and Type II experiments were both conducted at the same slow, constant creep rate of 0.2 mm/s and differ only by the extent of displacement, 15 cm and 4 cm, respectively (Fig. 4). Figure 5 shows the force and displacement over the course of sample experiments. A Type IV experiment follows a Type II experiment, thus Figure 5C is split between the two types. Both Type I and II experiments maintain a constant force
and increase in displacement throughout the experiment (Fig. 5A and 5C). The deformation of Type I experiments is more extreme, but the behavior of the model and the evolution of the structures is similar to Type II experiments. For this reason, only Type II experimental results are shown (Fig. 7–10; see Appendix A Fig. 1–4 for Type I results).

Gridded silicone runs reveal a zone of contraction above the fault, on the moving side of the table, with the most shortening slightly to the left of the transition point (Fig. 7A). A zone of extension below the fault is also observed, especially below the transition point and along the creeping portion of the fault (Fig. 7A). While the silicone-only model gives us a good general idea of how the system will behave, I also use a wet kaolin and silicone-layered model in order to show structures, such as faults and fractures, that develop.

In the wet kaolin, structures above and below the transition point develop to accommodate the zones of contraction and extension. These include a large opening or crack at the tip of the creeping portion of the fault in the zone of extension along with fault-perpendicular en echelon fractures, which together result in blocks of wet kaolin that rotate counterclockwise, as expected in a left-lateral system (Fig. 7B). Fault-parallel left-lateral faults begin to develop along the basement fault after ~ 6 cm of displacement over the locked portion of the fault in Type I experiments (see Appendix A Fig. 1). These faults appear to be a propagation of the creeping portion into the locked portion of the fault.

Displacement field contour plots reflect these zonal patterns showing areas of most fault-perpendicular displacement, indicative of deformation, above and
Figure 7. (A) Top-down view of a Type II gridded silicone only experiment over three steps of displacement (~1.5 min intervals). A trace of the grid is shown below the photos. The zone of contraction (blue) and the zone of extension (red) are highlighted approximately. (B) Top-down view of a type II kaolin and silicone experiment over three time steps of displacement (~1.5 min intervals) with major features indicated. (C) Oblique, side-view of a type II kaolin and silicone experiment over three time steps of displacement (~1.5 min intervals).
below the transition point of the fault in both the silicone-only and kaolin and silicone models (Fig. 8). The displacement contour plots for the kaolin and silicone models display a slightly less uniform, more diffuse pattern in which areas of most fault-perpendicular displacement are not as narrowly defined as the silicone-only experiments.

The average velocity fields shown in Figure 9 display both the vectors of the velocity field and a color overlay that corresponds to the v-component, or fault-perpendicular motion. The cool colors of the overlay correspond to fault-perpendicular motion upward relative to the frame, while warm colors represent fault-perpendicular motion downward, relative to the frame. The average velocity field for the silicone-only experiments show two ellipsoidal to parabolic regions above and below the transition point, consistent with the observed zones of contraction and extension, where fault-perpendicular motion is directed upward as vectors rotate counter-clockwise (Fig. 9A). Vectors at the transition from locked-to-creeping slip behavior on the shortening side point and shorten towards the creeping portion (Fig. 9A). Below the fault, vectors point and lengthen towards the locked portion (Fig. 9A). The average velocity field of the Type II kaolin and silicone model exhibit similar patterns to the silicone-only model; however, the v-component color overlay does not have the same clean ellipsoidal to parabolic patterns above and below the transition point (Fig. 9B). Instead, the distribution of the magnitude of fault-perpendicular motion is more disperse and, on the extensional side, corresponds to major extensive features observed qualitatively.

A negative sign in the cross-sectional plots, shown in Figure 10, for Type II experiments, like the color overlays, indicates a vector rotation upwards relative to the frame. Thus, a more negative value indicates a larger v-component directed upwards,
Figure 8. Displacement field contour plots of Type II experiments. These contour plots are generated in RStudio and represent the vertical (v) component displacement for 2 cm of overall displacement. The creeping portion of the fault is highlighted with a thick black line. (A) An example of a silicone only Type II experiment. (B) An example of a silicone only Type II experiment.
Figure 9. Average velocity field results from PIVlab of Type II experiments. The vector arrows shown represent the average velocity field: above the fault, the vectors are relative to the upper portion of the model, while the vectors below the fault are relative to the lower portion of the model. The color overlay indicates the magnitude of the vertical (v) component of the velocity field. The creeping portion of the fault is highlighted in white. (A) An example of a silicone only Type II experiment. (B) An example of a kaolin and silicone Type II experiment.
Figure 10. Average vertical (v) component velocity cross-sections of Type II experiments comparing silicone only models (red) and kaolin and silicone models (blue). The y-axis denotes the v-component in m/s, while the x-axis indicates the distance on the transect taken in m. The transect for each cross-section passes from the shortening side of the transition point (top) to the extensional side of the transition point (bottom). Each line plotted represents the average of velocity cross-sections taken for each model type. Error bars of one standard deviation are shown.
while a large positive value indicates a larger \( v \)-component directed downwards. The averaged cross-sections of all Type II silicone-only and kaolin and silicone experiments are compared in Figure 10. The error bars on the plot (one standard deviation) indicate that between the model types, the order of magnitude of the \( v \)-component is not significantly different; however, the overall pattern of velocity distribution varies between the two. Silicone-only experiments display more symmetric distribution of fault-perpendicular motion across the fault, while kaolin and silicone experiments display more fault-perpendicular motion on the shortening side of the fault (the moving side of the table) than the extensional side (the stationary side of the table).

*Type III & IV - fast rate experiments*

Type III experiments begin from an undeformed state. The table is held still such that no deformation occurs as force is built to the desired maximum (95 N, 105 N, 115 N, 125 N, or 135 N). The force is then released, and the table moves forward quickly simulating a faster creep rate that is dependent on the maximum force released (Fig. 4). Type IV experiments follow a similar sequence of events. However, these experiments begin from a previously deformed state, which is established by four centimeters of slow deformation, as in Type II experiments (Fig. 4). The force and displacement over the course of Type III experiments can be seen in Figure 5B, while that of Type IV experiments can be seen in the second half of Figure 5C.

In order to determine whether deformation prior to fast rate deformation has an effect on \( v \)-component velocity magnitudes, I produced a comparison of \( v \)-component velocity cross-sections between Type III and IV for each model type. A
**Figure 11.** Velocity field cross-section plots comparing Type III and IV experiments. These plots compare the v-component velocities, in m/s, (x-axis) along a cross-section, in m, (y-axis) of Type III (blue) experiments, which begin from no prior displacement or deformation, to Type IV (red) experiments, which begin after prior displacement or deformation. Each line represents a separate experiment. (A) Silicone only model experiments. (B) Kaolin and silicone model experiments.
representative of each model type is displayed in Figure 11 for simplicity. Figure 11B shows the results for the Type III and Type IV experiments in kaolin and silicone models with a maximum force released of 115 N. The comparison shows that, despite prior loading of Type IV experiments, the v-component velocities are of the same order of magnitude and are not significantly different than those of Type III experiments. Figure 11A shows the same results for experiments in a silicone-only model with a maximum force released of 115 N max. Below, Type III experimental results will be reviewed, while Type IV results may be found in the Appendix (Fig. 12–15; see Appendix A Fig. 5–8 for Type IV results).

Gridded silicone models exhibit a zone of contraction above the transition point and a zone of extension below the transition point (Fig. 12A). However, the wet kaolin of the kaolin and silicone experiments behaved differently from Type I and II experiments (Fig. 12B). In Type III experiments, material in the zone of contraction clearly builds up in front of the transition point; however, no obvious structures developed on the surface of the model. In the zone of extension, only many, small, fault-normal fractures developed to accommodate extension. The displacement field contour plots of silicone only models show clear patterns of most fault-perpendicular displacement corresponding to the observed zones of contraction and extension, while those of kaolin and silicone models are more diffuse (Fig. 13).

Type IV kaolin and silicone models differ slightly from Type III experiments; these experiments begin with deformation like that produced by Type II experiments. As Type IV experiments slipped, those structures continued to deform further along established fractures and faults, with the exception of the large opening,
Figure 12. (A) Top-down view of a Type III gridded silicone only experiment over three steps of displacement (~ 5 sec intervals). A trace of the grid is shown below the photos. The zone of contraction (blue) and the zone of extension (red) are highlighted approximately. (B) Top-down view of a type III kaolin and silicone experiment over three time steps of displacement (~ 5 sec intervals) with major features indicated.
Figure 13. Displacement field contour plots of Type III experiments. These contour plots are generated in RStudio and represent the vertical \((v)\) component displacement for 2 cm of overall displacement. The creeping portion of the fault is highlighted with a thick black line. (A) An example of a silicone only Type III experiment with a maximum force released of 105 N. (B) An example of a silicone only Type III experiment with a maximum force released of 95 N.
Figure 14. Average velocity field results from PIVlab of Type III experiments. The vector arrows shown represent the average velocity field: above the fault, the vectors are relative to the upper portion of the model, while the vectors below the fault are relative to the lower portion of the model. The color overlay indicates the magnitude of the vertical (v) component of the velocity field. The creeping portion of the fault is highlighted in white. (A) An example of a silicone only Type III experiment with a maximum force released of 125 N. (B) An example of a kaolin and silicone Type III experiment with a maximum force released of 95 N.
Figure 15. Average vertical (v) component velocity cross-sections of Type III experiments comparing maximum force released. The y-axis denotes the v-component in m/s, while the x-axis indicates the distance on the transect taken in m. The transect for each cross-section passes from the shortening side of the transition point (top) to the extensional side of the transition point (bottom). Each line plotted represents the average of velocity cross-sections taken for each model and force type. (A) The average v-component velocity cross-section of Type III silicone only models. (B) The average v-component velocity cross-section of Type III kaolin and silicone models.
which is abandoned as the fault propagated forward aided by new, smaller fractures forming in front of the large opening (see Appendix A Fig. 5). Sinistral transverse faults developed to the left of the transition point on the compressive side along with visible shortening and thickening of the kaolin layer by a couple of millimeters (2-4 mm) (see Appendix A Fig. 5).

Type III silicone-only runs produced average velocity fields, such as that in Figure 14A, which show similar vector patterns to Type I and II, in which the vectors are directed and slow towards the creeping portion of the fault on the compressive side and lengthen and point towards the locked portion of the fault on the extensive side. The v-component color overlay exhibits a parabolic pattern of similar magnitudes of fault-perpendicular motion. However, the v-component is an order of magnitude greater than that in Type I and II. The kaolin and silicone runs of Type III are similar to the silicone runs of Type III (compare Fig. 14A and Fig. 14B).

Analyzing the velocity cross-sections separately for each model in order to compare various maximum forces, Figure 15 shows that averaged v-component velocity cross-section plots for the silicone-only model increase proportionally as the maximum force released increases from 95N to 135 N. A maximum force of 135 N is the point at which the model begins to break down, and results become unreliable; Type IV experiments in both silicone only and kaolin and silicone models display large error bars for experiments with 135 N maximal force (see Appendix A Fig. 8). The kaolin and silicone model Type III experiments behave in a similar linear manner and at a similar order of magnitude.
DISCUSSION

Analysis of the average velocity fields and qualitative observations can be used to characterize off-fault deformation around a transition point from locked-to-creeping behavior along a strike-slip fault. The distribution and magnitude of fault-perpendicular motion in the model is indicative of the development of off-fault deformation because it records the rotational, non-parallel, motion of materials as strain is accumulated. The consistency of vector rotation directions and displacement field patterns appears to indicate that materials move in predictable directions in foreseeable areas and thus may deform similarly despite the creep rate. However, while vector patterns are similar between all experimental types, the distribution of fault-perpendicular, or v-component, magnitudes and the observed off-fault deformation do differ and complicate the predictability of the model.

The v-component magnitude distribution varies between model types. Type III and IV experiments (fast rate deformation) show similar distribution when run in silicone-only or kaolin and silicone models, while Type I and II (slow rate deformation) experiments in either model differ (compare Fig. 14A and Fig. 14B). Silicone only Type II runs exhibit more defined, narrow regions of the highest v-component velocities, while Type II kaolin and silicone experiments are more diffuse, especially on the upper shortening side, and are much less prominent on the extensional side (Fig. 14). In other words, the v-component magnitude patterns of silicone-only experiments are more defined and symmetrical across the fault than experiments conducted in kaolin and silicone models; this is also reflected in the overall patterns of the v-component velocity cross-section plots (Fig. 10). This difference in distribution of v-component velocity
magnitudes may be better explained by observing the qualitative features of experiments.

The off-fault deformation seen over the course of experiments varies notably between model and experimental types. General displacement trends indicate that materials closest to the transition point move more quickly than the material away from the fault on either side, as seen in the displacement contour plots (e.g. Fig. 8). Therefore, variation in structures observed must be due to material behaviors. All experiments developed a large anticline on the shortening side (the moving side of the table) and a basin or clear extensional structures on the extensional side (the fixed side of the table) (e.g. Fig. 7 and Fig. 12). The silicone-only models did not differ between experimental types, in contrast to the kaolin and silicone models, because silicone behaves linearly (Weijermars, 1985). As strain builds, the silicone will deform continuously, independent of strain rate. This is why the average velocity fields exhibit concentrated, symmetrical, and predictable behavior.

In kaolin and silicone models, the wet kaolin, during slow creep rates (Type I and II), behave as a brittle material exhibiting fault propagation and developing a large crack and wet kaolin blocks between en echelon extensional fractures that rotate counterclockwise on the extensional side of the experiment (Fig. 7). Type III and IV experiments, which have fast creep rates, did not develop these structures; the wet kaolin behaved as a ductile material (Fig. 12). Figure 2 shows the viscosity measurements of the wet kaolin mixture used in these experiments. It demonstrates that, at a slow strain rate, the wet kaolin has a high viscosity, while at fast strain rates, it has a low viscosity. The complex behavior of wet kaolin, unlike the linear behavior of silicone offers an explanation for the diffuse v-component velocities observed in average velocity fields of
kaolin and silicone models.

As mentioned above, the results gathered from these physical modeling experiments may be applicable to faults that exhibit creeping behavior, since wet kaolin is a Burger’s material, like the crust (Cooke and van der Elst, 2012). Ross (2017), who conducted similar experiments to this study, compared her results to GPS velocity field data and mapped geologic features from the Parkfield transition point collected by Titus and others (2011) (Fig.16). Her findings are consistent with geologic data both collected by Titus and others (2011), and more recently that of DeMets and others (2014), except for the vector pattern on the extensional side of the fault, which rotates in the opposite direction of GPS velocity field data (Fig. 16). The velocity field results from this study are similar to her velocity field results for both fast slip rates, in Type III and IV, and slow slip rates, in Type I and II experiments (Fig. 16).

While the average velocity field data is similar for fast and slow slip rate experiments, in comparison to the GPS data at Parkfield and Ross’s (2017) results, as described above, different structures do develop in the wet kaolin depending on slip rate. Real world faults do not all exhibit the same creeping rate. For example, the creeping portion of the San Andreas fault, explored by Ross (2017), slips right-laterally at ~35mm/yr, while the Hayward fault creeps right-laterally at ~ 5mm/yr (Titus et al., 2011; Schmidt et al., 2005). Therefore, by comparing the differences in behavior at fast and slow creep rates, the experiments described in this study provide insight into the possible differences in off-fault deformation that could be observed in the field at transition points along strike-slip faults.

Previous studies, such as that of d’Alessio and others (2005) and Burgmann and
Figure 16. Comparison of observed, numerical model, and physical model data. (A) Observed GPS velocity field data at the Parkfield transition point on the San Andreas fault. Adapted from Titus et al. (2011). (B) Numerical model of velocity field data at the Parkfield transition point. Adapted from Titus et al. (2011). (C) Physical model velocity field results adapted from Ross (2017). (D) Average velocity field from this study of a Type II experiment. (E) Average velocity field from this study of a Type III experiment.
others (2006), use GPS velocity data collected around the Hayward fault to determine creep rates along the fault. However, because GPS velocity data is limited by station availability and the locked and creeping segments are shorter and less defined, GPS velocity field patterns at transition points along the Hayward fault are less distinctive than those for the well-studied Parkfield transition on the San Andreas fault. Schmidt and others (2005) offer an interesting case for which the results of this study could have implications. They observe slip rate distribution on the fault at the transition point at Point Pinole where the Hayward fault creeps to the south and is locked to the north. Their slip rate estimates are complicated by a dip-slip component of the fault, and they could be further complicated by the presence of off-fault deformation structures that develop around the transition point. Shelef and Oskin (2010) found that off-fault deformation is capable of significantly affecting slip rate estimates. They implicate that without a consideration of off-fault deformation, inferred slip rates along strike-slip faults may be over-estimates. Thus, the experimental off-fault deformation patterns that are observed in this study due to a transition point from locked-to-creeping could affect Schmidt and others’ (2005) inferred slip rates at Point Pinole.

This study has implications for the behavior of materials around a transition point along strike-slip faults during an interseismic period depending on creep rates. To further our understanding of these transition points, the effect on off-fault deformation of an entire earthquake cycle—including the coseismic and interseismic periods—is a potential area that should be explored. These future physical models could introduce strain loading and release to test if deformation is completely elastic as the numerical and existent physical models of strike-slip faults assume (Bilham and King, 1989; Caniven et al.,
2015). This experiment could be done by altering the basement fault as well as the fault plane geometry to properly simulate both the strain accumulation during an interseismic period and the complete rupture of the locked portion of the fault during a coseismic event. Further exploration of the effects of a full seismic cycle is a necessary addition to physical modeling research about transitions points from locked-to-creeping slip behavior and to experimental physical modeling as a whole.

CONCLUSION

The physical model presented in this study adds complexity to our understanding of the parameters that govern the evolution of a transition point from locked-to-creeping slip behavior along a strike-slip fault. In comparing the average velocity field data and qualitative observations of relatively fast and slow slip rate experiments, I find that average velocity field vector patterns between experimental types do not differ notably. This suggests little variation despite slip rates. However, the structures that develop between the experimental types in the kaolin and silicone model do differ significantly. I analyze observations from the kaolin and silicone models because the upper wet kaolin layer behaves analogously to the upper crust, where off-fault deformation is observed in real-world settings. I find that wet kaolin tends to behave more viscously at slower rates of deformation and as a brittle material at faster rates of deformation.

The results from these physical models inform field observations by adding understanding to the effects variation of slip rates have on off-fault deformation. For example, GPS velocity data collected in the field at transition points, such as those along the San Andreas fault at Parkfield and the Hayward fault at Point Pinole, may not capture
the full story. Although velocity field data might suggest a predictable pattern of off-fault deformation, observations of the actual geologic structures that develop is crucial to garner a complete understanding of the fault behavior. Further, the unique patterns of off-fault deformation observed in the field may have implications for studying slip rates. This project demonstrates the importance of physical modeling for furthering our understanding of the varied and complex aspects that contribute to the behavior of strike-slip faults.

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APPENDIX A
Figure 1. (A) Top-down view of a Type I gridded silicone only experiment over three steps of displacement (~ 4 min intervals). A trace of the grid is shown below the photos. The zone of contraction (blue) and the zone of extension (red) are highlighted approximately. (B) Top-down view of a type I kaolin and silicone experiment over three time steps of displacement (~ 4 min intervals) with major features indicated.
Figure 2. Displacement field contour plots of Type I experiments. These contour plots are generated in RStudio and represent the vertical (v) component displacement for 2 cm of overall displacement. The creeping portion of the fault is highlighted with a thick black line. (A) An example of a silicone only Type I experiment. (B) An example of a silicone only Type I experiment.
Figure 3. Average velocity field results from PIVlab of Type I experiments. The vector arrows shown represent the average velocity field: above the fault, the vectors are relative to the upper portion of the model, while the vectors below the fault are relative to the lower portion of the model. The color overlay indicates the magnitude of the vertical (v) component of the velocity field. The creeping portion of the fault is highlighted in white. (A) An example of a silicone only Type I experiment. (B) An example of a kaolin and silicone Type I experiment.
**Figure 4.** Vertical ($v$) component velocity cross-sections of Type I experiments comparing a silicone only model (red) and a kaolin and silicone model (blue). The y-axis denotes the $v$-component in m/s, while the x-axis indicates the distance on the transect taken in m. The transect for each cross-section passes from the shortening side of the transition point (top) to the extensional side of the transition point (bottom).
Figure 5. (A) Top-down view of a Type IV gridded silicone only experiment over three steps of displacement (~ 5 sec intervals). A trace of the grid is shown below the photos. The zone of contraction (blue) and the zone of extension (red) are highlighted approximately. (B) Top-down view of a type IV kaolin and silicone experiment over three time steps of displacement (~ 5 sec intervals) with major features indicated. (C) Oblique, side-view of a type IV kaolin and silicone experiment over three time steps of displacement (~ 5 sec intervals).
Figure 6. Displacement field contour plots of Type III experiments. These contour plots are generated in RStudio and represent the vertical (v) component displacement for 2 cm of overall displacement. The creeping portion of the fault is highlighted with a thick black line. (A) An example of a silicone only Type III experiment with a maximum force released of 95 N. (B) An example of a silicone only Type III experiment with a maximum force released of 105 N. The grey area represents a portion of the experiment that is not relevant to this experiment.
Figure 7. Average velocity field results from PIVlab of Type IV experiments. The vector arrows shown represent the average velocity field: above the fault, the vectors are relative to the upper portion of the model, while the vectors below the fault are relative to the lower portion of the model. The color overlay indicates the magnitude of the vertical (v) component of the velocity field. The creeping portion of the fault is highlighted in white. (A) An example of a silicone only Type IV experiment with a maximum force released of 95 N. (B) An example of a kaolin and silicone Type IV experiment with a maximum force released of 95 N. The grey area represents a portion of the experiment that is not relevant to this experiment.
Figure 8. Average vertical (v) component velocity cross-sections of Type IV experiments comparing maximum force released. The y-axis denotes the v-component in m/s, while the x-axis indicates the distance on the transect taken in m. The transect for each cross-section passes from the shortening side of the transition point (top) to the extensional side of the transition point (bottom). Each line plotted represents the average of velocity cross-sections taken for each model and force type. (A) The average v-component velocity cross-section of Type IV silicone only models. (B) The average v-component velocity cross-section of Type IV kaolin and silicone models. Error bars of one standard deviation are shown.
Figure 9. Average vertical (v) component velocity cross-sections of Type III experiments comparing maximum force released with error bars. These plots are a reproduction of Figure 14 with the addition of error bars, which represent one standard deviation.