Relating Slip Behavior to Off-Fault Deformation Using Physical Models

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Abstract
Deformation in transform systems is accommodated by discrete fault slip and distributed off-fault deformation. Here, we consider how a change in slip behavior along a fault can influence the distribution between on- and off-fault deformation. We use a physical experiment to simplify the geometry, material properties, boundary conditions, and slip history along a strike-slip fault to directly observe patterns of off-fault deformation. We document deformation of a silicone slab on a simple shear apparatus using particle image velocimetry (2D) and photogrammetry (3D). The experimental results show regions of topographic highs and lows on either side of the slip transition that grow, evolve, and are displaced with progressive strain. The experimental dilatation field shares similarities with strain fields in central California along the San Andreas fault, which suggests that a change in slip behavior may explain some of the real-world patterns in short- and long-term deformation.

Plain Language Summary
Understanding where and why deformation occurs along a fault is important for quantifying future earthquake hazards and interpreting existing geological structures. In nature, creeping sections of strike-slip faults move slowly and continually, while locked sections are stationary for long periods and then release large amounts of energy rapidly in earthquake events. A portion of a strike-slip fault's total motion can be accommodated away from the main trace of the fault leading to permanent deformation. Here, we investigate how a change from locked slip to creeping slip affects deformation away from the fault trace by deforming silicone, an analog for the Earth's crust. Physical models are useful because they allow us to simplify the fault system and isolate a single variable affecting deformation. We track deformation in the experiments in two and three-dimensions. Our results show a pattern of extension and contraction which can be compared to a real-world change in slip behavior on the San Andreas fault.

1. Introduction
Lithospheric-scale strike-slip faults are controlled by numerous interconnected variables: fault geometry, plate motion direction, rock rheology, off-fault deformation, fault maturity, and inherited patterns of deformation all influence present-day deformation and, by extension, hazards due to motion on faults (Cooke et al., 2013; Giorgetti et al., 2006; Little et al., 2002). In addition to these variables, major strike-slip faults rarely have a single constant slip rate along their entire length, nor do they always have the same slip behavior along strike. Examples of a change in slip behavior, and hence a corresponding change in slip rate, have been identified using creepmeters, GPS, and InSAR on the San Andreas and Hayward faults in California (Lienkaemper et al., 1991; Ryder & Burgmann, 2008; Simpson et al., 2001; Titus et al., 2006), on the North Anatolian fault in Turkey (Rousset et al., 2016), and on the Philippine fault in the Philippines (Duquesnoy et al., 1994). Because many factors may influence the style of deformation and the distribution of on- and off-fault deformation within a fault system, it can be difficult to disentangle how each variable contributes to the observed deformation.

One way to isolate parameters that may affect fault systems, such as a change in slip behavior, is by using numerical models. For example, Bilham and King (1989) used a boundary element method to model the strain field and resulting crustal thickness of an idealized strike-slip fault that includes a stepwise change in slip behavior. Their model predicts temporary, symmetrical zones of contraction and extension on either side of the change in slip behavior. Several subsequent numerical models simulating real-world faults (e.g., Titus, Dyson, et al., 2011) or extending the investigation from 2D to 3D (ten Brink et al., 1996) showed comparable results.

While some recent numerical studies use an elasto-plastic crustal model (Liu & Konietzky, 2021), many numerical models are limited by their elastic framework. In nature, the crust exhibits a combination of elastic and
permanent, plastic deformation. While strictly elastic models capture the deformation distribution associated with the seismic cycle accurately, they do not include permanent deformation. We know from field observations that strike-slip faults accommodate deformation over wide regions via a combination of fault slip, granular flow, folding, rotation, cleavage development, and microcracking (Duebendorfer et al., 1998; Gray et al., 2017; Herbert et al., 2014; Karabacak et al., 2020; Shelef & Oskin, 2010; Titus, Crump, et al., 2011). Over decadal time scales, GPS velocity fields and InSAR have shown interseismic strain that is not fully recovered by earthquakes (DeMets et al., 2014; Rolandone et al., 2008; Titus, Dyson, et al., 2011). Over million-year time scales, palaeomagnetic block rotations, mylonitic lineation variations, and development of folds provide evidence for persistent regions of cumulative deformation away from the main trace of strike-slip faults (Bloch et al., 1993; Shelef & Oskin, 2010; Titus, Crump, et al., 2011). Considering long-term permanent deformation in addition to short-term elastic deformation is essential to estimate strain accumulation and accommodation along a fault.

Here, we investigate the impact of a change in slip behavior on off-fault deformation using physical experiments. This type of approach is invaluable because physical models isolate a single variable of interest—in this case slip behavior—and remove other variables such as differences in lithology, deformation history, erosion, deposition, and fault geometry that complicate the interpretation of data from natural systems. We use a linear-viscous silicone to capture permanent off-fault deformation, providing a longer-term view of deformation than is possible with elastic numerical models. Both 2D and 3D analyses of the results demonstrate that a transition from locked slip to creeping slip creates regions of contraction and extension away from the main fault trace. We compare these experimental results to a well-documented change in slip behavior on the San Andreas fault in central California, where hints of the same off-fault strain patterns are observed in short-term geodetic data as well as long-term geologic records of off-fault deformation.

2. Physical Modeling Methods

2.1. Experimental Setup

Figure 1 illustrates the setup of our physical model, where the experimental material is placed on top of a simple shear apparatus that imposes deformation from below (Birren & Reber, 2019; Schreurs, 1994). One side of the
experimental table remains stationary while the other side is pulled in a right-lateral manner by a stepping motor at a rate of 0.1 mm/s. Under one half of the experimental material, the transition from the stationary side of the table to the moving side is localized along a plane between two ⅛”-thick plexiglass sheets, leading to a discrete jump in velocity. Under the other half of the experiment, the transition from the stationary side to the moving side of the table is distributed over 34 acrylic slats that slide past each other freely like a deck of cards. Note that the thickness of the plexiglass sheets used to simulate the creeping portion of the system creates a small step in the experimental surface. The sheet thickness, however, is small relative to the change in elevation in the silicone due to deformation.

A 30 × 20 × 2 cm slab of PDMS SGM-36 silicone is placed on the table, covering the two halves that deform via localized and distributed deformation. The experimental material serves as a homogeneous, linear-viscous crustal analogue. The material has an experimental viscosity of ~5 × 10^4 Pa·s (Weijermars & Schmeling, 1986) and a density of 0.965 g/cm^3 (Dooley & Schreurs, 2012). This choice of experimental material allows for non-elastic deformation (Reber et al., 2020). The silicone is contained along the table edges by plexiglass strips to prevent viscous flow at the boundaries of the experiment. While viscous flow and relaxation is an important material property of silicone, flow toward the edges of the experiment is not observed during the short timeframe of a fifteen-minute experimental run.

The silicone slab is cut and lubricated using dish soap along the discrete velocity jump to simulate the “creeping” side of the experiment, preventing the silicone from sticking to itself and allowing for low-friction sliding. Silicone is left intact across the entire distributed-shear side of the experiment to simulate the “locked” portion of the fault. Note that we are not modeling any failure of the locked section of the fault. Colored sand grains are sprinkled on the surface to track motion between image frames using particle image velocimetry (PIV). In some experimental runs, a grid is pressed into the surface of the silicone using a ruler to highlight areas of contraction and extension. Deformation results are consistent across 16 tests of the experimental setup, indicating a high degree of reproducibility.

2.2. Model Limitations

We are not attempting to model a specific geographic location or to directly scale our experiments to nature. Instead, the goal of these experiments is to observe how an idealized material in an idealized configuration may still produce complex patterns of deformation. This approach uses scaling via similarity (Paola et al., 2009) rather than dynamic scaling (Hubert, 1937). We treat the model as a small system in its own right and not as a scaled model of the prototype (Reber et al., 2020). While this approach allows us to compare deformation patterns between the experiments and nature, a direct comparison of deformation magnitudes is not possible. As with any physical model, there are a number of simplifications that allow us to isolate a single variable of interest—slip behavior.

First, deformation in our experiments is driven from below using an externally imposed driver. This setup is common for strike-slip experiments where the system itself does not generate the energy needed to drive the process. In nature, far-field tectonic forces are driving plate motion and thus can be externally represented by a motor (Schellart & Strak, 2016).

Second, our model treats the transition from locked slip to creeping slip as a discrete point. Along a natural fault, this transition might be discrete but could be distributed over intermediate regions that display a mix of locked and creeping behaviors (Rousset et al., 2016). Due to the self-adhesive nature of the silicone, the material can be either completely detached or completely attached across the fault, and does not allow for an intermediate transition state between the two slip conditions.

Third, we use homogenous and linear-viscous silicone as the model material. Previously, the transition from creeping slip to locked slip has been modeled in homogeneous elastic systems (Bodin & Bilham, 1994; Chéry, 2008; Okada, 1985). These numerical models, however, are not typically concerned with patterns of long-term deformation nor the contribution to off-fault deformation. Here, we choose a linear-viscous material to test the simplest possible end-member rheology that allows for permanent deformation. The table speed of 0.1 mm/s ensures that silicone flow and relaxation is not a measurable source of motion relative to the table-driven deformation. The approximate viscosity and velocity we use here are widely used in models investigating crustal processes (Davy & Cobbold, 1988; Rudolf et al., 2016; Wu et al., 2009).
3. Physical Model Analysis and Results

3.1. 2D Deformation

To record deformation in 2D, we use top-down time-lapse photography. We position a Nikon D5300 camera approximately 40 cm above the experiment to record an image every three seconds for the entire length of the experiment. Camera settings of a high shutter speed (between 1/50 and 1/100 depending on lighting conditions) and low ISO (between 200 and 400) reduce motion blur and camera noise. A light above the experiment provides consistent brightness. Particle image velocimetry (PIV) software TecPIV is used to calculate velocity fields (Boutelier, 2016). To track surface particles over time, images of the experimental surface are divided into interrogation areas which are cross-correlated. In TecPIV, we use an initial interrogation area of 128 × 128 pixels followed by passes of 64 pixel and 32 pixel squares to increase vector resolution. A standard deviation filter of 3.0 removes outlier vectors that are common on the edges of the interrogation area.

Figure 2a shows an example velocity field from PIV. The results show a sharp jump in velocity magnitude from 0 mm/s (purple) to 0.1 mm/s (yellow) across the creeping portion of the experiment (red line). In contrast, there is a broad velocity gradient from 0 mm/s to 0.1 mm/s across the locked section of the experiment.

Figure 2b shows the dilatation field derived from the average velocity field between 3 and 6 mm of displacement. We use the average velocity field to minimize the PIV noise seen in individual frames and to emphasize the persistent velocity field pattern. We calculate the strain field from the velocity field using the program SSPX (Cardozo & Allmendinger, 2009). In 3D, the dilatation rate (Δ) quantifies the incremental change in volume:

\[
\Delta = (1 + e_{xx}) + (1 + e_{yy}) + (1 + e_{zz}) - 1
\]

where \(e_{xx}\) and \(e_{yy}\) are the horizontal principal strain rates, and \(e_{zz}\) is the vertical principal strain rate. Since the deformation of the silicone is volume constant (\(\Delta = 0\)), positive 2D dilatation rate (red in Figure 2b) is compensated by subsidence of the model surface (thinning of the silicone), while negative 2D dilatation rate (blue in Figure 2b) is compensated by uplift of the model surface (thickening of the silicone).

The dilatation field in Figure 2b shows alternating bands of contraction (blue) and extension (red) in the creeping section that cross the fault. On the moving side of the table, the most contraction occurs where material adjacent to the creeping segment is colliding with material adjacent to the locked segment of the fault (I in Figure 2b). Notably, this accumulation of silicone is next to a region of extension (b). On the fixed side of the table, extension is dominant (c). However, a region of contraction crosses the fault as the silicone folds during the experiment to accommodate the transition in slip behavior along the fault (d). These alternating regions of contraction and extension are oriented perpendicular to both the fault and overall sense of strike-slip motion.
3.2. 3D Deformation

For a qualitative understanding of ductile deformation around the slip transition, we take top-down photographs during an experimental run where a sand-filled grid is imprinted on the surface (Figure 3a). We compare photographs at three stages of displacement. Time-lapse photographs show contraction and extension of the grid on either side of the slip transition. On the moving side of the table, the grid contracts as the creeping portion pushes into the locked portion experiencing distributed shear, causing grid boxes to contract. On the fixed side of the table, the locked portion of the fault pulls away from the creeping portion, causing boxes to elongate parallel to the fault.

For a quantitative understanding of changes in the surface elevation, we use 3D photogrammetry. We take approximately 20 photographs in a circle around the experiment at a variety of heights and angles after each centimeter of displacement. Because it is necessary to stop and start the experiment repeatedly, separate experiments are conducted for this type of 3D analysis. Each set of photographs is aligned using Agisoft Metashape and then combined into a dense point cloud of the surface. These point clouds are then aligned with each other by matching the locations of six corners of two 2 cm registration cubes (Figure 1). These cubes are stationary throughout the experiment, ensuring that any changes in surface elevation are measured relative to a 3D fixed object. Once each point cloud is aligned, changes in elevation (z-axis) are quantified using CloudCompare. Each point cloud can be compared to the initial undeformed condition of the experiment as well as the point cloud immediately prior to track cumulative and incremental elevation changes.

Experimental results using 3D photogrammetry show changes in topography at 0 cm, 3 cm, and 6 cm of cumulative displacement (Figure 3b). On the moving side of the table, an increase in elevation is observed approximately perpendicular to the fault (I in Figure 3b, corresponding to I in Figure 2b). On the fixed side, a corresponding decrease in elevation appears in the surface (III). These elevation changes are largest next to the slip transition and less pronounced toward the edges of the experiment. At 3 cm of cumulative displacement, rising and sinking areas are slightly offset by right-lateral displacement and confined to their respective sides of the experiment. Between 3 and 6 cm of right-lateral displacement, elevation increases in the initial contractional region and decreases in the initial extensional region. As the initial contractional region and extensional region are offset, the low elevation zone on the fixed side (III) extends across the fault and forms a low elevation zone on the moving side of the fault (II). As the regions of contraction and extension move from the creeping to locked section of the...
fault, the regions of elevation change can be “felt” across the fault. These results support the expected vertical changes from the computed 2D dilatation rate (Figure 2b) and no volume change, namely subsidence in extensional areas, and uplift in contractional areas.

4. Discussion

Our physical model isolates the deformation resulting from a change in slip behavior along a strike-slip fault in a silicone slab. Even with this simple setup, several features emerge in both 2D and 3D over the course of the experiment. In 2D, the primary contractional region develops as the material adjacent to the creeping portion runs into the material adjacent to the locked portion (I in Figure 2b). Simultaneously a region of extension forms as the initial contractional region is displaced by the right-lateral motion of table (II in Figure 2b). This extensional region is followed by a secondary region of contraction (IV in Figure 2b), suggesting an interplay of contraction and extension as deformation progresses beyond the point of transition in slip. The alternating pattern is confirmed by 3D analysis, which shows the experimental material thinning as the initial contractional area moves past the slip transition point (Figure 3b). The extensional and contractional zones have opposite vertical motions, creating a slope between the topographic low point and topographic high point.

Our results can be compared to crustal data from central California along the San Andreas fault. Instead of the discrete change from a fully creeping fault to a fully locked fault in our experiments, the San Andreas transitions from creeping behavior to locked behavior with variable slip rates. The town of Parkfield is located between the segment to the NW with fast creep rates of 25–30 mm/yr and the locked segment SE of Cholame where interseismic slip is zero (Burford & Harsh, 1980; Scott et al., 2020; Titus et al., 2006).

Figure 4a shows the dilatation field derived from GPS stations in California, which is rotated in panel (b) for comparison with our experimental results in panel (c). The observed San Andreas fault dilatation field represents interseismic off-fault contraction and extension (DeMets et al., 2014; Titus, Dyson et al., 2011). With interseismic deformation in mind, we use distance-weighted dilatation rate (Cardozo & Allmendinger, 2009) to highlight large-scale decadal-scale crustal deformation patterns (Allmendinger et al., 2007). For the distance-weighted

**Figure 4.** Dilatation rate in central California (a) interpolated from vectors at GPS station locations (deMets et al., 2014). San Andreas fault earthquake-related motion before and after the 2003 San Simeon and 2004 Parkfield earthquakes has been excluded. This dilatational field is rotated in (b) for comparison to experimental dilatation field in (c) showing regions of extension (red) and contraction (blue). The segment of silicone which is cut and lubricated to mimic creeping slip behavior is traced in red, the creeping portion of the San Andreas fault is also traced in red. Note that the magnitude of dilatation cannot be directly compared between the experimental results and the GPS-derived field.
calculations we set the distance-weighting factor $\alpha$ to 12 km and used 146 stations and a 3-km grid. Because we are interested in long-term interseismic off-fault deformation we focus our comparison window (Figure 4b) on the creeping segment of the fault excluding velocity data from the locked segment south of Cholame. In the locked-fault segment elastic deformation complicates velocity field observations, making the interseismic GPS field unreliable (deMets et al., 2014; Rolandone et al., 2008; Ryder & Burgmann, 2008; Titus, Dyson et al., 2011). In our experimental frame, we are not limited to velocity vectors in the creeping segment of the transition and can therefore show both sides of the transition.

Because we compare our experimental results to the smoothed deformation field along the San Andreas fault, excluding earthquake-related elastic motion, the deformation of our linear-viscous silicone slab is a reasonable analogue for the observed velocity field. The irregular spacing of the existing GPS velocity field has previously been hypothesized as an explanation for the observed strain field, suggesting that a regularly spaced grid of stations would simplify the observed pattern (Titus, Dyson et al., 2011). In our experiments, however, particle tracking allows for extremely high-resolution velocity fields, eliminating station distribution as a potential source of error (Baxter et al., 2011). Despite the difference in velocity field resolution between the experimental and observed dilatation fields, both exhibit a pattern of alternating extension and contraction across the creeping segment of the fault.

Our physical model demonstrates a relationship between off-fault dilatation rate, off-fault topographic features, and the transition from locked slip to creeping slip. These correlations suggest that deformation associated with the slip transition accommodates a portion of the overall fault motion. Off-fault deformation as a result of a change in slip behavior should be considered in interpretations of interseismic velocity fields on strike-slip faults.

5. Conclusions

We conduct physical experiments using silicone slabs, modeling the change in behavior along a strike-slip fault from a frictionless creeping segment with localized deformation to a locked segment with a broad zone of distributed deformation. By tracking surface motion in 2D using PIV and in 3D using photogrammetry, we document patterns of off-fault strain that develop on either side of the slip transition. The experimental strain field shares similarities with the real-world strain field across the San Andreas fault in central California, where the fault transitions from creeping to locked slip. Over geodetic timescales, GPS velocity field patterns of contraction and extension can be compared to 2D experimental dilatation rate patterns. Over geologic timescales, 3D deformation serves as an analogue to geologic structures that may develop away from the fault trace. While purely elastic models fail to capture permanent off-fault deformation patterns resulting from persistent slip rate variations along strike-slip faults, our experiments highlight that a change in slip behavior can lead to off-fault deformation, potentially explaining some of the deformation patterns observed along the San Andreas fault in central California.

Data Availability Statement

All data including photographs, velocity fields, and 3D point clouds are available through Iowa State University FigShare: http://doi.org/10.25380/astate.19583395.v1.

Acknowledgments

E. O. Ross, J. E. Reber, and S. J. Titus were supported by NSF grants EAR-1916970 and EAR-1917048. Thank you to Alex Hatem, Nestor Cardozo, and Tim Dooley for helpful comments and suggestions. Open access funding provided by the Iowa State University Library.

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