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Key Points:

- Fault propagation work in sandbox models scales well with that in natural faults
- The strain threshold for weakening to occur is scale dependent
- Diffuse deformation in sandbox models corresponds to the damage zone in natural faults

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Growing Faults in the Lab: Insights Into the Scale Dependence of the Fault Zone Evolution Process

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Abstract Analog sandbox experiments are a widely used method to investigate tectonic processes that cannot be resolved from natural data alone, such as strain localization and the formation of fault zones. Despite this, it is still unclear to which extent the dynamics of strain localization and fault zone formation seen in sandbox experiments can be extrapolated to a natural prototype. Of paramount importance for dynamic similarity is the proper scaling of the work required to create the fault system, W_{prop} . Using analog sandbox experiments of strike-slip deformation, we show W_{prop} to scale approximately with the square of the fault system length, l , which is consistent with the theory of fault growth in nature. Through quantitative measurements of both W_{prop} and strain distribution we are able to show that W_{prop} is mainly spent on diffuse deformation prior to localization, which we therefore regard as analogous to distributed deformation on small-scale faults below seismic resolution in natural fault networks. Finally, we compare our data to estimates of the work consumed by natural fault zones to verify that analog sandbox experiments scale properly with respect to energy, that is, that they scale truly dynamically.

1. Introduction

Localization of strain into discrete shear zones and fault networks is a characteristic feature of the deformation of Earth materials on all scales from single grains to tectonic plates. In laboratory experiments on the deformation of brittle rocks the localization of strain into cracks and their subsequent coalescence into a throughgoing fracture are closely linked to a decrease in material strength known as strain weakening (Brady et al., 1973; Lockner et al., 1991; Paterson & Wong, 2004; Scholz, 2002). On the larger scale of entire sedimentary basins strain localization can be observed as deformation being initially distributed onto several small faults and subsequently concentrating onto one master fault (e.g., Cowie et al., 2005; McLeod et al., 2000). In the Andes, Oncken et al. (2012) were able to link this reduction in the number of active faults to a concurrent decrease in crustal strength. Their study uses field data to convincingly show the general behavior; however, the scarcity of geological data and the accuracy of available dating methods make it difficult to understand in detail the process of localization and its quantitative relation to strength evolution on various scales. Scaling laws have been employed to derive estimates regarding slip on faults below the resolution of a data set (Scholz & Cowie, 1990), but their predictions remain untested.

Scaled analog sandbox experiments provide physical models in which the processes of interest can be observed directly and practically without limitations of resolution apart from the particle size of the selected material. Previous sandbox experiments focusing on strain localization have shown a phase of diffuse (Adam et al., 2005) or ephemerally localized (Dotare et al., 2016) deformation to precede formation of localized faults in sand. This can be linked to global material hardening (Lohrmann et al., 2003; Rechenmacher, 2006) and is thus an essential part of the localization process (Tordesillas & Muthuswamy, 2009). By analogy it has been related qualitatively to distributed deformation preceding localization in nature (e.g., Dotare et al., 2016). However, quantitative verification for this analogy is still missing.

In general, the applicability and extrapolation of the laboratory observations to nature usually relies on geometric, kinematic, and dynamic similarity between the analog model and the natural prototype (Hubbert, 1937). Similarity criteria include dimensionless numbers relating length, time, and stress in the model and in nature, which should be the same. Rigorous dynamic similarity should result in proper scaling of energy, work, and eventually power. For a rate-independent deformation process as we consider here, kinematic scaling is arbitrary. Therefore, energy, or work, is the critical quantity to guarantee dynamic similarity.

Furthermore, the energy budget of the localization process has recently received increased attention due to its application in predicting fault growth through minimum-work models (Cooke & Madden, 2014; Cooke & Murphy, 2004; Dempsey et al., 2012; Hardy et al., 1998; Masek & Duncan, 1998; Mitra & Boyer, 1986). In this context the work of fault propagation, W_{prop} , is recognized as the crucial parameter determining strain distribution and localization (Del Castello & Cooke, 2007). As usual in these studies, we define W_{prop} to be the work per unit height of the fault, where height refers to the in-plane extent of the fault perpendicular to the slip direction. The unit of W_{prop} is thus J m^{-1} . The common estimate used in all the above studies assumes W_{prop} to depend on the volume of the fault zone. Its width depends on the displacement on the fault (e.g., Scholz, 1987) and thus on fault length l (Cowie & Scholz, 1992; Dawers et al., 1993). This leads to the prediction of an overall scaling of fault zone volume, and thus W_{prop} , with l^2 .

In contrast, shear zone width in granular media in general and in sandbox experiments, in particular, depends on grain size and is otherwise constant (Panien et al., 2006). Accordingly, Herbert et al. (2015) have reported results from which W_{prop} can be deduced to be directly proportional to l , although this relationship was not in the focus of their study. If this linear relationship is valid, it has significant implications for the applicability of sandbox experiments to understanding natural systems.

To resolve these issues, we carried out a series of analog sandbox experiments varying the fault system length l systematically over a wide range. By quantifying diffuse deformation and W_{prop} , as well as their mutual relation, we show that diffuse deformation in sandbox experiments is analogous to distributed deformation in natural fault systems. Our data also verify the dynamic similarity of sandbox experiments by means of scalability with respect to energy; that is, they show a similar scaling of W_{prop} with fault length as in nature.

2. Experimental Approach

In order to facilitate the formation of a sufficiently large fault system, we choose the tectonic setting of strike-slip deformation, in which l (defined here as the extent in slip direction) is not limited by crustal thickness. To further extend the range of l , we complement these experiments with measurements in a ring shear tester that allows very precise measurements of forces for short l at the cost of not permitting direct observation of the shear zone.

2.1. Analog Material

The analog material used in this study is quartz sand of type G23T, which is the standard sand used for analog modeling at GFZ Potsdam. It is a medium-grained and moderately sorted fluvial sand with rounded grains (mean grain size $300 \mu\text{m}$). Standard mechanical testing has been carried out on this sand by Klinkmüller et al. (2016), Ritter et al. (2016), among others. The latter study found tectonic models using this material to be scaled most properly with respect to strength and strain weakening for a length scaling factor of $l^* = 2 \times 10^{-6}$, that is, for the case of 1 cm in the model relating to 5 km in the natural prototype.

2.2. Deformation Rigs

2.2.1. Strike-Slip Shear Box

The strike-slip shear box is a custom built apparatus that is based on the deformation rig introduced in Ritter, Santimano et al. (2017). It essentially consists of a sand pack, one part of which is pushed forward by a combination of an indenter and a moving sidewall, while the other part is held in place by a stationary backwall and sidewall (Figure 1). The sand pack is resting on a layer of low-viscosity shear rate thinning silicone paste KORASILON M-B 2-285, $\eta = 10^2 \text{ Pa s}$ to 10^4 Pa s , rheometric measurement data given in Ritter, Rosenau et al. (2017) that, in combination with a low deformation rate of $30 \mu\text{m s}^{-1}$, reduces the basal traction to approximately 10 Pa. This is about 4% of the average sand strength and thus enables the sand pack to be pushed forward as a whole without internal thrusting (average sand strength $\tau_{\text{prop}} = \mu\sigma_n \approx 240 \text{ Pa}$, where $\mu = 0.57$ is the friction coefficient of sand and $\sigma_n = 416 \text{ Pa}$ is the normal load in the center of the sand pack). The yield strength of the silicone paste prevents the sand from sinking in. A strike-slip shear zone develops between the edges of the indenter and the stationary backwall. The force required to push the indenter forward is measured by a sensor attached to it (sampling rate: 1 kHz), and a digital camera captures images of the sand pack's surface (recording rate: 1 Hz), from which the surface deformation field is calculated by means of DIC (Digital Image Correlation).

The fundamental novelty of this shear box is the total absence of any preexisting basal shear zone, either distributed or discrete, which distinguishes it from the typical Riedel-type shear box and its derivatives

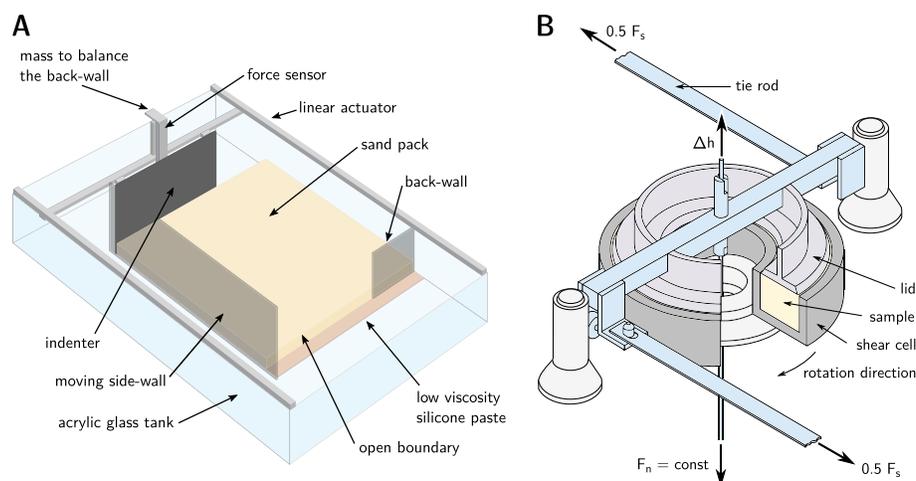


Figure 1. (a) Experimental setup for strike-slip experiments (SL). The sand pack is pushed by the indenter moving at a constant velocity. Due to a layer of low-viscosity silicone paste, the drag at the base of the sand pack is very small (≈ 10 Pa), such that when pushed the sand pack moves as a whole. A stationary backwall holds back a part of the sand pack, which causes a shear zone to develop between the edges of the indenter and the backwall. The parameters recorded are the force needed to push the indenter and its displacement. Additionally, a stereoscopic camera system (not shown) mounted above the set-up monitors the surface deformation of the sand pack. (b) Experimental setup for ring shear tests (RST). The sample is sifted into the shear cell, which is then covered with the lid. A constant normal load is applied to the lid, and the shear cell is rotated at a constant angular velocity, while the lid is kept stationary by tie rods. Radial vertical blades at the base of the lid (not shown) ensure mechanical coupling between lid and sample. The spacing l of these blades is varied between experiments. Sensors register the shear force F_s , the normal load F_n , and the decompaction of the sample Δh . Modified from Schulze (1994).

(Dooley & Schreurs, 2012). Such basal shear zone would result in mode-III deformation of the sand pack and vertical propagation of the already localized basal shear zone. Here only the starting and ending points are given as stress singularities, between which a fault can freely develop. This leads to mode-II deformation and does not prescribe localization away from the end points.

In all strike-slip experiments presented here the sand pack is 50 mm high and 750 mm wide. The sand is sifted into the box to ensure a reproducibly high density, and it is leveled by carefully scraping off the topmost approximately 1 mm to a uniform height. The variable parameter is the initial distance between indenter and stationary backwall, which is the fault system length l . It is set to $l = 200$ mm, $l = 300$ mm, and $l = 400$ mm in this study. In all experiments deformation is stopped only after about 10 mm of deformation after the force registered at the indenter became stable.

2.2.2. Ring Shear Tester

In order to extend the range of l toward lower values (≤ 100 mm), we carry out complementary experiments in a ring shear tester (RST). The RST is an industrial standard device (model *RST-01.pc*, manufactured by *Dr.-Ing. Dietmar Schulze Schüttgutmesstechnik, Wolfenbüttel*, Germany) that has already been used in several other studies in the analog modeling community (e.g., Klinkmüller et al., 2016; Lohrmann et al., 2003; Panien et al., 2006; Ritter et al., 2016; Rosenau et al., 2017). It was first introduced by Schulze (1994). The RST consists of an annular shear cell and a matching lid between which the sample is contained. The shear cell is 40 mm high; it has an inner radius of 50 mm and an outer radius of 100 mm. The lid is pressed onto the sample at a preset normal load, σ_n . The shear cell is then rotated (angular velocity $\omega = 0.39$ rad s^{-1} , corresponding to an average shearing velocity $v = 0.5$ mm s^{-1}), while the lid is kept stationary by tie rods (Figure 1). Thereby, the sample is sheared. Sensors record the torque and the normal load applied to the lid, as well as its vertical displacement due to volume changes of the sample.

The lid is equipped with small radial blades pointing vertically downward from its base to provide sufficient mechanical coupling with the sample. These blades are 5 mm high and extend over the whole width of the ring. Upon rotating the shear cell, shear zones will nucleate at the tip of each of these blades and propagate toward the respective next one. The distance between two such blades is therefore the equivalent to the fault system length l in the strike-slip setup and the parameter we vary in this study. We define the average

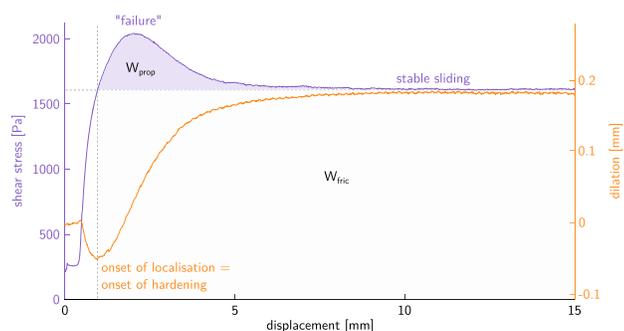


Figure 2. Shear stress and (blue) and sample dilation (orange) in a ring shear experiment at $\sigma_n = 3$ kPa. Shear stress increases toward a maximum (“failure”) and then decreases (“weakening”) again toward a stable sliding stress. At the same time dilation takes place, which can be taken as a proxy for localization. The work required for fault propagation (W_{prop}) is defined as the area under the hardening-weakening peak, as shown by the blue-shaded area, and normalized to fault height. W_{fric} is the work for continued frictional sliding on the fault, which is the area under the shear stress curve that does not belong to W_{prop} , as indicated by the gray shading.

circumferential distance between two blades as the distance along the imaginary circumferential line that separates the surface of the lid into two parts of equal area. For the sake of simplicity we will call this the “blade distance” from here on.

In the standard configuration of the lid there are 20 blades ($l = 24.4$ mm). From this configuration blades were removed systematically, to realize blade distances of $l = 48.8$ mm (10 blades) and $l = 97.6$ mm (5 blades). Samples are sifted into the shear cell and then scraped off to the correct height.

2.2.3. Kinematic and Mechanical Differences Between the Setups

Deformation in the two experimental setups is different to some degree: In the strike-slip box, normal load across the shear zone is due to lithostatic load, which increases from 0 Pa at the surface to approximately 850 Pa at the bottom of the sand pack. Thus, there is a gradient of normal load across the fault from the surface to the bottom. At the same time, the slip rate is constant over the entire height of the sand pack. This is exactly opposite in the RST, where a constant normal load of 500 Pa is applied on the entire fault surface by the lid, while the slip rate increases outward by a factor of 2, due to constant angular velocity. Although deformation of sand follows a velocity-independent rheology (Rosenau et al., 2017), the velocity gradient causes a displacement gradient, which leads to slightly diachronous material failure with a circular failure front moving through the material from the

periphery inward. This is likely to flatten the force peak (lowering and widening). However, this does not change the area below the force curve and therefore does not bias the work inferred. The gradient of normal load, on the other hand, has a direct influence on fault strength, which in this case increases with depth. As the relationship between normal load and strength is linear, average values for normal loads, strengths, and forces should nonetheless be reasonably good quasi-2-D representations of the actual processes.

2.3. Work of Fault Propagation

According to Herbert et al. (2015), the total work balance for analog sandbox experiments is as follows:

$$W_{ext} = W_{prop} + W_{fric} + W_{grav}. \quad (1)$$

W_{ext} is the external work done on the system, W_{fric} is the frictional work along the established (localized) shear zone, and W_{grav} is the work done against gravity. In the case of strike-slip deformation the vertical component of deformation is negligible, such that $W_{grav} \approx 0$ in our models. The remaining parameters can be easily determined from the experiments: Measurements of bulk shear force in either experiment yield shear curves (Figure 2) that reveal a hardening-weakening cycle during deformation. According to Lohrmann et al. (2003), this is associated to a compaction-dilation cycle. Based on the micromechanical model of Tordesillas and Muthuswamy (2009), we suggest the onset of dilation to be equivalent to the onset of localization. As can be seen from Figure 2, this coincides with the onset of hardening. We therefore define the work of fault propagation W_{prop} as the area beneath the hardening-weakening peak, and the work done in frictional sliding on the shear zone W_{fric} as the remaining area under the shear curve. Both values are normalized to fault height. Note that our definition of W_{prop} is slightly different from other definitions that can be found in literature, which usually exclude the period of hardening prior to the force maximum (e.g., Cooke & Madden, 2014; Herbert et al., 2015).

3. Results

3.1. Surface Deformation: Diffuse Versus Localized Deformation

In the strike-slip setup a total of nine experiments were carried out for different l . Surface displacement fields derived from DIC are used to analyze the fault evolution in these experiments. Figure 3 shows maps of the vorticity of the incremental displacement field for a representative experiment with $l = 300$ mm. The general pattern described in this example is independent of l in all experiments, as shown later.

In the beginning, deformation is diffuse and widely distributed in a sigmoidal patch between the edges of backwall and indenter. Directly at the edges, however, it becomes quickly, that is, within a few millimeters of indenter displacement, localized into narrow shear zones that are a few centimeters long. They are rotated

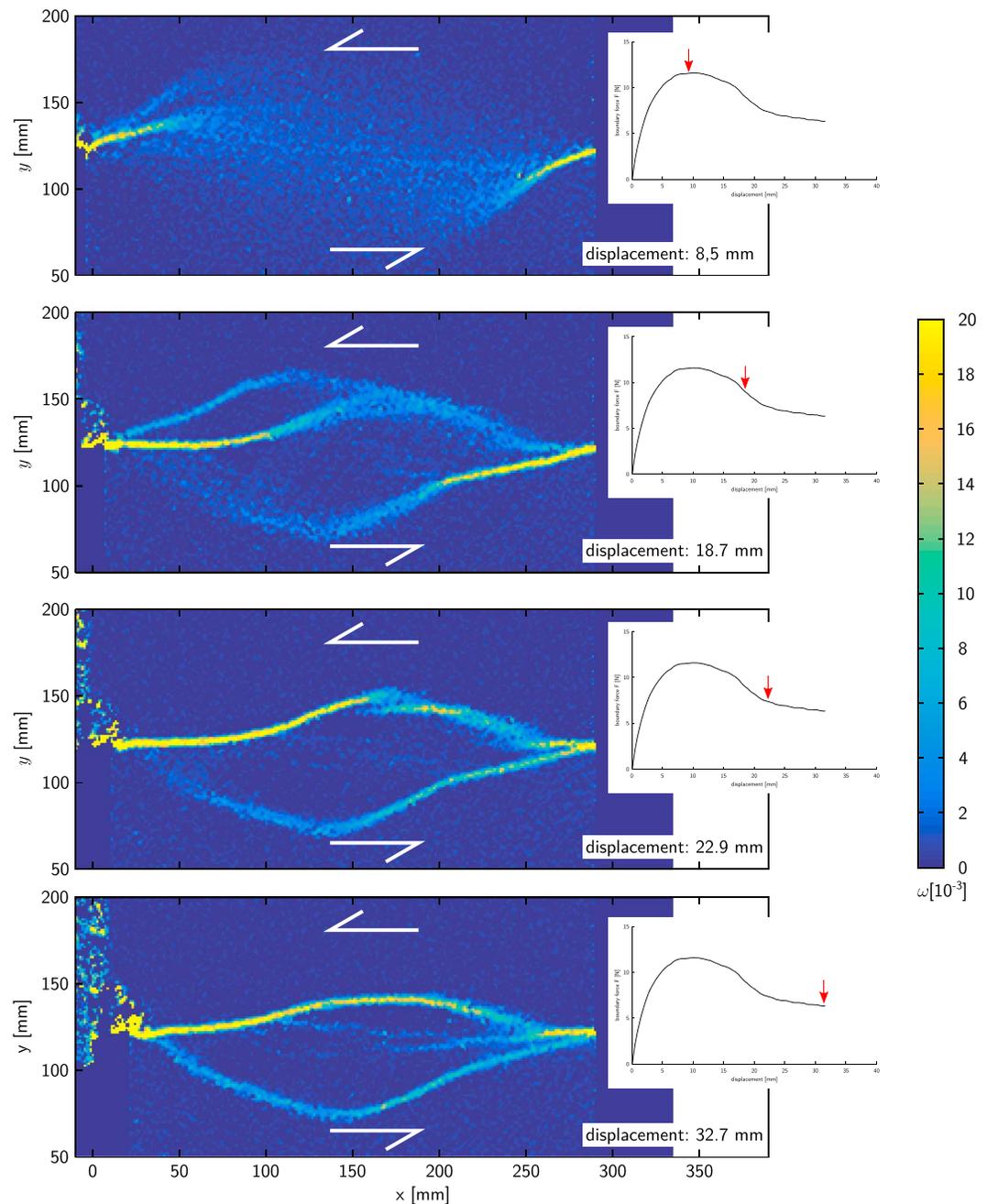


Figure 3. Evolution of a shear zone in strike-slip experiments, $l = 300$ mm. Data shown are the vorticity of the incremental displacement field. The shear zones evolve in a complex pattern until finally an approximately straight shear zone is formed. See text for detailed analysis.

about 25° to 30° outward with respect to the trace of the ideal, that is, direct connection between the edges of indenter and backwall. This corresponds to the angle predicted by the Mohr-Coulomb failure criterion, if one assumes the pushing direction to be equal to the direction of maximum compressive stress. In the gap between the two shear zones deformation remains diffuse.

After accumulating some more displacement (about 5 mm) without growing significantly, the two initial shear zones become replaced by new ones that are oriented closer to the direction of imposed deformation; however, their tips are still bending outward and away from each other (Figure 3). The new shear zones grow in a stepwise manner and eventually become replaced by a new, even more favorably oriented one. Before a

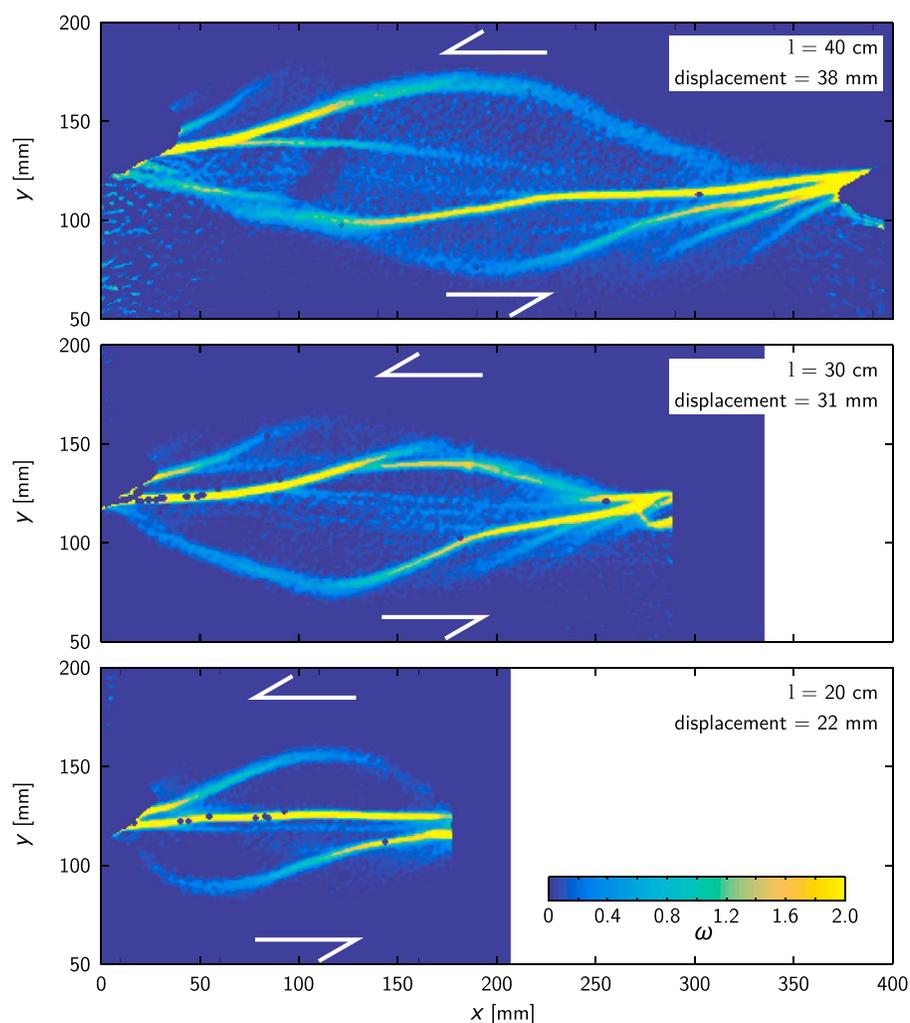


Figure 4. Maps of vorticity of cumulative displacement fields comparing experiments with different l . The overall structure is similar with shear zones curving around each other. However, the number of abandoned shorter shear zones and the amount of diffuse deformation increase significantly with l .

new shear zone takes over the deformation, both shear zones, new and old, show simultaneous activity for a short time span.

In this way the shear zones grow toward and around each other until they eventually connect. When they finally do so, they connect not to the other fault's tip but somewhere close to its starting point, such that there are two adjacent fault branches, both connecting backwall and indenter. In between the two branches, slight uplift (a few millimeters) can be observed. Activity then usually ceases on the more curved branch such that one main shear zone remains. It might straighten out slightly, but apart from that, deformation appears to have reached a steady state at this point.

To compare the evolution of experiments with different l , the cumulative displacement fields at the end of the experiments are used. Figure 4 shows maps of their vorticity for one experiment of each l . It is clear from the figures that the general behavior of fault growth is the same independent of l : In all cases there are several distinct, abandoned shear zones at decreasing angles toward the deformation direction, and two main branches that connect to the other side. Due to the maps showing the cumulative deformation, the main shear zone at the end of the experiment cannot be clearly identified from the figure. This is only possible in the case of $l = 200$ mm (bottom), where an additional straight and throughgoing shear zone forms in the center toward the end of the experiment.

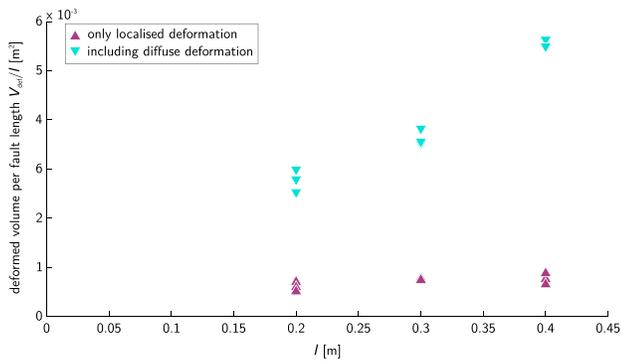


Figure 5. Deformed volume normalized to fault length in strike-slip experiments. The volume of the localized deformation is approximately constant, whereas the total volume including diffuse deformation shows a more-than-linear increase with l .

To quantify the extent of diffuse and localized deformation, we measure the deformed area by counting the number of pixels that have undergone measurable deformation. We use the second component of the displacement gradient tensor ($\frac{\partial u_x}{\partial y}$, where u_x is displacement along strike and y is in the direction perpendicular to it) and apply the algorithm of Otsu (1979) to find the best threshold between noise and measurably deformed area. This algorithm is designed to extract features from their background in an image based on intensity histograms. Because this relies on relative intensity differences, we are able to either include or exclude diffuse deformation in the pixel counting by applying the algorithm to displacement fields at two different, well-defined points during deformation. At peak stress practically no localized deformation has taken place yet. The algorithm thus finds a threshold that separates diffuse deformation from noise. This threshold can subsequently be applied to the final time step to measure overall diffuse deformation during the experiment. Applying the algorithm directly to the final time step, on the other hand, returns a threshold

that retains only localized deformation. This is due to the fact that the intensity difference between distributed and localized deformation is much larger than between distributed deformation and noise. We are thus able to measure total deformation (of which localized deformation is only a minor fraction) and localized deformation separately.

Assuming a quasi-2-D situation, the number of pixels displaying deformation can be transformed to the total volume V that has undergone deformation at any time during the experiment by multiplying with the height of the sand pack. Figure 5 shows V normalized by l as a function of l . Without diffuse deformation, the volume per fault length ($V_{loc} l^{-1}$) is approximately constant. If, on the other hand, diffuse deformation is included, the volume per fault length (V_{diff}) increases overproportionately with l .

Figure 6 shows along-strike profiles of distributed, cumulative slip for each experiment. These profiles are compiled by first masking out (i.e., setting to zero) areas of localized deformation and then summing up in y -direction all values $\frac{\partial u_x}{\partial y}$. The profiles show a maximum in the center of the shear zones, which is in accordance with the propagation of localization described above. Their maxima are slightly below the displacements required for formation of a throughgoing fault zone in the respective experiments and correspond to the displacements at which weakening is complete (see below). When normalizing both the position along strike and the displacement to l , the profiles show a good data collapse, with the maximum distributed slip in the center of the shear zone being about 6% of the fault length.

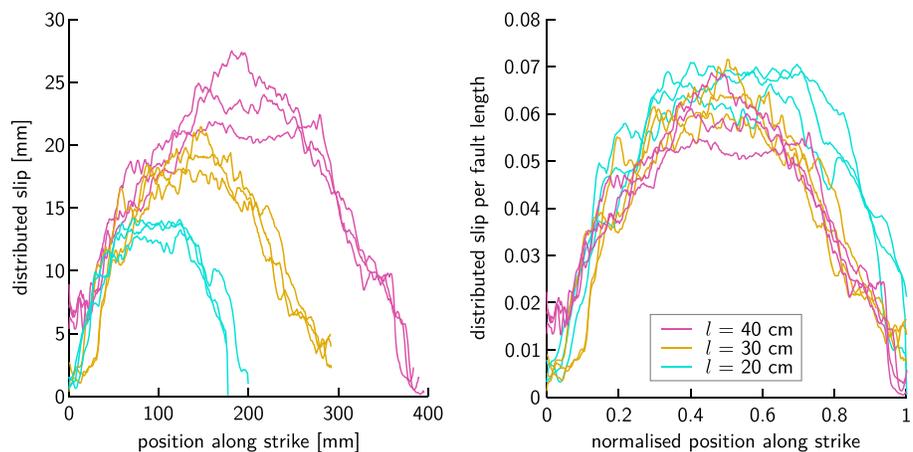


Figure 6. Distributed slip profiles for the strike-slip experiments. The profiles show a maximum in the center that corresponds to the amount of slip accumulated before weakening. Normalizing both axes to fault length results in a collapse of all experiments to one profile line with a maximum at about 6% of the fault length.

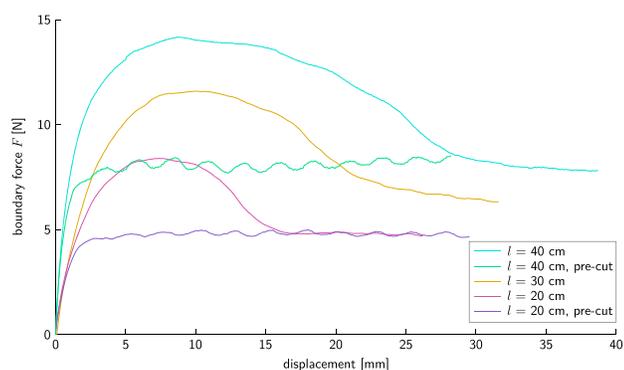


Figure 7. Boundary force versus displacement in strike-slip experiments for different shear zone lengths l . Both peak and stable sliding force increase with l , which can be explained by an increased shear zone area. Reference measurements with a precut sand pack were carried out for $l = 200$ mm and $l = 400$ mm. They do not exhibit any hardening-weakening behavior but begin directly in the regime of stable sliding. The oscillatory pattern in these curves is probably due to the limited mechanical accuracy of the ball screws driving the deformation. The oscillation frequency corresponds to the angular frequency of the ball screws.

3.2. Driving Forces: Strain Hardening-Weakening and Work Budget

In the strike-slip setup the pushing force was measured in all nine experiments. Figure 7 shows the shear force (corrected for basal drag) for one experiment of each l . The general behavior is similar for each of them: The curves show a hardening-weakening peak followed by a stable sliding phase in the end. Both peak height and stable sliding force increase with l , in accordance with an increasing fault surface area. The amount of displacement needed to achieve stable sliding increases with l , too, from approximately 15 mm for $l = 200$ mm to 30 mm for $l = 400$ mm (cf. Figure 6).

In addition to the experiments with undisturbed sand packs, experiments with a precut shear zone were carried out for $l = 400$ mm and $l = 200$ mm. The cut was made using a wire that was stretched between the edges of backwall and indenter directly above the layer of silicone and before the sand was sifted into the box. After filling in the sand this wire was carefully pulled out upward through the sand pack to create the cut. As shown in Figure 7, these experiments do not exhibit hardening-weakening but, after an initial increase, directly start into the regime of stable sliding. The force in these experiments shows a cyclic variation of maximally ± 0.5 N which is considered an artifact. It reflects the limited precision of the ball screws used to drive the deformation (repeat accuracy ± 0.02 mm).

The frequency of the variation corresponds to the angular frequency of the ball screws. The average level of the force is very similar to the stable sliding force at the end of the undisturbed experiments.

In the RST five independent measurements were carried out for each blade configuration. The normal load was set to $\sigma_n = 500$ Pa, which corresponds roughly to the average overburden load in the center of a 5 cm thick layer of sand, as used in the strike-slip experiments. Figure 8 shows one example of a shear curve for each blade configuration. The measurements are the total force at the sensors, which is integrated over the number of fault systems created, that is, the number of blades. As the final fault surface area is the same in all experiments independent of blade configuration, all three curves show almost identical stable shear forces and similar peak heights. The peak width, however, measured to the point where the shear force reaches a stable value, increases with blade distance, similar to what we observe in the strike-slip experiments.

To compare the weakening during fault formation for the different fault areas that occur in the two setups, we define the relative weakening in terms of force, ΔF :

$$\Delta F = 1 - \frac{F_s}{F_p}, \quad (2)$$

where F_p and F_s are the maximum of the force curve ("peak") and the subsequent plateau value ("stable"), respectively. ΔF will be between zero (no force drop, i.e., no peak) and one (drop to zero after the maximum). Figure 9 clearly demonstrates that ΔF is independent of l but differs between the two setups, being on average 0.19 in the ring shear experiments and 0.43 in the strike-slip experiments. This difference of approximately a factor of 2 is due to the different ways shear zones are induced in the two setups: In the RST, stress concentrations at the tip of each blade initiate one fault per blade. These faults propagate in the direction of shear (i.e., rotation) until they meet the faults initiated at the next respective blade. Consequently, there is only one fault evolving per fault system, with the number of blades being equal to the number of fault systems. This is sketched in Figure 10.

In the strike-slip experiments, on the other hand, two faults evolve in one fault system, one initiating at either side of the setup (Figures 3 and 10). They evolve simultaneously and overlap until finally one of the two faults is abandoned. The total area of the fault planes is hence twice as large as it would be in the RST for the same l , which for a given material strength also results in the force being twice as high. This changes toward the

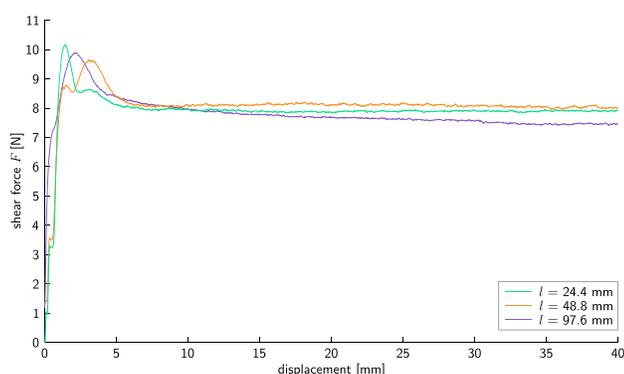


Figure 8. Shear curves from ring shear experiments for different shear zone lengths l . Peak and stable sliding strength are similar for all curves, but the peak width changes with l . All measurements carried out at $\sigma_n = 500$ Pa. All measurements are for total force at the sensors, that is, integrated over all fault systems.

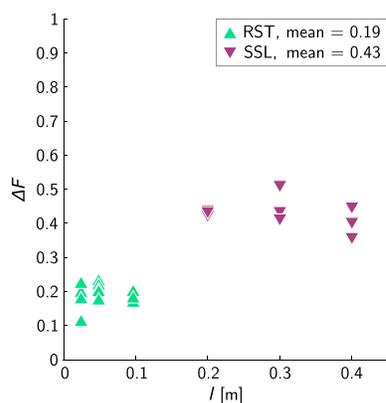


Figure 9. Relative weakening in the strike-slip experiments (SSL) is about twice as much as in the ring shear tests (RST). Within the respective setups it is independent of l .

end of an experiment when one of the fault branches is abandoned. Consequently, the stable sliding force is the same as it would be in the RST for the respective l , and thus, the weakening is twice as high.

From the shear curves the work for fault propagation W_{prop} is determined: The transition from weakening to stable sliding is picked by hand in each shear curve and the area under this peak is measured (see definition in Figure 2). The values obtained in this way represent the formation of two faults in case of the strike-slip experiments and of a variable number of faults depending on blade configuration in case of the RST (see above). Therefore, all measurements from the strike-slip experiments are divided by two, and all measurements from the RST are divided by the number of blades in the respective experiment, before being normalized to fault height. The resulting W_{prop} as a function of l is shown in Figure 11. The plot shows a strongly nonlinear increase of W_{prop} , with values ranging from 1 mJ m^{-1} to $1,260 \text{ mJ m}^{-1}$ for the range of l covered by our data.

Figure 12 shows W_{prop} normalized to the deformed surface area A . As W_{prop} is defined as work per height, dividing by the surface area effectively results in a work per volume. It increases with l , if $A = A_{loc}$, that is, when only localized deformation is taken into account. If the total diffuse deformation is considered as well ($A = A_{diff}$), the work per volume is approximately constant and about 55 J m^{-3} .

4. Discussion

4.1. Assessing the Complementarity of the Two Setups

Optical monitoring of the strike-slip experiments shows that the final shear zone is often curved; thus, it often deviates from the shortest possible fault path, which might be considered the energetically preferred one.

Hence, it is conceivable that the evolution of the shear zone at the end of our experiments has not yet reached a stable state, and more weakening might be possible. In this case ΔF and W_{prop} determined in our experiments would underestimate the true values. However, the average level of shearing force in the experiments with pre-cut, straight shear zones is similar to the stable sliding force in the experiments with undisturbed sand packs. From this we conclude that, despite the shear zones still being curved, weakening is largely complete at the end of an experiment and our estimates for ΔF and W_{prop} are good representations of the true values.

Furthermore, we have set the normal load in the RST experiments to $\sigma_n = 500 \text{ Pa}$, which equals the overburden pressure in the center of an approximately 5 cm thick sand pack. By comparing the result of RST and strike-slip experiments, we have implicitly assumed that this overburden load reflects the normal load on the shear zone and that variations with depth cancel out in total. This assumption can be justified by comparing the stable sliding forces in the two setups. It is approximately 7.9 in either one (for $l = 40 \text{ cm}$ in case of the strike-slip setup.) The fault area is $A_{RST} = 226.19 \text{ cm}^2$ for the RST and $A_{SSL} = 200 \text{ cm}^2$ for the strike-slip experiment. Stable sliding stress is thus slightly higher in the strike-slip case than in the RST, but the difference is still within the range of measurement variations of the strike-slip experiments. The two setups therefore can therefore be regarded as complementary with respect to the load conditions.

4.2. Interpretation at the Laboratory Scale

Our experiments show that the work of fault propagation in sand, W_{prop} , increases nonlinearly with fault length. In search for a law that describes both our data subsets, RST and strike slip, with a common set of parameters, we find the closest fit with a function of the form

$$W_{prop} = a l^b \quad (3)$$

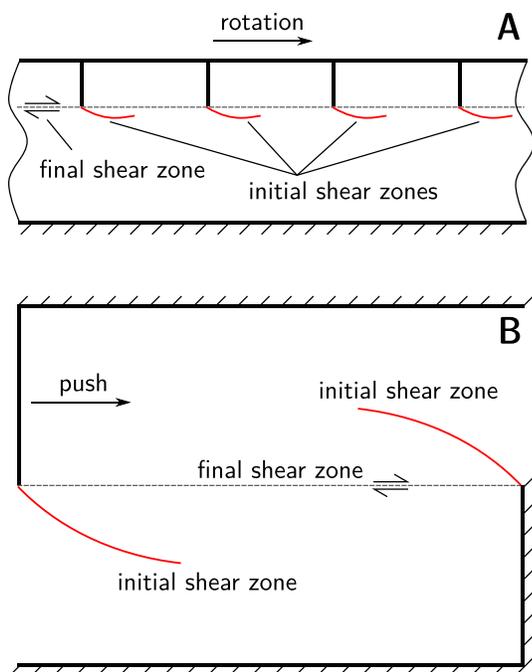


Figure 10. Conceptual sketch of shear zone formation in the two different setups. (a) Section of the ring shear tester. One shear zone forms at the tip of each blade and propagates in rotation direction toward the next blade. The fault system under consideration extends from one blade toward the next; several fault systems develop simultaneously. (b) Strike-slip setup. Only one fault system develops that contains two faults. The work required to deform this fault system on a given scale is twice as much as in the RST. Sketches are not to scale.

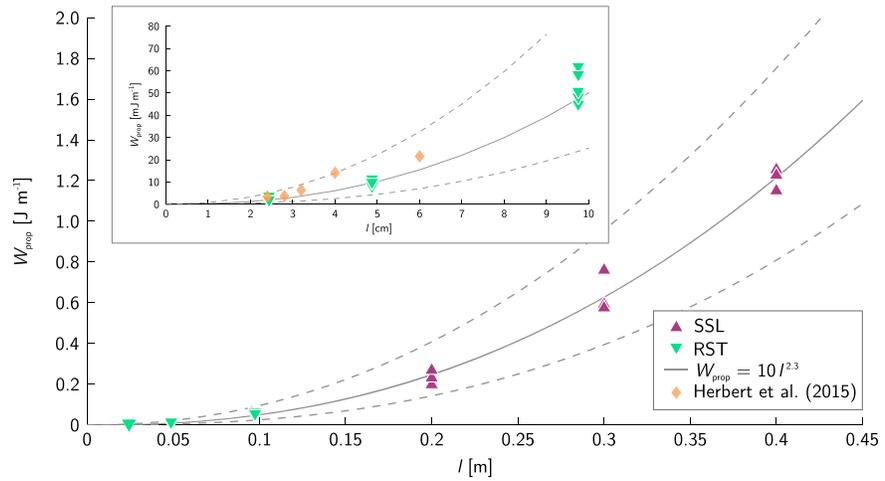


Figure 11. Work required for propagation of a single fault in ring shear tests (inset shows a close-up) and strike-slip experiments increases overproportionately with fault system length l . The gray lines show a power law fit to the data (solid) and its 95th percentile confidence limits (dashed). Data from Herbert et al. (2015) are shown for comparison (fault length derived from description of their setup and data projected to constant normal load).

Here a and b are free parameters that we determine through least squares fitting. Doing so for both subsets individually returns similar values for a and b , respectively (Table 1). A joint fit to the complete data set (“combined” in Table 1) yields the empirical relation for W_{prop} in sand under the given normal load conditions:

$$W_{\text{prop}} = (10 \pm 2) \text{J m}^{-1} \left(\frac{l}{l^\circ}\right)^{2.3 \pm 0.2}, \quad (4)$$

where l° is the unit length. This relation is also shown in Figure 11. The numbers given in parentheses are the numerical values of the uncertainty of the fit (95 % interval of confidence) and referred to the corresponding last digit of the respective fit parameter. They do not include the accuracy of the measurements themselves. Considering the low number of experiments conducted, it is reasonable to assume that the total error might be larger. Our data therefore do not exclude a simple quadratic dependency. Nonetheless, they are in definite contrast with the interpretation of Herbert et al. (2015) that implies a linear relationship on l . This discrepancy probably stems from the fact that their study relies on a limited range of values for l , as it was not intended to test for a relationship of W_{prop} on l but focused on normal load instead. They used a convergent wedge setting and varied the sand pack thickness from 12 mm to 20 mm to realize different normal load conditions. However, from the specifications of their experiments we are able to derive an approximate comparison of their data to ours: We transform the sand pack thicknesses to fault lengths (assuming a fault dip of 30°) and remove the normalization to fault length from their work data. The resulting data we project to a normal load

of 500 Pa to make them comparable to our normal load conditions. The results of this projection are shown along with our RST data in the inset in Figure 11. The two data sets show a good congruence, which verifies the experimental approaches used in either study.

From Figure 12a correlation between W_{prop} and A_{diff} can be deduced. Given that both parameters depend on l (Figures 5 and 11), the observation that their ratio does not change with l implies that their behavior regarding l is the same. This supports our hypothesis of diffuse deformation being the main energy sink during fault formation in sand. As the width of the total area affected by deformation, that is, the distance between the two outermost faults in the maps in Figure 4, is more or less constant, the total volume that is available for diffuse deformation increases only linearly with l . Nevertheless, the fraction of the volume that actually becomes deformed increases according to the above power law, resulting in an increasing density of deformed pixels in the recordings. Consequently, the maximum shear strain the material in the deformed area undergoes prior

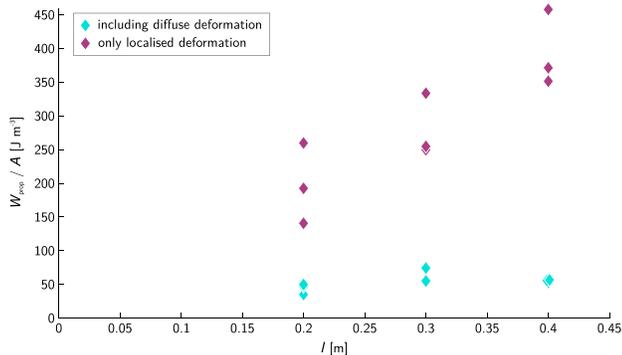


Figure 12. W_{prop} normalized to the surface area of the localized shear zone increases linearly with fault length l , while it is constant at 55 J m^{-3} , if diffuse deformation is included into the surface area.

Table 1
Parameter Returned From Fitting a Function of the Form $W_{prop} = al^b$ to Measurements of W_{prop}

| | a ($J m^{-1}$) | b |
|-------------|--------------------|---------|
| RST | 19 (22) | 2.3 (5) |
| Strike slip | 10 (4) | 2.3 (4) |
| Combined | 10 (2) | 2.3 (2) |

Note. The data were normalized to the number of faults and to fault height h prior to fitting. The numbers given in parentheses are the numerical values of the uncertainty of the fit (95 % interval of confidence) and referred to the corresponding last digit of the respective fit parameter. See text for explanation.

to failure is not a material property but depends on the size of the system. This is confirmed by the observation that failure on the system scale in all experiments occurs when the distributed slip has reached about 6 % of the fault system length. Taken together, this leads to the conclusion of the average rate of fault propagation being constant over the range of l tested. We interpret this to indicate localization to be at least partially driven by the kinematic boundary condition at the edges of indenter and backwall. Therefore, the propagation velocity is controlled mainly by the indentation velocity.

4.3. Application to Natural Systems

4.3.1. Comparison of Work Estimates

Estimates of W_{prop} in natural rocks are subject to large uncertainties, mainly because of the difficulty to directly measure it at the relevant scales. A common approach assumes W_{prop} to be the sum of the work done in creating the fault itself and the work done in creating a damage zone around it (Mitra & Boyer, 1986):

$$W_{prop} = \gamma l + \gamma l r w. \quad (5)$$

As all expressions for W_{prop} in this article, this is a two-dimensional, plane-strain formulation that implicitly assumes a unit length in the third dimension. γ is the surface energy per unit area of the fracture surface, ranging from $10^1 J m^{-2}$ to $10^4 J m^{-2}$ for common rock-forming minerals (Cox & Scholz, 1988; Del Castello & Cooke, 2007; Wong, 1982). l is the length over which the fault grows, and r is the density of fractures in the damage zone around and ahead of the fault tip, which is around m^{-1} according to Mitra and Boyer (1986). w is the width of the damage zone, which is 0.1 times to 0.01 times the fault displacement (Scholz, 1987). This in turn is linearly related to l by some material constant c' (Cowie & Scholz, 1992; Dawers et al., 1993), such that $w = c'l$, where c is a material parameter of the order of 10^{-2} (Scholz, 2002). Substituting w with $c'l$ results in

$$W_{prop} = \gamma (l + crl^2). \quad (6)$$

The quadratic term refers to the damage zone around the fault and the linear one to the fault itself. This dependence of the spatial dimension of the damage zone on l^2 is also in accordance with modern fracture mechanics (Scholz, 2002). However, the linear term implies the fault to be a discrete, planar feature that forms by a separate process, which is probably not the case. Instead, most faults encompass a granulated core of finite width that forms by frictional wear from the intensely fractured material of the damage zone (e.g., Scholz, 2002). This process occurs whenever a fault slips and does not cease after the initial localization that forms the through-going fault. Hence, we argue that formation of the fault core is not part of this localization process. A more accurate estimate of W_{prop} would thus omit the linear term in equation (6) and rather include the formation of the fault core in W_{fric} instead. However, the discrepancy between these two estimates is negligible; it is on the order of 0.1% to 1% for $l = 100$ m and quickly decreases for longer faults. Following this, we assume W_{prop} in nature to scale with l^2 which is, within the range of measurement accuracy, similar to the values determined experimentally in our sandbox models.

Another approach to determine W_{prop} in nature is to measure the surface area created by fracturing in a single earthquake, determine the surface energy spent, and sum this over the number of earthquakes experienced by the fault. For the Punchbowl fault in the San Andreas system, California, Chester et al. (2005) determine the fracture surface energy per earthquake to be approximately $0.5 MJ m^{-2}$. They estimate the total 44 km of displacement to have accumulated over about 10,000 earthquakes, which results in the total energy required for creation of a fault of comparable size to be $5 \times 10^3 MJ m^{-2}$ to $10^5 MJ m^{-2}$. Assuming a fault length of 440 km (Scholz, 2002), equation (6) results in values ranging from $2.2 \times 10^1 MJ m^{-2}$ to $2.2 \times 10^4 MJ m^{-2}$ for the same situation.

Applying the scaling factors for sandbox models derived in Ritter et al. (2016), we determine a model fault length of 0.88 m to be analogous to this case. From equation (4) this results in $W_{prop} = 8.47 J m^{-2}$ in the model. The scaling factor for energy per area can be calculated as the product of the scaling factors for stress and length, $\sigma^* l^* = 2.42 \times 10^{-12}$ (Ritter et al., 2016). Scaling the model result up to nature with this factor yields $W_{prop} = 3.5 \times 10^{12} J m^{-2}$. This is slightly higher than the values derived for natural faults above but still acceptably close considering the uncertainty of 4 orders of magnitude for the natural estimates. Consequently, our results are also numerically similar to natural fault systems.

4.3.2. Analysis of Strain Distribution

We interpret the fault system evolving in our experiments as representing a transfer fault system linking two segments of dip-slip faults, where the two displacement singularities (indenter and backwall) correspond to the edges of the dip-slip faults. This termination by conversion into a dip-slip fault is one of three geometrically possible terminations of a strike-slip fault (Mouslopoulou et al., 2007; Ramsay, 1980). Natural examples include the Tjörnes Fracture zone in Iceland (Gudmundsson, 1995) and the Las Vegas Valley Shear Zone in Nevada (Duebendorfer & Black, 1992).

The pattern of overlap of the shear zones we observe in our experiments is similar to that in restraining double bends occurring in natural strike-slip shear zones (e.g., Cunningham & Mann, 2007). Schrank and Cruden (2010) observed a similar kind of overlap also in a classical Riedel-type experiment, albeit without the diffuse deformation but another shear zone between the two branches instead. The uplift we observe resembles—although negligibly small with respect to the work calculations—the pop-up or positive flower structure that usually can be found in natural structures in this context (Cunningham & Mann, 2007; Cunningham, 2007). Commonly, natural restraining bends are interpreted to be related to inherited structures within the trace of a strike-slip shear zone, such as a step over in a preexisting basement fault (Cunningham & Mann, 2007). Our results contrastingly suggest that an inherited structure is not a necessary condition; instead, restraining bends seem to develop whenever two fault segments that follow the same fault trace approach each other. This is particularly well exemplified in Figure 4 for the case of $l = 30$ cm, where the two segments first propagate directly toward each other before they turn outward. We interpret this as being due to the stress distribution around each fault segment, which makes it impossible for the segments to link directly tip to tip.

Furthermore, we observe a succession of short-lived shear zones that occur directly at the edges of indenter and backwall during the hardening regime. They appear at decreasing angles with respect to the final fault trace, and their number is highest for long fault systems. Their initial orientation according to a Mohr-Coulomb failure criterion suggests that the first such shear zone represents the dynamically favored path. The final direction of the throughgoing shear zone, however, is strongly predetermined by the fixed kinematic boundary condition. We therefore interpret the succession of these shear zones as being the result of a competition between the dynamically preferred and the kinematically imposed shear zone direction. To our knowledge, similar shear zone patterns have not been reported from any natural fault system, so far. This might be either due to lack of preservation of such features or due to the edge of the dip-slip fault in nature being more compliant than the indenter in the experiment, resulting in a weaker kinematic boundary condition.

In natural basin-scale fault systems, the formation of a throughgoing, localized fault is preceded by deformation on multiple smaller-scale but nevertheless localized faults (Cowie et al., 2005; McLeod et al., 2000; Tchalenko, 1970). This precursory fault network, also referred to as penetrative strain, cannot be resolved as such in the sandbox. Instead, we regard the diffuse deformation observed in our experiments as analogous to this diffusely localized fault network, since persistent plastic deformation in brittle rock always takes the form of microcracks, fractures, and faults. From our measurements of diffuse strain we interpret the density of such fracture networks to be a function of fault system size in nature, too. This carries implications for bulk rock permeability in sedimentary basins and reservoir rock affected by faulting, which are often controlled by fractures that are below seismic resolution. Our findings provide a relative scaling for such fracture systems based on system size. Additionally, such increase of fracture density away from the throughgoing fault is identical to a decrease of strain localization. Therefore, no unique quantitative relation between the system property strain localization and the material property strain weakening can be formulated.

5. Conclusion

We have carried out analog sandbox experiments of strike-slip deformation in which we simultaneously monitored stress and strain. We find the work of fault propagation, W_{prop} , to be directly proportional to the volume of diffusely deformed material, V_{diff} , with a numerical value of about 55 J m^{-3} . In contrast to earlier sandbox studies, but consistent with theory of fault growth in nature, both W_{prop} and V_{diff} show an approximately quadratic dependence on fault system size, while at the same time the total stress drop during localization is constant. Numerical values of W_{prop} scale well to estimates from natural fault zones. Additionally, our data for the first time show quantitatively that distributed deformation in sandbox models mimics natural damage

zone evolution and can be interpreted as a proxy for deformation below seismic resolution in crustal-scale fault systems. We therefore support the traditional view of sandbox experiments being dynamically similar to their natural prototype.

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