Evolution of fault-surface roughness with slip

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Principal slip surfaces in fault zones accommodate most of the displacement during earthquakes. The topography of these surfaces is integral to earthquake and fault mechanics, but is practically unknown at the scale of earthquake slip. We map exposed fault surfaces using new laser-based methods over 10 µm-120 m scales. These data provide the first quantitative evidence that fault-surface roughness evolves with increasing slip. Thousands of fault profiles ranging from 10 micron to >100 m in length show that small-slip faults (slip <1 m) are rougher than large-slip faults (slip 10 to 100 m or more) on profiles parallel to the slip direction. Surfaces of small-slip faults have asperities on all scales, while large-slip fault surfaces are polished, with RMS values of < 3 mm up to 1-2 m profile length. Surprisingly, the large-slip surfaces show smooth, elongate, semi-elliptical bumps that are meters long and up to several centimeters high. We infer that these bumps evolve during fault maturation. This difference in geometry implies that the nucleation, growth and termination of earthquakes on evolved faults are fundamentally different than on new ones.

Introduction

Fault topography is fundamental to models of faulting. The amplitude and wavelength of bumps, or asperities, on fault surfaces affect all aspects of fault and
earthquake mechanics (Scholz, 2002), including rupture nucleation (Lay et al, 1982), termination (Aki, 1984), dynamics (Brodsky and Kanamori, 2001), resistance to shear (Biegel et al, 1992), fault gouge generation (Power et al, 1988), critical slip distance (Ohnaka, 2004), and the near-fault stress field (Chester and Chester, 2000).

Despite this, knowledge of fault geometry and roughness is relatively limited at the scale of earthquake displacements. Prior comparative studies of natural fault roughness on multiple surfaces were based on contact profilometer data (Power et al, 1987; Power and Tullis, 1991; Lee and Bruhn, 1996). The method is labor-intensive so only a few profiles were reported for each surface. It was found that fault surfaces are smoother parallel to the slip direction than perpendicular to it and that fault topography is proportional to the measured profile length (Power et al, 1987; Power and Tullis, 1991). Recent LiDAR measurements on one fault suggested a power law relationship between the measured profile length and the amplitude with slightly different exponents in the slip parallel and perpendicular directions (Renard et al, 2006).

In the present work we investigate the relationship between slip-surface roughness and fault displacement using a ground-based LiDAR (Light Detection And Ranging) instrument in the field and a laser profilometer in the laboratory. We cover a range of scales that includes the slip distances of observable earthquakes (microns through tens of meters). By comparing geometrical features of different faults, we find that mature faults are smoother at small scales and have distinct geometrical structures at larger scales.

**Scanned surfaces**

The definition of fault geometry is not trivial. The shear displacement on a fault can be carried by a single fault surface, by many of them, or by a zone depending on the
depth, the rheology of the faulted zone, and the faulting dynamics (Reches and Dewers, 2005; Dor et al, 2006). Here we focus on the geometry of striated surfaces. We chose seven fault outcrops that contain slip surfaces which are particularly well-preserved (Table 1, Fig. 1). The scanned targets include three strike-slip and oblique-slip faults with displacements <1 m as well as four normal fault surfaces that accommodated slip in excess of 10's to 100's of meters. Scanned sections are selected to be the areas with little erosion as evidenced by clear striations and the absence of pitting.

**Scanning methods**

The LiDAR system (Leica HDS3000) can measure precise distances over an area of up to hundreds of square meters with individual points spaced as close as 3 mm apart. The measured surface is combined with a digital photograph that is used to map and discriminate the study areas. We can then extract from the LiDAR data thousands of fault-surface profiles in any direction along the scanned surface (Fig. 2a). Each scan includes a portable, smooth, planar reference sheet with a few square blocks of different, known heights. Thus, the noise level and the resolution are constrained for each scan (Fig 2b). Like the LiDAR, the laboratory profilometer also produces a matrix of measurement points. It covers a range of 10 µm – 10 cm, allowing about 300-600 profiles on each hand sample.

The raw scan data is rotated so that the mean surface is parallel to one of the major axes and the mean striation direction is vertical or horizontal. The striation direction is established quantitatively by determining the orientation that maximizes the cross-correlation between adjacent profiles (Sagy et al., 2006). Non-fault related roughness was removed by discarding points with extremely high spatial derivatives and the data were
interpolated across the gap. The filtering was limited to 3% of the data to prevent excessive smoothing of the surface. To quantify fault roughness we calculate the values of the RMS heights (average deviation of the topography from a planar surface) and the values of the power spectral densities (Power et al, 1988; Brown, 1995).

**Results**

Our data clearly indicate that the net slip correlates with fault roughness. Small-slip faults (<1 m slip) are rougher (larger RMS values) than large-slip faults (~10-100 m slip) when measured parallel to the slip direction (Fig 2).

For instance, for 1 m profiles parallel to the slip direction (along the axis of the striations), the RMS heights of the small-slip faults is 6.5±3.5 mm. For 2 m profiles the RMS values are 11.5mm±5 mm (Fig. 2a). The RMS heights of the large-slip faults we measured is so low that it is below the LiDAR resolution limit for sections <3 m (Fig. 2a). Combining five scans of the same surface, we slightly decrease the errors to find that the true RMS is 3 mm for 2 m profile of a large fault. These values are calculated from averaged, detrended sections. Thus, at scales of 1-2 m in the slip-parallel direction, the roughness of the large-slip faults is about one order of magnitude smoother than small-slip faults (Fig. 2).

Another measure of roughness is the power spectral density. Fourier spectral analysis is found to be a reliable method for roughness analysis when based on many profiles (Simonsen and Hansen, 1998) and the spectral power is closely related to the RMS height of a profile. For example, for the special case of self-affine surfaces the power spectral density $p$ is related to the wavelength $\lambda$ by

$$p = C\lambda^\beta$$

(1)
where $C$ and $\beta$ are constants (Brown and Scholz, 1985; Power and Tullis, 1991). If $1<\beta<3$ for a section of length $L$, integrating (1) over wavelength $\lambda$ yields the RMS roughness $H$:

$$H = \left(\frac{C}{(\beta-1)}\right)^{0.5} L^{(\beta-1)/2} \quad (2)$$

For simplicity, we will describe one surface as rougher than another one at a given wavelength if its power spectral density is higher than that of the other at that wavelength (even when the surface is not necessarily self affine).

Power spectral density curves from profiles parallel to slip extend the conclusions based on RMS roughness. Figure 2b shows an example of the results from one small-slip fault and one large-slip fault, for profiles both parallel and perpendicular to the striations. In each case, the spectra of 200 LiDAR profiles separated by 3 mm and extending 3 m were computed with a multitaper method. The averaged result is presented only for wavelengths $<1$ m in order to avoid spurious finite length effects. The profiles parallel to the fault slip are smoother (have lower spectral densities) than those perpendicular to slip and large-slip faults are smoother than small-slip faults. The difference between parallel and perpendicular profiles is an obvious and expected consequence of striations, but the difference between large-slip and small-slip faults is novel to this study. Below wavelengths of about 0.5 m, the power spectral density of the large-slip faults is nearly that of our smooth reference surface (red dotted line in Fig. 2b).

These results are supported by our full data set (Fig. 3a). Large-slip faults have consistently lower power spectral densities than small-slip faults. The difference in the two populations is clear in both the LiDAR and laboratory data over scales from 10 microns through 10 meters.
The power spectral density results reflect the geometry for the large slip faults as seen in topographic maps of the surface (Fig. 4). At wavelength > 1 m, the large-slip faults have undulating 3D surfaces. At least three large-slip fault surfaces have smooth ellipsoidal ridges and depressions with dimensions that are ~1-5 m wide, ~10-20 m long, and ~0.5-2 m high. The long axes of these bumps, or asperities, are parallel to the slip direction. Below ~1 m wavelength, the LiDAR data are limited by the instrumental noise level. At longer wavelengths than can be measured on the outcrops, these asperities could represent the smallest scale of a geometrical network like that proposed by earthquake statistics and map-scale studies (Kagan, 1982; Aviles et al., 1987).

The power spectra measured by the lab profilometer and field LiDAR (Fig. 3a) for the large-slip faults do not easily connect across scales. One source of the discrepancy is that the surfaces are sufficiently smooth that the LiDAR data is limited by noise at wavelengths <1 m. A more subtle effect comes from joints that cross the scanned surfaces. Examination of sections along the large faults suggests that most of the measured roughness in the LiDAR at scales < 1 m is contributed by joints that cross the extremely smooth surface (Fig. 4a). Small hand-samples do not include these joints and are therefore smoother. The laboratory data suggests that the true, fault-related roughness of the surfaces at scales of centimeters is likely much smaller than measured by the LiDAR and may be consistent with the trend suggested by the laboratory data.

Taken together, the slip-parallel profiles of large-slip fault surfaces are best described as polished on length scales ≤ 1m and smoothly curved on larger scales (Fig. 4). The spectra show that the large-slip faults do not follow a power law. This behavior is in clear contrast to the former interpretation (Power et al, 1991; Renard et al, 2006) and,
combined with the differences between small- and large-slip faults, demonstrates that faults evolve during slip.

In the slip-perpendicular direction, the data more nearly fits a power law like that in Eq. 1 (Fig. 3b). This observation supports and extends the results of previous studies (Power et al., 1987; Power and Tullis, 1991; Lee and Bruhn, 1996). The connection between the laboratory and field data is relatively simple as the power spectra measured by the lab profilometer and field LiDAR follow a similar trend. This continuity across 5 orders of magnitudes demonstrates the consistency of the two different measurement tools. The slopes of the power spectra of the large-slip and small-slip faults are similar but the data fits the power law over different scales in each case. For instance, one of the small faults (magenta curves in Fig. 3b) from 10 µm to at least 1m is fit with a power law that yields $H = 0.015L^{0.98}$ (See Eq. 2). The power spectral density of one large-slip fault (green curves in Fig. 3b) fits $H = 0.009L^{0.94}$. Although different analysis methods can be used to better calculate the exact slope $\beta$ and its errors (Renard et al., 2005), the above two examples suggest that roughness values follow the spectrum of a self-similar surface with $H \approx 0.01L$ (Upper dashed black line in Fig. 3b). The relationship $H \approx 0.01L$ has previously been observed for many natural faults and fractures (Brown and Scholz, 1985; Power and Tullis., 1991) and we observe that an arbitrary erosional surface has a similar spectrum (upper grey curve in Fig. 3b). We therefore speculate that most of the measurements of the slip-perpendicular profiles may reflect a universal roughness for natural fractures that is little modified by slip. However, at least two of the large-slip faults fall significantly off this curve at scales < 1 m (Fig 3b). The physical structure
behind this variation is the finite width of the bumps in Fig. 4 which is manifested as a smoothing at intermediate and short wavelengths.

**Discussion**

The data presented are surprisingly consistent despite variations in lithology, fault type and the depth of slip (Table 1). In our dataset, the large-slip faults are all normal faults, one might conclude that the normal faults are systematically smoother than the others. However, there is no obvious reason why the normal faults should be smoother, while there are a number of physical reasons that slip should wear down and abrade faults, so we infer that displacement is the discriminating factor.

Smoothing of fault surfaces due to fault maturation processes may not be restricted to outcrop scales. Our surface measurements complement former map-scale observations of fault traces which suggested that the number of steps along strike-slip faults is reduced with increasing displacement (Wesnousky, 1988). We now have evidence that faults become geometrically simpler as they mature at the scale of earthquake slip. This observation agrees with experimental data, geological observations, and models of fault maturation (Tchalenko et al., 1970; Chester et al., 1993; Ben-Zion and Sammis, 2003). Fracturing and abrasional wear are the most obvious mechanisms for smoothing fault surfaces. Tensile fracture surfaces typically follow a power law (Bouchaud, 1990; Hansen and Schmittbuhl, 2003). Since the roughness of the observed large-slip faults can not be described by a single power-law form and the small protrusions are preferentially eliminated with slip, wear is the more likely mechanism.

If smooth fault surfaces and regular elongated bumps such as we have scanned at the surface also exist at earthquake nucleation depths on mature faults, they will strongly
influence the near-field stresses and the rupture characteristics (Chester and Chester, 2000). The probability that rupture will repeat along a pre-existing fracture increases when the fracture surfaces become larger and smoother, because the stress intensity factor depends strongly on the fracture geometry and length (Freund, 1998).

Note that we have also scanned faults with several anastomosing slip surfaces, and faults with two or more striae orientations. The roughness of such fault surfaces and zones are different from that presented here for these geometrically and kinematically simpler faults.

Conclusion

We have shown through the variations in RMS roughness, spectral shape and 3-D geometry that faults evolve with slip. Slip surfaces of small faults are relatively rough at all measured scales, whereas those of large faults are polished at small scales but contain elongated semi-elliptical bumps and depressions at scales of a few to several meters.

Acknowledgements

We thank J. Caskey, M. Doan, J. Fineberg, J. Gill, M. Jenks, R. McKenzie, Z, Reches, S. Skinner and A. Sylvester. Funding was provided in part by NSF grant EAR-0238455 and the Southern California Earthquake Center.
References


Wesnousky, S. G., 1988, Seismological and structural evolution of strike-slip faults:

Table 1: Scanned faults

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>Location</th>
<th>Displacement</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Mt.1</td>
<td>33.014° N 116.112° W</td>
<td>30±15 cm(^a)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Split Mt.2</td>
<td>33.0145° N 116.112° W</td>
<td>15±5 cm(^a)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Mecca Hills</td>
<td>33.605° N 115.918° W</td>
<td>20±10 cm(^a)</td>
<td>Fanglomerate (Calcite)</td>
</tr>
<tr>
<td>Little Rock</td>
<td>34.566° N 118.140° W</td>
<td>1-3 cm(^a)</td>
<td>Quartz Diorite</td>
</tr>
<tr>
<td>Flower Pit1</td>
<td>42.077° N 121.856° W</td>
<td>50m-300 m(^b)</td>
<td>Andesite</td>
</tr>
<tr>
<td>Flower Pit2</td>
<td>42.077° N 121.852° W</td>
<td>50m-300 m(^b)</td>
<td>Andesite</td>
</tr>
<tr>
<td>KF1</td>
<td>42.135° N 121.796° W</td>
<td>50m-300 m(^c)</td>
<td>Basalt+Andesite</td>
</tr>
<tr>
<td>KF2</td>
<td>42.332° N 121.819° W</td>
<td>50m-300 m(^c)</td>
<td>Basalt+Andesite</td>
</tr>
<tr>
<td>Dixie Valley</td>
<td>(The Mirrors)</td>
<td>&gt;10 m(^c)</td>
<td>Quartz</td>
</tr>
</tbody>
</table>

\(^a\) Based on direct measurements of offset of sedimentary layers or displacement of structural markers.

\(^b\) Belongs to the Klamath Graben Fault system and to the Sky Lakes fault zone, in the northwestern Basin and Range (Personius et al., 2003). The scanned faults are exposed by recent quarrying, so are relatively unweathered. Fault surfaces are on footwall Quaternary volcanic rocks (Fig. 1c) which were faulted against hanging wall Holocene gravels. Minimum displacement along a single slip surface is more than 50 m. Assuming Middle Pleistocene ages for the faulted volcanic rocks, and slip rates of 0.3 mm/year (Bacon et al., 1999), the cumulative displacement along them is probably no more than a few hundred meters. The surrounding region is seismically active, including a 1993 sequence of earthquakes with magnitude Mw =6.
The fault surface is exposed in fine crystalline rocks (Fig. 1a). The fault zone includes several other anastomosing slickensided and striated surfaces (see also Power and Tullis, 1992) in the ~10-20 m subjacent to the principal fault surface active in Quaternary time. The scanned surfaces probably formed at an unknown depth. The cumulative displacement along the fault zone may be 3 km or more, but individual slip surfaces probably accommodated much smaller displacement (Power and Tullis, 1992).

Small-slip faults from within the Little Rock fault zone (not the main fault surface).

No large fresh outcrop exposures exist so only profilometer measurements were made.
Figure 1. Two of the large-slip fault surfaces analyzed in this paper. a) Section of partly eroded slip surface at the Mirrors locality on the Dixie Valley fault, Nevada (Table 1). b) LiDAR fault-surface topography as a color-scale map rotated so that the the X-Y plane is the best-fit plane to the surface and the mean striae are parallel to Y. c) One of three large, continuous fault segments exposed at the Flower Pit, S. Oregon (Table 1).
Figure 2. Surface topography parallel and perpendicular to the slip orientation. a) Profiles from four different fault surfaces parallel to the slip direction. Upper two profiles are large-slip faults and bottom two profiles are small-slip faults. b) Power spectral density values for large-slip fault (green curves) and small-slip fault (Magenta). Thick curves: normal to the slip. Thin curves: parallel to the slip. Each curve represents data from 200 individual 3 m profiles spaced 3 mm apart. The red dotted line represents scans of smooth, planar reference surface. The bending of the power spectra at level of $\sim 10^{-7.5}$ corresponds to the resolution limit.
**Figure 3.** Power spectral density curves calculated from sections of seven different fault surfaces that have been scanned using ground-based LiDAR, and from eight hand samples scanned by a profilometer in the lab. Figure includes both LiDAR data (upper curves) and laboratory profilometer data (lower curves) from profiles of a variety of lengths. **a)** Profiles parallel to the slip. **b)** Profiles perpendicular to the slip. Red dotted lines represent scans of smooth, planar reference surfaces for the profilometer. Dashed black lines are slopes of $\beta = 1$ and $\beta = 3$. Arrow in (a) marks the scale at which roughness created by the large scale waviness is observed (see Figs. 4a, 4c).
Figure 4. Color-scale fault-surface topography of the large scanned faults.  

a) Profiles (left) and map (right) of a fault section (Klamath Falls 1). The map shows elliptical bulges (red) and depressions (blue) identical in their dimensions and aligned parallel to slip. The upper bulge (I) and the depression (II) are partly eroded.  

b) Negative and positive elliptical bumps (marked by roman letters) on large section of fault surface (Flower Pit 1, See also fig 1b).  

c) Bumps on three different fault surfaces (Dixie Valley-left, Flower Pit 2-middle, and Flower Pit 1-right). Right figure shows a single elliptic bump and profiles along it. The middle image outlines a single asperity with contours.