Evolution of fault surface roughness with slip

Amir Sagy

Emily E. Brodsky

Gary J. Axen

Department of Earth and Planetary Sciences, UC Santa Cruz, Santa Cruz, California

Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico

ABSTRACT

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 profiles ranging from 10 μm to >100 m in length show that small-slip faults (slip <1 m) are rougher than large-slip faults (slip 10–100 m or more) parallel to the slip direction. Surfaces of small-slip faults have asperities over the entire range of observed scales, while large-slip fault surfaces are polished, with RMS values of < 3 mm on profiles up to 1–2 m long. Surprisingly, the large-slip surfaces show smooth, elongate, quasi-elliptical bumps that are meters long and up to ~1 m 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.

Keywords: Faults, Earthquakes

Introduction

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

Despite its importance, 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., 1988; 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 in the perpendicular direction and the fault surface relief is proportional to measured profile length (Power et al., 1988; Power and Tullis, 1991). Recent LiDAR measurements on one fault also suggested a power law relationship between protrusion height and profile length (Renard et al., 2006).

Here we investigate the relationship between slip-surface roughness and fault displacement using ground-based LiDAR (Light Detection And Ranging) in the field and a laser profilometer in the laboratory. We cover a range of scales that includes the slip distances of observable earthquakes. By comparing geometrical features of different
faults, we find that mature fault surfaces are smoother at small scales and have quasi-elliptical bumps and depressions at larger scales.

**Scanned surfaces and scanning methods**

Fault geometry is not trivial. Shear displacement can be carried by a single fault surface, by many, or by a zone depending on depth, lithology, and dynamics (Dor et al., 2006). Here we focus on the geometry of striated surfaces because they are a direct manifestation of localized shear, and continued displacement along them should affect their geometry. We chose nine faults that contain particularly well-preserved slip surfaces with large (>5 m²) exposures and few pits (Table 1, Fig. 1). Selecting coherent surfaces favors smooth surfaces overall, but does not bias the data to correlate smoothness with any other measured feature. The faults have probably been exhumed from the upper 5 km of the crust, thus they do not necessarily represent the earthquake nucleation region.

The LiDAR (Leica HDS3000) measures 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 to discriminate the study areas from non-fault features (bushes, pits, etc.). We can then extract thousands of profiles in any direction (Fig. 2a). Each scan includes a portable planar reference sheet with a few square blocks of different, known heights to constrain the noise level and resolution (Fig. 2b). Like the LiDAR, the laboratory profilometer also produces a matrix of points. It covers a range of 10 μm – 10 cm, allowing ~300–600 profiles on each hand sample.
The scan data is rotated so that the mean surface is parallel to a major axis and the mean striation direction is vertical or horizontal. The striation direction is established by finding the orientation that maximizes the cross-correlation between adjacent profiles (Sagy et al., 2006). On each profile, spurious points with excessively large curvature (> 4 standard deviations from the mean) were removed and data interpolated across the gap. The data fraction removed is <3% in all cases.

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 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 slip (along the axis of striations), the RMS heights of the small-slip faults is 6.5 ± 3.5 mm. For 2 m profiles the RMS values are 11.5 mm ± 5 mm (Fig. 2a). The measured RMS heights of the large-slip faults we measured are so low that it is below the LiDAR resolution limit for sections <3 m (Fig. 2a). Combining five scans of the same surface decreases the errors and we find that the true RMS is 3 mm for a 2 m profile of a large fault. These values are calculated from averaged, detrended sections. Thus, at scales of 1–2 m parallel to the slip, 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 power spectral density. Fourier spectral analysis is a reliable indicator of roughness when based on many profiles (Simonsen and Hansen, 1998). 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

$$P = C \lambda^\beta$$  \hspace{1cm} (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 $H$:

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

For simplicity, we will describe one surface as rougher than another at a given wavelength if its power spectral density is higher 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 normal to 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 slip are smoother (have lower spectral densities) than those normal to slip and large-slip faults are smoother than small-slip faults. The difference between parallel and normal
profiles is an obvious and expected consequence of striations, but the observed difference between large-slip and small-slip faults is novel to this study. Below wavelengths of ~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 μm-10 m.

The power spectral density results reflect the geometry for the large slip faults which can also be seen in topographic maps of the fault surface (Fig. 4). The 3D LiDAR data allows us to map lateral variability. At wavelengths > 1 m, the large-slip faults have undulating structures. 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. Below ~1 m wavelength, the LiDAR data are limited by the instrumental noise.

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. Examination of sections along the large faults suggests that most of the measured roughness in the LiDAR scans at scales < 1 m is contributed by joints and small faults that cross the extremely smooth surface (Fig. 4a). 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 $\leq 1\text{ m}$ 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 and Tullis, 1991; Renard et al., 2006) and, combined with the differences between small- and large-slip faults, demonstrates that during slip faults evolve to geometrically simpler shapes.

In the slip-normal direction, the data more nearly fits a power law (Fig. 3b). This observation supports and extends the results of previous studies (Power et al., 1988; Power and Tullis, 1991; Lee and Bruhn, 1996). The connection between the laboratory and field data is relatively simple for small-slip faults, 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 in Fig. 3b) is fit with a power law that yields $H = 0.015L^{0.98}$ from $10\text{ \mu m}$ to at least $1\text{ m}$ (See Equation 2). The power spectral density of one of the large-slip fault (green 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., 2006), the above two examples suggest that roughness values follow the spectrum of a self-similar surface.
with $H=0.01L$ (Upper dashed black line in Fig. 3b). Such a relationship has previously been observed for many natural faults and fractures (Brown and Scholz, 1985; Power and Tullis, 1991) and an arbitrary erosional surface has a similar spectrum (upper gray curve in Fig. 3b). We speculate that most of the slip-normal profiles reflect the roughness of natural fractures unmodified 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 Figure 4.

**Discussion**

The data presented are surprisingly consistent despite variations in lithology and fault type (Table 1). Since the large-slip faults are all normal faults in our data, at first it may appear that normal faults are systematically smoother than others. However, there is no obvious reason why normal faults should be smoother, but there are a number of physical reasons that slip should abrade faults. Therefore, we infer that displacement is the discriminating factor.

Smoothing of fault surfaces due to fault maturation may extend beyond outcrop scales. If the scale of the polished zones is slip-dependent, then these zones should be much larger on faults that slip kilometers (Ben-Zion and Sammis, 2003). Our surface measurements complement previous map-scale observations of fault traces which suggested that the number of steps along strike-slip faults reduces with increasing displacement (Wesnousky, 1988).

Experiments, geological observations, and models also suggest that faults become geometrically simpler as they mature (Tchalenko, 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 et al., 1990), but wear preferentially eliminates small protrusions with slip. Thus wear is the more likely mechanism to produce the observed non-power law surfaces.

If the observed smoothness and regular elongated bumps are typical of mature faults at seismogenic depths and all other factors between faults are equal, then there are predictions for earthquakes that may be testable with modern seismic data. The mature faults should have more homogeneous stress fields and preferentially accumulate slip over geological time. High-frequency radiated energy should be less for mature faults than immature ones.

**Conclusion**

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

**ACKNOWLEDGMENTS**

We thank R. Arrowsmith, Y. Ben-Zion for their reviews. We thank J. Caskey, M. Doan, J. Fineberg, B. Flower, J. Gill, M. Jenks, B. Krantz, R. McKenzie, Z. Reches, S. Skinner, E. Smith and A. Sylvester. Funding was provided in part by NSF grant EAR-0238455 and the Southern California Earthquake Center.
REFERENCES CITED


Chester, F.M., Evans, J.P., and Biegel, R.L., 1993, Internal Structure and Weakening  

Dor, O., Ben-Zion, Y., Rockwell, T.K., and Brune, J., 2006, Pulverized rocks in the  
Mojave section of the San Andreas Fault Zone: Earth and Planetary Science Letters,  


Dixie Valley, Nevada, and Implications for Fault Mechanics: Journal of Geophysical  
Research, v. 97, p. 15425–15435.

Power, W.L., and Tullis, T.E., 1991, Euclidean and fractal models for the description of  

Power, W.L., Tullis, T.E., and Weeks, J.D., 1988, Roughness and Wear During Brittle  


Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes:


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


<table>
<thead>
<tr>
<th>Fault Name</th>
<th>Location</th>
<th>Displacement</th>
<th>Lithology</th>
<th>Sense</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Mt.1</td>
<td>33.014° N 116.112° W</td>
<td>30 ± 15 cm²</td>
<td>Sandstone</td>
<td>Strike slip</td>
</tr>
<tr>
<td>Split Mt.2</td>
<td>33.0145° N 116.112° W</td>
<td>15 ± 5 cm²</td>
<td>Sandstone</td>
<td>Strike slip</td>
</tr>
<tr>
<td>Mecca Hills</td>
<td>33.605° N 115.918° W</td>
<td>20 ± 10 cm²</td>
<td>Fanglomerate (Calcite)</td>
<td>Strike slip</td>
</tr>
<tr>
<td>Near Little Rock</td>
<td>34.566° N 118.140° W</td>
<td>1–3 cm³</td>
<td>Quartz diorite</td>
<td>Normal</td>
</tr>
<tr>
<td>Chimney Rock</td>
<td>39.227° N 110.514° W</td>
<td>8 m²</td>
<td>Limestone</td>
<td>Normal</td>
</tr>
<tr>
<td>River Mountains</td>
<td>36.062° N 114.831° W</td>
<td>500 m- 1 km³</td>
<td>Dacite breccia</td>
<td>Normal</td>
</tr>
<tr>
<td>Flower Pit 1</td>
<td>42.077° N 121.856° W</td>
<td>100 m-300 m²</td>
<td>Andesite</td>
<td>Normal</td>
</tr>
<tr>
<td>Flower Pit 2</td>
<td>42.077° N 121.852° W</td>
<td>100 m-300 m²</td>
<td>Andesite</td>
<td>Normal</td>
</tr>
<tr>
<td>Klamath Hill 1</td>
<td>42.135° N 121.678° W</td>
<td>50 m-300 m²</td>
<td>Basalt+Andesite</td>
<td>Normal</td>
</tr>
</tbody>
</table>
Klamath Hill 2  42.332° N 121.819° W  50 m-300 m\textsuperscript{a}

Dixie Valley (The Mirrors)  39.795° N 118.075° W  >10 m\textsuperscript{b}  Basalt+Andesite  normal

\textsuperscript{a} Direct measurements of offset of sedimentary layers or displacement of structural markers.

\textsuperscript{b} Belongs to the Klamath Graben Fault system in the northwestern Basin and Range (Personius et al., 2003). The faults are exposed by recent quarrying, so are relatively unweathered. Surfaces are on footwall Quaternary volcanic rocks (Fig. 1c) faulted against 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 is probably no more than a few hundred meters. The region is seismically active, including a 1993 sequence of earthquakes (Mw = 6).

\textsuperscript{c} The fault is exposed in fine crystalline rocks (Fig. 1a). The fault zone includes several other anastomosing 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 smaller displacement.

\textsuperscript{d} Small-slip faults from within the Little Rock fault zone (not the main fault surface).

\textsuperscript{e} No large fresh outcrop exposures exist so only profilometer measurements were made.

\textsuperscript{f} Personal communication with Eugene I. Smith, University of Nevada, Las Vegas.

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 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 at the Flower Pit, Oregon (Table 1).

Figure 2. Surface topography parallel and normal 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) and small-slip fault (magenta). Thick and thin curves are normal...
and parallel to slip, respectively. Each curve includes data from 200 individual 3 m
profiles spaced 3 mm apart. The red dashed line represents scans of smooth, planar
reference surface. The bending of the power spectra at level of ~10.75-7.5 corresponds to
the resolution limit.

Figure 3. Power spectral density 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. Each curve includes 200-600 continuous individual
profiles from the best part of the fault. 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 normal to the slip. Red dashed line represent scans
of smooth, planar reference surfaces for the profilometer. Dashed black lines are slopes
of β = 1 and β = 3. Arrow in (a) marks the scale at which roughness created by the large
scale waviness is observed (see Figs. 4a, 4c).

Figure 4. 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 (III) 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. 1c). C) Bumps on fault surfaces (Dixie Valley-left, Flower Pit 2-middle, and Flower
Pit 1-right). Right figure shows a single elliptical bump and profiles along it. The middle
image outlines a single asperity with contours.
A. Profile topography with profile length and measurements:
- Dixie Valley
- Flower Pit 1
- Split Mt. 1
- Mecca Hills

B. Power spectral density graph with wavelength (m):
- Flower Pit 1 (Large-slip fault)
- Split Mt. 1 (Small-slip fault)

Legend:
- Normal
- Parallel
**Data Analysis**

- **Power spectral density (m^3)**
- **Wavelength parallel to slip (m)**

**Noise levels:**
- 1.0
- 10
- 100
- 10^2
- 10^3

**Erosional surface:**

**Runoff**
- Small faults
- Little Rock
- Split Mt. 1
- Split Mt. 2
- Mecca Hills
- Chimney Rock

**Faults**
- Large faults
- Flower Pit 1
- Flower Pit 2
- KF 1
- KF 2
- Dixie V.
- River Mt.

**Notes:**
- H = 0.01
- Dashed line represents noise level
- Linear and log-log scale graphs