POSTER 115

A Curvature-based Approach to Measuring Permanent Off-fault Deformation: Applications to the Volcanic Tablelands, CA

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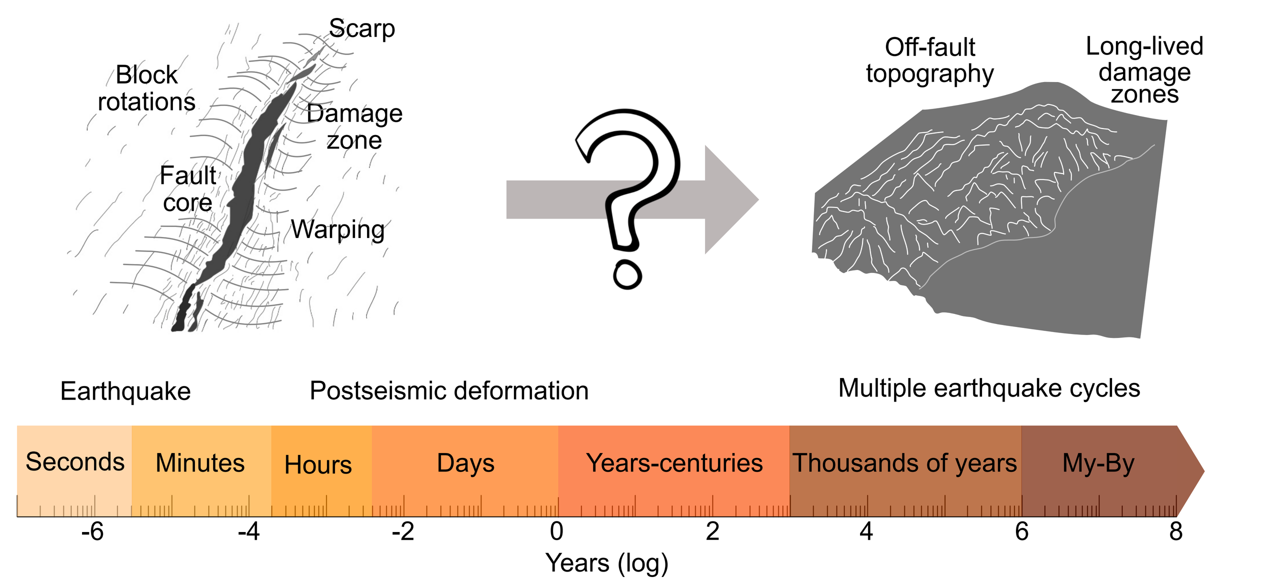
The Problem



Detailed and continuous geomorphic measurements of permanent off-fault deformation are challenged by incomplete knowledge of the pre-faulted landscape, sparse data coverage, erosion, and limited chronologies. These limitations hinder establishing robust relationships between deformation from individual earthquakes and the cumulative deformation history of a fault.

A Natural Laboratory

- At the Volcanic Tablelands (CA), the Bishop Tuff forms a topographic plateau rising 100 meters over the Owens Valley. The tuff has undergone brittle faulting in the past 738 ky.
- The dimensions of the Volcanic Tablelands and the relatively low off-fault strains make this locale a good thin plate analog, which enables simple quantification of permanent strains using curvature analysis.
- The well constrained ages and material properties of the Bishop Tuff permit estimating the total strain energy absorbed by elastic and plastic deformation at this site over the lifespan of the tuff.

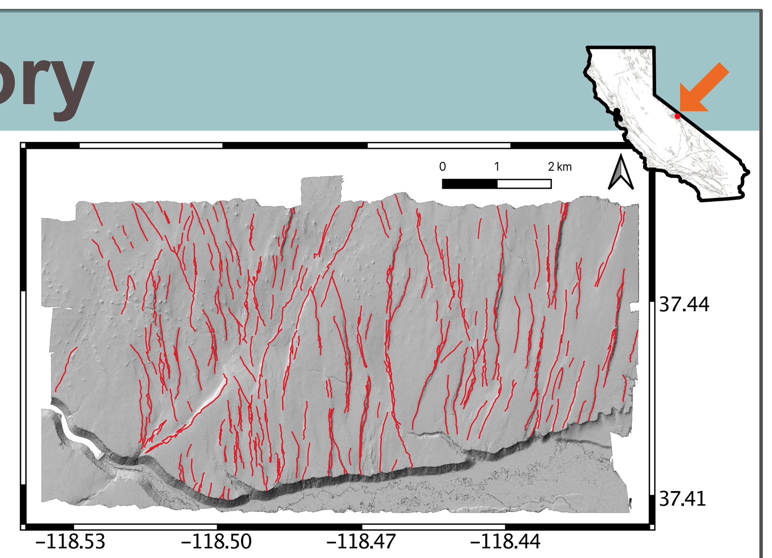
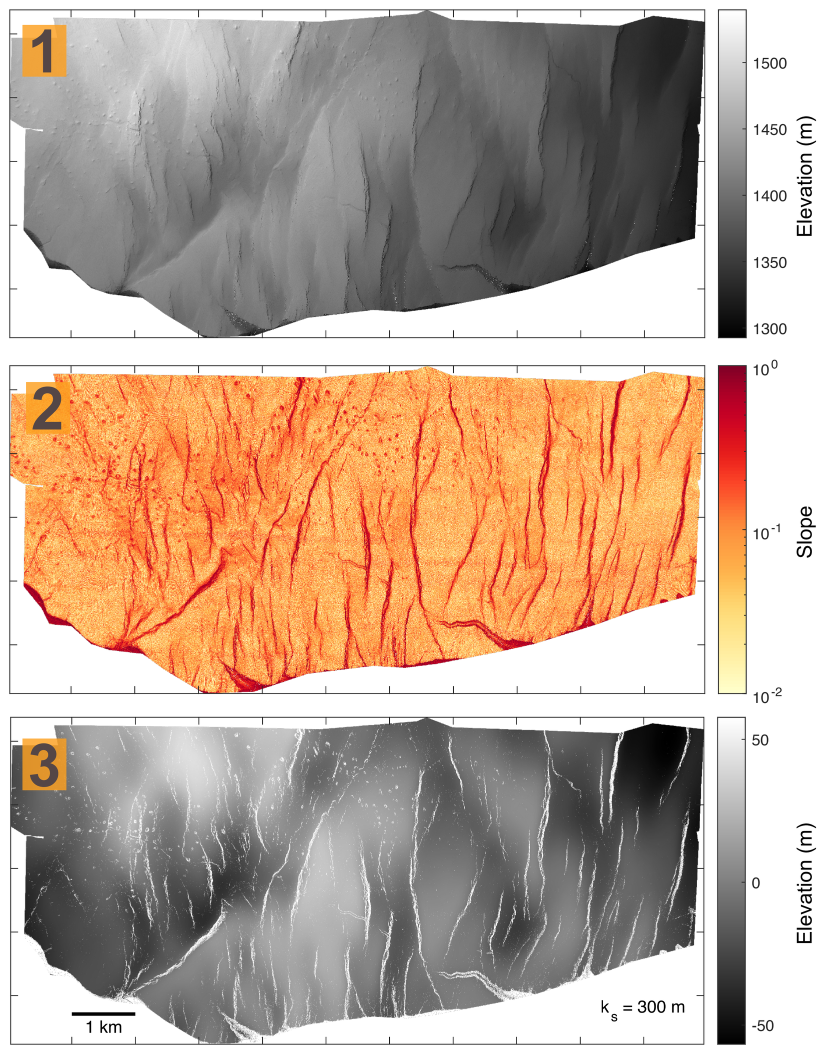


Figure 1: Lidar hillshade of the Volcanic Tablelands with faults mapped in red.

Preparing the DEM

DEMs encode many frequencies related to real features and all sorts of noise. Isolating off-fault deformation from these signals requires a multi-step filtering process.



Original lidar DEM

Detrend regional slope by fitting and removing least squares plane

Generate slope map

Scarps have slopes >0.3

Remove sections where slope >0.3

Low-pass filter landscape to isolate off-fault deformation (kernel = 100-400 m)

Landscape ready for strain measurements

Figure 2: Filtering of the lidar digital elevation model. Top: Original lidar DEM. Middle: Slope map of the DEM. Bottom: Low-pass filtered (ks = 300 m) and detrended digital elevation with scarps and noise removed.

Stewart and Podolski (1998), Bergbauer et al. (2003), Perron et al. (2008)

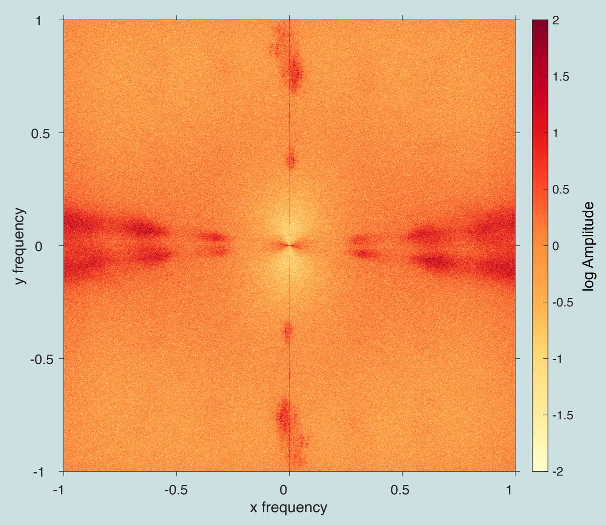
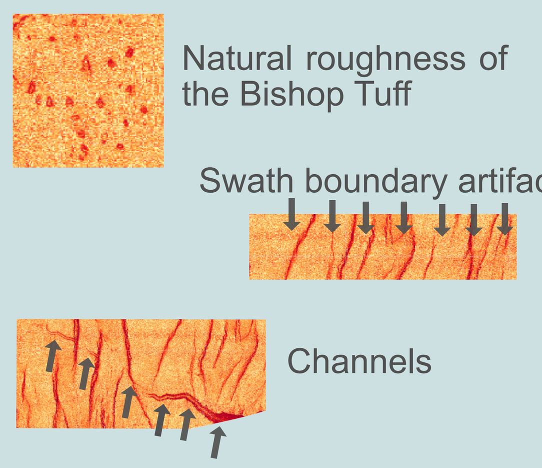


Figure 3: 2D Spectrogram of the lidar DEM of the Volcanic Tablelands.

Features to remove:

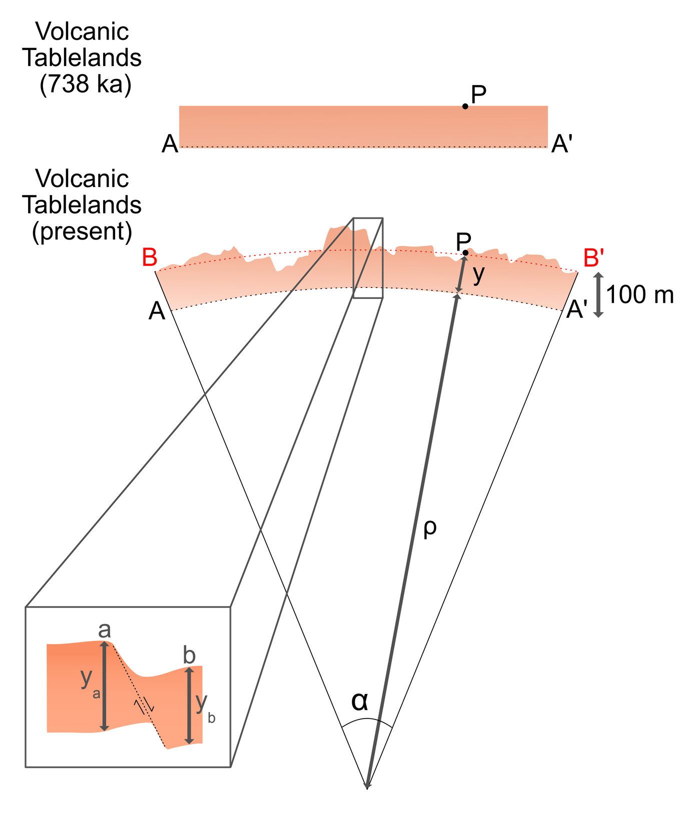


Natural roughness of the Bishop Tuff

Swath boundary artifacts

Channels

Strain Measuring Approach



To estimate permanent bending strains, we use topographic curvature. The association of curvature to strain stems from thin plate theory, which dictates that the bending strain acting in a thin layer is given by:

$$\varepsilon = y\frac{d^2w}{dx^2}$$

Turcotte and Schubert, 2002

where y is the distance to the neutral axis (see cartoon). To estimate bending strains in two dimensions, we calculate total curvature as root mean squared sum of the second derivatives of elevation calculated over a 9x9 kernel:

$$\varepsilon = y\kappa_{total} \qquad \kappa_{total} = \sqrt{z_{xx}^2 + 2z_{xy}^2 + z_{yy}^2}$$

Wilson and Gallant, 2000

At the Volcanic Tablelands, bending strains are imposed regionally by warping of the entire tuff sheet (BB') but also locally by flexural folding in response to fault slip (see inset). Local bending strains exceed regional bending strains by over two orders of magnitude so we neglect them.

Assumptions: Normal faults extend to the base of the tuff sheet but not beyond (Dawers et al., 1993). Strains are close enough to infinitesimal to approximate thin plate theory. The plate is much wider and longer than it is thick. Local bending strains far exceed regional bending strains.

Distribution of off-fault strains

We calculate bending strains based on curvature calculated over four different low-pass filter kernel sizes:

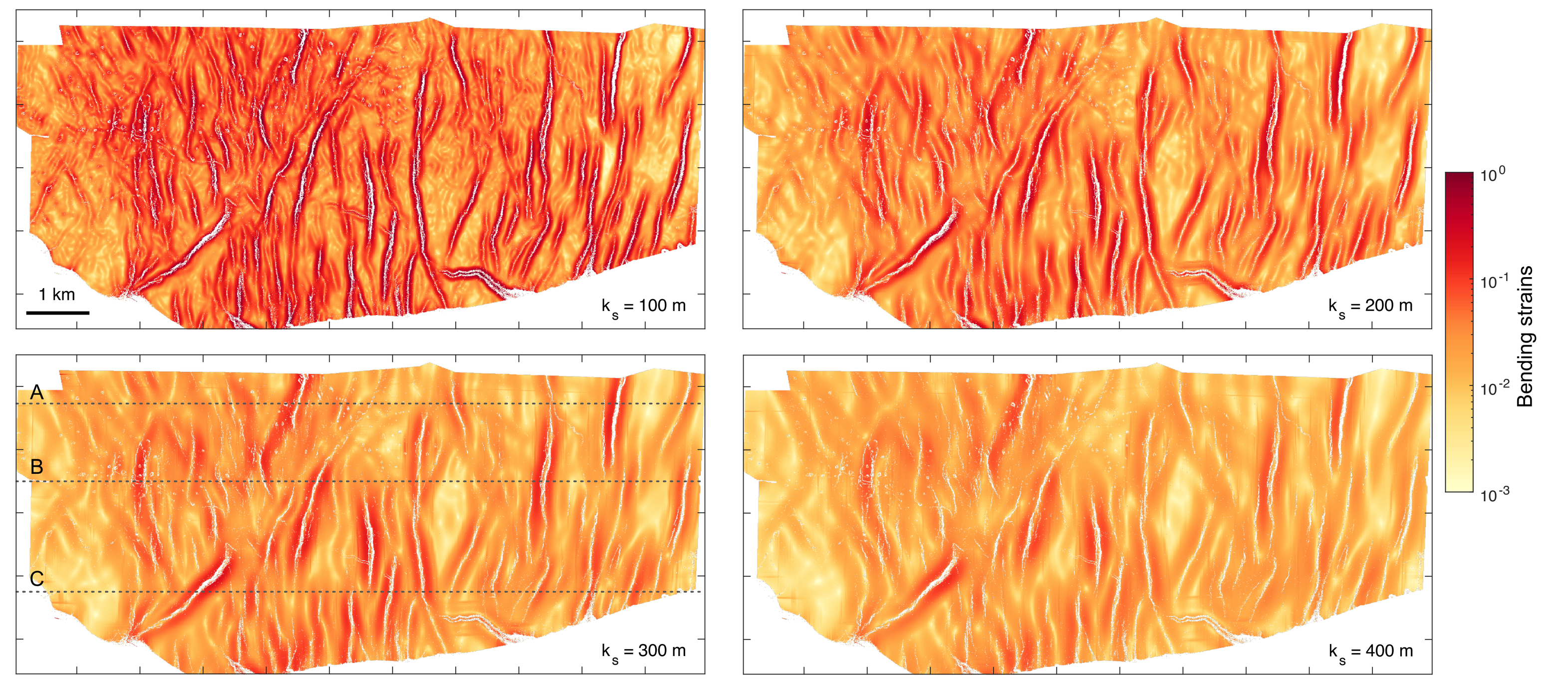


Figure 4: Bending strain maps of off-fault deformation at the Volcanic Tablelands calculated using low-pass filter kernel sizes of 100 m, 200 m, 300 m, and 400 m. Lines A, B, and C in bottom left correspond to the profiles in figure 5.

The maps highlight halos of high bending strains localized around major fault scarps. These halos have wavelengths spanning 50-300 meters and are wider and higher in strain magnitude for longer faults. The zone of permanent deformation remains constant along most of the fault strike until it decreases at the fault tip, following a quasi-elliptical distribution.

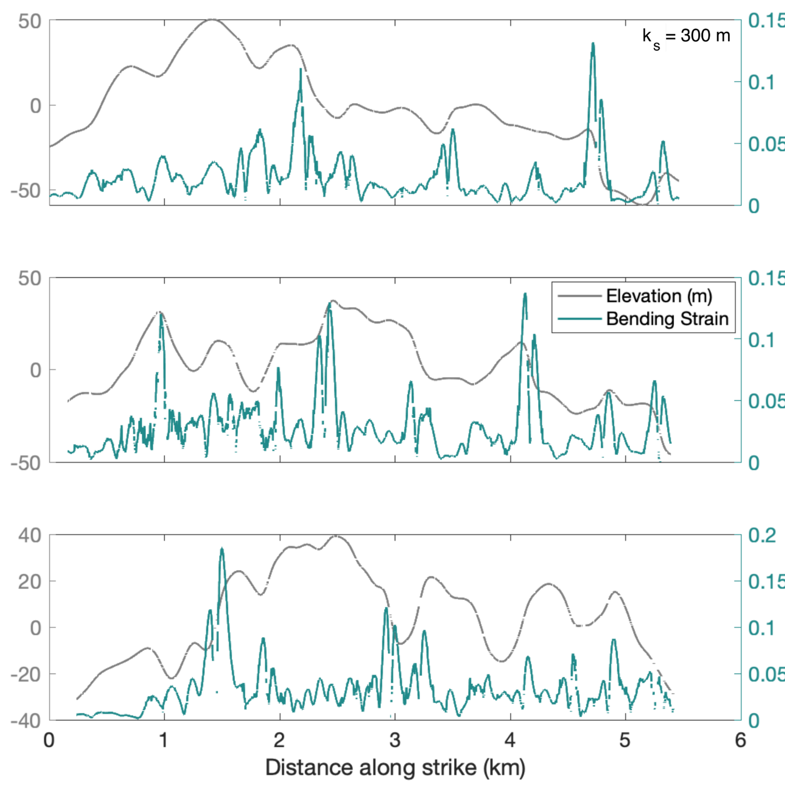


Figure 5: Cross-sections through Figure 4, bottom left. The grey lines show elevation through the de-trended, low-pass filtered DEM (Figure 2, bottom). The teal lines show the bending strains through each profile.

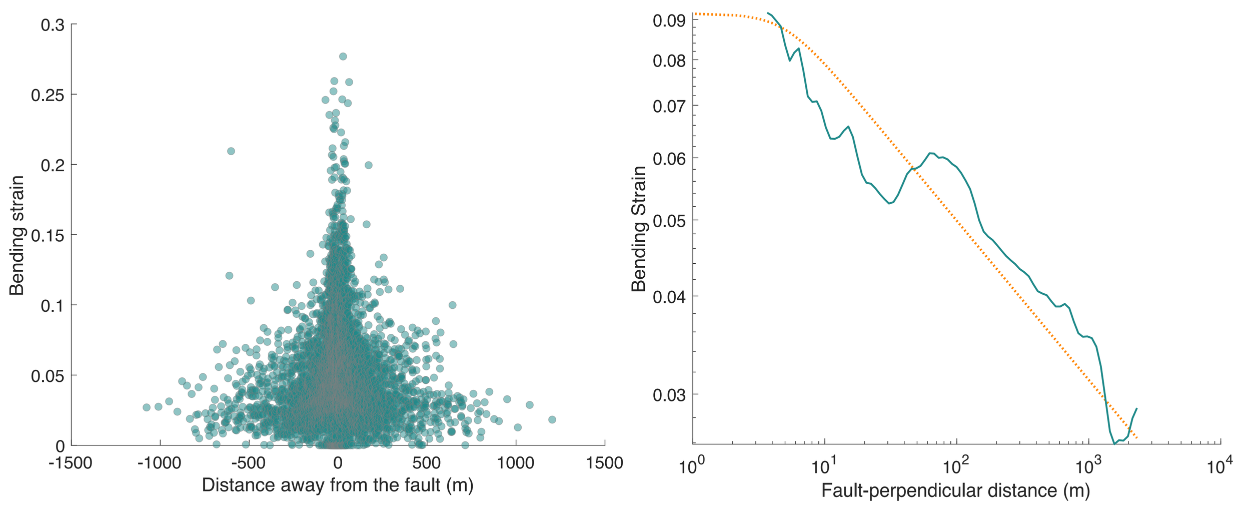


Figure 6: Left: Stacked fault-perpendicular cross sections through the mid-points of faults in Figure 1. Right: Decay in median strain intensity with distance away from the fault (teal). The orange line is fit through the power-law below.

The median bending strains decay with distance away from the faults as an inverse power-law of the form (Powers and Jordan, 2010):

$$\epsilon = v_o\left(\frac{d^m}{|x|^m + d^m}\right)^{\frac{\gamma}{m}}$$

where v_o = 0.090 (0.087-0.092), d = 6 (5-10) meters, m = 1 (0.9-1.2), and γ = 0.3 (0.25-0.32).

Energy Dissipated by Off-fault Deformation

If we make some simplifying assumptions, we can use our strain maps to estimate the total strain energy absorbed by off-fault deformation at the Volcanic Tablelands since the inception of the Bishop Tuff and per event.

738 ky

Upper bound: elasticity

$$E_\epsilon = \frac{1}{2}G\epsilon_{total}^2$$

G = 5 GPa (De Natale et al., 1991)

Lower bound: plasticity

$$E_\epsilon = \frac{1}{2}\sigma_y\epsilon_{total}$$

σ_y = 50-70 MPa (Barahim et al., 2018)

To convert strain energy density to total strain energy, we multiply times the dimensions of the plate (~8 km x 12 km x 100 m).

Kernel size	Rheology	Strain energy
100 m	Elastic	$4.2\text{x}10^{18}$
100 m	Plastic	$4.6\text{x}10^{16}$
200 m	Elastic	$1\text{x}10^{18}$
200 m	Plastic	$2.3\text{x}10^{16}$
300 m	Elastic	$4.1\text{x}10^{17}$
300 m	Plastic	$1.4\text{x}10^{16}$
400 m	Elastic	$2\text{x}10^{17}$
400 m	Plastic	$1\text{x}10^{16}$

Per earthquake

Assuming that most of the permanent deformation is contributed by large events and assuming a characteristic M_w 7.2 event (Pinter, 1995), the Tablelands have hosted ~120 earthquakes of that size. This would make the energy absorbed by off-fault deformation per event ~8.3 x 10^{13} - 3.5 x 10^{16}J. The upper portion of this range is comparable to the radiated energy of a Mw 7.2 event (~10^{15}J).

Discussion

- Average off-fault bending strains are ~10^{-2}. Off-fault deformation zones form symmetric halos where strain intensity is highest for longer faults (more slip). These narrow zones of strain remain relatively constant along fault strike until they narrow towards the fault tip.
- Bending strains decrease rapidly with distance away from the fault following an inverse power-law with exponent ~0.3. This decay is gentler than the decay of fracture density and strain intensity with fault-perpendicular distance found in prior studies (0.8-1.6) (e.g. Savage and Brodsky, 2010; Rodriguez Padilla et al., under review).
- The approach to mapping off-fault deformation based on curvature may be extended to crustal-scale faults with longer-term or more complex deformation histories than the Volcanic Tablelands.

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