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1 Off-fault deformation rate along the southern San Andreas fault
2 at Mecca Hills inferred from landscape modeling of curved
3 drainages

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6
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12

13 **ABSTRACT**

14 Quantifying off-fault deformation (OFD) rates on geomorphic timescales (10^2 - 10^5 yr)
15 along strike-slip faults is critical for resolving discrepancies between geologic and geodetic
16 slip-rate estimates, improving knowledge of seismic hazard, and understanding the influence of
17 tectonic motion on landscapes. Quantifying OFD over these timescales is challenging without
18 displacement markers such as offset terraces or geologic contacts. We present a landscape
19 evolution model coupled with distributed lateral tectonic shear to show how drainage basins
20 sheared by lateral tectonic motion can reveal OFD rates. The model shows that OFD rate can
21 control the orientation of drainage basin topography: the faster the OFD rate, the greater the
22 deflection of drainage basins towards a fault-parallel orientation. We apply the model to the

23 southern San Andreas Fault near the Mecca Hills, where drainages basins change in orientation
24 with proximity to the fault. Comparison of observed and modeled topography suggests that the
25 OFD rate in the Mecca Hills follows an exponential-like spatial pattern with a maximum rate
26 nearest the fault of 3.5 ± 1.5 mm/yr, which decays to approximately zero at ~600 m distance
27 from the fault. This rate is applicable since the initiation of differential rock uplift in the Mecca
28 Hills at approximately 760 ka. Our results suggest that OFD in this 800 m study area may be as
29 high as 10% of total plate motion. This example demonstrates that curved drainage basins may
30 be used to estimate OFD rates along strike slip faults.

31

32 INTRODUCTION

33 Strike-slip fault systems can release stress by two means: slip on a master fault, and off-
34 fault deformation (OFD). OFD, here defined as permanent fault-parallel displacement at the
35 surface (Gold et al. 2015), has been recognized along many faults, yet the controls on OFD are
36 poorly understood (Milliner et al. 2015). Neglecting OFD can lead to underestimation of slip-
37 rates, plate loading rates, and associated seismic hazard (e.g. Shelef and Oskin, 2010). There
38 are two major hypotheses for the dominant control on OFD. The first holds that the occurrence
39 and rate of OFD depends on the structural maturity of the fault system, with increased maturity
40 and decreased geometric complexity leading to decreased OFD (Dolan and Haravitch, 2014).
41 An alternative view is that the occurrence and extent of OFD depends on the underlying
42 lithology. For example, weakly lithified sediments could be more susceptible to non-
43 recoverable plastic strain due to granular flow and porosity changes (Maltman, 2012). The
44 former implies that OFD rates will decrease with time whereas the latter suggests they should
45 be steady in the absence of strain hardening/softening, all else equal. To uncover the controls

46 on OFD, measurements over a range of timescales are needed. OFD measurements over single-
47 earthquake timescales using pixel-tracking methods show promise (Gold et al., 2015), as have
48 longer-term (10^6 yr) studies (Shelef and Oskin, 2010), yet measuring OFD over intermediate
49 (10^2 – 10^5 yr) timescales remains challenging.

50 One approach is to use basin shape or trunk stream orientation as a proxy for the OFD
51 at the surface (Goren et al., 2015). In strike-slip landscapes, lateral tectonic motions re-orient
52 drainage patterns through stream deflection and piracy (e.g. Duvall and Tucker, 2015). At the
53 100–1000 km scale, entire drainage basins can be rotated by plate motion (Hallet and Molnar,
54 2001; Castelltort et al., 2012) and this rotation can be used to quantify OFD (e.g. Goren et al.,
55 2015). However, the geomorphic effects of OFD at the sub-basin scale (10-1000 m) are not
56 well known. This is a critical knowledge gap because the 0-1 km scale takes up most of the
57 OFD, and thus has significant implications for tectonic dynamics (Shelef and Oskin, 2010).

58 We develop a model of hillslope and channel evolution that incorporates OFD as
59 distributed tectonic shear to understand and quantify the effects of OFD at the sub-basin scale
60 over geomorphic timescales. We use this model to address two questions. First, can fault-
61 parallel OFD produce a measurable deflection in the orientation of ridges and valleys within an
62 area subjected to distributed shear? Second, does the model predict a systematic relationship
63 between the OFD rate and the ridge and valley orientation, such that one could infer OFD
64 directly from topography? To test these concepts, we apply the model to dextrally curved
65 drainage basins in the Mecca Hills along the San Andreas Fault (SAF; Fig. 1).

66

67 **CURVED DRAINAGE BASINS AT MECCA HILLS, SAN ANDREAS FAULT**

68 Our study focuses on dextrally curved drainage basins within the Mecca Hills in the
69 Coachella valley of Southern California. Here, drainage basin ridgelines and channels deviate
70 from the regional fault-perpendicular trend towards a fault-parallel configuration with
71 proximity to the fault (Fig. 1). The curved Mecca Hills drainage basins are ~100 m wide and
72 extend up to 700–800 m from the SAF trace. Basins on the southwestern side of the fault do not
73 demonstrate curvature. The northern part of the field area is bracketed by the NE dipping
74 Skeleton Canyon Fault, which exhibits reverse faulting without lateral motion (Lindsay et al.,
75 2014; McNabb et al., 2017). As the fault is small near the border of our study area, and shows
76 no evidence of lateral motion, we do not model it or consider it in our quantification of OFD
77 rates. The basins are underlain by the weakly lithified to unlithified Late Cenozoic fluvio-
78 lacustrine silts of the Palm Spring Formation (McNabb et al., 2017). The presence of the
79 Bishop Ash in regional stratigraphy implies that compression started after ~760 ka (McNabb et
80 al., 2017) and that ongoing rock uplift is occurring due to transpression (Gray et al., 2014). We
81 hypothesize that the dextrally curved basins result from OFD. To test the feasibility of this
82 hypothesis, we develop a model of landform evolution under OFD, and compare its predictions
83 with the observed topography in the Mecca Hills.

84

85 **LANDSCAPE EVOLUTION MODELING**

86 Following Duvall and Tucker (2015), we express landscape development and tectonic
87 OFD using the equation:

88

$$89 \frac{\partial z}{\partial t} = U - V(y) \frac{\partial z}{\partial x} - KA^{1/2}S - D\nabla^2 z \quad (1)$$

90

91 where z is elevation, x is the fault-parallel direction, y is the fault-perpendicular direction, U is
92 rock uplift rate (m/yr), V is the local lateral off-fault deformation/advection rate (m/yr), K is
93 erodibility (1/yr), A is upstream drainage area (m^2), S is local slope (unitless), and D is
94 hillslope diffusivity (m^2/yr). The first term in (1) represents rock uplift relative to baselevel, the
95 second represents lateral advection, the third is river incision, and the fourth is hillslope
96 transport. Here, Equation 1 is appropriate given the cohesive but fine-grained local lithology,
97 which avoids complications associated with the wear and transport of large clasts (Shobe et al.,
98 2016; Glade et al., 2017). Here we assume that all fault-perpendicular shortening is
99 accommodated via spatially uniform rock uplift. Duvall and Tucker (2015) give a full non-
100 dimensionalization and parameter space exploration of this model. We modify the Duvall and
101 Tucker model (1) by adding a definition of $V(y)$ that represents OFD:

$$103 \quad V(y) = v_0 e^{\frac{-y}{y^*}} \quad (2)$$

104
105 where V is the fault-parallel OFD rate relative to interior North America (m/yr), at distance y
106 (m) away from the fault. The maximum off-fault displacement rate, v_0 (m/yr), occurs
107 immediately adjacent to, but not on, the fault, and the characteristic length scale for
108 deformation is y^* (m). In the model, y^* is chosen as the value (200 m) that recreates the width of
109 the zone of curved terrain in the field area, and v_0 is obtained by finding the best-fitting model
110 using geomorphic metrics described below. Note that v_0 is not the fault slip rate; rather, it
111 represents the maximum deformation rate on the northeast side of the fault relative to a fixed
112 North American datum.

113 Equations (1) and (2) are implemented on a rectangular grid using the Landlab 1.0
114 modeling toolkit (Hobley et al., 2017). Values for fluvial erodibility K and the hillslope
115 diffusivity D are obtained from a full model parameter exploration and sensitivity analysis
116 ($n=480$) minimizing misfit between the model and modeled total relief (200 m), mean elevation
117 above base level (90 m), and basin reorientation index (1.38, discussed below) of the study
118 landscape (Fig. S1). We find best-fit values of $K = 0.08 \text{ kyr}^{-1}$ and $D = 0.02 \text{ m}^2/\text{kyr}$. We use a
119 rock uplift rate of 1.8 m/kyr (Gray et al, 2014). The model produces curved basins that match
120 the three landscape metrics and visually resemble those in the study area (Fig. 2).

121 We introduce a basin reorientation geomorphic metric (B_R) to compare observed and
122 modeled topography. The B_R value is computed from digital terrain data following:

123

$$124 \quad B_R = \frac{\text{total pixels with fault-subperpendicular aspect}}{\text{total pixels with fault-subparallel aspect}} \quad (3)$$

125

126 where pixels with an aspect within $\pm 45^\circ$ of the fault strike are classified as subparallel; others
127 are subperpendicular. We measure the B_R value for the study area using the B4 LiDAR dataset
128 (Bevis et al., 2005; Fig. 1), obtaining a value of 1.38 ± 0.02 . By contrast, modeled landscapes
129 of the size of our study area (2 km wide and 0.8 km long) without any imposed OFD have B_R
130 values of ~ 1.05 and catchments that do not appear curved.

131 To assess whether the model predicts a systematic relationship between curvature and
132 deformation rate, we ran the model at various maximum deformation-rate values (v_o) and
133 recorded the B_R value at each time step for 2 Myr to collect statistically robust results. The
134 modeled landscape demonstrates quasi-cyclic behavior in which OFD serves to increase the
135 curvature of basins, whereas hillslope diffusion and stream piracy tend to straighten the

136 channels (Fig. 3a, Movie S1). We count the number of time steps in which the model has a B_R
137 value within the interval 1.38 ± 0.02 , and then divide this count by the total number of time
138 steps. This number represents the likelihood that a model run with a given deformation rate will
139 produce a B_R value comparable to that of our field area. This process is repeated for a range of
140 OFD rates to obtain a likelihood value associated with each rate. We fit the resulting likelihood
141 values with a Rayleigh distribution to estimate a mean and standard deviation for our
142 deformation-rate estimates (Fig. 3b). The distribution implies a most probable OFD rate of 3.5
143 ± 1.5 mm/yr. We assume that development of the curved basins began concurrently with local
144 rock uplift after 760 ka (McNabb et al. 2017). Thus, our best-fit OFD rate at Mecca Hills is an
145 average since the beginning of the mid Pleistocene.

146

147 **SAN ANDREAS DEFORMATION-RATE ESTIMATES**

148 *Origin of the Curved Basins*

149 OFD appears to be the most likely process to form the curved basins. Duvall and Tucker
150 (2015) found that an elastic strike-slip fault intersecting drainage basins can generate shutter
151 ridges that divert streams. Their results show that pure on-fault deformation does not lead to
152 curved basins, instead limiting channel diversion to the fault trace. Strike-slip fault motion
153 alone does not appear sufficient to create curved basins. Another possibility is that bedding
154 layers produce curved basins. However, the underlying submember of the Palm Spring
155 Formation is only weakly lithified and exhibits no evident bedding control on drainage
156 structure, nor do exposures of this submember elsewhere appear to control stream orientation.
157 A final possibility is that the curved basins are a relic of an antecedent drainage network prior
158 to the onset of uplift post 760 ka. While we cannot fully discount this possibility, the regional

159 drainage pattern prior to uplift was orthogonal to the trace of the SAF as alluvial fans drained
160 the upstream mountains (McNabb et al. 2017). It seems unlikely that the streams would divert
161 from the direction of steepest descent, and such diversion is not observed in non-uplifted
162 alluvial fans north of the Mecca Hills (Gray et al., 2014). The only remaining viable
163 mechanism for formation of the curved basins is distributed tectonic shear, and the observed
164 basin curvature is consistent with model predictions for distributed shear. We therefore
165 interpret the curved basins in the Mecca Hills to be a consequence of OFD. If this interpretation
166 is correct, it raises the question of whether modeling the curved basins yields a unique
167 prediction of OFD rate. To address this issue, we conducted a model sensitivity analysis and
168 calibration procedure, with the goal of identifying an OFD rate that provides the best match
169 between observed and simulated terrain.

170

171 *Model Sensitivity Analysis and Calibration*

172 We conduct a three-dimensional parameter study consisting of 480 model runs over a
173 wide parameter space to assess whether our values for K , D , and OFD rate represent a unique
174 combination that describes the curved drainages. We systematically vary K , D , and v_o , and
175 compare misfit in time-averaged B_R , time-averaged mean elevation, and time-averaged total
176 relief between the 480 model runs and the study landscape. Model results are sensitive to all
177 three parameters, but we observe a coherent region of the parameter space with uniquely low
178 misfit. We find that $K = 0.08 \text{ kyr}^{-1}$, $D = 0.02 \text{ m}^2/\text{kyr}$, and $v_o = 3.5 \text{ mm/yr}$ produce the minimum
179 misfit between observed and modeled topography (Fig. S1). We interpret the low best-fit
180 diffusivity as reflecting the steep relief of the study site, which is characterized by narrow
181 ridgelines ($\sim 3 \text{ m}$) and quasi-planar, heavily rilled hillslopes that are probably dominated by

182 overland flow. This morphology is better represented by the water-erosion term in equation (1)
183 than by the linear diffusion (soil-creep) term, and therefore the optimization procedure
184 identifies a low value for D. The most important result of the parameter sensitivity study is that
185 the calibrated model adequately captures the characteristic relief and ridge-valley structure of
186 the study area (Fig. 1,2), and yields a unique best-fit value for v_o .

187

188 ***Model Applicability***

189 The applicability of our model to a given landscape depends on: (1) the appropriateness
190 of an exponential function to describe the OFD profile, (2) the effectiveness of B_R , mean
191 elevation, and total relief as metrics for the field site comparison, and (3) the presence of
192 curved basins. For (1), The appropriateness of an exponential function to describe OFD has
193 theoretical and empirical support. England et al. (1985) derived a model for crustal deformation
194 treating the crust as a thin viscous sheet, which resulted in an exponential model. Nelson and
195 Jones (1987) and Rahl et al. (2011) found that this exponential model explained their OFD
196 measurements at the 30 km and 150 km scales respectively. Shelef and Oskin (2010) noted that
197 an exponential function described their OFD measurements at the 200-meter scale and
198 concluded from a review of the literature that a nonlinear displacement pattern is not unique to
199 the location or scale of the faults involved. An alternative approach using elastic dislocation
200 theory produces approximately linear displacement profiles at the scale of our field area which
201 do not appear to produce curved basins (see supplemental material). Although beyond the
202 scope of this study, an exploration of the underlying OFD mechanisms presents an interesting
203 avenue for future research.

204 For (2), our analysis relies on the assumption that the B_R metric is sensitive to basin
205 curvature and OFD, but insensitive to other morphologic characteristics, such as aspect ratio.
206 Comparison of model runs with different degrees of OFD demonstrates that B_R is indeed
207 sensitive to curvature and OFD rate (Fig. 3). Alternative metrics that we tested, such as basin
208 angle, proved to be less robust. Moreover, sensitivity analysis shows that the B_R metric is
209 insensitive to the basin length-width ratio, provided the ratio is greater than unity (most basins
210 are typically ~ 3 ; see Supplemental Information for details). Our analysis also assumes that
211 drainage orientation in the Mecca Hills was perpendicular to the SAF prior to the onset of
212 OFD, which is supported by field evidence as discussed above.

213

214 ***Model Implications***

215 The smoothly curved topography in the field and our model results provides some clues
216 to OFD mechanisms. OFD can occur in a range of styles, from pervasive shear to discrete faults
217 to block rotation (Shelef and Oskin, 2010). Rotation of a block the size of the field area (700-
218 800 m long) would lead to a linear displacement profile, which is inconsistent with the
219 curvilinear drainage basin geometry of the Mecca Hills. How rotation of small blocks (~ 10 -100
220 m long) would affect the landscape is unclear, but one possibility is that the creation of fault-
221 perpendicular shear zones to accommodate small-block rotation would lead to fault-
222 perpendicular drainage patterns as rivers preferentially erode the less-resistant zones between
223 rotating blocks (e.g., Roy et al., 2016). A series of discrete, parallel faults would be expected to
224 produce a landscape with shutter-ridge-like ridgelines and rectilinear channel networks (Duvall
225 and Tucker, 2015), which are not observed in the Mecca Hills. A remaining option is pervasive
226 continuous shear in which inelastic deformation is distributed across many sub-meter scale

227 faults. In this case, we would expect that a drainage network would progressively shear,
228 creating the apparent ductile-like deformation pattern in the Mecca Hills area. Lithology is
229 unlikely to be the main control on OFD in this location as there are no curved basins northward
230 along the SAF despite the occurrence of the same submember of the Palm Spring Formation.
231 We conclude that pervasive continuous shear from a structural control remains the most
232 probable first-order control of the curved basins in our field site. The exact mechanism of
233 structural control is not clear, but could be a wide shear zone in the underlying crystalline
234 bedrock distributed into weakly-lithified overlying sediments. As a final note, there is a
235 possibility that fault-perpendicular shortening has contributed to reorientation of the basins,
236 which would cause our model to slightly overestimate OFD rates. However, we note that the
237 SAF is oriented nearly parallel to the plate motion vectors and thus the effect of any shortening
238 on topography is likely to be small compared to the lateral deformation.

239 Our results suggest that OFD may play a significant role in accommodating plate
240 motion along the southern SAF. Generally, OFD can vary from 0-100% of the deformation rate
241 of the main fault trace (Milliner et al. 2015). The 3.5 mm/yr of OFD measured across the 800 m
242 study area accounts for 9-10% of total plate motion (35-40 mm/yr) and is consistent with
243 distributed lateral motion across the region (Lindsay et al., 2014). Our values agree with the 9-
244 14% OFD percent at Durmid Hill, 30 km SE along the SAF, based on stratigraphic data
245 (Bürgmann, 1991). Our findings provide both evidence for a structural control on OFD, and a
246 new method that can obtain OFD data using topography. The model presented here should be
247 generally applicable to locations where curved drainage basins are present along strike-slip or
248 transpressional faults, which we suggest can be found where such faults uplift and/or cross-cut
249 weakly lithified sediments.

250

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256

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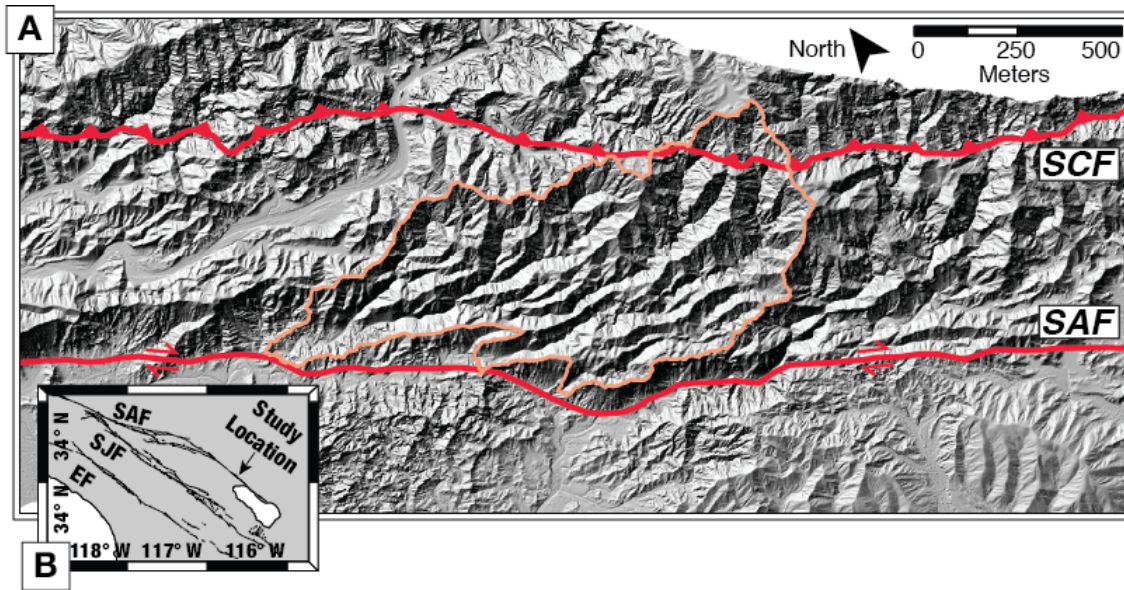
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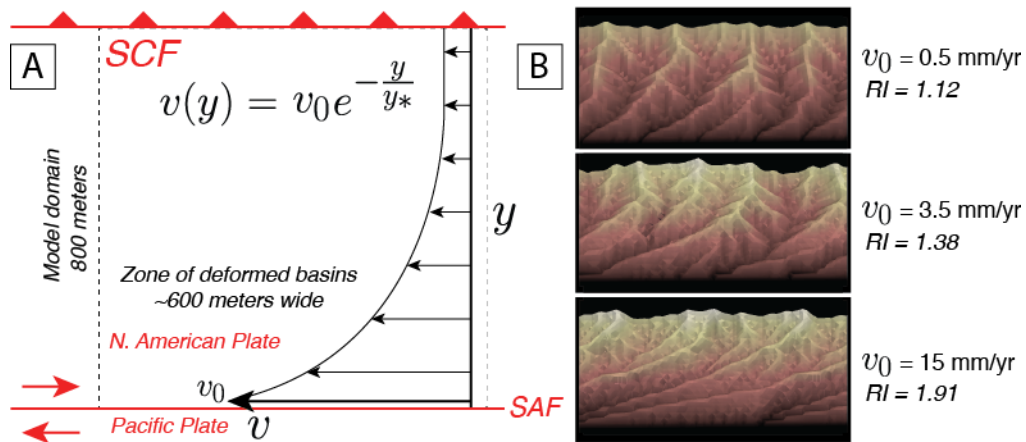
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302
 303 **FIGURES AND CAPTIONS**

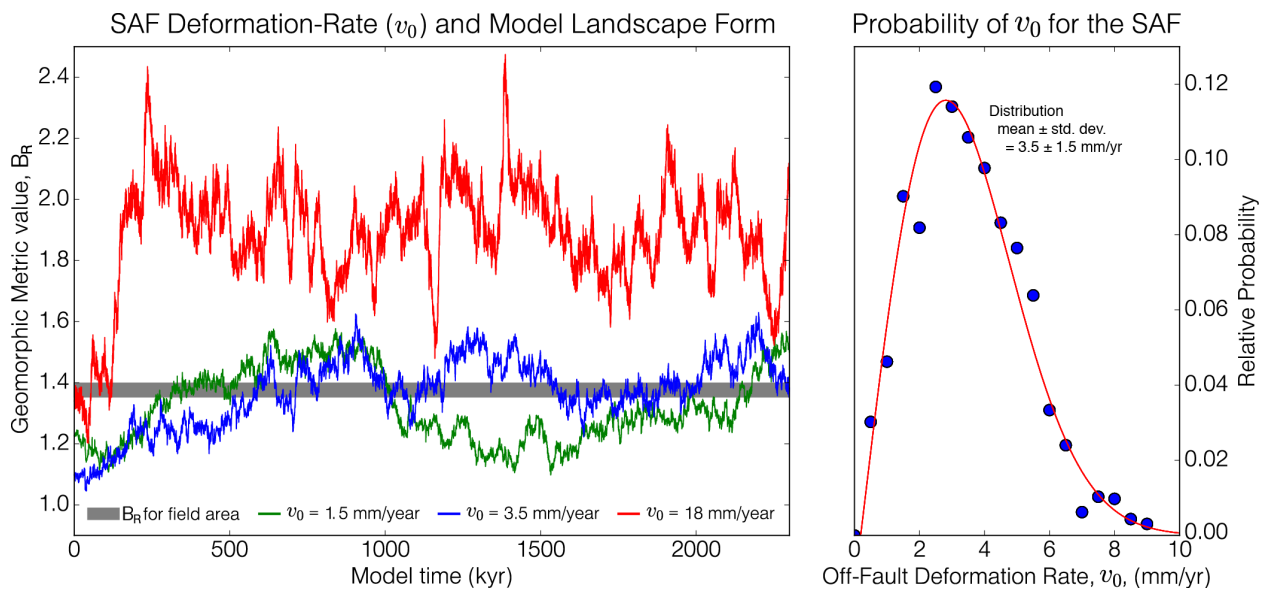


304
 305 **Figure 1:** A) Drainages deformed by right-lateral motion on the San Andreas Fault near
 306 Mecca, CA. The center of the figure is approximately at 33.5925° N / -116.0050°W. Red lines
 307 indicate fault trace. Tan line indicates study area. SAF: San Andreas Fault; SCF: Skeleton
 308 Canyon Fault. Image is a LiDAR hillshade (Bevis et al., 2005). B) Location of study area in
 309 southern California. SJF: San Jacinto Fault. EF: Elsinore Fault.

310



311
 312 **Figure 2:** A) Definition diagram for the model described with equations 1 and 2 in the main
 313 text. SCF: Skeleton Canyon Fault. SAF: San Andreas Fault. B) Examples of modeled
 314 topography after 700 ka of simulated landscape evolution. Increasing off-fault deformation (v_0)
 315 rate leads to an increase in drainage basin curvature, which is reflected in the geomorphic
 316 metric B_R (defined in main text).
 317



319 **Figure 3: A)** Geomorphic metric, B_R , plotted versus time for three different landscape
320 simulations. Off-fault deformation (OFD) increases the B_R value, whereas stream piracy and
321 hillslope diffusion decrease it. The landscape and metric reach a quasi-steady-state wherein the
322 B_R value varies around a mean. **B)** Relative likelihood that a model run with a given OFD rate
323 will produce an B_R with the same value as the field area. Because of the B_R value's variations,
324 there is a probability that different OFD rates can produce the same landscape. Blue dots
325 represent the relative likelihood that a model with given OFD rate matches the field area. Red
326 line is a Rayleigh distribution fit to the data. We take the mean and standard deviation of the
327 Rayleigh distribution fit of 3.5 ± 1.5 mm/yr as the most probable OFD rate.