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Climatic influence on the expression of strike-slip faulting

Nadine G. Reitman[1]*, Yann Klinger[2], Richard W. Briggs[1] and Ryan D. Gold[1]
[1]U.S. Geological Survey, Geologic Hazards Science Center, Golden, Colorado 80401, USA
[2]Université de Paris Cité, Institut de Physique du Globe de Paris, CNRS, Paris 75005, France

ABSTRACT

Earthquakes on strike-slip faults are preserved in the geomorphic record by offset landforms that span a range of displacements, from small offsets created in the most recent earthquake (MRE) to large offsets that record cumulative slip from multiple prior events. An exponential decay in the number of large cumulative offsets has been observed on many faults, and a leading hypothesis is that climate controls the rate of decay. We present offset measurements compiled from 31 studies of strike-slip faults with evidence of multiple paleoearthquakes and corresponding climatic and tectonic information to test this hypothesis. Both the global compilation and numerical landscape evolution modeling reveal that the decay rate in large offsets is negatively correlated with mean annual precipitation. Faults in dry regions with high drainage density more commonly preserve small MRE offsets, and faults in wet regions with lower drainage density more commonly preserve a mix of small MRE and large cumulative offsets. Geomorphology of faults in different climates supports this result and illustrates precipitation's effect on the development and preservation of offset channels. Our findings imply that current and past climate affect how displacement on strike-slip faults is recorded and interpreted to inform earthquake history.

INTRODUCTION

Together, climate and tectonics control the expression of strike-slip faulting in a landscape. Wallace (1968) famously observed that offset stream channels along the San Andreas fault (California, USA) result from the interaction of geomorphic and tectonic processes. Since then, many studies have documented and measured displaced landforms, most commonly channels, that record slip from the most recent earthquake (MRE) and cumulative slip from multiple past events to interpret earthquake history. From these data sets of offset measurements, cumulative offset probability density (COPD) curves are constructed, and the COPD peaks are inferred to represent amounts of slip in past earthquakes (McGill and Sieh, 1991; Zielke et al., 2010, 2015; Klinger et al., 2011).

Peaks in COPD curves exponentially decline with increasing cumulative displacement (Klinger et al., 2011; Zielke et al., 2012), representing a lack of large cumulative offsets in a landscape as compared to small MRE offsets. The observed decay in the occurrence of large offsets is represented by the equation

$$y = ae^{-bx}, \tag{1}$$

in which y, the number of offset measurements, is dependent on offset size (x), the rate of decay of large offsets (b), and a coefficient that scales by the number of measurements (a). The b parameter is the distribution of small to large offsets in a data set, with higher b values indicating faults with mostly small offsets.

Two of the first studies to measure dense data sets of offset features, along the Fuyun (China) and San Andreas strike-slip faults, found similar b values, though the faults span an order of magnitude difference in slip rate (Klinger et al., 2011; Zielke et al., 2012). These studies provide an example indicating that slip rate does not affect the decay in large cumulative offsets, and support the hypothesis that climate may exert a primary control on the exponential decay rate (b value) and the distribution of offset landforms in a landscape.

Multiple aspects of climate may affect offset channel development and distribution. The decay in the number of large offset channels preserved is often attributed to the erosion and degradation of offset features as they age (Zielke et al., 2015). Other hypotheses are that the relative frequencies of intense storms and earthquakes (Ludwig et al., 2010) or the interaction between drainage density and cumulative slip (Reitman et al., 2019) control the number and size of offset channels preserved. A definitive answer to what controls the distribution of offset channels and expression of strike slip has remained elusive, but with the widespread availability of high-resolution landscape data (e.g., lidar, photogrammetry, and imagery), sufficient data are now available to reexamine this question.

To quantify climate's influence on the geomorphic expression of strike-slip faulting, we compiled offset measurements from published studies of strike-slip faults with evidence of multiple past earthquakes, and corresponding climatic and tectonic information (Fig. 1). We used landscape evolution models and example faults to test the influence of precipitation rate, steady versus variable precipitation, and climate shifts on strike-slip fault geomorphology.

GLOBAL DATA

We compiled 35 offset measurement data sets from 31 published studies of 23 strike-slip faults with geomorphic evidence of multiple earthquakes (Fig. 1; see Table S1 in the Supplemental Material[1]). We excluded data sets with (1) majority MRE offsets, (2) reported mean MRE slip of <1 m, (3) an order of magnitude difference in measurement density, or (4) mixed creep and seismogenic slip, which resulted in 28 data sets from 24 studies of 19 faults in the filtered compilation.

Mean annual precipitation (MAP) and monthly precipitation variability (standard deviation/mean) data were selected for one location on each fault or fault section from the

*E-mail: nreitman@usgs.gov

[1]Supplemental Material. Supplemental methods, figures, and tables, as well as plots of each data set showing the b value calculation. Please visit https://doi.org/10.1130/XXXXX to access the supplemental material, and contact editing@geosociety.org with any questions.

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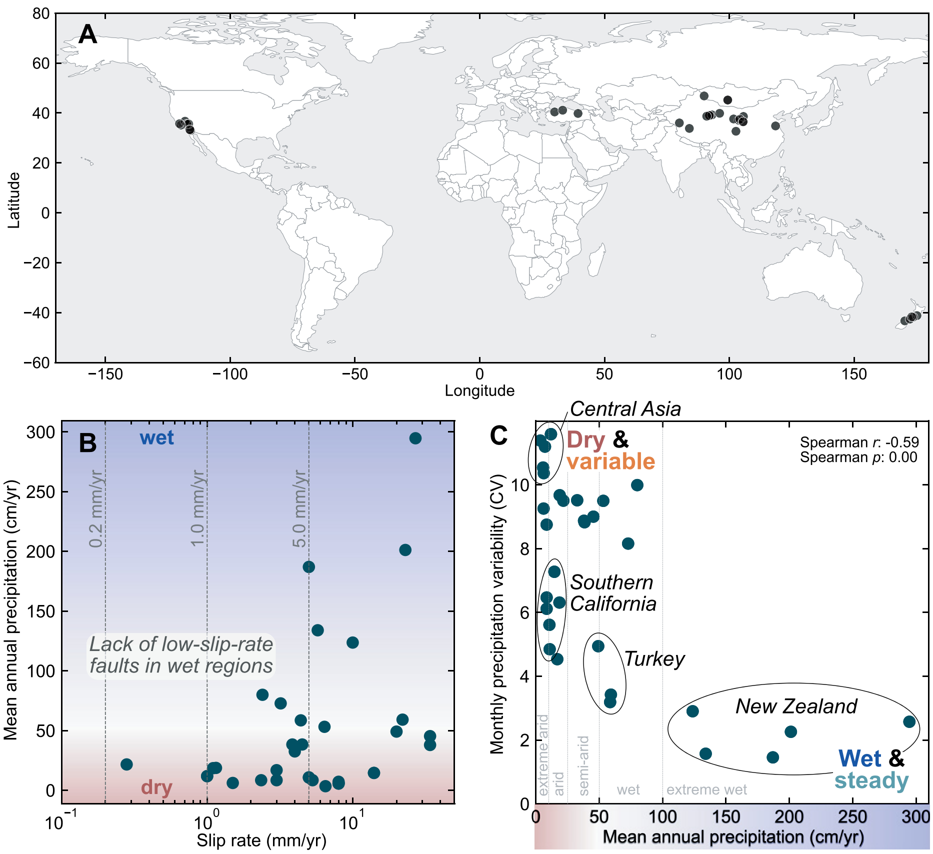

Figure 1. Fault and climate data. (A) Strike-slip faults in our global data compilation shown by their midpoints (black circles). (B) Mean annual precipitation (MAP) for 1970–2000 CE (Fick and Hijmans, 2017) plotted against fault-slip rate. Lines show slip-rate bins. (C) The correlation between MAP and monthly precipitation variability (CV) (Fick and Hijmans, 2017) is strongly inverse for the faults in the data compilation. Vertical lines show aridity bins (Holzapfel, 2008).

WorldClim2 (http://www.worldclim.com/version2) data set gridded at ~20 km resolution and spanning 1970–2000 CE (Fick and Hijmans, 2017). The relationship between MAP and precipitation variability is strongly inverse (Spearman $r = -0.59$, $p \approx 0.00$); wet locations have more constant monthly precipitation and arid locations have more variable monthly precipitation (Fig. 1C). We use MAP because it is a primary control on erosion and diffusion rates (Richardson et al., 2019; Adams et al., 2020) and can be related to numerical models.

RELATIONSHIP BETWEEN OFFSET CHANNEL DISTRIBUTION, CLIMATE, AND TECTONICS

To find the decay rate of large offsets (*b* value) for each data set, we fit exponential decay curves (Equation 1) to all offset measurements, the peaks in a COPD curve, and histogram bin midpoints (Figs. 2A–2C; see the Supplemental Material). We used the *b* values derived from all measurements (not from COPD peaks or histograms bins) in the analysis because they are the simplest to derive, and this is the most reproducible method.

To evaluate the influence of tectonic parameters on the decay rate of large offsets, we compared *b* values from the filtered compilation to slip rate, MRE magnitude, approximate years since MRE, length of MRE surface rupture, and measurement density. We found no significant correlation between *b* and any of the tectonic characteristics ($p > 0.05$, Fig. 3A), which indicates that fault activity rate and earthquake recurrence do not control the decay rate of cumulative offsets.

To evaluate the influence of climate on the on the decay rate of large offsets, we compared *b* values to MAP and monthly precipitation variability. We found no significant correlation between *b* and precipitation variability ($p > 0.05$; Fig. 3A; Fig. S4), and a strong inverse correlation between *b* and MAP (Spearman $r = -0.65$, $p \approx 0.00$) (Fig. 3B). An exponential relationship provides the best fit to the data set, with the R^2 values of 0.31–0.41 (Fig. 3B), but other nonlinear relationships cannot be ruled out with the available data (Fig. S4).

THE INFLUENCE OF PRECIPITATION RATE ON OFFSET CHANNEL DISTRIBUTION

The filtered compilation shows that *b* nonlinearly decreases as MAP increases (Fig. 3B). This finding implies that faults in wet climates more commonly record a mix of small MRE and large cumulative offsets (low *b* values), and faults in arid climates more commonly record small MRE offsets and fewer large cumulative offsets (high *b* values). One explanation for this relationship is that in extremely arid regions, where precipitation is often more variable, channels are usually small, shallowly incised, barren, ephemeral, and densely spaced. These factors promote channels that record small amounts of slip because they are more likely to avulse or be captured by a nearby channel (Schwartz and Yeats, 1994; Dascher-Cousineau et al., 2021). In wet regions, which commonly have more steady precipitation, channels are usually larger, deeply incised, vegetated, more permanent in a landscape, and sparsely spaced. These factors promote channels that record cumulative slip and large offsets. Additionally, small offsets in wet climates with high erosion and diffusion rates may be more quickly modified after an earthquake, leaving relatively more large offsets in the landscape.

Geomorphology along strike-slip faults in different climates supports the correlations found in the global compilation and provides examples of the influence of precipitation on offset channel distribution (Fig. 4). The Garlock fault, in arid southern California with 8–10 cm/yr MAP, is a very dissected landscape with many small channels and high channel density, and records a high ratio of small offsets to cumulative offsets (Fig. 4A). In contrast, the Hope fault, in wet South Island, New Zealand, with ~200 cm/yr MAP, is a smoother landscape with large landforms and low channel density and records a lower ratio of small to cumulative offsets (Fig. 4C). Semiarid locations (25–50 cm/yr MAP) tend to have a greater range of channel sizes and offsets, as illustrated by the Carrizo Plain section of the San Andreas fault (Fig. 4B), which lies in the middle in terms of MAP rate, channel density, and ratio of small to large offsets.

Landscape evolution models that simulate lateral displacement on a section of a strike-slip fault show the same effect, in which wet landscapes have lower drainage density than arid landscapes. Using the model of Reitman et al. (2019), we investigated the influence of MAP by varying the diffusion rate (*D*; a proxy for MAP) from 0.001 to 0.01 m²/yr, values that approximately encompass the natural range for faults in the compilation. The diffusion rate has a strong effect on channel spacing and landscape dissection (Fig. 4). Higher diffusion rates, which simulate wet environments, result in smooth landscapes with low drainage density, whereas lower diffusion rates, which simulate dry environments, result in dissected landscapes with high drainage density (Figs. 4A–4C). Offset channel measurements in the models are affected by topography adjacent to the fault trace, but

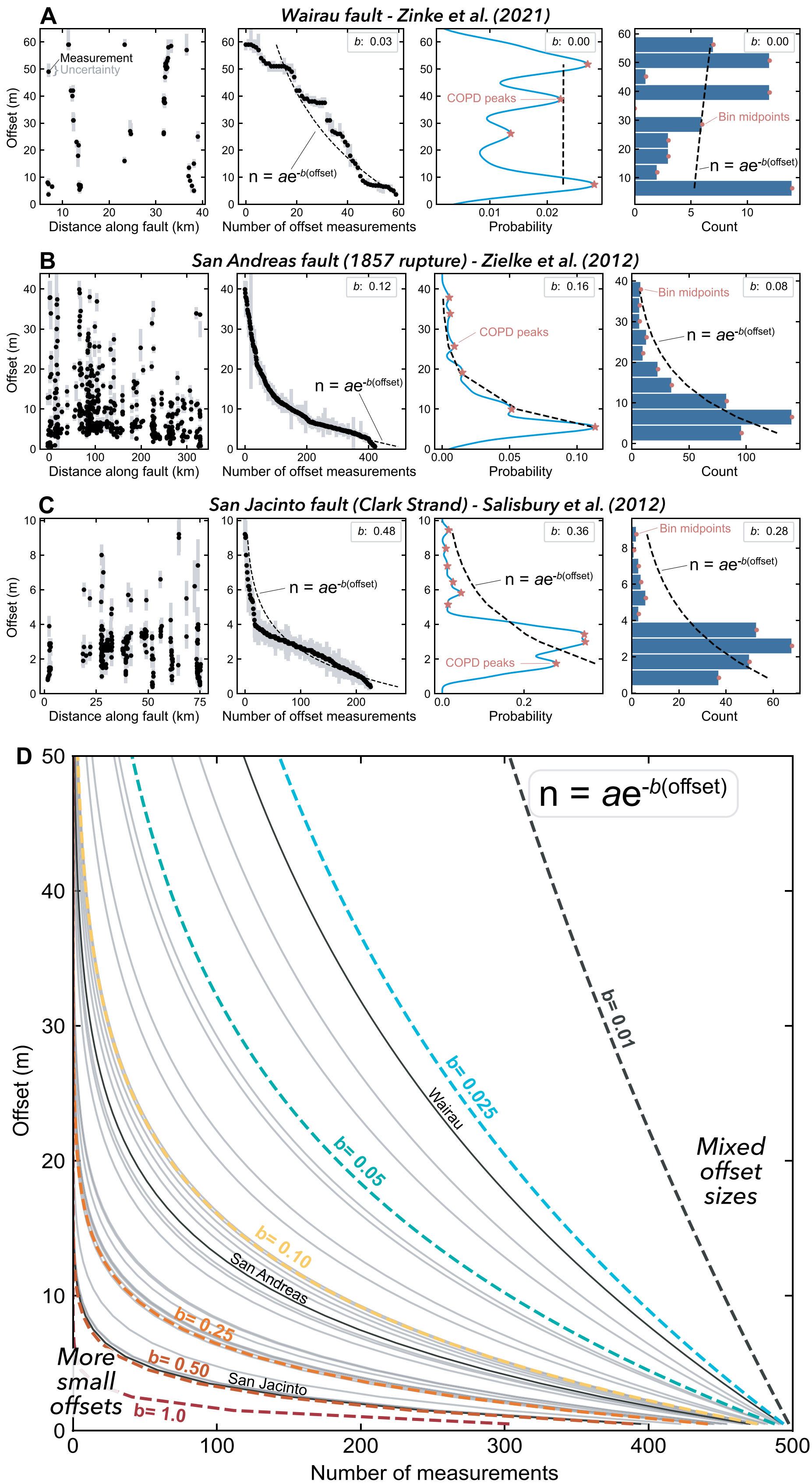

Figure 2. Calculation of exponential decay rates (b values) from offset measurements. (A–C) Example offset data from the (A) Wairau, South Island, New Zealand; (B) San Andreas, California, USA; and (C) San Jacinto, California, faults that span a range of b values (the distribution of small to large offsets in a data set). (D) Conceptual illustration of different b values (dashed colored lines) with scaled curves using b values derived from each data set in our filtered global compilation (solid gray lines). Black lines show b values from the Wairau, San Andreas, and San Jacinto faults. Offset is x, n is y, and a is a coefficient that scales with n in Equation 1.

the b values for the arid models ($D = 0.001$ m^2/yr; $b = 0.11$–0.17) are higher than for the wet models ($D = 0.01$ m^2/yr; $b = 0.06$), which is consistent with the global data set.

The tight correlation between drainage density and precipitation rate indicates that MAP is a control on the upper limit of cumulative slip recorded by channels. When channels are closely spaced along a strike-slip fault, channel aliasing becomes common as upstream portions of channels (heads) abandon their original downstream segments (tails) and incise new tails or capture tails that have slipped toward them along the fault. Channel aliasing makes it difficult to preserve cumulative offsets because channel heads and tails frequently rearrange (Salisbury et al., 2018; Reitman et al., 2019). Conversely, in wetter climates, the larger distance between channels favors preservation of cumulative offsets. Despite the strong relationship between MAP and decay rate, some scatter is in the data set (e.g., regions with MAP of < 25 cm/yr; Fig. 3B), which is indicative of additional influences on offset channel distribution.

THE INFLUENCE OF PRECIPITATION VARIABILITY ON OFFSET CHANNEL DISTRIBUTION

The relative occurrence of earthquakes and rare intense storms that incise new channels may affect the distribution of offset channels preserved in a landscape (Ludwig et al., 2010; Zielke, 2018). However, correlation between precipitation variability and b value was not significant for the faults in the compilation (Fig. 3A), and simple landscape evolution models with earthquakes every 200 yr that simulate frequent (every 50 yr) and infrequent storms (every 500 yr) reveal no significant difference in offset sizes (Fig. S5). The effect of a storm depends on the size of the storm, the state of the landscape (e.g., steady-state versus transient), and the spatiotemporal scale of observation and analysis; these details are too complex and regional to be captured by this global data set.

NON-CLIMATIC INFLUENCES ON OFFSET CHANNEL DISTRIBUTION

Topography along a fault that is unrelated to climate (e.g., pressure ridges built in successive earthquakes, or displacement of lower topography against higher topography) also affects offset channel development. Landscape evolution models show how uphill- and downhill-facing fault scarps affect the channel pattern that develops along a strike-slip fault (Fig. 4D). Uphill-facing scarps encourage channels to flow along

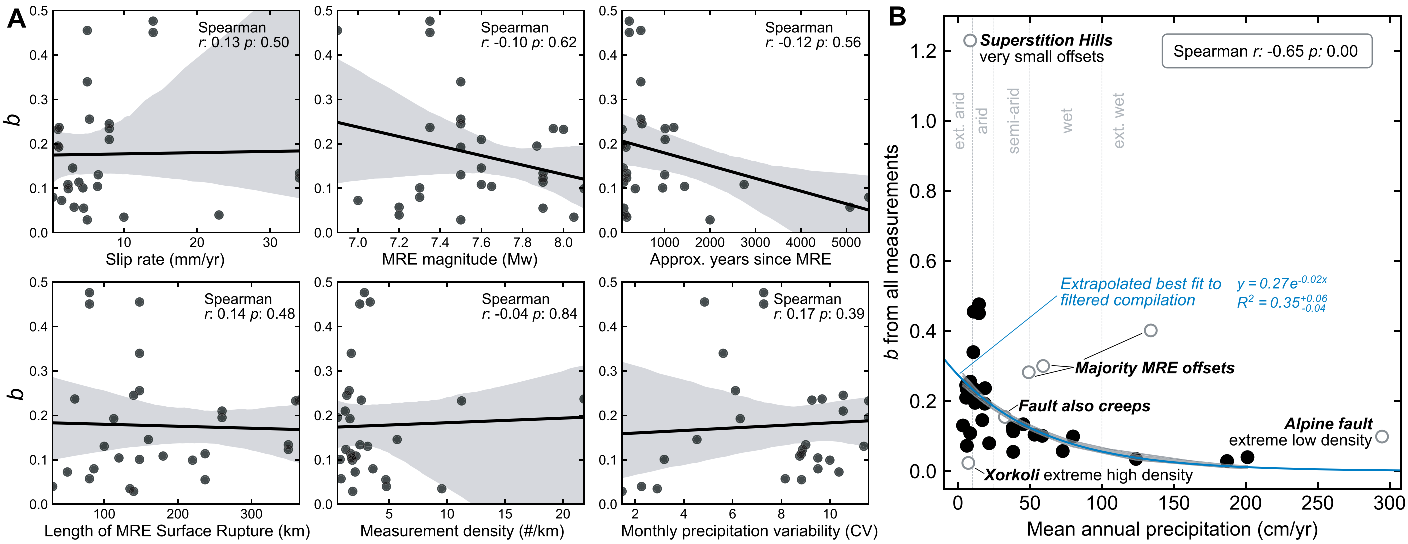

Figure 3. Relationships between exponential decay rate (*b*) and climatic and tectonic variables. (A) There is no significant correlation between *b* value and slip rate, estimated magnitude of the most recent earthquake (MRE), years since the MRE, length of MRE surface rupture, measurement density, or monthly precipitation variability (CV). (B) The nonlinear inverse correlation between mean annual precipitation and *b* value is significant. Data are shown for faults included (closed circles) and excluded (open circles) from the filtered global data set, with uncertainty (gray lines) and the best-fit curve (blue line).

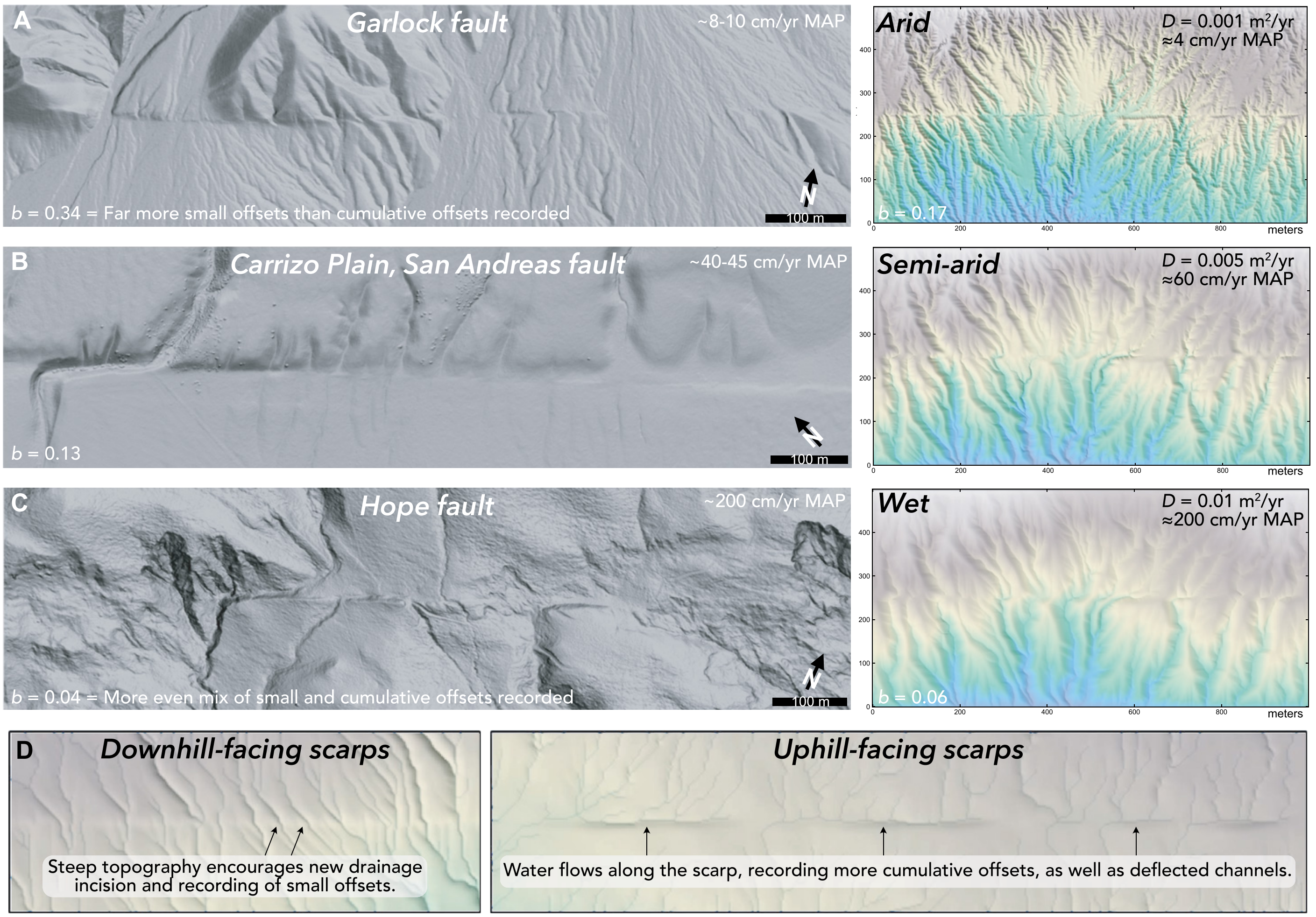

Figure 4. Geomorphology along strike-slip faults is influenced by mean annual precipitation (MAP) rate. Lidar (left) and landscape evolution models (right) illustrate the influence of precipitation rate (A–C) and downhill- and uphill-facing fault scarps (D) on the size and distribution of offset channels. MAP rate affects channel spacing and thus the distribution and size of offset channels preserved along a fault. Scarp direction is unrelated to climate, but affects the drainage pattern that develops along a fault. D—diffusion rate. Data used to calculate *b* values are from McGill and Sieh (1991), Zielke et al. (2012), and Manighetti et al. (2015).

the fault, causing more cumulative offsets to be preserved (lower *b* values) and more deflected channels that may be confused for cumulative slip. In contrast, steep, downhill-facing scarps encourage channels to incise across the fault, creating and recording more small offsets (higher *b* values). Similarly, small grabens along a fault may encourage existing channels to incise and record cumulative slip, while headward incision across scarps without grabens is faster. Faster incision causes more new channels to form and thus increases channel density so that fewer earthquakes are recorded. Although these patterns are evident along many strike-slip faults, compiling data sets that span entire faults may mitigate biases created by local topography.

IMPLICATIONS FOR RECORDING EARTHQUAKE HISTORY

Gaps in the compilation are indicative of which landscapes best record strike slip. The majority of faults in the compilation are in arid regions (54%, MAP $<$ 25 cm/yr), and all faults in extremely wet regions (14%, MAP $>$ 100 cm/yr) have high slip rates. Low-slip–rate faults in wet regions are missing from the compilation (Fig. 1B). These faults likely exist but may be more difficult to study because subtle strike-slip geomorphology can be obscured by vegetation and hidden by large-wavelength landforms, or these faults may not be well preserved if small offsets are modified soon after an earthquake.

Additionally, the correlation between *b* value and precipitation rate implies that extreme climatic shifts can affect how slip is recorded. For example, the Mojave Desert of the southwestern United States experienced a period of high precipitation rates from ca. 20 ka to 12 ka, unlike the present arid conditions (Tchakerian and Lancaster, 2002). Larger offset channels on strike-slip faults in the region may be relicts from a wetter time. Indeed, landscape evolution models that simulate a shift from wet to arid conditions have lower drainage density and larger offsets than those with steady arid conditions (Fig. S6). This indicates that some of the observed scatter in the compilation for arid regions is due to variable climate history for faults that are now characterized as arid and that climate shifts can affect the interpretation of earthquake history on strike-slip faults.

Finally, the results indicate that MRE slip distribution for faults in wet regions and long-term slip rate for faults in arid regions may not be well preserved by offset channels. In arid regions, large-scale features such as offset alluvial fans may provide better records of long-term slip because channels are subject to aliasing. In wet regions, slip from recent earthquakes may not be preserved in the landscape following an earthquake and may be better recorded by anthropogenic or small-scale features. Both climate and landform type contribute to the preservation of strike slip in a landscape.

This global data set demonstrates the strong correlation between precipitation rate and the distribution of offset channels. Models and example faults illustrate the primary control climate exerts on the geomorphic record of strike-slip displacement, and thus how earthquake history is recorded in a landscape.

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