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Lithologic and Climatic Controls on Offset Channel Development: Implications for Slip-per-Event Measurements

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Project Abstract: Offset geomorphic piercing points, such as stream channels, are commonly used to determine fault slip rates from historic and paleoseismic earthquakes, under the assumption that they record coseismic slip. Though researchers dating back to Wallace (1968) recognized that both tectonic and geomorphic factors control the appearance and preservation of offset channels (e.g., Figure 1), few studies have explored the development of offset channels through multiple earthquake cycles or their evolution post-earthquake. In this project, we systematically investigate the formation and evolution of offset channels using numerical landscape evolution models that simulate different lithologic and climatic settings. The project includes exploration of how offsets form and evolve through 1-5 earthquake cycles depending on lithologic and climatic controls in both numerical landscape evolution models and along real strike-slip faults. Results of this work will build a fundamentally better understanding of how offset stream channels record tectonic slip under different climatic settings and evaluate how well and for how long the geomorphic paleoseismic record retains reliable information on large surface rupturing earthquakes.

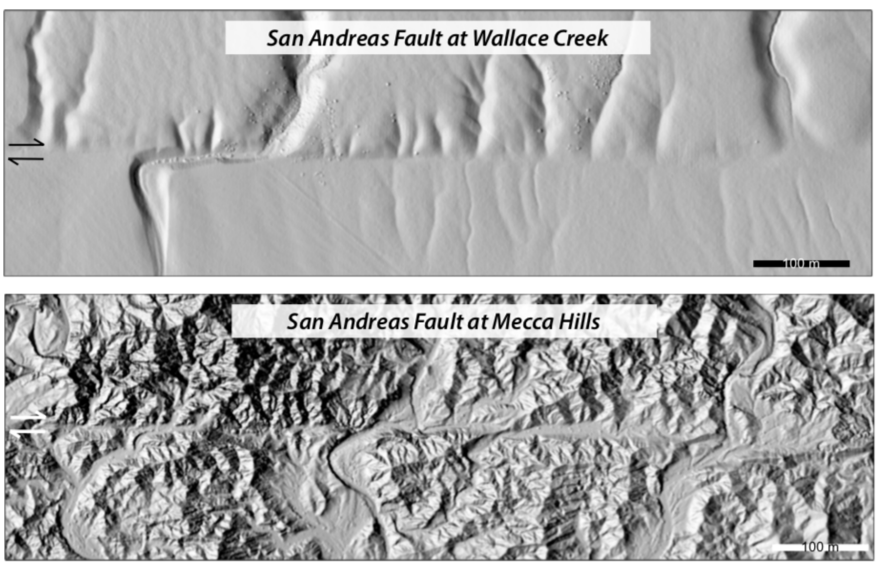

Figure 1: *Portions of the San Andreas Fault at Wallace Creek (top) and the Mecca Hills (bottom) illustrate the effect of differences in erosion rate. The two sites have similar slip rates (~34 vs 25 mm/yr, respectively), but differences in climate and lithology create very different erosional settings. Topographic data from the B4 lidar collection.*

Numerical Landscape Evolution Modeling:

Methods

Using suites of numerical landscape evolution models, we test the effects of drainage direction, storm recurrence, diffusion coefficient, and slip rate on the development and evolution of offset channels. The numerical landscape evolution model is implemented with Landlab (Hobley et al., 2017; Barnhart et al., 2020), a modular Python toolkit for modeling earth surface processes. Landscape evolution is governed by the equation:

$$\frac{\partial z}{\partial t} = \underbrace{U}_{\text{baselevel lowering}} - \overbrace{V(y)\frac{\partial z}{\partial x}}^{\text{lateral deformation}} - \overbrace{(\underbrace{K_{sp}}_{\text{erodibility}} A^{1/2} S - E_{crit})}^{\text{incision}} + \overbrace{\underbrace{D}_{\text{diffusivity coefficient}}\nabla^2 z}^{\text{diffusion}} \qquad \text{eq. 1}$$

Where dz/dt is change in landscape height over time and V(y) is the slip rate at y distance from the fault. We explore different values of erodibility as a proxy for lithology and different values of the diffusivity coefficient as a proxy for climate. The model setup simulates an interior portion of a linear strike-slip fault with constant slip along strike and without distributed deformation. Each simulation begins with the same initial topography, with self-similar random roughness and a ramp in the y-direction (Figure 2). The initial landscape includes relative topographic highs in the upper right and left corners, which sets up an experiment to test the geomorphic effects of drainage in the direction of and opposite the direction of fault slip. The landscape evolves and channels incise concurrently with lateral slip accumulation.

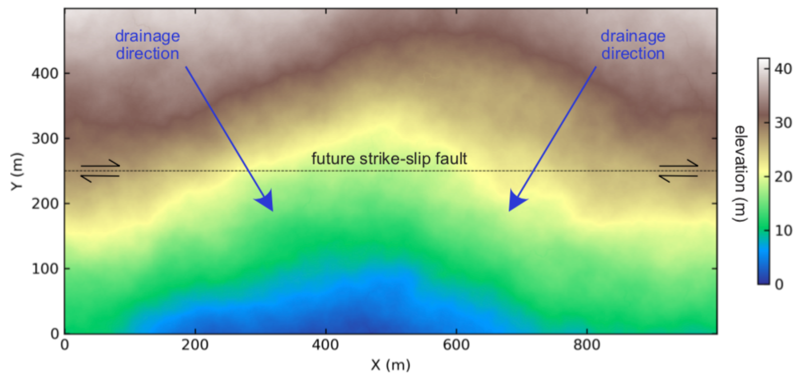

Figure 2: *Initial topography with self-similar random roughness, a ramp in the y-direction, and topographic highs in the upper corners. The strike-slip fault runs across the middle of the model space.*

For the base case model, we simulate periodic earthquakes with 6 m of right-lateral slip in 10,000 years. For the parameter exploration, we explore slip rate values of 1-30 mm/yr, diffusivity coefficient values of 0.001-0.01 m^2/yr, and the occurrence of large "storms" (timesteps with an order of magnitude higher erodibility) spaced more frequently and less frequently than earthquakes (Figure 3).

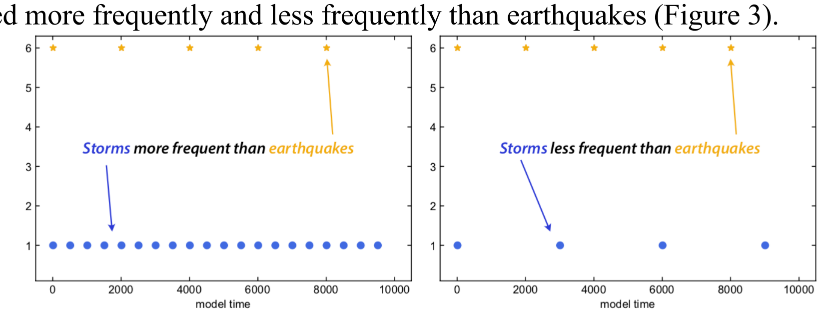

Figure 3: *Graphical depiction of earthquake occurrence (yellow stars) and storm occurrence (blue circles) in two 10,000-year-long simulations to test the effects of storm occurrence more and less frequently than earthquakes.*

Results:

Numerical model sets testing ranges of diffusivity coefficient and slip rate illustrate the effects that each parameter has on the geomorphic evolution of a strike-slip fault zone at the Earth's surface. Diffusivity is used a proxy for climate, with arid regions having lower diffusion and erosion rates than wet regions. The value of the diffusivity coefficient has an effect of the expression of the fault zone and channels offset along a fault, as well as how the geomorphic fault zone and offset channels evolve after an earthquake occurs (Figure 4).

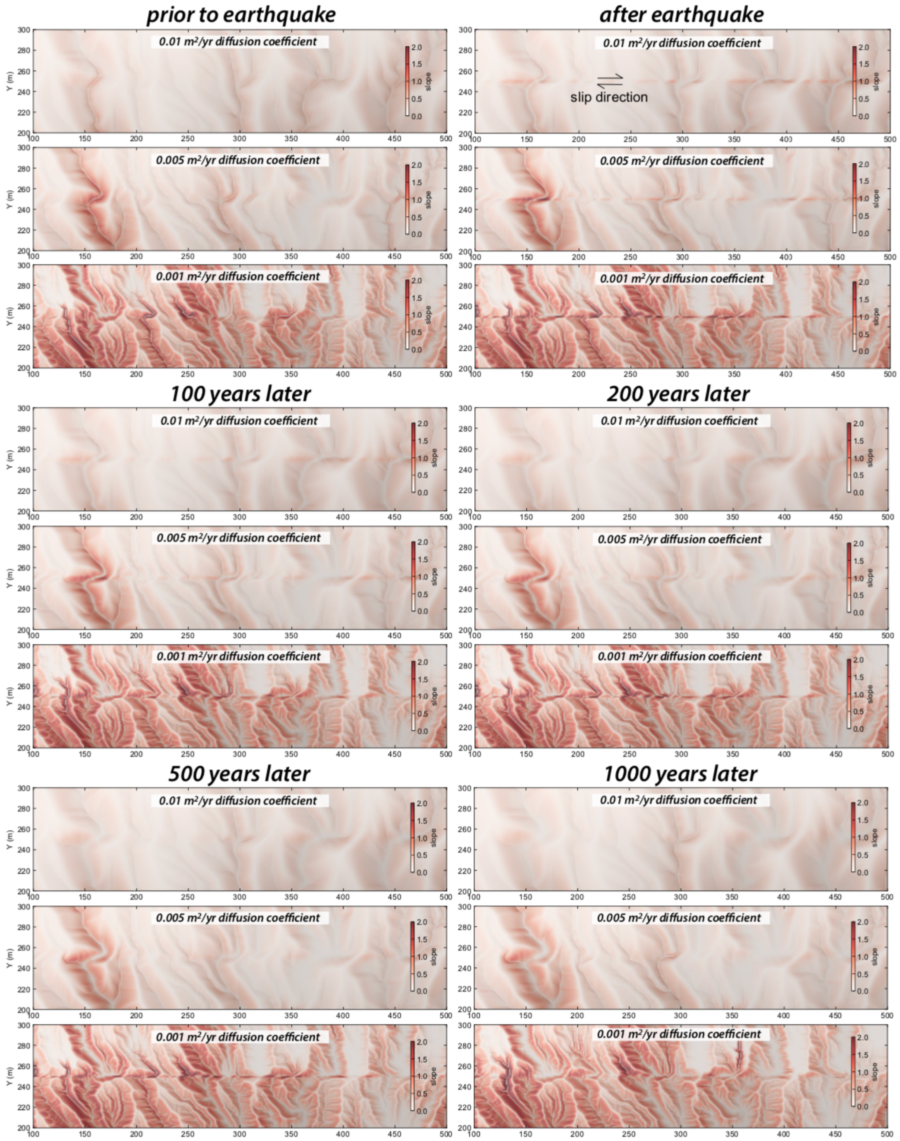

Figure 4: *Numerical simulations illustrate the effect of diffusion coefficient (as a proxy for aridity) on fault zone and offset channel evolution following a right-lateral earthquake. Images are hillshade with slope overlay in red.*

In the above simulations, the expression of the strike-slip fault and lateral offsets in channels are preserved longer following an earthquake in regions with lower diffusion rates (i.e., more arid regions). In regions with higher diffusion rates (i.e., wetter regions), the expression of the fault is more diffuse and lateral offset is harder to measure in correlative channels.

Drainage direction and slip rate are also primary controls on the development of strike-slip fault zone topography (Figure 5). From the faster slip rate simulations (10-30 mm/yr), it is evident that drainage direction in relation to fault slip direction plays an outsize role on the development of fault zone topography. On the left side of the model run, where channels drain in the opposite direction of fault slip and lower topography is faulted downstream of higher topography, steep triangular facets form along the strike-slip fault and many channel offsets form, though channels appear to be offset in both right-lateral and left-lateral orientations. On the other hand, on the right side of the model run, where channels drain in the same direction of fault slip and higher topography is faulted downstream of lower topography, a shutter ridge forms, causing ponding upstream of it and drainage is deflected along the shutter ridge. This situation makes it hard to measure discrete offsets along this region of the fault.

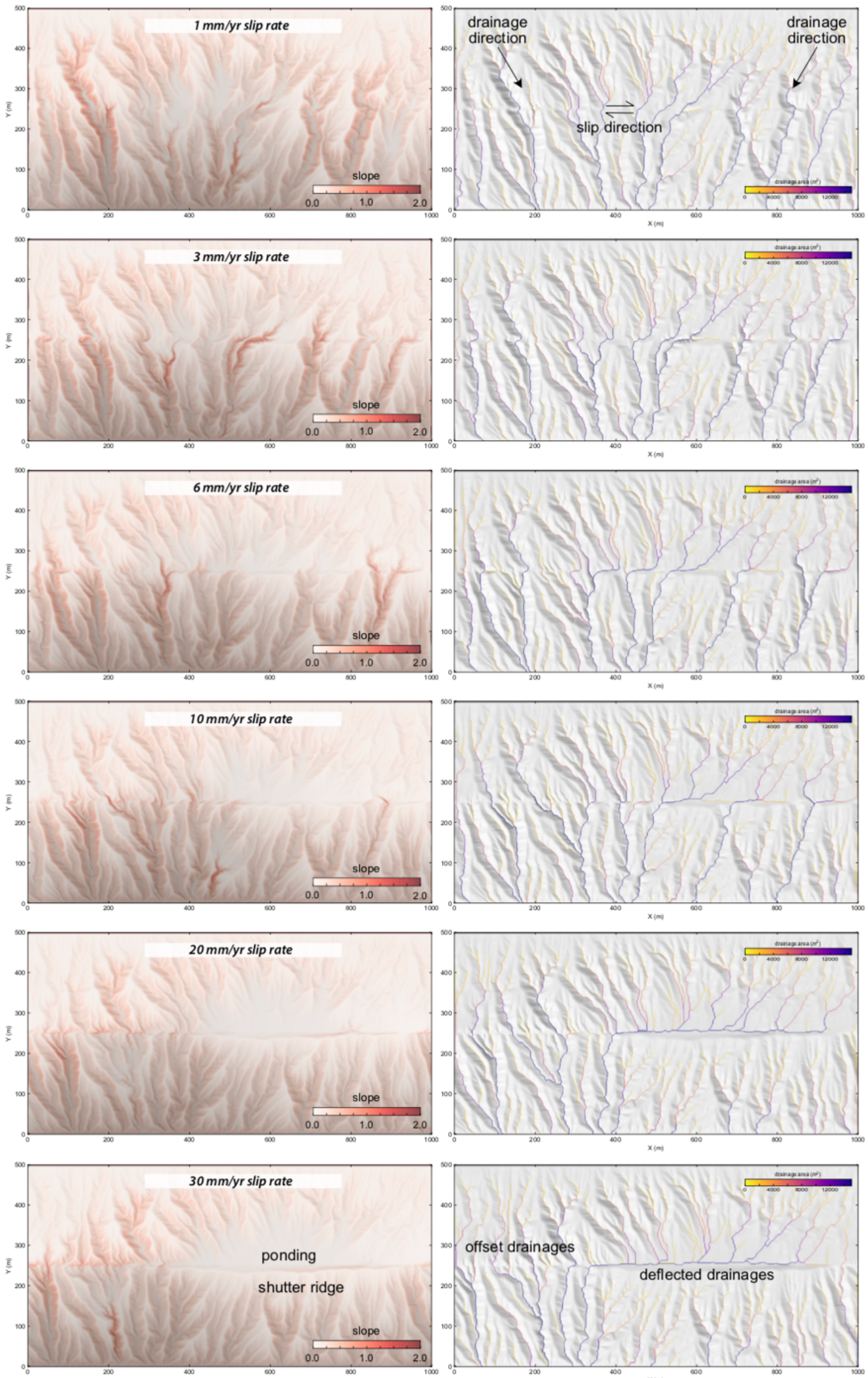

Figure 5: *Six simulations illustrating the effect of fault slip rate and drainage direction of the development of fault zone topography and offset features along a right-lateral strike-slip fault at the end of a 10,000-year-long run.*

Finally, the effects of the distribution of storms in relation to earthquakes also has a large effect on fault zone topography. When storms are less frequent than earthquakes (Figure 6, left-hand panels), offset channels tend to record cumulative slip from multiple earthquakes. In the example in the figure, initial small offsets from the last earthquake become cumulative offsets as more earthquake happen. However, when the next storm happens, the channels are refreshed and new channels form, erasing some of the offsets. The next earthquake then creates new small offsets. In this scenario, channels in the landscape may record both small offsets from the most recent earthquake and larger, cumulative offsets. However, when storms are more frequent than earthquakes (Figure 6, right-hand panels), the channels are refreshed so frequently that many of them do not record cumulative slip. In this scenario, there are many small offsets recorded from the most recent earthquake, but larger, cumulative slip is not recorded frequently. Of course, in the real world, external factors such as different lithologic units or channels of very different ages might help with interpreting offset.

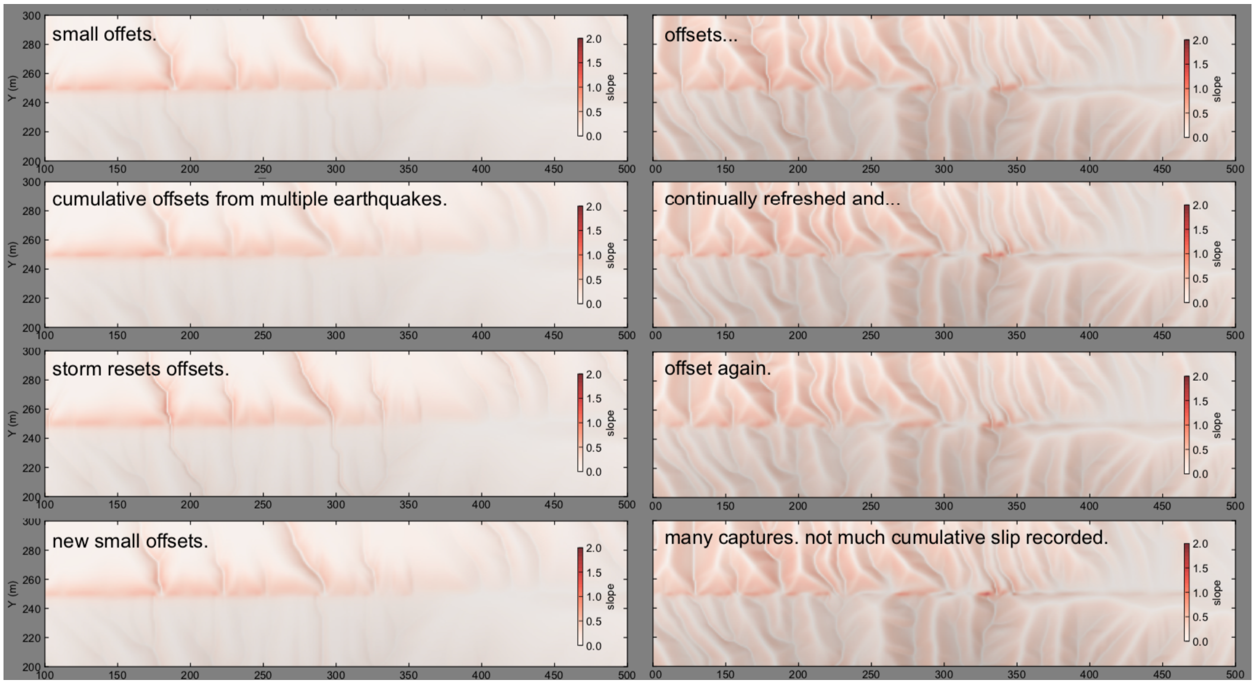

Figure 6: Left panels – Storms (every 500 years) less frequent than earthquakes (every 200 years). Right panels – Storms (every 100 years) more frequent than earthquakes (every 200 years).

Comparative Datasets:
The second part of this work is to compare observations from numerical models with fault data from different climates. We compiled 28 studies that document lateral offsets from multiple earthquakes on 22 faults that fall primarily into six climate classifications. We are still in the process of compiling climate data for each fault centroid and fault section. The climate parameters we will use to investigate trends in offset preservation include mean annual temperature, time in the frost window, seasonality, total annual precipitation, age of major storms or wet periods (if available), and the Köppen climate classification.

Future Work Plan:
Most of the work of this project is complete. Two tasks remain. One is to analyze offset data from faults around the world in different climate zones to test the relationship between offset preservation and climate. We have compiled the studies that contain offset measurements, and we are in the process of compiling climate data for each fault. The second task is to measure offset geomorphic markers in some of the landscape evolution simulations that simulate at least five earthquakes in different climates. These data will be analyzed to see if there is a correlation between diffusivity coefficient in each model run and the distribution in size and number of offset features that are preserved. This work will be presented at the 2021 SCEC annual meeting and submitted for publication in a peer-reviewed journal. We expect all work to be completed and a manuscript submitted by the end of 2021.

References:
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