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Fault Network Geometry Influences Earthquake Frictional Behavior

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Understanding the factors governing the stability of fault slip is a crucial problem in fault mechanics^{1–3}. The importance of fault geometry and roughness on fault-slip behaviour has been highlighted in recent lab experiments^{4–7} and numerical models^{8–11}, and emerging evidence suggests that large-scale complexities in fault networks play a vital role in the fault-rupture process^{12–18}. Here we present a new perspective on fault creep by investigating the link between fault-network geometry and surface creep rates in California, USA. Our analysis reveals that fault groups exhibiting creeping behaviour show smaller misalignment in their fault-network geometry. The observation indicates that the surface fault traces of creeping regions tend to be simple, whereas locked regions tend to be more complex. We propose that the presence of complex fault-network geometries results in geometric locking that promotes stick-slip behaviour characterized by earthquakes, whereas simpler geometries facilitate smooth fault creep. Our findings challenge traditional hypotheses on the physical origins of fault creep explained primarily in terms of fault friction^{19–21} and demonstrate the potential for a new framework in which large-scale earthquake frictional behaviour is determined by a combination of geometric factors and rheological yielding properties.

25 The mechanisms that govern fault creep remain a topic of debate. The stability of fault slip
26 is typically attributed to frictional parameters of the rate-and-state law¹⁹⁻²¹, and fault creep has been
27 linked to factors including low shear strength of fault materials²²⁻²⁴ and increased pore pressure^{25,26}
28 within this framework. However, recent studies also emphasize the potential importance of fault
29 geometry on fault slip behavior. Laboratory experiments and numerical models have highlighted
30 the importance of fault plane roughness, although there are divergent interpretations on whether
31 rough faults promote or suppress stable sliding^{4-7,10}. Studies based on InSAR and GPS observations
32 have demonstrated fault creep in segments with simple fault geometries^{27,28}, creep promoted by
33 heterogeneous stress fields resulting from fault roughness²⁹, and variable creep rates associated
34 with local fault strike and regional stress orientations³⁰⁻³². Given the diverse evidence and lack of
35 consensus, a comprehensive understanding of fault creep remains elusive².

36 Recent findings suggest that the often-overlooked effects of larger-scale complexities in
37 fault networks, such as bends, gaps and stepovers, play a pivotal role in the earthquake rupture
38 process^{9,12-18}. Geometric complexities in fault systems give rise to localized stress concentrations,
39 which can either facilitate or impede earthquake rupture initiation and arrest. However, given the
40 difficulties of including large-scale fault complexities in standard numerical earthquake rupture
41 models, there has been limited research on the impact of such geometric complexity. We propose
42 that the geometrical complexity of fault networks can have a significant role in suppressing fault
43 creep, and establish a quantitative connection between the two through observations. We test the
44 correlation between quantitative metrics of fault network geometry¹⁵ and measurements of surface
45 creep rate along some of the major fault zones in California. We find that statistical metrics of
46 geometrical fault network complexity have strong explanatory power for the occurrence of fault
47 creep.

48

49 **Fault Complexity and Creep Measurements**

50 California has extensively documented fault creep. Large surface creep rates of about 30
51 mm/year are observed along the central section of the San Andreas Fault, and surface creep rates
52 of about 5 mm/year are observed along the creeping sections of the Maacama, Calaveras, Bartlett-
53 Springs, Coachella, Hayward, and Superstition Hills fault segments³³. While there is no unified
54 perspective to explain the spatial variation in why some faults exhibit creep while others remain
55 locked, understanding the key factors driving fault creep is essential for analyzing fault slip
56 behavior and its implications for seismic events in California and beyond. Here we test the
57 hypothesis that the spatial variability in creep can be explained in terms of large-scale fault
58 complexity, using high-resolution fault maps from the USGS Quaternary Fault Database³⁴.

59 As detailed in the Methods section, we quantify fault network complexity by measuring
60 the degree of fault misalignment and fault density along these documented fault segments and
61 explore their connections with surface creep rates. For a fractal fault geometry, fault misalignment
62 remains independent of fault map resolution, making it a robust indicator of fault complexity,
63 whereas fault density is resolution dependent¹⁵ (see Methods). The spatial pattern of fault
64 misalignment is diverse, ranging from 0.1 to 0.8 across California (Fig. 1). The largest fault
65 misalignments of 0.6 to 0.8 are observed in complex fault zones, such as the region near the
66 southern tip of the San Jacinto Fault, or in areas where major fault zones intersect, as in the Big
67 Bend area. The smallest fault misalignments, ranging between 0.1 and 0.2, are in regions where
68 fault strands predominantly run parallel to each other. Examples of such regions include a ~120-
69 km segment along the Central San Andreas Fault, as well as areas along the Maacama and
70 Hayward faults. Importantly, these measurements involve intersecting fault strands between

networks of faults at scales ranging from 10 to 15 kilometers. These measurements are distinct from the highly localized, sub-kilometer scale fault geometry features related to fault damage zones³⁵ or fault roughness^{36,37}.

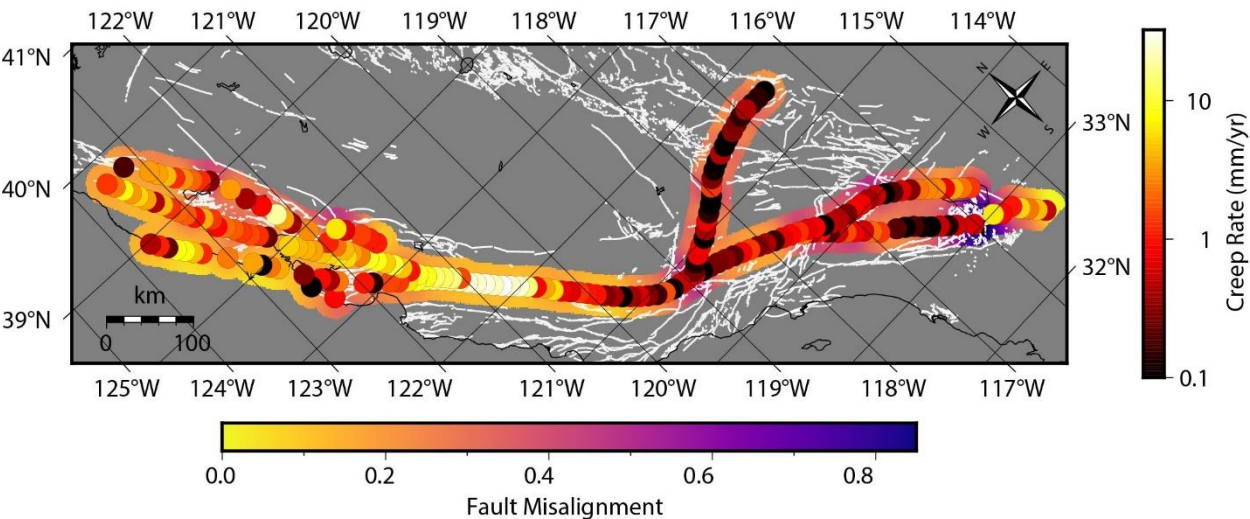


Figure 1. Fault misalignment and surface creep rates along major faults in California. Surface fault traces from the USGS Quaternary Faults Database plotted in white, with fault misalignments as colored background and creep rates as colored circles. Fault misalignments calculated within 15-km radius circles are shown using 25-km radius circles here for clarity.

A low degree of fault misalignment is generally observed in many regions with significant surface creep rates. A negative correlation between creep rates and fault misalignment is observed with a rank correlation coefficient of -0.35 (Extended Data Fig. 1a). We further quantify this by categorizing the slip behavior into either “locked” or “creeping” based on the absolute values of the estimated creep rates. We find a distinct difference in these two categories, with fault misalignment being larger along locked sections of faults compared to creeping sections (Fig. 2a). The average value of misalignment is 0.28 for the locked sections and 0.19 for the creeping sections, with standard deviations of 0.13 and 0.11 respectively. This observation indicates that,

with respect to the orientation of surface fault traces, creeping regions tend to be simple, whereas locked regions tend to be more complex. A two-sample Kolmogorov–Smirnov test of the fault misalignment distribution between locked and creeping fault sections rejects the null hypothesis that the two distributions are identical with a confidence level of 99.9%. These findings extend the qualitative explanations made for fault creep at individual fault sections with simple fault geometries^{27,28} to a broader analysis for the entire California region. Our study focuses on California due to the availability of detailed creep measurements and fault network maps, but other fault systems with sufficient data quality and resolution, such as the North Anatolian Fault and the Chaman Fault, also demonstrate negative correlations between fault network misalignment and surface creep rates (Extended Data Fig. 2). The consistent negative correlations observed in other creeping faults globally indicate that the influence of fault complexity on fault creep may be a universal behavior.

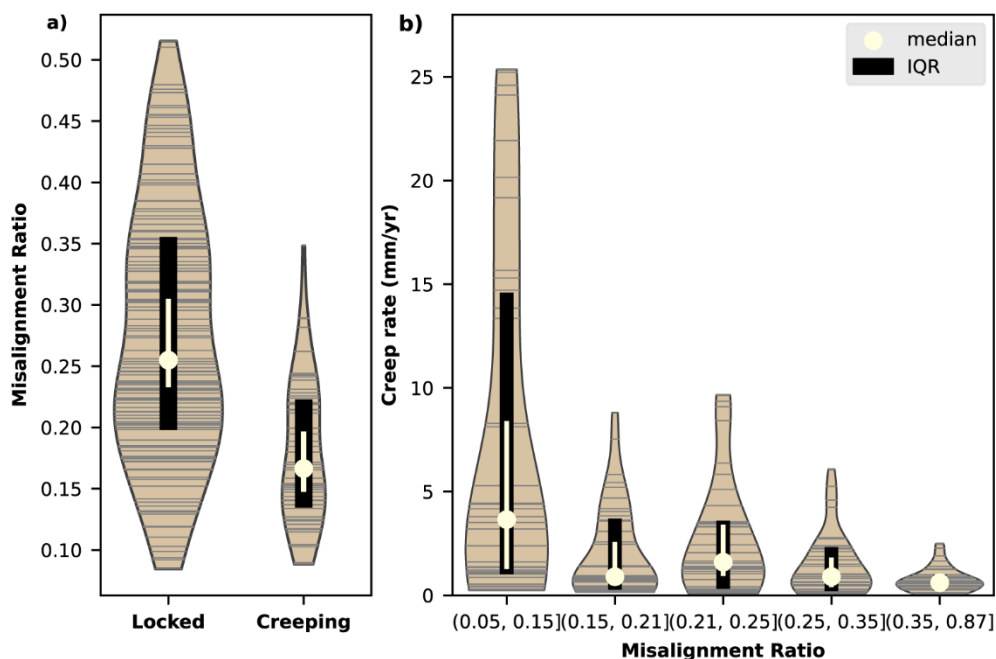


Figure 2. Fault misalignment versus creep rates. **a**, Violin plot of fault misalignments according to whether the surface creep rates indicate locked or creeping. **b**, Violin plot of surface creep rates

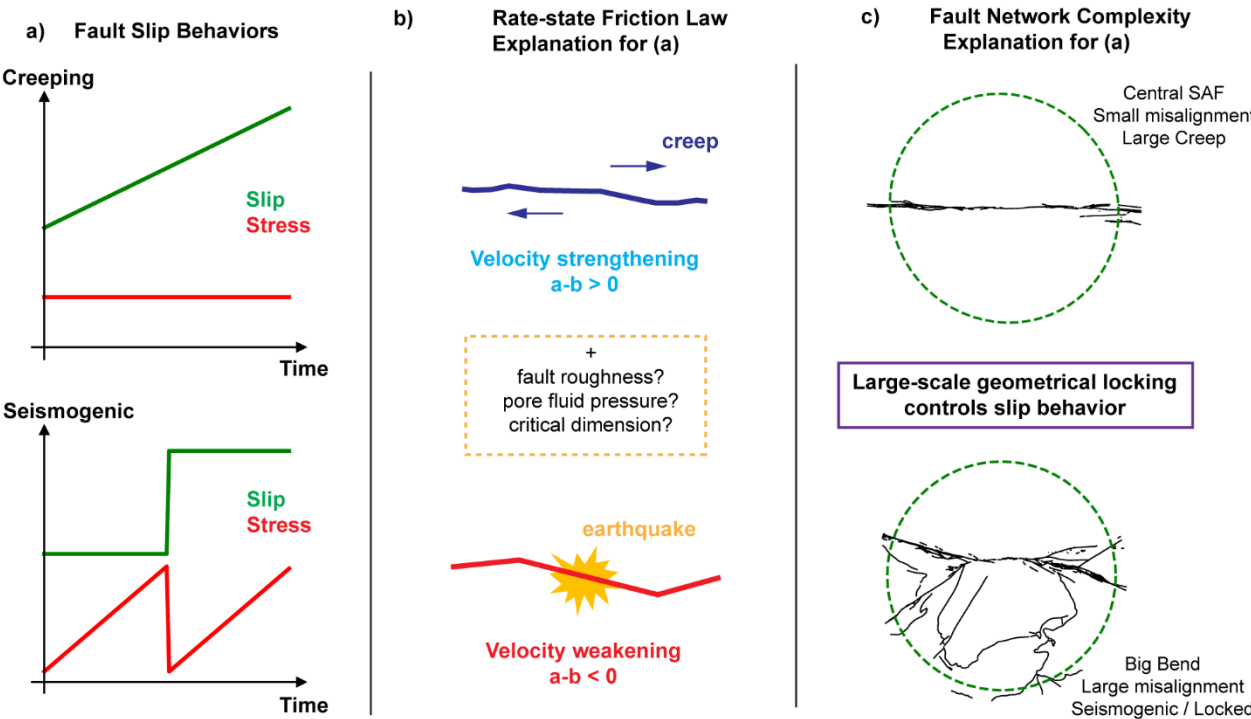
according to fault misalignments binned in five quantile bins. Black bars indicate 1st and 3rd quartile bounds, and the yellow circles indicate median values within each bin, with yellow error bars indicating 95% confidence intervals. In a, 60 data points are categorized as creeping and 148 data points are categorized as locked. Violin plots exclude 2.5% outliers at both ends, showing 95% of the distributions, and horizontal ticks indicate data points.

When examining the distribution of surface creep rates grouped into five quantiles bins of increasing fault misalignment, we find that large surface creep rates are observed almost exclusively in regions of small misalignment ratio (Fig. 2b). For example, in the lowest quantile bin of fault misalignment, 40% of the associated creep rates surpass 5 mm/year, while only 12% of the data exceed the same threshold in the remaining bins on average. This implies that fault creep is considerably more probable along fault sections where the misalignment ratio is below 0.15. However, not all simple faults exhibit creep - there are data points where a low surface creep rate (or locking) is measured at low misalignments, suggesting that other physics beyond geometry plays a competing role. While locked fault sections are present in all five quantile bins, the percentage of locked faults in each bin relative to the total number of locked faults increases with fault misalignment. In ascending order of misalignment, 12.2%, 18.2%, 18.2%, 24.3%, and 27.0% of creep rates lower than 3 mm/year are found in each bin. This observation indicates that locked faults are more prevalent in regions with more misaligned fault networks. Furthermore, the negative correlations remain consistent when applying the same analysis to normalized creep rates (see Extended Data Fig. 1b) or when grouping the data by fault systems (see Extended Data Fig. 3).

Implications for Fault Slip Behavior

We have introduced and demonstrated a potential relationship between fault network complexity and surface creep rates, an idea that has not been explored previously. Fault network misalignment does not account for all of the observed variability in creep rates. However, robust correlations between fault creep behavior and properties such as heat flow, gouge mineralogy and pore-fluid pressure are hard to assess owing to the difficulty in resolving the local fault-scale properties at depth. Our findings indicate that the accommodation of regional stress loading in large-scale geometrical incompatibilities may be a primary controlling factor on the seismogenic nature of faults. Furthermore, our work suggests that unstable slip behavior is influenced by the response of the entire fault system, not solely by the properties of a planar slip surface. The mechanisms governing the rupture process in complex fault networks may be entirely different from simple frictional sliding or frictional resistance caused by on-fault asperities. Unlike micro-scale asperities or fault roughness, which can be overcome through elastic/plastic deformation, larger fault network complexities are features that are difficult to overcome through either mechanism³⁸. Our analyses intimate that fault network complexities function as geometric incompatibilities that significantly suppress steady fault motion as ‘geometric asperities’. The instability of complex geometries may arise because the rupturing of geometrically locked surfaces involves inherently unstable physical processes like the elastic unmating of surfaces¹⁷ or fracture³⁹, whereas surficial frictional processes are more stable⁴⁰. Within such a framework, we suggest that locked faults are found more frequently in fault systems with complex geometry, while faults with simpler geometries are more prone to steady creep. It is difficult to determine the precise control of fault geometry on the fault slip behavior, but we anticipate an intermediate behavior between stable sliding and stick-slip behavior in real fault networks with intersecting fault strands of

147 varying sizes, and this may be a reason for some of the uncertainty in the observed correlations at
 148 the scale of our reported observations. The frictional behavior of fault networks may demonstrate
 149 a wide range of behaviors primarily controlled by the fault network geometry, but also influenced
 150 by local properties of individual fault segments. Depending on the interaction of geometric
 151 complexities and frictional properties of fault segments, faults may: (a) rupture together as a large
 152 complex system^{41,42}, (b) undergo significant regional deformation⁴³, or (c) simply creep under the
 153 background stress loading⁴⁴. It is also possible that creeping aligned fault regions become
 154 seismogenic and undergo rapid slip when nearby complex junctions yield.



156 **Figure 3.** Schematic illustrations of explanations of seismogenic behavior. **a**, Two distinct fault slip
 157 behaviors, creeping and seismogenic. **b**, The standard rate-and-state friction framework
 158 explanation. **c**, Our explanation of how we propose fault geometry controls fault creep.

Our hypothesis suggesting that the large-scale frictional behavior of faults is influenced by the complex geometry of fault networks could illuminate the interaction between friction and fault system geometry that has been overlooked in traditional perspectives based on microscopic laboratory-derived rate-and-state frictional parameters. It has been the general understanding that either geometric or material complexities controlling slip behavior are limited to localized properties, and dynamic earthquake simulations have aimed to reproduce fault slip characteristics mostly within this framework⁴⁵. Smooth and stable sliding of creeping faults has been modeled to result from velocity-strengthening friction behavior coupled with factors such as fault roughness, rheological properties, pore-fluid pressure, and critical slip distance. Earthquakes, on the other hand, have been thought to occur due to the instability of friction on faults with velocity-weakening behavior. Our study introduces a new perspective on earthquake behavior, highlighting the significance of slip resistance caused by geometric incompatibilities rather than variations in laboratory-measured frictional properties (Fig. 3). Our findings suggest that the characterization of stick-slip frictional behavior may be better achieved through measurements of fault geometry together with yielding material properties rather than relying solely on smooth-fault friction experiments, indicating potential future directions for earthquake rupture modeling.

While we have primarily concentrated on understanding how fault complexity controls fault stability, the two can influence each other in a complex way. For example, dilatation can be observed in the transition zones from creeping to locked, which can generate new local fractures and increase both the density and misalignment of faults⁴⁶. In addition, when earthquakes are hosted in locked regions with significant complexity, breakthrough of faults may be required to overcome the geometric incompatibilities. Thus, some complex regions may become even more complex, at odds with the traditional view that fault systems only get simpler as they mature.

Moreover, the presence or removal of significant geometric features may promote a transition from seismogenic to creeping behavior, and vice versa. As an example, the removal of a geometric complexity initially triggering a mainshock could explain post-seismic fault creep, and initiation of changes in long-term creep behavior may require the re-organization of fault system geometry over geologic time. This implies that seismogenic and creeping behavior may coexist on a single fault segment due to geometric and stressing constraints. This study does not delve into the origins of fault complexity, but it is likely that such complexity is influenced by fracture and yielding properties, as well as the maturity of the fault.

Determining whether slip behavior is primarily governed by rate-and-state type frictional laws or the geometric complexities of fault networks poses a challenging question. The impact of fault geometry continues to be a subject of debate, as various studies have produced conflicting conclusions. Our findings contradict the previous understanding that creep occurs along faults with high roughness, heterogeneous structure and certain compositions³. Although creep in subduction zones has been observed to be more prevalent in rough seafloor relief³⁸, oceanic transform faults that typically exhibit simpler structures accommodate significant aseismic slip^{47,48}. The possibility of effectively modeling the frictional effects of complex fault network geometry within a rate-and-state friction framework can be considered as well. For instance, dynamic simulations have demonstrated that simple geometric complexities, such as overlapping faults, can reproduce slow slip events without the need for complex frictional characteristics on the fault⁹. However, discrepancies in experimental findings regarding frictional behavior at tectonic rates persist, even for well-known minerals like clay⁴⁹, which introduces further uncertainty into the application of rate-and-state friction at geologic conditions, and it remains unclear how a rate-and-state framework would predict our observations. Consensus remains elusive, and it is crucial to gather

more real-world observational evidence to gain a deeper understanding of the complex relationship between fault network geometry, fault friction, and fault slip behavior.

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METHODS

Surface Creep Estimates

We use the compiled surface creep measurements in California³³ to estimate creep rates at regular intervals along major fault segments. We resample surface creep rates from the raw data at 10-kilometer intervals along all of the fault zones (resulting in 208 creep data points) in order to mitigate potential spatial sampling biases, given the concentrated measurements in regions with significant surface creep rates (see Extended Data Fig. 4). Most of the observed fault sections demonstrate right-lateral creep, with a few exceptions along the Bartlett Springs, Maacama, and North Coast San Andreas Fault faults. Based on the absolute values of the estimated creep rates,

we categorize them into two distinct groups: those larger than 3 mm/year, referred to as "creeping", and those smaller, referred to as "locked". To check whether our results are sensitive to the precise value of this creep categorization cutoff, we test other values of the cutoff from 1 to 5 mm/yr and find that our results are insensitive to such differences in cutoff choice (see Extended Data Fig. 5a). We define normalized creep rates by dividing observed surface creep rates by the cumulative seismic moment for all earthquakes with magnitudes larger than 1 within a 15-km radius area during 1980-2022.

Fault Misalignment and Fault Density

For each point with a creep rate estimate, we calculate the misalignment ratio of the fault strands within a 15-km radius circle using the surface fault traces from the USGS Quaternary Faults Database³⁴. We determine fault misalignments by calculating the ratio of the minimum and maximum length of the summed fault trace projections for every possible rotation angle¹⁵. The misalignment ratio represents the extent of misaligned faults in the area, with a value of zero indicating perfectly parallel fault strands and a value of one indicating random fault orientations. We also examine the potential correlation with fault density, defined as the sum of fault lengths within an area divided by the length of the perimeter. We assume that measurements of fault complexity using surface fault traces are adequate for shallow depths, where surface creep is commonly observed and attributed to fault properties, but note that there may be uncertainties introduced related to this assumption. Geodetic studies have suggested that surface creep rates can extend to depths ranging from 5 to 15 km, depending on the specific creeping fault system^{50,51}.

While our measurements of fault network complexity encompass both fault density and fault misalignment, we concentrate our study on fault misalignment and not on fault density primarily because fault density displayed minimal to no correlation with surface creep rates (see Extended Data Fig. 1c). This lack of correlation with fault density may be attributable to the poorer scaling properties of fault density compared to fault misalignment. While fault misalignment remains independent of fault map resolution for a fractal fault geometry, fault density increases with higher-resolution fault maps¹⁵. Therefore, our measurements of fault misalignment made at the kilometer scale are more likely to remain valid at smaller, relevant scales (see Extended Data Fig. 5b) whereas areas with high fault density may be inaccurately measured as having low fault density due to the limitations of fault map resolution. This inconsistency may account for the little or no correlation observed between fault density and fault creep.

The North Anatolian Fault and the Chaman Fault

To demonstrate that the correlation between surface creep rates and fault misalignment is not only limited to faults in California, but may be a common behavior for other creeping faults globally, we examine two additional, well-documented faults: the North Anatolian Fault and the Chaman Fault. The Ismetpasa and Izmit segments of the North Anatolian Fault are known to be slipping aseismically, with surface creep rates of up to 1 cm/yr, while the Bolu-Gerede segment is identified as being locked⁵². Using surface creep rates derived from InSAR measurements^{53,54}, we estimate the surface creep rates at sampled locations along different segments of the North Anatolian Fault. Sampling was conducted at intervals of 0.4° in longitude, focusing only on faults known to be locked or where surface creep rate measurements are available. Surface creep rates were prescribed as 0 mm/yr at segments known to be locked. The fault misalignments at these

sampled locations were calculated within 18-km radius circles, using active faults with confidence levels of ‘A’ and ‘B’ from the Active Faults of Eurasia Database⁵⁵.

For the Chaman fault, several segments including the Nushki segment, are known to exhibit creeping behavior, with surface slip rates ranging from 5 to 10 mm/yr⁵⁶⁻⁵⁸. We use the Map of Quaternary faults in Afghanistan⁵⁹ to calculate fault misalignment within 18-km radius circles. Only the fault section between 29° and 32° N was considered, due to large uncertainties regarding the creeping or locking behavior of the northern segments. The choice of 18-km radius circles was somewhat arbitrary to capture significant fault complexities around the sample points. In the analysis of both faults, surface creep rates derived from InSAR data were smoothed by computing a 40-km average for each sample point to reduce noise. For the Chaman fault, reliable measurements with uncertainties smaller than the mean uncertainty of 1.7 mm/yr were used for average creep rate estimation⁵⁶. We note that variations in the sampling distance or in the radius size did not significantly affect the observed trend.

DATA AND CODE AVAILABILITY

The surface creep data used in this study is available from Johnson et al. (2022) (<https://www.usgs.gov/data/creep-rate-models-california-faults-2023-us-national-seismic-hazard-model>). The surface fault traces are from the USGS Quaternary Fault Database (<https://www.usgs.gov/programs/earthquake-hazards/faults>). The earthquake catalog data can be downloaded from NCEDC and SCEDC. Codes used in this research⁶³ are available on Zenodo at <https://doi.org/10.5281/zenodo.10982013>.

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Contributions

VCT conceived and designed the study, JL led the investigation, including data analysis, visualization, and interpretation. DTT and AC contributed to the statistical analysis and interpretation of fault complexity and creep rate data. GH helped with the interpretation of results in the framework of rock mechanics and frictional theory. JL took the lead in drafting the manuscript. All authors provided input on the analysis, reviewed the results, contributed to editing the manuscript and approved the final version of the manuscript. VCT, DTT and GH secured funding to support the project.

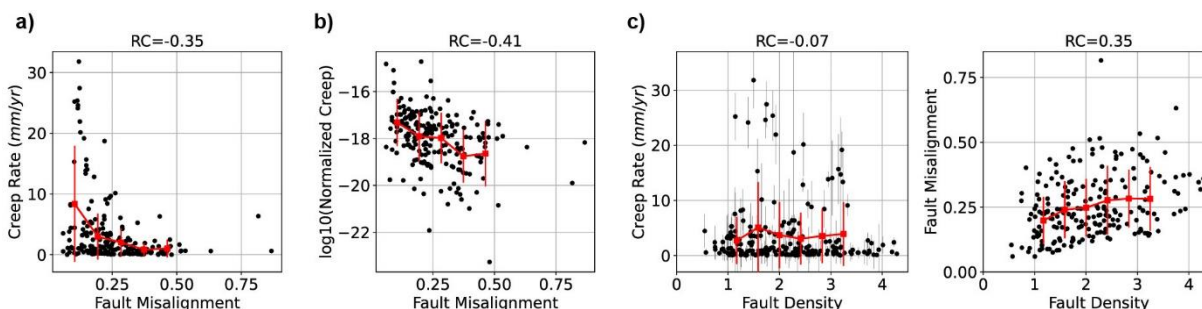
AUTHOR STATEMENT

The authors declare no financial or non-financial competing interests. Correspondence and requests for materials should be addressed to Victor C. Tsai at <victor_tsai@brown.edu>.

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EXTENDED DATA FIGURES



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476 **Extended Data Figure 1. Scatter plots for fault misalignment and fault density. a,**

477 Scatter plot of surface creep rate versus fault misalignment. **b,** Scatter plot of surface creep rate

478 normalized by accumulated seismic moment versus fault misalignment. The negative correlation

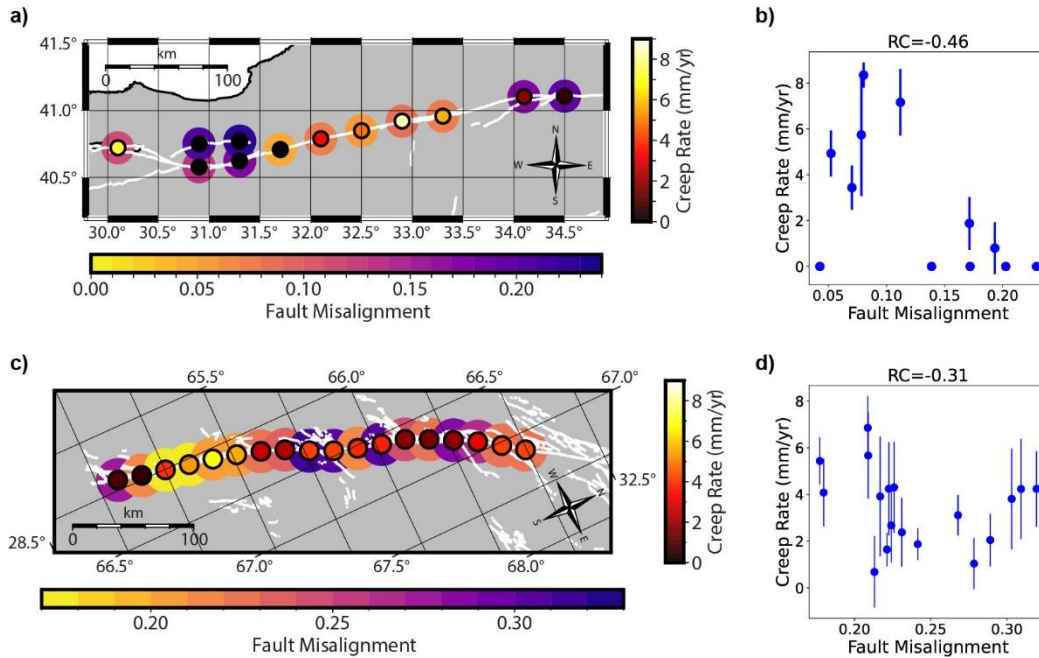
479 between fault misalignment and normalized creep remains consistent. **c,** Scatter plot of surface

480 creep rate and fault misalignment versus fault density. Fault density correlates with fault

481 misalignment, but does not show any correlation with creep rates. **a, b, c,** Spearman's rank

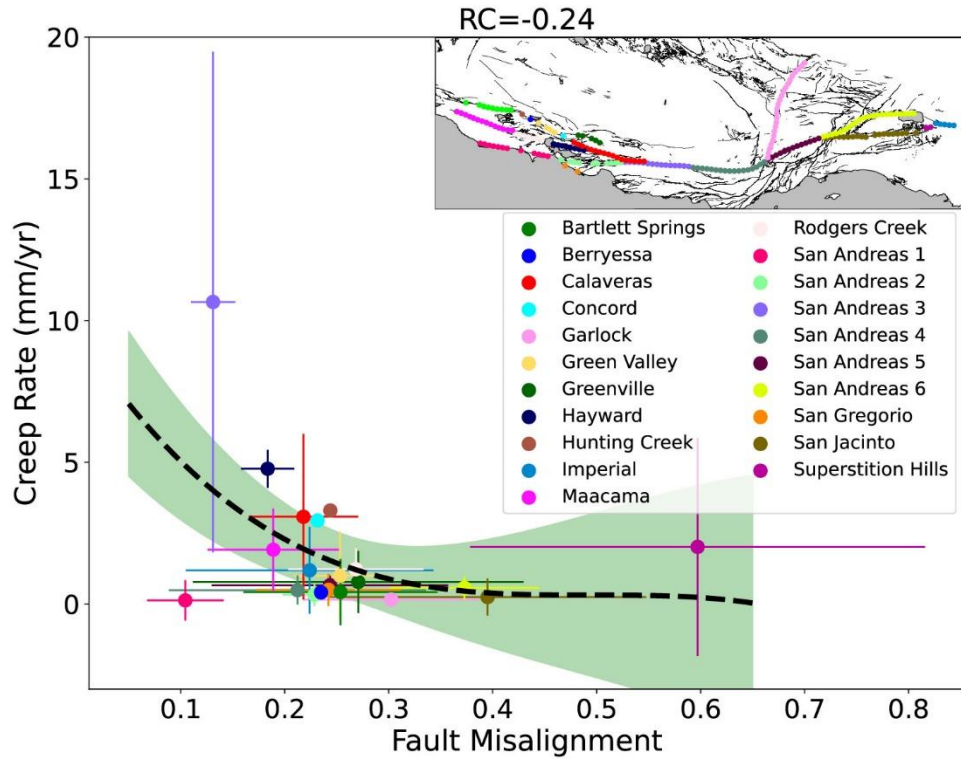
482 correlation (RC) coefficients between the variables are in the subplot titles, and the red error bar

483 plots indicate the means and standard deviations for the binned intervals.

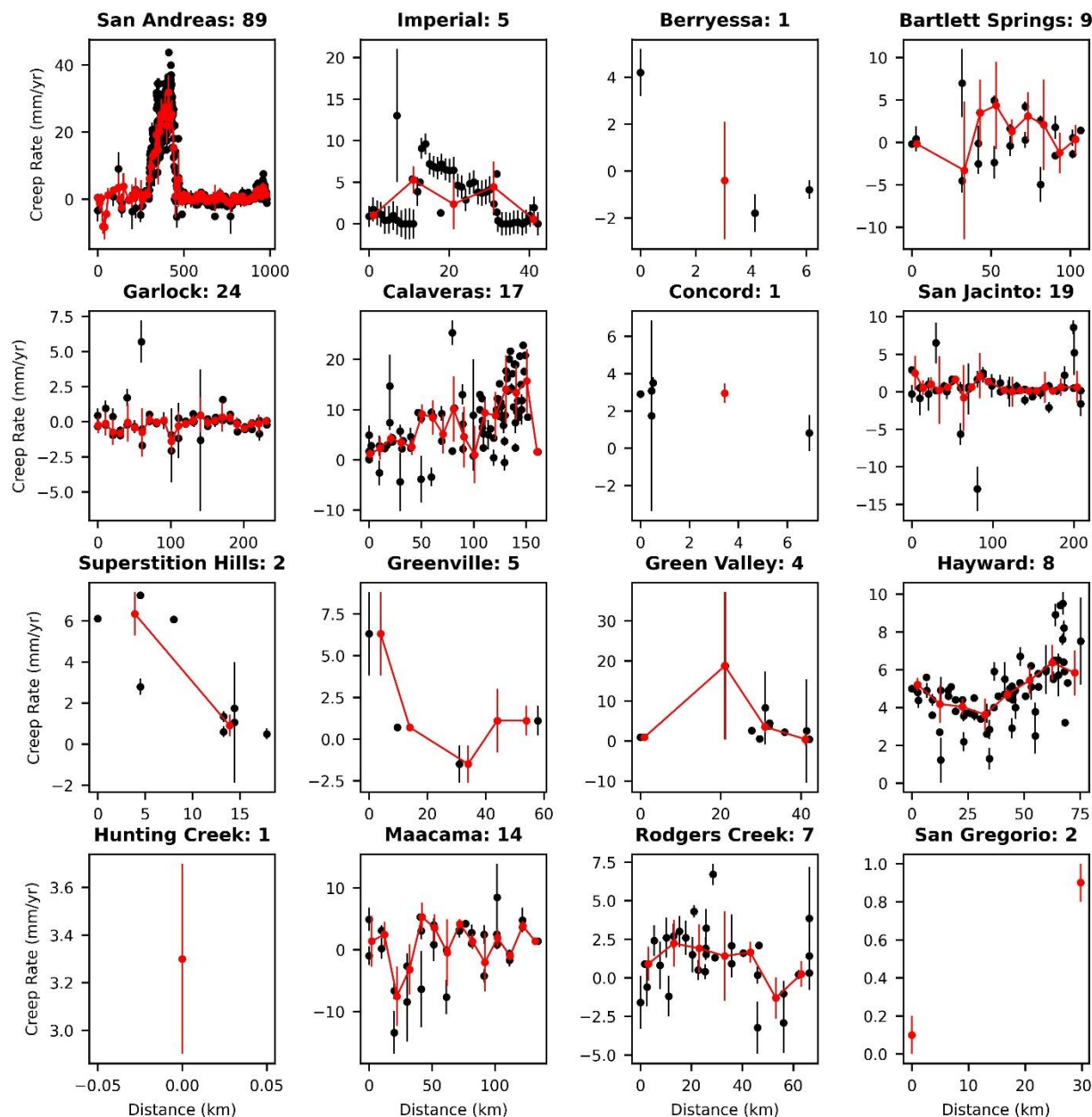


Extended Data Figure 2. Fault misalignment and creep outside California. a, Fault

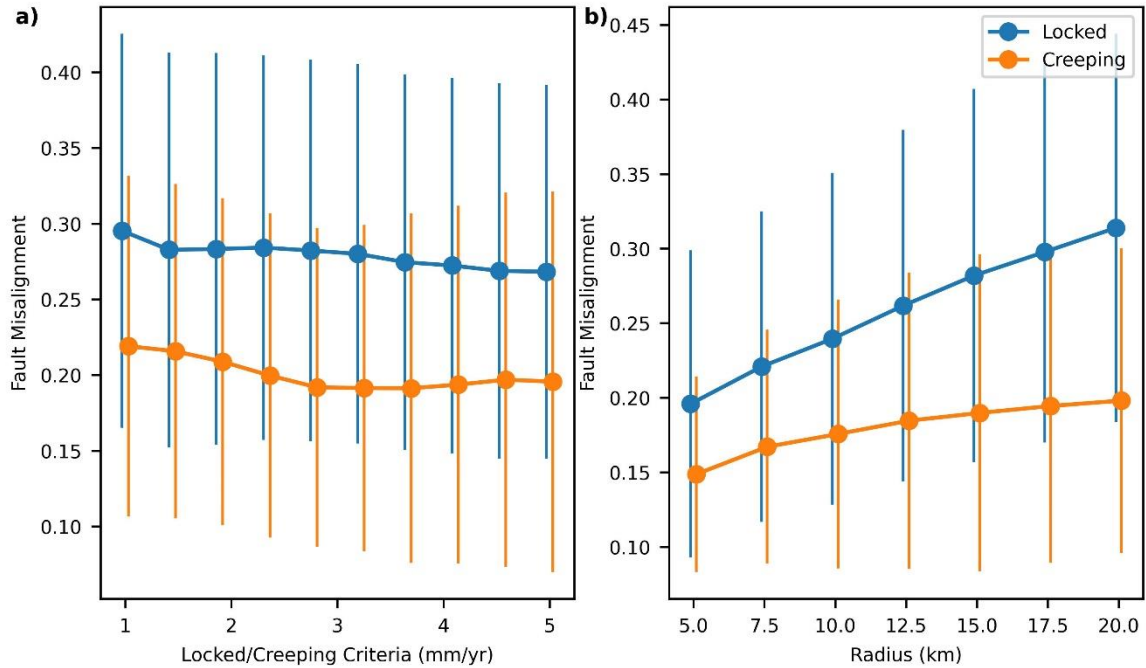
misalignment and fault creep rate along the North Anatolian Fault. Inner circles indicate surface creep rates⁵²⁻⁵⁴ and outer circles indicate measured fault misalignments. Surface fault traces are colored in white⁵⁵. **b,** Scatter plot of fault misalignment and surface creep rates along the North Anatolian Fault. Spearman's rank correlation (RC) coefficient between the two is indicated in the subplot title. **c,** Fault misalignment and fault creep rate along the Chaman Fault. Inner circles indicate surface creep rates⁵⁶ and outer circles indicate measured fault misalignments. Surface fault traces are colored in white⁵⁹. **d,** Scatter plot of fault misalignment and surface creep rates along the Chaman Fault. Spearman's rank correlation (RC) coefficient between the two is indicated in the subplot title.



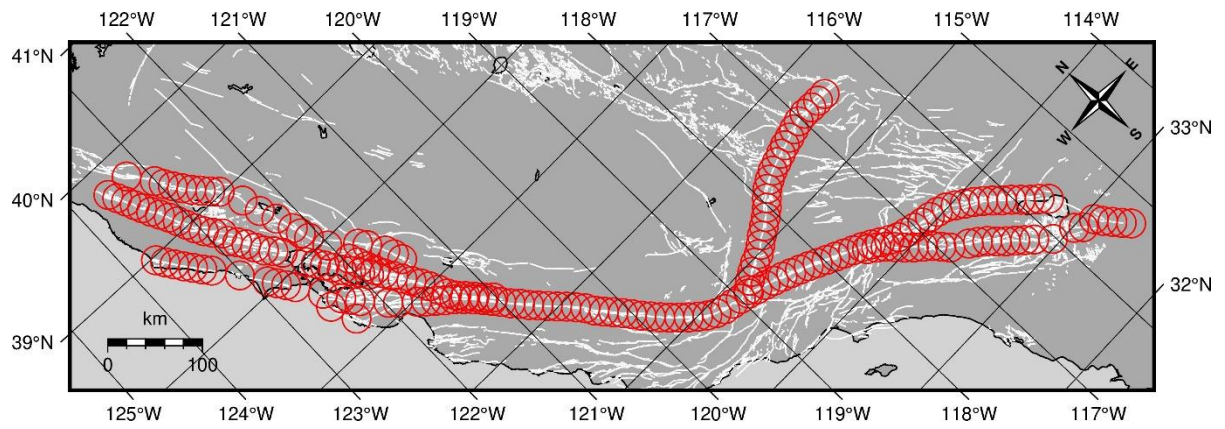
Extended Data Figure 3. Average surface creep rates and fault misalignment for different fault segments in California. Spearman's rank correlation (RC) coefficient between the two is indicated in the subplot title, and the black dashed line indicates a monotonic cubic polynomial of best fit⁶⁰. The green shaded area is a 95% confidence interval around the best fit. The inset map in the upper right corner depicts the fault segments using the same colors as in the main plot.



Extended Data Figure 4. Creep rate sampling. Comparison of surface creep rates sampled at 10 km intervals along faults in California (red) with the compiled measurements from ref. 33 (black). The number of estimates for each fault are indicated in the subplot titles. Estimates and errors at the sampled locations are calculated as the weighted average of measurements within 10 km.



Extended Data Figure 5. Tests of robustness. a, Variation in the mean and standard deviation of fault misalignment for locked and creeping faults for different creep cutoff thresholds. **b,** Changes in the mean and standard deviation of fault misalignment for locked and creeping faults (threshold: 3 mm/year), considering various radius circles for measuring fault network misalignment. The distinct distribution of fault misalignment between locked and creeping faults remains consistent, regardless of the chosen cutoff threshold or radius circle used to measure fault complexity. As the radius increases, the fault misalignment in creeping faults with simple geometries remains relatively constant. In contrast, for locked faults with complex geometries, fault misalignment increases due to the violation of the fractality assumption at smaller scales, attributed to limited resolution.



Extended Data Figure 6. Fault metric regions. Fault metrics are computed within the red circles.