

The impact of mapper experience and data on the quality of geomorphic fault mapping

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Abstract Mapping of potentially active faults is critical to characterizing earthquake processes and surface rupture hazard. Geologists map tectonic faults from remote sensing datasets by interpreting tectonic landforms formed during past earthquakes. However, evidence for faulting is often ambiguous, incomplete, and challenging to interpret. Conventional wisdom suggests that mapping skill improves with experience. In contrast, prior work has shown that experienced geologists can still miss faults and disagree on fault location. To test whether, when, and to what extent mapping improves with experience, we designed a repeat mapping experiment involving 23 participants, ranging from undergraduate students to senior professionals. Each participant created regional-scale fault maps using pre-earthquake remote sensing data and a systematic, geomorphology-based approach. While professionals slightly outperformed students, some graduate students produced similar quality maps, and all participants missed identifying tectonic landforms indicative of future ruptures. Using participant mapped fault data, we quantify inter-mapper epistemic uncertainty in fault location to be between 55 and 117 m. Our work gives insight into approaches to improve fault mapping and suggests that experience beyond a graduate student level does not significantly improve mapping results.

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Non-technical summary Mapping active faults is essential to understanding how earthquakes work and identifying where surface rupture may occur. Geologists commonly map faults by analyzing satellite imagery and topographic data to identify landforms created by past earthquakes. However, the evidence can be difficult to recognize, incomplete, or open to different interpretations. It is often assumed that fault mapping improves with experience, but previous studies have shown that even experienced geologists can miss faults or disagree about their locations. To test how fault mapping changes with experience, we conducted a study with 23 participants, including undergraduate students, graduate students, and professional geologists. Each participant created fault maps using satellite and topographic data collected before several earthquakes. We then compared their maps to the ruptures that occurred during those earthquakes. Professional geologists performed slightly better than students overall, but some graduate students produced maps of similar quality. All participants failed to identify some of the ruptures. We calculated fault mapping uncertainty from differences in knowledge. Our study helps identify ways to improve how faults are mapped and shows that having more experience than a graduate student does not lead to much better results.

1 Introduction

Characterizing active faults is important for evaluating surface rupture hazard (e.g., Baize et al., 2020; Chen and Petersen, 2019; International Atomic Energy Agency, 2021; Nurminen et al., 2022; Petersen et al., 2011; Valentini et al., 2025; Youngs et al., 2003) and earthquake rupture processes (e.g., Johnson et al., 1997; Reitman et al., 2019; Scholz, 2019). Geologists commonly map active faults from tectonic landforms formed from repeated earthquakes and modified by surface processes (e.g., Burbank and Anderson, 2011; McCalpin, 2009b; Yeats et al., 1997). However, this fault evidence is often complicated to observe or interpret. The interpretability of tectonic features depends on the size and frequency of past surface-rupturing earthquakes and the vigor of the subsequent surface processes (Arrowsmith and Rhodes, 1994; Hanks et al., 1984; Reitman et al., 2024; Wallace, 1990; Zuckerman et al., 2026b). Geomorphic fault mapping is inherently interpretive, requiring geomorphic observation and benefiting from structural geology training to identify and map tectonic landforms. Differences in experience, education, and familiarity with fault processes can lead to variability in fault mapping interpretations among mappers (Bond et al., 2007, 2011; Caulkins, 2010; Petersen et al., 2011; Salisbury et al., 2015; Scott et al., 2023).

Uncertainty in predicting the location of future surface ruptures arises from two sources: aleatory variability and epistemic uncertainty. Aleatory variability is the inherent randomness of natural rupture processes and includes phenomena such as the rupturing of new fault traces or the absence of surface rupture along older fault traces. Epistemic uncertainty is the error in mapped fault location due to mapper bias, incomplete knowledge, and other limitations on interpretive ability, which varies based on mappers, data quality, and tectonic landform clarity. Untangling these two sources of uncertainty is a central challenge in geomorphic fault mapping and probabilistic fault displacement hazard analysis.

Uncertainty in mapped fault locations has long been recognized as a limitation in both tectonic geomorphology and fault hazard studies. Petersen et al. (2011) measured mapped fault location error to be 18–45 m based on seven southern California earthquakes and the subsequent ruptures. For the 2019 Ridgecrest earthquake sequence, Thompson Jobe et al. (2020) found that only 50–70% of the ruptures were evident in pre-event remote sensing data and field verification and that not all late Quaternary faults ruptured in 2019. Ferrario et al. (2025), referencing five earthquakes in Italy and the United States, found that faults in geological maps capture $32 \pm 30\%$ of subsequent coseismic ruptures. Young et al. (2024) found that mappers using post-earthquake remote sensing data produced rupture maps that differed by 10–20% due to interpretive differences in geomorphic expression. Additionally, map accuracy is impacted by topographic landform sharpness and improves with field verification and collaboration (see also Scott et al., 2023). These studies highlight the need to

quantify and understand the sources of uncertainty and nuance in fault mapping (e.g., Tikoff et al., 2023). Past work shows that prior knowledge and biases can influence mapping outcomes (Bond et al., 2007, 2011) and that experience sometimes improves the reproducibility of fault trace mapping and interpretation (Salisbury et al., 2015).

Our work builds directly on two studies that compared pre-earthquake mapped fault traces with coseismic ruptures, and addressed how standardized mapping approaches can improve fault mapping. Scott et al. (2023) quantified fault location uncertainty as the separation distance between mapped faults and coseismic rupture traces from seven M 6.0–7.8 earthquakes, finding that mapped faults predicted 12–68% of coseismic ruptures and a median separation distance of 15–30 m for high-confidence faults. The authors showed examples of errors made by novice mappers and expert disagreement for fault location near tectonic landforms. Adam et al. (2025) advanced the standardized mapping approach introduced in Scott et al. (2023) and examined how well the approach serves as a method for consistent documentation in fault mapping.

This study quantitatively evaluates how the level of experience affects fault map accuracy and offers insights into how training, experience, and a standardized mapping approach impact fault mapping outcomes and epistemic uncertainty. Quantifying epistemic uncertainty improves hazard models by capturing interpretation-based variability in fault location. We assessed and compared maps created by 23 mappers, ranging from senior undergraduate students to senior professional geologists, who all applied the same standardized, structured mapping approach. Participants mapped on topography data and imagery collected before four earthquakes (pre-rupture mapping). To assess fault map accuracy, we compared the mapped faults to coseismic ruptures with a focus on fault traces near tectonic landforms. We define accuracy as how closely the mapped faults follow the subsequent coseismic rupture traces, aligning with the goals of rupture location prediction for fault displacement hazard assessment, where pre-rupture fault maps are used to characterize the location and uncertainty of future surface ruptures for critical infrastructure protection. We note that other studies define accuracy differently. Mapping fault traces remains challenging regardless of expertise. With the repeat fault mapping around tectonic landforms data, we quantified epistemic uncertainty. High-resolution topographic data significantly improved mapping accuracy, while the addition of a geologic map offered limited benefit. These results highlight that experience does not consistently improve mapping accuracy, especially in areas with ambiguous geomorphology.

2 Data and Methods

2.1 Data and methods summary

We ran three experiments (Figure 1; Section 2.3; Tables S2–S4) to collect fault trace mapping data from partic-

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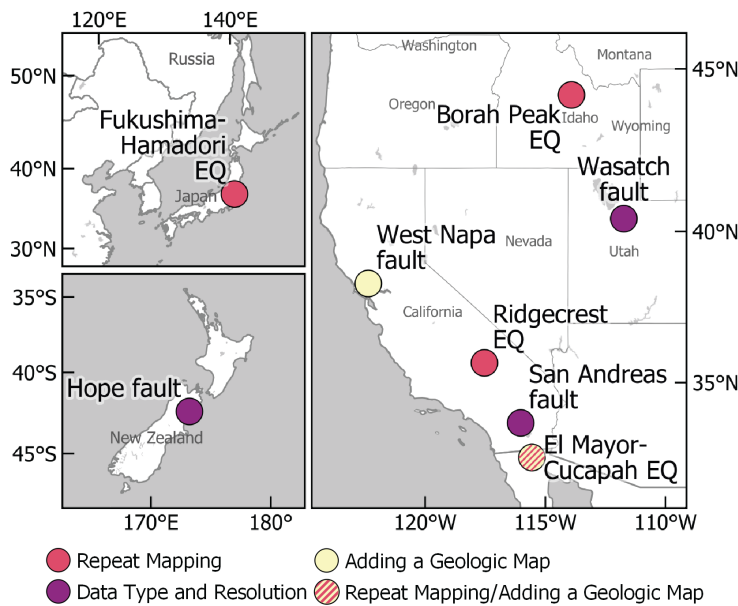


Figure 1 Locations of mapping areas. Markers colored by the four project types within our analysis. Locations with “EQ” (earthquake) indicate pre-rupture mapping areas. More information is available in Tables S2–4.

ipants in a mapping course and from professional geologists (Section 2.2; published by Adam et al., 2025). Participants used a systematized desktop mapping approach (no field work; Section 2.5; Adam et al., 2025; Scott et al., 2023) to complete the mapping projects focused on repeat mapping and the impact of provided data type, resolution, and a geologic map (Figure 1; Section 2.5). Our study focused mainly on the participant mapping data from the Repeat Mapping Project and the role of experience (Sections 2.3.1 & 2.5). We examined how data type (topography, imagery, increasing resolutions) and the use of a geologic map impact mapping accuracy (Sections 2.3.2 & 2.3.3). Participant fault map shapefiles are in the supplemental data.

2.2 Fault mapping course

In Spring 2022, Scott and Arrowsmith (Arizona State University) and Koehler (University of Nevada, Reno) conducted a virtual class comprising participants from Arizona State University (ASU), McGill University, Oxford University, the University of California, Davis, and the University of Nevada, Reno. Industry professionals taught portions of the course. The class included four senior undergraduate students, 11 graduate students in master’s and PhD programs, and two postdoctoral scholars. Class participants were geoscience students or recent graduates (e.g., postdocs) and had structural geology and geomorphology prerequisites.

In the fault mapping course, students learned to produce regional-scale fault maps. Instruction and assignments during the first month focused on faulting and tectonic geomorphology. Participants used a systematized mapping approach (Figure 2; Section 2.5; Adam et al., 2025; Scott et al., 2023) and completed three week-long assignments focused on different fault types and geographic information system skills. Participants had

four weeks to complete two main fault mapping activities: (1) the Repeat Mapping Project, which was completed by all participants, and (2) either the Data Type and Resolution Project or the Adding a Geologic Map Project (Section 2.3).

To broaden the range of mapper experience in the study, we also included six professional geologists. Three mid-career and three senior professional geologists completed only the Repeat Mapping Project using the same datasets and written instructions as the class participants (Section 2.5). In 40 hours, they familiarized themselves with QGIS and the mapping approach and completed the mapping.

2.3 Description of three projects

2.3.1 Project 1: Repeat Mapping

The goal of the Repeat Mapping Project was to quantify differences in mapped fault trace location relative to the coseismic ruptures as a function of geomorphic context and mapper experience (Sections 3.1 & 3.2). All participants mapped the same areas using the approach described in Figure 2 and Section 2.5. Borah Peak, El Mayor-Cucapah, and Fukushima-Hamadori are presented in Section 3.1, and Ridgecrest areas are presented in Section S3.2.

Each mapping area comprised a 2 km-long section of a surface-rupturing earthquake: the 1983 moment magnitude (M_w) 6.9 Borah Peak (USA), 2010 M_w 7.2 El Mayor-Cucapah (Mexico), 2011 M_w 6.6 Fukushima-Hamadori (Japan), and two sections from the 2019 M_w 6.4 Ridgecrest (USA) earthquake (Figure 1; Table S2; OpenTopography, 2019). These areas represent different climates, fault slip sense, and cumulative offset (Table S2; Peel et al., 2007), and the clarity of tectonic landforms in each area reflects a combination of these factors along with the time since the most recent surface-rupturing earthquake, ranging from as little as 118 years in El Mayor-Cucapah (Mueller and Rockwell, 1995) to 5–7 ka in both Borah Peak (DuRoss et al., 2022; Hanks and Schwartz, 1987) and Ridgecrest (Roquemore, 1981; Thompson Jobe et al., 2020; Scott et al., 2024). Each mapping area had a specific challenge. Borah Peak (semi-arid, normal-sinistral) ruptured, in some cases, oblique to the range front. El Mayor-Cucapah (desert, dextral strike-slip) has linear fluvial channels often misidentified as scarps by novice mappers (Scott et al., 2023). Fukushima-Hamadori (subtropical, normal dip-slip) has dense vegetation and terraced agricultural plots. Ridgecrest (desert, sinistral strike-slip) contains faults with subtle expression and low cumulative slip.

All mappers worked individually and without access to existing geologic maps, fault maps, or post-earthquake datasets. Generally, participants mapped areas outside of their regions of expertise. A few participants were vaguely familiar with the 2019 Ridgecrest earthquake sequence. Table S1 summarizes specific experiences and regional familiarity for each participant. Although mapping instructions did not suggest a preferred fault orientation, the rectangular shape of the mapping areas may have introduced a subtle bias, as

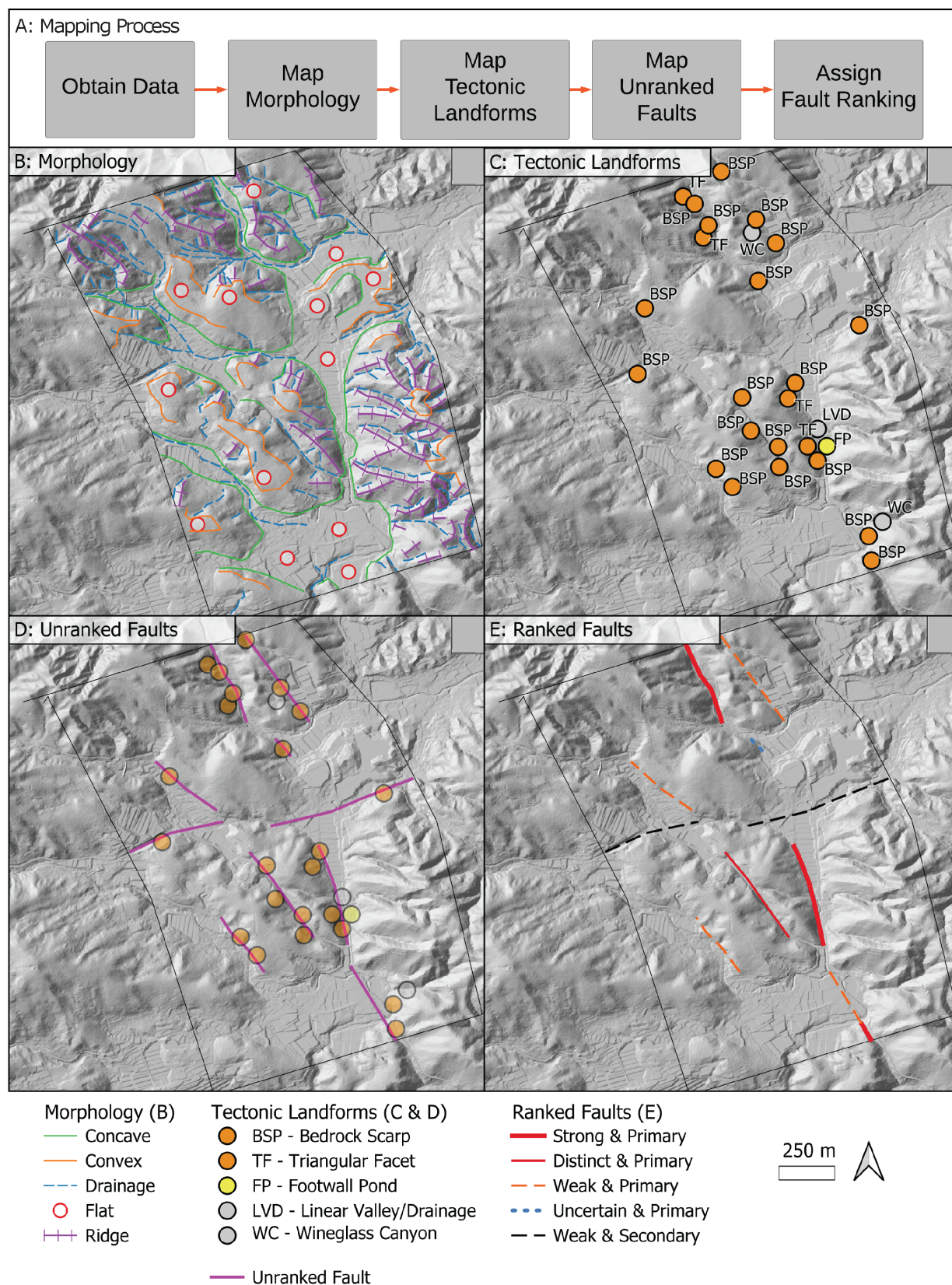


Figure 2 (A) Flow diagram outlining the mapping workflow. (B-E) One participant's mapping for Fukushima-Hamadori. B: Morphologic mapping of concavities, convexities, ridges, flat areas, and possible drainages. C: Tectonic landforms (Adam et al., 2025; Scott et al., 2023). D: Mapped fault traces. E: Faults with confidence and primary or secondary ranking. Basemap from Nissen et al. (2014). See general location in Figure 1.

participants may have expected fault traces to align with the long axis of the mapping area.

2.3.2 Project 2: Data Type and Resolution

This project assessed how data type and resolution affect fault mapping accuracy. Datasets used in this study included NASA's 30 m/pixel Shuttle Radar Topography Mission (SRTM; [Farr and Kobrick, 2000](#)), 1 m/pixel aerial or satellite imagery ([Earth Resources Observation and Science \(EROS\) Center, 2017](#)), and high-resolution airborne lidar- and/or Structure-from-Motion-derived topography datasets (1 m/pixel or less). Two participants mapped each location, including portions of the Southern San Andreas fault (Section 3.3 [Bunds et al., 2021](#)), Wasatch fault near Salt Lake City, Utah (Section S3.2 [Benson et al., 1990](#); [Machette et al., 1991](#); [OpenTopography, 2014](#)), and Hope fault in New Zealand (Section S3.2 [Manighetti et al., 2015](#); [OpenTopography, 2016](#)). Participants created successive fault maps using these data sets in the order listed above and in Table S3, strictly finishing (and submitting) one before moving to the next.

2.3.3 Project 3: Adding a Geologic Map

To assess the utility of an existing geologic map, mappers created pre-rupture fault maps first using high-resolution topography and satellite imagery only (Figure 2; Section 2.5) and then revised their map based on a provided geologic map produced before the earthquake of focus (Table S4). We focused on two locations: (1) A portion of the 2010 El Mayor-Cucapah earthquake rupture that also ruptured in the 1892 M7 earthquake, and for which a 1,10:000-scale geologic map was available, and (2) a portion of the 2014 South Napa earthquake rupture selected for its relatively dense vegetation and anthropogenic development and the availability of a 1:100,000 scale geologic map (presented in Section S3.3 [Graymer et al., 2007](#); [OpenTopography, 2010](#)).

2.4 Fault mapping approach overview and example

The regional-scale desktop mapping approach provides a systematic workflow for mapping faults based on tectonic landforms (Figure 2; [Adam et al., 2025](#); [Scott et al., 2023](#)). The mapper (1) obtains data and prepares the base maps, including topographic derivatives and imagery, (2) conducts preliminary morphologic mapping, (3) maps tectonic landforms that show or conceal fault deformation (e.g., [Adam et al., 2025](#); [Burbank and Anderson, 2011](#); [Scott et al., 2023](#)), (4) maps lineaments interpreted as fault traces, and (5) ranks faults based on degree of confidence in their tectonic origin. This approach is intended to be followed in order, but steps can be skipped or repeated (see discussion in Section 4.4.2).

Figure 2 presents the mapping workflow: A participant mapped the morphology from a topographic hillshade for Fukushima-Hamadori, highlighting vegetation and anthropogenic alteration. The participant mapped what they interpreted as tectonic landforms, such as triangular facets and bedrock fault scarps, as points of reference to guide the fault trace mapping.

The participant assigned each mapped fault a confidence ranking and characterized the fault as either primary or secondary based on indicator ranking and geologic context. Primary faults host the main coseismic slip, while secondary faults have discontinuous splay or shear geometry, and appear to host less or no slip ([Sarmiento et al., 2021](#)). When referring to principal and distributed ruptures, we apply the same distinction.

2.5 Data analysis: Assessing rupture prediction from repeat fault mapping

With the Repeat Mapping Project maps, we evaluated the location variability of mapped pre-rupture fault traces relative to published coseismic rupture traces (mapped in the field following each earthquake, with additional remote sensing data used for the El Mayor-Cucapah, Fukushima-Hamadori, and Ridgecrest ruptures; [Crone et al. 1987](#); [Teran et al. 2015](#); [Mizoguchi et al. 2012](#); [DuRoss et al. 2020](#); [Ponti et al. 2020](#)) using two metrics: For each participant, we calculated the percentage of (1) coseismic ruptures predicted by the pre-rupture fault maps and (2) pre-rupture faults mapped by participants that later ruptured (Figure 3; cf. [Ferrario et al., 2025](#)). A mapped fault or rupture also had to have a local trend within 15° of the corresponding fault or rupture, ensuring that we accounted for both intentional and geologically reasonable mapping. Metric 1 is more important for hazard assessments as missed faults have greater consequence than overmapped ones, while Metric 2 reflects map quality. Throughout this study, we use accuracy to refer to the spatial correspondence between mapped fault traces and coseismic rupture locations (Metric 1), and quality to refer to the geological reasonableness of mapped fault traces as reflected by the proportion that later ruptured (Metric 2).

It is important to note that our definition of mapping “accuracy” is operational: we evaluate how closely pre-rupture fault traces correspond to the coseismic rupture location in the next earthquake, effectively treating that rupture as the reference against which mappers are evaluated. In cases where participants mapped plausible fault traces that did not rupture in the subsequent event, those outcomes may reflect aleatory variability in rupture strand activation rather than mapping error. Our method, therefore, evaluates predictive correspondence to one rupture realization while recognizing that not all valid fault traces will necessarily re-rupture.

These two metrics primarily capture interpretation-based, or epistemic, uncertainty in fault-trace location. However, a component of aleatory variability is also embedded in the separation distances. Consequently, the computed fault-to-rupture distances represent an upper bound on epistemic uncertainty, reflecting both mapper interpretation differences and the natural variability of rupture behavior. Because all mappers are evaluated against the same coseismic rupture for each mapping area, the aleatory component is constant across mappers within a given area. Differences in performance between mappers therefore primarily reflect epistemic variability in fault interpretation.

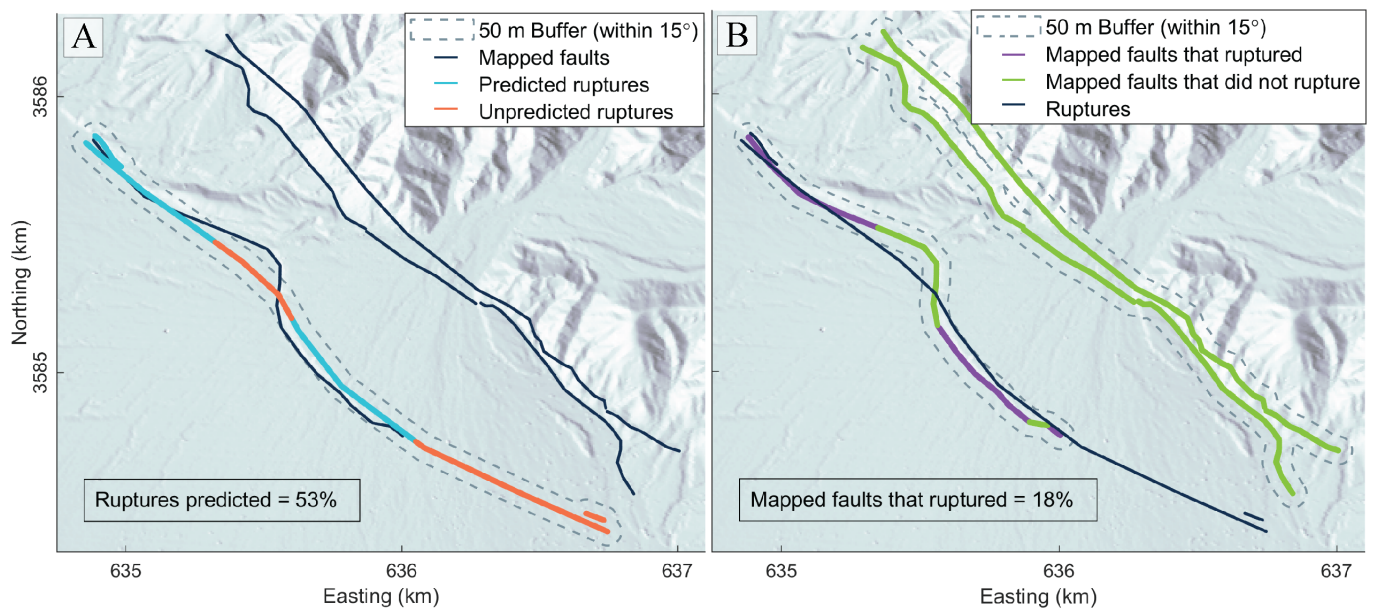


Figure 3 Assessing rupture prediction and faults ruptured using our buffer method (for one participant). (A) Metric 1: Predicted (blue) and unpredicted (orange) ruptures compared with bounding buffer (dashed gray) and mapped fault traces (navy). (B) Metric 2: Mapped faults that ruptured (purple) or did not rupture (green), and ruptures (navy).

Following Scott et al. (2023), we created buffer zones with widths of 15, 50, and 150 m surrounding mapped faults or ruptures (Figure 3; Table 1). For Metric (1), we calculated the percentage of fault length within the buffer surrounding each rupture. For Metric (2), we calculated the percentage of rupture length within the buffer around the mapped fault traces. In our results, we display percentages in uncertainty notation with the main number referencing the 50 m buffer result, and 150 m and 15 m defining the upper and lower bounds, respectively.

To inform our buffer width choice, we reviewed fault zone widths for fault zoning from literature studies (Table 1) that examined rupture location and fault width from field data (Boncio et al., 2012, 2018; Zhou et al., 2010), coseismic displacement and rock damage measurement (Shelef and Oskin, 2010), remote sensing datasets (Rodríguez Padilla et al., 2022; Rodríguez Padilla and Oskin, 2023), trenching (California Geological Survey, 2018), and rupture-to-fault separation distances (Petersen et al., 2011; Scott et al., 2023). This ensemble represents the distribution of coseismic surface deformation with respect to fault-zone width and rupture location relative to mapped fault traces. Fault zone half-widths, or the distance from a primary fault trace, range from 5–2000 m, depending on the defining criteria (Table 1).

The selected 15, 50, and 150 m buffer widths reflect fault location uncertainties and rupture proximities reported in the literature (Table 1) and are likely useful for end users with differing goals. These buffer widths are informed by observed rupture distributions and therefore include some aleatory variability, but they are used here as a practical spatial tolerance for comparing mapped fault locations. The 15 m buffer corresponds to typical regulatory setbacks for structures intended for human occupancy (e.g., California Geological Sur-

vey, 2018) and falls near the lower end of pre-rupture to rupture distances reported by Petersen et al. (2011) and Scott et al. (2023). The 50 m buffer captures the upper end of Scott et al. (2023)'s desktop mapping range and lies near the midpoint of the mean fault-to-rupture distances in Petersen et al. (2011). The 150 m buffer encompasses the full width of most primary surface rupture zones, as defined in regulatory zoning guidelines (California Geological Survey, 2018) and rupture studies (e.g., Boncio et al., 2012).

We evaluate the Repeat Mapping Project using Metrics (1) and (2) (see Figure S1 for graphical explanation of equations 1 and 2). The computation is made for each map separately and works as follows:

1. Specify buffer width (e.g., 15, 50, and 150 m; Table 1).
2. Convert the fault and rupture traces from latitude-longitude to the local Universal Transverse Mercator coordinate system (UTM) zone and resample to a 1-m spacing. The resampling ensures that each 1 m of fault trace has equal weight. UTM provides horizontal coordinates in meters and eases our Euclidean distance computations.
3. Distance calculation: For Metric 1 (described here), calculate distances from rupture traces (r) to mapped faults (f). For Metric 2, the roles of r and f are reversed.

We define rupture prediction with buffer distance and angle thresholds (equations 1 and 2). Predicted rupture vertices are within the buffer zone around the mapped pre-rupture fault vertices. For each rupture vertex, we calculate the minimum separation distance to all n fault vertices representing the rupture-to-fault separation distance,

Publication	Type	Zone half-width	Criteria
Boncio et al. 2012	N	Setback: 40 m FW, 15 m HW Fault zone: 150 m FW, 30 m HW	Asymmetric earthquake fault zone and setback distances from well-mapped surface ruptures from global $M5.6$ – 7.6 earthquakes.
Boncio et al. 2018	T	(full widths) 60 m 840 m	Fault zone width based on 11 historical $M5.4$ – 7.9 earthquakes. > 30% of ruptures expected within 60 m of a well-mapped primary fault trace. 90% of distributed ruptures are within this fault zone width.
California Geological Survey 2018	A	Setback: 15 m Fault zone: 150 m	Alquist-Priolo Zoning Act: "the area within fifty feet of such active faults shall be presumed to be underlain by active branches of that fault unless proven otherwise by an appropriate geologic investigation and report." Earthquake fault zone: Faults that are "sufficiently active and well-defined". Zone width accommodates imprecise locations and possible fault branching.
Petersen et al. 2011	S	18–90 m	Mean distance between mapped fault trace and surface rupture for all mapping accuracies and fault complexity (simple and complex).
Rodriguez Padilla et al. 2022	S	100 m	For 2019 Ridgecrest earthquakes, the fracture density decreased to 1% over 100 m.
Scott et al. 2023	A	6–50 m	Median pre-rupture fault to predicted coseismic rupture separation distance based on desktop-based fault mapping.
Shelef and Oskin 2010	S	100–200 m to 1–2 km	Most displacement is within 100–200 m of faults, with zones extending to 1–2 km from the fault.
Zhou et al. 2010	R	25 m	For the 2008 $M7.9$ Wenchuan earthquake (China), surface rupture traces were within 40–60 m of mapped faults.

Table 1 Literature review of fault zone widths. FW = footwall, HW = hanging wall. Fault types: N = normal, S = strike-slip, T = thrust, R = reverse, A = all. Where footwall and hanging wall widths are noted separately, values represent that side of the fault only.

$$d_{r,i} = \min \left[\sqrt{(x_{r,i} - x_{f,1:n})^2 + (y_{r,i} - y_{f,1:n})^2} \right] \quad (1)$$

$d_{r,i}$ equals the separation distance between the i^{th} rupture point and all n fault points, $(x_{r,i}, y_{r,i})$ is the i^{th} coseismic rupture vertex, and $(x_{f,1:n}, y_{f,1:n})$ are all n fault vertices.

Ruptures and fault trend must also be within 15° . For this calculation, we represent the fault ($\hat{f}$) and rupture ($\hat{r}$) linework as unit vectors. We take the dot product of an ($\hat{r}$) and the nearby ($\hat{f}$) and require the minimum θ to be less than 15° .

$$\theta = \cos^{-1}(\hat{r} \cdot \hat{f}) \quad (2)$$

3 Results

3.1 Assessing rupture prediction based on mapper experience level

3.1.1 1983 Mw 6.9 Borah Peak earthquake

The 1983 $M_w 6.9$ Borah Peak earthquake ruptured a 34 km-long section of the Lost River fault in Idaho (Figure 1; Crone and Machette, 1984), with a dominantly normal slip sense and 2.6 m maximum vertical displacement (Bello et al., 2021; Crone et al., 1987; DuRoss et al.,

2019, 2022; Mapel et al., 1965). The most recent surface-rupturing earthquakes along the Lost River fault prior to 1983 date to 5–7 ka (DuRoss et al., 2022; Hanks and Schwartz, 1987). The mapping area is along a step-over in the mountain foothills with principal and distributed ruptures, alluvial fan deposits, and south-to-southwest trending drainages (Figure 4). The principal rupture trace is adjacent to a bedrock and alluvium contact. The distributed trace cuts through the foothills and an alluvial fan located ~750 m WSW of the principal trace (~175 m lower in elevation). We define principal and distributed ruptures using the primary and secondary fault definitions, respectively (Sarmiento et al., 2021; Scott et al., 2023).

Unsurprisingly, participants predicted more principal ($27^{+21}_{-22}\%$; Location 1) than distributed ruptures ($5^{+13}_{-5}\%$; Location 2; Figure 4A; Table S4). Participants identified bedrock and Quaternary fault scarps along higher elevation (northeastern) slope breaks. The lower elevation tectonic landforms are less well-expressed, and many mapped fault scarps are actually stream channels. Beyond the mapping area, the trend of primary faulting is expressed well. One postdoctoral scholar, who mentioned looking at the regional scale, mapped $65^{+32}_{-48}\%$ faults that later ruptured, the highest in our mapping (Figure 4B). In Scott et al. (2023), a graduate student mapped $52^{+23}_{-30}\%$ of faults that ruptured when mapping at the regional scale using the same pre-

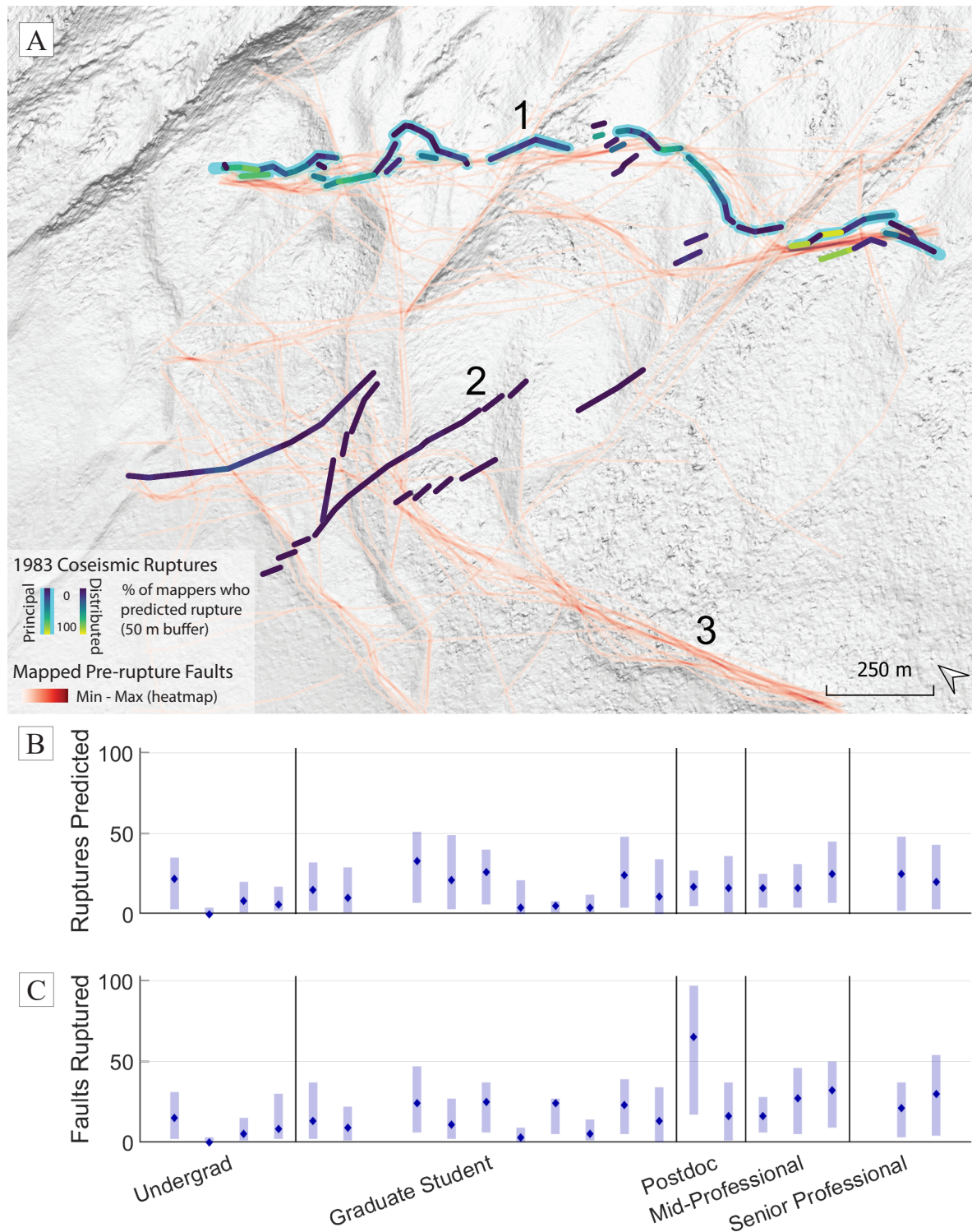


Figure 4 (A) Borah Peak, Idaho, earthquake showing mapped fault traces and coseismic ruptures. In the mapped fault heat map, red traces indicate faults mapped by more participants. 1983 coseismic principal (cyan outline) and distributed ruptures (Crone et al., 1987; Sarmiento et al., 2024) are colored by the percentage of mappers who predicted the rupture using a 50 m buffer. The basemap is a topographic hillshade from a historical pre-earthquake digital surface model (Table S1; Reitman and Briggs, 2024). (B) Percentage of ruptures and (C) percentage of faults inside the buffer zones by mapper grouped by experience level. The symbol bottom, center, and top represent the 15, 50 and 150 buffer, respectively. Labels referenced in text.

rupture dataset, exceeding all participants in our study except that postdoc. These two participants missed the distributed ruptures, exemplifying the challenge in mapping secondary faults, whose subtler geomorphic expression degrades more rapidly than primary fault scarps (Zuckerman et al., 2026b). We conclude that the pre-event indicators for principal ruptures exhibit more obvious regional trends than distributed ruptures and thus are easier to map.

There is a modest increase in success with experience, with postdocs and professional geologists ($17^{+19}_{-13}\%$) predicting a slightly greater percentage of ruptures than undergraduates and graduate students ($11^{+20}_{-9}\%$; Figure 4B). Some undergraduate and graduate students mapped fault traces along fluvial scarps (drainages), likely reflecting their lack of experience. Participants of all experience levels mapped fault traces along an alluvial fan edge, suggesting that certain non-tectonic features can be misinterpreted even by experts (Location 3). Participants indicated that this was an especially challenging area and cited the lack of high-quality data. In this location, mappers predicted at most $33^{+18}_{-26}\%$ of the ruptures, the lowest maximum for any mapping area. The digital surface model (DSM) created using 1966 photographs has blocky artifacts and does not show the sharp slope breaks expected from faults in many cases (Reitman and Briggs, 2024; Scott et al., 2025b). However, we note that the 1966 DSM resulted in the highest quality map in the Scott et al. (2023) study, indicating the importance of older, lower-quality data for fault mapping (Scott et al., 2025b).

3.1.2 2010 Mw 7.2 El Mayor-Cucapah earthquake

The 2010 M_w 7.2 El Mayor-Cucapah earthquake occurred in the arid desert of northern Baja California, Mexico (Figure 1). The mapping area includes part of the Sierra de Los Cucapah range front with alluvial fans up to 50 ka in age (Mueller and Rockwell, 1995) and northwest-trending faults (Figure 5). The previous surface-rupturing earthquake, the 1892 M_w 7.1–7.3 Laguna Salada earthquake, produced 5 m-high scarps cutting the alluvial fan (Mueller and Rockwell, 1995). The 2010 earthquake ruptured traces that were also active in the 1892 Laguna Salada earthquake, as documented in published rupture datasets (Sarmiento et al., 2024; Teran et al., 2015) and cut alluvial fans with 3 m oblique offset (Fletcher et al., 2014). Field-confirmed faults in the bedrock range (Mueller and Rockwell, 1991, 1995) did not rupture the surface in 1892 or 2010.

Most participants' mapped fault traces aligned with the NW-trend of the 2010 ruptures and the regional-scale topography (Figure 5A). Nearly all mappers mapped the 1892 Laguna Salada ruptures visible in the satellite imagery and DEM, and thus identified at least part of the 2010 ruptures that cut the alluvial fans. At Location 1 (Figure 5), mapped traces indicated by curvilinear Quaternary scarps that ruptured in the 1892 earthquake, offset or cut alluvial fans and fan complexes, and beheaded channels were within 100 m of the comparatively linear 2010 rupture. At Location 2 along the range front, participants observed saddles, triangular facets,

and an over-steepened range front. The mapped range-front faults closely follow those documented by Mueller and Rockwell (1995), with 90% of the mapped traces located within 30 m of the field-confirmed faults. This area did not rupture in 2010.

Participants with more experience generally predicted more ruptures. Senior professional geologists often produced the most accurate results, predicting a median of $83^{+17}_{-50}\%$ of the 2010 ruptures (Figure 5B). The least experienced mapping group mapped $16^{+4}_{-9}\%$ of faults that ruptured and frequently misinterpreted geomorphic features, mapping fault traces along fan and channel edges. Participants of all experience levels recorded fault traces along the bedrock range-front scarps (Location 2). Because these faults did not rupture in 2010, these mapped faults decreased the scores for the percentage of faults that ruptured analysis (Figure 5C). However, mapping these geomorphically expressed range-front faults was geologically reasonable — their absence from the 2010 rupture reflects aleatory variability rather than mapping error.

3.1.3 2011 Mw 6.6 Fukushima-Hamadori earthquake

The 2011 M_w 6.6 Fukushima-Hamadori, Japan, normal-fault earthquake ruptured NNW-striking faults in a subtropical region that is densely vegetated with terraced agricultural plots and fluvial activity (Nissen et al., 2014; Toda and Tsutsumi, 2013). Regionally, the ridges and mapped faults trend in the same direction (Figure 6). The most recent surface-rupturing earthquake prior to 2011 occurred between 800 and 6200 years ago (Miyashita, 2018).

Anthropogenic and fluvial activity may obscure evidence of past earthquakes. At Location 1 in Figure 6A, only one participant, an undergraduate student, identified the fault passing through agricultural plots. 80% of participants placed faults along the range front (Location 2), citing Quaternary and bedrock scarps, triangular facets, and over-steepened range fronts. Mapped faults near Location 2 follow a road and did not rupture in 2011. 90% of participants placed faults in the western half of the mapping area, following linear and curvilinear roads, agricultural terraces, and streams (all present at Location 3). However, the 2011 earthquake did not rupture here, and the mapped faults and local topography have different trends.

Mapping accuracy did not consistently improve with experience (Figures 6B & C). However, individuals who considered the regional context tended to perform better, regardless of experience level. An undergraduate student who performed the best, predicting $81^{+16}_{-21}\%$ of ruptures and identifying $80^{+20}_{-19}\%$ of faults that ruptured in 2011, reported looking beyond the mapping area to identify the regional trend of the ranges. A mid-career professional geologist reported doing the same and performed second best. Participants from all experience groups mapped faults that did not rupture in 2011 (and where none exist in other geological maps; Styron and Pagani, 2020) across the western half of the study area (Location 3 in Figure 6A; Figure 6C), suggesting regional

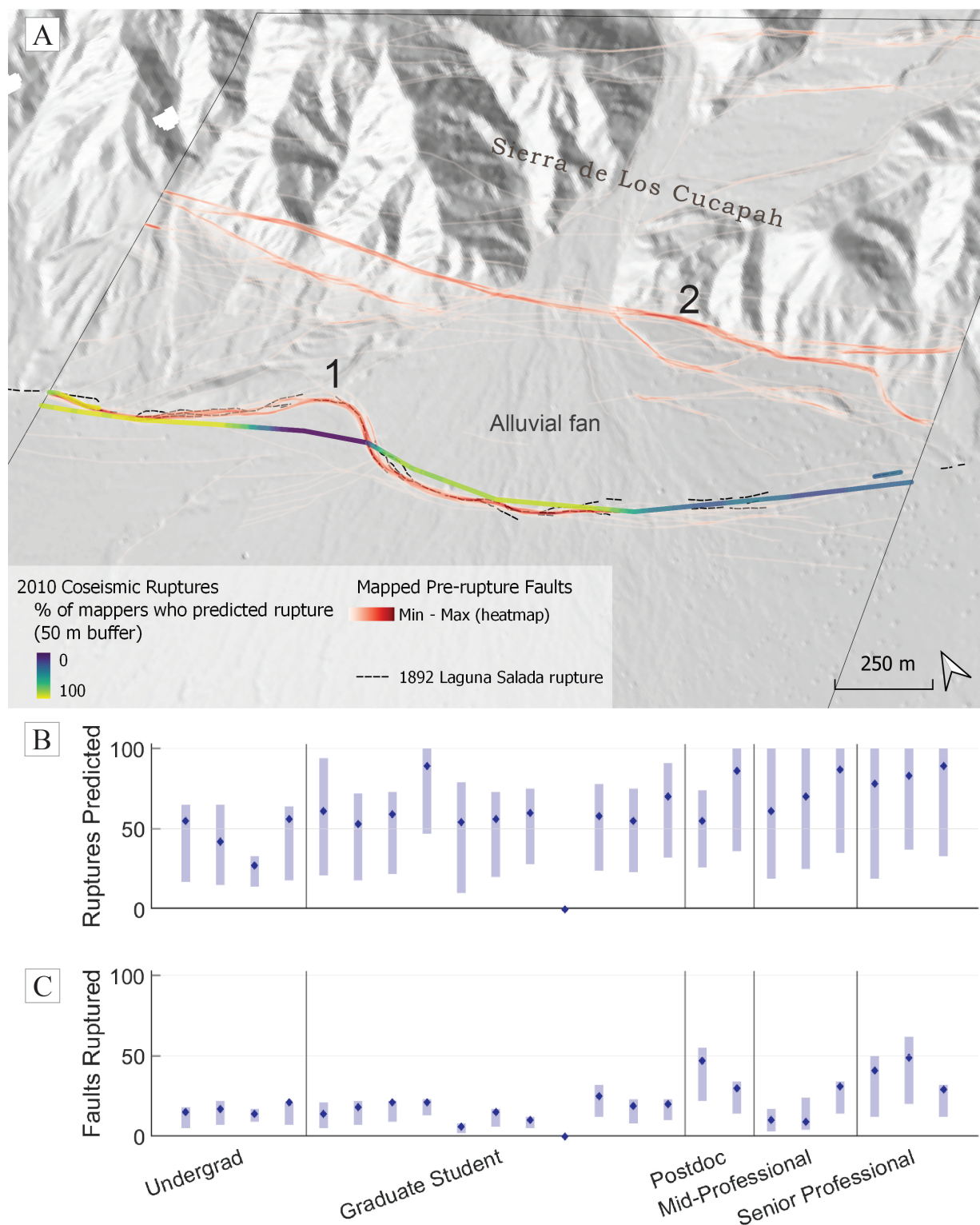


Figure 5 (A) El Mayor-Cucapah hillshade (OpenTopography, 2012) with a heat map of mapped pre-rupture faults and 2010 coseismic ruptures (Sarmiento et al., 2024; Teran et al., 2015) colored by the percentage of mappers who predicted the coseismic rupture trace using a 50 m buffer. (B) Percentage of ruptures and (C) mapped faults inside the buffer zones for each mapper. The symbol bottom, center, and top represent the 15, 50, and 150 m buffer, respectively.

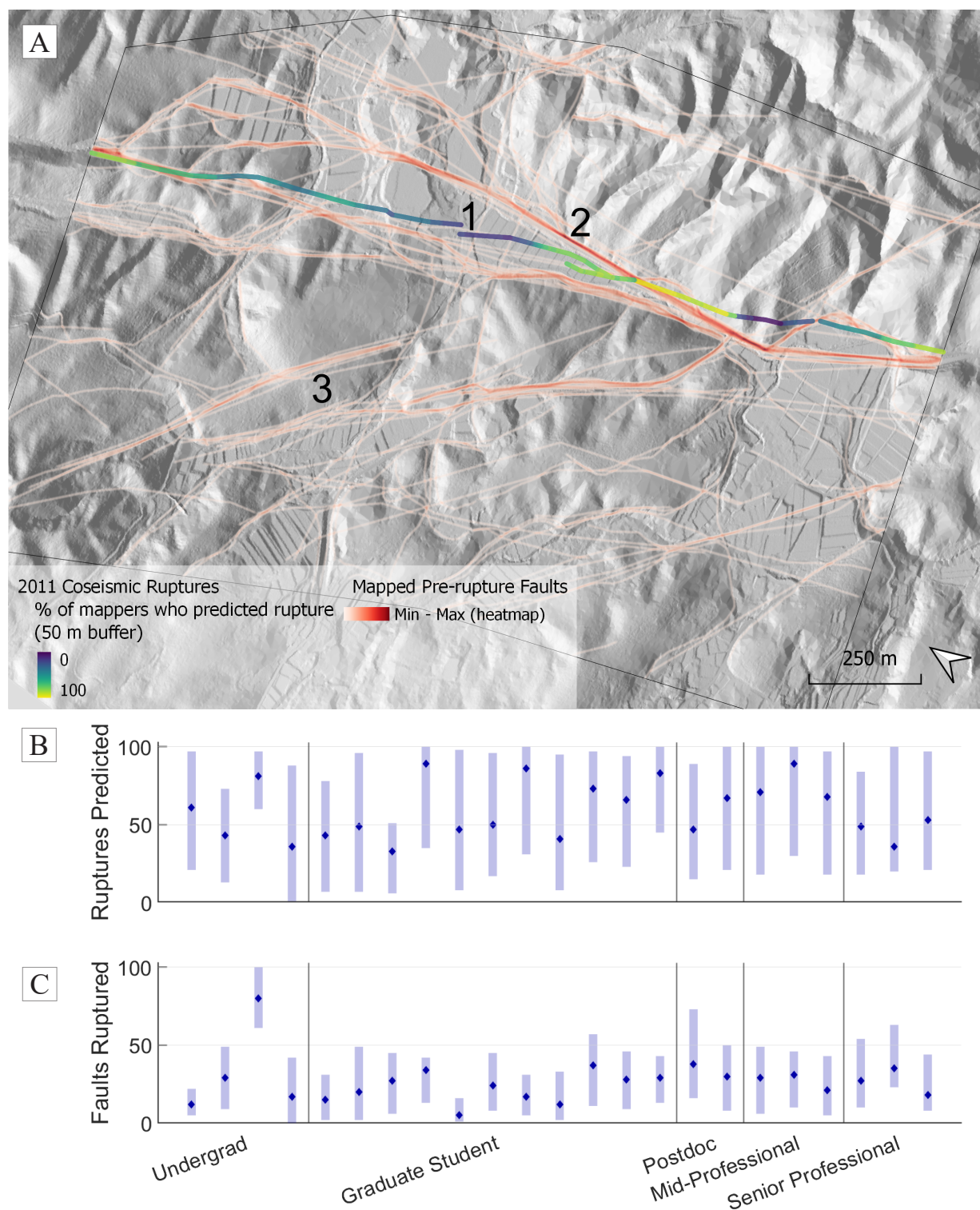


Figure 6 (A) Fukushima-Hamadori mapping results displayed as a pre-rupture fault heatmap along with 2011 earthquake coseismic ruptures (Mizoguchi et al., 2012; Sarmiento et al., 2024), colored by percentage of mappers who predicted the ruptures using a 50 m buffer. Basemap: topographic hillshade from a lidar-derived digital terrain model (Nissen et al., 2014). (B) Percentage of ruptures and (C) faults inside the buffer zones for each mapper. The symbol bottom, center, and top represent the 15, 50, and 150 m buffer, respectively.

context is critical.

3.2 Spatial spread of mapped faults near tectonic landforms

3.2.1 Overview

We consider how participants with varying experience levels interpret fault location relative to key tectonic landforms (Figure 7). We evaluate the spatial distribution of mapped pre-rupture fault locations (within 1-m bins) along a profile perpendicular to the coseismic rupture (Figure S2) and centered on landforms mapped by multiple mappers (see Section S2.4 for detailed methods). The fault scarp and a triangular facet landforms were easily identified by mappers and have a high predictive value, consistent with Scott et al. (2024).

3.2.2 El Mayor-Cucapah

The 2010 M_w 7.2 El Mayor-Cucapah earthquake ruptured a pre-existing fault scarp cutting an alluvial fan surface that ruptured in the 1892 Laguna Salada earthquake (Figure 7A). Topographic profile (A-A') extends across an 8 m-tall southwest-facing slope.

All faults mapped by the entire group are in a ~40 m zone that crosses two 1892 Laguna Salada rupture traces and one 2010 rupture (Figure 7A) and trend north-westerly, perpendicular to the fan slope. A ~6 m-high fault scarp, visible in the pre-earthquake topography, is just downslope of the 2010 rupture. 90% of faults are mapped 5–20 m from the 1892 Laguna Salada rupture at the fault scarp base. In contrast, only 15% of mapped faults are within 10 m of the 2010 rupture trace at the fault scarp top. This distribution indicates that geomorphology from the 1892 Laguna Salada rupture largely guided the mapping rather than the 2010 rupture, which had not yet occurred. Participants noted the fault scarp's height as a key feature in their interpretations.

Four out of five faults mapped by senior professionals and all three faults mapped by mid-career professionals were within 10 m of an 1892 Laguna Salada rupture trace, downslope of the 2010 rupture. Graduate students mapped over the broadest range, and undergraduates mapped only downslope of the ruptures.

3.2.3 Fukushima-Hamadori

For the 2011 M_w 6.6 Fukushima-Hamadori earthquake, 50% of the participants mapped faults near a triangular facet (Figure 7B). Topographic profile (B-B') extends across a 13 m-high hillslope, a valley, and a 48 m-tall range front expressed as a triangular facet. The 2011 earthquake rupture occurred at the upper third of the triangular facet.

Of the six professional geologists, two listed the slip sense as normal, referencing the steep topography and the triangular facet. The other four indicated a strike-slip fault, and one noted left-offset landforms. One professional indicated the triangular facet was an artifact of the topographic data, emphasizing the expertise required to interpret lidar correctly.

No participants predicted the rupture location within 24 m, and there was no significant mapping improvement by experience level. Although professional geologists differed in their interpretations of slip sense and data quality, these differences did not translate into more accurate predictions of the subsequent rupture location. 50% of the participants mapped the triangular facet, and 75% placed faults at its base, consistent with a plausible strike-slip interpretation (McCalpin, 2009b), despite triangular facets being more commonly associated with normal faulting. This example indicates that experience was insufficient to anticipate the future rupture location.

These results are consistent with prior observations that experienced mappers can disagree when interpreting similar geomorphic landforms. Scott et al. (2023) reported an example where participants disagreed on the fault location at a range front for the oblique strike-slip 2016 M_w 7.0 Kumamoto earthquake. In that study, a professional geologist mapped a fault at the range-front base and anticipated the rupture, and a different professional mapped an upslope fault. A partially upslope location is referenced in textbooks (McCalpin, 1987, 2009b).

3.2.4 Ridgecrest, northwest

In the northwest Ridgecrest mapping area, we analyzed mapped fault locations near a linear 14 m-tall bedrock ridge identified as a bedrock or Quaternary scarp (Figure 7C; profile C-C'), and one of the few elevated landforms in the mapping area. Two coseismic rupture traces cross the profile (DuRoss et al., 2020; Ponti et al., 2020). A portion of the 2019 ruptures last ruptured within 5–7 ka, evidenced by vertical displacement of ~3.4 m on a 5–7 ka alluvial surface (Roquemore, 1981; Thompson Jobe et al., 2020).

All mapped faults are within 53 m of one of many rupture traces. 80% of mapped faults follow the vertical fault scarp (from -20–40 m along the x -axis of the topographic profile), and 62% are clustered within 15 m of ruptures along the bedrock ridge base. The bedrock ridge is likely a product of repeated earthquakes given its high relief in an otherwise low-relief landscape (Philibosian et al., 2020; Thompson Jobe et al., 2020). With few definitive landforms, many participants mapped faults along the base of the ridge, which corresponded to the rupture trace.

Graduate student performance is representative of the group at large: 90% mapped faults on the vertical slope and 73% mapped within 15 m of the rupture traces. Faults at the slope base in this strike-slip regime predicted the rupture locations. Five out of six professional geologists mapped faults along one side of the bedrock ridge, and the other professional mapped on the opposite side. All professionals indicated the limited topographic expression and mapped faults along the bedrock ridge as it aligned with regional-scale evidence and was relatively prominent. Professionals indicated that this mapping was “humbling,” and, due to the paucity of preserved geomorphic evidence for prior surface rupture, several participants indicated that they

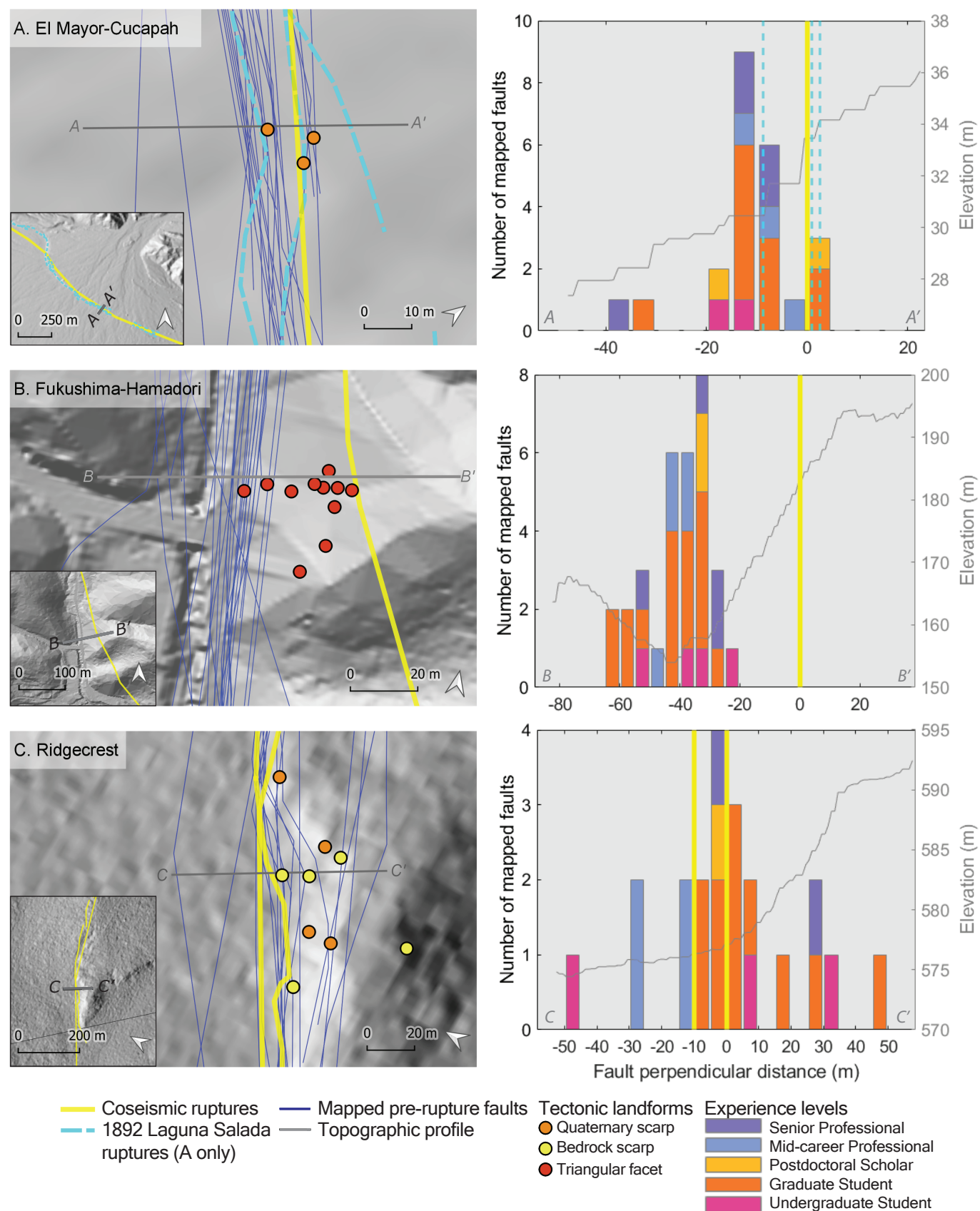


Figure 7 Mapped faults, coseismic ruptures, and some tectonic landforms with a pre-rupture DSM basemap (left); insets show location in mapping area and of the topographic profiles. Bar plots show the count of mapped faults, coseismic rupture traces (yellow line), and the topographic profile. Locations: (A) El Mayor-Cucapah fault scarp, (B) Fukushima-Hamadori triangular facet, and (C) Ridgecrest, NW section fault scarp.

only mapped faults because that was the assignment.

3.3 Impact of data type and resolution

To explore how fault mapping varies by data type and resolution (30 m–0.1 m/pixel), we compared fault maps derived from different topographic and imagery datasets (Figure 8), following the sequential dataset design described in Section 2.3.2 and Table S3. We focus on one of the two participants' mapping of the desert environment of the mature Southern San Andreas fault (total offset 200 km; [Darin and Dorsey, 2013](#)) mapping area, which includes ~4 km of the fault through the Mecca Hills in California (Figure 8; approximate location in Figure 1) that last ruptured 300 years ago ([Philibosian et al., 2011](#); [Rockwell et al., 2018](#)). Here, the San Andreas fault cuts through sedimentary bedrock. The red landforms visible in Figure 8H are an older alluvial fan ([Gray et al., 2014](#); [Sylvester and Smith, 1976](#)) or a sheared mudstone ([Fattaruso et al., 2014](#); [McNabb, 2013](#)). An alluvial fan extends southwest from Painted Canyon (center of Figures 8A–E).

Using the 30 m SRTM DEM (Figure 8A), the participant mapped fault traces and tectonic landforms ~0.25 km apart. Using the 1 m/pixel airphoto, the participant placed twice as many tectonic landforms as in the SRTM map. The 'deflected stream' landform supported high-precision mapping. When using the airphoto data, the participant increased the fault confidence ranking northwest of the canyon and decreased the confidence southeast of the canyon. Northwest of Painted Canyon, there are lineaments visible in the airphoto (and successive datasets) but not in the 30 m SRTM DEM. Southeast of Painted Canyon, multiple weak-confidence faults follow the topographic trend (Figure 8G).

The 1 m/pixel color satellite imagery (Figures 8C & H) has more variable color yet shows topography less well than the black-and-white National Aerial Photography Program (NAPP) airphoto (Figures 8B & G; see Table S3 for a full description of all datasets). The participant placed 35% more tectonic landforms in the satellite imagery relative to the airphoto (Figures 8C & H), half of which are high-quality indicators (offset drainage channels; red dots in Figure 8C). The satellite imagery showed bedrock scarps not visible in the airphoto (orange dots in Figure 8C). The map prepared using satellite imagery lacks fault traces and landforms in the inset area.

The lidar-generated map (Figures 8D & I) contains fewer and more dispersed mapped tectonic landforms as the satellite imagery map. The high-detail fault traces northwest of Painted Canyon are discontinuous. In the inset, the participant placed five fault traces and 11 tectonic landforms not in the satellite imagery map (Figure 8I), noting the ease of seeing streams and fluvial deposits in the lidar. However, the participant mapped faults with lower precision than what the lidar data allow (Figure 8I), using fewer vertices than with the airphoto (Figure 8G); the reason is unclear.

The participant mapped twice as many landforms in the 10 cm Structure-from-Motion (SfM)-derived topography (Figures 8E & J) relative to the lidar, yet none with

the strongest rank. The SfM contains the most mapped landforms of all datasets including shutter ridge, deflected stream, beheaded drainage, and bedrock and Quaternary scarp landform points (unlabeled in Figure 8E). The primary fault northwest of Painted Canyon remained largely unchanged from the lidar map, but most secondary faults were removed.

Generally, the participant mapped with higher detail with increasing dataset resolution. The participant indicated that the topographic and imagery datasets were most useful for morphologic and surficial mapping, respectively. The participant noted the complementary nature of all datasets for producing a quality map. The participant placed linear features such as offset and beheaded drainages in all six datasets. The participant noted that the high-resolution lidar and SfM datasets were the most helpful.

3.4 Fault mapping using a published geologic map

We investigate how consulting a published geologic map produced from fieldwork affects regional-scale fault mapping (see Sections 2.3.3 & S3.4). When available, most fault mapping projects consult geologic maps (e.g., [Morell et al., 2020](#)). In our experiment, class participants first created a fault map based on topography data and imagery only (Figure 9A). Then, they reviewed a published geologic map and could adjust the fault linework (Figure 9B).

We evaluate one participant's mapping here. The mapping area includes the Sierra de Los Cucapah bedrock range and Quaternary alluvial fans, both ruptured by the 2010 El Mayor-Cucapah earthquake. The 1:10,000 scale map shows bedrock and Quaternary surficial geology and the height of mapped fault scarps ([Mueller and Rockwell, 1991](#)). The participant mapped at a 1:6,000 and 1:3,000 scale using the DEM and satellite imagery, respectively.

The participant's and published fault traces are similar in the range front and alluvial fans (Figure 9A). In both cases, a single fault trace follows the range-front base and two continuous fault traces cut outboard alluvium. The participant made few changes after reviewing the geologic map. At Location A, the participant added several discontinuous fault traces from the geologic map. These 1 m-high fault scarps are subtle in the imagery and not visible in the 6 m/pixel topographic data. At B, the mapper deleted a secondary weak-confidence fault at the alluvial fan edge. At C, the participant increased fault confidence ranking where the mapped and geologic map faults overlapped. At D, the participant did not add a fault trace where one was mapped in the geologic map, suggesting the participant did not see fault evidence here. Results from the Napa project were similar, with the participant making limited adjustments to their map (Section S3.4; Figure S7).

For all participants who completed this project, in their El Mayor-Cucapah and Napa (Section S3.4) project reports, the participants indicated that the strongest impact of the geologic map was the validation of their interpretations. When the participants' and geologic

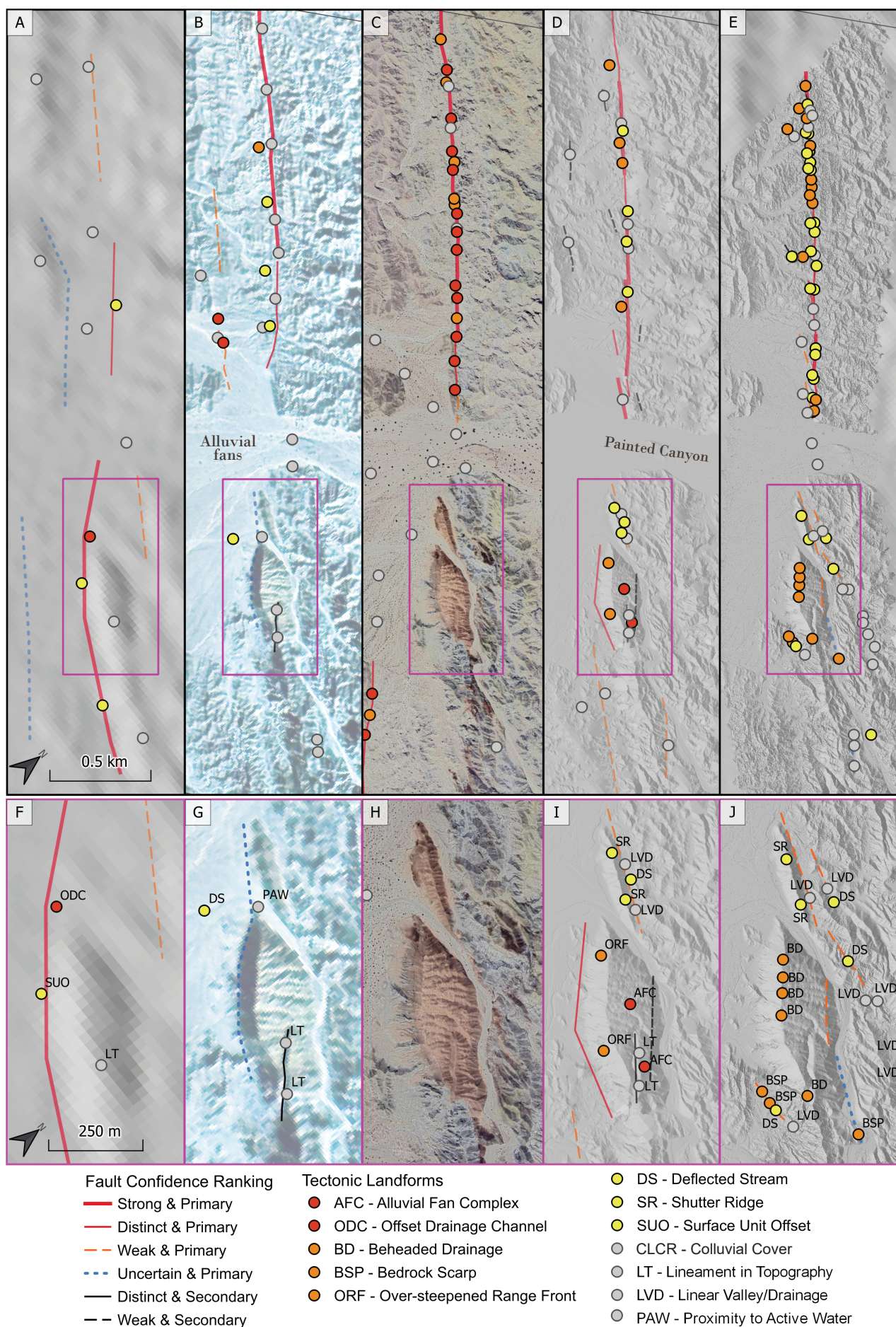


Figure 8 Previous page. Fault mapping with different data types and resolution along the Southern San Andreas fault (one class participant's maps). Mapped faults and landforms on basemaps: (A) SRTM DEM (30 m/pix), (B) National Aerial Photography Program (NAPP) airphoto (1 m/pix), (C) Google satellite imagery (1 m/pix), (D) airborne lidar (1 m/pix; [DeLong, 2017](#)) and (E) Structure-from-Motion-derived topography (0.1 m/pix; Table S3; [Bunds et al., 2021](#)). (Magenta inset in F–J) Tectonic landforms are colored by ranking: red=4 (high-quality), orange=3 (strong), yellow=2 (moderate), gray=modifier (see description of tectonic landform ranking in [Adam et al. \(2025\)](#); Section 3.2).

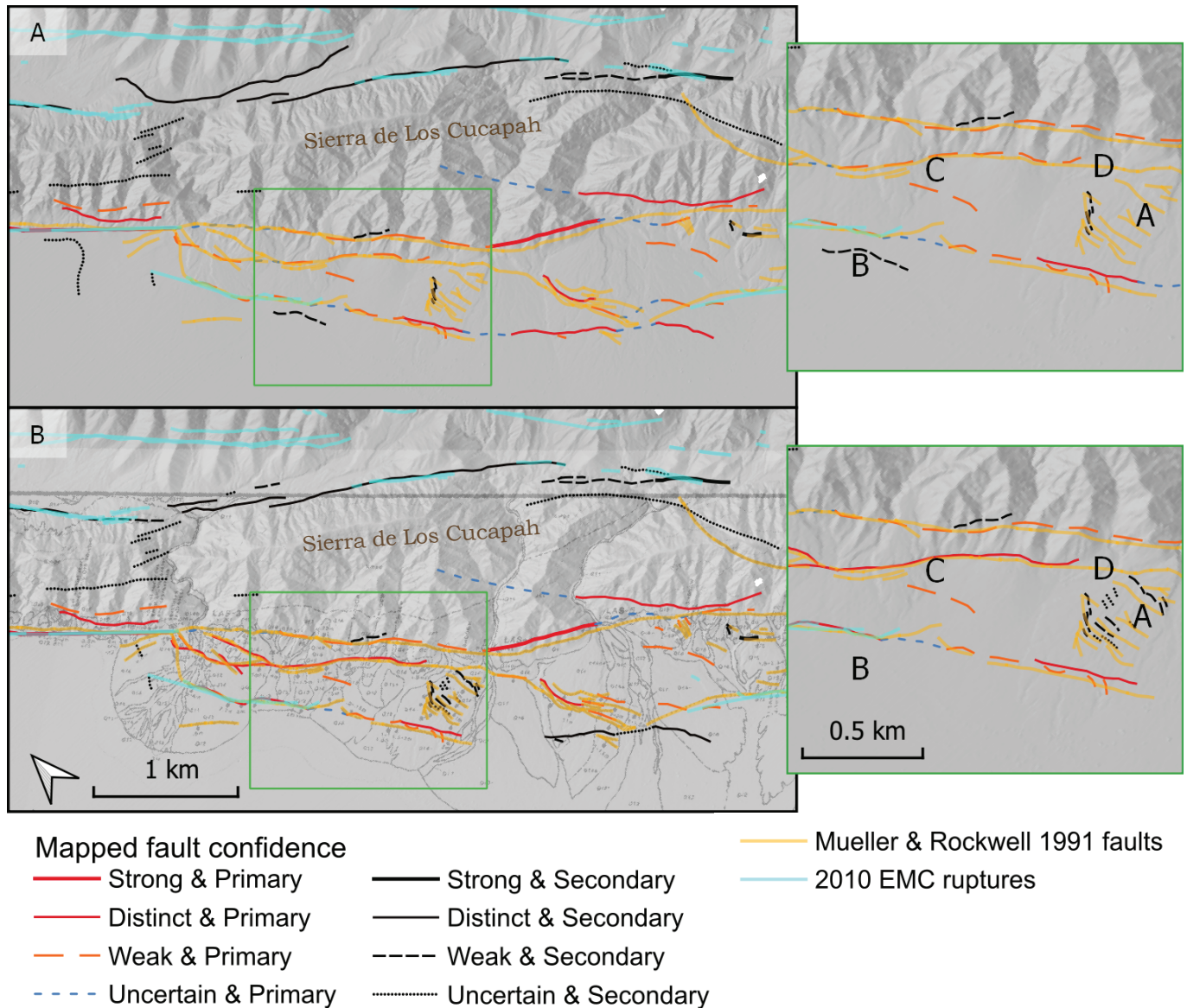


Figure 9 Faults mapped before (A) and after (B) consulting a geologic map for a portion of the 2010 El Mayor-Cucapah earthquake ([Mueller and Rockwell, 1991](#)), displaying 2010 EMC ruptures ([Sarmiento et al., 2024](#); [Teran et al., 2015](#)). Labels are referenced in text.

map faults aligned, the participants increased their fault-ranking confidence. Examining the geologic maps prompted the participants to critically assess their maps and sometimes map previously unnoticed landforms and faults. Most of the fault locations remained unchanged, indicating that in our experiment, geologic maps only motivate minor adjustments.

4 Discussion

4.1 Overview

We used repeated mapping and a systematic regional-scale fault mapping approach ([Adam et al., 2025](#); [Scott et al., 2023](#)) to evaluate how experience level influences fault mapping outcomes. Our findings carry implications for (1) the role of experience on fault mapping outcomes, (2) the impact of data type and quality on mapper decision making, (3) the influence of a standardized geomorphic mapping approach, and (4) the quantifica-

tion of epistemic uncertainty in fault mapping. Our outcomes reinforce a growing recognition of the need to quantify uncertainty generally (e.g., Bond et al., 2007; Tikoff et al., 2023) and specifically for fault mapping (e.g., Petersen et al., 2011; Salisbury et al., 2015; Scott et al., 2023, 2024).

An important assumption underlying geomorphic fault mapping is that past surface ruptures have created tectonic landforms indicative of past coseismic rupture location. The clarity of this record depends on the recency, frequency, and size of past ruptures and the rate of subsequent landscape modification (Zuckerman et al., 2026b). Consistent with this, mappers achieved higher accuracy in predicting ruptures at El Mayor-Cucapah (median mapper predicted 59% of faults within a 50 m buffer), where the most recent surface rupture preceded the 2010 earthquake by only 118 years, compared to Borah Peak (16%) and Ridgecrest (15% average for northwest and southeast), where longer intervals (5–7 ka) since the most recent surface rupture may have significantly reduced geomorphic clarity. Where the geomorphic record is incomplete or absent, mapping accuracy is limited regardless of mapper experience or data quality, as we discuss in the following sections.

4.2 What defines a high-quality fault map?

We evaluate the mapped fault locations by comparing the location of mapped pre-rupture faults relative to subsequent surface rupture locations using three buffer distances. The 15 m buffer approximates site-specific regulatory setbacks for the state of California (California Geological Survey, 2018). The 50 m buffer captures a mid-range uncertainty level that aligns with reported fault-to-rupture separations from empirical studies (Table 1). The 150 m buffer encompasses most primary surface rupture zones and is the basis for regulatory zoning (California Geological Survey, 2018). These results underscore how the interpretation of mapping performance is scale-dependent across different fault mapping applications.

High-quality maps have full spatial coverage, appropriate detail for the data resolution and/or mapping task, geologically reasonable fault placement, and reflect geologically accurate interpretations with the use of confidence ratings to reflect perceived uncertainty. We note that field mapping textbooks do not explicitly define map “quality” (e.g., Compton, 2017; Lisle et al., 2011). High-quality fault maps include accurate interpretations of tectonic landforms using structural geology principles such as fault kinematics and geometry (McCalpin, 2009b). Mapping choices such as mapping scale, data smoothing, and fault segmentation influence map quality (Ferrario et al., 2025; Scott et al., 2023). Maps improve when mappers engage with the entire map extent (Libarkin et al., 2011), as regional context helps mappers correctly interpret local features and avoid missing faults outside areas of obvious expression.

An important consideration in evaluating mapping performance is the tradeoff between comprehensive

fault identification and overmapping. A mapper who traces all linear features resembling fault scarps may predict a higher percentage of subsequent ruptures, but at the cost of mapping faults (or apparent faults) that never rupture. Conversely, a more conservative mapper may prioritize geomorphic confidence and miss some ruptures. Our use of two complementary metrics, the percentage of ruptures predicted and the percentage of mapped faults that later ruptured, partially addresses this tradeoff by capturing both sensitivity to rupture location and specificity of fault interpretation. High-quality fault maps, therefore, balance coverage with interpretive restraint, rather than maximizing either metric alone.

4.3 The impact of experience level on fault mapping

4.3.1 How does geological experience and training affect mapping accuracy?

We compared fault trace maps by participants with varying experience, from upper-division undergraduate students through senior professionals. A reasonable hypothesis is that individuals with more experience would map more accurately (e.g., Baker et al., 2016). However, we found that, in general, maps created by graduate students and professional geologists were of similar quality (Figures 4, 5, & 6). This suggests that targeted instruction can effectively and efficiently prepare individuals with graduate-level training to produce high-quality maps. Undergraduates more frequently misinterpreted non-tectonic features, such as fluvial scarps, as fault traces compared to more experienced mappers, though mappers at all experience levels made some misinterpretations. More experienced mappers used more technical terms to describe mapped features, while less experienced mappers were vaguer and more generalized (Adam et al., 2025).

Experience shapes mapping decisions. As a general observation, mappers trained on fixed-scale maps may rely on the expected level of detail and precision for that scale, whereas digital mappers can zoom and pan dynamically. Digital data support this flexibility, but each landform type has an optimal scale of observation, and excessive zooming can be counterproductive. Effective mappers balance zooming with the appropriate scale of the landforms (cf. Adam et al., 2025).

Experienced mappers may be susceptible to cognitive biases such as anchoring, availability, and confirmation bias (Bond et al., 2007). Anchoring bias may cause individuals to maintain an initial interpretation despite conflicting evidence, for example, when identifying landforms as tectonic in origin and continuing with that interpretation despite divergent observations. Availability bias occurs when recent experiences disproportionately influence interpretation, which may be more likely among mappers who have worked on similar fault systems or settings. Confirmation bias involves seeking evidence that supports a preconceived idea, such as assuming a particular fault slip sense based on previous work in similar landscapes.

4.3.2 What are the limitations of experience?

Participants of all experience levels mapped faults similarly near prominent tectonic landforms such as the base of fault scarps or triangular facets. Thus, these major tectonic features are often recognizable by mappers of all experience levels.

In the Northwest Ridgecrest area (Figures 7C; S3), all participants mapped the fault trace that later ruptured along the elongated bedrock ridge (Figure S3). Thus, in settings with a single mappable landform, extensive experience may not be necessary to achieve or improve accurate mapping, as the single somewhat ambiguous landform provides little room for different interpretations.

For the normal-faulting Fukushima-Hamadori rupture near the triangular facet, the closest mapped fault was 24 m from the actual rupture (Figure 7B). All participants mapped faults at the range-front base, within 7 m of the facet, consistent with textbook guidance that faults often rupture near range fronts (McCalpin, 2009b). Two-thirds of professional geologists assumed a strike-slip mechanism rather than normal. Although the 2011 rupture involved normal slip, likely triggered by stress changes from the M_w 9.0 Tohoku-Oki megathrust event, the fault's long-term behavior may include strike-slip motion (Hardebeck and Okada, 2018). What may appear as a misinterpretation instead highlights the difficulty of inferring fault kinematics from geomorphology in remote sensing datasets alone.

Data from our experiment do not support the hypothesis that experience improves interpretation reliability in areas of subtle tectonic geomorphic signals or extensive anthropogenic activity. In Southeast Ridgecrest, the tectonic landforms are subtle as topographic relief is only 24 m (Figure S4), resulting in low mapping accuracy. Participants of all experience levels noted that they only mapped faults here because they were instructed to. For Fukushima-Hamadori, mappers of all experience levels predicted the highest percentages of ruptures. However, where the rupture passed through agricultural plots and other anthropogenically altered landscapes, only one mapper—an undergraduate—accurately located the future fault trace.

No mapper is able to anticipate future fault location when rupture occurs on a new strand or when a previously active fault does not rupture in a subsequent event (aleatory variability). This is evident in the El Mayor-Cucapah area. Led by fault scarps from by the 1892 earthquake, participants did not predict part of the 2010 rupture that had not ruptured in the 1892 earthquake (Sections 3.1.2 & 3.2.2).

These cases highlight that while experience can improve fault mapping in some settings, it does not ensure accuracy in all cases. While experienced mappers bring refined judgment and geologic knowledge, they may be susceptible to cognitive bias and over-reliance on heuristics (Rankey and Mitchell, 2003). Conversely, less experienced mappers can achieve accurate results when using a structured mapping approach.

Our analysis necessarily evaluates mapping accuracy

relative to a rupture that occurred in a single subsequent earthquake. This comparison treats the observed rupture as a practical reference case for quantifying performance. In some instances, mappers reasonably identified actual faults that did not rupture. Such cases illustrate aleatory variability rather than epistemic error and highlight that high-quality fault mapping can include actual faults that remain inactive during a given earthquake.

4.3.3 How and when does experience enhance mapping accuracy?

We discuss two examples where experience improved map quality. For Borah Peak and El Mayor-Cucapah, there was a $16^{+27}_{-1}\%$ and $34^{+35}_{-17}\%$ improvement from least to most experienced participants, respectively (Section 3.1; Figures 4 & 5). In both areas, only undergraduates and junior graduate students mapped fault traces along fluvial scarps. Prior experience helped the mapper to filter out features of non-tectonic origin (Tikoff et al., 2023). The filtering skill develops through repeated exposure to geologic concepts in education and practice. Experienced participants correctly excluded fluvial scarps, which in these two settings often trend nearly perpendicular to fault scarps. Less experienced mappers more often misinterpreted these features, possibly mapping extra traces to cover all possibilities (Bond et al., 2011).

4.4 Suggestions for approaches to fault mapping

4.4.1 Use all available data types

Topography, imagery, and geological maps each offer advantages for fault mapping. Participants noted that lidar- and SfM-derived shaded-relief and slope maps most clearly show lineaments and slope breaks. Aerial photos and satellite imagery elucidate surficial desert geology and vegetation lineaments. However, dense vegetation can obscure landforms in all dataset types, including lidar and SfM, as demonstrated in the Fukushima-Hamadori case.

Using multiple datasets, including color imagery and high-resolution topography data, is best for mapping arid environments. For El Mayor-Cucapah, participants used 6 m/pixel lidar data and 1 m/pixel satellite imagery to produce high-quality maps. Yet for Borah Peak, the 2 m/pixel digital surface model processed from 1966 aerial imagery (Reitman and Briggs, 2024; Scott et al., 2025b) did not include the sharp features that participants were trained to look for, likely reflecting the image quality and the presence of vegetation. Participants reported that the detail visible in the highest resolution SfM data (<1 m/pixel; Southern San Andreas fault), the highest resolution in our study, confused some participants because of the increased detail. In a related study, novice mappers were less distracted when they used high-resolution topography hillshades versus high-resolution satellite imagery to identify tectonic landforms (Robinson et al., 2017).

The use of a geologic map did not substantially alter the mapped fault trace locations but resulted in increased fault confidence for mapped faults that coincided with faults in the geologic map (Section 3.3; Figure 9). This likely reflects the validation provided by published geologic maps produced by experienced geoscientists through field investigations and peer review. The relatively small impact of the geologic maps underscores the value of regional-scale mapping, particularly with high-quality remote sensing data, even if geologic maps are not available. We note, however, that some geologic fault maps are themselves derived from remote sensing, which reduces their independence as a validation source for desktop mapping. Still, geologic maps provide a foundational starting point and can help refine mapping in areas in which fault morphology is unclear in other datasets.

Geomorphic fault mapping conducted remotely has limitations. Mappers are reliant on the surficial evidence present in the remote datasets, which do not provide subsurface information. The tectonic landforms in remote sensing have been modified by the interaction with surface processes, decreasing available information (e.g., Zuckerman et al., 2026b). The most accurate model of regional-scale faulting would be resolved from a combination of desktop mapping and targeted field work. At a 10–100 m scale, the best practice would include paleoseismic trenching (e.g., Akyüz et al., 2014; McCalpin, 2009b), drilling, and/or geophysical explorations such as seismic or ground penetrating radar surveys (e.g., Chow et al., 2001; McCalpin, 2009a) if resources are available.

4.4.2 Apply a systematic fault mapping approach

The systematic mapping approach (Figure 2; Section 2.5; Adam et al., 2025; Scott et al., 2023) particularly supports novice mappers. The mapping approach was teachable in a semester and enabled some less experienced participants to produce maps generally similar to those made by more experienced mappers (Sections 2.2 & 2.4; Figures 4, 5, & 6). The mapping workflow promotes an iterative mapping and refinement process, allowing mappers to revisit and revise their interpretations. More experienced participants (postdocs and professionals in particular) interacted flexibly with the approach, often skipping and repeating steps.

The requirement to assign confidence to each fault trace provides a path to better assessing uncertainty, enhances the transparency and reproducibility of mapping decisions, and communicates nuance (Tikoff et al., 2023). This is especially important where geomorphic expression is ambiguous or where non-tectonic features resemble tectonic landforms. The end user of the map can use the assigned confidences to evaluate the data for themselves and use the confidences to assign weights for probabilistic approaches (Valentini et al., 2025).

Participant feedback highlighted the approach's limitations, especially for experienced mappers. Some felt that the method was cumbersome and overly time-consuming, possibly due to the level of detail of each step. Experienced participants preferred beginning

with a broader, conceptual understanding of the landscape before detailed mapping. While the first step of the tool, interpreting surface geology and morphology, does provide a “big picture” starting point, the experienced participants' perspective highlights the flexibility in mapping large-scale features and finer details. Adding an iterative scaling between coarse and fine observations is a valid enhancement to the process (see also Adam et al., 2025).

A next step would be to evaluate the effectiveness of the systematic, geomorphology-based mapping approach, for example, with an experiment where one group applies the standardized approach and another their own mapping methods. As many experienced fault mappers have developed individualized strategies over time, comparing the performance of less experienced individuals using the systematic approach against more experienced mappers using their personal methods would allow for a direct assessment of the approach's value relative to experience.

4.4.3 Considerations for selecting fault mappers

While expert mappers are typically assumed to provide the most reliable interpretations, our study indicates that less experienced mappers still map well, especially with appropriate training and a systematic mapping approach. We note, however, that these conclusions are based on a relatively small sample of 23 mappers across four tectonic settings, and practical considerations such as cost and availability of experienced geologists may also influence staffing decisions for mapping projects.

We explored several possible scenarios for fault mapping by individuals of different experience levels. A very experienced mapper would produce a high-quality map with good accuracy. However, the difference in mapping performance between senior professionals and graduate students is limited. For a particularly sensitive case, employing the most experienced mapper may be warranted, as professionals have consistently performed somewhat better than undergraduates, though comparably to graduate students (Table S5), than less trained mappers. Or, if employing multiple mappers, it may be reasonable to replace an experienced mapper with an exemplary novice (recall that a senior undergraduate student produced the best Fukushima-Hamadori map).

Ideally, fault mapping projects would employ collaborative approaches. Each mapper's set of experiences can influence differences in interpretation of the same dataset. A combination of the results from several mappers could provide better constraints on map (un)certainity. In a collaborative mapping approach, it may be more practical for each mapper to work individually and then for the group to combine their mapped faults, possibly in a heat map (like here) or through discussion. Alternatively, co-mapping, or mapping simultaneously, could be less helpful if more experienced mappers' self-assurance overshadows the novices', who may be reluctant to put forth their own ideas due to lack of confidence. Our results show that comparing maps from multiple individuals can improve the accuracy of fault

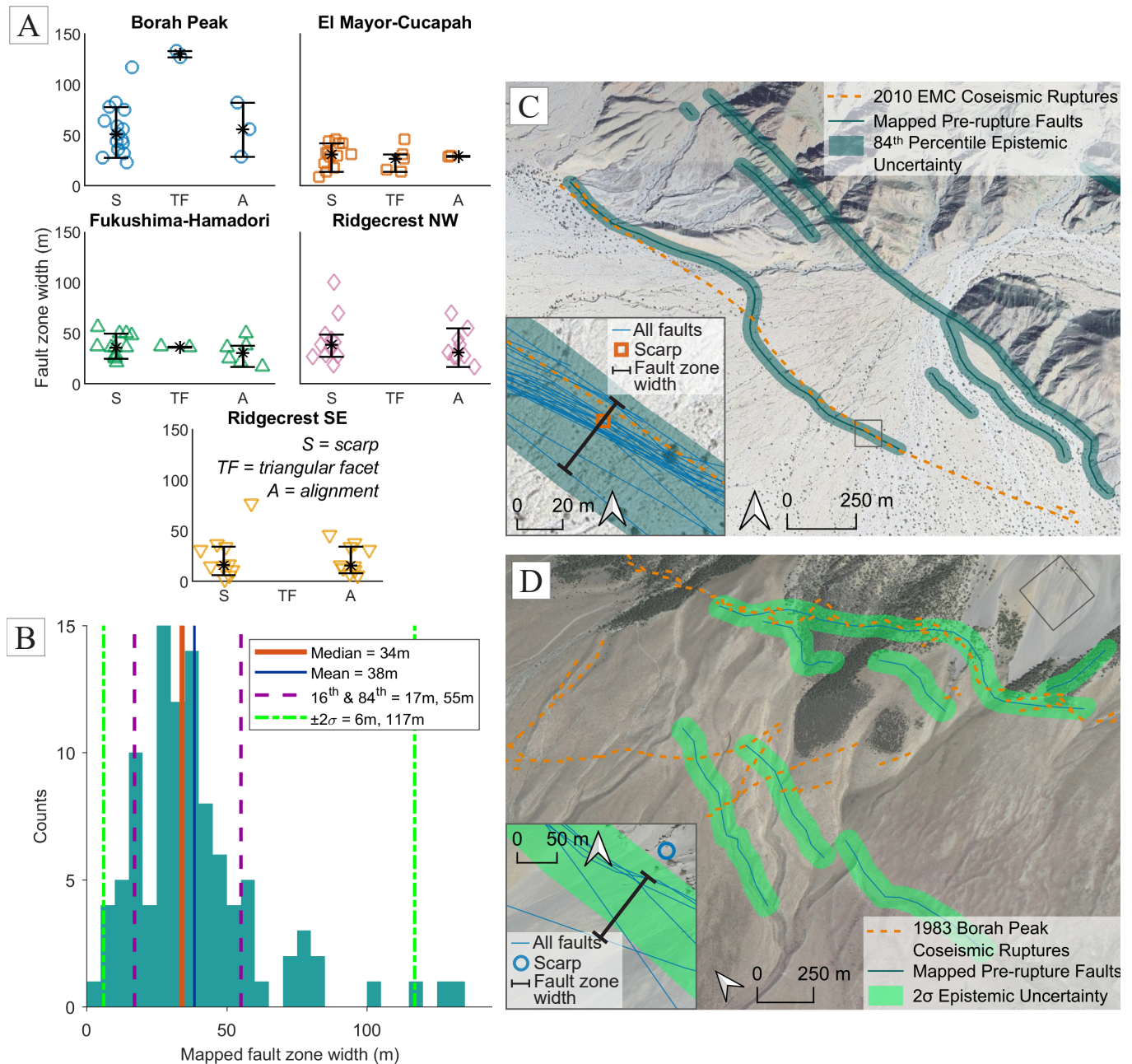


Figure 10 Epistemic uncertainty. **(A)** Spread (width) of mapped faults from the Repeat Mapping Project around 100 landforms (fault scarps, triangular facets, and alignments), with 20 measurements per location. Black bars indicate the 16th and 84th percentiles, and asterisks mark the median. **(B)** Histogram of mapped fault zone widths from (A), representing the quantified epistemic uncertainty in fault location. **(C-D)** Examples from two single participants' mapped faults (teal lines) in the El Mayor-Cucapah (C) and Borah Peak (D) areas. The 84th-percentile (analogous to 1σ) is plotted as a buffer zone in (C), and the 2σ width in (D) (Scott et al., 2025a). Coseismic ruptures are indicated by dashed orange lines. The insets in (C) and (D) show mapped faults and epistemic buffers for all participants, while the larger maps show only a single participant's mapping.

trace identification. In practice, a team could decide which faults are more accurate or plausible.

4.5 Epistemic uncertainty in fault mapping

Epistemic uncertainty represents the component of fault-location uncertainty due to differences in interpretation. While previous studies have not explicitly separated epistemic from the full uncertainty, our set of maps from multiple individuals enables us to quantify epistemic uncertainty. Recognizing the geologic settings where epistemic uncertainty is large informs the

width of fault zone buffers used in hazard assessments.

We quantified epistemic uncertainty by measuring the spread of mapped fault traces across 100 tectonic landforms (20 per location; Figure 10A). Epistemic uncertainty varies with location and landform type: The widest spread of mapped fault traces occurs near a triangular facet at Borah Peak (133 m; Figure 10D), whereas the narrowest spread occurs at a scarp in southeast Ridgecrest (2 m; Figure 10C). The mean epistemic uncertainty across the three landforms and all locations is 34 m and the 16th–84th spread is 55 m.

The case studies illustrate these contrasts (Figure 10). At El Mayor-Cucapah, the fault zones are narrow and consistently mapped; the epistemic-uncertainty buffer contains both mapped faults and the coseismic rupture (Figure 10C inset). By contrast, at Borah Peak, participants mapped more diffusely and often where future ruptures did not occur. The epistemic uncertainty for Borah Peak is larger, and mapped traces near the triangular facet can extend outside even the 2σ buffer (Figure 10D inset). Ruptures located outside of the buffer can reflect either aleatory variability in rupture location (i.e., a new rupture formed) or a systematic misinterpretation of the landscape by the mappers.

While our experiment primarily quantifies interpretation-based (epistemic) variability, the rupture datasets themselves contain aleatory variability associated with the inherently random spatial distribution of surface faulting. Some coseismic ruptures occurred on previously unrecognized or unmapped strands, whereas other well-expressed scarps did not rupture during the subsequent event. These outcomes reflect the natural variability of rupture processes rather than errors in mapping. Our results therefore capture both epistemic uncertainty—differences in human interpretation—and a component of aleatory variability inherent in the Earth system. This distinction is critical for linking geomorphic fault mapping to PFDHA, where epistemic uncertainty is modeled through multiple realizations of alternative fault geometries and aleatory variability is represented through statistical rupture displacement distributions.

Quantifying epistemic uncertainty is an important component of fault displacement hazard assessments, with direct applications in engineering practice. The range of epistemic uncertainty values reported here (2–133 m) spans the full spectrum of regulatory fault zone widths (Table 1), from below the Alquist-Priolo setback distance (15 m) at well-defined scarps to approaching the regulatory fault zone width (150 m) at ambiguous landforms such as triangular facets. For example, when infrastructure such as pipelines must cross active faults, accommodation zones should explicitly incorporate epistemic uncertainty in mapped fault location, along with aleatory variability, which can be characterized through PFDHA (Youngs et al., 2003). Sites with ambiguous geomorphology, similar to the triangular facets in Borah Peak, require larger uncertainty zones, while sites with sharp, well-defined scarps may justify using a narrower uncertainty buffer based on the mean or median epistemic spread.

5 Conclusion

We evaluated how mapper experience influences the accuracy of regional-scale fault maps made using remote sensing datasets with a systematic mapping approach. We compared pre-rupture fault trace maps produced by 23 participants with varying levels of experience with coseismic ruptures to assess map accuracy. While professional geologists generally performed best in identifying future ruptures, trained geoscience graduate students frequently produced maps of similar qual-

ity, especially in areas with prominent tectonic landforms. All experience groups were challenged by areas with ambiguous or obscured tectonic landforms. Experts still missed rupture locations, though in some cases landforms may not have been detectable in the pre-event remote sensing data or ruptures may reflect first-time surface expression (Thompson Jobe et al., 2020), and we found that experience beyond a graduate level provided limited improvement to the generated maps. Systematic mapping of geomorphology can help less experienced mappers produce quality and consistent results. However, map quality is influenced by expertise, the nature of the landscape (Ferrario et al., 2025; Scott et al., 2024), and the type and resolution of the available data. Our analysis quantifies epistemic uncertainty in fault mapping and highlights the value of structured workflows that incorporate landform-based confidence ranking. These findings contribute to ongoing efforts to improve fault displacement hazard analysis by quantifying uncertainty in pre-rupture fault maps.

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Data and code availability

We have published the mapped fault shapefiles for the Repeat Mapping Project on Zenodo: Zuckerman et al. (2026a).

Competing interests

The authors declare no competing interests.

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