Evaluation of Remote Mapping of Active Fault Traces

by

Rachel Adam

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Graduate Supervisory Committee:

Chelsea Scott, Co-Chair
Ramon Arrowsmith, Co-Chair
Darryl Reano

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ABSTRACT

Accurate fault maps are an important component in the assessment of hazard from fault displacement. Different mapping techniques, biases and ambiguous geomorphic evidence for faulting can drive even expert mappers to produce different fault maps. Another challenge is that future ruptures may not follow past ruptures, so available evidence in the landscape may not lead to accurate rupture prediction.

The ultimate goal of my work is to develop a systematized approach for fault mapping so that resulting maps are more evidence-based and ultimately of higher quality I systematized the active fault mapping process and the documentation of evidence for potential fault rupture. I developed and taught a systematic mapping process based on geomorphic landforms evident in remote sensing datasets to undergraduate students, graduate students, and geologic professionals. My approach uses data acquired before historic ruptures to make and test “pre-rupture” fault traces based on the landscape morphology, geomorphology, and geology. The mappers used the Geomorphic Indicator Ranking system (GIR) to represent the geomorphic evidence for faulting such as scarps, triangular facets, offset features, beheaded drainages, and many more.

I evaluated the approach in three ways: (1) To assess the geomorphology that best predicts future rupture, I compared the separation distance between the mapped geomorphologic features and the rupture. Scarps and lineaments performed best. (2) I compared the fault confidence chosen by the mapper versus that computed from GIR elements (i.e., mapped geomorphology) near the fault traces. Accurately characterizing fault confidence requires a balance between the mapper input and the calculated confidence rankings. (3) I conducted listening sessions with 21 participants to understand each participant’s approach to fault mapping to highlight best practices and challenges of geomorphic fault mapping. The terminology and mapping process vary by experience level. My approach works both as a teaching tool to introduce tectonic geomorphology and fault mapping to novice mappers, but also works in an industry setting to establish consistent documentation for fault maps. These higher quality fault maps have implications applications of fault mapping including easier dissemination of information, comparison between different fault maps, and hopefully more accurate fault locations for hazard mitigation.

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ACKNOWLEDGMENTS

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This work was supported by Pacific Gas & Electric. I would like to thank Dr. Chris Madugo for providing me with an enriching research topic that will have a tangible impact on reducing fault displacement hazards. I thank the School of Earth and Space Exploration for the First-Year Fellowship. This study was reviewed and considered exempt by Arizona State University Institutional Review Board; IRB ID: STUDY00015172. As a student of ASU, I acknowledge that the Tempe campus sits on the ancestral homelands of those American Indian tribes that have inhabited this place for centuries, including the Akimel O’odham (Pima) and Pee Posh (Maricopa) peoples.

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CHAPTER 1

INTRODUCTION

Risk to infrastructure, such as critical facilities and lifelines from earthquake fault rupture, is dependent on earthquake frequency, displacement amplitude, and fault location. While there are a variety of accepted tools employed to characterize fault location, including geophysics, trenching, and drilling, the most common technique, and the starting point for most fault rupture hazard studies, is geomorphic mapping to identify evidence of past surface rupture or deformation in the landscape, which are assumed to be strong predictors of future rupture location.

Active fault maps produced by experienced geologists may differ depending on how the geologist interprets the landscape and evaluates the geologic, geomorphic, and morphologic evidence (surficial deposits, offset units, scarps, disruption of the landscape) in the landscape. Until recently, there were few quantitative data on how well geomorphic mapping works as a predictor of future rupture location. Thompson Jobe et. al (2020) identified and mapped tectonic features that existed in the landscape prior to the M 6.4 and M 7.1 Ridgecrest, CA earthquakes in 2019 to map faults and found that while not all the faults mapped in the study ended up rupturing in the 2019 earthquake, prominent features identified both in remote mapping and field mapping provided the most accurate locations for the faults which ruptured in 2019. Scott et al. (2023) examined how well geomorphic fault maps developed by students and professional geologists utilizing pre-earthquake imagery and digital elevation models for seven historical surface-rupturing earthquakes predicted rupture location. Scott et al. (2023) found that accurate fault mapping is challenging regardless of the experience level of the mapper due to the range of geomorphological evidence and its interpretation as well as variations in mapping style. Another challenge is that future ruptures may not follow past ruptures, so available evidence in the landscape may not lead to accurate rupture prediction. Furthermore, the way a mapper documents their evidence and final fault maps may differ.

Differences in geomorphic interpretation, mapping style and documentation all contribute to epistemic uncertainty in geomorphic fault mapping. Understanding how geologists map faults can be leveraged to improve the reliability of geomorphic fault mapping. Low skill and bias can lead to epistemic error in fault mapping. Biases include anchoring and confirmation bias. Anchoring bias is the failure to depart from initial ideas which include the opinions formed after receiving initial information about the faults such as the tectonic setting or specific fault information (Salisbury et al., 2015; Bond, 2007). The more experience the mapper has, the more anchoring bias they may bring to the mapping based on their pre-existing knowledge of faults from prior work. This is also known as availability bias or heuristic, where the mapper relies on examples that come to their mind immediately when observing an area (Jones, 2005). Confirmation bias is when the mapper seeks to support their results based on prior similar experience while actively disregarding conflicting observations (Salisbury, et al., 2015). Due to these biases, a fault map may not encompass all of the evidence. It is important to decrease the effect of these biases to decrease the dependence on prior knowledge of the landscape. There is wide variation in how fault trace linework and supporting geomorphic, geologic, and morphologic evidence is documented (e.g., Zielke et al., 2015; Jobe et al., 2020; Koehler et al., 2013; and Toké et al., 2014 and many others). Not having a uniform system to convey how geomorphic evidence supports the existence and location of a fault trace makes communicating the mapping results challenging.

My research examines the process by which students and geologic professionals develop geomorphic-based active fault maps and compare the mapping to subsequent surface ruptures to identify ways to improve the reliability of geomorphic fault mapping. My work makes ‘pre-rupture’ fault maps using data acquired before the historic earthquakes I reference in this study. I start by outlining the process I helped develop to teach fault mapping both to students enrolled in the course taught by Dr. Chelsea Scott, Dr. Ramon Arrowsmith, and Dr. Rich Koehler, and to the hired consultants. I developed a standardized workflow to create a fault map which includes the Geomorphic Indicator Ranking System (GIR) used to create the pre-rupture fault maps listed in Figure 2. I compare the fault confidence ranking of traces when they are assigned by the mapper against the same traces determined automatically by the mapped GIR features. I assess the performance of different geomorphologic features in predicting ruptures by measuring the distance between mapped GIR features to the subsequent surface rupture traces. My fault symbology follows the ‘Fault Confidence Ranking’ scheme (Scott et al., 2023; inspired by Scharer et al.; 2007; Seitz, 1999) in which the fault trace is ranked based on the mapper’s confidence in fault location (strong, distinct, weak, uncertain). Finally, I discuss observational analysis derived 30-minute listening sessions with all participants to better understand the fault mapping process and understand where sources of bias arise in the mapping process. These analyses demonstrate the utility of my abstracted mapping fault process with the Geomorphic Indicator Ranking System (GIR) and provide information on sources of uncertainty in existing mapping processes.

CHAPTER 2

TEACHING FAULT MAPPING

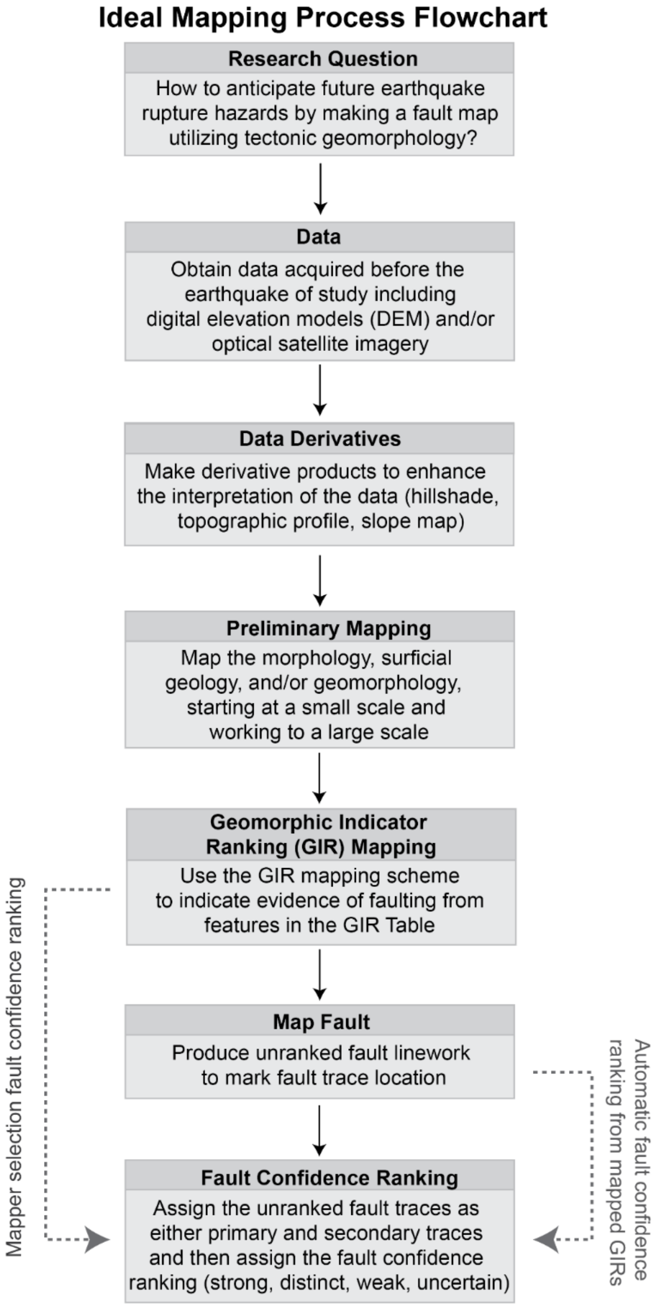
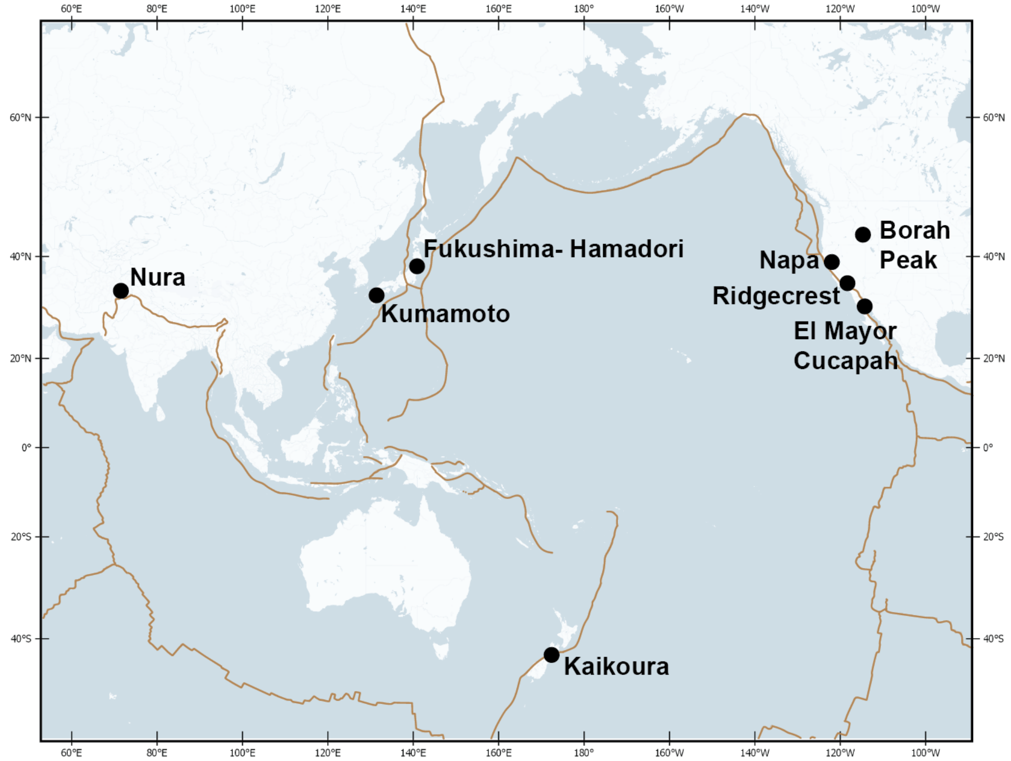


Figure 1. Flow chart for the idealized fault mapping process utilizing tectonic geomorphology and remote sensing data. Once a motivating research question is defined (step 1), the workflow includes: (step 2) prepare the remote sensing data, (3) make data derivatives including topographic hillshades, slope maps, and topographic profiles (4) map preliminary geologic, geomorphic, and geologic evidence for faulting, (5) apply the Geomorphic Indicator Ranking system, (6) map unranked faults, (7) and apply the fault confidence ranking to the unranked mapped fault traces.

In Spring 2022, Dr. Chelsea Scott, Dr. Ramon Arrowsmith (Arizona State University), and Dr. Rich Koehler (University of Nevada- Reno) co-taught a course, ‘Mapping tectonic fault from geomorphology,’ with students from McGill University and Oxford University to teach students how to map faults based on topography data and imagery acquired before an earthquake to make a ‘pre-rupture’ fault map (Figure 1). Twenty-one students enrolled in the course: four undergraduates, 14 graduate students, and three post-doctorates. All students had pre-requisites of structural geology and geomorphology with varying levels of prior experience in fault mapping. The course was designed to teach students how to produce high-quality fault maps while minimizing the dependence on prior knowledge and experience. Six industry geologists were hired to make pre-rupture fault maps for the same areas. I refer to all students and consultants as ‘mappers’ or ‘participants.’

The mappers made a series of pre-rupture fault maps for part or all the following earthquakes: 1983 M6.9 Borah Peak, 2008 M6.6 Nura, 2010 M7.2 El Mayor Cucapah (EMC), 2011 M6.6 Fukushima-Hamadori, 2014 M6 Napa, and 2019 M7.1 Ridgecrest (Figure 2). The remote sensing datasets included pre-event optical imagery available from Google Earth as well as historic digital elevation models, lidar topography and Shuttle Radar Mission Topography (SRTM; Farr et al., 2007) mostly available from OpenTopography (http://opentopography.org). Other data was sourced internally from colleagues.

Figure 1 illustrates the ideal mapping process for mapping faults that I taught the mappers (students and professionals). The process begins with a research question. The motivating question was, “How can we best anticipate future earthquake rupture hazards based on mapped faults and tectonic geomorphology?” In the first and second steps, the researcher organizes base data (DEM and imagery) and produces derivatives prepared in a Geographic Information System (we mostly have used QGIS; https://qgis.org/). In the third step, the researcher implements morphologic mapping which includes mapping breaks in slope, ridges, saddles, and other changes in topography. The researchers also implement geologic mapping which emphasizes mapping the extents and establishing relative ages of Quaternary surficial geologic units to understand the relative timing of any surface disruptions. Researchers also documented the geomorphic mapping which includes geomorphic indicators of faulting (e.g., triangular facets, scarps; see below) but can include other features that may not be tectonic in origin (e.g., drainage network, fluvial terraces, anthropogenic traces) where GIR feature placements are not applicable. Depending on the landscape and related vegetation, one type of mapping may be more advantageous than another to observe faulting evidence. For example, in an arid landscape, it may be more advantageous to construct a surficial Quaternary geologic map to observe disruption in the natural progression of the landscape and alluvial fans. Researchers may use a hybrid of all the mapping types to characterize the landscape. In the fourth step, the researcher maps the GIR (Section 3.1) features, basing their decisions off of their preliminary mapping. In the fifth step, the researcher uses the GIR features with their respective quantities and rankings to map an unranked fault trace. In the final step, the researcher assigns the unranked fault trace as either primary or secondary and assigns them a confidence ranking (strong, distinct, weak, uncertain).



Earthquake	Slip	Mapping area fault length	Climate	Optical	Topography
1983 M6.9 Borah Peak	N	35 km	Semiarid	No	2 m DSM
2008 M6.6 Nura	R	8 km	Semiarid	Yes	30 m SRTM
2010 M7.2 El Mayor Cucuaph	SS-N	55 km	Desert	Yes	6 m lidar
2011 M6.7 Fukushima -Hamadori	N	11 km	Subtropical	Yes	2 m DTM
2014 M6.0 Napa	SS	25 km	Mediterranean	Yes	1 m lidar
2016 M7.0 Kumamoto	SS-N	20 km	Subtropical	Yes	0.6 m lidar
2016 M7.8 Kaikoura	SS	18 km	Oceanic	Yes	1 m DTM
2019 M6.4 Ridgecrest	SS	6 km	Desert	Yes	2 m DSM

Figure 2. Map showing major tectonic plates (brown) and pre-rupture fault mapping locations (top). Table (bottom) lists the mapping locations, magnitude, earthquake year, slip sense (N-normal, R -reverse, SS - strike-slip), the fault length within the mapping area, climate, and the available imagery for mapping (optical, Digital Elevation Models - DEM, Shuttle Radar Topography Mission-SRTM, lidar).

CHAPTER 3

METHODS

3.1 Geomorphic Indicator Ranking System

The Geomorphic Indicator Ranking (GIR) approach is a tool that facilitates mapping potentially active tectonic faults and the supporting geomorphic evidence, labelling known tectonic geomorphology and assigning the features a confidence ranking (Scott et al., 2023). The GIR was introduced in Scott et al. (2023) as an approach to standardize and teach the tool to novice mappers to create fault maps that are more evidence-based. We advance the methodology here and provide a workflow that mappers can easily adapt to their projects.

Examples of geomorphic features indicating fault activity include scarps, triangular facets, vegetation lineaments. We also mapped modifiers, which may indicate faulting if they appear with other strong features, but they are not enough on their own to indicate active faulting. Geomorphic features are assigned a ranking with a rank of 4 providing the strongest evidence for faulting and a rank of 1 providing the weakest evidence. Features with a rank of 4 are almost unequivocally a result of tectonic activity. These features include offset drainage channels, offset alluvial fan complexes, and triangular facets. Features with a 3 ranking are strong evidence for faulting. For example, a beheaded drainage provides strong evidence because it is likely offset along the fault zone. Features with a 2 ranking are moderate evidence for faulting. For example, depression/sag pond provides this level of evidence because they are possibly localized along a fault zone and elongate parallel to its trace. Features with a 1 ranking provide little evidence of faulting. Features with this ranking can be a result of tectonic activity but may also be a result of other geomorphic processes. For example, a topographic bench can indicate tectonic faulting but can form from other processes. The modifiers have a score of +/- 1 and should only be mapped when near a main GIR feature. Positive modifiers fortify the fault evidence but do not serve as stand-alone evidence. For example, a lineament in topography may result from a number of processes including faulting. Negative modifiers obscure evidence of faulting. They reduce the mapper's confidence on fault existence and location. For example, erosion will remove features and decrease their continuity. Below (Table 1) are the first few features listed in the 'GIR Table' (Appendix A) that lists all features included in the approach that participants use to map geomorphological evidence of active faulting.

Feature	Rank	Description	Justification as fault indicator
Offset Terraces (OT)	4	Laterally and obliquely offset fluvial terraces	Coseismic slip offsets terraces and terrace risers
Offset drainage channel (ODC)	4	A channel with two ~90° bends that is otherwise straight	Offset caused by differential translation of a stream by a fault
Offset or cut Alluvial Fan Complex (AFC)	4	Series of fan-shaped alluvium deposits that are offset or cut by a fault	Faults can cut across and offset alluvial fans of different ages
Single Offset or cut Alluvial fan (AF)	3	A single fan-shaped alluvium deposit that is offset or cut by a fault	Faults can cut across and offset a single alluvial fan unit

Table 1: First few lines of the GIR Table including the feature name, feature rank, feature description, and the feature's justification as a fault indicator (Appendix A).

With the GIR approach, the mapper uses a point shapefile in a desktop geographic information system (GIS) to label tectonic geomorphologic features every ~100 m where applicable. Once preliminary mapping (geologic, geomorphic, morphologic) is complete (Figure 1), the mapper uses the GIR to indicate the faulting based on the GIR features (Table 1). Features are colored according to ranking (4-red, 3- orange, 2 -yellow, ±1- gray) to guide the mapper's eye to the strength of the evidence in the landscape (Figure 3).

Figure 3 illustrates the GIR approach to fault mapping applied to Washoe City, northwestern Nevada. Figure 3a shows the topographic hillshade (Zaepfel, 2017). Figure

3b illustrates the preliminary mapping step in which ridges, drainages, debris flows/landslides, anthropogenic alteration, and slope breaks are mapped. Figure 3c shows the GIR features that illustrate the fault evidence. Figure 3d shows the unranked, mapped fault traces. Figure 3e shows the fault traces with a confidence ranking (strong, distinct, weak, or uncertain) and their designation as primary or secondary. Mappers choose to segment the fault traces at natural breaks in the geomorphology. Table 2 distinguishes characteristics of primary and secondary traces (e.g., Nurminen et al., 2020, 2022; Sarmiento et al., 2021). Geomorphic ranking does not determine whether the trace is primary or secondary. The mappers may iteratively loop through the last few steps of the workflow to update their mapping and confidence rating as they continue to consider the evidence for faulting.

Primary	Secondary
• Continuous trace • Multiple identifiers • Follows similar strike to other primary faults • Can be found en echelon, parallel sequence • Slip is typically synthetic to the main deformation of the fault	• Broken or discontinuous trace • Few identifiers • Can deviate from the main fault strike • Can be found in singular, stray locations • Slip can be antithetic of synthetic to slip along the primary fault

Table 2: Primary versus secondary fault distinctions (e.g., Nurminen et al., 2020, 2022; Sarmiento et al., 2021).

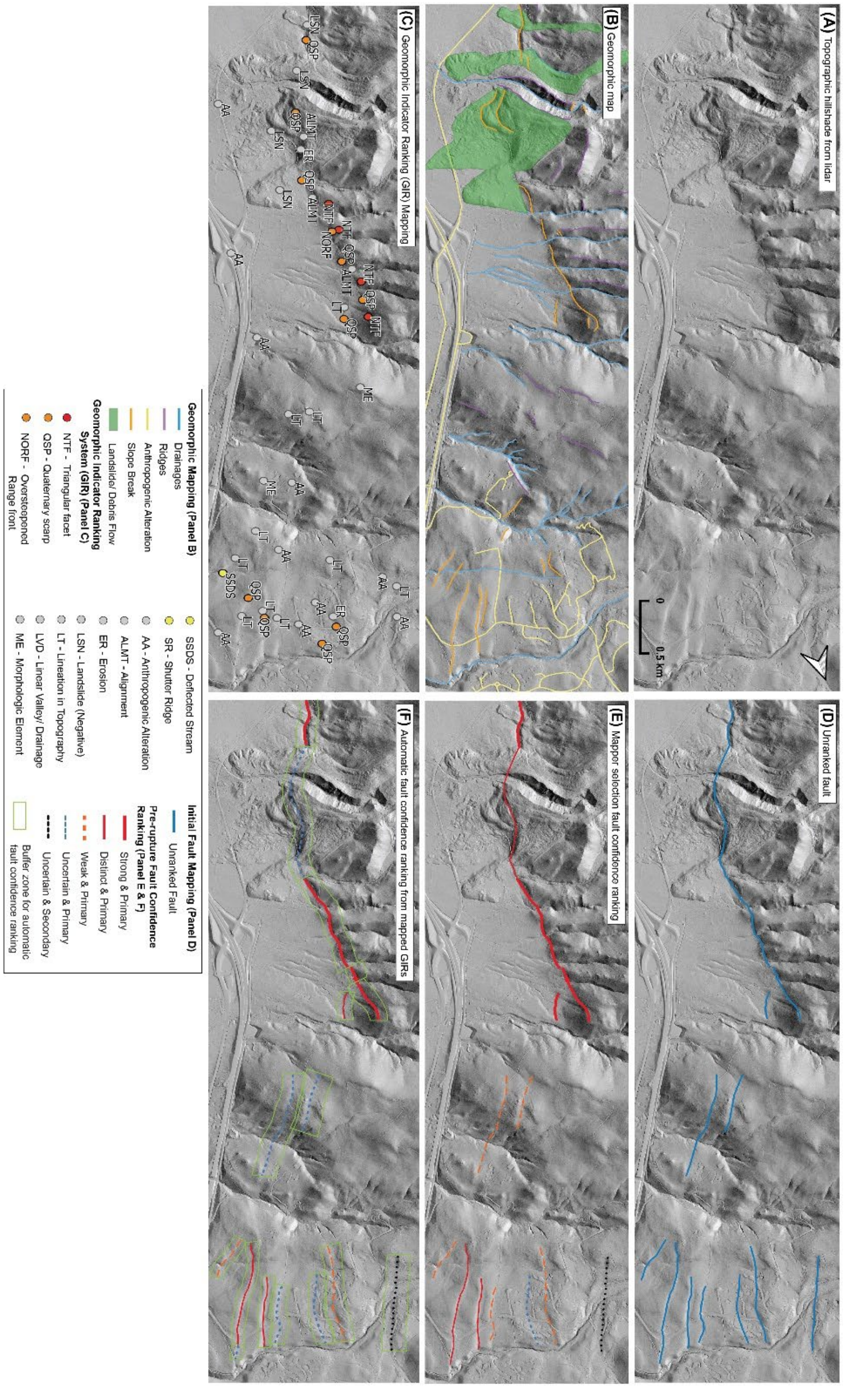


Figure 3. Example of mapping workflow (Figure 1) applied along a set of faults in Washoe City, northwestern Nevada. (A) Lidar-derived topographic hillshade (Zaepfel, 2017). (B) Geomorphic map. (C) Geomorphic Indicator Ranking (GIR) mapping. (D) Unranked fault. (E) Mapper selection fault confidence ranking. (F) Automatic fault confidence ranking from mapped GIRs.

3.2 Geomorphic Feature to Rupture Distance Analysis

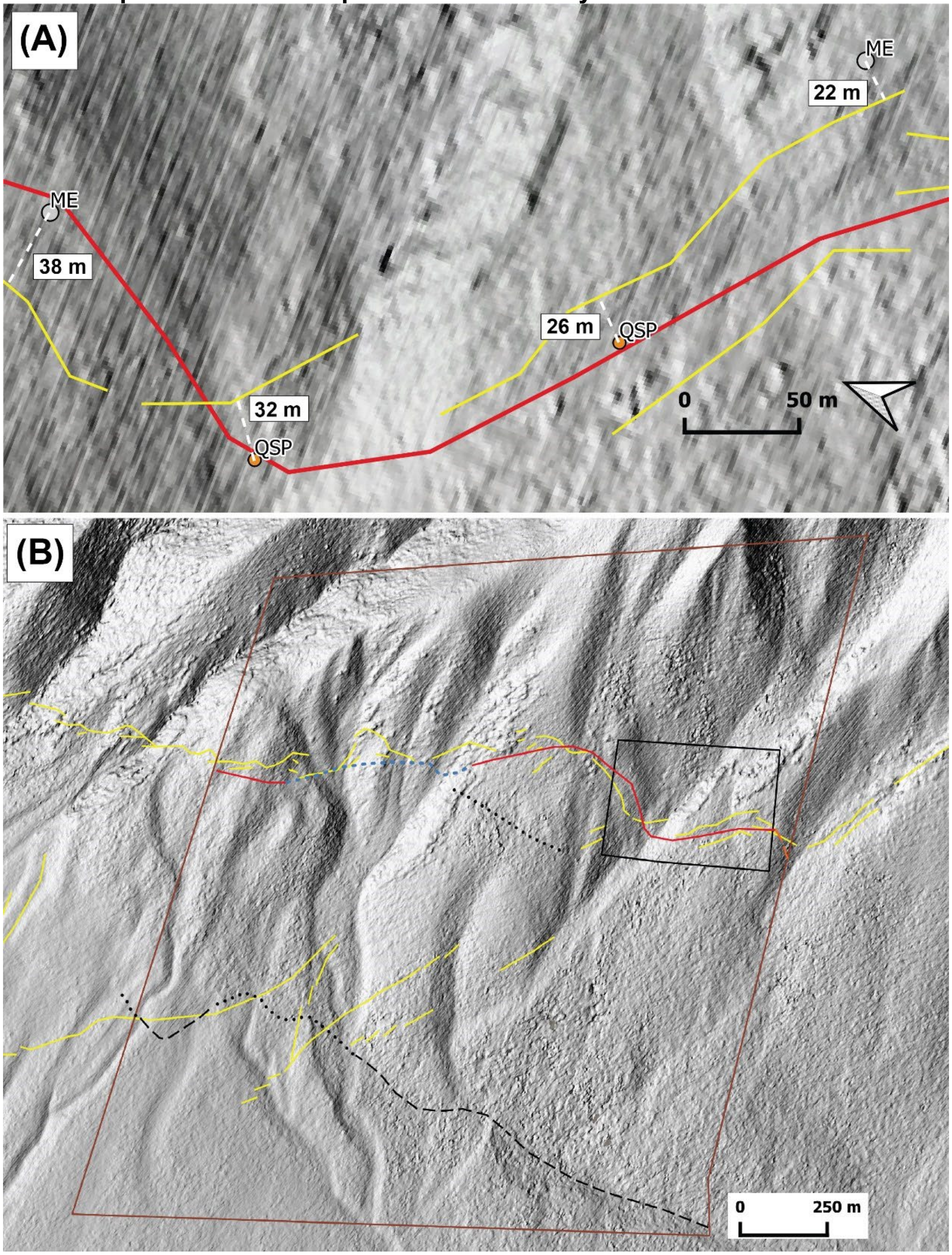


Figure 4. (A) Example of geomorphic indicator ranking feature to rupture analysis with mapped faults (red), GIR features, rupture traces (yellow) and the GIR feature-to-rupture distance. (B) Borah Peak Idaho example with mapping boundary (brown), inset for A (black), rupture linework (yellow) and pre-rupture fault confidence traces.

The geomorphic feature-to-distance rupture analysis can give metrics on which geomorphic features are closer to ruptures than others. This can indicate which features are best at predicting future fault location and assess the overall performance of the GIR. More specifically, the feature rankings and the utility of having the system as a point feature in GIS software. The goal of this analysis is to assess the performance of the geomorphologic features in predicting the subsequent rupture location. The 'Geomorphic Indicator Ranking Feature to Rupture Distance by Location' statistical analysis is based on the mapped GIR points from high-quality pre-rupture mapped faults and post rupture published linework. Figure 4 shows an example of this analysis in Borah Peak, Idaho where the mapped GIR features (Figure 4a) are measured to the closest coseismic surface rupture shown in yellow.To increase the quality of the results at the cost of the size of the dataset, I used only high-quality geomorphology maps. In high-quality maps, the mapped geomorphology was over 80% correct based on internal discussion with other instructors in the course. The majority of high-quality maps were from senior students and the consultants.

3.3 Mapper Versus GIR Fault Confidence Ranking Analysis

. I want to observe how much the GIR approach can be standardized while maintaining the mapper's intention with the proposed GIR mapping and fault locations. The fault confidence ranking ranks the mapped fault traces based on the mapper's confidence in fault location (strong, distinct, weak, uncertain). In this analysis, I compare the mapper assigned fault confidence ranking (Figure 3E) with fault confidence ranking from the automatic GIR scoring technique (Figure 3F). The mappers may not have used all four fault confidence rankings in each area, whereas the automatic approach does use all four confidence rankings provided enough faults are mapped.

I break each fault trace into 1-kilometer segments to capture the mapped GIR features and encompass the scale of mapping. To calculate the score of each fault segment, the surrounding GIR features are counted with their respective rankings to get a segment score (Equations 1 & 2). The segment scores are scaled so they reflect a 1 -4 ranking similar to the fault confidence ranking (Equation 3).

Example of segment scores:

$$\begin{aligned} segment\ 1\ score &= \mathbf{4}\ triangular\ facets\ (rank = 4) + \mathbf{2}\ scarp\ (3) + \mathbf{1}\ erosion\ (-1) \\ &= 19 \end{aligned} \tag{1}$$

$$\begin{aligned} segment\ 2\ score &= \mathbf{1}\ deflected\ stream\ (2) + \ \mathbf{1}\ cross\ cut\ (+1) + \mathbf{1}\ saddle\ (+1) \\ &= 4 \end{aligned} \tag{2}$$

The segment scores are scaled so they reflect a 1 -4 ranking similar to the fault confidence ranking (Equation 3). The segment score represents the individual scores of each segment illustrated in Equations 1 & 2. Symbols a and b are the smallest and largest segment scores, respectively, for the fault traces in a given mapping area.

$$scaled\ score = 3 * \frac{segment\ score - b}{a - b} + 1 \tag{3}$$

I use a buffer zone (the polygon that encapsulates the GIR points to calculate the segment score) of 100 meters perpendicular to the strike of the plotted fault trace to capture any related GIR features within each 1 km segment (Figure 3F).

3.4 Observational Analysis

Understanding the fault mapping process is a critical component of my goal of making more accurate fault maps. Once the nuances and differences between each individual's mapping process can be observed, I can determine sources of epistemic error and anchoring and confirmation bias to try and mitigate them. These differences may be a result of level of experience and knowledge, so they may not result in an inaccurate map. However, it is important to assess how and if a mapper deviates from our ideal fault mapping process, and if that deviation results in a less accurate fault map. It is also important to gain perspective on the differences between what a mapper thinks from their verbal explanation of their process versus what their resulting mapping shows.

To understand the fault mapping thought processes, I conducted 30-minute listening sessions with six professional geologists and 12 students enrolled in the Spring 2022 course. I conducted the sessions over Zoom while the participants shared their screen open to QGIS. I recorded and transcribed the sessions. I received approval from the International Review Board (IRB) for a study including human participants.

I modeled the methodology for the listening sessions after a guide from Oregon Health & Science University (Toney, 2018) which includes recommendations for receiving IRB approval, and the outline for the listening sessions. I utilized the proposed outline of an introduction, discussion, conclusion, and tips to direct participants to answer or expand on their responses.

I conducted the student listening sessions while the students were completing the final fault mapping assignment in the first month of the course. The students used a Digital Elevation Model (DEM) base map to a fault map in the arid, normal faulting area outside of Washoe City, northwestern Nevada (Figures 3 & 4). I selected this area because of its well-exposed geomorphology including triangular facets, scarps, landslides, and beheaded drainages. Before the listening session, some students completed only their preliminary morphologic, geologic, or geomorphic mapping while others completed all required aspects of the assignment. I completed the consultant interviews after they finished their pre-rupture fault maps for five mapping locations (Ridgecrest [2], El Mayor Cucapah, Borah Peak, and Fukushima; Figure 2). The student and consultant interviews reflected the different locations: The extensional tectonics and arid landscape setting of student mapping assignment presented landforms such as linear rangefronts, debris flows, Quaternary scarps, and disrupted drainages. In contrast, the consultants mapped areas included several tectonic regimes and climates.

The interview questions centered around understanding fault mapping processes and testing the utility of the GIR tool. In the interviews, I asked the following questions: 1) "What features immediately pop out to you in the landscape?", 2) "What is the evidence for your fault location?", and 3) Follow up questions varied based on initial responses and focused on gauging prior experience with relevant topics (geology, geomorphology, fault mapping), their initial process to survey the area, and the tools the participants found most useful during the mapping process.

I transcribed the interviews using Zoom software and coded the session using NVivo. NVivo is a qualitative analysis software that helps researchers analyze large quantities of written or transcribed data. I 'coded' textual data by highlighting certain responses that reflect mapper's prior experience and mapping process, as shown in Table 3. With the codes, I organize the responses into subcodes. I completed the coding with the sub-codes in Table 1 and co-chair Dr. Scott completed an inter-rater reliability to validate the methodology and coding results.

Code	Sub-code
Prior experience	Research, prior courses, fault mapping, geomorphology, our fault mapping course, technology, work
Mapping process	Look for linear patterns/ lineaments, faults first, geologic mapping, geomorphic indicator mapping, morphologic mapping, zoom out then in
Geomorphic indicator mentions	Lineament, alignment, triangular facet, (over-steepened) range front, ridge/ pressure ridge, scarp, (offset, deflected, or altered) drainage/stream, slope break, horst & graben, landslides

Table 3: List of codes and sub-codes used to code participant responses in NVivo. I generalized the geomorphic indicator features are to encompass terminology the participants used to describe the same feature.

The three codes are (1) prior experience, (2) mapping process, and (3) geomorphic indicator mentions (Table 2). These codes encompass critical components of the mapping process and suggest potential points of bias depending on prior experience or mapping process. More specifically, participants mentioning mapping or information acquired before the course instead of the course curriculum as rationale for their mapping decisions can indicate confirmation or anchoring bias. Responses that fit multiple sub-codes were coded as many times as appropriate. For example, a student that mentioned prior experience as a course that included geomorphology and fault mapping was coded twice, once for geomorphology and once for fault mapping.

CHAPTER 4

RESULTS

4.1 Geomorphic Feature-to-Rupture Distance Analysis

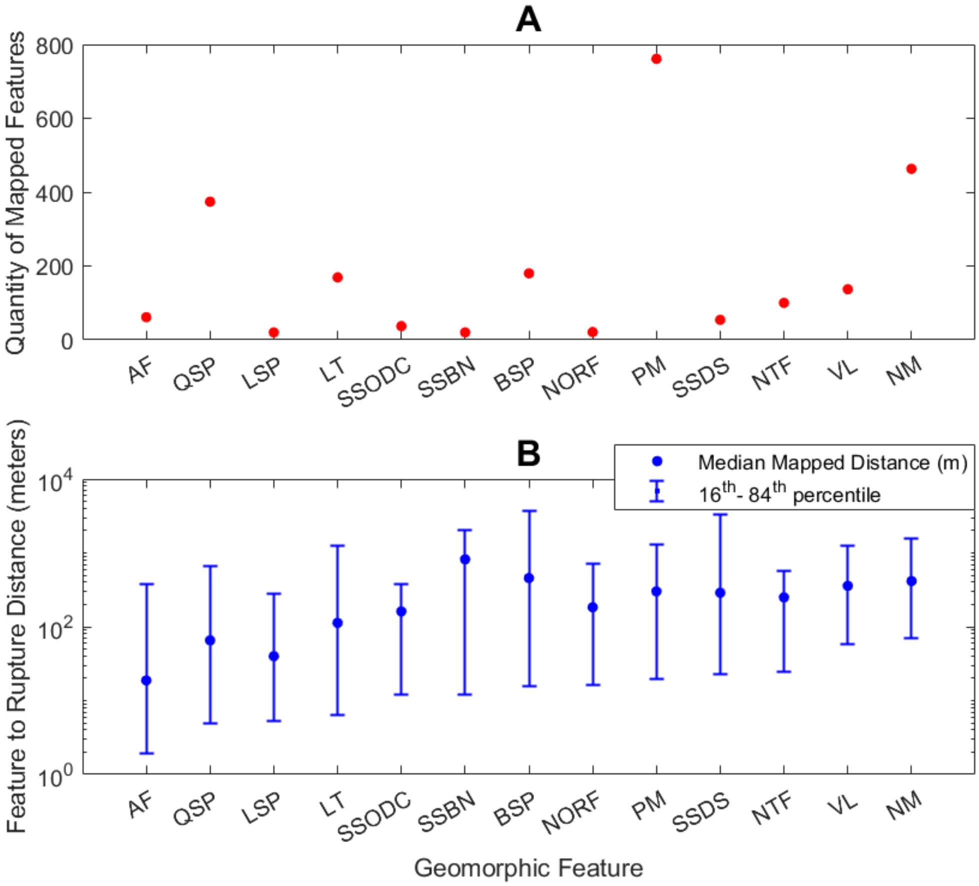


Figure 5: (A) Summary plot showing the thirteen most mapped features and their quantities (red point) for all areas. (B) The features' 16th (lower bound), 50th (blue middle point; median), and 84th (upper bound) percentile distributions of the separation between the GIR feature and the closet rupture. We applied a weighting so that each location has approximately the same contribution to these statistics. Sorted by increasing 16th percentile distances. Geomorphic features abbreviation from left to right: strike-slip/normal/ reverse offset or cut alluvial fan (AF), strike-slip/normal/ reverse quaternary scarp (QSP), landslide (positive) (LSP), lineation in topography (LT), strike-slip offset drainage channel (SSODC), strike- slip bench (SSBN), strike-slip/normal/ reverse bedrock scarp (BSP), normal over steepened range front (NORF), positive modifiers (PM), strike-slip deflected stream (SSDS), normal triangular facet (NTF), vegetation lineament (VL), negative modifiers (NM).

Feature	Mapped Quantity	Feature-to-Rupture Distance Percentile (m)		
		16th	50th	84th
Normal/reverse/strike-slip offset/cut alluvial fan (AF)	61	2	19	384
Normal/reverse/strike-slip quaternary scarp (QSP)	374	5	65	650
Landslide (positive) (LSP)	20	5	40	284
Lineation in topography (LT)	169	6	113	1240
Strike-slip offset drainage channel (SSODC)	37	12	161	372
Strike-slip bench (SSBN)	20	12	820	2022
Normal/reverse/strike-slip bedrock scarp (BSP)	180	16	183	704

Table 4: Statistics for the seven features with the lowest mapped feature-to-rupture distances.

Figure 5 shows the 16th, 50th, and 84th percentiles for the geomorphic features mapped by participants in all locations. The 16th percentile represents informs the feature-to-rupture proximity for features mapped adjacent to a fault that later ruptured. The 50th percentile represents the median feature-to-rupture distance. The 84th percentile represents features that are relatively distant from the ruptures and can reflect features mapped in error, features with no fault relationship (anthropogenic alteration), or aleatoric variability (i.e., feature near an actual fault that, by chance, did not rupture in the earthquake of interest).

Cut or offset alluvial fans had the lowest distances with 16th and 50th percentile feature-to-rupture distances of 2 m and 19 m, respectively. This feature was mapped most in EMC (Figure 6) and its high performance likely reflects that the feature is easy to identify and is often well-preserved. The Quaternary Scarp (QSP) was mapped 374 times and has 16th and 50th percentile feature-to-rupture distances of 5 meters and 65 meters, respectively. Landslide (LSP) and lineation in topography (LT) performed the next best. These features are modifiers (score +1), meaning that alone they do not provide strong evidence of faulting. However, the 16th percentile feature-to-rupture distances of 5 m (LSP) and 6 m (LT) indicate high performance. LSP was only mapped 20 times across all mapping locations, so while it is a good indicator of faulting, it may not be as prevalent as other geomorphic indicators. The 84th percentile for LT is 1240 m, while the 16th indicates it can be a good indicator, the high 84th percentile demonstrates that the feature may not always indicate faulting. The bedrock scarp (BSP) has a 16th and 84th percentile feature-to-rupture distance of 16 m and 704 m, respectively. The 84th percentile distance reflects the challenges of locating bedrock scarps that are eroded, especially if the faults have not ruptured recently.

In the next section, I present the geomorphic feature-to-rupture distance in EMC and Kaikoura focusing on Quaternary scarps and lineaments in topography.

4.2 M7.2 2010 El Mayor Cucapah Earthquake

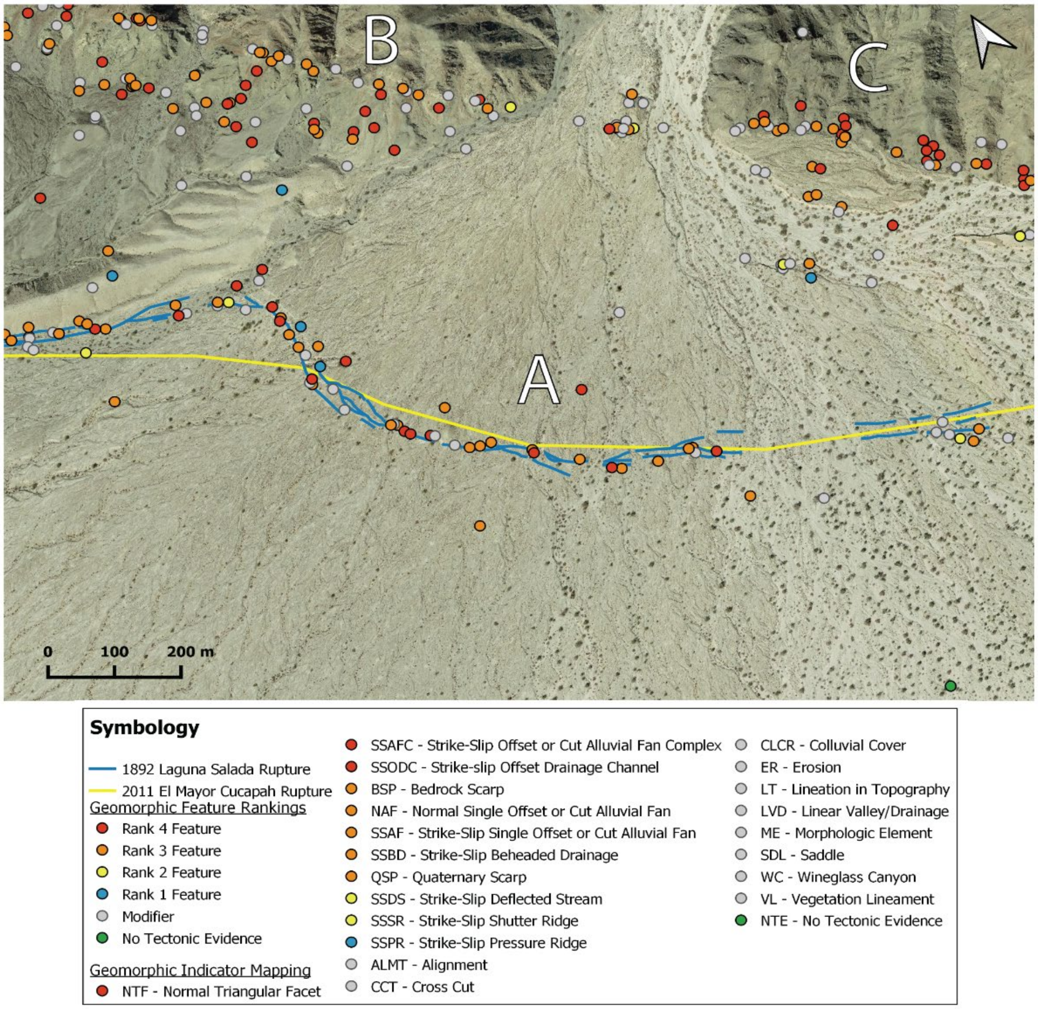


Figure 6: Map of a portion of the 2010 El Mayor Cucapah rupture traces (yellow, Fletcher et al., 2014) and 1892 Laguna Salada rupture traces (blue, Rockwell et al, 2015) with all Geomorphic Indicator Ranking (GIR) points displayed on satellite imagery acquired in 2006. Location A highlights rupture traces and GIR points in the alluvial fan. Locations B & C highlight GIR points along the range-front where the 2010 earthquake did not rupture.

Feature	Mapped Quantity	Feature-to-Rupture Distance Percentile (m)		
		16th	50th	84th
Offset/cut alluvial fan (AF)	53	1	9	399
Quaternary scarp (QSP)	164	2	19	390
Alignment (ALMT)	101	4	179	488
Morphologic element (ME)	128	28	322	820
Lineament in topography (LT)	31	56	376	1156
Erosion (ER)	44	19	383	819
Bedrock scarp (BSP)	63	155	433	699
Triangular facet (TF)	67	153	454	569

Table 5: Eight features with the lowest median feature-to-rupture distance mapped at least 30 times for El Mayor Cucapah.

The Quaternary scarps (QSP) median distance (20 m) and are mapped 1-50 m from the 1892 and 2010 rupture traces at Location A (Figure 6). These distances are relatively small and are mapped along or near the 1892 and 2010 rupture traces. The rupture trace for the 2010 rupture is basin-ward and follows the same trend as the features mapped along the range front. Triangular facets (TF) and bedrock scarp (BSP) have the highest median feature-to-rupture distance of 433 m and 459 m, respectively (locations B & C). These features mapped along the range front typically thought of as strong fault indicators (Axen et al., 1999; Dong et al., 2018). However, this bedrock scarp did not rupture in 2010 (Mueller & Rockwell, 1995). Assuming the fault was correctly mapped, this represents aleatoric variability in rupture patterns (1892 and 2010). The mapped geomorphology indicates the mappers thought the features along the range front are tectonically formed.

4.3 M7.8 2016 Kaikoura Earthquake

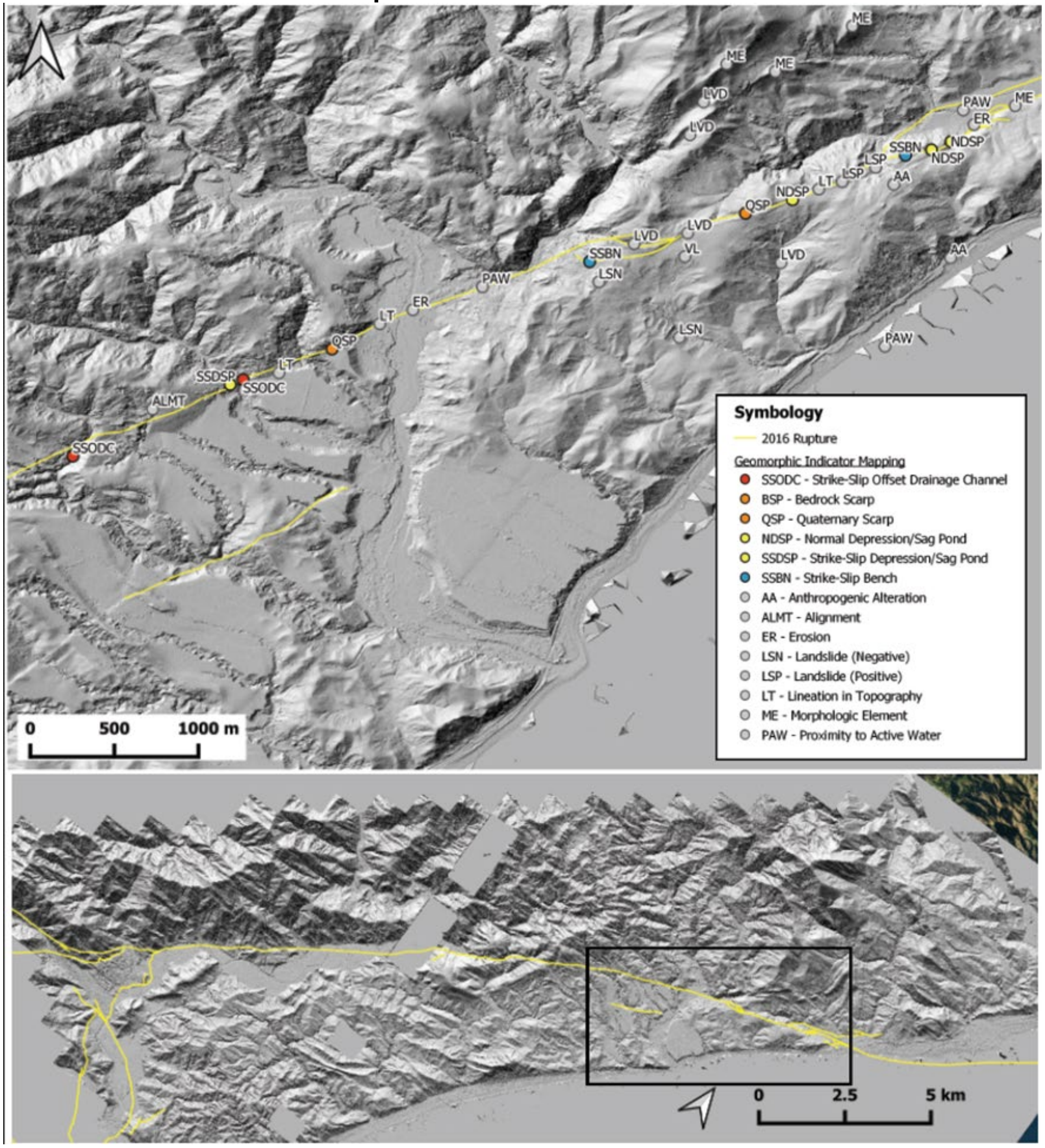


Figure 7: Map of the Kaikoura (2016) rupture (yellow) with Geomorphic Indicator Ranking (GIR) points.

Feature	Mapped Quantity	Feature to Rupture Distance Percentile (m)		
		16th	50th	84th
Lineament in topography (LT)	7	0.1	7	43
Quaternary Scarp (QSP)	6	2	11	108
Landslide (positive, result of shaking) (LSP)	6	4	31	111
Linear Valley/ Drainage (LVD)	14	24	191	692
Proximity to Active Water (PAW)	9	6	1293	5416
Morphologic Element (ME; ridges & slope breaks)	37	481	1601	3372
Anthropogenic Alteration (AA)	9	38	2658	5033

Table 6: Seven features mapped at least 5 times with the lowest median feature-to-rupture distance for Kaikoura.

The Quaternary scarp (QSP) and the landslide (positive LSP) were both mapped six times and have meter-scale feature-to-rupture distances. Landslides can form from coseismic shaking and thus indicate fault activity, but they can also obscure other evidence for faulting. In this instance, the pre-rupture landslides were good indicators of the future rupture. Lineament in topography (LT) performed well in this assessment with meter-scale 16th and 50th percentiles. Distinguishing a scarp from a more general "lineament" can be challenging in areas with high erosion and vegetation as the evidence can be more obscured and less preserved. The performance of LT indicates that this feature can serve as a good indicator of faulting.

4.2 Mapper versus GIR Fault Confidence Ranking Analysis

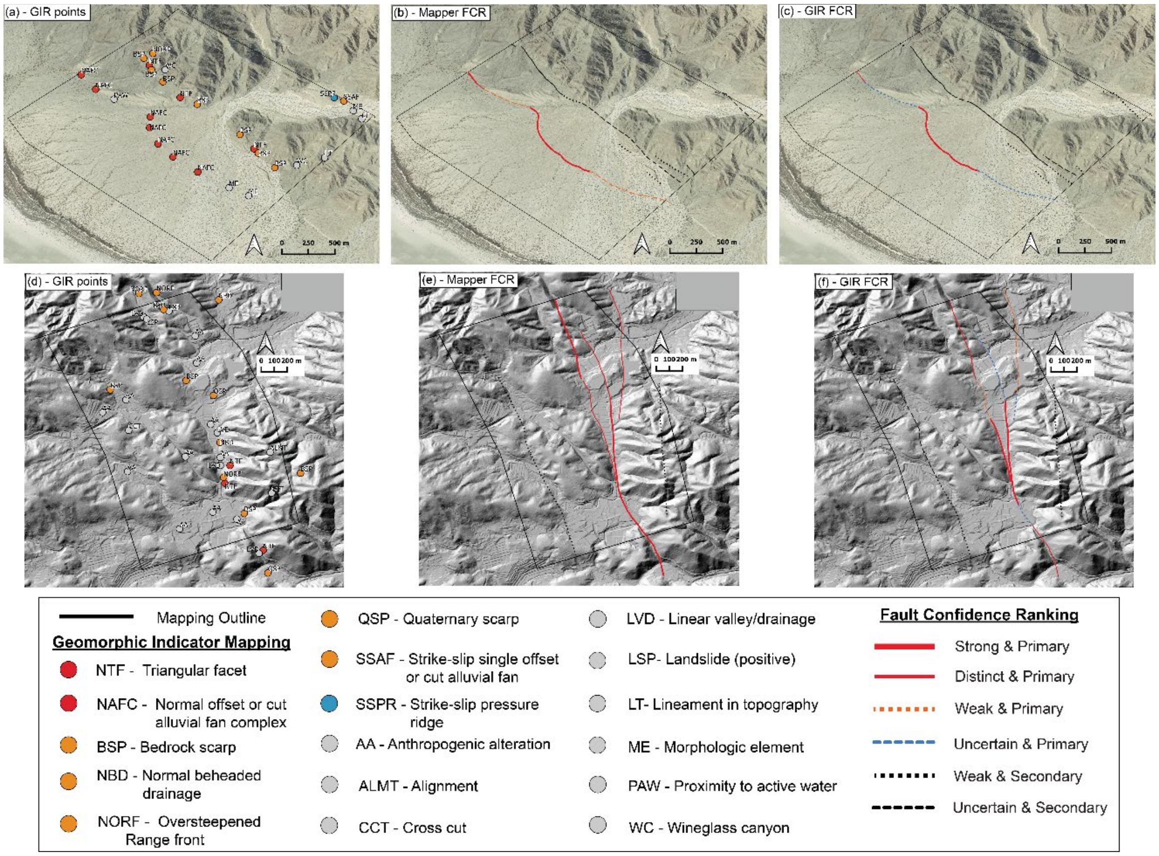


Figure 8. (a) Consultant map of geomorphic indicator mapping (b) Consultant fault linework using mappers decision for fault confidence ranking. (c) Consultant fault linework using the automatic scoring technique from the mapped GIR features.

El Mayor Cucapah

The rankings do not differ greatly from the mapper's intuition to the GIR score fault linework apart from the segments on either side of the strong fault in the alluvial fan and the segment crossing the alluvial plane along the range front. Figure 8a shows the mapped GIR features along the rangefront with triangular facets and bedrock scarps. There are no mapped GIR features where the alluvial fan exits the rangefront.

The mapped GIR features in the alluvial fan are offset/cut alluvial fan complexes and morphologic elements. The segments change from weak to uncertain within the alluvial fan because there are only modifiers to support the fault placement. The segment across the fan along the range front increases in confidence due to the scarp features on either side of the fan deposit.

Fukushima-Hamadori

Fault segments using the highest ranking GIR features (4 – triangular facet) maintain the highest ranking across both ranking techniques and anticipate the rupture well. These features were mapped along the rangefront shown in Figure 8d with triangular facets and beheaded drainages The fault confidence ranking determined by the GIR scoring technique captures the local changes in geomorphology better than the mappers' intuition, especially in areas with anthropogenic alteration and erosion in the central area of the mapping polygon.

4.3 Observational Analysis

Prior Experience

My questions surrounding mappers' prior experience were to establish a baseline for all participants and understand if prior experience impacted the mapper's decision making. Below is a table showing the sub-codes for the prior experience code and how many times each was coded for both students and consultants (Table 7)

Sub-code	Student (12 total)	Consultant (6 total)
Research	13	2
Prior courses	11	
Fault mapping	10	4
Geomorphology	9	
Our course	5	
Technology	4	2
Work/Job	2	6

Table 7: The sub-codes for the prior experience code listed with the number of times each sub-code was coded by the students and the consultants.

Students who mentioned experience with fault mapping (either through a relevant course, research, or specific project) tended to map faults first and geomorphology afterwards. Among the consultants, a common approach was to map potential fault locations based primarily on lineaments, then iteratively refine the traces based on geologic, geomorphic, or morphologic evidence in the landscape. In the course, students were taught to map all the supporting evidence (geomorphic, geologic, morphologic)- which may include lineaments- before mapping faults (Figure 1). This process differed between the students and consultants as consultants tended to immediately map either lineaments or faults first and map supporting evidence to refine their traces afterwards as described below.

Mapping Process

The results from the mapping process code and sub-codes are listed in Table 8. I hope to use my understanding of the mapping process and the assumptions made by the mappers to improve the mapping processing, resulting fault map and ultimately hazard characterization for PFDHA. More specifically, I can understand where a mapper may deviate from the ideal fault mapping processes and if that deviation results in errors in the final fault map. Also, I can observe which tools are most beneficial to mappers so they can be emphasized to future mappers.

Sub-code	Student (12 total)	Consultant (6 total)
Look for linear patterns/lineaments	5	4
Zoom out then in	4	3
Faults first	2	2
Geologic mapping	3	0
Geomorphic indicator mapping	5	2
Morphologic mapping	1	0

Table 8: The sub-codes for the mapping process code listed with the number of times each sub-code was coded by the students and the consultants.

There were two common sub-codes participants used when starting their mapping process: 1) look for linear features/trends. Below is a quote from a consultant mapper summarizing their mapping approach:

> “I started by mapping lineaments that cuts across the landscape.”
>
> **- Consultant Mapper**

And 2) start at a small map scale (e.g., looking at the whole dataset/mapping area) then zooming in to specific locations. Below is a quote from a novice mapper summarizing their initial mapping approach:

> "I can kind of see like patterns from farther away and then […] I need to maybe zoom in on just especially like if we're looking at large scale features."
>
> - **Novice Student Mapper**

Looking for linear trends is a common first step in the first sub-code (Table 8). Linear trends can indicate faulting (e.g., scarps, pressure ridges) or non-tectonic processes (e.g., fluvial terraces, urbanization).

Geomorphic Indicator Mentions

For the 'geomorphic indicator mentions' code, I identified which geomorphic features are mentioned the most and interpreted as strong fault indicators by the mappers. This mirrors the 'Geomorphic Indicator Ranking Feature to Rupture Distance Analysis' that quantitatively shows the frequency of GIR usage. Below is a table that lists all the GIR features mentioned by students and consultants with a total percent distribution of the sub-codes.

Sub-code – Geomorphic Indicator	Student (12 total)	Consultant (6 total)	Percent Feature is Mentioned
Lineament	15	5	23%
Scarp	4	8	14%
Alignment	5	5	12%
Triangular facet	9	1	12%
(Over-steepened) range front	8	1	10%
(Offset, deflected, or altered) drainage/stream	5	4	10%
Ridge/pressure ridge	6	1	8%
Slope break	3	3	7%
Horst and graben	1	1	2%
Landslides	2	0	2%

Table 9: Results from the ‘geomorphic indicator mentions’ code sorted by students, consultants, and the total percent distribution of the sub-code. An individual participant could have several counts for a feature if the feature was mentioned multiple times.

The top three most mapped features (i.e., lineament, alignment, and scarp) are linear (Table 9). This is congruent with the mapping process responses in which participants mention linear trends as the features that first draw their eye to the faulting.

Students and consultants sometimes describe the same feature differently. For example, consultants used the term ‘scarp’ and students used the terms ‘break in slope’ or ‘linear stuff’ to describe the same features. Below is a quote from a senior studetn mapper mentioning linear features:

> “I'm definitely seeing like this linearness and it's connected like across the front of the rangefront.”
>
> - **Senior Student Mapper**

Similarly, consultants used ‘offset and/or deflected’ while students’ used ‘something happening to the drainage/topography.’

> “Most often the faults are responsible for breaks in slope or scarps, and aligned ridges and troughs that persist across an area and are somewhat laterally extensive.”
>
> - **Consultant Mapper**

The difference in language can be attributed to the difference in experience between the consultants and students where the consultants have learned to use more descriptive and precise terms to describe a feature.

CHAPTER 5

DISCUSSION

Geomorphic Indicator Ranking System

The GIR system is an effective tool for mappers to systematically document their geomorphological evidence for faulting in a systematic and repeatable manner. I made several improvements to the GIR mapping system (relative to its introduction in Scott, et al., 2023):

(1) The new color-coded symbology (red-strongest indicator, orange - second strongest, yellow - third strongest, blue- weakest, gray- modifier) better visualizes the mapped geomorphic evidence for the fault location.

(2) The GIR table includes more geomorphic indicator features including lineament in topography (LT), differentiation of scarps for bedrock (BSP) and Quaternary (QSP), fissures (FS), pressure ridges (PR), horst and grabens (HG), sackungs (SG), footwall ponds (FP), and range-front sinuosity (RS). The advancements to the GIR also include better documentation and instructions of use in QGIS (Appendix A).

(3) I added the option for mappers to add new features as needed, discussed in more detail below. The catalog of features is meant to evolve with more users working along a range of fault types and geomorphic settings.

(4) I suggest adding one GIR point at least every 100 meters depending on the scale of mapping.

(5) I have developed MATLAB code that converts the mapped GIR points into a fault confidence ranking for each 1 km-long segment of a fault trace. This streamlines

the calculation for and evidence-based confidence ranking of mapped fault traces. I hope that these improvements make the tool more user friendly and increase its usably among fault mappers.

Most participants indicated that the GIR tool was useful to accumulate evidence in a systematic way. The consultant mappers indicated a balance between the tool's rigid and systematic nature versus the flexibility needed to accurately convey evidence and interpretations in a timely manner. Mapper Ethan Leuchter, who was a student in the course and now a consultant mapper, mentioned that he was a novice to fault mapping before the course, and still implements our process and GIR in the industry. While useful to convey evidence systematically, each fault mapping task is different depending on the slip rate, earthquake recurrence, climate, and the tectonic environment. As such, the GIR approach should be flexible to accommodate the complex nature of each mapping site.

The GIR methodology can be improved in several ways:

(1) Remove the slip-sense nomenclature (SS, R, N) to the features. I originally added these prefixes to fully describe the fault geomorphology. However, indicating the slip sense forces the mapper to make a conclusion about the fault kinematics even when the evidence may be weak.

(2) Participants also added new features that illustrate more nuanced fault evidence such as tonal lineament (TL), stream constriction (SC), differential incision (DI), subtle lineament (SL), and a feature that indicate uncertainty about the feature identity (scarp?). Adding a queried feature addresses the fact that an eroded and fresh scarp

provides varying quality of evidence for faulting and allows the mapper to indicate different relative strength of a feature.

(3) The GIR shapefile geometry should be modified such thaut linear or large-2D features can be represented by a line or polygon, respectively. For example, a long, continuous scarp could be mapped with a line feature instead of point features every ~100 meters. Landslides or triangular facets which benefit by being represented as polygon features.

(4) Some negative features should have a rank less than -1 to add symmetric to the scoring (largest positive score is 4). For example, this approach could be used to degrade feature rating within suburban development versus spatially localized erosion.

Geomorphic Feature-to-Rupture Distance Analysis

We assessed which features had the lowest median GIR feature to rupture distance regardless of the mapped quantity. The cut or offset alluvial fans were the best performing features. This is likely because this feature is either spatially large and easy to identify in the landscape or it is well-preserved. This feature was mapped most frequently in the EMC location, where the climate is arid, and the features are well-preserved. The Quaternary scarp (QSP) performed well in this assessment and was mapped frequently, but a feature of note is the landslide. Originally, we ranked this feature with a score of 1 and as a modifier, meaning its appearance in the landscape may not be strong enough to indicate a fault on its own. However, the median feature to rupture distance is 68 meters, indicating it performed better than other higher-ranking features.

I hypothesized that Quaternary scarp features would be good indicators for fault location. The results from the analysis (Table 3) show that the median mapped feature to rupture distance for the NQSP (40 m) performed better than the NBSP (183 m). QSP features are on younger surfaces and may be more pronounced in the landscape in relation to BSP features where the exact location can be ambiguous due to age and level of erosion. There is a larger variability with the feature to rupture distance with the BSP with the minimum distance under 10 m and the largest distance over 3 km away. So, while the bedrock scarp placement can be more accurate than other features, it may not be as strong an indicator of fault location as we previously thought.

There are several ways that the design of the experiment may have impacted the results. (1) It is important to note the implication from using rupture maps from only one earthquake per location. The GIR features can be mapped accurately to convey fault location; however, they can locate faults that did not rupture in the earthquake that the rupture maps were sourced from (aleatoric variability). This can skew the distance measurements as we are only measuring the features close to the faults that actually ruptured in a specific earthquake and not the cumulative effect of several earthquakes which are more likely to show the average fault behavior. (2) We directed the students to map the assigned areas with the GIR. Students were instructed to have even coverage of the area with GIR points. This led to more, sometimes inaccurate, points that ultimately reduced the amount of high-quality maps we could source from and ultimately a smaller (but still accurate) data set for this analysis. If the analysis were done again, we would emphasize to students that the number of points is not as important as their quality. We would also add a GIR feature, ‘NTE’ or No Tectonic Evidence, for students to use to show that they have searched the area but did not find any geomorphology to support other GIR feature or fault placements.

Mapper versus GIR Fault Confidence Ranking Analysis

Here, I discuss our analysis focused on comparing the fault confidence ranking assigned by the mapper versus that determined by our MATLAB code based on the number and rank of the geomorphic indicators surrounding the mapped fault trace (termed “automatic GIR scoring approach”). I had two motivating questions: (1) Do the confidence rankings from the mappers and automatic approach differ? (2) How well are the fault traces and their confidence rankings supported by the GIR and surrounding topography?

The mappers may not use the full range of fault confidence rankings in each area, whereas the automatic approach is designed to characterize faults with the full range of the four confidence rankings (provided enough faults are mapped). The mapper and automatic approach segment the confidence interval boundaries differently: A mapper may change the confidence ranking along geomorphic contacts, for example between a range front and alluvial fan. The automatic GIR score will segment the confidence traces every 1 kilometer, irrespective of the change in geomorphology. In some mapping areas, the 1-kilometer segmentation resulted in a fault map that still matched the local topography (see Figure 13b) where there is anthropogenic alteration and erosion. However, in Fig 8, the 1-kilometer segments do not reflect the local geomorphology where the mapper broke the trace between the range front and alluvial fan deposit.

Significant changes in ranking (i.e., strong to uncertain and vice versa) varied based on how the mapper used modifying features such as lineament in topography (LT), morphologic element (ME), etc. The modifying features (features with a score of +/-1) were used more liberally in areas where there was other, stronger geomorphological evidence and sparingly where there were no high ranking GIR features.

To improve this analysis and the automation of the fault confidence rankings, I can revise the code to not have to adhere to the 1-kilometer segment ranking, instead breaking up the segments where the mapper originally chose. This will increase the likelihood that the confidence ranking for the fault traces not only accurately match the surrounding GIR evidence but match the local topography as well.

Observational Analysis of Listening Sessions

I conducted listening sessions with students and geologic consultants to understand how geologists map active faults using a desktop-based approach with remote sensing datasets. From the observational analysis, I determined the following:

(1) Mappers tend to look for linear features as geomorphic indicators of faulting. 79% of the features mentioned by participants were linear features such as lineament, scarp, alignment, (over-steepened) range front, ridge, and pressure ridge. While there are many linear geomorphic features that indicate faulting (scarps, pressure ridges), linear features can also result from fluvial processes and urbanization. The proximity of topographic fault scarps and lineaments (<10 m) to subsequent ruptures indicate that looking for and mapping linear features can be a useful first step to locating a fault. However, due to the high 84th percentile distances for Quaternary scarps (650 m) and lineaments in topography (1240 m) in the 'geomorphic feature to rupture distance' analysis, it is important to not rely on these features for fault location without other supporting evidence. It is possible that these features are mapped accurately along faults that did not rupture in the subsequent earthquake, but they can also be mapped in error as other non-tectonic linear features and draw the mappers eye away from other, potentially stronger evidence for faulting.

(2) Consultants and students use different terms to describe the same or similar features. For example, consultants often use the word 'scarp' while novice mappers may use the word 'break in slope' or 'linear stuff.' This different terminology may be a result of different levels of experience: Experienced mappers can often make a more confident judgment on feature identity. In this example, fault scarps indicate a tectonic origin while 'break in slope' simply explains the morphology of the landscape. The consultants and

students may interpret the same area differently. For example, consultant mappers highlighted the underlying sense of motion for faulting to support their decisions whereas students often relied on what was immediately visible in the landscape. Students may ponder the underlying sense of motion but often did not verbalize the larger tectonic relationships.

(3) A common method amongst students with fault mapping experience and consultants is to map the faults first and then refine the trace location with supporting geomorphological evidence afterwards.

CHAPTER 6

CONCLUSION

The goal of my work is to understand how students and professional geologists map tectonic faults based on geomorphic landforms visible in remote sensing datasets utilizing the pre-rupture fault mapping approach with the ultimate goal of improving the fault mapping process. I want to build up the approach introduced by Scott et al. (2023) to systematize the fault mapping process. By comparing pre-rupture fault maps made by participants to subsequent coseismic ruptures, I can assess how well our approach to fault mapping utilizing remote sensing data predicts where future ruptures are located for increased certainty for fault displacement hazard analysis. The ‘fault mapping process’ (e.g., Figure 1) works towards an evidence-based fault map that can be disseminated and widely understood using the GIR methodology. I hope that by using our approach to fault mapping, the certainty and accuracy for PFDHA calculations will increase.

Identifying and mapping landforms indicative of faulting (GIR) is a useful tool in fault mapping. Linear features like scarps, vegetation lineaments, and topographic lineaments performed well in my assessment and anticipated future rupture location well. This analysis also highlights the importance of mapping all geomorphic indicators and not relying only on linear features to locate faults.

The Geomorphic Indicator Ranking system presents a systematic approach to mapping geomorphological evidence for fault mapping. Based on the results from the observational analysis, this approach is critical for quantifying the surficial evidence for faulting in a repeatable manner using consistent terminology. The approach works both as a teaching tool to introduce tectonic geomorphology and fault mapping to novice mappers, but also works in an industry setting.

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APPENDIX A

GEOMORPHIC INDICATOR RANKING (GIR) TABLE

This document is a reference tool for consistent labeling of geomorphic landforms in QGIS.

Please note that the input is case sensitive, and everything must be capitalized when entered. If the symbol is entered correctly, it will display as a white circle. If the symbol is not entered correctly, the feature will plot as a 'red star' in QGIS as shown in the images below.

Remember: Map every occurrence of the feature along the fault trace. The same feature may appear more than once along a single segment (e.g. 3 beheaded drainages within 1-km)

SS (strike-slip), N (normal), and R (reverse) are prefixes to the feature symbology to indicate what type of faulting cause the feature to appear on the surface.

Strike-Slip Geomorphic Indicator Ranking

Feature	Rank	Description	Justification as fault indicator
Offset Terraces (SSOT)	4	Laterally and obliquely offset fluvial terraces	Coseismic slip offsets terraces and terrace risers
Offset drainage channel (SSODC)	4	A channel with two ~90° bends that is otherwise straight	Offset caused by differential translation of a stream by a fault
Offset or cut Alluvial Fan Complex (SSAFC)	4	Series of fan-shaped alluvium deposits that are offset or cut by a fault	Faults can cut across and offset alluvial fans of different ages
Single Offset or cut Alluvial fan (SSAF)	3	A single fan-shaped alluvium deposit that is offset or cut by a fault	Faults can cut across and offset a single alluvial fan unit
Bedrock Scarp (SSBSP)	3	A linear cliff-like slope or face that breaks a bedrock unit	Produced by strike-slip faulting or lateral offset of sloping surfaces
Quaternary Scarp (SSQSP)	3	A linear cliff-like slope or face that breaks a quaternary unit	Produced by strike-slip faulting or lateral offset of sloping surface

Beheaded Drainages (SSBD)	3	Up- and down-stream channels are separated.	Fault-offset beheads down-stream channel
Deflected Stream (SSDS)	2	Diverted stream that runs parallel to the fault. Smaller than offset drainage and can be diverted at angles less than 90°	Fault capture or blockage alters the stream course
Depression/Sag Pond (SSDSP)	2	Low elevation between strike-slip or normal faults, sometimes filled with water	Produced by extensional bends or stepovers along strike-slip faults
Shutter ridge (SSSR)	2	A ridge that blocks or diverts a drainage	The ridge was translated by faulting
Surface Unit Offset (SSSUO)	2	The original deposition order is obscured	Faulting offsets units
Spring (SSSPR)	1	Upwelling of subsurface water	Caused by faulting that disrupts the groundwater and bedrock
Bench (SSBN)	1	A long, relatively narrow strip of relatively level or gently inclined land that is bounded by distinctly steeper slopes above and below it	Faults can produce linear, inclined land.
Fissures (SSFS)	1	Subvertical, downward-tapering zones bounded by sharp fractures, and filled with younger sediments. Infrequently preserved well enough to see in satellite imagery or DEM, DTM, DSM.	Form as tension cracks that opened coseismically
Pressure ridge (SSPR)	1	A linear or sinuous broken bulge on the surface	Form where lateral motions on a curving fault force bedrock or sediment into a smaller space, pushing them upward

Normal Geomorphic Indicator Ranking

Feature	Rank	Description	Justification as fault indicator
Triangular facet (NTF)	4	A broad base and a upward pointing apex	Often formed by erosion of the fault plane along range fronts
Beheaded Drainages (NBD)	3	Up- and down-stream channels are separated.	Fault-offset beheads down-stream channel
Offset or cut Alluvial Fan Complex (NAFC)	4	Series of fan-shaped alluvium deposits that are offset or cut by a fault	Faults can cut across and offset alluvial fans of different ages
Quaternary Scarp (NQSP)	3	A linear cliff-like slope or face that breaks a quaternary unit.	Produced by normal faulting or lateral offset of sloping surfaces
Bedrock Scarp (NBSP)	3	A linear cliff-like slope or face that breaks a bedrock unit.	Produced by normal faulting or lateral offset of sloping surfaces
Horst and grabens (NHG)	3	Topography consisting of alternating raised and lowered fault blocks. Large-scale feature.	Features are created by normal faulting and rifting caused by crustal extension
Single Offset or cut Alluvial fan (NAF)	3	A single fan-shaped alluvium deposit that is offset or cut by a fault	Faults can cut across and offset a single alluvial fan unit
Unit Offset (NOF)	3	Offset of bedrock or geomorphic units	Faulting is often responsible for offset
Over-steepened range front (NORF)	3	Dramatic change in slope near mountain base	Likely due to faulting when present along large topographic features
Depression/Sag Pond (NDSP)	2	Low elevation between strike-slip or normal faults, sometimes filled with water	Produced by extensional bends or normal faults.
Surface Unit Offset (NSUO)	2	The original deposition order is obscured	Faulting offsets units

Fissures (NFS)	1	Subvertical, downward-tapering zones bounded by sharp fractures, and filled with younger sediments. Infrequently preserved well enough to see in satellite imagery or DEM, DTM, DSM.	Form as tension cracks that opened coseismically
Spring (NSPR)	1	Upwelling of subsurface water	Caused by faulting that disrupts the groundwater and bedrock
Sackung (NSG)	1	Deep-seated gravitational spreading of mountain ridges and slopes considered a ‘half-landslide’	Spreading is due to normal faulting that is located high on mountain slopes

Reverse Geomorphic Indicator Ranking

Feature	**Rank**	**Description**	**Justification as fault indicator**
Quaternary Scarp (RQSP)	4	A linear cliff-like slope or face that breaks a quaternary unit	Produced by dip-slip faulting or lateral offset of sloping surfaces
Bedrock Scarp (RBSP)	4	A linear cliff-like slope or face that breaks a bedrock unit	Produced by dip-slip faulting or lateral offset of sloping surfaces
Offset or cut Alluvial Fan Complex (RAFC)	4	Series of fan-shaped alluvium deposits that are offset or cut by a fault	Faults can cut across and offset alluvial fans of different ages
Over-steepened range front (RORF)	3	Dramatic change in slope near mountain base	Likely due to faulting when present along large topographic features
Single Offset or cut Alluvial fan (RAF)	3	A single fan-shaped alluvium deposit that is offset or cut by a fault	Faults can cut across and offset a single alluvial fan unit
Triangular facet (RTF)	3	A broad base and an upward pointing apex	Often formed by erosion of the fault plane along range fronts
Footwall Pond (RFP)	2	Pooling of water/ sediment along the footwall of the fault	Ponding occurs in the footwall due to relative subsidence

Topographic Hills (RTH)	2	Half-cylindrical-shaped hills	Blind reverse faults create sinuous topography
Surface Unit Offset (RSUO)	2	The original deposition order is obscured	Faulting offsets units
Fissures (RFS)	1	Subvertical, downward- tapering zones bounded by sharp fractures, and filled with younger sediments. Infrequently preserved well enough to see in satellite imagery or DEM, DTM, DSM.	Form as tension cracks that opened coseismically
Rangefront sinuosity (RRS)	1	Parallel-like strike along the base of a mountain front	Fault plane can drop and mark the rangefront at the fault strike

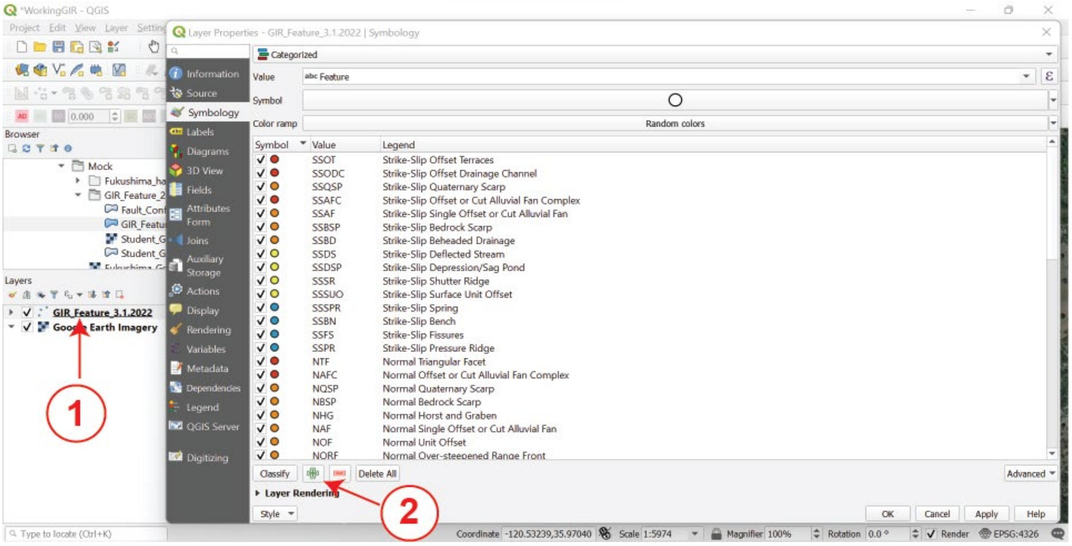
Modifier Geomorphic Indicator Ranking

Modifiers are meant to be mapped only if they occur in conjunction with other, higher ranking geomorphic indicator features that are mapped along the proposed fault location.

Feature	**Rank**	**Description**	**Justification as modifier**
Alignment (ALMT)	+1	The repeated appearance of a geomorphic indicator feature within ~1 km	Locally repeated and offset features may be due to faulting
Cross cut (CCT)	+1	A lineation or other feature that cuts across the landscape	Faulting is responsible for some cross-cutting relationships
General Pond (GP)	+1	Small body of water formed apart from anthropogenic alteration	Ponds in alignment can help locate fault even if it is not a sag pond or depression.
Saddle (SDL)	+1	A depression located along the ridge crest	Due to a dropped hanging wall or differential erosion across a ridge
Vegetation lineament (VL)	+1	Natural lines between high and low vegetation densities.	Can be caused by faulting

Wineglass canyons (WC)	+1	The cross sectional shape resembles a wine glass. The base is the alluvial fan that slopes down the mountainside	Indicates recent uplift
Landslides (LSP)	+1	Downward movement of sediment or rock	Form from coseismic shaking
Linear Valley/ Drainage (LVD)	+1	Extended linear patterns of streams, rivers, lakes, and valleys	Linear drainages often indicate faulting control.
Lineation in Topography (LT)	+1	Extended linear appearance of the topography on a basemap	Apparent extended lineation can help narrow down faulting features and location
Morphologic elements (ME)	+1	Features such as ridges, slope breaks, troughs.	Increase confidence of faulting
Pirated Chanel (PC)	+1	A channel diverted from its own path and joins a neighboring channel	Fault offset or weaknesses in the bedrock can lead to stream capture
Stream Knickpoint (SK)	+1	Abrupt change in channel slope (i.e., a waterfall)	Faulting or folding causes stream disequilibrium, forming a knickpoint
Anthropogenic Alteration (AA)	-1	Alteration from infrastructure e.g., roads, farming & buildings	Obscures a fault's precise location
Colluvial Cover (CLCR)	-1	Loose and unconsolidated rock on hillslope base	Can obscure evidence of a fault scarp
Erosion (ER)	-1	Sediment and rock are worn away by water and wind	Removes evidence of faulting
Landslides (LSN)	-1	Downward movement of sediment or rock	Cover faulting evidence
Proximity to active water (PAW)	-1	Fault traces located near active water	Water is an erosion agent and can remove the evidence of faulting

If you would like to add your own feature to the GIR shapefile, do the following:



Categorized

Value: Feature

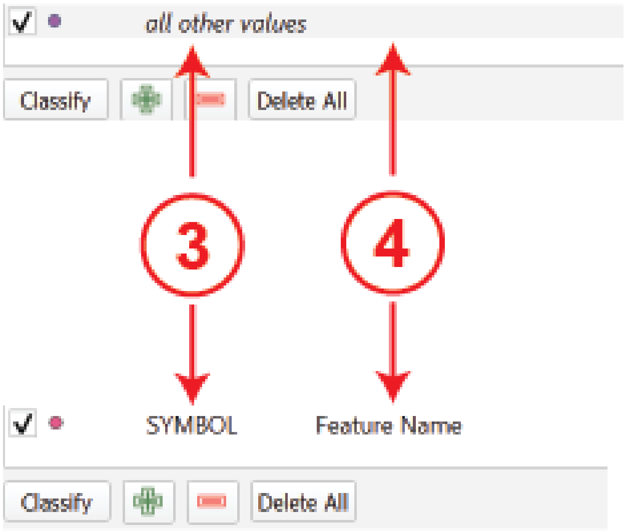
Color ramp: Random colors

Symbol	Value	Legend
✓ ●	SSOT	Strike-Slip Offset Terraces
✓ ●	SSODC	Strike-Slip Offset Drainage Channel
✓ ●	SSQSP	Strike-Slip Quaternary Scarp
✓ ●	SSAFC	Strike-Slip Offset or Cut Alluvial Fan Complex
✓ ●	SSAF	Strike-Slip Single Offset or Cut Alluvial Fan
✓ ●	SSBSP	Strike-Slip Bedrock Scarp
✓ ●	SSBD	Strike-Slip Beheaded Drainage
✓ ○	SSDS	Strike-Slip Deflected Stream
✓ ○	SSDSP	Strike-Slip Depression/Sag Pond
✓ ○	SSSR	Strike-Slip Shutter Ridge
✓ ○	SSSUO	Strike-Slip Surface Unit Offset
✓ ●	SSSPR	Strike-Slip Spring
✓ ●	SSBN	Strike-Slip Bench
✓ ●	SSFS	Strike-Slip Fissures
✓ ●	SSPR	Strike-Slip Pressure Ridge
✓ ●	NTF	Normal Triangular Facet
✓ ●	NAFC	Normal Offset or Cut Alluvial Fan Complex
✓ ●	NQSP	Normal Quaternary Scarp
✓ ●	NBSP	Normal Bedrock Scarp
✓ ●	NHG	Normal Horst and Graben
✓ ●	NAF	Normal Single Offset or Cut Alluvial Fan
✓ ●	NOF	Normal Unit Offset
✓ ●	NORF	Normal Over-steepened Range Front

Coordinate -120.53239,35.97040 Scale 1:5974 Magnifier 100% Rotation 0.0 ° Render EPSG:4326

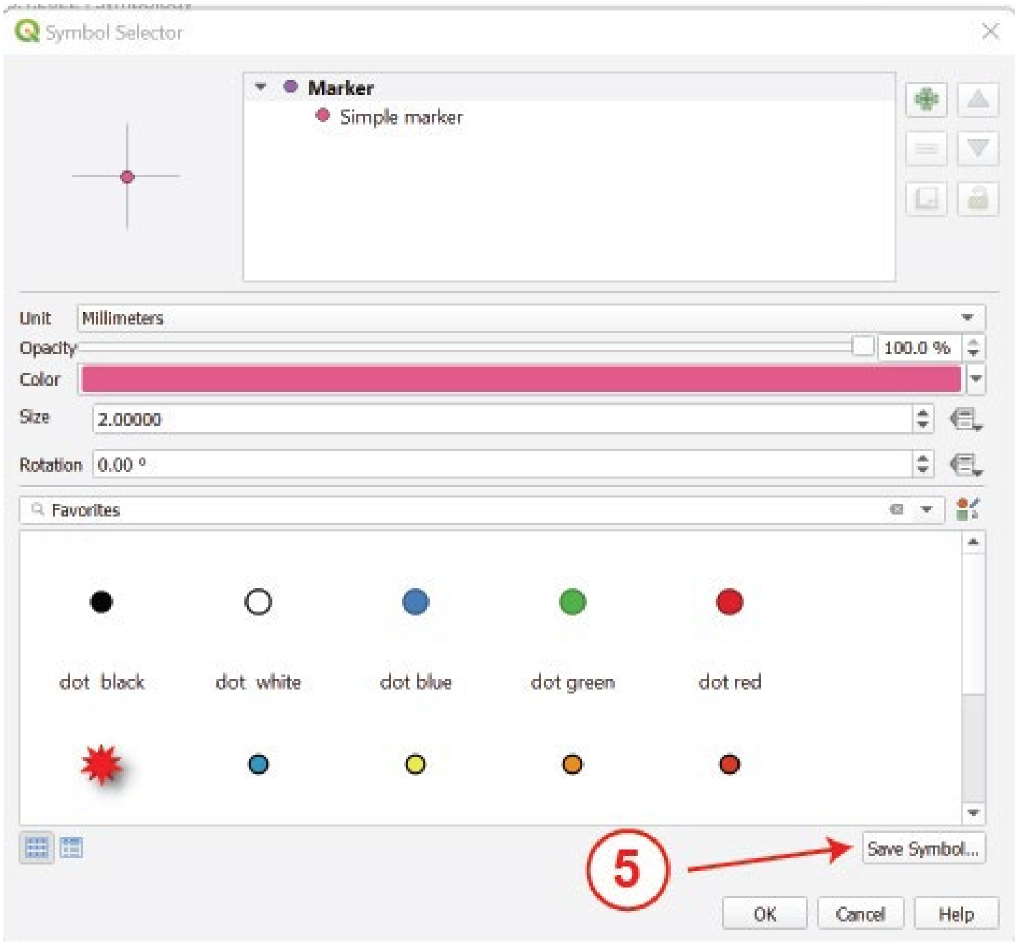
1. Double-click on the GIR_Feature layer and toggle to the symbology tab

2. Click the green (+) button to add a new feature



3. Input the symbol for the name of the feature. Remember, the input must be capitalized and should have prefix (SS, N, R) to indicate the type of faulting- unless it is a modifier- and a short two to three letter acronym for the feature.

4. Input the full name of the feature



Unit: Millimeters
Opacity: 100.0 %
Size: 2.00000
Rotation: 0.00 °

5. Double- click on the ‘dot’ symbol to open the Symbol Selector to change the symbology. You can try to match the style of the existing features, but an easier way to do this is to toggle to the same window of another feature (ex. SSBD) and click ‘Save Symbol’. You can call that feature GIR_Rank3 and it will save the symbol with the color and size for all GIR Rank 3 features.

   Save the symbol for the rest of the ranking symbols (Rank 1 – red, Rank 2 – Yellow, Rank 4- blue). Now, when you create a new feature, you can toggle to your now saved symbols for easy access and continuity.

   It will be up to you to decide what ranking you assign a new feature. Use your knowledge to decide how strong of a feature it is to indicate a fault.

APPENDIX B

LISTENING SESSION CODEBOOK

This document is a codebook containing the codes, sub-codes, and themes used to analyze the listening sessions for the observational analysis. The format and language used to describe the terms in this document are modeled after Saldana (2016) with other terms described in the attached glossary (Appendix C).

Overview

Theme	Code
Prior experience	Research, prior courses, fault mapping, geomorphology, our fault mapping course, technology, work
Mapping process	Look for linear patterns/ lineaments, faults first, geologic mapping, geomorphic indicator mapping, morphologic mapping, zoom out then in
Geomorphic indicator mentions	Lineament, alignment, triangular facet, (over-steepened) range front, ridge/ pressure ridge, scarp, (offset, deflected, or altered) drainage/stream, slope break, horst & graben, landslides

Prior Experience

Theme	Definition
Prior Experience	Participants mention structural geology, geomorphology, fault mapping, or other related topics like GIS software or work.

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Code	Definition
Research	Participant mentions relevant formal or informal geoscience research that they have participated in outside of coursework either in undergraduate or graduate research.
Example: "I've done a lot of mapping of primary and secondary features around the 2016 rupture in Australia"	
Prior courses	Participants mentions courses or classes taken in either undergraduate or graduate school that can include geomorphology, structural geology, GIS, and/or fault mapping.
Example: "Yeah I've done a little bit of this kind of stuff in my undergrad before with a tectonic geomorphology class kind of mapping fault geomorphology and making small fault maps and that kind of thing"	
Fault mapping	Participant mentions prior experience with making fault maps either in the field or remotely.
Example: "[For PhD] was mostly fault mapping using lidar and satellite imagery"	

Geomorphology	Participant mentions prior experience understanding and observing tectonic or fluvial geomorphology.
Example: "I've taken geomorphology at ASU"	
Our course	Participant mentions knowledge gained from our course including lectures, assignments, readings, or course instructors
Example: "The last couple classes we've had Rich Koehler showing some examples of mapping he's done"	
Technology	Participant mentions technology directly related to the course (ArcGIS, QGIS, lidar/satellite imagery, digital elevation models – DEM)
Example: "I got actually my minor is geospatial analysis using QGIS so I'm familiar with the software"	
Work	Participant mentions any amount of time doing paid or unpaid work- whether or not the work is related to their current position- spent outside of academia that are related to geology, earthquake science, and/or and fault mapping.
Example: *"When I graduated I worked for the USGS for a year and I worked for the digital cooperative geologic mapping program"*	

Mapping Process

Theme	Definition
Mapping Process	Participants' general process when they begin creating a fault map that includes creating derivative products, their workflow, and specific tools they utilize while they map.

Code	Definition
Looking for linear patterns/lineaments	Participant mentions linear features or linear appearances in the landscape as one of the initial steps to making a fault map
Example: "I'm definitely seeing this like linearness." "A lot of linear stuff catches your eye right away. "I started by mapping lineaments that cuts across the landscape."	
Zoom out then in	Participants describes their process as mapping or observing at a small scale then zooming into a larger scale
Example: "I always prefer to start with the big picture to establish a context and then add more detail and refine linework with subsequent phases of more detailed (zoomed in) mapping."	
Faults first	Participant describes their initial process as placing fault linework or symbology first
Example: "So I typically I'll start with the fault traces themselves"	

Geologic mapping	Participant describes their initial process as mapping a geologic map or aging surficial units.
Example: I thought geologic mapping was very helpful just because I was able to see where different units were either abruptly changing or where they were displaced.”	
Geomorphic indicator mapping	Participant describes their initial process as mapping geomorphic indicators of faulting.
Example: “I am sort of like visually doing geomorphic mapping”	
Morphologic mapping	Participant describes their initial process as mapping the morphology in the landscape.
Example: “I think for this assignment I might use some of the morphology mapping just for kind of picking out some of the breaks in slope and the little kind of subtle features”	

Geomorphic Indicator Mentions

Theme	Definition
Geomorphic Indicator	Participants mention the Geomorphic Indicator Ranking system (GIR)

Code	Definition
Lineament	Apparent lines between either vegetation or topography unnatural to the existing landscape
Example: “I started by mapping lineaments that cuts across the landscape.”	
Scarp	A linear cliff-like slope or face that breaks a bedrock or quaternary unit
Example: “For sure we can see that, like there's a big scarp running here”	
Alignment	The repeated appearance of a geomorphic indicator feature within ~1 km
Example: “I’m seeing like an alignment here”	
Triangular facet	A broad base and an upward pointing apex
Example: “So I started with the most obvious which are the triangular facet”	
(Over-steepened) range front	Dramatic change in slope near mountain base
Example: “There are other features that are standing out for me that I would certainly map as well, like, here we got like a range here”	
(Offset, deflected, or altered) drainage/stream	A drainage that has been altered from its originally depositional orientation
Example: “You also see a marked difference in the development of the drainages as you go across the face of the- across this fault.”	
Ridge/pressure ridge	A linear or sinuous broken bulge on the surface
Example: “Here's a ridge that I'm seeing in the landscape”	
Slope break	Abrupt change in topography

Example: “Oh here's the biggest thing that I see mapping that, and saying here's a really big change in slope	
Horst and graben	Topography consisting of alternating raised and lowered fault blocks. Large-scale feature.
Example: “… and what I think is horst and grabens”	
Landslides	Downward movement of sediment or rock
Example: “I was looking at the landslides or other features that can tell my eyes in”	

APPENDIX C

GLOSSARY OF TERMS

This glossary lists the terms used in the text and the definition in which I frame the use of the term within the text.

Term	Definition
Aleatoric variability	The natural stochastic propensity of fault surface rupture location.
Anchoring bias	The failure to depart from initial ideas, such as those about the tectonic setting or past knowledge of the earthquake
Codebook	The document that outlines the codes and sub-codes used to organize and analyze data in the listening sessions
Confirmation bias	When a mapper looks to support their results based on past experience and disregards conflicting observations.
Epistemic uncertainty	A gap in knowledge of a natural model, in this case, faulting processes. Can result from lack of knowledge or tools given to the mapper.
Fault confidence ranking	The style used to assign a confidence ranking to a fault trace based on how strong the mappers believe the fault is and how certain there are of the fault's location
Geomorphic indicator ranking system	The tool mappers use to document geomorphological evidence for potentially active faults in QGIS software

APPENDIX D

IRB APPROVAL

ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Ramon Arrowsmith
CLAS-NS: Earth and Space Exploration, School of (SESE)
480/965-3541
ramon.arrowsmith@asu.edu

Dear Ramon Arrowsmith:

On 1/14/2022 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Understanding the importance of prior knowledge in mapping tectonic faults from geomorphology
Investigator:	Ramon Arrowsmith
IRB ID:	STUDY00015172
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• CITI Completion Arrowsmith, Category: Other; • CITI Completion Reano, Category: Other; • CITI Completion Scott, Category: Other; • IRB Social Behavioral 2019_posted 09082021_4_Arrowsmith_v5.pdf, Category: IRB Protocol; • Model Recruitment_Arrowsmith_v4.pdf, Category: Recruitment Materials; • Model Short Consent_0_Arrowsmith_v5.pdf, Category: Consent Form; • Study procedures compiled into pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 1/14/2022.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

If any changes are made to the study, the IRB must be notified at research.integrity@asu.edu to determine if additional reviews/approvals are required. Changes may include but not limited to revisions to data collection, survey and/or interview questions, and vulnerable populations, etc.

REMINDER – Effective January 12th 2022, in-person interactions with human subjects require adherence to all current policies for ASU faculty, staff, students and visitors. Up-to-date information regarding ASU's COVID-19 Management Strategy can be found here. IRB approval is related to the research activity involving human subjects, all other protocols related to COVID-19 management including face coverings, health checks, facility access, etc. are governed by current ASU policy.

Sincerely,

IRB Administrator

cc:
Darryl Reano
Rachel Adam
Chelsea Scott
Ramon Arrowsmith