**Reply to interactive comment by Michael Hodge:**

**November 10, 2019**

The authors greatly appreciate Michael Hodge's thoughtful comments and have taken them into consideration in our revised manuscript. As suggested, we streamlined sections of the manuscript that are included in the User Manual and improved the code to include a simple option for users that are not working with geologic age data. This removes the tedious work-around that was previously incorporated into the workflow. Our changes are reflected in the revised manuscript and the User Manual. We also included rationale as to why the Taupo Volcanic Zone was chosen for the case study and made technical corrections throughout. We are very thankful for Michael Hodge's review and believe that is has helped to focus the manuscript on the key conclusions that are novel to our study and new workflow.

- Franklin Wolfe

*It is in my opinion that the paper spends much time talking about ArcGIS and QGIS, i.e. background and steps to pre-processing scarps and post-visualisation. However, the novelty of this work is the Python scripts and what they can do, which should the authors should highlight more. The selection of profiles across scarps, points along profiles et cetera has been covered in work previously, and whilst it is important and imperative for the pipeline of this work (and therefore rightly sits in the User Manual) too much space is used for this in this manuscript.*

> Some of this language is also covered in the User Manual; hence, it would be simple to streamline these sections into sharp sentences and then reference the User Manual for further inquiry. We very much appreciate the reviewer's suggestions on which sections can be removed from the manuscript and have chosen to do so. For example, the *Define Fault Scarp Profiles in QGIS or ArcGIS and Extract Data for Profiles* sections have been condensed into one section comprised of three sentences. We believe that this helps to focus the manuscript.

*Here, the paper is about the code, and the case study is an short case study application more so. Therefore, my main recommendation is for the author and code developer to choose their battle: ArcGIS scripts or Jupyter Notebooks. It will be hard to update both during the rigours of academia. I propose the latter (Jupyter), because as the author mentions ArcGIS is commercial software (they give a great reason in point five C2 of 'section: Principles of Design for MCSST' as to why the focus should be on open source software), and also because I envisage a greater shift towards Python by Earth Scientists soon (whereby your users may not even use QGIS to select profiles, but use a pure Python approach instead). That is not to say you cannot mention that you have spent effort in creating ArcGIS plugins for those who want them, but this should be a side-feature of your work.*

> We appreciate the concern that it will be more difficult to maintain two parallel codes; however, a major
> focus of our research effort has been developing the ArcGIS codes, which utilizes a software many in the

scientific community are using. Our goal with this project is to provide a means for all to enjoy our scripts with little barrier to entry. Providing a workflow that can utilize a selection of tools is a means of achieving this end goal. Thus, we do not wish to abandon the language devoted to the ArcGIS approach – though, we do share the author's sentiment that more researchers will use QGIS and python in the future. We hope that the User Manual will adequately support this approach.

*Abstract (and throughout)*

*The use of the word 'rapid'. Rapid in this sense is relative to what you compare it against. The authors are right that it is rapid compared to traditional methods, but if someone built a machine learning neural net would it be as rapid as that once training had been successful? I recommend using a softer tone that 'rapid'.*

We have chosen to focus on 'space' rather than time and replace some instances of 'rapid' with 'bulk fault slip analysis' to highlight to codes ability to permit analysis of multiple faults at once. This is exemplified in the updated title of the manuscript.

*Introduction*

*Line 24 – This may be where my knowledge has faded. But here it looks like we are working with surface topography data. So, can we accurately calculate fault slip? Or can we only calculate surface displacements?*

The 'Calculate slip statistics section' and Figure 1 explain how we arrive at estimates of near-surface fault slip from surface displacements. Thompson et al. (2002) includes a detailed explanation of this calculation.

*Background*

*Lines 46 to 47 – Later you use the word component to talk about the hanging-wall, scarp and footwall. I like that, or feature, rather than 'variable' used in line 47.*

Changed to 'component'

*Principles of Design for MCSST*

*Lines 78 to 86 – as mentioned in my general comments I think this section can be removed, or at least shortened.*

We appreciate this concern and have chosen to remove this section to streamline the manuscript.

*Define Fault Scarp Profiles in QGIS or ArcGIS and Extract Data for Profiles*

*Both sections don't contain anything novel or imperative to the manuscript; perhaps this should just be covered in the manual and replaced here with a simple paragraph stating that 1) the user creates fault trend (perpendicular?) profiles across the scarp, 2) extracts elevation from the DEM (and optionally, geological age) at spaced intervals. Then more information can be found in the user manual.*

> This is great insight and we have chosen to combine these two sections into one section with just three sentences. The additional text is covered in the User Manual and thus not needed here in the manuscript. Thank you for helping to clarify where we could remove text that is not needed.

*Line 89 – the authors don't address whether the profiles should be perpendicular to the scarp trend, or parallel to local/regional extension direction. I think this needs to be a little clearer and the reasons for it (changes to scarp dip etc). Also, the next sentences 'To do this' 'Within this layer', make little sense to me and probably don't need to be here (save for the User Manual).*

> We define that profiles should be drawn perpendicular to the scarp trend in this section. This is mentioned in the text of the manuscript.
> The confusing section has been removed and is explained in the User Manual where it is more appropriate to discuss specific steps in the methodology.

*Lines 95 to 96 - citation needed for "A spacing of 1-5 meters has proven to be adequate in defining meter-scale features".*

> This was referring to the spacing density adequate for our case study. It has been removed from the manuscript since it is no longer needed (see previous comments).

*Lines 98 to 99 – "If geologic ages are not defined within the GIS environment, the user can manually generate these features with a few simple steps outlined in the user manual." I've only have a brief look at the code, but can you not add something to the code to skip this if it's not included in the input variables. Rather than get the user to time-consumingly add this to GIS before they start calculating scarp information?*

> This is a great suggestion and we appreciate this criticism! We have added additional functionality to the code that allows the user to specify whether this data is available. Applying this new functionality of the code will limit the users from having to do the tedious workaround and further improve the ease-of-use. It is reflected in the updated user manual and manuscript as well. Thanks!

*Monte Carlo Slip Statistics Toolkit (MCSST)*

*Line 117 – 'previous method' are these methods published? If so, needs a citation. If not, would be interesting to compare how the functionality has improved (time spent?)*

We agree that this would be a very interesting metric to provide. Unfortunately, we do not have a specific comparison of the time spent with different methods. One of the authors, Tim Stahl, hasn't published that workflow, but has published results based on that workflow in Stahl et al. (2016) *NZJGG*; Stahl and Niemi (2017) *Nature Sci. Rep.*

*Check Your Selections*

*Line 123 – 'checked for accuracy' – by whom? The user?*

Yes, by the user. The workflow allows for a convenient display of the user's choices.
The text now includes the reference to the 'user check' to make this clearer

*Case Study*

*For me I'd like to see more of the rational as to why this area was chosen. Has it proven too large for previous methods? What are the limitations of this area compared to other dip-slip fault scarps in other areas? This can be resolved either by using the tool elsewhere or commenting on the limitations etc of the tool.*

We appreciate the reviewer's interest for included additional rationale for choosing this study area and include additional language to this portion of the manuscript to reflect our thought-process. In regards to choosing the TVZ, it is an ideal local due to (i) heaps of fault scarps across relatively narrow tectonic province (so ideal method for characterising the region); (ii) clear offsets of (relatively) planar unit that is easily correlated and has been mapped across the area; (iii) studied in detail so can compare with past results; (iv) known fault kinematics and near-surface geometries from one of the best paleoseismic datasets in the world.
We only provide one case study within this research project and thus do not choose to comment on or provide results from another area.
Later in the Case study section, we address the reviewers concern to include limitations of the code by including this language:
   o *"We attempted to obtain data from as close to the transect line as possible because scarp heights appear to vary along strike of the fault traces due to the complex nature of faulting in the TVZ. This is one limitation of the MCSST. The user must define unique profiles along the fault scarp for each measurement and thus may not choose the position of maximum displacement, a location that can resolve the full 3D slip vector, or reveal the complex nature of displacement on the fault (Mackenzie and Elliot, 2017)."*

*Efficiency of the MCSST Toolkit*

*Lines 232 to 233 - "To confirm the results, the entire process was completed again by multiple users, which resulted in similar outcomes across the board." I'd love to see the*

*results from multiple users. This sort of thing really interests me as no matter how we develop code, or who uses it, there will always be a degree of bias. Limiting that bias is the aim, not creating perfect code for a single user.*

I agree with the reviewer's comments that this would be very interesting to include. Unfortunately, this analysis was not saved and thus I do not have access to the results from other users. The analysis was completed during a mini workshop I conducted at GNS Science. Because of this, we decided to omit this sentence from the manuscript.

*Technical corrections.*

*Introduction*

*Line 29 – Possibly rewrite this sentence. "When Light Detection and Ranging (LiDAR) data have adequate resolution, the images can be used to identify submeter scale geomorphic features from a workstation". The resolution of LiDAR is relative to the distance captured from the object. For me, it only needs "LiDAR can be used to identify submeter scale geomorphic features from a workstation", then give a citation.*

Done

*Line 33 – lower case 't' on The.*

Done

*Principles of Design for MCSST*

*Line 65 – add a : after 'to'.*

Done

*Define Fault Scarp Profiles in QGIS or ArcGIS*

*Line 92 – 'In this example' – which one?*

This sentence was removed as it is confusing and not needed in the section.

*Extract Data for Profiles*

*Line 95 – remove 'user-defined', unneeded.*

Done

*Monte Carlo Slip Statistics Toolkit (MCSST)*

*Line 109 – add 'scarp' after fault? If we are looking at scarp components that is.*

Done

*Lines 110 to 112 – Possibly rewrite as "'To make it easier for the user, a slider has been included to select the distance along the profile each scarp component exists at".*

Done

*Lines 132 to 134 – I found the sentence "If the hanging wall and footwall strain marker surfaces are not parallel, as is commonly the case, the calculated vertical separation is a function of horizontal distance to the fault and the dip slip calculation requires a knowledge of the position or projection of the fault tip onto the scarp." difficult to read.*

The sentence was simplified to read: "If the hanging wall and footwall strain marker surfaces are not parallel, as is commonly the case, the dip slip calculation requires a knowledge of the position or projection of the fault tip onto the scarp."

*Calculate Slip Statistics*

*Line 146 – maybe 'calculates' rather than 'conducts a calculation for', simpler.*

Done

*Figures*

*All are difficult to read as font is too small.*

The figures should be larger when high resolution images are uploaded for the final manuscript submission. Thank you for this comment. We will ensure all font is legible.

*Other*

*Use of capitals in headers needs addressing*

All headers have been updated. The first word of each title and proper nouns (e.g., locations and toolkit name) are capitalized.

**Reply to interactive comment by Christoph Grüztner:**

**November 4, 2019**

We greatly appreciate the feedback provided by Christoph Grüztner, who outlined specific and concise improvements that could be made to the manuscript. The most substantial changes include removing superfluous sections to streamline the manuscript and adding text to motivate the study within the abstract. Additionally, minor critiques and corrections were made throughout the manuscript. We are very thankful for Christoph's focused review.

- Franklin Wolfe

*Abstract: - I recommend to add one or two sentences at the beginning of the abstract that explain the need for such a tool. What is the problem with current software, and why is it necessary to present a better one?*

We appreciate this constructive feedback and will amend the beginning of the abstract to address this point.

> "Manual approaches for analyzing fault scarps in the field or with existing software can be tedious and time-consuming. Here, we introduce an open source, semi-automated, Python-based graphical user interface (GUI) called the Monte Carlo Slip Statistics Toolkit (MCSST) for estimating dip slip on individual or bulk fault datasets that (1) makes the analysis of a large number of profiles much faster, (2) allows users with little or no coding skills to implement the necessary statistical techniques, (3) and provides geologists a platform to incorporate their observations or expertise into the process.."

*1 Introduction: - Also see the MatLab code in:Mackenzie, D., & Elliott, A. (2017). Untangling tectonic slip from the potentially misleading effects of landform geometry. Geosphere, 13(4), 1310-1328.*

> The reviewer mentions a novel new method for calculating the full 3D slip geometry of a fault zone, which is very relevant for this study, and thus we include this new citation in the revised manuscript.

> "Several relatively complete and distinct sets of computational tools and libraries also exist for completing an array of complex topographic and fault zone analysis at the outcrop scale [e.g., SPARTA, Structure-from-Motion, etc.] (Westoby et al., 2012; Bemis et al., 2014; Hodge et al., 2019], including those that attempt to resolve the full 3D slip vector (Mackenzie and Elliot, 2017).

> Added to references:

> Mackenzie, D., and Elliott, A. Untangling tectonic slip from the potentially misleading effects of landform geometry. Geosphere, 13(4), 1310-1328, 2017.

*2 Background - Lines 55-62: Although an interesting and valuable collection of case studies, I think this should be deleted in a "short communication"*

> Lines 55-62 have been removed while the references remain in the previous sentence to refer to these studies.

*4 Workflow: - Line 90: Do the DEMs need to be in UTM?*

> Yes, they do. Meters are the units best suited for this workflow.

> "The user first defines profiles across fault scarps imaged in high-resolution digital elevation models with UTM coordinates."

*6 Case Study – Taupo Volcanic Zone (TVZ), NZ In general: I recommend to shorten the geological introduction to the study site substantially. Although it is interesting, please only include the information necessary to show your new tool. For this, most of the background is not needed and a "short communication" is not the right format for telling the whole story*

> We appreciate the reviewer's concern about the length of the geologic background and have chosen to streamline this section of the manuscript. We reduced the section from 1153 to 867 words (~25% reduction), while keeping the most important parts and cutting unnecessary ones.

*- line 181-182: "Ideally,..." Will problems arise if this is not the case?*

> The short answer is no. The analysis will yield faulty rates, but this can be overcome with manual intervention and is a data issue as opposed to toolkit/methodology issue. This text was removed in the process of streamlining the TPZ discussion and should no longer be an issue to the reader or user of the code. If the expected age is different than the age extracted, then the user can manually manipulate the data frame (csv file) outside of the general workflow.

*- line 199: This is extremely steep for normal faults (Jackson, J. A., & White, N. J. (1989). Normal faulting in the upper continental crust: observations from regions of active extension. Journal of Structural Geology, 11(1-2), 15-36).*

> We appreciate the reviewers concern about the relatively high values employed for fault dip in our calculations. The values we chose for our case study are consistent with data obtained from geological observations of near surface fault morphologies made in the field by Pilar Villamor and others over numerous field excursion (Grindley 1959; Villamor and Berryman, 2001; Lamarche et al., 2006; Villamor et al., 2010, 2017). Thus, we do not seek to re-do the analysis with new values and explain later in the manuscript how these values represent near surface fault dips and are scaled to include shallower fault dips and larger fault slips at depth.

*- lines 224-229: Again, this is all very fascinating, but check if it is necessary to present your tool. In the next section you argue that the results derived from your (great!) new tool agree with previous studies on the fault*

*system, and this is surely a great outcome - but do you need it to prove that the code is right? To be clear: I do like the story with the rifting and I wouldn't mind to keep it in the paper; i just wonder if the format "Short Communication" allows for this. I'd hope so, but this is the editor's choice.*

> This section was removed for the reasons suggested by the reviewer. We believe that it helps to streamline and focus the discussion by leaving it out.

*7 Efficiency of the MCSST Toolkit - Line 233-234: "To confirm the results, the entire process was completed again by multiple users, which resulted in similar outcomes across the board." Can you give error bars? This would be very interesting! How much do the results depend on the user's choices?*

> We agree with the reviewer's comments that this would be very interesting to include. Unfortunately, this analysis was not saved and thus I do not have access to the results from other users. The analysis was completed during a mini workshop I conducted at GNS Science. Because of this, we believe have decided to omit this sentence from the manuscript.

*Figures: - Make all figures larger. In figure 4, arrange the panels vertically and increase the size of each. Currently, the text is too small to be legible. - Figure 4c: Is this the example from Fig. 2 and 3? Perhaps show figure 4 before you explain the example profile.*

> Figures will presumably be larger when final versions are submitted.
> Panels have been rearranged vertically.
> Caption for Figure 4 is now corrected to state: "… For simplicity, only the Earthquake Flat Formation of the Okataina Group is shown from the Geologic Map of New Zealand Projected (GMAP). This is the formation that was analyzed in this study. The light blue box represents the map extent of part (c). c) LiDAR hillshade map of the location of the profile shown in Figure 2 and analyzed in Figure 3.

*Technical corrections - line 92: scarps - line 144: could have - line 181: where - line 225: chronological - Check last line of the caption of figure 4.*

- Done

# Short communication: A semi-automated method for ~~rapid~~ bulk fault slip analysis from topographic scarp profiles

Franklin D. Wolfe[1], Timothy A. Stahl[2], Pilar Villamor[3], and Biljana Lukovic[3]

[1]Earth and Planetary Sciences, Harvard University, Cambridge, 02143, USA
[2]College of Science, University of Canterbury, Christchurch, 8041, NZ
[3]GNS Science, Lower Hutt, 5040, NZ
**Correspondence:** Franklin D. Wolfe (wolfe_franklin@g.harvard.edu)

**Abstract. Manual approaches for analyzing fault scarps in the field or with existing software can be tedious and time-consuming.** Here, we introduce an open source, semi-automated, Python-based graphical user interface (GUI) called the Monte Carlo Slip Statistics Toolkit (MCSST) for estimating dip slip on individual or bulk fault datasets. That makes the analysis of a large number of profiles much faster, (2) allows users with little or no coding skills to implement the necessary statistical techniques, (3) and provides geologists a platform to incorporate their observations or expertise into the process. Using this toolkit, profiles are defined across fault scarps in high-resolution digital elevation models (DEMs) and then relevant fault scarp components are interactively identified (e.g., footwall, hanging wall, and scarp). Displacement statistics are calculated automatically using

5 Monte Carlo simulation and can be conveniently visualized in Geographic Information Systems (GIS) for spatial analysis. Fault slip rates can also be calculated when ages of footwall and hanging wall surfaces are known, allowing for temporal analysis. This method allows for rapid analysis of tens to hundreds of faults in rapid succession within GIS and a Python coding environment. Application of this method may contribute to a wide range of regional and local earthquake geology studies with adequate high-resolution DEM coverage, both regional fault source characterization for seismic hazard and/or

10 estimating geologic slip and strain rates, including creating long-term deformation maps. ArcGIS versions of these functions are available, as well ones that utilize free, open source Quantum GIS (QGIS) and Jupyter Notebook Python software.

## 1 Introduction

The field of tectonic geomorphology is increasingly employing computer-based algorithms for displaying and analyzing digital topographic data (Whittaker et al., 2008; Kirby and Whipple, 2012; Zhou et al., 2015; Whipple et al., 2016). As a result, broad

15 scale tectonic geomorphology toolboxes for automated high-level stream channel analysis and landscape evolution have been rapidly evolving (e.g., TopoToolbox, Topographic Analysis Kit (TAK), Stream Channel and Floodplain Metric Toolbox, etc.) (Whipple et al., 2007; Schwanghart and Scherler, 2014; Hopkins et al., 2018; Forte and Whipple, 2019). Several relatively complete and distinct sets of computational tools and libraries also exist for completing an array of complex topographic and fault zone analysis at the fault zone and outcrop scale [e.g., SPARTA, Structure-from-Motion, etc.] (Westoby et al., 2012; Bemis et al., 2014;

20 Hodge et al., 2019), including those that attempt to resolve the full 3D slip vector (Mackenzie and Elliot, 2017).

These toolboxes are ~~is is~~ important because fault zones can be extraordinarily complex and require a method for systematically estimating net slip and slip rates across them (Fossen and Rotevatn, 2016). Where original landform geometries are known or can be inferred, fault scarp profiles from GPS surveys or transects across high-resolution digital elevation models (DEMs) can be used to characterize components of fault slip (DeLong et al., 2010; Spencer, 2010; Klimczak et al., 2018). The deformation within

~~25~~ these fault zones can be spatially and temporally variable, thus motivating the analysis of large numbers of faults over broad areas (Wallace, 1977; Avouac, 1993; Villamor and Berryman, 2001; Personius et al., 2017; Pérouse and Wernicke, 2017). In most cases, where along-strike variability in slip and/or slip rate are observed, multiple measurements from the same fault are required just to delineate the slip history of one feature.

~~When~~ Light Detection and Ranging (LiDAR) ~~data have adequate resolution, the images~~ can be used to identify submeter-
30 scale geomorphic features from a workstation (Dong, 2015). Currently, this is done by analyzing individual profiles across fault scarps, manually picking fault components on distance vs. elevation plots, calculating statistics and regressions for each, and then running unique analyses for each profile, which is both tedious and time consuming.

In this paper we introduce a new Python-based graphical user interface (GUI), The Monte Carlo Slip Statistics Toolkit (MC-SST), that streamlines and improves on the approach for calculating slip statistics from fault scarps present in high-resolution
35 digital elevation models (DEMs). We describe the basic functionality of MCSST and provide a representative example of the potential utility of this approach for selecting and analyzing fault scarps across a 25 km-wide transect. Using this approach, hundreds of profiles can be analyzed in a few hours, allowing for efficient analysis of spatial and temporal patterns of deformation. The methodology also allows for easy visualization of slip statistics on the original fault profiles in GIS so that spatial patterns of fault slip can be identified and anomalous values quickly identified and interrogated. A detailed user manual that
40 lays out step-by-step usage of these tools and discusses how the underlying functions and algorithms work is included as a supplement and within the code repository.

## 2 Background

The concept and mathematics behind using a Monte Carlo approach to calculating dip slips were developed by Thompson et al. (2002). The motivation behind using this approach is that it accounts for uncertainty in key parameters required for
45 calculating slip from structural data and topographic profile (Fig. 1). Regression statistics are calculated for lines fit to each of the hanging wall, scarp, and footwall. Each line has a mean value of slope and y-intercept, with 95 percent confidence intervals for each component~~variable~~, and can thus be modelled as a normal distribution. The fault dip can be modelled as any type of distribution depending on how well constrained the values are. For example, if fault dips can be measured in adjacent outcrops, it may be most appropriate to model the value as a normal distribution with a mean and 95 percent confidence interval; if dip
50 is constrained only by regional fault geometry data, the user may choose a uniform or trapezoidal distribution to reflect the additional epistemic uncertainty. In the simplest case, the only other parameter required to calculate dip slip is the location of the fault projected up to the scarp.

This approach has been widely used on dip slip faults around the world (Thompson et al., 2002; Amos et al., 2010; Rood et al., 2011; Stahl et al., 2016; Stahl and Niemi, 2017). Thompson et al. (2002) first used their method to quantify slip rate
55 variability in a transect across the Kyrgyzstan Tian Shan. Amos et al. (2010) showed that it could be used to identify previously unrecognized offsets along the Kern Canyon fault in east-central California, highlighting its role in accommodating internal deformation of the southern Sierra Nevada. Rood et al. (2011) analyzed a suite of geomorphic markers along the transition from

the Sierra Nevada to the Eastern California Shear Zone-Walker Lane belt to reveal interactions among multiple faults. Stahl et al. (2016) used manually surveyed GPS profiles along the Fox Peak fault in New Zealand to demarcate segment boundaries based on slip rate. Stahl and Niemi (2017) compared manually surveyed fault scarps to geodetic estimates of strain in the Sevier Desert, Utah to discern a local magmatic versus far-field tectonic extension regime along the Wasatch Front. The broad interest in calculating slip statistics from fault scarps around the world, and the increasing access to high-resolution DEMs and powerful coding environments, motivates our development of a semi-automated toolkit for analyzing bulk fault datasets.

## 3 Principles of Design for MCSST

The primary goals of creating the MCSST are to (1) lower the barrier to entry for scientists by limiting the required knowledge of coding languages or general programming techniques; (2) allow the user to check for consistency and accuracy in their interpretations of fault components (e.g., fault scarp, hanging wall, and footwall) before proceeding with the slip statistics calculations; (3) optimize the functionality of GIS environments by combining previously created plugins when possible; (4) introduce a methodology for efficiently analyzing numerous fault scarps and delineating distributions of spatial and temporal patterns for slip statistics; and (5) provide open source software for those who do not have access to commercial products. We reference hanging wall and footwall throughout because this code was developed for use in a rift setting; however, upthrown and downthrown are equally viable terms considering the underlying math should be consistent for reverse faults as well.

MCSST was designed to leverage the power and broad code base of the open source QGIS plugin environment. It also utilizes the key data manipulation and visualization tools developed for comma-separated, value-file formats analyzed in the Jupyter Notebook Python coding environment. Free, open source applications, such as QGIS and Jupyter Notebook, provide increased access and functionality for scientific computing and displaying and analyzing spatial datasets. We also provide version compatible with ArcGIS, which is commonly used by academic institutions.

QGIS is a professional GIS application that runs on Linux, Unix, Mac OSX, Windows, and Android (Hugentobler, 2008). It is written in C++ supports numerous vectors, rasters, and database formats and functionalities and allows the user to visualize, manage, edit, and analyze data and compose printable maps. The scientific computing packages accessible within QGIS can be downloaded as plugins and used with internal graphical user interfaces (GUIs) or from a command line within the QGIS environment. They have been used for developing both desktop and web applications, facilitating complex scientific and numeric applications and improving data analysis and visualization (Bartolini et al., 2013; Westra, 2014; Tebano et al., 2017).

Jupyter Notebook is an open source web application developed through Project Jupyter, a non-profit organization that exists to develop open-source software, open-standards, and services for interactive computing across dozens of programming languages. QGIS and Jupyter Notebook both utilize the Python coding language.

## 4    Workflow

### 4.1    Define Fault Scarp Profiles in QGIS or ArcGIS

The user first defines profiles across fault scarps imaged in high-resolution digital elevation models with UTM coordinates. Profiles are defined on a vertical plane normal to the structural trend of the fault. For each profile in Step 1, distance and elevation (and optionally, geologic age) data are extracted at a user-defined spacing interval (see User Manual). To do this within the QGIS environment, the user creates a new Shapefile Vector Layer. Within this layer, the user defines unique vector profiles across fault scarp imaged in the DEM. Each one of these profiles should correspond to a unique fault scarp that the user wants to interrogate. In this example, we consider that the fault has cut an originally planar geomorphic surface (e.g., an ignimbrite). Profiles are defined on a vertical plane normal to the structural trend of the fault.

### 4.2    Extract Data for Profiles

For each user-defined profile in Step 1, distance, elevation, and geologic age data are extracted at a user-defined spacing. A spacing of 1-5 meters has proven to be adequate in defining meter-scale features. Surface age can be provided by a Shapefile [in this case the New Zealand geological map, Leonard et al. (2010)]. Surfaces on either side of the fault can be different ages, which would result in minimum or maximum values when calculating net slip rates in Step 3. If geologic ages are not defined within the GIS environment, the user can manually generate these features with a few simple steps outlined in the user manual. To extract data, compiled plugins 'Points Along Geometry' and 'Point Sampling Tool' are utilized within QGIS. In the ArcGIS environment, the ArcGIS tool titled, 'createProfileCSV', or its companion standalone Python script, which were developed for this study, can be used to reproduce the same functionality.

### 4.3 4.2    Monte Carlo Slip Statistics Toolkit (MCSST)

Automated methods of extracting fault scarp components have shown that can be fraught with peril (Gallant and Hutchinson, 1997; Hilley et al., 2010; Stewart et al., 2018; Hodge et al., 2019). mMathematically identifying inflection points in a profile is often not adequate (Gallant and Hutchinson, 1997; Hilley et al., 2010; Stewart et al., 2018; Hodge et al., 2019).; however, recent algorithms, such as SPARTA, show promise (Hodge et al., 2019). Therefore, the input of a geologist is needed to analyze each fault scarp and our methodology makes this as easy as possible.

Within the Jupyter Notebook Python coding environment, the MCSST is used to analyze each profile. Profiles are loaded individually and then interactively displayed continuously to identify relevant scarpfault components (e.g., footwall, hanging wall, and scarp) (Fig. 2). As opposed to identifying specific rows and columns of the CSV files, which is time consuming, the user usesTo make it easier for the user, a slider has been included to select the distance along the profile each fault scarp component exists at s to choose relevant data points as shown in Figure 2b (e.g., the red line in Figure 2a was fit using the data selection shown in Figure 2b).

The choices are visualized in real-time as a regression line is automatically fit to the values within the modified data frame and displayed in the interactive plot (e.g., red line in Figure 2a fit to the footwall surface). The least squares linear regressions of

these points in an x-y coordinate system determine the mean and standard error of both the slope and the intercept of the lines, which represent the hanging wall and footwall, where the tangent of the surface dip is the slope. This functionality improves greatly upon our previous method of analyzing individual profiles across fault scarps, manually picking fault components on distance vs. elevation plots (e.g., in Excel), and then exporting statistics and regressions individually to MATLAB.

### 4.~~4~~4.3    Check Your Selections

120    Though potentially subject to bias, picking fault scarp components requires human input (Gillespie et al., 1992; Zielke et al., 2015; Middleton et al., 2016; Hodge et al., 2019). Therefore, it is vital that users check each fault scarp component for accuracy. As shown in Figure 2a, selections are checked for accuracy by the user and updated, as necessary, by repeating Step 3 until a solution that fits the observations is obtained. If the user does not like a specific selection, the user can reselect data from the initial profile, and thus a new best fit least squares linear regression can be redefined for a surface and that data selection saved

125    instead. Once the user has the desired representation for the fault scarp components, it is saved by running the next code box. The user then loads in the next fault profile and repeats Steps 3 and 4 for each new profile. Data selections are saved as a comma-separated file format, where different columns represent the separated data for the hanging wall, footwall, and scarp segments of the profiles. These data are saved together in a separate folder for organization and to be read by the MC Slip Statistics calculator.

### 4.~~5~~4.4  Calculate Slip Statistics

130    Dip slip (assumed to be net slip in this instance), as well as horizontal and vertical displacement are calculated automatically in this step (Thompson et al., 2002). The advantage of this step is that multiple transects, faults, and uncertainties in input parameters are analyzed simultaneously. If the hanging wall and footwall strain marker surfaces are not parallel, as is commonly the case, ~~the calculated vertical separation is a function of horizontal distance to the fault and~~ the dip slip calculation requires a knowledge of the position or projection of the fault tip onto the scarp. A line fit to the scarp face contains all possible points for the intersection of the fault tip and scarp. The amount of dip slip is then split into two parts: the distance from the footwall

135    projection up to this point and the distance from the hanging wall down to this point.

Additional input parameters are first defined, including fault dip and intersection with the scarp distributions and geologic age distributions, if available (Fig. 1). Fault dip and uncertainty therein are determined through direct measurement from outcrops, nearby paleoseismic trenches, or by estimating from geomorphic expression. A range of probability density functions (PDFs) can be assigned for fault dip as well as uncertainty of where the fault projects onto the scarp. For example, in our case study

140    below, we chose a trapezoidal distribution for fault dip centered around the most probable dip values and a uniform distribution for the geologic age since only a minimum and maximum age are given for surfaces. Normal distributions for both parameters could have also been chosen. The user would simply signify this option (see the User Manual, which is included as a supplement to the manuscript). If the user was interested in defining separate input values for different combinations of fault scarps, the user would manually define these values for each iteration and run the code more than once.

The code conducts a calculation for the net dip-slip component, as well as the vertical separation and horizontal extension,

145    as stated above. Geologic age data can be used to define an age distribution for the geologic surface in question and thus slip

150  rates can be conveniently calculated.

The Monte Carlo approach to calculating slip statistics relies on bootstrapping repeated random samples from the PDFs   of the input parameters to obtain numerical results and generate histograms with 95 percent confidence intervals for the slip statistics from multiple uncertain estimations.

Plots of slip distributions for each fault profile are displayed as output, so the user can easily visually analyze for anomalies
155  in the dataset (Fig. 3). Lastly, the script outputs a CSV file for each group of faults analyzed simultaneously. This can be useful if the user wants to categorize data based on spatial or temporal differences; this was useful in determining displacements on different geologic surfaces, corresponding to different geologic ages, separately.

## 5   Display Data in GIS

The data calculated in the previous step can be added to the original shapefile layer to allow for spatial analysis. As outlined in the user manual, the QGIS software allows for seamless 'joining' of the CSV file with the original fault scarp profile shapefile layer. When using the ArcGIS software, the ArcGIS tool developed in this study, 'attachStats2Profiles', and its
160  Python standalone version can also complete this task.

## 6 Case Study – Taupo Volcanic Zone (TVZ), NZ

The Taupo Volcanic Zone (TVZ), in the central North Island of New Zealand, is a northeast-southwest trending, 250-km long, 14 to 40-km wide active rift, the Taupo Rift (Wilson et al., 1995; Wallace et al., 2004; Seebeck et al., 2014). the volcanic arc associated with the subduction of the Pacific Plate beneath the Australian Plate (Fig. 4) (Wilson et al., 1995). Within this region, a northeast-
165  southwest trending, 250-km long, 14 to 40-km wide active rift, the Taupo Rift, has formed as a result of fore-arc rotation and subducting slab roll back (Wallace et al., 2004; Seebeck et al., 2014). Extension across the TVZ over the last 1.6 Myr is expressed primarily as regional volcanism, extensional fractures, and northeast-southwest trending normal faults (Pilar Villamor et al., 2017). Late Quaternary extension rates derived from contemporary geodetic and Quaternary fault data increase northward from 2-4 mm yr$^{-1}$ at the southern termination of the Taupo Rift to 10-15 mm yr$^{-1}$ at the Bay of Plenty coast (Fig. 4) (Villamor and Berryman, 2001; Wallace et al., 2004; Lamarche et al., 2006; Villamor and Berryman, 2006).

170  The TVZ represents the ideal case study area to test our methodology because the Quaternary geology of the region has been extensively studied through detailed mapping of geological units and active fault locations (Fig. 4). The regional kinematics and near-surface geometry of faults are known and contribute to one of the best paleoseismic data sets in the world and results from which we can compare our findings (Villamor and Berryman, 2001). Many fault scarps are clearly imaged to offset a relatively planar geologic horizon that is easily correlated and has been mapped across the relatively narrow tectonic province.
175  Additionally, many high resolution datasets exist (e.g., the QMAP Geologic Map of New Zealand Project, LiDAR-based DEM of 1-meter horizontal resolution, and regional active fault map) [GNS Science; Leonard et al., 2010; Villamor et al., 2010] (Fig. 4).

180 ~~The QMAP Geological Map of New Zealand Project, produced by GNS Science, provides the most current mapping of geology for New Zealand in a single dataset at a scale of 1:250,000 (compiled at 1:25,000 to 1:50,000 scale), which has up-to-date lithology distinctions for our study area (Leonard et al., 2010). A high resolution DEM exists (e.g., 1 meter horizontal resolution LiDAR based) that adequately resolves meter to 50-meter scale displacements along active normal faults. A hillshade derivative was made from the DEM to image the geologic features. A detailed active fault map, previously developed to produce a fault avoidance map for the Rotorua District Council ( 1:10,000 scale; (Villamor et al., 2010) has been used to define~~
185 ~~the location of profiles across faults. The 1: 250;000 geological map has less resolution than the fault map used and thus we have constrained our selection of profile locations to a unit that is clearly identifiable in the LiDAR and with boundaries that are relatively well represented in the lesser resolution geological units ArcGIS coverage, were the geological unit age is extracted from. Ideally the resolution of the different data layers should be of the same order.~~

We analyzed fault surface displacements on the Earthquake Flat Formation ignimbrite of the Okataina Group (Nairn, 2002),
190 a volcanic formation of pyroclastic material, lapilli, and ash, which has been dated to 60-62 ka (Wilson et al., 2007). The constructional surface of the ignimbrite is well-preserved and represents a previously continuous, sub-horizontal, planar feature, which has displaced by normal faults in the TVZ.

Here, we applied the methodology for the QGIS-based tool to a transect across the Central TVZ. By choosing to analyze fault displacements of a single age surface we can get a picture of the deformation rates across the region occupied by the
195 surface for the time period represented by the surface chosen. In this case the Earthquake Flat ignimbrite covers practically the entire width of the active rift (only a couple of moderately high scarps on the western margin of the rift do not displace the ignimbrite). We attempted to obtain data from as close to the transect line as possible because scarp heights appear to vary along strike of the fault traces due to the complex nature of faulting in the TVZ. This is one limitation of the MCSST. The user must define unique profiles along the fault scarp for each measurement and thus may not choose the position of maximum displacement, a location that can resolve the full 3D slip vector, or reveal the complex nature of displacement on the fault
200 (Mackenzie and Elliot, 2017).

We analyzed 33 faults in a 25-km transect from northwest to southeast in the direction of regional extension. From the primarily northeast to southwest striking fault systems of the Central TVZ, we chose faults with significant offset (>5 m) because smaller faults contribute insignificantly to the overall extension of the region and often represent splays of the larger faults. Thus, because of the filtering small scarps and two missing moderately high-relief scarps on the west of the transect in this study, we report a minimum extension rate for the Central TVZ below.
205 For each fault, we identified the key fault components (e.g., fault scarp, hanging wall, and footwall) and determined slip estimates using MCSST. For our fault geometry distribution, we chose a trapezoidal distribution, centered around 70-80 degrees in dip. This is consistent with data obtained from geological observations in trenches and superficial exposures within 40 meters from the ground surface (Villamor and Berryman, 2001).

The dip slip values obtained for each fault were in line with reasonable estimates based on extensive experience conduct-
210 ing field campaigns in the region (e.g., altimeter measurements along transects and detailed logging of faults in exploratory trenches) and visual inspection of the digital elevation model (Villamor and Berryman, 2001; Villamor et al., 2010; P. Villamor et al., 2017). Further, the values plotted in Figure 3 are consistent with visual inspection of the distance vs. elevation profile

(this study). We used recently derived age constraints on the Earthquake Flat Formation to convert these values into dip slip rates.

MCSST automatically converts dip slip rate estimates into horizontal extension rate values by using a trigonometric relationship defined by the fault angle distribution we input. This resulted in a minimum cumulative near-surface horizontal extension rate of 2.77 mm yr$^{-1}$ ($\pm$ 0.69 mm yr$^{-1}$) summed across the mean net slip rate value for all faults along the transect. The minimum cumulative near-surface horizontal extension rate when summed across the median net slip rate values for all faults along the transect is 2.73 mm yr$^{-1}$ with a 95 percent confidence interval of 0.56-5.26 mm yr$^{-1}$.

This is similar to the values provided by the current best-estimate of Quaternary extension rates derived from fault data of: 2.4 mm yr$^{-1}$ ($\pm$ 0.4 mm yr$^{-1}$) for the Central TVZ (Villamor and Berryman, 2001) and only 8 km southwest of this study's transect; 2.9 mm yr$^{-1}$ ($\pm$ 0.74 mm yr$^{-1}$) for the Northern TVZ immediately offshore (Lamarche et al., 2006); and 2.7 mm yr$^{-1}$ ($\pm$ 0.3 mm yr$^{-1}$) for the Southern TVZ at the Tongariro Volcano latitude (Gomez-Vasconcelos, 2017).

Note that near-surface fault derived extension rates along the TVZ have been converted to higher (more realistic) total extension rates (from 4 to 15 mm yr$^{-1}$ from south to north) in the various studies by applying correction factors that include shallower fault dips and larger fault slips at depth, and contribution from small to moderate earthquakes (small faults that do not rupture the surface) (see Villamor and Berryman, 2001 for method). The differences in fault-derived total extension rate from south to north are mainly dependent on the average "deep" fault dip value chosen (60 degrees for Southern and Central TVZ and 45 degrees for Northern TVZ), which remains on the largest uncertainties for the TVZ faults. Geodetic derived extension rates show a clear extension rate increase from north to south (Wallace et al., 2004).

The near-surface extension rate obtained by Villamor and Berryman (2001) contains a mixture of ages, i.e., individual fault slip rates were obtained with chorological marker ranging from 8 to 60 ka. They were converted to slip rates for a chosen 20 ka timeframe and then added to estimate rift extension rate. Given the large temporal variations in slip rate for some faults in the area of our transect (some faults can have quiescence periods of 10 ka (Nicol et al., 2006) and the fast rift evolution (rapid rift narrowing; Villamor et al 2017), the near-surface extension rate can be considered to better represent the average extension rate calculated here for the last 60 ky.

## 7    Efficiency of the MCSST Toolkit

The utility of the MCSST toolkit is best demonstrated by the efficiency with which this study was conducted and the agreement with the current geological understanding of the Central TVZ. Once our methodology was defined and the workflow implemented, the analysis of the transect (33 faults across 25 km) was completed in one day at a work station. To confirm the results, the entire process was completed again by multiple users, which resulted in similar outcomes across the board. We note that installing and running the Python code packages, navigating the GIS software, and inputting parameters and gaining comfort with the interface for the Jupyter Notebook pose the greatest challenges to employing the MCSST toolkit, so we provide a detailed user manual to accompany the manuscript to lower the barrier of entry.

## 8    Conclusions

245  The Monte Carlo Slip Statistics Toolkit (MCSST) allows users to rapidly and accurately estimate fault slip across several faults imaged in DEMs. This approach improves upon similar studies because it allows for rapid analysis of tens to hundreds of faults simultaneously within GIS, and anomalous values can quickly be identified. The underlying functions are built upon open-source Python code base and are specifically designed to lower the bar of entry for researchers wishing to include robust, quantitative fault scarp analysis in their work or teaching.

Application of this method may contribute to a wide range of regional and local paleoseismic studies with adequate high-resolution DEM coverage, both regional fault source characterization for seismic hazard and/or estimating geologic slip and strain rates. In our case study, initial estimates for minimum near-surface extension rates along a northwest to southeast transect (33 faults; 25 km) across the Taupo Volcanic Zone are in line with the current paleoseismological and tephrochonological

250  understanding of the region and provide useful constraints on the uncertainty associated with these values (Villamor and Berryman, 2001).

*Code availability.* All codes, as well as the User Manual can be found at this Github Repository: https://github.com/wolfefranklin/MCSST_2019

*Team list.* Franklin D. Wolfe (FW), Timothy A. Stahl (TS), Pilar Villamor (PV), Biljana Lukovic (BL)

*Data availability.* Datasets used in this study include the New Zealand Active Fault database, which can be found here: http://data.gns.cri.nz/af/, the Geologic Map of New Zealand, which can be found here: https://www.gns.cri.nz/Home/Our-Science/Land-and-Marine-Geoscience/Regional-Geology/Geological-Maps/1-250-000-Geological-Map-of-New-Zealand-QMAP/Digital-Data-and-Downloads, and elevation data, which can be found here: https://data.linz.govt.nz/data/category/elevation/

255

*Author contributions.* FW, TS, BL contributed to code development and testing. PV contributed to data analysis and case study development. All authors contributed to drafting the manuscript. BL and PV contributed data sets. PV and TS contributed background material and context.

265

260

*Competing interests.* The authors declare that they have no conflict of interest.

*Disclaimer.* MIT License Copyright

(c) 2019 wolfefranklin

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the "Software"), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.

THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGE-MENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

*Acknowledgements.* The authors would like to recognize support from Andy Howell, Kate Clark, and Regine Morgenstern (GNS Science) for support with this project. We would also like to thank the Structural Geology and Earth Resources Group and Earth and Planetary Sciences Department at Harvard University for funding and support for this project.

## References

Amos, C. B., K. I. Kelson, D. H. Rood, D. T. Simpson, and R. S. Rose, Late Quaternary slip rate on the Kern Canyon fault at Soda Spring, Tulare County, California, Lithosphere, 2, no. 6, 411–417, doi: 10.1130/L100.1, 2010.

Avouac, J.-P., Analysis of scarp profiles: Evaluation of errors in morphologic dating, J. Geophys. Res. Solid Earth, 98, no. B4, 6745–6754, doi: 10.1029/92JB01962, 1993.

Bartolini, S., A. Cappello, J. Martí Molist, and C. Del Negro, QVAST: A new Quantum GIS plugin for estimating volcanic susceptibility, doi: 10.5194/nhess-13-3031-2013, 2013.

Bemis, S. P., S. Micklethwaite, D. Turner, M. R. James, S. Akciz, S. T. Thiele, and H. A. Bangash, Ground-based and UAV-Based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology, J. Struct. Geol., 69, 163–178, doi: 10.1016/j.jsg.2014.10.007, 2014.

DeLong, S., G. E. Hilley, M. J. Rymer, and C. S. Prentice, Fault zone structure from topography: Signatures of en echelon fault slip at Mustang Ridge on the San Andreas Fault, Monterey County, California: Fault Zone Structure at Mustang Ridge, 2010.

Forte, A. M., and K. X. Whipple, Short communication: The Topographic Analysis Kit (TAK) for TopoToolbox, Earth Surf. Dyn., 7, no. 1, 87–95, doi: https://doi.org/10.5194/esurf-7-87-2019, 2019.

Fossen, H., and A. Rotevatn, Fault linkage and relay structures in extensional settings—A review, Earth-Sci. Rev., 154, 14–28, doi: 10.1016/j.earscirev.2015.11.014, 2016.

Gallant, J. C., and M. F. Hutchinson, Scale dependence in terrain analysis, Math. Comput. Simul., 43, no. 3, 313–321, doi: 10.1016/S0378-4754(97)00015-3, 1997.

Gillespie, P. A., J. J. Walsh, and J. Watterson, Limitations of dimension and displacement data from single faults and the consequences for data analysis and interpretation, J. Struct. Geol., 14, no. 10, 1157–1172, doi: 10.1016/0191-8141(92)90067-7, 1992.

Gomez-Vasconcelos, M. G., Paleoseismology, seismic hazard and volcano-tectonic interactions in the Tongariro Volcanic Centre, New Zealand, PhD Thesis, Massey University, Palmerston North, Manawatu, 2017.

Hilley, G. E., S. DeLong, C. Prentice, K. Blisniuk, and J. Arrowsmith, Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data, Geophys. Res. Lett., 37, no. 4, doi: 10.1029/2009GL042044, 2010.

Hodge, M., J. Biggs, Å. Fagereng, A. Elliott, H. Mdala, and F. Mphepo, A semi-automated algorithm to quantify scarp morphology (SPARTA): application to normal faults in southern Malawi, Solid Earth, 10, no. 1, 27–57, doi: https://doi.org/10.5194/se-10-27-2019, 2019.

Hopkins, K. G., S. Lamont, P. R. Claggett, G. B. Noe, A. C. Gellis, C. B. Lawrence, M. J. Metes, M. P. Strager, and J. M. Strager, Stream Channel and Floodplain Metric Toolbox, US Geol. Surv. Data Release, 2018.

Hugentobler, M., Quantum GIS, in Encyclopedia of GIS S. Shekhar, and H. Xiong (Editors), Springer US, Boston, MA, 935–939, 2018.

Kirby, E., and K. X. Whipple, Expression of active tectonics in erosional landscapes, J. Struct. Geol., 44, 54–75, doi:

10.1016/j.jsg.2012.07.009, 2012.

Klimczak, C., C. L. Kling, and P. K. Byrne, Topographic Expressions of Large Thrust Faults on Mars, J. Geophys. Res. Planets, 1123, no. 8, 1973–1995, doi: 10.1029/2017JE005448, 2018.

Lamarche, G., P. M. Barnes, and J. M. Bull, Faulting and extension rate over the last 20,000 years in the offshore Whakatane Graben, New Zealand continental shelf, Tectonics, 25, no. 4, doi: 10.1029/2005TC001886, 2006.

Leonard, G. S., J. G. Begg, and C. J. N. Wilson, Geology of the Rotorua area, Digital Database, GNS Science, Lower Hutt, QMAP, Digital Database, 1:250,000, 2010.

Mackenzie, D., and A. Elliot, Untangling tectonic slip from the potentially misleading effects of landform geometry, Geosphere, 13, no. 4, 1310-1328, 2017.

Middleton, T., R. T. Walker, B. Parsons, Q. Lei, Y. Zhou, and Z. Ren, A major, intraplate, normal-faulting earthquake: The 1739 Yinchuan event in northern China, J. Geophys. Res. Solid Earth, 12, no. 1, 293–320, 2016.

Nairn, I. A., Geology of the Okataina Volcanic Center, 1 sheet + 156 p., GNS Science, 1 sheet + 156 p., 1:50,000.

Nicol, A., J. Walsh, K. Berryman, and P. Villamor, 2006, Interdependence of fault displacement rates and paleoearthquakes in an active rift, Geology, 34, no. 10, 865–868, doi: 10.1130/G22335.1, 2002.

Pérouse, E., and B. P. Wernicke, Spatiotemporal evolution of fault slip rates in deforming continents: The case of the Great Basin region, northern Basin and Range province, Geosphere, 13, no. 1, 112–135, doi: 10.1130/GES01295.1, 2017.

Personius, S., R. W. Briggs, J. Z. Maharrey, S. J. Angster, and S. A. Mahan, A paleoseismic transect across the northwestern Basin and Range Province, northwestern Nevada and northeastern California, USA, Geosphere, 13, no. 3, 782810, doi: 10.1130/GES01380.1, 2017.

Rood, D. H., D. W. Burbank, and R. C. Finkel, Spatiotemporal patterns of fault slip rates across the Central Sierra Nevada frontal fault zone, Earth Planet. Sci. Lett., 301, no. 3, 457–468, doi: 10.1016/j.epsl.2010.11.006, 2011.

Schwanghart, W., and D. Scherler, TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences., Earth Surf. Dyn., 2, 1–7, doi: 10.5194/esurf-2-1-2014, 2014.

Seebeck, H., A. Nicol, P. Villamor, J. Ristau, and J. Pettinga, Structure and kinematics of the Taupo Rift, New Zealand, Tectonics, 33, no. 6, 1178–1199, doi: 10.1002/2014TC003569, 2014.

Spencer, J., Structural analysis of three extensional detachment faults with data from the 2000 Space-Shuttle Radar Topography Mission, GSA Today, 4–10, doi: 10.1130/GSATG59A.1, 2010.

Stahl, T., and N. A. Niemi, Late Quaternary faulting in the Sevier Desert driven by magmatism, Sci. Rep., 7, doi: 10.1038/srep44372, 2017.
Stahl, T., M. C. Quigley, A. McGill, and M. S. Bebbington, Modeling Earthquake Moment Magnitudes on Imbricate Reverse Faults from Paleoseismic Data: Fox Peak and Forest Creek Faults, South Island, New ZealandModeling Earthquake Moment Magnitudes on Imbricate Reverse Faults, Bull. Seismol. Soc. Am., 106, no. 5, 2345–2363, doi: 10.1785/0120150215, 2016.

Stewart, N., Y. Gaudemer, I. Manighetti, L. Serreau, A. Vincendeau, S. DOMINGUEZ, L. Matteo, and J. MALAVIEILLE, "3D_Fault_Offsets," a Matlab Code to Automatically Measure Lateral and Vertical Fault Offsets in Topographic Data: Application to San Andreas, Owens Valley, and Hope Faults, J. Geophys. Res. Solid Earth, 123, no. 1, 815–835, doi: 10.1002/2017JB014863, 2018.

Tebano, C., F. Pasanisi, and S. Grauso, QMorphoStream: processing tools in QGIS environment for the quantitative geomorphic analysis of watersheds and river networks, Earth Sci. Inform., 10, no. 2, 257–268, doi: 10.1007/s12145-016-0284-0, 2017.

Thompson, S. T., R. J. Weldon, C. M. Rubin, K. Abdrakmatov, P. Molnar, and G. W. Berger, Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, central Asia, J. Geophys. Res., 107, no. B9, 2002.

Villamor, P., and K. Berryman, A late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data, N. Z. J. Geol. Geophys., 44, no. 2, 243–269, doi: 10.1080/00288306.2001.9514937, 2001.

Villamor, P., and K. R. Berryman, Late Quaternary geometry and kinematics of faults at the southern termination of the Taupo Volcanic Zone, New Zealand, N. Z. J. Geol. Geophys., 49, no. 1, 1–21, doi: 10.1080/00288306.2006.9515144, 2006.

Villamor, Pilar, K. Berryman, S. Ellis, G. Schreurs, L. M. Wallace, G. S. Leonard, R. Langridge, and W. Ries, Rapid Evolution of Subduction-Related Continental Intraarc Rifts: The Taupo Rift, New Zealand: Rapid Evolution: Taupo Rift, New Zealand, Tectonics, 36, doi: 10.1002/2017TC004715, 2017.

Villamor, P., K. R. Berryman, S. M. Ellis, G. Schreurs, L. M. Wallace, G. S. Leonard, R. M. Langridge, and W. F. Ries, Rapid Evolution of Subduction-Related Continental Intraarc Rifts: The Taupo Rift, New Zealand, Tectonics, 36, no. 10, 2250–2272, doi: 10.1002/2017TC004715, 2017.

Villamor, P., W. F. Ries, and A. Zajac, 2010 Rotorua District Council hazard studies: active fault hazards., Consultancy Report 182, GNS Science, 28 p., 2010.

Wallace, R. E., Profiles and ages of young fault scarps, north-central Nevada, GSA Bull., 88, no. 9, 1267–1281, doi: 10.1130/0016-7606(1977)88<1267:PAAOYF>2.0.CO;2, 1977.

Wallace, L. M., J. Beavan, R. McCaffrey, and D. Darby, Subduction zone coupling and tectonic block rotations in the North Island, New Zealand, J. Geophys. Res. Solid Earth, 109, no. B12, doi: 10.1029/2004JB003241, 2004.

Westoby, M. J., J. Brasington, N. F. Glasser, M. J. Hambrey, and J. M. Reynolds, 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology, 179, 300–314, doi: 10.1016/j.geomorph.2012.08.021, 2012.

Westra, E., Building Mapping Applications with QGIS, Packt Publishing Ltd., 2014.

Whipple, K. X., M. Shirzaei, K. V. Hodges, and J. Ramon Arrowsmith, Active shortening within the Himalayan orogenic wedge implied by the 2015 Gorkha earthquake, Nat. Geosci., 9, no. 9, 711–716, doi: 10.1038/ngeo2797, 2016.

Whipple, K., C. Wobus, B. Crosby, E. Kirby, and D. Sheehan, New Tools for Quantitative Geomorphology: Extraction and Interpretation of Stream Profiles from Digital Topographic Data, GSA Annu. Meet., 30, 2007.

Whittaker, A. C., M. Attal, P. A. Cowie, G. E. Tucker, and G. Roberts, Decoding temporal and spatial patterns of fault uplift using transient river long profiles, Geomorphology, 100, no. 3, 506–526, doi: 10.1016/j.geomorph.2008.01.018, 2008.

Wilson, C. J. N., B. F. Houghton, M. O. McWilliams, M. A. Lanphere, S. D. Weaver, and R. M. Briggs, Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review, J. Volcanol. Geotherm. Res., 68, no. 1, 1–28, doi: 10.1016/0377-0273(95)00006-G, 1995.

Wilson, C. J. N., D. A. Rhoades, M. A. Lanphere, A. T. Calvert, B. F. Houghton, S. D. Weaver, and J. W. Cole, A multiple-approach radiometric age estimate for the Rotoiti and Earthquake Flat eruptions, New Zealand, with implications for the MIS 4/3 boundary, Quat. Sci. Rev., 26, no. 13, 1861–1870, doi: 10.1016/j.quascirev.2007.04.017, 2007.

Zhou, Y., B. Parsons, J. R. Elliott, I. Barisin, and R. T. Walker, Assessing the ability of Pleiades stereo imagery to determine height changes in earthquakes: A case study for the El Mayor-Cucapah epicentral area, J. Geophys. Res. Solid Earth, 120, no. 12, 8793–8808, doi: 10.1002/2015JB012358, 2015.

Zielke, O., Y. Klinger, and J. R. Arrowsmith, Fault slip and earthquake recurrence along strike-slip faults — Contributions of high-resolution geomorphic data, Tectonophysics, 638, 43–62, doi: 10.1016/j.tecto.2014.11.004

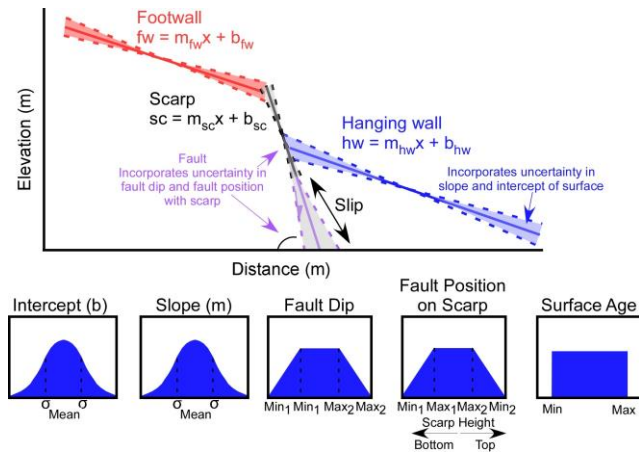



**Figure 1.** Slip statistics inputs. A schematic of inputs into the Monte Carlo Slip Statistics code, which include uncertainty in intercept, slope, fault dip, fault position on scarp, and the age of the geologic surface in question. For surface age, a uniform distribution is shown; however, the user could define a normal or trapezoidal distribution as well.

**Figure 2.** The general workflow. a) A user-defined profile drawn perpendicular to the strike of a mapped fault. For location of this feature, see Figure 4. The red, blue, and black lines represent linear least square fits to the footwall, hanging wall, and scarp of a normal fault, respectively. The purple line is a representation of the geometry of a fault responsible for this scarp. b) Sliders can be used within the data frame manipulation tool to select data points to represent each relevant component of the fault scarp (e.g., hanging wall, footwall, and scarp). Initially, the red line is fit to all the data in the profile. By using the sliders, you can select a subset of the data as shown in (a) for the generation of the red line. Once data points are selected, the user can visualize the choices for fault component selection before moving forward and calculating slip statistics for the fault in the same Jupyter Notebook environment. The red, blue, and black lines in (a) are generated through this method.

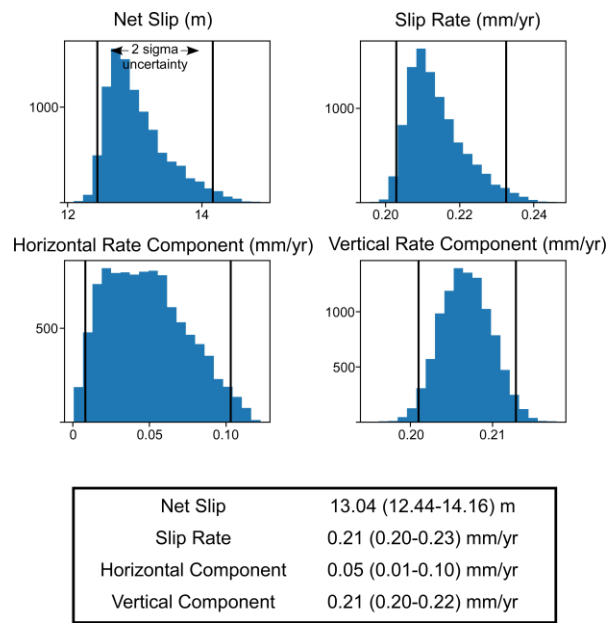
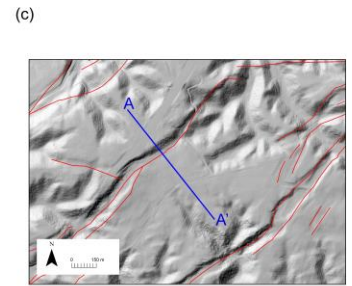
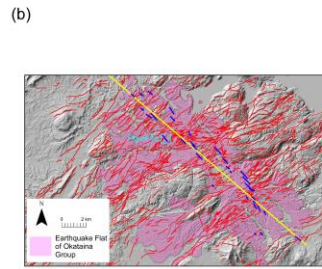
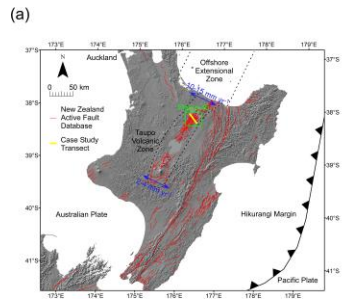
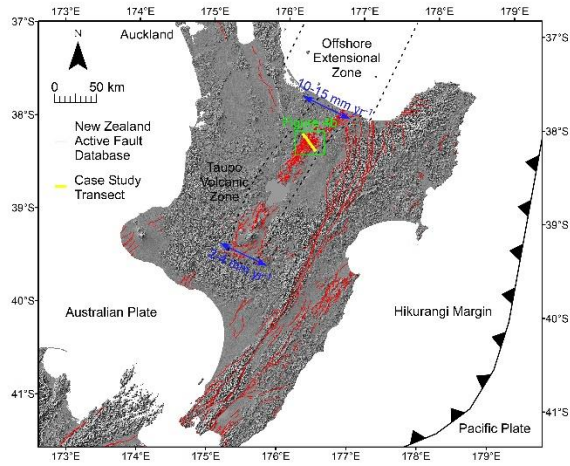
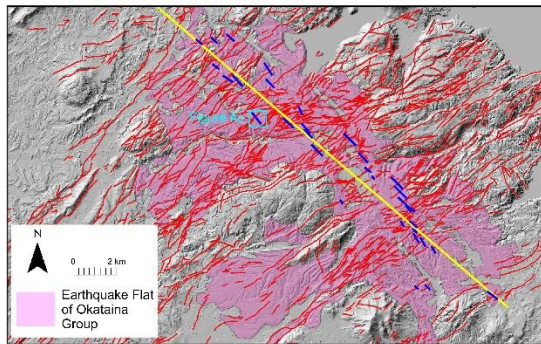



**Figure 3.** The slip statistics results from the fault scarp visualized in Figure 2 and with location shown in Figure 4.

(a)              (b)              (c)

(a)

(b)

(c)

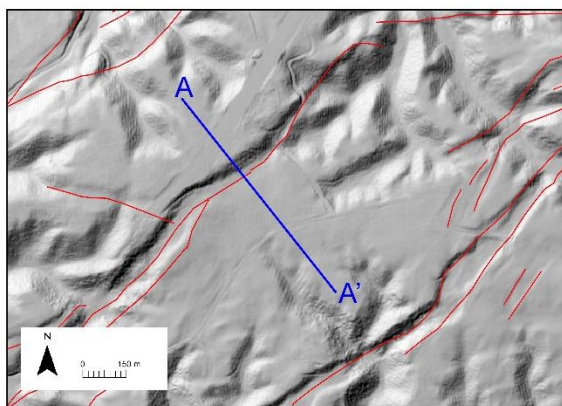



**Figure 4.** Taupo Volcanic Zone Case Study. Base images of (a), (b), and (c) are LiDAR hillshade maps of the North Island and Taupo Volcanic Zone, New Zealand. a) Tectonic features of New Zealand where the green box represents the enlarged image in (b). The red fault traces are from the New Zealand Active Faults Database (NZAFD). Active faults have deformed the ground surface of New Zealand within the last 125,000 years. The blue arrow and rate

represents geologic extension rates from geodetic and Quaternary fault data (P. Villamor et al., 2017). The yellow line represents the Case Study Transect. b) Fault scarp profiles used in this case study are shown in blue and across the northwest-southeast transect shown in yellow. Mapped faults in the region are shown in red (NZAFD). For simplicity, only the Earthquake Flat Formation of the Okataina Group outcrops is shown from the Geologic Map of New Zealand Project (GMAP). These are the formations that were analyzed in this study. The light blue box represents the extent of part (c). c) LiDAR hillshade map to demonstrate the resolution of the DEM and location of profile shown in Figure 2 and with location shown in Figure 4.