THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF GEOSCIENCES

# DO EARTHQUAKES ON LARGE STRIKE SLIP FAULTS FOLLOW A GUTENBERG-RICHTER DISTRIBUTION?

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of the requirements
for baccalaureate degrees
in Geosciences with honors
and Mathematics

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# ABSTRACT

We address the important question of the magnitude-frequency distribution for large strike-slip faults. Some recent studies have argued in favor of Gutenberg-Richter distribution, while others have argued for statistics that favor large earthquakes of a characteristic size. In an initial examination of this question, we considered the century-long instrumental catalog of earthquakes for two large strike-slip faults that ruptured along most of their length during the 20th century: the Queen Charlotte-Fairweather Fault in western Canada and southeastern Alaska, and the North Anatolian Fault in Turkey. For each of these faults, we analyzed the available earthquake catalogs, took into consideration their detection thresholds, and tested the confidence with which the observed earthquake activity could be considered a realization of a Gutenberg-Richter distribution using the Kolmogorov-Smirnoff test on the cumulative distributions. The relatively inaccurate locations in both areas prevent us from restricting our analysis to earthquakes on the fault itself. Instead, we were forced to consider earthquakes from a band of substantial width (~100 km) astride the fault. We tested over a range of possible b-values to construct a 95% confidence interval bounding an area believed to contain the true b-value if one exists. We found that in both cases the seismicity could be considered a realization of a Gutenberg-Richter distribution. The confidence interval for the Queen Charlotte region spans a b-value range of 0.5-0.63 and for the North Anatolian Fault spans 0.54-0.88. However, the near total lack of moderate earthquakes along the rupture zones of the M 7-8 events suggests that the Gutenberg-Richter distribution may not accurately characterize the size distribution of earthquakes on individual faults.

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# Acknowledgements

First, I would like to extend my thanks to my honors advisor, Chuck Ammon, for his help constructing this thesis. I would like to thank my advisors Dr. Gregory Beroza of Stanford University and Dr. William Ellsworth of the United States Geological Survey in Menlo Park for their advising while formulating my problem and developing the procedure.

Additionally, I thank Volkan Sevilgen of the USGS – Menlo Park and Gary Rogers of the Geological Society of Canada for their help gathering data through regional earthquake catalogs.

## Introduction

Regional catalogs of seismicity have been long understood to be well described by the Gutenberg-Richter relation:

$$\log(n) = a - bM, \qquad (1)$$

where n is the number of events of magnitude M and a and b are constants. Typical values for the slope of the distribution (referred to as b-values) of regional catalogs tend around 1.0, with some variability [Gutenberg and Richter, 1944]. Fault zones that can be characterized by equation 1 are said to be understood using a Gutenberg-Richter model. It remains unclear whether this model describes seismicity at smaller scales, such as the set of events which nucleate directly on the fault plane or events that occur on subsections of the total length of the fault [Page et al, 2010]. A synthetic GR distribution for a fault with a largest event of size Mw=8.3 is shown in Figure 1. A second model, the Characteristic Earthquake model, describes seismicity on a fault in a similar manner with the exception that the largest event (the characteristic event) should be approximately 1 magnitude unit larger than the second largest event on a fault [Wesnousky, 1994; Schwartz and Coppersmith, 1984]. A synthetic characteristic distribution is illustrated in Figure 2.

Understanding magnitude-frequency distributions is important in seismic hazard analysis in that it gives an estimate of the expected ratio of smaller to earthquakes on a fault. The GR model indicates that seismic events occur continuously as part of a stationary process bounded by the maximum ($M_{max}$) events that define a complete earthquake cycle [Wesnousky, 1994]. The characteristic model, however, argues that the GR distribution describes an oversaturation of large events and that the time between $M_{max}$ events is best understood as a series of foreshocks, aftershocks, and noise [Schwartz and Coppersmith, 1984]. Problems such as understanding scaling patterns of these distributions on faults and catalog incompleteness impede conclusions regarding the realization of either model for various zones around the world. The further understanding of magnitude-frequency distributions could shed insight on the mechanisms of quantized

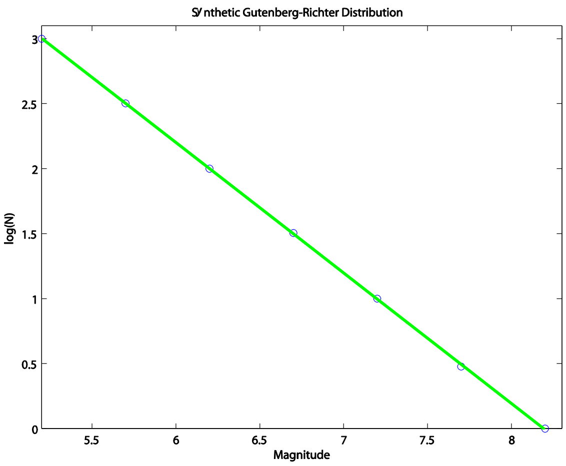

***Figure 1:*** Synthetic GR distribution with maximum event Mw=8.3 , b=1.0.

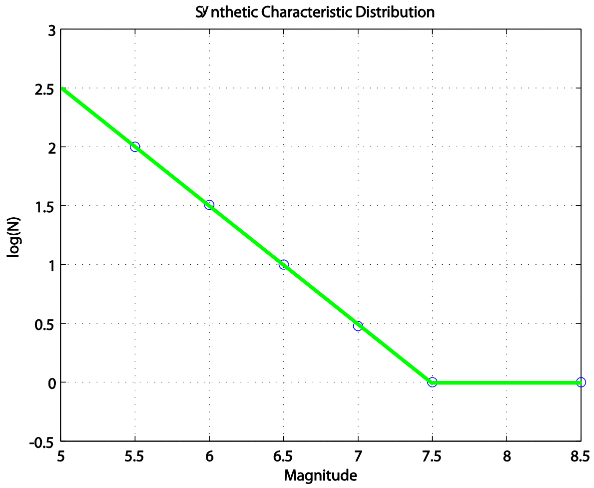

***Figure 2:*** Synthetic characterisitc distribution with maximum event Mw=8.5 , second largest event Mw=7.5, b=1.0 (for Mw<=7.5).

energy release along faults through individual seismic events.

This study aims to provide a method of testing earthquake catalogs for the exhibition of a GR distribution and to attain an interval of b-values that captures the catalogs true value within confidence. Previous studies have employed a statistical test called the maximum-likelihood estimator, a parametric test that selects model parameter values most likely to have produced the resulting data [Wesnousky, 1994; Lombardi, 2003]. An alternative to this method has been the use of the Kolmogorov –Smirnov (KS) test, a completely nonparametric test that tests a rigid hypothetical distribution to the observed data using a null hypothesis that the observed data could have been selected from the hypothetical distribution [Karnik and Klima, 1993; Kagan, 1994]. Here we manipulate the KS test by performing the test over and over, each time altering the b-value of the hypothetical distribution. This provides an interval of b-values over which the KS test accepts the null hypothesis within a 95% confidence. By altering the b-values between completed tests, the stipulation of the KS test requiring that the parameters of the hypothetical distribution be nonadjustable is not violated.

The primary limiting factor when analyzing seismic catalogs is the completeness of the data and its effective representation of the true structure of event magnitude frequencies. Reliable seismic data rarely extends back circa 1900, although regional seismic networks have more complete data from this period such as the networks around the two faults analyzed in this study, the Queen Charlotte-Fairweather Fault of western Canada and the North Anatolian Fault in Turkey. To account for this problem, regional catalogs were cross-referenced with larger digital catalogs and older, paper catalogs for completeness. In addition, density analysis of the space-time and magnitude-time plots for each fault shed light on the reliability of smaller magnitude events through time.

## Methods

This study focused on two large continental strike-slip faults, the Queen Charlotte-Fairweather fault (henceforth referred to as the Queen Charlotte fault) that strikes roughly SSE through the continental shelf off the west coast of Canada (Figure 3)and the North Anatolian fault that strikes approximately E-W through northern Turkey (Figure 4). The Queen Charlotte fault has ruptured in what is considered as a maximum-size event during the instrumental seismic period in 1949 in an $M_W = 8.1$ event [Natural Resources Canada]. The North Anatolian fault experienced a similar maximum sized event in 1939 in an $M_s = 7.9$ event. Data from the instrumental seismic period indicate that there exist several segments within the North Anatolian system with a potential for similar rupture events indicated by a lack of seismicity along sections of the main fault (Figure 4). Particularly in the case of the North Anatolian system, constraints on true b-values for fault zones with similar characteristics is important for regional seismic hazard analysis since the “danger zone” of potential moderate to large-sized events coincides with major population areas. The proximity of Istanbul, Turkey (population 13.1 million [2010 Turkey Census]) to a segment of the North Anatolian fault without a major rupture during the instrumental period is an example of the importance of seismic risk assessment for this and similar fault systems.

The study has focused on these fault zones for three primary reasons: 1) the relative ease of constraint when considering the focal mechanisms of catalogued events (primarily strike-slip within confidence), 2) the positioning of these faults through continental crust, and 3) the exhibition of a maximum-sized rupture event within the instrumental period (based on analysis of historical records of regional seismicity in these areas).

Data were collected from the catalogs of the Canadian Geologic Survey (Queen Charlotte-Fairweather) and the Turkish national catalog (North Anatolian). Although there is much debate over the nucleation of earthquakes on slip surfaces versus the nucleation of such events “in the bulk” or on smaller, unmapped faults, [Page et al, 2010; Hakusson et al., 2010] fault zone catalogs for this study were selected based on a 100 kilometer wide box that spans the fault trace with rough geometric estimations of the surface curvature of the traces (Figures 3,4). The resultant catalogs were cross-referenced with the Global Centroid Moment Tensor Catalog and the Advanced National Seismic System catalogs to ensure the most complete regional catalogs for the two fault zones. We address the important question of reliable data density by analyzing plots of both magnitudes versus time and space versus time (Figures 5, 6).

Based on the relative densities of the magnitude data collected over time, we selected three scenarios of reliable data for the Queen Charlotte-Fairweather fault and two scenarios for the North Anatolian fault. The scenarios reflect the ability of seismic systems to accurately capture smaller magnitude events traced backward through the 20th century. The scenarios themselves are parameterized by a threshold magnitude and time after which the threshold magnitude is an acceptable reliability measure for earthquakes of equal or greater value. Once these scenarios were used to compiled subcatalogs corresponding to these parameters, the question of agreement with Gutenberg-Richter statistics was tested using the Kolmogorov-Smirnov test.

*The Kolmogorov-Smirnov Test*

The Kolmogorov-Smirnov (KS) statistical test is used to tell whether a sample population is drawn from either a theoretical or other empirical distribution. We use it to determine the viability of the hypothesis that observed seismicity is drawn from a Gutenberg-Richter (GR) distribution. A GR distribution posits a logarithmic relationship between the number of earthquakes of a given magnitude, M, according to the equation:

$$\log \boldsymbol{N} = \boldsymbol{a} - \boldsymbol{bM} \qquad \textbf{(Equation 1)}$$

Where N is the cumulative number of events of lesser magnitude than a given magnitude M, and *a* and b are empirical constants. More specifically, b is the slope of the (linear) distribution and $a$ signifies the

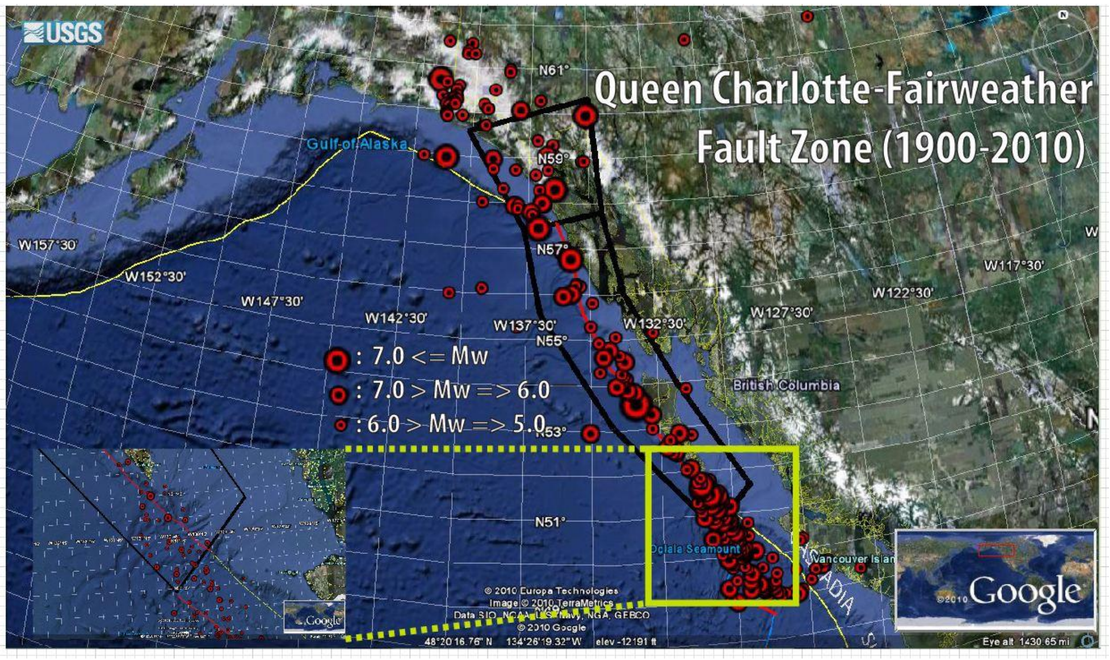

*Figure 3: Schematic diagram of the Queen Charlotte-Fairweather fault zone. The area within the black boxed regions indicates the boundaries used to compile the fault zone catalog for this fault. The plotted events are those that are contained within the regional catalog.*

*Figure 4: Schematic diagram of the North Anatolian fault zone. The area within the black boxed region indicates the boundaries used to compile the fault zone catalog for this fault. The plotted events are those that are contained within the regional catalog.*

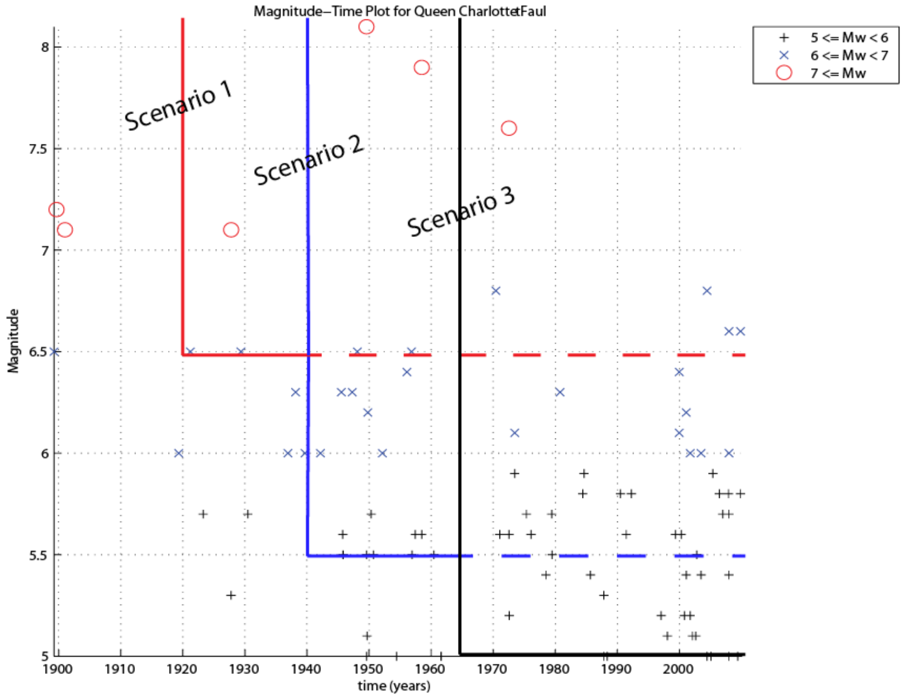

*Figure 5: Magnitude-time plot for the Queen Charlotte fault. The three test scenarios, defined by a minimum threshold magnitude and a time interval ending as of August 2010, are depicted as bounding colored boxes. Note that the data for each scenario is constituted by all events located to the right of the vertical bounding line and above the horizontal bounding line for each scenario.*

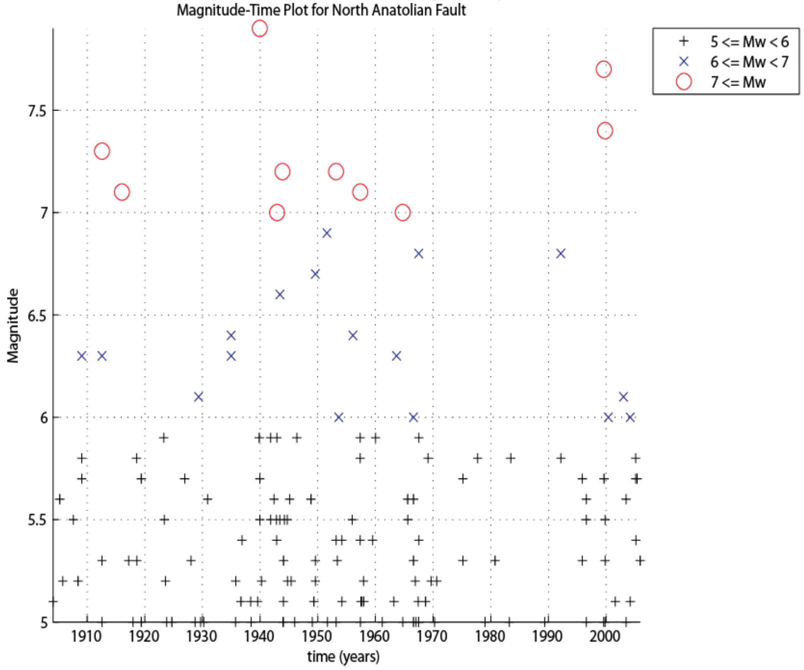

*Figure 6: Magnitude-time plot for the North Anatolian fault. Since the scenarios have identical time intervals, the scenarios are not shown. Note that scenario 1 encompasses all data in this figure, while scenario 2 encompasses all data of magnitude 5.5 and above.*

logarithm of the cumulative number of greater than or equal to M=0. The value of b is dynamic in space and possibly time, but has a value near 1.0 for many earthquake catalogs. KS tests, using various b values, should provide insight into the frequency-magnitude behavior of fault zones. Figure 1 shows the general shape of a GR distribution.

Although the GR relation is widely known, there is much debate regarding the frequency-magnitude distribution of earthquakes. As described earlier, the Gutenberg-Richter hypothesis states that the proportion of large to small earthquakes follows Equation 1. An alternative hypothesis, known as the characteristic earthquake model, holds that the proportion of large magnitude events is higher than predicted by the extrapolation of a GR event distribution. The KS test was used to test both of these distributions, with the assumption that $M_{max}$ is the largest observed event of any data set. We attempted no extrapolation for $M_{max}$ through information such as paleoseismic observations.

The KS test is a nonparametric test of probability distributions in a single dimension that focuses on minimum distance estimation between an empirical distribution function and the theoretical cumulative distribution function. The null hypothesis of the test is that the underlying distribution of the data set comes from the reference distribution. The first step is to determine the KS statistic ($D_n$), defined to be the maximum distance in the vertical dimension between the empirical and theoretical distribution functions, or:

$$\boldsymbol{D_n = \underset{x}{sup}|F_n(x) - F(x)|} \qquad \textbf{(Eq. 2)}$$

Where $sup_x$ denotes the supremum of the set, $F_n(x)$ is the empirical distribution and $F(x)$ is the reference CDF [Wilcox 2005].

To understand the nature of the division between the acceptance and rejection of the null hypothesis, it is important to understand the relationship between the sensitivity/confidence level (taken to be 0.05 sensitivity, or 95% confidence), noted as Ω, and the KS statistic. If the sample is drawn from the theoretical distribution, the KS statistic multiplied by the square root of the sample size ***n*** should converge to the supremum of the absolute value of the quantity |B(F(t))|, where B(t) is the Brownian Bridge, a continuous-time stochastic process that has a probability distribution equal to the conditional probability of a process that reflects Brownian motion, in abstract terms a check against random motion of a simultaneously random variable. This is summarized in the following expression:

$$\sqrt{n}\cdot D_n \xrightarrow{n\to\infty} \sup_{x} |B(F(t))| \qquad \textbf{(Eq. 3)}$$

This implies that under the null hypothesis, the quantity $\sqrt{n}\cdot D_n$ converges to the Komolgorov distribution, which is defined as the distribution of K, the random variable equal to the supremum of the Brownian Bridge over the interval 0 ≤ t ≤ 1. Thus:

$$K = \sup_{t\epsilon[0,1]} |B(t)| \qquad \textbf{(Eq. 4)}$$

[Wilcox 2005]. The CDF of K is defined as the probability that K is less than or equal to a value x from the range of x-values (in this case magnitudes) and is calculated according to the equation:

$$Pr(K \leq x) = \frac{\sqrt{2\pi}}{x}\sum_{i=1}^{\infty} e^{\frac{-(2i-1)^2\pi^2}{8x^2}} \qquad \textbf{(Eq. 5)}$$

[Massey 1951] The comparative part of the test incorporates the KS statistic and the distribution of the variable $K_\Omega$, calculated from the value of K such that the probability of K ≤ $K_\Omega$ is equal to 1-Ω **(**i.e. $\Pr(K \leq K_\Omega) = 1 - \Omega$**)**. If the KS statistic is greater than $K_\Omega$, the null hypothesis is rejected at level Ω.

The KS test provides a reliable test with which to estimate the source distribution from a sample because of its sensitivity not only to sample size, but to random error possibly stemming from event magnitude calculation and uncertainty. In addition, the test is sensitive to both shape and location of the empirical CDF, thus bolstering its effectiveness.

The KS test takes two primary forms, a one-sample test that compares a sample with a reference probability distribution and a two-sample test that compares the distributions of two samples. The one-sample test was employed to test whether an earthquake catalog was consistent with a GR distribution. The b-values corresponding to tests that accepted the null hypothesis form a continuous interval in for each catalog. The reference probability used was a cumulative distribution function (CDF) corresponding to a GR distribution. The test was repeated with different values of b, thus treating *a* as a dependent variable with respect to the entire set of tests for a specific data set.

The catalogs for the individual fault zones were tested against hypothetical distributions with maximum event values corresponding to the maximum events realized within each catalog. In practice, the KS test employs no adjustable parameters within the body of the test. The hypothetical distributions were calculated by integrating the moment magnitude functions with maximum event magnitudes that correspond to the maximum events within the catalogs. To gain a more detailed picture of significant parameters of interest, here the *b* values, the KS test here is “modified” by successive runs of the KS test, each test incorporating a slightly different hypothetical *b* value than the previous test. This modification effectively circumvents the stipulation of zero adjustable parameters by compiling results of many tests with different hypothetical distributions into an interval in which the hypothetical curve yields statistical significance when compared to the data.

## Results and Analysis

### *--Queen Charlotte-Fairweather Fault*

Based on threshold magnitudes suggested by Dr. Garry Rogers of the Geological Survey of Canada and the magnitude-time plots of the Queen Charlotte fault (Figure 5), the three time-magnitude scenarios were constructed for analysis by the Kolmogorov-Smirnov test. Figure 8 contains the parameters of these scenarios, the magnitude frequency distributions of the data that comprises each scenario, and the results of the KS test, where green curves indicate cumulative distributions functions that, when tested against the sample data, resulted in an accepted null hypothesis.

Scenario/Bounds

1

=> Time Threshold:
1920-present
=> Magnitude Threshold:
6.5 <= Mw
=> Passing Bounds:
0.24 <= b <= 3.02

2

=> Time Threshold:
1940-present
=> Magnitude Threshold:
5.5 <= Mw
=> Passing Bounds:
0.5 <= b <= 1.27

3

=> Time Threshold:
1965-present
=> Magnitude Threshold:
5.0 <= Mw
=> Passing Bounds:
0.39 <= b <= 0.63

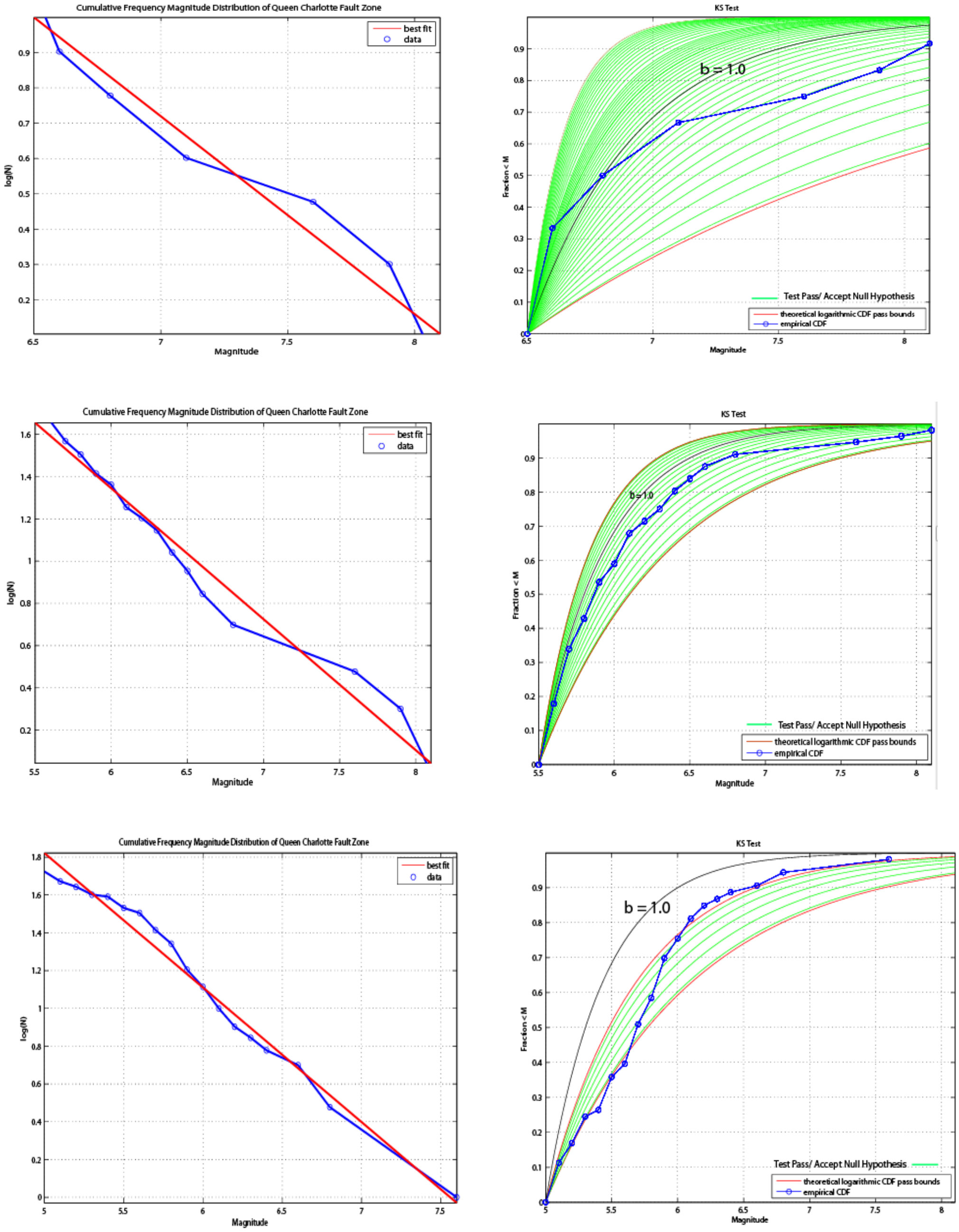

*Figure 8: Scenario parameters (left column), magnitude-frequency plots (middle column), and KS test results (right column) for each Queen Charlotte magnitude-time scenario. Red lines on the magnitude frequency plots are least-squares best fit lines to the data. The green curves on the KS test plots are CDFs that, when tested against the data, passed (accepted null hypothesis), red curves are the boundaries of the failing CDFs, the black curve in each plot is the hypothetical CDF with b-value equal to 1.0, and blue curves are the empirical CDFs.*

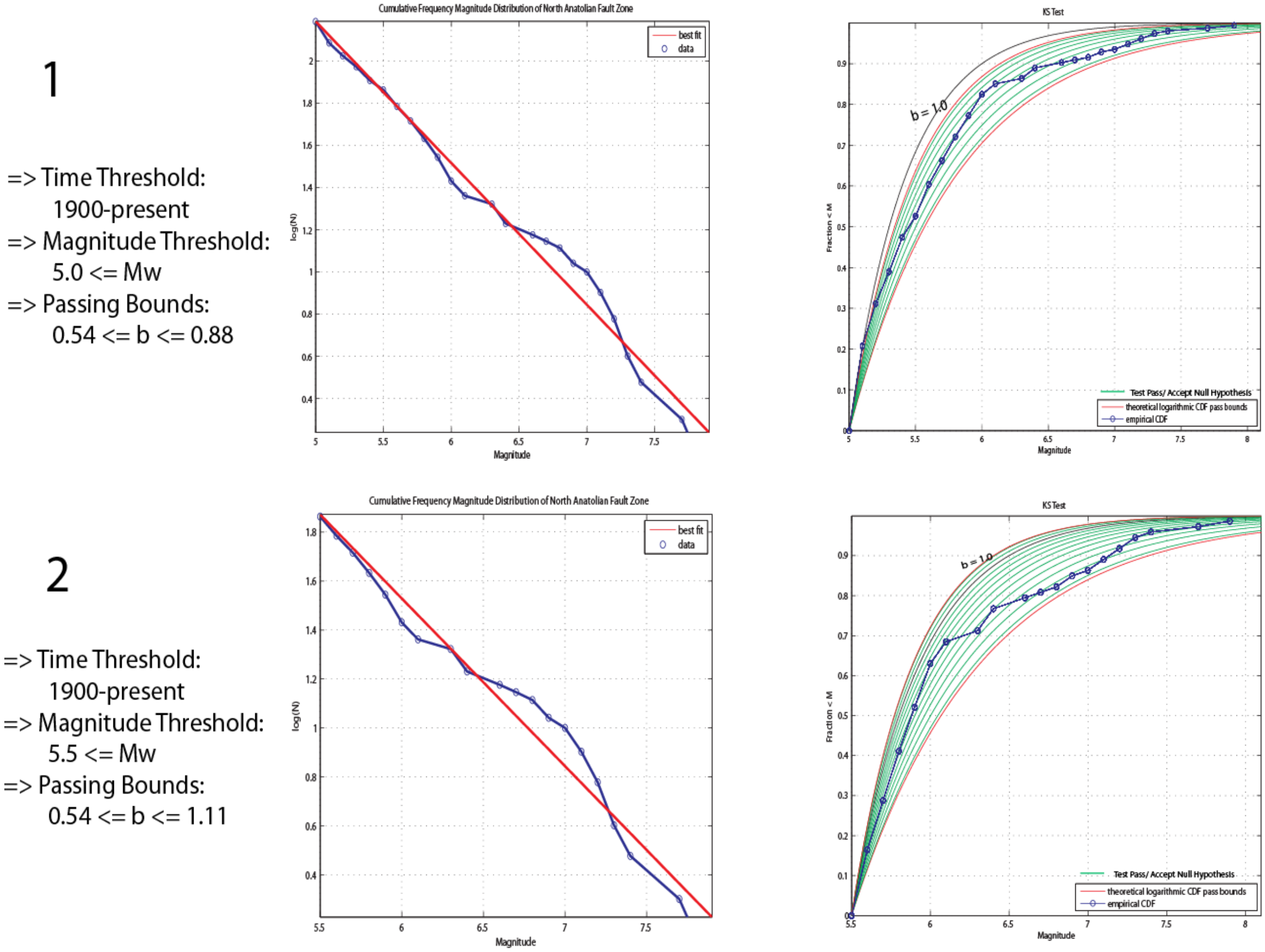

*Figure 9: Scenario parameters (left column), magnitude-frequency plots (middle column), and KS test results (right column) for the North Anatolian magnitude-time scenario. Red lines on the magnitude frequency plots are least-squares best fit lines to the data. The green curves on the KS test plots are CDFs that, when tested against the data, passed (accepted null hypothesis), red curves are the boundaries of the failing CDFs, the black curve in each plot is the hypothetical CDF with b-value equal to 1.0, and blue curves are the empirical CDFs.*

*--North Anatolian Fault*

The magnitude thresholds for the North Anatolian fault data are as suggested by the Turkish National Seismic Network. Two scenarios have been constructed based on these suggestions and analysis of the magnitude-time plot of the North Anatolian data (Figure 6). These two scenarios have identical time ranges. In the interest of comparable results, the magnitude threshold for the second scenario (Mw=5.5) was raised by a half unit over the suggested threshold value of Mw=5.0. Since the data from scenario 2 is a subset of the scenario 1 data, it was expected that the impact of the raised threshold magnitude would be through a broadening of the b-value interval due to the decrease in sample size, n (see Equation 3). This broadening was observed, however this has no consequence in reference to the interpretation of the test results. Figure 9 contains the parameters of the two scenarios, the magnitude frequency distributions of the data that comprises each scenario, and the results of the KS test.

The results of these tests are used to construct 95% confidence intervals that are thought to contain the true b-value for the two faults. By overlapping the results of the various scenarios for the individual faults and observing the resulting intersection, the confidence intervals are found to be 0.5-0.63 for the Queen Charlotte fault and 0.54-0.88 for the North Anatolian fault.

## Conclusion

The ranges of b-values estimated to fit the true form of the data from the two studied faults are found to be lower than the typical values assumed for fault zones. Generally, b-value of approximately 1.0 properly characterize broad fault zones although there is much debate over whether such distributions accurately characterize more precise zones or the set of events that nucleate on the fault plane itself [Hauksson and Jones, 2010; Page et al, 2010]. The application of the KS test to instrumentally recorded seismicity on the North Anatolian and Queen Charlotte-Fairweather faults, however, suggests that historical seismicity in a broad neighborhood around these faults can be adequately described with Gutenberg-Richter statistics. Despite smaller b-values than typically observed with other fault zones, the underlying trend of the data is of the Gutenberg-Richter logarithmic form. These low b-values suggest that slip on these faults, possibly generalized to the class of large, continental strike-slip faults, are dominated by large earthquakes and that there may be characteristic earthquake size distribution on the faults themselves that would be more apparent if we had more accurate earthquake locations.

This method is a promising approach to earthquake catalog analysis because it provides a clearer picture of statistical test results by compiling many separate test results that construct an interval over which b-values can be tested without violating the stipulations of nonadjustable parameters within the Kolmogorov-Smirnov test itself. Additionally, this method could be used as supplemental evidence in cases where the maximum likelihood estimator (MLE) is employed because the KS test does not assume a Gutenberg-Richter distribution as would a parametric test such as the MLE. As with any statistical analysis, results could be improved by acquisition of data than spans longer time intervals or with threshold magnitudes that could be held as reliable markers farther back in time.

This study focused on faults that are simple compared to other possible choices of continental strike-slip faults, such as the San Andreas Fault that runs through California. Although sophisticated regional seismic networks exist for the San Andreas Fault zone, which would translate to high quality data density for longer intervals and better earthquake locations, the complex nature of the fault system make the isolation of a proper zone band particularly difficult. Extension of this testing method to faults such as the San Andreas, however, would provide a better answer to whether the class of large, continental strike-slip faults can be accurately characterized by Gutenberg-Richter statistics and whether atypically low b-values are a shared property of faults of this class.

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## EDUCATION

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Candidate, B.S. Mathematics
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Expected Graduation: May 2011

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## SKILLS / ABILITIES

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**Related Coursework**

- *Geosciences*:
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  - 201: Earth's Materials
  - 202: Chemical Processes in Geology
  - 203: Physical Processes in Geology
  - 204: Geobiology
  - 310: Earth History
  - 444: MATLAB Applications
  - 452: Hydrogeology
  - 465: Structural Geology
  - 472A/B: Field Geology
  - 488: Seismology*
  - 561: Numerical Modeling in the Geosciences
  - 597: Multivariate Data Analysis*
- *Mathematics*:
  - 140/141: Calculus w/ Analytic Geometry I & II
  - 220: Matrices
  - 230: Multivariable Calculus and Vector Analysis
  - 251H: Honors Ordinary and Partial Differential Equations
  - 311W: Discreet Math (aka Proofs, Sets, and Logic)
  - 312: Real Analysis
  - 403: Classical Analysis*
  - 414: Introduction to Probability Theory
  - 417: Qualitative Theory of Differential Equations
  - 427: Foundations of Geometry
  - 436: Linear Algebra
  - 451: Numerical Computations*

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**Undergraduate Activities/ Memberships**

- Member of Penn State's Geological Sciences Club
- Member of the Society of Exploration Geophysicists

- Member of the American Association of Petroleum Geologists

**Undergraduate Accolades**

- Recipient of Schreyer Honors Academic Achievement Scholarship
- Recipient of Penn State Dean's Scholarship
- Recipient of Marathon Oil Scholarship
- Recipient of Society of Exploration Geophysicists/ Anadarko Petroleum Scholarship
- Recipient of the **Robert F. Schmalz Award in the Department of Geosciences (x2)**
- **Recipient of the Benjamin Howell, Jr. Award in Geosciences**

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## RELEVENT WORK HISTORY

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**Geotechnical Division Intern**
*Gannett Fleming, Inc. Engineering,* Camp Hill, PA
May 2008 – Jan 2010
Extensive geophysical fieldwork experience with Gannett subdivision Quantum Geophysics
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**Research Intern (Southern California Earthquake Center)**
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