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Seismic Trends of the Salton Sea Fault Systems

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SUMMARY

This project aims to categorize earthquake sequences. There are two phenomena to consider: a typical aftershock sequence or a swarm sequence. In order to distinguish these types, a Time Series - event magnitude over time - graph is best used. An aftershock sequence has a main event. A point of highest magnitude where the remaining events will decrease from. A swarm sequence has a main event, but data further in the sequence do not decrease as significantly. A swarm contains multiple events with large magnitudes, while having the possibility of data silence for hours or days until new activity is recorded. This behavior is typical of anthropogenic seismicity. The behavior is sporadic and not bounded by the same energy reduction as in typical aftershocks sequences. Analyzing Time Series will provide the first assumption into categorization, but Omori's Law and Gutenberg-Richter are important to uncover other factors. Omori's Law plots the number of events over time, where the assumption is occurrences decrease exponentially. This is the same reason for Gutenberg-Richter which plots the number of events over magnitude. Both values will provide an analysis of the sequence itself, and not necessarily important in categorizes between the types. When considering case studies between definitions, these plots may become useful if focused on length of decay.

The region of study is a seismically active zone of the San Andreas Fault. With the observed activity, there is a significant threat to surrounding areas, and future industrial endeavors. The

region provides insight into less commonly used techniques, and contains an underwater portion. These factors require diverging from the new, cheapest techniques of satellite imagining. It is important to note how these regions are overlooked by newer technology, and even more important for their geological and geographic setting.

1 INTRODUCTION

1.1 Observing Aftershock Sequences

Earthquakes occur as a sequence rather than a single event. Commonly, a large event will trigger smaller events as aftershocks. It follows a predictable decay in magnitude as time goes on, so the smaller events proceed in main shock. These are the characteristics of an earthquake aftershock sequence. The aftershocks pose a dangerous threat when considering surrounding faults. Recent developments in data and sensing techniques show stress migrates to surrounding faults rather than dissipates. A better understanding of fault systems considers the stress-triggering hypothesis as an important factor in neighboring slippage. Clusters of seismic activity can help demonstrate the migration of stress - the aftershocks are clustered spatially but not focused on a single fault. This typically follows two predictable models: (1) Omori (2) Gutenberg-Ritcher.
The Omori's Law describes aftershock sequences as a exponential decay of magnitude over time Stein (2003). The Gutenberg-Ritcher's Law describes aftershock sequences as an exponential decay of frequency over magnitude Gutenberg (1955).

$$y = \frac{a}{(x+t)} \tag{1}$$

$$N = 10 \cdot \exp{(a - bM)} \tag{2}$$

$$y = 10 \cdot \exp{(ac + b)} \tag{3}$$

These equations work to mathematically demonstrate how each law is modeled. In Equation(1), the 'a' and 'x' are constants and 'n' modifies with the time value. In Equation(2), the constants are 'a' and 'b' while 'N' is the number of events greater than 'M' - the magnitude value. Equation(1) - Omori's Law, expresses the decay rate as the magnitude decreasing over a given period. This is the dissipation of energy in the system from the main shock causing slippage in neighboring ones. Equation(2) - Gutenberg-Ritcher's Law, expresses the decay rate as the frequency decreasing over a given magnitude. This is not directly related to time, but due to Omori's Law, time allows smaller magnitude events to accumulate after the onset. If a sequence follows both of these predictable laws, it is considered an aftershock, there is an obvious main event. Figure 1 shows a typical aftershock sequence with a main event and decay. This sequence contains few higher order magnitudes with the bulk of data in the lower ranges. There is a consistent evolution of the sequence without gaps or interrupting events. Equation(3) is a simple linear regression with a logarithm attached. This will come up later in Section 3 and 4 when logarithmic scaling is explained.

1.2 Geographic Region

In Southern California, there is a region containing multiple fault systems. The San Andreas (SAF) begins in this region with numerous perpendicular fault blocks Brothers (2011). The region contains three more major faults the Elsinore, Imperial, and San Jacinto Faults. Known as the Quaternary Faults, this region has the potential to propagate energy among these major systems. In the Salton Sea, the behavior of the perpendicular faults leading into the SAF poses risk to the greater Los Angeles region by the San Gorgonio Pass Philibosian (2011). The SAF is overdue for a historical slippage, which could be triggered through the energy migration from the Southeastern Salton Sea.

This study began with an in-depth look into Westmorland activity during 2020. News outlets as well as Scripps IGPP made news on this phenomenon due to interest in the area. This region has seen a great deal of seismicity recorded on Figure 2. This region lands on important geological features as well as disruptive anthropogenic activity. The region of study is important to the burgeoning fields of green energy and tech, but requires safeguards and analysis of the seismic risk. This became a concern when the study found an interruption in the Westmorland sequence - the inclusion of the Niland activity. Futher in the study, these sequences were separated and observed for each behavior. The Niland sequence exhibits different behavior as well as is offset from the plate boundaries (Figure 4). This Niland region is where the majority of geothermal energy production is located. Our assumption is this behavior may result from fluid injection from these power plants.

As the Niland sequence peaked interest, there needed be more comparisons drawn in the region. From this, the study focused on Bombay Beach and the Salton Sea for comparisons. Swarms differ by their decay rates and time series. An aftershock follows predictable models based on a main event of highest magnitude, while swarms have no obvious main event or limited decay. In this area, a potential triggering event is geothermal energy production as well the proposed lithium mining where fluids are injected into the crust. These anthropogenic factors work in the architecture of these fault systems to induce certain barriers to break. Swarms are induced typically by these processes instead of stress-triggering Ross (2020).

2 DATA

2.1 Datasets

The USGS provides a searchable catalog used to download sequences like these as .csv files. This is a catalog of known earthquakes in a given region and across the globe. Entries are logged by the determined positions and times of rupture, and is calculated by numerous stations not all in the region. Figure 3 shows the study area on the interactive USGS website with terrain overlay. Current earthquakes in the area would show as color coded circles. The regions we chose to explore in detail requires the Advanced Search methods, setting the timeline and the location. The study focuses on four sequences along the Southeast edge of the Salton Sea. These were chosen to discuss the difference in terminology of aftershocks and swarms, and to compare seismic trends in the region. As the area is prone to anthropogenic swarms and lake loading, it is possible this has impact on the SAF. The first sequence is from March 2009 in the Bombay Beach region. The remaining sequences are from late 2020. The second sequence is from August 2020 in the Bombay Beach region as well - referred to as the Salton Sea, which is centralized below the water and just south of Bombay Beach. The third sequence is from September 2020 in the Westmorland region, where the study began. The fourth and final sequence is from October 2020 in the Niland region, by the southeast shoreline where geothermal power plants are situated. These four sequences were chosen for their locations with the last three chosen for their closeness in time (Figure 4). Below are the instructions to obtain the same .csv files for each sequence:

Sequence	Coordinates	Dates
Bombay Beach 2009	33.314N -115.615E 33.213S -115.722W	03/21-04/11
Salton Sea 2020	33.344N -115.622E 33.184S -115.882W	08/10-08/30
Westmorland 2020	33.133N -115.516E 32.969S -115.751W	09/30-10/20
Niland 2020	33.253N -115.47E 33.132S -115.615W	10/22-11/01

Steps	Description
1	Access: https://earthquake.usgs.gov/
2	Click: Search Earthquake Catalog
3	Set Parameters
4	minMag=0, maxMag=7
5	See Sequences for Date and Time
6	Expand: Advanced Options
7	See Sequences for Coordinates
8	Repeat for each Sequence

2.2 Python Modeling

Search the catalog with these parameters and download as a .csv file. Using Python3, these datasets will provide Section 3 with the proper x and y values to create the graphs referred to in Section 3. The following section will detail the code in order to replicate similar cleaning. Each .csv dataset was cleaned for time using the provided python3 script. Using a simple csv reader, python accesses the first entries to find the day, hour, and minute of each event. This is required as the x-values in Time Series Graphs (Figure 5a-d):

```
import csv
import matplotlib.pyplot as plt
import numpy as np

with open('file.csv') as swarmData:
    catalog = csv.reader(swarmData)
    quake_mags = []
    quake_times = []

    col = swarmData.readline()
    for quake in catalog:
        mag = quake[4] #magnitude

        #clean format '0000-00-00T00:00.000Z'
        date = quake[0].split('T')
        day = date[0].split('-')19
        pst = quake[0].split('T')
        hrs = pst[1].split(':')

        #int-cast string values
        month = int(day[1])
        day = int(day[2])
        hour = int(hrs[0])
        minute = int(hrs[1])
```

Once these values are found, each event must be organized properly based on the date and time. This becomes an exercise when crossing different months as opposed to a sequence ending on the same month. This can be done with a few if statements. Using the code below, python3 will find a curve of best fit to these x and y values:

```
#Bombay Sequence 2009 | Organize Dates into X-Values
if month ==3:
    if day != 21"
        dif = (day - 21)*24*60
        total_min = ((hour*60) + minute + dif)
    else:
        total_min ((hour*60) + minute)
elif month == 4:
    dif = 10*24*60
    temp = (day - 1)
    total_min = ((temp*1440) + (hour*60) + minute + dif)
elif month == 5:
    dif = (10*24*60) + (30*24*60)
    temp = (day - 1)
    total_min = ((temp*1440) + (hour*60) + minute + dif)
else: #months after May
    continue

#Salton Sea Sequence | Organize Dates into X-values
if day == 10:
    total_min = ((hour*60) + minute)
else:
    dif = (day - 10)*1440
    total_min = ((hour*60) + minute + dif)

#Westmorland Sequence | Organize Dates into X-values
if day == 30:
    total_min = ((hour*60) + minute)
```

```
else:
    dif = day*1440
    total_min = ((hour*60) + minute + dif)

#Niland Sequence | Organize Dates into X-values
if day == 22:
    total_min = ((hour*60) + minute)
elif month == 10:
    dif = (day - 22)*1440
    total_min = ((hour*60) + minute + dif)
else:
    dif = (9*1440) + (day*1440)
    total_min = ((hour*60) + minute + dif)

#create plot points; same for all sequences
quake_mags.append(float(mag))
quake_times.append(total_min)
```

When modeling Omori's Law and Gutenber-Richter, the data requires being log-scaled. This gives a linear modeling of the dataset, so curvefit can produce a proper output. The difference from Figures 5 is these plot 'Occurrences' over time for Omori's Law, and 'Occurrences' over magnitude for Gutenberg-Richter. See Figures 6a-d for Omori's Law adjusted for foreshocks, and see Figures 7a-d for Gutenber-Richter adjusted for foreshocks. Results are described in Table 3, Section 4.

```
#scipy curve_fit
popt, pcov = curve_fit(func, x, y)
plt.plot(np.unique(quake_times), func(np.unique(np.asarray(
quake_times)), *popt), 'r-')
```

2.3 Data Handling & Missteps

During the process of Python Modeling, several analyses were used in determining the decay rate. They all relied on python3's scatter and curvefit functions, while running specific exponential decays:

Using the Scipy's Curvefit function will run either of the functions passed into it. This provides a line of best fit related to the equation's x value. Similar results are achieved when using Scikit's Linear Regression Model.

$$y = a \cdot \exp{(x, n)} \tag{4}$$

$$y = \frac{a}{(x + n)} \tag{5}$$

Equation(4) is a normal exponential decay, and does not require properly scaled axes. If we did not know about Omoris Law, we would infer the data exhibit an exponential decay. We would therefore apply Equation(4). We have experienced difficulty to fit an exponential decay when the raw data set exhibits some cloudiness and/or a heightened frequency of events at a later time. This is an issue when using data from Westmorland or Niland, which do not follow normal decay or with extra events later in the sequence or before the main shock or if the sequence is a true swarm, e.g., geothermally induced seismicity. The Westmorland Sequence contains foreshocks, which need to be eliminated in order to obtain a proper estimate. The Niland Sequence lacks data to be able to model properly - portions of the sequence have lots of time separating clusters of events.

Equation(5) is Omori's law, which should better represent the decay modeling with a '1/x' comparison. Although this should be the best result, there are still complications when it comes to the number of small events and data that contain large gaps between clusters. In the next section, scaling is discussed as a potential solution.

A now commonly used modification of Omori's law allows the power, p, in the denominator of Equation(5) to vary. This study did not investigate the importance of the p value as it only adds precision increasing the denominator through the sequence into smaller values. Here is the modified Omori's Law:

$$y = \frac{a}{(x + n) \exp p} \tag{6}$$

Due to the time limitation of the 199 project, we will not investigate the success of this law any further, but would be worthwhile exploring. Studies have shown that p ranges between 0.7 and 1.5, which is close to 1 in the original Omori's Law.

3 DATA PROCESSING

For all sequences additional cleaning is needed. There are foreshocks to the main events, which tends to distract the Curvefit modeling from analyzing the sequence as a decay. In order to account for the foreshocks, all events before the highest magnitude are removed. These raw plots can be found in the Appendix Section. In addition to modifying the foreshocks for all plots, the Gutenberg-Richter plots were altered by magnitude rounding. In the Appendix, these GR plots contain a rounding method:

```
def halfBin(num):
    return round(num*2) / 2
```

This replaces the original math.floor(num) method, which gave much better Gutenberg-Richter values - closer to 1. This change was in order to take care of missing lower magnitudes; however, in the finalized plots (Figures 7a-d) this is taken care of by removing the 0, 0.5, and 1.0 bins from the modeling. It should be noted that the method of rounding will produce different results, and is best to round downwards. See Appendix A3a-d for raw graphs.

3.1 Time Series of Events

The time series plots the individual event magnitudes over the time. This gives a broader representation how the sequence unfolds. The importance is to gauge whether the sequence appears to decay as in aftershock sequences or take on a different behavior. The catalogs were chosen to best encompass the fore-shocks, main event, and aftershocks, which are all considered in this study part of the sequence. The time series graph will show a natural decay in most cases, but sporadic activity without decay is possible. When observing the following time series, we classify two sequences as aftershocks and the others as potential swarms.

As seen in Figures 5d, the Niland Sequence behaves sporadically. The main event is difficult to determine while there is no normal decay rate and/or the sequences are extremely short. This will be further discussed in the explanation of Omori's Law. From the time series graphs, this is the apparent swarm. There are two models to use in our data after time series. First is the Omori's law, and second is the Gutenberg-Ritcher. Omori's law requires graphing frequency over time while the Gutenberg-Ritcher requires graphing frequency over magnitude bins of (0.5). Each is expected to show an exponential decay for typical aftershock sequences (see Figure 1 for aftershock sequence). Comparing the Time Series (Figures 5a-d) with a typical aftershock sequence, the immediate outlier is the Niland sequence while questionably the others.

Both the Bombay Beach and Westmorland Sequences show the expected pattern over a long period of time. With over 20 days in these sequences, a general decay pattern is obvious. There is a main event - highlighted in yellow - along with an exponential decay. These will be compared by slopes in regression fitting (see next section). The Niland sequence contains large portions of silence in the data, which shows this is not a typical aftershock decay. Finally, the Salton Sea varies in the perspective. It does not have significant decay, but follows a main shock event. There is additional information later in the sequence possible due to other factors, which are taken into account when solving curvefit functions.

3.2 Changing the Axes

The time series requires graphing the magnitude over time of each event. This is the first filter of sequence or swarm to look at - the indicator of a swarm is silence or no simple decay rate. In the next subsection, both the Omori and Gutenberg-Richter require changing the axes. Omori's law requires the y-axis to become number of events while keeping time as the x-axis. This attempts to plot how activity lessens after the main event. Gutenberg-Richter requires the y-axis to become number of events, while the x-axis becomes magnitude. This attempts to plot how magnitude should narrow in the higher ranges with the bulk of activity in the lower magnitudes. Both are critical to determine an aftershock sequence vs a swarm, as a swarm will have more large magnitude events than normal with no clear decay.

3.3 Logarithmic Scaling

With the next section, data is modeled twice. The curvefit function uses either the raw scatter plot, or the x and y axes have been scaled logarithmically. This provides a linear relationship between the points rather than an exponential decay. As discussed previously, the exponential decay functions vary in success, especially in the case of the Westmorland and Niland Sequence. The results of these tests are in Table 3, Section 4. With log-scaling, the use of Equation(6) becomes more reliable.

3.4 Omori & Gutenberg-Richter

For the Figures 6a-d and 7a-d, the study uses python3's Curvefit ability to find Omori's and Gutenberg-Richter. The same x and y values are used without log-scaling producing similar results as the second round of figures. Modeling a linear function will find the relationship without complicated decay functions:

$$log(y) = mx + b \tag{7}$$

In a typical aftershock sequence, the decay rate follows Omori's law. There will be a decrease in number of events as energy dissipates - or hits another barrier - in the system.

4 MODELING & RESULTS

The following table shows the varying degrees of success with using Curvefit and the given equations. There is a proper Gutenberg-Richter decay, which should be around 1. The issue is in Omori's Law. The Niland sequence is a suspected earthquake swarm as the decay in magnitude in not present, as well as large silences between data clusters. As shown in Figures 6a-d, the Curvefit plots a linear regression either way. The current values from this modeling shows Omori's Law can not accuractely be described in terms of slope. There is a negative slope for all sequences indicating a decay rate, but margins of error and R-values should be examined in further research. The best fit is Figure 6a for Bombay Beach with a significant amount of data points above the curve. This represents the dataset much better than Figures 6b or 6d. The Gutenberg-Richter slope values show another facet in distinguishing between an aftershock or swarm. Here there are two results that puzzle. The data shown in the table below does not trend towards the expected value of 1. This is without the foreshocks of events and adjusted for a best fit modeling - removed 0.5, 1.0 and 1.5 magnitudes. Values obtained here need to consider how magnitude is divided up in bins. With the python3 code used to round values, this causes discrepancy when creating bins.

Location Name	Omoris (m)	Gutenberg-Ritcher (m)	of Events
Bombay Beach	-21.25465996	0.81436207	467
Salton Sea	-9.63085208	0.71118314	268
Westmorland	-17.52840853	0.62563054	1355
Niland	-14.26871662	0.77169421	67

5 DISCUSSION & CONCLUSION

This study aims to categorize earthquake sequences into either an aftershock sequence or swarm. This is purely descriptive as neither has clear definitions or case studies in literature. It is important to understand the differences here when considering how fault systems interact with neighboring systems. The migration of energy gives insight into future techniques of forecasting and warning systems. A warning system for a main event may give important information to the public, but may overlook the possibility of further large magnitude events if this sequence is a swarm.

When researching python3 regression methods, there are two resources used. Both gave the same results in Table 3. The Scipy Curvefit will find the best fit modeling for a given x and y using either Equation (1) or Equation (3). The Scikit Linear Regression will best fit a linear regression to data. The Omori's Law requires logarithmic scaled axes in order to provide a linear representation with Equation (1) rather than using a typical exponential decay. This provides a better visualization with the same results. The Gutenberg-Richter requires extra processing in order to allow Curvefit to find a proper best fit decay with Equation (3).

Considering the chosen sequences, there is one definite outlier, which should be characterized as an earthquake swarm, Niland. The Niland sequence shows the exact information expected in a swarm with no decay and silence in the Time Series. Resulting values should be taken with the understanding Curvefit forces a model even when the data is not representative. To further research into whether or not these values may be used, studies may focus on the modified Omori's Law as well as a difference in magnitudes. Solving for differences in magnitude requires further splitting up of data into clusters of the larger sequence. There are events that cluster in time with larger periods of a few minutes to hours separating these clusters. Finding these and analyzing how they evolve can given better insights into whether it is a true aftershock or not. With the USGS catalog, there are a significant number of high uncertainty earthquakes as well as lower recording of smaller magnitude events as in most catalogs. The use of high-resolution catalogs shows there are discrepancies when calculating Gutenberg-Richter and needs amending to the smaller magnitudes or simply removing these values altogether Herrman (2020).

The region of study was chosen specifically for the anthropogenic factors. There is significant fluid injection from geothermal power plants as well as lake loading of the Salton Sea. These all influence the ease of slippage for a region containing numerous unknown fault blocks. In future studies, the geographic migration of sequences can be used to better understand these invisible faults. With current techniques, there is uncertainty of the 3D architecture of these systems, but observing where events occur can uncover where faults are. With the vast majority of this plate boundary underwater, this technique may be the best way to understand the geographic orientation of these fault systems. The use of inSAR will not work for these underwater systems, while other techniques on-ground have become out dated. The use of strainmeters in the Bombay Beach region has been decommissioned, so new analyses need to work on other resources.

The implications of this research stretches beyond the Salton Sea. There is concern for seismicity to migrate along larger faults such as the San Andreas. This would cause devastation in the LA Basin with the potential to initialize other large faults in the area. With the future of lithium mining focused on the area, this region's anthropogenically caused seismicity may increase possibility of larger earthquakes in the future. This region is not unique and finding here can apply to other regions such as in Yellowstone geothermal power plants, Oklahoma fracking fields, and various other regions experiencing swarm behaviors. A critical analysis is needed for what these earthquake swarms can cause. Whether or not these provoke neighboring faults or reduce stress faster than natural is unknown.

With the scope of this project restricted to a single course SIO 199, there are limitation on the resources used and techniques. Further research is needed to better understand the implications of earthquake swarms. Working off of these definitions, there is information for forecasting, warning systems, underwater fault systems, and anthropogenically caused sequences. With more investment for on-the-ground research capabilities, the use of a strainmeter, more monitoring systems, or underwater sensing is needed in understanding the significance of swarms.

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REFERENCES

Brothers, D., Kilb, D., Luttrell, K., Driscoll, N., Kent, G. (2011). Loading of the San Andreas fault by flood-induced rupture of faults beneath the Salton Sea. *Nature Geoscience*, **4(7)**, 486 – 492.

Gutenberg, B., Richter, C. F. (1955). Magnitude and energy of earthquakes. *Nature*, **176(4486)**, 795-795.

Herrmann, M., Marzocchi, W. (2020). Inconsistencies and Lurking Pitfalls in the Magnitude–Frequency Distribution of High-Resolution Earthquake Catalogs. *Seismological Research Letters*

Philibosian, B., Fumal, T., Weldon, R. (2011). San Andreas fault earthquake chronology and Lake Cahuilla history at Coachella, California. *Seismological Society of America*, **101(1)**, 13-38.

Ross, Z. E., Cochran, E. S., Trugman, D. T., Smith, J. D. (2020). 3D fault architecture controls the dynamism of earthquake swarms. *Science*, **368(6497)**, 1357-1361

Stein, R. S. (2003). Earthquake conversations. *Scientific American*, **288(1)**, 72-79.

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