GEOS 620: Senior Experience Final Paper

Earthquakes in Nepal: Past, Present, and Future

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Abstract

The last great earthquake to occur in Western Nepal was 515 years ago and there is concern that due to the accumulated stresses the next great earthquake may occur here. However, our current models (Bollinger et al., 2016) do not account for the stresses released by smaller earthquakes (Mw < 7). Our findings suggest that the frequent smaller earthquakes in Western Nepal are capable of releasing some if not most of the accumulated stresses and the slip deficit may be lower than expected. We will also be exploring how past studies that looked at detritus layers (Bollinger et al., 2015; Ader et al. 2012), Turbidite layers (Ghazoui, 2019), and historic records (Pant, 2002) support this hypothesis. This study does not prove or disprove the likelihood of a future earthquake but rather aims to direct attention to the possibility of a future earthquake being less likely to occur in Western Nepal.

Background

The 2015 Gorkha earthquake has had a tremendous impact on Nepal and its people with 8510 deaths and 10 billion US dollars' worth of damages(Goda, 2015). Unfortunately, this earthquake was long expected as the most recent magnitude 7.8 2015 Gorkha earthquake is only one of a series of large earthquakes that have affected Nepal since historic times. Due to Nepal residing right above an active convergent plate boundary, it lies in an earthquake-prone zone. Around 40-50 million years ago the landmass that we now know as India made contact with the proto-Tibetan landmass (Powell, 1973). The earthquakes that occur can be attributed to the underthrusting of the Indian plate along the Main Himalayan thrust under the Eurasian plate. The continent-continent collision settings result in the Main Himalayan thrust absorbing around 20mm/year of north-south convergence a year (Ader et al., 2012) and over time, this steady tectonic motion creates enormous stresses that are intermittently released by devastating earthquakes. This leads to a seismic cycle of earthquakes that can be reconstructed to some extent using historic records. However, because Nepal's earliest scientific records are from the 18th century, the magnitudes, locations, and dates of the earthquakes may be subject to error. Geologic studies including analysis of turbidite layers in ancient lakes and sediments on paleo-seismological trenches can complement and extend the historical data. Findings from these studies in addition to historic records suggest the western part of Nepal is less seismically active however this hypothesis is inconsistent with findings from more recent earthquakes. The spatial distribution of earthquakes after the 18th century shows that the far western and eastern parts of Nepal have higher earthquake activity (Thapa, 2018). In this paper, we will be looking at the possible reasons as to why the discrepancy exists between spatial data on ancient great earthquakes and more recent earthquakes.

The underlying system of thrusts is responsible for the distribution of earthquakes in Nepal. The convergence between the Indian and Eurasian plates has resulted in the formation of three faults that extend from the eastern to the western border of Nepal. These faults are the Main Central Thrust, Main Boundary Thrust, and the Main Frontal thrust (Fig 1). As convergent pressures build up in these faults over time, they are periodically released in large earthquakes that create surface ruptures. Out of the three faults, the Main Central Thrust is the closest to the convergent boundary and hence absorbs most of the stresses. Though all three faults have the potential to trigger earthquakes the Main Central thrust is the most active due to the high stresses it experiences. This can be confirmed by looking at the spatial distribution of more recent

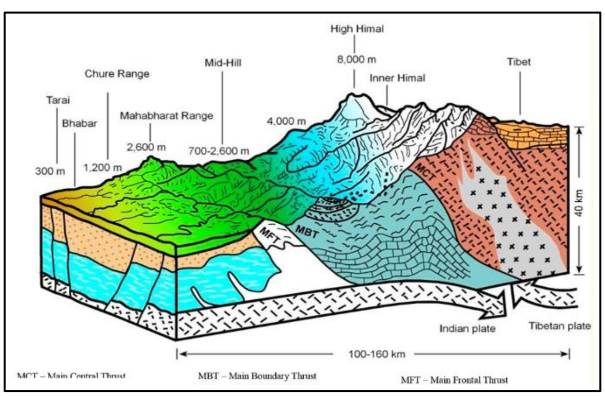

Figure 1: Topographical differences of Nepal (Hagen, 1998)

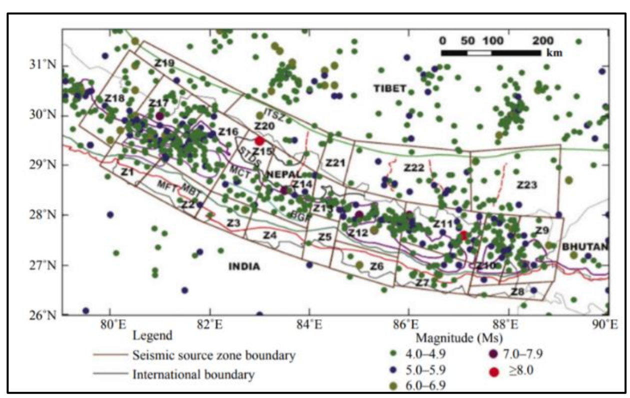

Figure 2: Spatial distribution of all earthquakes in Nepal (D. Thapa, 2004)

earthquakes in Nepal. We see that the northern part of Nepal is more seismically active than the southern part due to it being directly above the Main central thrust (Thapa, 2018).

Crosschecking the dates from multiple studies that use different methods indicates that there have been around 9 confirmed great earthquakes between 1000 AD and 2020 AD (Bollinger et al., 2016; Ghazoui, 2019; Pant, 2002). This may suggest that a particular kind of earthquake sequence recurs in a pattern of regular slips (Bollinger et al., 2016). The magnitude released from earthquakes before the 18th century is estimates based on geologic records such as sediments from detritus and turbidites due to the lack of scientific records. These estimates are calculated using a combination of historic records and geologic data from multiple proxies and comparing them to known earthquakes that have scientific records. The historically documented great earthquakes are presented in Table 1.

Table 1: Descriptions on historic records based on translations by Pant (2002) and National seismological Center(NSC).

Year	Magnitude	Description on record
1223	*NA*	This is the earliest known record of an earthquake in Nepal obtained from two chronicles translated from Sanskrit and Newari (Pant, 2002). Details have remained indecipherable due to defaced letters however, due to only large earthquakes being recorded during this time it is assumed to have been devastating. Geologic records are also inconclusive possibly due to it occurring not long before another great earthquake.
1255	*7.5~*	Immense destruction to temples and houses killing 1/3rd of the Nepali population including king Abhaya Malldeva. Aftershocks were felt after 4 months. Only documented in Kathmandu valley (Pant, 2002)
1344	*7.6~*	Fatally wounded King Ari Malla. Documented only in Kathmandu valley suggesting the epicenter was not far away (Pant, 2002).
1505	*8.1~*	Affected about 600km long stretch of the high Himalayan range according to eyewitness reports. Mainly affected far western territories in Nepal which may be why few historic records of this earthquake exist. Geologic records suggest this is possibly the largest earthquake that has occurred in Nepal in the past 1000 years.

1681	*7~*	Occurred 5 months after observation of the great comet. Very little information was recorded despite occurring at a Chronicle-rich period in Nepal.
1833	*7.6*	Tremors were felt as far as Calcutta in India and impacted the Ganges basin. Aftershocks were felt after 3 months. Most similar to the 2015 Gorkha earthquake in terms of epicenter and magnitude.
1934	*8*	Known as the 'Bihar-Nepal' earthquake. Surface rupture extended from east to west. (Sapkota et al., 2012). Detailed scientific records exist for this earthquake however due to it occurring in a different
2015	*7.8*	Ruptured a segment of the Main Himalayan thrust fault. Rupture did not extend past the southern part of Kathmandu similar to 1833.

The convergence rate of the two colliding plates was determined using by documenting geodetic strain across the Himalayas using GPS times series from 30 stations in Nepal and southern Tibet. Using the convergence rate of 20mm/year of the two colliding plates we can create a seismic moment model which compares the predicted moment released with the actual moment released (Bollinger et al., 2016). This model can be used as an indicator of how much moment deficit is still present. A higher moment deficit would suggest that the underlying thrusts are under immense pressure and there may be a high chance of an earthquake (Fig 4). However, the existing model presented by Bollinger et al. (2016) is limited by the data that is available which could yield incorrect moment deficit values. A lot of ancient earthquakes such as the 1505 earthquake have little data recorded and are hence not accounted for in these models. This could be a major error in the moment deficit model proposed by Bollinger et al. as evidence from paleoseismic trenches and turbidites suggest that the 1505 earthquake could be one of the largest seismic events in the past 1000 years. Not only that but many large earthquakes that may have occurred in the past in less urbanized parts such as western Nepal may have been unrecorded.

The spatial distribution of ancient earthquakes shows that the western part of Nepal had very few great earthquakes, yet the spatial distribution of more recent earthquakes shows that the western part of Nepal has a high frequency of earthquakes. What this suggests is that the western part of

Nepal may have fewer great earthquakes (Mw > 7) but a higher frequency of medium to large (Mw < 7) (Thapa, 2004). This hypothesis is consistent with findings in paleoseismic trenches and turbidities as great earthquakes are more likely to create an observable disturbance in the sediment layers while medium to large earthquakes leaves little to no evidence in the sediment layers. Historic records also do not mention of many earthquakes occurring in the western part of Nepal. Since historic times, the population distribution of Nepal has been least dense in the western region and due to this, there are few records of events that occur here (Fig 3). Only the largest earthquakes were vaguely mentioned such as the 1505 earthquake. This lack of historic data creates a false sense that the western region is less seismically active. The architecture of this region is also different compared to the more densely populated central region. People in this region live in single floored wooden houses and are often spaced far apart. During a large earthquake, the destruction would seem less in comparison to the densely populated central region where people live in tall stone/concrete houses. What this suggests is that the western region may be as seismically active as the central part of Nepal. Instead of having period large earthquakes, this region seems to have a higher frequency of medium to large earthquakes (Thapa, 2004). These earthquakes are not accounted for in Bollinger et al.'s seismic model which could be a reason why a large moment deficit still exists.

These unrecorded earthquakes could bring the actual moment released closer to the predicted hence making a future earthquake less likely to occur soon. According to current calculations the moment released from the most recent 2015 Gorkha earthquake is not enough to account for the moment deficit that had been accumulating since ancient times. Another large earthquake may already be due. However, if we account for the 1505 earthquake the other unaccounted earthquake in the past that may have occurred in the western part of Nepal the moment deficit is expected to be lower. Such analysis must be done carefully as suggesting a lower moment deficit is akin to suggesting the next earthquake may not occur anytime soon. It is dangerous to assume Nepal is risk-free regardless of how much moment deficit there is, it is always best to be prepared for an earthquake at any time especially since Nepal resides above a very active convergent boundary (Ader et al., 2012).

Since scientific record-keeping only started after the 18th-century data for all earthquakes prior had to be obtained through analysis of sediment layers in paleoseismic trenches and turbidites.

The historic records for the past earthquakes could be used to cross-reference possible dates from different surveys. Data obtained from radiocarbon dating detrital carbon from paleoseismic trenches (Bollinger et al., 2016) and turbidite layers from ancient lakes (Ghazoui, 2019) yielded data that matched with historic records (Pant, 2002) will be the key focus for this paper. These two methods are used as indicators as they show clear differences between a high-energy seismic event and natural sedimentation processes in the sediment record. Large earthquakes have immense damage in the form of destroyed houses, landslides, fallen trees, etc which creates a district detritus layer that can be easily distinguished from other natural processes. Additional information such as magnitude and epicenter can also be determined using this method. In addition to looking at paleoseismic trenches a great way to cross-reference earthquake data is to look at turbidite layers in large lakes. High energy events such as earthquakes often trigger slope failures that result in the formation of turbidity layers. The magnitude of the earthquakes can be calculated by looking at sediment cores from turbidites layers. Since there are many large lakes in Nepal this method can also be used to get a general sense of the epicenter of a particular earthquake by comparing turbidite data from other neighboring lakes.

Sediments from Lake Rara, the largest and deepest lake in western Nepal suggest that there may have been more large earthquakes in the past than historic data would suggest (Ghazoui, 2019). Turbidite layers that would have been formed by earthquake-triggered slope failures are observed in the lake sediments. Eight turbidite layers were formed in the last 800 years where three coincided with documented records while the other 5 were undocumented and could represent large seismic events. Due to the scarce population in the western part of Nepal, most historic records were based on data from around central Nepal so earthquakes in the western part may have passed unnoticed or undocumented. The implications of this finding suggest there may have been other earthquakes in the past that would have balanced out the slip deficit caused by major earthquakes. These unrecorded earthquakes along with smaller earthquakes may be capable of releasing some if not most of the accumulated stresses in Western Nepal. Using the spatial distribution data and magnitudes of more recent earthquakes we will determine the estimated slip. We will then be comparing this value with the expected slip based on the known convergence rate of 20.5mm/year (Ader et al., 2012). Our findings suggest that the mechanism for releasing accumulated stresses in western Nepal is different from the rest of Nepal where stresses are released little by little through frequent smaller earthquakes as opposed to periodic great earthquakes. Due to this, the next great earthquake may be less likely to occur in western Nepal and it is important to focus on other parts along the Main Himalayan thrust to carry out a seismic risk analysis. The same model used to predict slip deficits for central and eastern Nepal can not be used for western Nepal.

Methods

Scientific records in Nepal for seismic activity only go back to the late 18th century (Bollinger et al., 2014; Thapa, 2004) which makes it tricky to make inferences on ancient earthquakes. Several methods can be used to predict past earthquake events such as using detrital charcoal carbon dating from paleo seismological trenches, turbidites, historical records, and spatial distribution of known earthquakes. Each method comes with varying levels of accuracy and limitations so in this paper we will employ a multi-proxy analysis using data obtained for multiple studies. The use of multiple methods not only improves the accuracy of the data but also provides regional level data that could potentially help fill in the gaps that remain in our knowledge of Nepal's seismicity. The central part of Nepal has always been known to be more seismically active in comparison to the west (Bollinger et al., 2014). This assumption has yielded moment deficit models that suggest there are large dormant stresses that have not been released yet (Ader et al., 2012). By comparing data from multiple studies conducted in different parts of Nepal we get a more detailed look at ancient earthquakes on a regional scale. This not only provides evidence that current predictions on the moment deficit may be larger than it is but also suggests the western part of Nepal is as seismically active as central Nepal. To confirm this hypothesis, we compile all the data obtained from past studies to create a catalog of great earthquakes (Table 1). By comparing data from past studies (Bollinger et al., 2014; Alder et al., 2012; Ghazoui, 2019; Pant, 2002) in addition to publicly available data from the National Seismological Center (NSC) and International Seismological Center (ISC) we can create a dataset that includes the year, magnitude and epicenter coordinates. This dataset is plotted into a district-level map of Nepal using ArcGIS. We then compare our data with more recent smaller earthquakes (Thapa, 2018) to see how much slip is accounted for by smaller earthquakes. By using the known convergence rate of 20.5mm/year of western Nepal (Ader et al., 2012) we can determine the expected slip and by using the spatial distribution/magnitude of all known earthquakes we can calculate the estimated slip.

Historic data:

Historic data presents a vague glimpse of Nepal's seismic past but is still the baseline method that all other methods are dependent on. Though historic records before the 18^{th} century contain little to no seismic data there are accounts of casualties, damages, general location, and date which can be used to make estimates of ancient earthquakes. More than 200 old manuscripts such as holy texts and early chronicles were looked at by Iyenger et al. (1999). A more detailed analysis was done on local Nepalese chronicles by Rana (1936) and later by Pant (2002) which were from the Sthiti Malla period between 1057-1389AD. The historic records consisted of the extent of damages, deaths, and eyewitness testimonies. These historic records had accurate dates and times of earthquakes which is considered reliable by historians (Regmi, 1969). The first mention of an earthquake was in 1223 however, due to most records of this era being lost or in poor condition little is known about this earthquake other than the date it occurred. There are mentions of earthquakes in 1255, 1344, and 1808 with information on casualties, damages to buildings and temples, and often the whereabouts of the King.

Limitations

Many records especially in the earlier years have either been lost or have defaced letters. Due to the population density being disproportionately concentrated in the central region of Nepal most events recorded were from around central Nepal. Earthquakes in the western part of Nepal, where the population is sparse could have been unrecorded. There are periods in Nepal's history where no historic records are available (the 1400s). There have also been inconsistencies in the Nepali calendar which could have caused subtle errors in the exact date of the earthquakes.

Turbidites:

High energy events such as earthquakes, floods, or landslides trigger slope failure around lakes that form turbidite layers. The composition and thickness of these turbidite layers can be used to obtain data on past earthquakes. The study by Ghazoui (2019) looked at turbidite layers in Lake Rara which is not only the deepest lake in Nepal but is also located in the western part of Nepal. Lake Rara is an ancient lake that has turbidite layers that go as far back as 1135 (Ghazoui, 2019). The other reason why this lake is ideal for this study is due to its low relief making it possible for only large earthquakes (Mw >~6.5) to trigger a slope failure. This study yielded valuable data on large seismic events around western Nepal which can be used to cross-reference data from historic records.

Limitations:

Only 5 out of 8 turbidite layers could be accurately dated to a known past earthquake. The other 3 could either represent an error in the data or could be undocumented earthquakes which could tie into the slip deficit estimates of Nepal's earthquake history.

Detrital Charcoal Carbon Dating:

This method is based on the study by Bollinger et al. (2016) and Ader et al. (2012) which looked at detrital charcoal content at 4 paleo seismological trenches: Koilabas, Mahra, Sir Khola, and Hokse. Detritus are deposited in sediment layers in paleoseismic trenches as a result of the damages caused by large seismic events. The damages are in the form of fallen trees, landslides, collapsed buildings, etc, which create a distinct layer of detritus that can be easily distinguished from normal sedimentary layers. This method focuses on the radiocarbon dates of detrital charcoal which would have formed by fires or the destruction of homes/fire pits. By cross-referencing, the radiocarbon dating data from the 4 sites a fairly accurate prediction on when the earthquake occurred can be made (Bollinger, 2016). This data can then be compared with historic records and turbidite data by Ghazoui (2019) to create an accurate catalog of great earthquakes that have occurred in the past 1000 years.

Limitations:

Some of the wood from homes or hardwood trees could have been decades old before being burned down by fire so radiocarbon dating will have a fairly large range of error.

Data analysis and spatial distribution of earthquakes using GIS.

Using a combination of seismic data obtained from the National Center for Environmental Information (NOAA), Disaster Preparedness Network Nepal (DPNET Nepal), National Seismological Center (NSC), the International Seismological Center (ISC), United States National Earthquake Information Center (NEIC) and previous studies (Bollinger et al., 2016; Ghazoui, 2019; Pant, 20020; Thapa 2008; Thapa and Wang 2010; Thapa and Wang 2013) the coordinates and magnitude of past earthquakes were cataloged in a custom dataset. Since some methods yielded varying data, only data that were consistent with multiple methods were used. This dataset included estimated magnitudes for past earthquakes obtained from previous studies (Bollinger et al., 2016; Ghazoui, 2019; Ader et al., 2012). Data from the dataset was imported into ArcGIS in a district-level Nepal map along with the population density (Fig 3). Only data for great earthquakes (Mw>7) was included.

We then calculated the expected slip from the 20.5mm/yr convergence rate (Ader et al., 2012) and then compared it to the estimated slip from all the earthquakes that have occurred in the western part of Nepal. Assuming that the convergence rate of the Indian and Eurasian plate has been constant for the last 1000 years we can assume that the seismic distribution of earthquakes after 1800 is the same as before 1800. Hence, by multiplying the convergence rate and the no. of years since 1255 we get an expected slip value of 15.7m.

Next, we determine the number of earthquakes and the amount of slip in Western Nepal. Since 1255 there have been 709 earthquakes of Mw = 4 – 4.9, 121 earthquakes of Mw = 5 – 5.9, 42 earthquakes of Mw = 6 – 6.9, 9 earthquakes of Mw = 7 – 7.9 and 2 earthquakes of Mw > 8 (Thapa 2013). In Table 2 we have the spatial distribution function of earthquakes of different magnitudes along with the Seismic source zone from 1255 to 2021 (Thapa, 2004). By isolating the zones that lie on the western part of Nepal and using Spatial distribution data (Table 3), we can determine how many earthquakes have occurred only in western Nepal since 1255 using the following formula.

$$Number\ of\ earthquakes\ in\ West = \sum Spatial\ distribution\ function \times Total\ number\ of\ earthquakes$$

Next, we can determine the amount of slip that has occurred based on the magnitude of the earthquake (Scholz, 1990) where smaller magnitude earthquakes result in less slip and higher magnitude earthquake result is more (Table 3). Using the convergence rate of 20.5mm/yr we expected a slip of 15.7m between 1255 and 2021. The estimated slip we obtained from earthquakes in the western part of Nepal is 20.9m (Table 3). This shows that there has been more slip from earthquakes in this region than expected. What this suggests is that the seismic gap is not as large as previous studies predicted (Bollinger et al. 2016). However, there are multiple thrusts present in Nepal and our calculations only account for the convergence rate of the Main

Frontal Thrust which could be a potential source of error. Our slip estimates show that smaller earthquakes of higher frequency in western Nepal account for a comparable amount of moment released to great earthquakes in Central and Eastern Nepal (Table 3).

Table 2: Spatial distribution functions for seismic source zones

Number	Seismic source zone	Maximum magnitude	Spatial distribution functions				
			M= 4.0–6.4	M= 6.5–6.9	M= 7.0–7.4	M= 7.5–7.9	M= 8.0–8.4
1	Z_1	6.5	0.0220	0	0	0	0
2	Z_2	6.5	0.0332	0	0	0	0
3	Z_3	6.5	0.0243	0	0	0	0
4	Z_4	6.5	0.0292	0	0	0	0
5	Z_5	6.5	0.0215	0	0	0	0
6	Z_6	6.5	0.0299	0	0	0	0
7	Z_7	7.0	0.0452	0.0873	0	0	0
8	Z_8	6.5	0.0169	0	0	0	0
9	Z_9	8.0	0.0506	0.0977	0.1071	0.1113	0
10	Z_{10}	8.5	0.0344	0.0664	0.0727	0.0756	0.1166
11	Z_{11}	8.5	0.0562	0.1086	0.1190	0.1237	0.1909
12	Z_{12}	8.0	0.0537	0.1038	0.1137	0.1182	0
13	Z_{13}	7.5	0.0179	0.0346	0.0379	0	0
14	Z_{14}	8.5	0.0464	0.0896	0.0982	0.0251	0.0750
15	Z_{15}	8.5	0.0400	0.0772	0.0846	0.0479	0.0557
16	Z_{16}	8.5	0.0579	0.1118	0.1225	0.1073	0.0564
17	Z_{17}	8.5	0.0597	0.1153	0.1263	0.1313	0.2026
18	Z_{18}	8.0	0.0555	0.1073	0.1175	0.1222	0
19	Z_{19}	6.5	0.0368	0	0	0	0
20	Z_{20}	6.5	0.0541	0	0	0	0
21	Z_{21}	6.5	0.0191	0	0	0	0
22	Z_{22}	6.5	0.1035	0	0	0	0
23	Z_{23}	6.5	0.0914	0	0	0	0

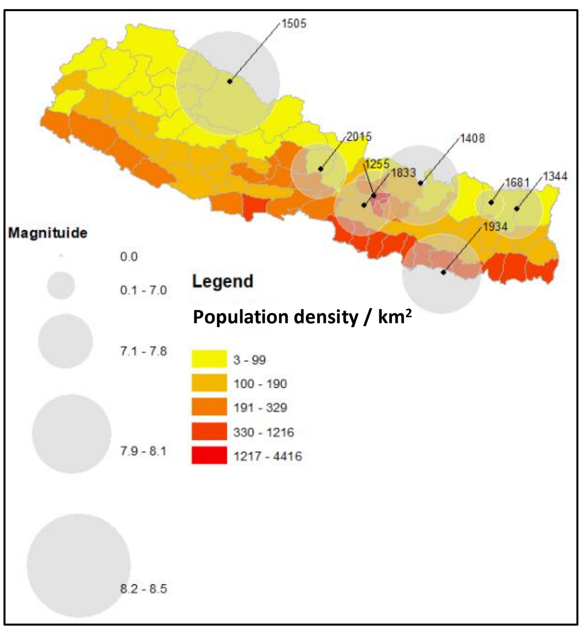

Figure 3: Distribution of great earthquakes and population density of Nepal

Table 3: Slip estimates based on magnitude and frequency of earthquakes and magnitude to slip conversion rubric.

Magnitude (Mw)	4 - 4.9	5 - 5.9	6 - 6.9	7 - 7.9	> 8	Total slip (m)	Expected Slip (m)
Earthquakes in Nepal	709	121	42	9	2		
Earthquakes in West (Higher estimate)	287.1	49.0	21.1	4.4	0.8		
Earthquakes in West (Lower estimate)	233.5	39.9	17.3	3.9	0.6		
Slip (m) (Lower estimate)	11.7	6.0	2.6	0.6	0.1	20.9	15.7
Slip (m) (Higher estimate)	14.4	7.4	10.5	6.6	3.9	42.8	

Magnitude (Mw)	Slip (m)
4~	0.05
5~	0.15
6~	0.5
7~	1.5
8~	5

Results

To make any inferences on Nepal's seismic history it is important to have detailed information on earthquakes that have happened in the past. However, since scientific records for seismic events in Nepal were not prevalent before the 1800s, we do not have a complete earthquake catalog (Thapa, 2013). Multiple methods must be employed to extend the known timeline of earthquakes. For our study we used the following 3 methods; carbon dating of charcoal in detritus layers in paleoseismic trenches, analyzing turbidite layers from lake Rara and going through historic documents (Bollinger, 2016; Ghazoui, 2019; Pant, 2002). By looking at the data from these methods we find varying results due to the limitations of the method. These limitations arise due to regional differences in samples or uncertainty in the method. To overcome the limitations the year, magnitude, and epicenter data from the 3 different methods are cross-referenced and inconsistent data is discarded. 8 great earthquakes were identified and compiled into a district-level database (Table 4). Using ArcGIS, the spatial distributions of the great earthquakes were plotted on a district-level map of Nepal (Fig 3).

Table 4: Catalogue of great earthquakes 1255 – 2021(Pant, 2002; Bollinger et al., 2016, Ghazoui, 2019; Ader et al., 2012, NSC, ISC)

YEAR (A.D)	MAGNITUDE (MW)	EPICENTER	DISTRICT
1255	7.50	27.7° N, 85.3° E	Kathmandu
1344	7.60	27.5° N, 87.5° E	Taplejung
1408	8.10	27.9° N, 86° E	Sindhupalchok
1505	8.50	29.5° N, 83° E	Baglung
1681	7.00	27.6° N, 87.1° E	Sankhuwasabha
1833	7.60	27.553ºN 85.112ºE	Makwanpur
1934	8.00	26° 51′ 36″ N, 86° 35′ 24″ E	Udayapur
2015	7.80	28° 13′ 48″ N, 84° 43′ 51.6″ E	Gorkha

From Fig 3 we see that since 1255 all except the 1505 earthquake occurred in the central or eastern part of Nepal. Based on this figure it would seem that western Nepal is less seismically active. However, one shortcoming of the methods used to obtain seismic data is that usually only large seismic events with magnitudes Mw > 6.5 create enough disturbance on the surface to be recorded in sediment layers or historic documents (Ghazoui, 2019). Due to this fact, all records of earthquakes before 1800 only represent the largest of earthquakes (Thapa, 2018) leaving a void in our knowledge of Nepal's seismic past. Using the well-recorded earthquake data after 1800 we can create a seismic distribution map of all earthquakes with Mw >= 4. The catalog of all earthquakes was compiled by using data from the International Seismological Center(ISC), United States National Earthquake Information Center (NEIC), and the National Seismological Center (NSC) (Thapa, 2013). Comparing the seismic distribution of earthquakes from this dataset to the spatial distribution of great earthquakes since 1255 A.D (Fig 1) we see a stark contrast in terms of earthquake hotspots. This is most evident in western Nepal. The westerns part of Nepal is considered to be less seismically active based on the fact that the last great earthquake occurred 515 years ago in 1505 A.D. In contrast, when looking at all earthquakes that have occurred in Nepal since 1800, we see that the distribution of earthquakes is very dense in the western part of Nepal(Thapa, 2013). What this suggests is that unlike the central and eastern part of Nepal where the accumulated stresses from crustal shortening are released in periodic large seismic events, the western part of Nepal instead has smaller seismic events but at a higher frequency. The eastern part of Nepal experiences convergence at a rate of 17.8mm/yr. (Ader et al, 2012) the western portion of the Main Himalayan thrust has a convergence rate of 20.5mm/yr

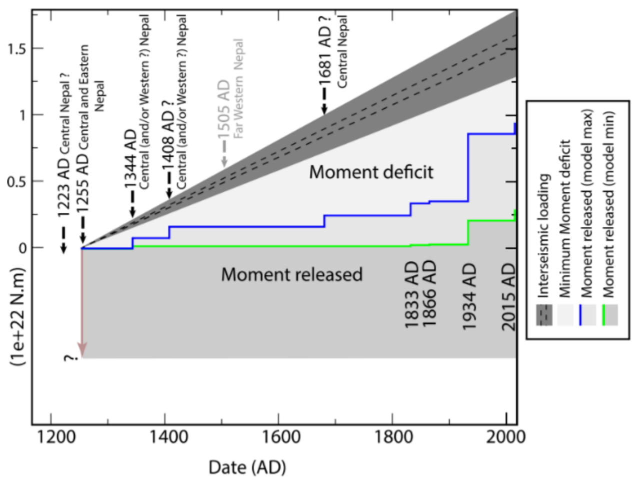

Figure 4: Moment dificit based on great earthqakes in the past 1000 years (Bollinger et al., 2016)

(Ader et al, 2012). Since the 1505 earthquake the western part of Nepal has been accumulating stresses for 515 years and our current understanding suggests there is a large moment deficit (Fig 4). Due to the higher frequency of medium to large earthquakes in this region, the accumulated stresses could have been released over time slowly through medium to large earthquakes as opposed to periodic high energy great earthquakes.

Discussion

Past studies have suggested that the western part of Nepal is less seismically active than the rest of Nepal (Ghazoui, 2019). By strictly looking at the spatial distribution of only the great earthquakes it is consistent with this hypothesis(Fig 3). However, looking at multiple studies that employ different methods across Nepal paints a slightly different picture. The translated historic documents by Pant (2002), Detrital carbon analysis by Bollinger et al.(2016), and turbidite layer analysis by Ghazoui (2019) look at this issue through completely different lenses but pairing their findings with data from more recent earthquakes (Thapa, 2018) we get a different perspective on Nepal’s seismic past. Unlike central and eastern Nepal that has a known history of parodic large earthquakes, our findings suggest that the western part of Nepal may have a different mechanism for releasing the accumulated stresses. Instead of releasing these stresses periodically through large earthquakes, our evidence suggests that in western Nepal the accumulated stresses could have already been released through smaller but more frequent earthquakes. The key findings that support our hypothesis are:

Population density differences

Nepal has historically always been an agricultural country due to its unique topography (Shrestha, 2004). The northern part of Nepal also known as the Himalayan region consists of infertile terrain due to the harsh weather conditions of the Himalayas. The middle part of Nepal is known as the hilly region and consists of most of the big cities. The southern part of Nepal is known as the Terai region and consists of fertile soil due to river deposited nutrients. Most of Nepal's population is concentrated in the Terai region and a few select cities in the hilly region. As a result, the western part of Nepal has always been less populous compared the central and eastern Nepal (Fig 3). All of Nepal's historic records and ancient manuscripts on past earthquakes were recorded and stored in Kathmandu which is in the hilly region of Central Nepal. These records were based on eyewitness testimonies and visible damages and due to the sparse population of western Nepal, a lot of the seismic events in the region could have gone by unrecorded. Since scientific recordkeeping did not start until the 1800s in Nepal historic records and recent studies on sediment layers are our only source of information on earthquakes before 1800. Due to the bias in terms of information available when looking at historic records it is possible that events that occurred around the capital were more likely to have been recorded. There would have been very few reports of seismic events from Western Nepal as a result of the low population and possibly lower fatalities from even larger earthquakes.

Architectural and cultural differences

Figure 5: A traditional house is Western Nepal.

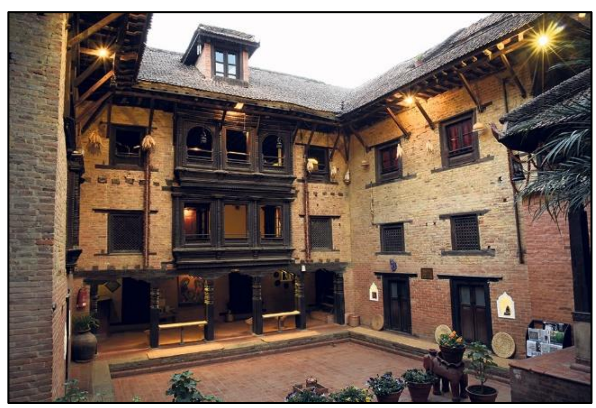

Figure 6: A traditional collection of connected houses in Kathmandu

In addition to population density differences between Western Nepal and the rest of Nepal, there are also Architectural and Cultural differences that could create a bias when comparing sediment records (Sharma, 1983). Due to the rural nature of western Nepal, most houses are spaced out and made with simple materials such as wood, mud, and straw. A traditional house in Western Nepal would be single floored and most daily activities such as farming, hunting, washing clothes, cooking would have taken place outdoors (Sharma, 1983). In contrast houses in more population-dense areas were not only larger but also housed more people. These houses are usually made of materials such as cement, bricks, rock, etc. Culturally these areas would have also been very different where people lived a more modern lifestyle that usually did not involve being outdoors. Just like with population biases these Architectural and cultural differences would also create biases in historic records and sediment records. The Architectural and cultural differences between Western Nepal and the rest of Nepal would have made seismic events look less devastating and the death toll lower. When looking at the sediment record from Bollinger et al.'s study we see that the detritus layers from Western and Central Nepal would look very different even for the same magnitude earthquake (Bollinger et al. 2016). Due to the larger more closely packed buildings in Central Nepal after a large earthquake, there would be more destruction which in turn would form a very distinct detritus layer. A similar earthquake if occurred in the west would resemble a much smaller earthquake. This may be a reason why even larger earthquakes in Western Nepal could have been unrecorded in historic and sedimentary records.

Turbidite corresponding to unknown great earthquakes:

Since cultural and architectural differences create biases when looking at detritus layers, looking at turbidite layers is another great way to get a glimpse of past large earthquakes. The study by Ghazoui(2019) in particular provided great insight especially because it looked at a western ancient lake with low relief called lake Rara. Due to its low relief, only high-energy events such as large earthquakes are capable of triggering turbidites. This makes this method ideal for tracking large ancient earthquakes. As seen in (Fig 7) most of the data from these turbidite layers correspond with the data from historic records and detritus layers. However, 3 earthquakes do not match any recorded earthquakes; 1617 – 1774AD, 1643 – 1819AD, and 1905 – 1947AD. This finding supports our previous hypothesis as to why some earthquakes may have gone by unrecorded in historic records and detritus layers. Architectural and cultural differences along with lower population density would make detritus layers in western Nepal look smaller than it was. Another possible reason as to why Bollinger et al.'s (2016) study of paleoseismic trenches did not show evidence of these 3 unknown earthquakes maybe since none of the studies looked at trenches that lie in Western Nepal. The closest site was in Koilaibas (Fig 8) which lies in mid-western Nepal and even for this site, the data was inconclusive, possibly due to the distance from the epicenter of western earthquakes.

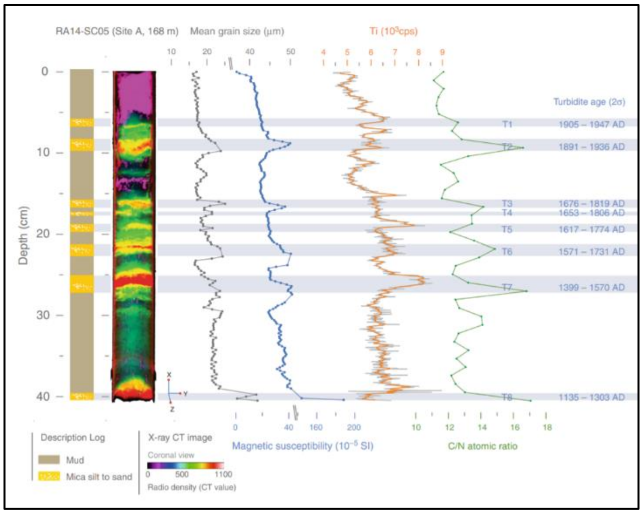

Figure 7: Turbidite core data with dates of earthquakes highlighted in grey (Ghazoui, 2019)

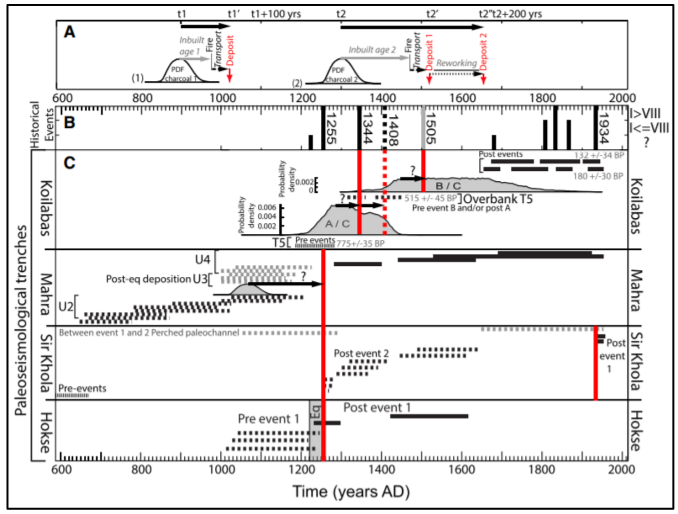

Figure 2: Detritus carbon data from 4 paleoseismic trenches (Bollinger et al., 2016)

Different convergence rates:

As the Indian plate subducts under the Eurasian plate, it creates crustal shortening at an average rate of around 20mm/year. However, this rate is higher in Western Nepal at 20.5mm/year compared to eastern Nepal's 17.8mm/year (Ader et al. 2012). Due to the higher convergence rate, there is a higher amount of accumulated stresses in Western Nepal. As a result of higher stresses, we expect the seismic activity to be higher as well. However, this is not consistent when looking at the spatial distribution of great earthquakes in the past 1000 years (Fig 3). In stark contrast to this when looking at (Fig 2) we see that the frequency of smaller earthquakes (Mw 4 – 6.9) is very high in western Nepal. The reason why there is such a big difference between the spatial distribution of great earthquakes (Mw > 7) and smaller earthquakes may be because the underlying mechanism responsible for releasing the accumulated stresses is different. The higher convergence rate may facilitate the release of stresses through smaller yet more frequent seismic events instead of accumulating stresses over an extended period and then releasing everything at once in a large seismic event. This could explain why we see most of the great earthquakes occurring in central and eastern Nepal.

Slip estimates from convergence rate:

To test if the smaller earthquakes in western Nepal can fill in the seismic gap, we calculated the estimated slip and compared it with the expected slip. Based on the known convergence rate of 20.5mm/year we calculated an expected slip of 15.7m since 1255AD. To estimate the actual amount of slip we can use the spatial distribution functions calculated by Dilli Ram Thapa (2018) and the total number of earthquakes in western Nepal. The closer our number is to the expected 15.7m the more likely it is that the accumulated stresses have already been released by smaller earthquakes that occurred in western Nepal. From our estimates in (Table 3), we see that the earthquakes in western Nepal account for about 20.9m of slip. The fact that our estimated slip value is larger opposed to smaller than the expected 15.7m strongly suggests that the smaller earthquakes in western Nepal are capable of releases some if not most of the accumulated stresses. This finding supports our hypothesis that the mechanism of releasing accumulated stresses in western Nepal is different from the rest of Nepal. It also explains why most great earthquakes occur in central and eastern Nepal and why the frequency of smaller earthquakes is higher in western Nepal. Our current slip deficit models only account for large earthquakes Mw > 7 (Fig 4) and not smaller earthquakes Mw < 7. This could be a source of error in these models. Our findings point out the importance of including smaller earthquakes, as well as they, are capable of releasing the accumulated stresses not just in Western Nepal but also along with the entire Main Himalayan thrust (Table 3). It is crucial to consider these smaller earthquakes as they greatly affect our understanding of dormant stresses in Nepal. Since great earthquakes recur periodically when the accumulated stresses are high enough it is important to known which parts of the thrust are under more stress as zones under higher stress are more likely to be where the next great earthquake will occur. Our evidence suggests that most of Western Nepal's accumulated stresses have already been released through frequent smaller earthquakes. However, since our estimated slip of 20.9m is higher than the expected slip of 15.7m there may be an error due to our assumption that the convergence rate is constant at 20.5m. As seen in Fig 1 there are 3 different main thrusts along with micro faults in between and each thrust may have a different convergence rate. The expected amount of slip could be higher due to the unique geometry of thrusts in Nepal. Further research on these individual thrusts and micro thrusts is required to determine the true amount of slip the thrust has experienced in 1255.

Conclusion

The last great earthquake in western Nepal was in 1505 and due to the gap of 515 years, there is concern that the next imminent great earthquake may occur here. Comparing multiple studies and methods we find that, though there has been a large gap between the last great earthquake in western Nepal the accumulated stresses could have been released already through smaller more frequent earthquakes. Our findings from the estimated slip values in addition to studies by Pant(2002), Bollinger et al. (2016) and Ghazoui (2019) fit together to suggest that Western Nepal is just as seismically active if not more than the rest of Nepal. The only difference is that instead of releasing seismic stresses periodically in large earthquakes they are released through smaller more frequent earthquakes. The reason why our estimated slip is higher than the expected slip may an error due to assuming the fixed convergence rate of 20.5mm/year. Further study is required in terms of understanding the stresses present in the individual faults of western Nepal to determine why our slip estimates were higher than the expected slip. The multiple faults present in addition to micro faults in-between could have different convergence rates that need yet to be determined. The goal of this study is not to prove or disprove the likelihood of a future earthquake but rather to direct attention to the possibility of a future earthquake being less likely to occur in Western Nepal.

This study does not prove or disprove the likelihood of a future earthquake but rather aims to direct attention to the possibility of a future earthquake being less likely to occur in Western Nepal. Our findings only show that the accumulated stresses in Western Nepal may not be as high as past studies would suggest (Bollinger et al.2016). What this means is that the slip deficit is not as high for western Nepal and other areas along the Main Himalayan Thrust may be at greater risk of slipping during the next great earthquake. The cultural, architectural, population density, and convergence rate differences between western Nepal and Central Nepal also provide strong evidence for our hypothesis. To calculate the true convergence rates of individual faults and micro faults further research will be required.

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