Supporting Information for

Millenary $M_w>9.0$ earthquakes required by geodetic strain in the Himalaya

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Introduction

Here we give more details of the methods and data used in the main text. Figures S1 to S2 help clarify the method while figures S3 and S4 show the results of changing assumptions. Figure S5 shows a comparison of moment build-up and release through time. Tables S1 and S2 show original and binned data respectively for the historical and paleoseismic earthquakes.

Text S1. METHOD 1

Text S1.1. Introduction

We use the instrumental, historical and paleoseismic earthquakes catalogs, along with the total moment build-up rate each year, to find the maximum likely earthquake size. In this first method, we assume earthquakes follow a GR distribution,

$$\log_{10}N = a - bM_w$$

where $a$ and $b$ are constants, $M_w$ is the magnitude, and $N$ is the number of earthquakes above magnitude $M_w$. $a$ is the number of earthquakes above $M_w=0$, and can be thought of as the
productivity. We also assume the b value is $1.1 \pm 0.1$, the largest aftershock is $1.2 \pm 0.1$ below the mainshock, and the seismic moment build-up is $15.1 \pm 1.1 \times 10^{19} \text{Nm/yr}$.

The total moment line is found from the integration of the number and magnitude of earthquakes, assuming the GR law as above, and the relation between moment ($M_0$) and magnitude:

$$M_0 = 10^a (M_w + b)$$  

where $a = 2/3$ and $b = 10.7$.

$$N_0 = 10^a - 10^{(a-bM_w)}$$

where $N_0$ is the number of earthquakes below magnitude $M_w$.

$$\text{Total moment release} = \int_{-\infty}^{M_w} M_0 (M_w') N_0 (M_w') \ dM_w'$$

So we get

$$a = \log_{10} \left( \frac{M_0}{10^{(1.5-b)M_w-1}} \right) - \log_{10} (3) - 9 - \log_{10} (b) - bM_w \ .$$

Since we have estimates of $M_0$ and $b$ we can use this equation to find the relation between $M_w$ and the recurrence time, if $M_w$ were to be the maximum sized earthquake.

**Text S1.2. Data**

*Instrumental Seismicity*

We use the NSC catalog (from 1995 to 2001), which covers five years of microseismicity in Nepal, and contains 12,201 earthquakes with magnitudes 0.3 to 5.5. These magnitudes are reported in local magnitudes ($M_L$), and we use the method of Ader et al. 2012 who used a subset of events reported also in the CMT catalog, to convert into moment magnitude ($M_w$):

$$M_w^{NSC} = 0.84 M_L^{NSC} + 0.21$$

Since this catalog contains only earthquakes recorded in Nepal, we scale up by a factor of 3, assuming the microseismicity is consistent along the arc.

We use the NEIC catalog between 1976 and August 2015. We take earthquakes within 100 km of the surface trace of the Main Frontal Thrust. To account for the fact that some of these earthquakes are not on the MHT, we use the CMT catalog covering the same area to find the percentage of the total that are thrust events. We find that 75% are thrusts, so we scale the NEIC catalog by 0.75. Large earthquakes are reported as $M_w$ in the NEIC catalog, however for those reported as $m_b$ we use [Scordilis, 2006]

$$M_w^{NEIC} = 0.85 m_b^{NEIC} + 1.03$$
The catalog we use then contains 1,465 earthquakes between magnitudes 4.9 and 7.8. Figure 2B shows lateral variations of the seismicity rate of derived from the NEIC catalog from 1976 to present after declustering. The earthquakes were declustered using ZMAP [Wiemer, 2001] and Reasenberg’s method [Reasenberg, 1985] with the optimum parameters obtained by Ader and Avouac for this catalog [Ader and Avouac, 2013]. The magnitude of completeness is estimated to be Mw4.9.

Historical and Paleo-Earthquakes

The historical earthquakes considered in this study are listed in Table S1. This list is based on the historical catalogs of Ambraseys and Douglas [2004], Bilham [2004] and Pant [2002]. We revised the magnitudes of the 1934 Bihar Nepal and 1950 Assam earthquakes to Mw 8.4 and 8.7 respectively, based on the moment determined from the long period seismic waves [Chen et al., 1987; Molnar et al., 1984] assuming a dip angle of 5°-10° consistent with the estimated dip angle of the seismogenic portion of the MHT.

The magnitudes of the 1344 and 1505 earthquakes are debated. We have assigned Mw 8.4 to the 1505 event. Some authors argue that this earthquake was in fact more minor [Rajendran et al., 2013] and that the major event in western Nepal is actually the 1344 earthquake [Mugnier et al., 2011]. This earthquake could match the paleoseismic event in the Kumaon-Garwal Himalaya dated to 1400 AD [Kumar et al., 2006]. A recent study (Schwanghart et al.., 2015) confirms the probability of significant earthquakes in 1110, 1255 and 1344 from catastrophic valley infilling events corresponding to these dates.

Based on Table S1 we constituted a possible model of the long-term averaged rate of large earthquakes in the Himalaya (Table S2). For earthquakes >= Mw9, there are two earthquakes which could be in this range – the 1100AD and 1400AD earthquakes (see Table S1), however these could both be below Mw 9. So we choose the range 0-2 earthquakes >= Mw9 in the past 1000 years to be the 1σ uncertainties.

For earthquakes >=Mw8.5 we consider the two above, 1100AD and 1400AD earthquakes, which have a larger certainty of being above 8.5 than 9. We also consider the 1255 and 1950 earthquakes, though we are less certain if the 1255 earthquake was over magnitude 8.5, so we assign the 1σ range as 3-4 in the past 1000 years.

For earthquakes >=Mw8, we have the four potentially above 8.5 and the 1505 and 1934 events. We consider these six events to be a lower bound on the 1σ uncertainty, but we may be missing some, for example if the 1100 and 1400 earthquakes were actually two earthquakes of around 8 instead of nine, so we consider 9 as an upper 1σ bound.

For the earthquakes in the range Mw7.5-8, we used only the past 220 years of data (with the oldest earthquake being the 1803 Garwhal earthquake). This is because for these smaller earthquakes, the historical record deteriorates more quickly than for the larger earthquakes as the shaking created is lesser and over a smaller area, so may more easily be missed. We then assume a similar rate of earthquakes for the past 220 years as for the past 1000 years. There have seen six recorded earthquakes of size Mw7.5-8 in the past 220 years (Table 1). We take this as the 1σ lower bound, and assuming perhaps at least 3 missed earthquakes in this size range, take nine as the 1σ upper bound, so there is a 68% chance that there were between six and nine earthquakes in this magnitude range.
The data used is summarized in table S2.

**Text S1.3. b Value and moment released by aftershocks**

The b value is used in calculating the slope of the line that takes up the seismic moment buildup, in simulating the aftershocks and in calculating the equivalent a value for the pieces of data. The latter is the most affected by the uncertainty in the b value.

We find the b value using the NSC catalog. We use the maximum likelihood method [Aki, 1965] to find the b value, after choosing \( M_c \) (the lower cutoff value) using a bootstrap method, implemented in ZMAP [Wiemer, 2001]. We find \( M_c = 3.2 \) and \( b = 1.1 \pm 0.04 \). We increase the formal uncertainty on the b value to \( 1.1 \pm 0.1 \), as the NSC catalog only contains one third of the arc and only contains magnitudes up to 5.5 so the uncertainty may be more than the actual value obtained from the NSC catalog alone.

We are missing aftershocks of large earthquakes in the instrumental catalogs, as there have been no great (>\( M_{w} 8 \)) earthquakes since instrumental records began. We simulate aftershocks simply by assuming they follow a GR distribution with b value \( 1.1 \pm 0.1 \), and that they follow Bath’s law, with the largest aftershock \( 1.2 \pm 0.1 \) below the mainshock.

For example, every time we have a magnitude 8 in the record, we assume an aftershock sequence with largest aftershock 6.8, with smaller earthquakes with frequency in accordance with GR. If the magnitude 8 occurred once every 100 years, this aftershock sequence would also occur every 100 years. In this way, we add missing aftershocks to the current catalogue. We add missing aftershocks for magnitudes 7.5, 8, 8.5 and 9.

Adding aftershocks increases uncertainties due to b value uncertainty and uncertainty in magnitude-frequency relations of the larger earthquakes. The addition of the aftershocks does not change the maximum predicted earthquake size significantly, but it shows that the full earthquake catalog may follow more closely the GR law.

We can compare our aftershock model with aftershocks seen elsewhere. For the Gorkha 2015 earthquake, the first aftershock sequence had the largest aftershock 1.1 below the mainshock, whilst the second larger earthquake was only 0.5 below. Using the same method as described above, we find the b value for the Gorkha aftershock sequence to be 1.08. For the Kashmir 2005 earthquake, the largest aftershock was 1.2 below the mainshock.

**Text S1.4. Finding the Maximum Earthquake**

*Instrumental earthquakes*

If we use the NSC catalog, by simply extending the line using the b value found to the line that takes up the maximum moment, we find the results would be very high (\( M_{w} 10.4 \)) as we’re missing aftershocks. If we add aftershocks it becomes \( M_{w} 9.8 \). There are large uncertainties on this because of the large uncertainties in the number of aftershocks and b value uncertainties have the largest effect for extending smallest earthquakes. The answer gives us a magnitude of between 8.5 and 10.5 with 60% probability.
We can do the same for the NEIC catalog, which gives a magnitude 9.1 without aftershocks and 9 with. The aftershocks here have less of an affect here because the earthquakes are larger, so there will be fewer added earthquakes of this size.

**Larger earthquakes**

We then look at four points – the average recurrence times seen of magnitudes 7.5, 8, 8.5 and 9, which is discussed in the data section. We use Monte Carlo analysis using $b = 1.1 \pm 0.1$, Baths Law = $1.2 \pm 0.2$, the earthquake recurrence time data in Table 2 and a seismic moment buildup rate of $15.1 \pm 1 \times 10^{19}$ Nm/yr. We run 40 million simulations to get a probability density function (pdf) of the probable maximum earthquake, and its recurrence time, predicted by each point (shown in Figure S1).

**Text S1.5. Afterslip**

Afterslip is a large unknown in the model. Aside from the Gorkha 2015 and Kashmir 2005 earthquakes (afterslip respectively ~10 % and ~56% as mentioned in the main text), we see that for other large earthquakes, afterslip has varied between 10% and up to 70%. For the Chile $M_w$8.8 earthquake in 2010, 20-30% of the moment was released as afterslip [Lin et al., 2013]. In Sumatra $M_w$9.1 earthquake, about 30% was released as afterslip (Chlieh et al. 2008). However in the Chichi $M_w$7.6 earthquake, only 13% was released postseismically [Hsu et al., 2006]. For the Tohoku-Oki earthquake, about 20% of the moment was released as afterslip [Yamagiwa et al., 2010]. For the seismogenic portion of the Central Peru megathrust, 50-70% of the moment may be released aseismically [Perfettini et al., 2010].

If we assume no afterslip at all, we get a maximum magnitude of roughly 9.5 (grey line in Figure S2).

**Text S2. METHOD 2**

For the second method we relax the assumption of the GR distribution. We use the observation of one $M_w$8.7 and possibly one $M_w$9.0 in the past 500 and 1000 years respectively, along with the assumption that independent earthquakes follow a Poisson distribution. The probability of observing $k$ event over a time $\tau$ given the seismicity rate $\lambda$ is:

$$ P_1 = \frac{e^{-\lambda \tau} \lambda^{k} \tau^{k}}{k!}, \quad (8) $$

where $\lambda =$ occurrence rate, $\tau =$ time window considered, $k =$ number of occurrences.

Knowing that we have seen one $M_w$8.7 in 500 years, and one $M_w$>9.0 in 1000 years, we can work out the probability of not observing a possible larger magnitude event with a given return period $(1/\lambda)$.

We then find the probability that these different sizes of earthquakes and recurrence times would take up the moment needed ($P_2$).

We then multiply these two probabilities together to find the probability that the earthquake occurs and that all earthquakes combined (including this largest event with its specific magnitude and return time, and all smaller earthquakes) balance the interseismic moment deficit.
For example, $P_1$ for one $M_{w}8.5$ event in 500 years is close to 1, and $P_1$ for four $M_{w}8.5$ events in 500 years is only about 7%. $P_2$ for the first event is almost zero, whilst $P_2$ for the second event is 95%. This leads to their final probabilities both being low (almost zero in the former case and roughly 7% in the latter case).

We also test alternative assumptions.

As well as assuming here that the maximum earthquake is the largest in a catalog of earthquakes, we also show the end member where the largest earthquake is the only earthquake. With the former assumption, two-thirds of the moment is taken up in the largest earthquake, and one-third in all the other earthquakes. As expected, having no other earthquakes decreases the chance that a certain magnitude can take up all the moment (purple line in Figure S3).

We also test the method assuming zero afterslip (green line), and assuming we have 50% less seismic moment build-up on the MHT (due to distributed deformation) as well as 50% afterslip (also shown in Figure S4). Distributed deformation could occur if faults or folds north of the MFT took up some of the slip. 50% is an upper bound, we expect only up to 10% of the deformation to be distributed (Stevens and Avouac 2015).

Figure S1. All data sets used separately to predict the maximum moment.
Figure S2. Data sets combined. Grey line shows the case with zero afterslip.
**Figure S3.** The red line shows 50% afterslip and this is used in the main text. The green line assumes zero afterslip. The purple line shows the probabilities if we assume the largest earthquake releases all the moment, with 50% afterslip. The blue line shows 50% afterslip and a 50% decrease in moment build-up due to distributed deformation.

**Figure S4.** Same as Figure 3 in the main text, but now assuming anelastic shortening of the Himalayan wedge takes up all the shortening across the Himalaya. The underlying MHT is still assumed seismic but long-term slip rate tapers linearly to zero at the surface. The rate of seismic moment build-up is halved.
Figure S5. Seismic moment released from major earthquakes along the Himalayan Front compared to moment accumulation since 1000 AD. Blue lines show moment build-up calculated from the coupling model of Stevens and Avouac (2015). The solid line shows the mean, the two dashed lines show the one-sigma errors. The dotted line shows the mean reduced by 50% - used in most of the calculations. The black lines show moment release. The solid line shows the preferred model, whilst the dashed lines show the highest and lowest reasonable magnitudes for past earthquakes.
Table S1. Earthquakes above magnitude 7.5 for the past 1000 years from paleoseismic, historical and instrumental catalogs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>&gt;8.5</td>
<td>Eastern Himalaya</td>
<td>(2, 4)</td>
</tr>
<tr>
<td>1255</td>
<td>8-8.5</td>
<td>Nepal</td>
<td>(35)</td>
</tr>
<tr>
<td>1344</td>
<td>&gt;8.0</td>
<td>Nepal</td>
<td>(28)</td>
</tr>
<tr>
<td>1400</td>
<td>&gt;8.5</td>
<td>Western Himalaya</td>
<td>(3)</td>
</tr>
<tr>
<td>1505</td>
<td>8-8.5</td>
<td>Western Nepal</td>
<td>(34)</td>
</tr>
<tr>
<td>1555</td>
<td>7.6</td>
<td>Kashmir</td>
<td>(34)</td>
</tr>
<tr>
<td>1720</td>
<td>7.5</td>
<td>N Uttar-Pradesh</td>
<td>(34)</td>
</tr>
<tr>
<td>1803</td>
<td>7.5</td>
<td>Garwhal</td>
<td>(34)</td>
</tr>
<tr>
<td>1806</td>
<td>7.7</td>
<td>Samye</td>
<td>(34)</td>
</tr>
<tr>
<td>1833</td>
<td>7.7</td>
<td>Nepal</td>
<td>(34)</td>
</tr>
<tr>
<td>1905</td>
<td>7.7</td>
<td>Kangra</td>
<td>(34)</td>
</tr>
<tr>
<td>1934</td>
<td>8.4</td>
<td>Bihar-Nepal</td>
<td>(1, 37)</td>
</tr>
<tr>
<td>1950</td>
<td>8.7</td>
<td>Assam</td>
<td>(1, 37)</td>
</tr>
<tr>
<td>2005</td>
<td>7.6</td>
<td>Kashmir</td>
<td>(40)</td>
</tr>
<tr>
<td>2015</td>
<td>7.8</td>
<td>Gorkha-Nepal</td>
<td>(24)</td>
</tr>
</tbody>
</table>

Table S2. Proposed rate of large earthquakes estimated based on the data of Table S1. Range of number of earthquakes at the 1-\(\sigma\) confidence level. For magnitude 7.5, we use the past 200 years of data, and scale up to 1000 years.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Number per 1000 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;=9</td>
<td>0-2</td>
</tr>
<tr>
<td>&gt;=8.5</td>
<td>3-4</td>
</tr>
<tr>
<td>&gt;=8</td>
<td>6-9</td>
</tr>
<tr>
<td>&gt;=7.5</td>
<td>33-50</td>
</tr>
</tbody>
</table>