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EDITORIAL

Himalayan Seismic Belt, Seismic Gaps and Related Issues

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INTRODUCTION

The Himalayan Mountain belt running some 2500 km is seismically one of the most active continental regions. The largest recorded continental earthquake of Mw 8.7 occurred on 15 August 1950 in Assam, close to India China border. The period 1897 to 1952 had been seismically very productive with 5 M~8 earthquakes occurring in the region including the 1897 Shillong, 1905 Kangra, 1934 Bihar-Nepal, 1950 Assam and an aftershock of the Assam earthquake in 1952. No M 8 earthquake has occurred in the region since 1952. In the present article, the proposed 'seismic gaps', the return periods of large to great earthquakes as inferred from paleoseismological investigations, the precursory swarm and quiescence observed preceding the 1988 Mw 7 ½ earthquake in the Assam-Arakan Yoma seismic belt, and what is the need of the hour is briefly presented.

SEISMIC GAPS

The concept of plate tectonics and elastic rebound theory gave birth to seismic gap hypothesis (Fedotov, 1965; Sykes, 1971). It can be defined as: *"The energy for large and great earthquakes along plate boundaries is accumulated by plate motions, from low to maximum levels. This process takes decades to centuries to load a plate boundary. Great earthquakes are more likely in "loaded" segments called "seismic gaps", than in segment recently unloaded by great ruptures. Seismic gaps are likely to rupture in one or a small number of large, gap-filling earthquakes"* (Wyss and Wiemer, 1999). One of the earliest and clearest applications of the seismic gap theory to earthquake forecasting was by McCann et al. (1979), who postulated zones of high, medium, and low seismic potential around the Pacific rim. Kagan and Jackson (1991) reported that in the following 10 years, after the publication of McCann et al. (1979) paper where they had postulated zones of high, medium, and low seismic vulnerability, over 40 major earthquakes of M ≥ 7 occurred, and the McCann et al.'s forecast did not fructify. Kagan and Jackson (1991) also analyzed the forecast of Kelleher et al. (1973) and did not find it useful. They concluded that the increased earthquake potential hypothesis following a long quiet period does not hold good, rather the locales of recent earthquake activity possess higher seismic hazard. They further opined that "clustering" of earthquake times is not in contradiction with the plate tectonics hypothesis as it addresses long-term average slip rates and does not regulate the occurrence of earthquakes.

This concept has been applied to Himalayan region where the great earthquakes occurred before the deployment of modern instrumentation. Inadequate instrumentation does not permit to have accurate information about the rupture extent. Khattri and Wyss (1978) and Khattri (1987), analyzed space-time distribution of earthquakes in the vicinity of the Himalayan plate boundary and identified three seismic gaps. Quoting Khattri (1987*): "(1) The "Kashmir gap" lying west of 1905 Kangra earthquake; (2) The "Central gap" situated between 1905 Kangra and the 1934 Bihar earthquakes; and (3) The "Assam gap" between the 1897 and 1950 Assam earthquakes."* Bilham et al. (2001) also applied the concept of seismic gaps in the Himalayan region and concluded that the Kashmir, Central and the Assam gaps have accumulated strains to be released in future great earthquakes, they could host at least one, three and two great earthquakes respectively. Gupta and Gahalaut (2014, 2015) reviewed all the available evidence and concluded that an M~ 8 earthquake could occur anytime anywhere in the Himalayan region. There is no indication as of now as where and when it would occur. They underlined the importance of being prepared and developing earthquake resilient society.

PALEOSEISMOLOGICAL INVESTIGATIONS

In the past few decades several paleo-seismological investigations have been undertaken in key seismically active sectors of the Himalayan earthquake belt (for example Jayangondaperumal et al, 2017 and 2018). Starting from the north-east, one of the earliest studies was by Sukhija et al. (1999) where they provided evidence of periodicity of large prehistoric earthquakes in Shillong Plateau that had hosted the devastating 1897 Shillong earthquake of M 8.7. They investigated well-preserved paleo-liquefaction and deformed depositional features around the same time at 10 well located sites along two north flowing tributaries of Brahmaputra River. ^{14}C dating was used. In addition to finding features and ^{14}C dates for the 1897 event, they also discovered three other similar events during 1450-1650, 700-1050 AD and the third event going back to 600 AD. From these paleo-seismological investigations they suggested a return period of 400 to 600 years for the 1897 like events. This was one of the first study of its kind in the Himalayan seismic belt. However, it may be mentioned that the 1897 Shillong earthquake does not strictly belong to the Himalayan seismic belt. Work of Coudurier-Curveur et al. (2020) and Singh et al. (2021) have inferred a recurrent interval of 1800 year for the 1950 Assam earthquake.

Moving west-ward from Shillong, a very interesting paleo-seismological investigation result has been reported by Le Roux-Mallouf et al. (2020) where they present a paleoseismic record for 2600 years from the Himalayan Main Frontal Thrust in western Bhutan. They observe that paleoseismological studies along the Main Frontal Thrust (MFT) between Wang Chu and Ramphu Chu rivers provides an excellent window to the chronology and deposition phases going back to ~2600 years. Using retro-deformation analysis

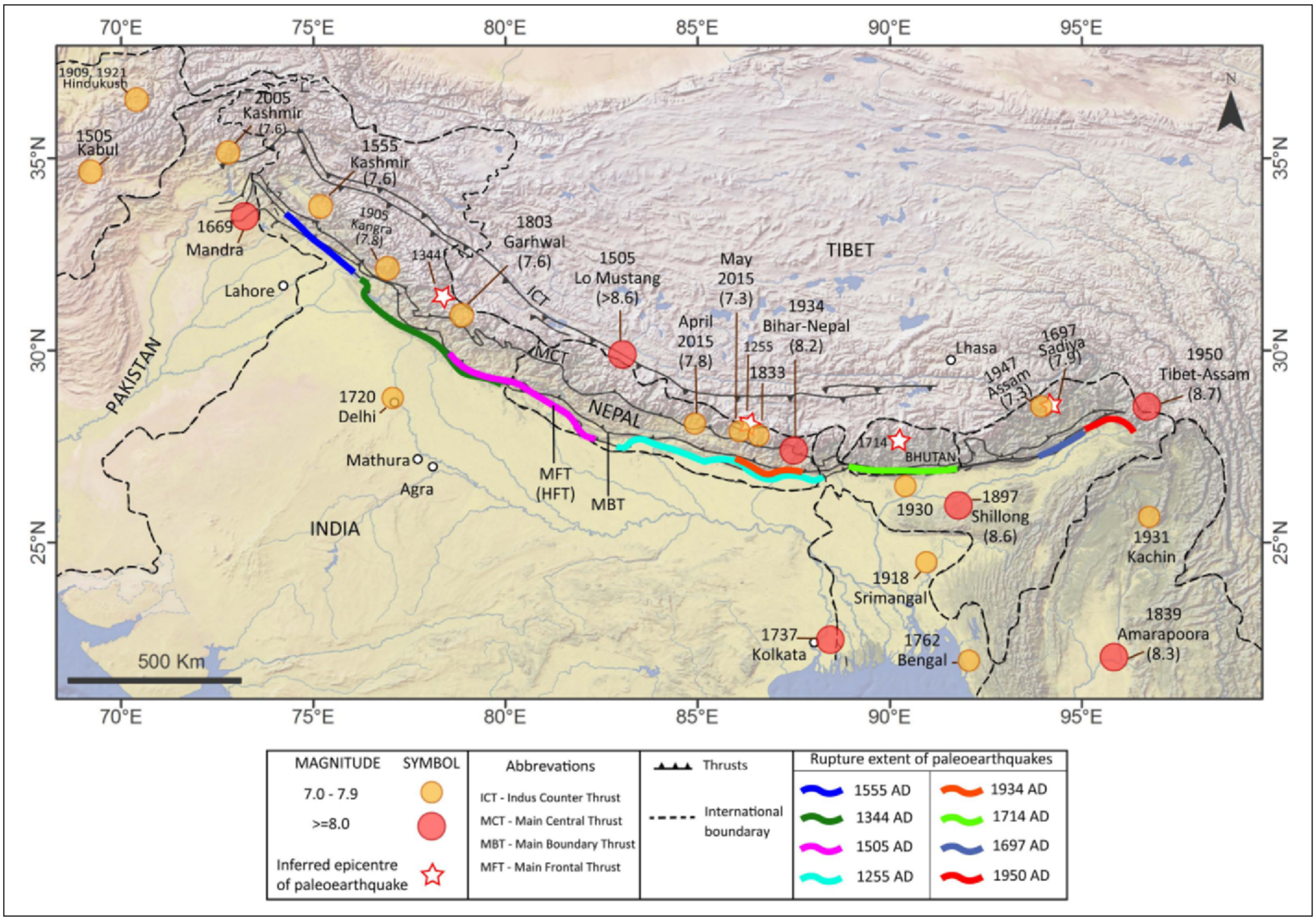

Fig. 1. Depiction of the instrumentally located earthquakes of M 7 and larger, paleo-seismologically inferred earthquake epicenters for the 1255, 1344, 1697 and 1714 earthquakes, as well as rupture extent for 8 earthquakes inferred from paleo-seismological investigations in the Himalayan region. Instrumentally located earthquakes of M 7.0 and larger in the Himalayan region (after Jayangondaperumal et al., 2017 and 2018). (Thanks to Dr. R. Jayangondaperumal of the Wadia Institute of Himalayan Geology, Dehradun, India for preparing this diagram and permitting me to use it).

and chronostratigraphic model, Le Roux-Mallouf et al. (2020) discovered 5 surface rupturing earthquakes during the period 485±125 BCE and 1714 CE. An average recurrence interval of 550±221 years. However, when they considered the events with large coseismic slip, the recurrence interval worked out to be 610±238 years. Another important inference is that the estimated slip rate of 24.9 ± 10.4 mm/year inferred by Le Roux-Mallouf et al. (2020) is consistent with geodetic measurements as reported by Marechal et al. (2016).

Further west from Sikkim, several earthquakes have hit Nepal and the nearby territory. The Mw 7.8 Gorkha earthquake of 25 April 2015 with a magnitude of Mw 7.8, which claimed ~ 9,000 human lives rekindled interest in seismicity and recurrence intervals of major to great earthquakes in the region. In an interesting paper, Bollinger et al. (2016) have observed that major earthquakes hit Nepal in 1255, 1344 and 1408 AD and then in 1883, 1934 and 2015. It may be noted that there is a gap of 475 years between the 1408 and 1883 earthquakes. These inferences are based on reports in the gazettes, old scriptures and paleoseismological studies. They have also estimated the accumulated moment deficit in the region and infer that the current situation in the vicinity of Nepal is like the fourteenth century and a major to great earthquake is due for the region. Similar results are presented by Jayangondaperumal et al. (2018) and Daniels et al. (2023) for the western part of the Central seismic gap.

In the farthest west, in an interesting study, Vassallo et al. (2020) have reported recurrence of large earthquakes in Kashmir Himalaya. They have analyzed samples from two trenches located in Riasi area. The paleo-seismological investigations have provided information for 3500 years. The earliest rupture investigated by them dates to 1600 to 1000 BC and the youngest one occurred after 1470 AD. Vassallo et al. (2020) have inferred a recurrence interval of a M ~ 7 ½ earthquake to be 500 to 700 years. The last earthquake in this magnitude range occurred was in 1555 AD and hence they believe that a region is due for a repeat of an M 7 ½ magnitude earthquake.

The above paleoseismological studies spanning from north-east to north-west of the Himalayan earthquake belt indicate that the minimum recurrence interval in the northeast is 400 to 600 years for an M~ 8 earthquake; moving west in the vicinity of Bhutan Himalaya the recurrence interval is inferred to be 550 ± 221 to 610 ± 238 years for an M~ 8 ½ earthquake; moving further west in the Nepal region the recurrence interval is estimated to be ~ 400 years for an M ~ 8 earthquake; while farthest west in the Kashmir Himalaya the recurrence interval is estimated to be 500 to 700 years for an M ~ 7.5 earthquake. These are a few sample paleoseismological studies, there are many more which are not referred to. The moot point is that the paleo-seismological investigations carried out along the Himalayan seismic belt indicate a recurrence interval of 400 to 750 years for M 7 ½ and larger magnitude earthquakes. The Kashmir Himalaya has the oldest M 7 ½ earthquake of 1555, and no other earthquake of that magnitude has occurred since then. This may indicate that the Kashmir region is one of the most vulnerable regions in the Himalayan earthquake belt for a future ~ 7 ½ M earthquake.

PRECURSORY SWARM AND QUIESCENCE

It is appropriate at this stage to mention about the study of precursory swarm and quiescence before earthquakes. Way back, Evison (1977), while studying earthquake sequences in New Zealand and California found that strong to great earthquakes were preceded by precursory swarms and quiescence. Through a systematic study, relations were developed among the time interval between the onset of a swarm and the time of the main shock, and the largest magnitude of the swarm events. The magnitude of the main event was found to be related with the time interval between the beginning of the swarm and the occurrence of the main shock as well as the magnitude of the largest event in the swarm. Gupta and Singh (1986) noted that during the period 1897 through 1950, in the northeast India region bounded by latitudes 20 and 30 N; longitudes 87 and 100 E, ten earthquakes of $M \geq 7\frac{1}{2}$ had occurred. Seven among these were preceded by well-developed swarms and quiescence. The main shock magnitude (M_m) was found to be related the largest event in the swarm (mp) and the time interval in days, T_p. The following regression relations were developed:

$$M_m = 1.37\, mp - 1.41 \quad \text{and}$$

$$M_m = 3 \log_{10} T_p - 3.27$$

Gupta and Singh pointed out that the most important issue is to recognize a swarm in real time and then try to make a forecast of the main shock to follow. They recognized one such region in the northeast India, and concluded:

1. Moderate magnitude to great earthquakes in the north-east India region are found to be preceded, generally, by well-defined earthquake swarms and quiescence periods.

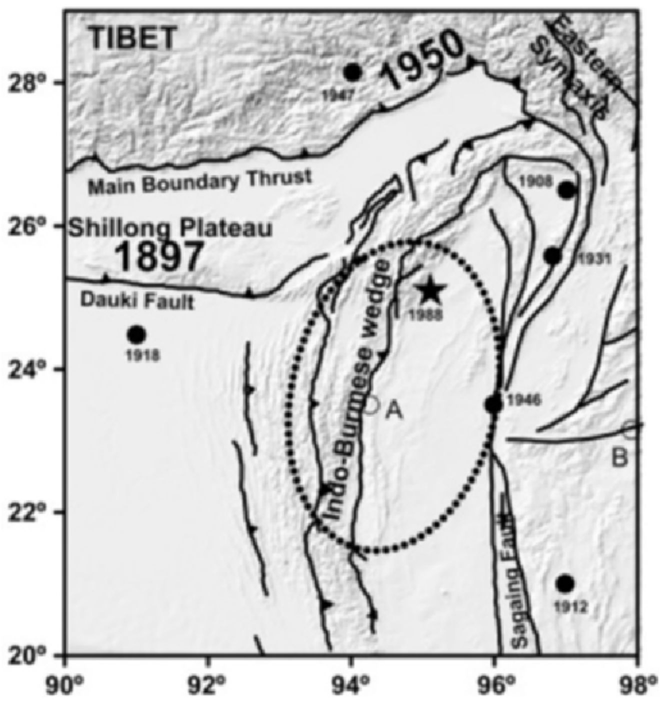

Fig.2. Earthquakes of M ≥ 7.5 in the north-east India region since 1897 (filled circles). Elliptical area shows the preparation zone for an M=8±0.5 earthquake identified by Gupta and Singh (1986). After the last M 7 ½ earthquake of August 17, 1952 the first largest earthquake of M 7 ½ in the entire region occurred on 6 August 1988, shown by the star. This was followed by two more earthquakes of M 7.3 on November 6, 1988 (A) and January 5, 1991 (B) (after Gupta and Singh, 1986)

Table 1. Forecast of August 6, 1988, Earthquake

Earthquake Parameters	Prediction [Gupta and Singh, 1986]	Occurrence NEIS (Preliminary Determination)
Epicenter	21°N-25.5° N 93°E-96°E	25.116°N 95.171°E
Magnitude (M)	8 ± ½	7 ½
Depth	100 ± 40 km	115 km
Time	February 1986-December 1990	August 6, 1988 (00:36:26.9 G.C.T.)

2. On the basis of an earthquake swarm and quiescence period, an area bound by 21° N and 25.5° N latitude and 93° E and 96° E longitude is identified to be the site of a possible future earthquake of M 8 ± ½ with a focal depth of 100 ± 40km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as a false alarm.

Occurrence of 6 August 1988 event made this forecast come true (Table 1).

As can be noted in Table 1, the 6 August 1988 earthquake occurred within the forecasted parameters. Figure 2 depicts the earthquakes of M ≥ 7½ in the northeast India region studied by Gupta and Singh (1986, 1989), elliptical area indicates the preparation zone for the M = 8 ± 0.5 forecasted earthquake and the star is the location of the 6 August 1986 M 7 ½ earthquake. They have pointed out several short comings of their work. However, success of this forecast encourages to take up similar studies in the other parts of the Himalayan earthquake belt.

CONCLUDING REMARKS

In the foregoing, the *seismic gap hypotheses* and its application in the Himalayan region has been examined. It appears that due to very limited information available about the past earthquakes, it is difficult to use this approach for finding more likely sites for the occurrence of major or great earthquake in the near future. In the recent years, several trenches have been dug to carry out paleoseismological studies, and results are available for the most sectors of the Himalayan earthquake belt. The recurrence interval for major and great earthquakes appears to vary from 400 years to 800 years. The Kashmir region is the one where no major earthquake has occurred since 1555. There is a line of thinking, because of this observation, to consider the Kashmir Himalaya to be more vulnerable than the other segments of the Himalayan earthquake belt. The case of a successful medium term forecast in the north-east Himalayan region is presented. It is desirable to carry out similar studies in the other sections of the Himalayan earthquake belt. Finally, a case is made to develop an earthquake resilient society in the vicinity of the Himalayan earthquake belt (Gupta et al., 2020). The 2005 Muzaffarabad earthquake that occurred in the vicinity of India and Pakistan of M 7.6 claimed ~ 87,000 human lives. This situation does need attention, so the future major and great earthquakes do not cause such huge loss of lives.

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