Time clustering of earthquakes in the Sumatra–Andaman and Himalayan regions

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Increased frequency of earthquakes in the Sumatra–Andaman region in the past 10 years reflects time clustering of earthquakes and does not necessarily imply low recurrence interval of earthquake in the region. Time clustering of earthquakes can occur either due to the stress change (either through static or dynamic stress transfer) caused by the occurrence of a great earthquake in the region, or it could just be a chance in which earthquake occurrence is almost simultaneous in two or more segments, despite differences in the earthquake cycle due to difference in the phase of strain accumulation, rheology, plate convergence rate, etc. in these segments. We note that the Himalaya and the adjoining regions too showed earthquake time clustering during 1897–1950.

Keywords: Earthquake, stress, Sumatra–Andaman region, time cluster.

TIME clustering of earthquakes in a region can be defined as the increased frequency in a narrow time window (say a few years) against the general low frequency over a longer time window, spanning a few decades to centuries. Some of these earthquakes might have been triggered by the occurrence of a great or major earthquake in the neighbouring segment, either by the transfer of coseismic dynamic or static stress or by the post-seismic relaxation of the stresses[1–8]. In case of dynamic triggering, earthquakes can be triggered even in the far-field regions by the passage of seismic waves through the earthquake causative fault region. However, since the stress change in this case is only temporary, triggered earthquake should occur immediately after the triggering earthquake and during the passage of the seismic waves through the region. In the case of static (purely elastic effect) and post-seismic (including the poroelastic and viscoelastic effect) stress triggering, there could be some delay of the order of few days to few years to decades, in triggering the subsequent earthquake(s). In this case the two regions, i.e. the region of triggering and triggered earthquakes, should not be very far from each other. We agree that some of the earthquakes in the earthquake-prone regions might occur due to the above processes[9,10], however, in some cases, the distance between two consecutive earthquakes is too long to suggest stress interaction amongst the earthquakes. Sometimes, it has been referred as 'long-range interaction'[11], purely on the basis of statistical analysis without giving any definite mechanism. In such cases, time clustering of earthquakes could just be a chance and hence it could be just a coincidental occurrence. We elaborate it further. Each region can be divided into several blocks depending upon the size of the considered earthquake. Each block may have some slight difference in the rheology, rate of strain accumulation, etc., which may cause them to be in different phase of earthquake deformation cycle and strain accumulation. The phase of strain accumulation may also be affected by the stress transfer from the earthquakes in the nearby segment. Thus, this will cause a randomness in the time of occurrence of earthquakes in each block, though they could be periodic or at least quasi-periodic in the individual block. However, during several earthquake cycles over a period of time, there could be some epochs when several or few earthquakes will occur in all or in majority of the blocks, in a narrow time window, causing time clustering of earthquakes. This could purely be a chance and may not have a physical connection amongst each other. In all the above cases, it is not necessary that the triggering and triggered earthquakes should have similar focal depths or similar nature of faulting. For example, the earthquakes in the frontal arc of an oblique subduction zone, which generally occur through reverse faulting, may stress trigger earthquakes in the outer rise with normal faulting and earthquakes in the back arc with strike-slip faulting. The focal depths may also be different, particularly when the time clustering is not due to the stress transfer.

Many regions, which have produced large earthquakes, have exhibited time clustering of earthquakes, e.g. California, Mongolia, Mexico[12–14]. Here we show that the Sumatra–Andaman region (which includes the frontal and back arc) in the Sunda arc and the Himalayan and adjoining regions too exhibit time clustering.

The Sumatra–Andaman trench is the part of the long convergent boundary that extends from the Eastern Himalaya Syntaxis in the northwest to Java in the southeast[15]. Along this convergent plate margin, the Indo-Australian plate obliquely subducts under the Sunda plate. The oblique motion between the Indo-Australia and Sunda plates is accommodated through a predominantly thrust motion in the Sumatra–Andaman frontal arc region and through predominantly strike-slip and normal motion in the Andaman Sea ridge-transform fault system in the north and through strike-slip motion along the Sumatra fault system in the south, both located in the back arc region[16,17]. This region has produced one of the deadliest earthquakes of the world on 26 December 2004 (Mw 9.2) which is best known for its devastating tsunami[18]. Since then the sequence of large and great earthquakes has not stopped and this region has produced on an average at least one major or great earthquake in a year. Earthquakes since 1900 along the Sumatra–Andaman subduction zone

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with $Mw \geq 7.5$ have been plotted in Figure 1 which are taken from various earthquake catalogues such as International Seismological Centre, United States Geological Survey, Incorporated Research Institutions for Seismology, European Mediterranean Seismological Centre, and Centroid Moment Tensor, and are also listed in Table 1. Magnitudes of the earthquakes in the catalogue before 1800 in this region are not reliable and hence not considered here. Their temporal variation (Figure 2) shows that the frequency of earthquakes is very low during the period between 1900 and 2000 which increased tremendously in the past 10 years. Specifically, only eight earthquakes of $Mw > 7.5$ occurred during the previous century, whereas 10 such earthquakes occurred in the past 10 years (from 2000 to 2010), indicating the time clustering

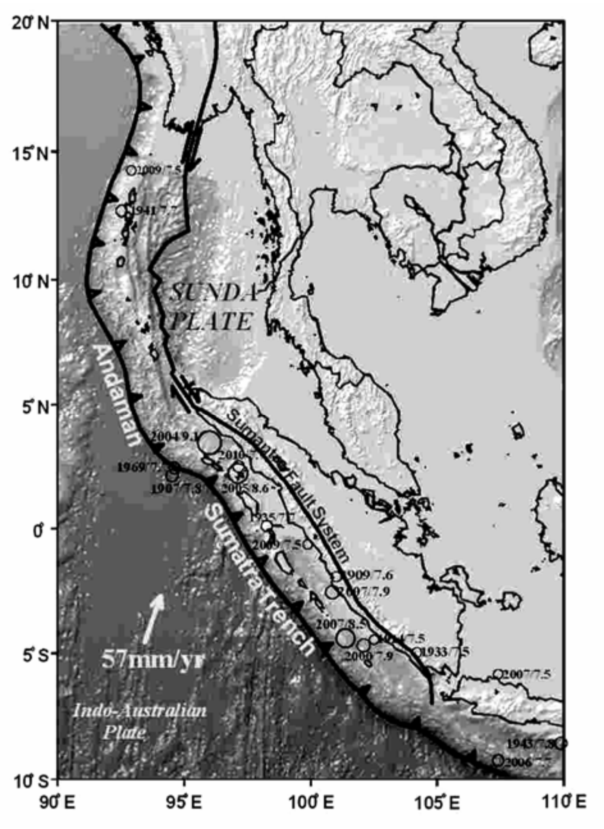

Figure 1. Great and major earthquakes in the Sumatra–Andaman region since 1900. The velocity of Indian–Australian plate is about 57 mm/yr (ref. 21). The year of occurrence and magnitude of the earthquakes are also given.

Table 1. Great and major earthquakes in the Sumatra–Andaman region in the past 100 years

Year/month/day	Latitude	Longitude	Magnitude
1907/01/04	2	94.5	7.8
1909/06/03	–2	101	7.6
1914/06/25	–4.5	102.5	7.5
1933/06/24	–5	104.2	7.5
1935/12/28	0	98.25	7.7
1941/06/26	12.5	92.5	7.7
1943/07/23	–8.6	109.9	7.8
1969/11/21	2.3	94.6	7.7
2000/06/04	–4.72	102.09	7.9
2004/12/26	3.3	95.98	9.1
2005/03/28	2.09	97.11	8.6
2006/07/17	–9.28	107.42	7.7
2007/08/08	–5.86	107.42	7.5
2007/09/12	–4.44	101.37	8.5
2007/09/12	–2.62	100.84	7.9
2009/08/10	14.1	92.89	7.5
2009/09/30	–0.72	99.87	7.5
2010/04/07	2.36	97.132	7.7

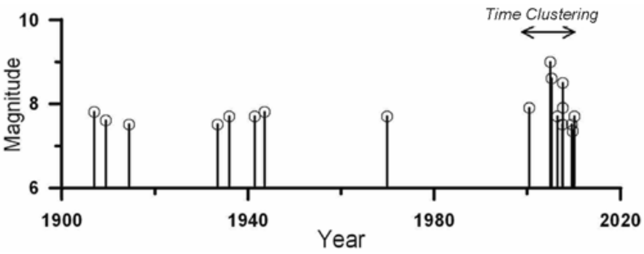

Figure 2. Temporal variation in the occurrence of great and major earthquakes in the Sumatra–Andaman region since 1900.

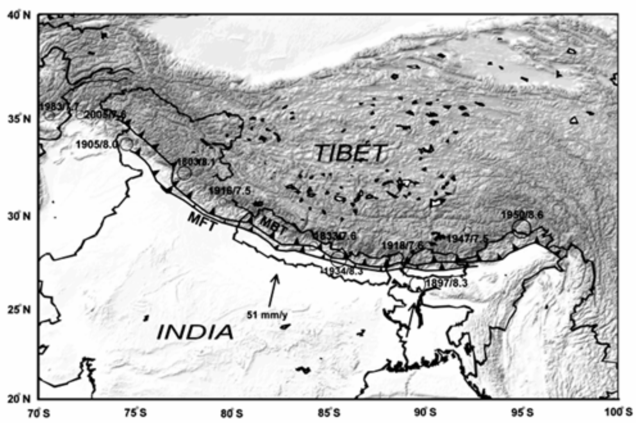

Figure 3. Great and major earthquakes in the Himalaya and the adjoining regions since 1800. The year of occurrence and magnitude of the earthquakes are also given. The velocity of the Indian–Australian plate is about 57 mm/yr (ref. 22).

Table 2. Great and major earthquakes in the Himalayan region in the past 200 years

Year/month/day	Latitude	Longitude	Magnitude
1803/09/01	31.5	79	8.1
1833/08/26	27.7	85.7	7.6
1897/06/12	25.7	91.1	8.3
1905/04/04	33	76	8
1916/08/28	30	81	7.5
1918/07/08	26.5	90.4	7.6
1934/01/15	27	87	8.3
1947/07/29	28.5	93.7	7.5
1950/08/15	28.6	96.5	8.6
1983/12/30	34.5	72	7.7
2005/10/08	34.54	73.59	7.6

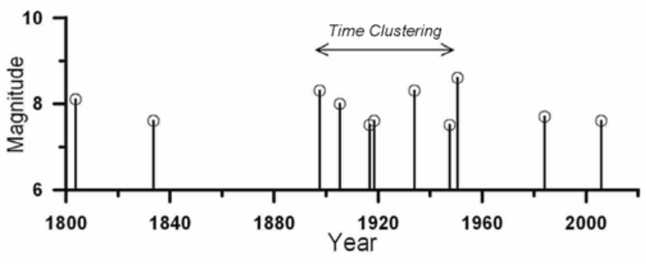

Figure 4. Temporal variation in the occurrence of great and major earthquakes in the Himalaya and adjoining regions since 1800.

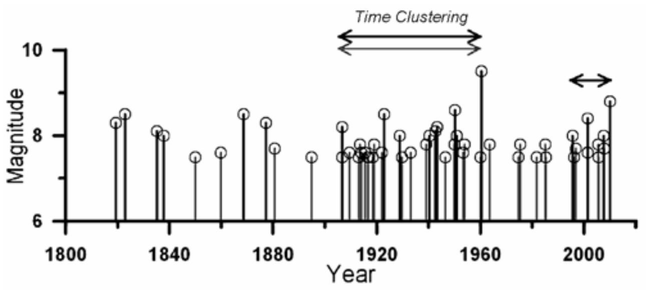

Figure 5. Temporal variation in the occurrence of great and major earthquakes in the Chile subduction zone since 1800. *Mw* > 8.0 are shown in black colour and *Mw* > 7.5 in grey colour.

of earthquakes in the later period. It does not imply that earthquakes are really so frequent here or their recurrence interval is very low. In fact recurrence interval of the 2004 Sumatra–Andaman type of earthquakes could be as high as several hundred years[19] or even thousands of years[20].

Similar time clustering can be seen in the earthquakes in the Himalayan and the adjoining regions. We considered the earthquakes of *Mw* > 7.5 shown in Figure 3 in the Himalayan and the adjoining regions from 1800 to the present from various earthquake catalogues mentioned here (Table 2). In Figure 4, clustering of earthquakes can be seen during the period between 1897 and 1950. Nearly seven great and large earthquakes occurred in about 50 years (during the period from 1897 to 1950), whereas only two earthquakes occurred in the preceding 100 years between 1800 and 1897 and only two earthquakes in the following 50 years from 1950 to the present. Since these earthquakes occurred in distinct and far off segments along the Himalayan convergent plate margin, and stress interaction may not be possible at such large distances, we suggest that the time clustering of the earthquakes during 1897–1950 in this region could just be a chance.

We acknowledge here that though the period of reliable catalogue of earthquakes in both the regions is relatively short (i.e. from 1960s onwards), the two regions exhibit time clustering of earthquakes. In the Sumatra–Andaman region, time clustering could also be due to stress interaction, e.g. the 2004 great Sumatra–Andaman earthquake triggered the 2005 Nias earthquake[21,22] through viscoelastic stress relaxation[23]. The 2004 Sumatra–Andaman earthquake may not be responsible for stress triggering all the other major and great earthquakes in the region, as some of the earthquakes occurred at distances as far as 700–800 km from the 2004 Sumatra–Andaman earthquake (e.g. the 2007 Bengkulu earthquake)[24] skipping the abutting region. In such cases, neither static (elastic or viscoelastic) nor dynamic stress triggering can explain the occurrence of the earthquake. Hence, the time clustering earthquake could just be a chance. This statement is further supported by analysing the earthquakes (*Mw* > 7.5) in the Chile subduction zone, wherein the clustering of earthquakes is observed before the 1960 giant earthquake (9.5) and no clustering can be seen in the period following the earthquake. Specifically, the Chile region exhibited time clustering during 1907 to 1963 (Figure 5). Here also, not all, but some of the earthquakes might have been triggered by the preceding earthquakes. Additionally, a clustering during 1995 to 2010 can also be seen in the region.

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Saluvankuppam coastal temple – excavation and application of soil micromorphology

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The 26 December 2004 tsunami exposed an inscription of the 10th century engraved on a rock boulder at Saluvankuppam, 6 km north of Mamallapuram. The inscription indicates the existence of a Subramanya temple. The temple and the mound around the granite inselberg were excavated by the Archaeological Survey of India, Chennai Circle. The excavation exposed the entire Subramanya temple complex constructed over a period of time (4th/5th CE to 12th/13th CE). The temple complex and the litho sections reveal phases of temple building activity. The cement and lime used for the temple complex contain fragments of shells. Soil micromorphology technique was applied to understand the type of textures and fabric in soil sediments, bricks, potsherds, well rims, bone fragments, etc., using a polarized microscope. Thin sections of the laterite bricks which formed the foundation indicate high content of hematite, magnetite, kaolinite patches and the porosity of the laterite brick varies from 5% to 10% only, whereas thin sections of potsherds indicate that the firing temperature was fairly low and that the pots were well fired. Geoarcheology study of this temple complex indicates that a number of naturally occurring raw materials have been used for constructing this temple that were locally available.

Keywords: Coastal temple, excavation, soil micromorphology.

THE 26 December 2004 tsunami caused a colossal damage towards loss of life and property along the east coast of Tamil Nadu. It was a catastrophic flood event but opened up new vistas of research for the geoarchaeologists. An inscription of the 10th century engraved on a rock boulder at Saluvankuppam, 6 km north of Mamallapuram (Figure 1) was exposed consequent to the tsunami. This donatives inscription mentioned the existence of a temple for Subramanya. The mound around the granite inselberg was excavated and the entire Subramanya

Figure 1. Study area.

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