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Earthquake forecast appears feasible at Koyna, India

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At the Koyna reservoir in western India, it is observed that earthquakes of magnitude (*M*) 4–5 are often preceded by well-defined clusters of foreshocks of $M \leq 3$, referred to as nucleation that is found to last typically for 100–400 h. Based on continuous monitoring of seismic activity, a nucleation pattern was identified and an earthquake of *M* 4+ was forecasted on 16 May 2006. An earthquake of *M* 4.2 did occur on 21 May 2006 within the forecasted parameters. The continued seismic activity in such an isolated and well-monitored site probably makes Koyna a suitable locale to pursue meaningful study of earthquake precursors.

Keywords: Earthquake, forecast, Koyna reservoir, precursors.

THE Koyna reservoir located close to the west coast of India is a classic example of reservoir triggered seismicity (RTS), where artificial water reservoir-triggered earthquakes have been occurring in a restricted area of 20 × 30 sq. km for the last 44 years. Since the impoundment of the Koyna reservoir 44 years ago and nearby Warna reservoir 21 years ago, 19 earthquakes of magnitude $M \geq 5$ and several thousand smaller triggered earthquakes have occurred in this region (Figure 1), making it the most significant site among about 100 sites of artificial water reservoir-triggered earthquakes, globally. The largest triggered earthquake of *M* 6.3 occurred here on 10 December 1967, and over the years several thousand smaller earthquakes have occurred[1–5]. The shallow (depth ≤ 10 km) seismic activity is confined to an area of 20 × 30 sq. km in the Koyna–Warna region (henceforth referred as the Koyna region), and there is no other seismic source within 50 km radius. Every year, following the rainy season, the reservoirs get filled and seismic activity increases. The main seismic activity is confined to the period from August to December. It is to be noted that out of 19 $M \geq 5$ earthquakes, 16 including the largest earthquake of 10 December 1967, occurred during this period[6]. Over the past 44 years, some 170 $M \geq 4$ earthquakes have occurred. However, there have been some years when no such earthquakes occurred. Earthquake sequences in Koyna region fall under Type 2 of Mogi's classification[7] of foreshock–aftershock pattern, implying that mainshocks are preceded by foreshocks and followed by aftershocks. In a series of articles[6,8,9], it has been shown that the rate of loading, highest water levels reached and duration of retention of high water levels in the reservoirs play an important role in the level of triggered earthquake activity at Koyna. $M \geq 5$ earthquakes occur when the previous maximum of reservoir water level is exceeded[6,10,11].

From among the known earthquake precursors, foreshocks are important and have a potential in forecasting earthquakes[12,13]. Ohnaka[14] has noted that immediate foreshock activity is a part of the nucleation process leading to mainshock dynamic rupture[14,15]. Rastogi and Mandal[15] observed that main shocks in the magnitude range of 4.3–5.4 were preceded by clearly defined nucleation of 50–110 h duration. Therefore, in this communication onset of seismic activity clustered in space and time before $M \geq 4.0$ earthquakes is considered to be the beginning of nucleation.

The seismic activity at Koyna has been monitored by a closely spaced network of seven modern, three-component seismic stations (Figure 1), four of them being broadband (CMG3ESP) and the remaining three short-period (L4-3D) seismometers, all equipped with REFTEK recorders and time synchronized through GPS. Typically, location of epicentres has an accuracy of ±500 m. Beginning from August 2005, data are being collected from each station every 24 h and analysed on a daily basis.

Around the middle of August 2005, it was seen that both at Koyna and Warna reservoirs the rate of loading was higher than in previous years, and levels higher than the previous maximum had been reached[16]. This implied that the Koyna region would have higher level of seismic activity than the previous years. In fact, activity during the period August through December 2005 has been much higher than previous years (Table 1).

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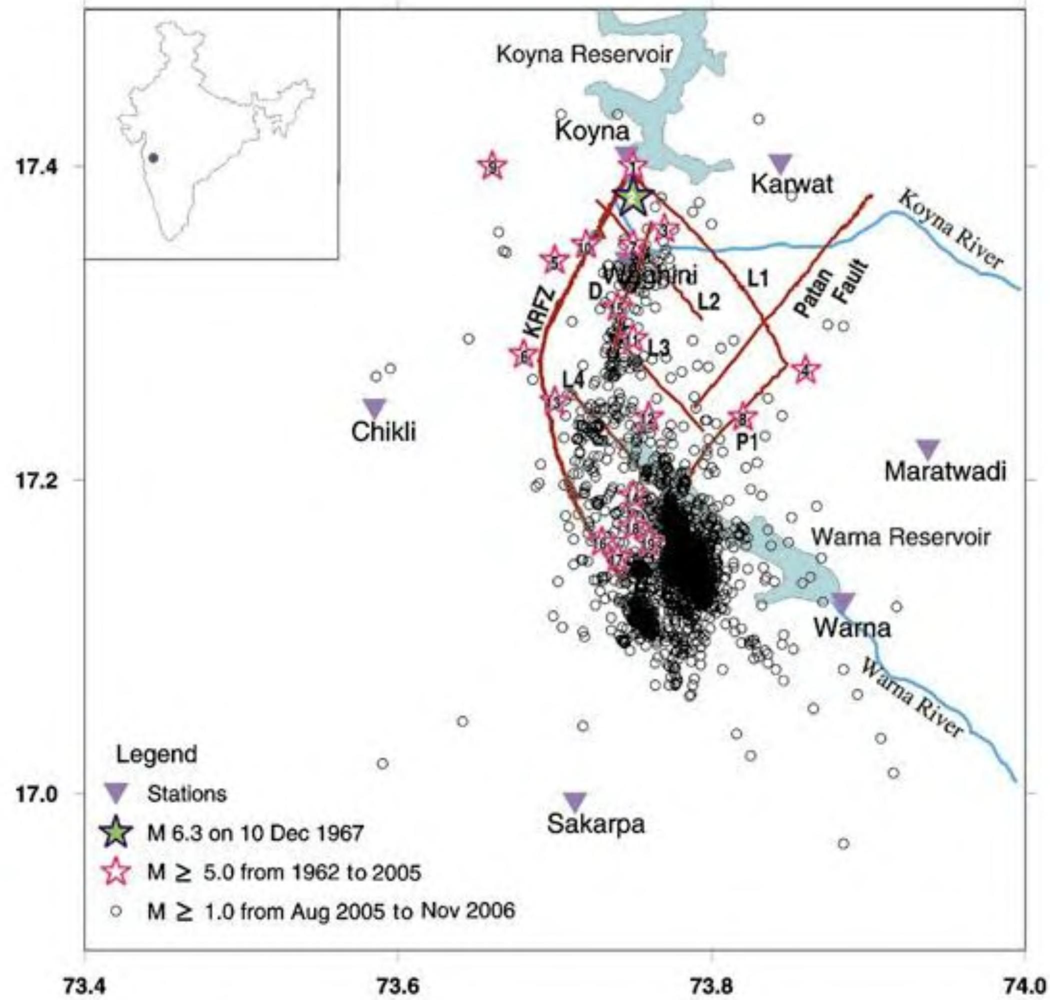

Figure 1. Earthquakes in Koyna–Warna region in western India. In the recent years, seismic activity has been higher in the vicinity of the Warna reservoir, where $M \geq 5$ earthquakes numbered 14, 16, 17, 18 and 19 occurred. Over the past one year, there has been a further SEE shift in seismic activity. The important faults and lineaments (thick lines) are KRFZ, Koyna River fault zone; D, Donichiwada Fault; P1, a NE–SW trending fault parallel to the Patan Fault. L1–L4, NW–SE trending fractures representing boundaries of crustal blocks.

Seismic activity preceding $M \geq 4$ earthquakes since August 2005 has been examined in detail. It has been found that earthquakes on 30 August 2005, 13 November 2005, 26 December 2005 and 17 April 2006 were preceded by well-defined nucleation. Space-time distribution of all the events with $M \geq 1$ that occurred in the Koyna region before the M 4.8 earthquake of 30 August 2005 was examined, and beginning of the nucleation could be identified about 110 h before the earthquake (Figure 2 *a*). During this period, eight events of M 2.0–2.9, and 13 events of M 1.0–1.9 occurred in an area of 10 km radius. The largest event was of M 2.9. During the 50 h preceding the beginning of nucleation, there were just two events. Similar pattern preceded the M 4.0 earthquake of 13 November 2005, (Figure 2 *b*), M 4.2 earthquake of 26 December 2005 (Figure 2 *c*) and the M 4.7 earthquake of 17 April 2006 (Figure 3, Table 2). Nucleation for all these earthquakes was well confined within a 10 km radius space and the largest event during the nucleation period was at least one order of magnitude smaller than the main earthquake. No well-defined nucleation was found before the M 4.2 earthquake of 14 August 2005. For the M 4.0 earthquake of 20 November 2005, it was difficult to decipher between the aftershocks of 13 November, M 4.0 earthquake and nucleation preceding the 20 November earthquake, the time interval being only 7 days (Table 1). The duration of nucleation preceding the $M \sim 4$ earthquakes during the period August–December 2005 was of the order of 110–160 h, whereas the 17 April 2006 earthquake was preceded by a nucleation lasting 380 h. The duration of nucleation does not appear to be magnitude-dependent as the M 4.8 earthquake of 30 August 2005 had a nucleation lasting only 110 h. May be earthquakes that occur following the filling up of the reservoir (August–December) have a

Table 1. $M \geq 4$ earthquakes in Koyna region during August–December 2001 through 2005 (left) and 1990 through 2006 (right)

Year	Earthquakes of $M \geq 4$ during August to December	
2001	Nil	
2002	Nil	
2003	Nil	
2004	16 December	4.0
2005	14 August	4.2
	30 August	4.8
	13 November	4.0
	20 November	4.0
	26 December	4.2

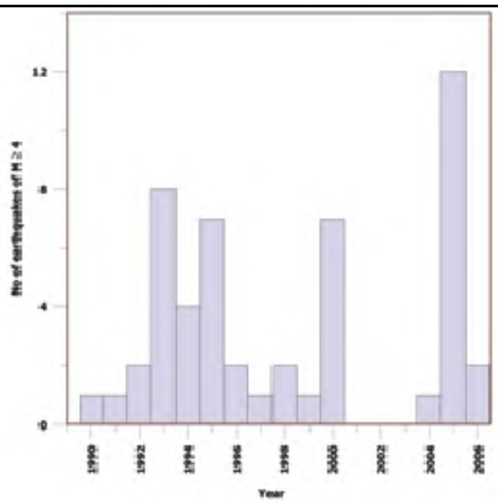

Table 2. Events preceding $M \geq 4$ earthquakes in Koyna region

Main earthquake	Duration of nucleation period (h)	Number of events before the main earthquake				
		M 1.0–1.9	M 2.0–2.9	M 3.0–3.9	Largest earthquake	50 h prior to beginning of nucleation period
30 August 2005 (M 4.8)	110	13	8	0	2.6	2
13 November 2005 (M 4.0)	160	18	8	1	3.0	3
26 December 2005 (M 4.2)	150	22	8	0	2.9	6
17 April 2006 (M 4.7)	380	40	10	0	2.7	2

shorter duration nucleation period compared to those that occur from January onwards, a few weeks after the reservoirs begin to be emptied. We also tried to see whether 'α' and 'β' phases as described by Talwani[17], occurred in the seismicity pattern preceding the main earthquake, but did not find it consistently. There is some indication that the volume of the nucleation zone has correspondence with the size of the mainshock. However, more data are required to establish the same.

An interesting situation arose during the middle of May 2006. Figure 4 *a* depicts the events in the Koyna region for the period 11–16 May 2006. By the afternoon of 16 May, 21 events of M 2.0–2.9 and 29 events of M 1.0–1.9 had occurred, the largest event being M 2.7, during the preceding 107 h in a small area. The focal depths ranged between 2 and 8 km. A nucleation was therefore inferred (Figure 4 *c*). During the 50 h preceding the beginning of nucleation, seismic activity was comparatively much lower. Based on the experience of observing nucleation preceding $M \sim 4$ earthquakes, particularly the 17 April 2006 earthquake, where nucleation had lasted for about 380 h, the following forecast was made on 16 May 2006 at 13:35 h UTC, and communicated to the Editor, *Current Science*, and the President, Geological Society of India: 'On the basis of the data available from seven seismic stations operating in the Koyna region, we have identified a nucleation which started on 12 May 2006. This may lead to the occurrence of an $M \sim 4$ earthquake in the next 15 days. This shallow earthquake (focal depth less than 8 km) will occur within a radius of 10 km centred at 17.1°N, 73.8°E. On the basis of our previous experience of studying nucleation preceding earthquakes in the Koyna region, we expect this earthquake to occur over the next 15 days time (till 31 May 2006), with a 50% probability'.

The clause of 50% probability was included as no nucleation could be identified preceding two out of five $M \geq 4$ earthquakes during August–December 2005.

An earthquake of M 4.2 occurred on 21 May 2006 at 20:29:01.2 UTC. The epicentre of this earthquake (17.171°N lat., 73.777°E long.) lay within 10 km of the forecasted epicentre, with a focal depth of 4.7 km[18,19]. Thus the forecast had come true (Figure 4 *b* and *c*). The 21 May 2006 earthquake had four events of M 2.4, 2.8, 2.0 and 2.8, occurring 8 h 20 min, 9 h 25 min, 13 h 21 min and 14 h 30 min before it. There was also a lack of $M \geq 1$ events between 25 and 38 h before the 21 May earthquake. Similar observations were made before the M 4.7 earthquake of 17 April 2006.

The success of forecasting the 21 May 2006 earthquake of M 4.2 gives hope to improve our understanding of triggered earthquakes in the Koyna region. It may be noted that Talwani[20] succeeded in making successful forecast of

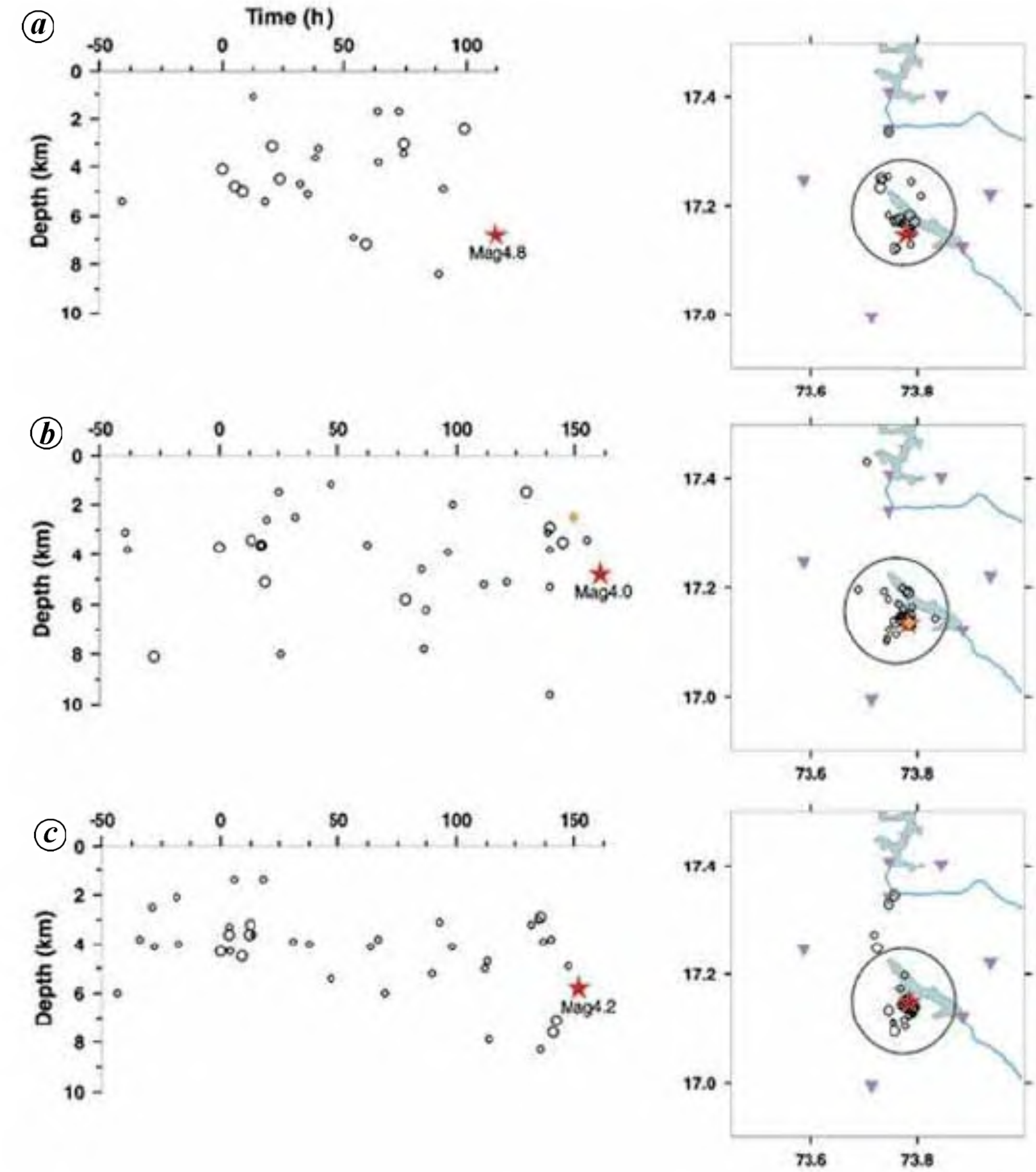

Figure 2. Seismic activity for the period 50 h before the start of nucleation till the occurrence of $M \geq 4$ earthquakes in Koyna region during August–December 2005. (Right) Foreshocks clustering before the mainshocks in a region of 10 km radius (right). (Left) Temporal distribution of events within the circle with depth. o, O, ♦ and ★ are events in M 1.0–1.9, 2.0–2.9 and 3.0–3.9 ranges, and main earthquake respectively. Onset of identified nucleation period is given '0' time mark. Nucleation period lasted for 110, 160 and 150 h for (a) 30 August, (b) 13 November and (c) 26 December 2005 earthquakes respectively (Table 2).

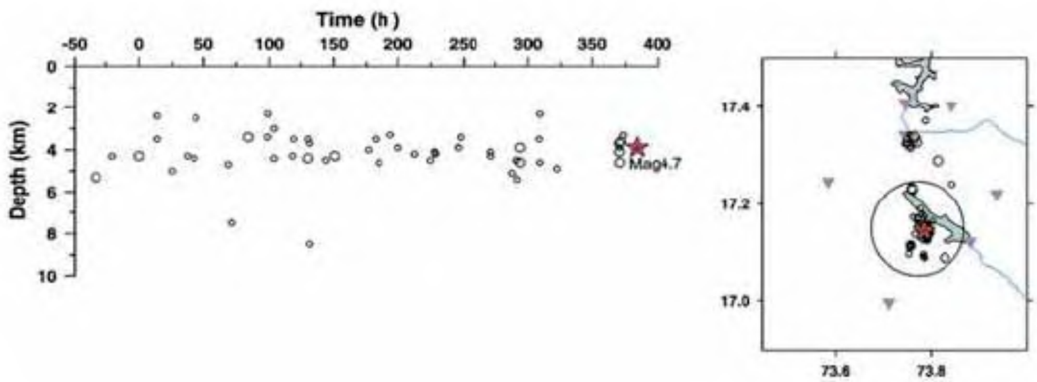

Figure 3. Symbols as in Figure 2. For the M 4.7 earthquake of 17 April 2006, nucleation lasted for 380 h.

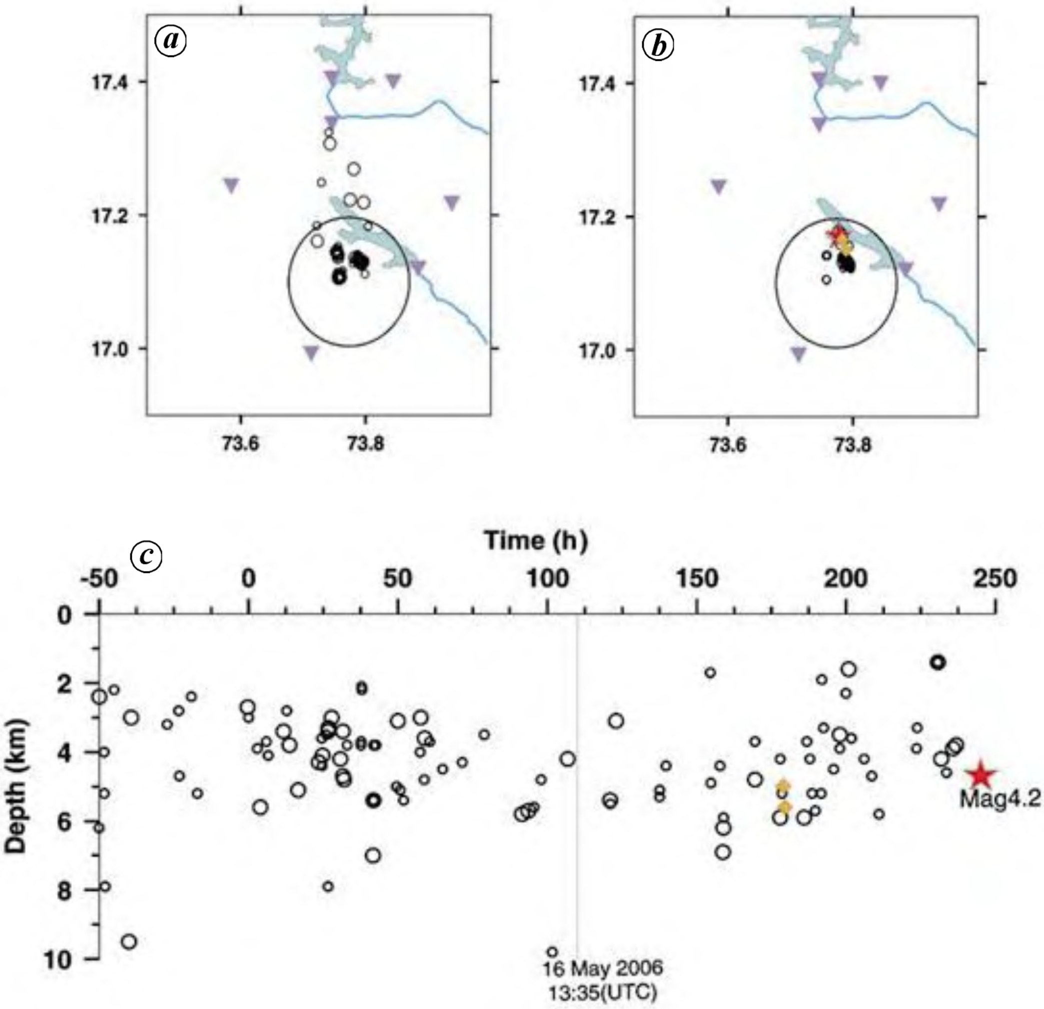

Figure 4. Symbols as in Figure 2. ***a***, Events that occurred during 157 h (11–16 May) preceding identification of nucleation. ***c***, Temporal–depth plot of the events within the 10 km radius circle. Nucleation was inferred to have started 107 h before, where 0 h is put on the time axis. ***b***, Seismic activity from 13:35 UTC on 16 May till the occurrence of the *M* 4.2 earthquake on 21 May 2006, on the right side of (***c***).

triggered earthquakes in the *M* 2–3 range at Lake Jocassee, South Carolina, USA. Koyna is a special case of isolated seismic activity in a small area, which is relatively simple to monitor. The continued seismic activity makes it an excellent natural laboratory to conduct earthquake forecast-related studies of precursors. Several issues remain to be investigated in detail, such as the relationship between duration of nucleation, largest events, temporal and spatial spread of precursory events and size and interval after which the earthquake would occur. Detailed monitoring of water levels in 21 boreholes[21] and other studies such as radon emission, repeat GPS and gravity measurements, ts/tp ratios, etc. being carried out in the Koyna region, would perhaps strengthen the quantification of real-time forecast of earthquakes in this unique site of reservoir-triggered siesmicity in western India. However, it still needs to be verified, how such type of forecasting of earthquakes can be attempted in other regions with different tectonic set-up.

Clear foreshock nucleation patterns were visible for most of the *M*4+ earthquakes in the Koyna during August 2005–May 2006. Based on such a nucleation pattern, an *M*4+ earthquake was forecasted in Koyna on 16 May 2006, which came true on 21 May 2006. It appears that isolated, well-monitored sites like Koyna are probably most suitable locales for the pursuit of short-term earthquake precursory studies in future.

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The 14 February 2006 Sikkim earthquake of magnitude 5.3

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On 14 February 2006, an earthquake of magnitude 5.3 struck to the west of Phodong, a small town in the Himalayan State of Sikkim. The earthquake was followed by a large number of aftershocks that were recorded by a network of digital seismic stations operated by the National Geophysical Research Institute, Hyderabad. The study indicates an east-west trend of the epicentral distribution of earthquakes, which is correlated with the decollement plane of the Main Boundary Thrust dipping northward in Sikkim Himalaya. The Sikkim region is surrounded by several damaging earthquakes of the past, although it has not experienced a magnitude 8.0 earthquake so far. However, it remains to be seen whether the Sikkim region is a potentially less hazardous zone or there is likelihood of occurrence of a great earthquake in the near future.

Keywords: Main Boundary Thrust, Main Central Thrust, Sikkim earthquakes, Tista and Gangtok lineaments.

A moderate earthquake of magnitude (M) 5.3 occurred in the early hours (00 : 55 UTC) of 14 February 2006, west of the small town of Phodong in Sikkim with lat. 27.415°N, long. 88.551°E and a focal depth of 20 km. The earthquake was located by the National Geophysical Research Institute (NGRI), Hyderabad as well as other agencies, namely the United States Geological Survey and the India Meteorology Department, Pune. Most of the damage was observed in Phodong and Theng. In the capital city of Gangtok, maximum damage was reported for government establishments like the Police Headquarters, school buildings and some old constructions. The Raj Bhavan, which is one of the oldest constructions in Gangtok, was severely damaged. Even some modern RCC buildings in Gangtok developed multiple cracks.

The Sikkim region falls between Nepal and Bhutan and comprises the lesser active part of the 2500 km stretch of the active Himalayan belt (Figure 1). The region has only experienced moderate seismicity in the past. The most significant earthquake that occurred in its neighbourhood is the 1934 Bihar–Nepal border earthquake of M 8.3 to the west, that caused intensity VIII damage in Sikkim Himalaya[1]. Earlier, an earthquake of M 7.7 was reported to its west in 1833. More recently, in 1988 the region again witnessed an M 6.6 earthquake with intensity VII in Gangtok.

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