reversals of the geomagnetic field during their eruption. Courtillot *et al.*[10] and Vandamme *et al.*[1] notice that about 80% of the Deccan Traps were reversely magnetized with a chron sequence of N–R–N at the K–T boundary. They further argue that this reverse chron is Chron 29 R and the most active phase of Deccan volcanism lasted for a period of approximately one million years. In such a situation the subsurface flows encountered in the borehole at Killari with their reverse magnetization resting above the Precambrian basement located in the S–E fringes might represent the earliest eruptions of the Deccan flood basalts along with other flows in the central, eastern and southeastern regions of the Deccan Traps. This might also mean that the older flows belonging to the Narmada Normal epoch[22] are missing or did not erupt in the Killari region.

1. Vandamme, D., Courtillot, V. and Besse, J., *Rev. Geophys.*, 1991, **29**, 159–190.
2. Pradhan, S. R., *Geol. Surv. India Spl. Publ.*, 1995, **27**, 129–133.
3. Gupta, H. K. and Dwivedy, K. K., *J. Geol. Soc. India*, 1996, **47**, 129–131.
4. Jaffri, S. H., Dayal, A. M., Rao, R. U. M., Roy, S. and Srinivasan, R., *Geol. Mag.*, 1998 (communicated).
5. Nagata, T., *Rockmagnetism*, Maruzen, Tokyo, 1961, p. 149.
6. Radhakrishnamurty, C., in *Palaeogeophysics* (ed. Runcorn, S. K.), Academic Press, London, 1970, pp. 235–241.
7. Sahasrabudhe, P. W., in Proceedings of the Seminar on Geophysical Investigations in Peninsular Shield, Osmania University, Hyderabad, 1963, pp. 226–243.
8. Athavale, R. N. and Anjaneyulu, G. R., *Tectonophysics*, 1971, **14**, 87–103.
9. Bhimasankaram, V. L. S. and Pal, P. C., *J. Osmania Univ.*, 1968, **43**, 43–61.
10. Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger, J. J. and Cappetta, H., *Earth Planet Sci. Lett.*, 1986, **80**, 361–374.
11. Pal, P. C. and Bhimasankaram, V. L. S., *Bull. Volcanol.*, 1971, **35**, 721–735.
12. Pal, P. C. and Bhimasankaram, V. L. S., *Earth Planet Sci. Lett.*, 1971, **11**, 109–112.
13. Poornachandra Rao, G. V. S. and Bhalla, M. S., *Geophys. J. R. Astron. Soc.*, 1984, **77**, 847–862.
14. Wensink, H., *Tectonophysics*, 1973, **17**, 41–59.
15. Venkata Rao, K. and Prasad, V., *Geol. Surv. India Spl. Publ.*, 1995, **27**, 99–108.
16. Poornachandra Rao, G. V. S. and Mallikharjuna Rao, J., 1999 (under preparation).
17. Verma, R. K. and Appa Rao, A., in Proceedings of the Seminar on Geophysical Investigations in Peninsular Shield, Osmania University, Hyderabad, 1963, pp. 161–168.
18. Pascoe, E. H., *A Manual of Geology of India and Burma*, Govt India Press, 1964, vol. 3, pp. 1345–2130.
19. Verma, R. K. and Pullaiah, G., *Bull. Volcanol.*, 1971, **XXXV**, 750–765.
20. Verma, R. K., Pullaiah, G., Anjaneyulu, G. R. and Mallik, P. K., *J. Geomagn. Geoelectr.*, 1973, **25**, 437–446.
21. Pal, P. C., *Geophys. Res. Bull.*, 1975, **13**, 279–288.
22. Sreenivasa Rao, M., Ramasubba Reddy, N., Subba Rao, K. V., Prasad, C. V. R. K. and Radhakrishnamurty, C., *J. Geol. Soc. India*, 1985, **26**, 617–639.

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Probabilities of occurrence of great earthquakes in Himalaya

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The long-term conditional probabilities of occurrence of great earthquakes along the Himalaya plate boundary seismic zone have been estimated. The chance of occurrence of at least one great earthquake along this seismic zone in a period of 100 years (beginning with the year 1999) is estimated to be about 0.89. The 100-year probability of such an earthquake occurring in the Kashmir seismic gap is about 0.27, in the central seismic gap is about 0.52 and in the Assam gap is about 0.21. The 25-year probabilities of their occurrence are 0.07, 0.17, and 0.05 for the Kashmir, the central and the Assam seismic gaps, respectively. These probabilities will serve in the assessment of the seismic hazard in the Himalaya and the adjoining Ganga plains.

THE Himalaya have risen out of a process involving fracturing and stacking of rocks over a period of long geologic time. The occurrence of great earthquakes is inherent in such a process. Although the historical evidence is quite incomplete, a number of such earthquakes in this region have been recorded since 1250 BC[1]. In the most recent sequence four great earthquakes have ravaged the Himalaya: 1897 in Assam, 1905 in Kangra, 1934 in Bihar–Nepal, and 1950 in Assam taking a toll of over 30,000 human lives and causing heavy economic losses (Figure 1). As the relative convergence of India and Eurasia, which provides the energy released in the earthquakes, is continuing unceasingly, similar great earthquakes are expected to occur in the future also. In order to assess the seismic hazard from such earthquakes we estimate the probabilities with which they are likely to occur in various sections of the Himalaya in a given interval of time in the future. We also estimate the combined probability of the occurrence of one or more such earthquakes in any section of the Himalaya.

We employ the time-predictable model of earthquakes to obtain the probabilities. The model envisages that strain builds up in a steady manner in a fault zone under a geodynamical process. After the same is released by an earthquake, the recovery of strain begins preparing the region for the next one to occur. The probability of occurrence of the next strain-relieving earthquake on a particular fault segment is proportional to the time elapsed since the last one[2,3]. That such a process is operative in the Himalaya has been shown by the analysis of the repeat levelling data on the Saharanpur–Mussorie profile[4].

The active tectonics in Himalaya is imaged by the earthquakes occurring there. An arcuate belt of moderate-

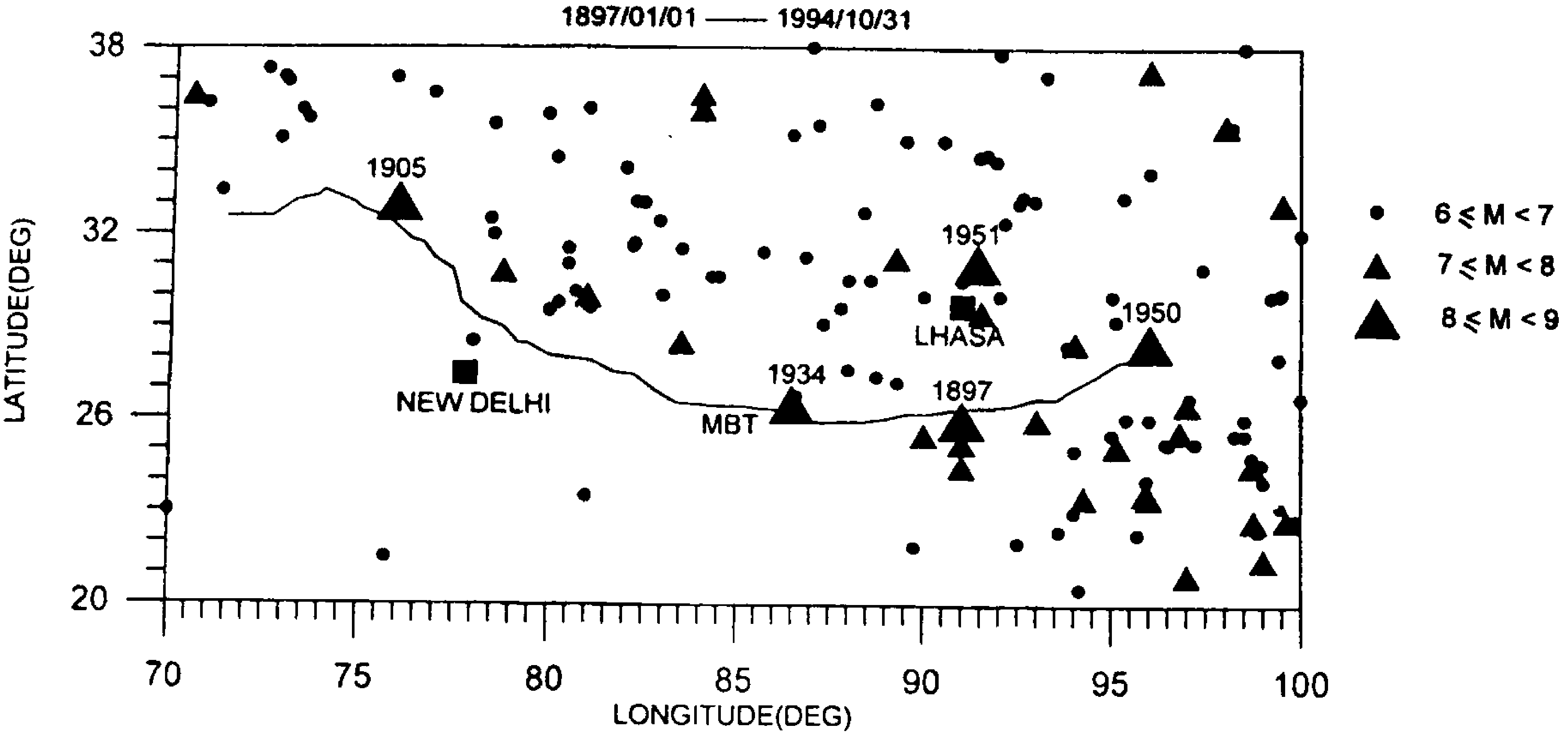

Figure 1. Locations of most recent great earthquakes.

sized earthquakes occurs close to the Main Central Thrust (MCT). The depth of focus of the earthquakes in this belt lies at about 15–20 km and their fault plane solutions show thrust faulting along gently dipping planes towards the north[5–7]. The rupture zones of the great earthquakes on the other hand, occur on a sub-horizontal fault plane which extends southward from the zone of the moderate magnitude earthquakes up to the domain of the outer Himalaya[5,8,9]. This is called the Plate Boundary Thrust (PBT). It dips gently at ~ 6° approximately towards the north and is about 17 km deep at its northern edge in the region of the MCT. The rupture plane has been mapped by reflection surveys by the Oil and Natural Gas Commission (ONGC) in the Doon and the Himachal re-entrants in the foot-hills of the Himalaya[10]. The deep crustal profiles in southern Tibet have mapped a fault plane called the Main Himalayan Thrust (MHT) which matches with the PBT when extrapolated into the Himalaya in the south[11,12]. The above model is consistent with the geological interpretation that the major thrusts in the Himalaya dip towards the north normal to its strike and flatten at depth[13,14]. The rupture plane required for modelling of the co-seismic elevation changes during the 1905 great Kangra earthquake is consistent with the PBT model[15,16]. Similarly, the fault plane determined by modelling of the elevation data in Nepal is a similar sub-horizontal plane[4,17–19]. The 1934 Bihar–Nepal earthquake has been interpreted to have been caused by slip over PBT which is constrained in N–S direction between the MCT and the Main Boundary Thrust in this section of the Himalaya[9]. Similar inferences have been derived for the cases of the 1897 and the 1950 great Assam earthquakes[9,20,21].

The episodic slips (displacement during faulting) over sections of this fault cause the occurrence of great earthquakes. The four most recent great earthquakes of $8.1 < M < 8.8$ involved rupturing of sections of the PBT having lengths of about 250–400 km along the strike[5]. These rupture zones define intervening sections, which have not ruptured for a long time (several hundreds of years), form seismic gaps. Due to the unceasing convergence of the plates the elastic strain which accumulates in these gaps will ultimately be released in the next gap-filling earthquake. The average time cycle of occurrence of great earthquakes in the same section of the plate boundary fault is governed by the strain rate. The processes that underlie the great Himalayan earthquakes are of the same nature as those for similar earthquakes of the subduction zones along the Pacific Ocean rim. Hence, the earthquake processes in the Himalaya which involve large segments of the PBT are cyclic[4].

The slip rates in the Himalaya have been estimated for a wide range of time scales. They are consistent among themselves and are used here for estimating the probabilities of occurrence of future great earthquakes.

A long-term (time scale of ~ 1 to 10 million years) slip rate of 15 ± 5 mm/yr has been obtained from the rate of onlap of Siwalik sediments on to the Indian shield in front of the Garhwal–Kumaon Himalaya[22]. Powers *et al.*[10] analysed balanced cross-sections in the Kangra and Dehradun re-entrants and estimated rates of shortening of 14 ± 2 mm/yr and 6–16 mm/yr, respectively, in these regions. Farther west in the eastern and western Potwar Plateau, the shortening rates are estimated on the basis of balanced cross-section to be 7 mm/yr[23] and approximately 13 mm/yr, respectively[24,25]. Avouac and Tapponnier[26] estimated convergence rate of 18 mm/yr across the Himalaya.

The slip rate on the time scale of several thousand years (Holocene) estimated in the Doon valley is $> 11.9 \pm 3$ mm/yr[27] and 21.5 ± 1.5 mm/yr in the frontal Himalaya of central Nepal[28]. An analysis of the strain rate distribution in the mobile zone between India and Eurasia using finite element analysis has estimated a strain rate between India and the Himalaya of 18 mm/yr in the Assam and Nepal regions which gradually reduces in the westerly direction to 15 mm/yr in the Garhwal Himalaya and to 10 mm/yr in the Jammu Himalaya[29].

The slip rate from the seismic moment released in great earthquakes during approximately the past one hundred years is estimated to be 17 mm/yr[5,30]. Khattri[31] obtained a slip rate of 35 mm/yr on primary faults using the fractal model of earthquakes and the complete set of available earthquake catalogues. Thus the slip rate is observed to decrease from a value of 20 mm in Assam in the east to 10 mm/yr in the west which is due to the obliqueness of the plate convergence with respect to the Himalaya.

The location of the rupture zones of the four most recent great earthquakes is shown in Figure 2. On the basis of this most recent cycle of the great earthquake activity three seismic gaps have been recognized: the Kashmir gap to the west of the Kangra earthquake; the central seismic gap between the Kangra and the Bihar–Nepal earthquakes and the Assam gap between the two Assam earthquakes[21]. The extent of the small section of the PBT between the rupture zones of the 1934 and the 1897 earthquakes is inadequate to support a great earthquake. Hence, it has not been included as a seismic gap in the analysis.

The last great earthquake in the Kashmir gap was in 1555 for which the maximum intensity has been estimated to be XII (ref. 1). Thus, strain has been accumulating in this gap for the past 450 years. There is at present no clear-cut information about the last great earthquake in the central seismic gap. The available earthquake catalogues document the occurrence of two large earthquakes in 1803 and 1833 in this seismic gap. However, neither of these had a magnitude 8 or greater and were not in the class of great earthquakes[32–34]. The last great earthquake in the Nepal sector of Himalaya (the site of the 1934 event) was in 1255 which destroyed Kathmandu[33]. The time between these two events is 679 years. This interval may serve as a guide for determining a possible time window for the date of the last such event having occurred in the central seismic gap.

From the historical records the occurrence of three large earthquakes in 1548, 1596 and 1696–1697 in the Assam gap region has been identified[1]. The latest of these events is taken as the most recent great earthquake in the Assam gap. A sequence of three earthquakes has been identified from paleo-seismological studies to have occurred around 500, 1100, and 1500 years ago in the rupture zone of the 1897 earthquake (Shillong massif area)[35]. We may, therefore, take the average recurrence interval of great earthquakes in this region to be ~ 500 years.

In addition to the above gap, the section of the Himalaya lying to the north of the 1897 rupture may also form a seismic gap. The evaluation of this section is beset with two difficulties. Firstly, the interaction between this section and the southern Shillong massif section and its influence on the strain cycle is not understood as yet.

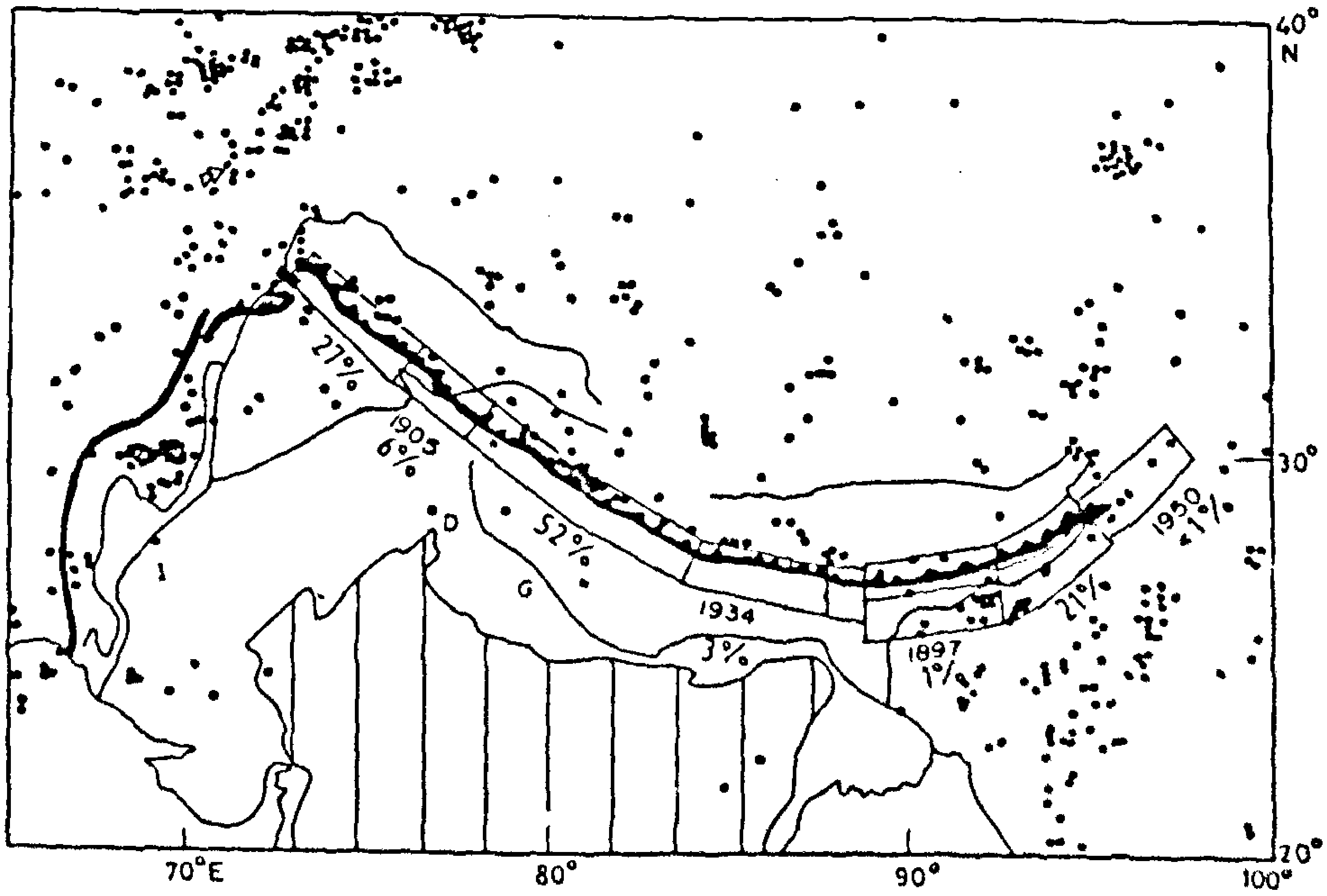

Figure 2. Conditional probabilities of occurrence of earthquakes of $M > 8$ in sections of Himalaya in a time window of 100 yr (beginning with the year 1999). The dots show smaller magnitude earthquakes. D, Delhi; G, Ganga river; I, Indus river.

Secondly, no information is available about the previous event there. Thus, in the present analysis we have not attempted to estimate the probability for this section separately. The entire strain cycle has been assigned to the 1897 rupture zone.

The procedure to estimate probabilities of recurrence of great (characteristic) earthquakes is based on the time predictable model of earthquake occurrence[36]. The strain accumulates continuously which is 'cyclically' relieved over a fault segment in characteristic earthquakes. There is a positive correlation between the time interval T between successive events on a fault segment and the co-seismic random slip D in the previous event. The most probable recurrence time, T^*, to the next earthquake is given by:

$$T^* = (D/V), \tag{1}$$

where D is the best (median) estimate of displacement in the previous segment-rupturing earthquake, and V is the best (median) estimate of the long-term slip rate.

The conditional probability of earthquake recurrence is determined from a probability density function of the random time of recurrence T. The great (characteristic) earthquakes have a relatively narrow range of magnitude and correspondingly narrow range of associated fault slip. Therefore, the associated recurrence time may follow a relatively narrow probability distribution in comparison to the case of Poissonian recurrence model. Other workers[36,37] have concluded that the results are not sensitive to the choice and have used a log normal distribution. The same has been adopted in the present study also. The probability of occurrence of the next great earthquake in a time window T is given by:

$$\begin{aligned} &P(T_e < T < T_e + \Delta T \mid T > T_e) \\ &= \{P(T_e < T < T_e + \Delta T)\}/\{1 - P(0 < T < T_e)\}, \end{aligned} \tag{2}$$

where T_e is the elapsed time since the last segment rupturing earthquake, and $P(\cdot)$ the fraction of all earthquake recurrence times in the interval $(t, t + \Delta T)$ is given by:

$$\begin{aligned} &P(T_e < T < T_e + \Delta T) \\ &= \int_t^{t+\Delta T} \{1/(u\sigma\sqrt{2\pi})\} \exp\{-[\ln u/T^*]^2/2\sigma^2\}\, du, \end{aligned} \tag{3}$$

where T^* is the median recurrence interval of the next segment rupturing earthquake, σ is a measure of the dispersion in the recurrence time distribution which includes a parametric uncertainty arising in T^* from the uncertainties in D and V and an intrinsic variability of event-to-event time when T^* is perfectly known.

For the calculations we have to specify T_e, the time elapsed till the present time since the date of the last characteristic earthquake in a fault segment, the time window ΔT, and the value of σ. In the absence of requisite data to empirically estimate the value of σ its choice has been guided by the studies in California and the Pacific[36,37]. Two values have been investigated, viz. 0.2 and 0.4. The lower value gives higher probabilities by a factor of 1.7 (for 100 yr) to 2.8 (for 10 yr) compared to the values in the case of 0.4. A value of 0.4 is considered to be an appropriate choice at the present state of knowledge. Further, experimentation with the date of the last rupturing earthquake as well as the value of T^* shows that the probabilities change by about ten per cent for a change of about eight per cent in the value of an input parameter. The estimates of the probabilities are shown in Table 1 and Figure 2. The time window starts from the year 1999.

The last great earthquake is estimated to have occurred in 1555 in the Kashmir seismic gap. The magnitude and the associated fault slip of this event may be taken to be the same as for the 1905 Kangra earthquake, i.e. 8.1 and 6.2 m, respectively[5]. Then, with the constant slip rate of 9 mm/yr for this section the value of T^* will be 555 yr. The 100-year probability in this gap is 0.27.

We may assume the year of the last great earthquake in the central seismic gap to be 1505, which coincides with the great destruction of Agra[1]. The return period T^* is estimated to be 350 yr using a slip rate of 18 mm/yr and a slip of 6.2 m in the last great earthquake (corresponding to the 1934 Bihar earthquake). The 100-year probability of a great earthquake in this gap is estimated to be 0.52. However, since the central gap is long enough to be able to support two great earthquakes of the size of the 1934 event, this probability applies to either of them.

We will discuss later in this article the change in the probability values on account of a change of ± 100 years in the date of the last great earthquake.

The year of the last great event in the Assam seismic gap was in the year 1696–1697 (ref. 1). The slip in this event is taken to be 9 m, the same as in the 1950 event. With the slip rate of 18 mm/yr the return period T^* is found to be 500 yr. The probability of the next great earthquake in this gap to occur in the next 100 years is 0.21.

Table 1. Probabilities of characteristic (great) earthquakes along various sectors of the Himalaya (time windows w.e.f. the year 1999)

		Probability			
	Previous event (yr)	10-year	25-year		100-year
Section		$\sigma = 0.4$	0.2	0.4	0.4
Kashmir gap	1555	0.03		0.07	0.27
Kangra Rupt.	1905	< 0.00		< 0.00	0.06
Central gap	1505	0.07	0.42	0.17	0.52
Bihar Rupt.	1934	< 0.00		< 0.00	0.03
Assam Rupt.	1897	< 0.00		< 0.00	0.01
Assam gap	1697	0.02		0.05	0.21
Assam Rupt.	1950	< 0.00		< 0.00	< 0.00

The probabilities for 10- and 25-year time windows are small in all sections except in the central gap. However, these will be about three times the values shown, i.e. become quite significant, in case the dispersion parameter is indeed about 0.2. In the central gap the 25-year probability is 0.17 and the 10-year probability is 0.07. The sections of the plate boundary which had ruptured in the last cycle have low probabilities of experiencing a great earthquake in the next 100 years.

Assuming that the occurrence of individual earthquakes is independent, the total 100-year probability of experiencing one or more great earthquakes in the Himalaya is given by:

$$P = 1 - (1 - P_1)(1 - P_2)(1 - P_3)\ldots, \qquad (4)$$

where P_i, $i = 1, 2, 3 \ldots$ are the individual probabilities of the occurrence of earthquakes in various segments, respectively. This probability is 0.89. In this calculation, because of its dimensions the central gap is treated as capable of supporting two great earthquakes of the 1934 type.

The unavailability of a definite date for the last great earthquake in the central gap poses a source of uncertainty. However, it is reasonable to argue that there is little chance of it having occurred within the last 400 years and not having been recorded historically. Thus, in case the last event occurred in the year 1600, the probability for the 25-year period will drop by about 12% to 0.15 compared to 0.17 for the case of the previous earthquake having occurred in the year 1505. Similarly, in case the last event occurred earlier in the year 1400, the probability will remain more or less the same, i.e. 0.17. A ± 50 yr (~ 14%) variation in the value of T^* (i.e. due to the variation in the slip in the last event) causes a corresponding change of ± 0.03 (~ 17%) in the probability in the central seismic gap. Thus, the estimated probabilities are providing an approximately correct order of chance for expecting a future great earthquake in the given time window. The above conclusions apply equally to the other sectors as well. Thus, the estimates may be used to define the seismic hazard in the Himalaya and the contiguous Ganga plains due to future great earthquakes.

The potential of damage that can be perpetrated by the great earthquakes is underlined by the experiences of the past such events. For example, the remote 1905 Kangra earthquake claimed 19,000 lives, while a great devastation occurred in a vast expanse of tract in the Nepal Himalaya and the plains of Bihar during the 1934 Bihar–Nepal earthquake. It has been estimated that a repeat of the Kangra earthquake now may kill as many as 150,000 people[38]. Khattri[21,39] has shown that the ground motions will be quite severe in an extensive area in the Ganga plains also, as indeed was the case in Bihar in the 1934 earthquake, in the event of such an earthquake. Therefore, both in terms of the number of lives that are threatened, as well as the extent of the economic damage which may run well into thousands of crores of rupees, and its after-effects, we are confronted by a problem of Himalayan proportions.

The situation outlined above calls for an immediate and sustained national effort for earthquake hazard mitigation. The organization of such a programme could benefit from the experiences at USA (California) and Japan. The UN initiative under the 'Decade for Natural Hazard Reduction' programmes could also be a source of valuable information.

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1. Iyengar, R. N. and Sharma, D., *Earthquake History of India in Medieval Times*, Central Building Res. Inst., Roorkee, 1998, p. 124.
2. Rikitake, T., *Tectonophysics*, 1974, **23**, 299–312.
3. Hagiwara, Y., *Tectonophysics*, 1974, **23**, 313–318.
4. Gahalaut, V. K. and Chander, R., *Geophys. Res. Lett.*, 1997, **24**, 225–228.
5. Molnar, P., *J. Himalayan Geol.*, 1990, **1**, 131–154.
6. Chandra, U., *Phys. Earth Planet. Inter.*, 1978, **16**, 109–131.
7. Ni, J. and Barazangi, M., *J. Geophys. Res.*, 1984, **89**, 1147-1163.
8. Seeber, L. and Armbruster, J. G., in *Earthquake Prediction: An International Review* (eds Simpson, D. W. and Richards, P. G.), Maurice Ewing Series 4, American Geophysical Union, 1981, p. 215.
9. Chander, R., *Tectonophysics*, 1989, **170**, 115–123.
10. Powers, P. M., Lillie, R. J. and Yeats, R. S., *Bull. Geol. Soc. Am.*, 1998, **110**, 1010–1027.
11. Zhao, W., Nelson, K. D. and Project INDEPTH Team, *Nature*, 1993, **306**, 557–559.
12. Hauck, M. L., Nelson, K. D., Brown, L. D., Zhao, W. and Ross, A. R., *Tectonics*, 1998, **17**, 481–500.
13. Valdiya, K. S., in Proceedings of International Symposium on Neotectonics, South Asia, Survey of India, 1986, p. 434.
14. Valdiya, K. S., *J. Geol. Soc. India*, 1997, **49**, 479–494.
15. Chander, R., *Tectonophysics*, 1988, **149**, 289–298.
16. Gahalaut, V. K. and Chander, R., *J. Geol. Soc. India*, 1992, **39**, 61–68.
17. Gahalaut, V. K., Gupta, P. K., Chander, R. and Gaur, V. K., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1994, **3**, 401–411.
18. Jackson, M. and Bilham, R., *J. Geophys. Res.*, 1994, **99**, 13897–13912.
19. Gahalaut, V. K. and Chander, R., *Geophys. Res. Lett.*, 1997, **24**, 1011–1014.
20. Gahalaut, V. K. .and Chander, R., *Tectonophysics*, 1992, **204**, 163–174.
21. Khattri, K. N., *Himalayan Geol.*, 1999, **20**, 1–46.
22. Lyon-Caen, H. and Molnar, P., *Tectonics*, 1985, **4**, 513–538.
23. Pennock, E. S., Lillie, R. J., Zamin, A. S. H. and Yousuf, M., *Bull. Am. Assoc. Petrol. Geol.*, 1989, **73**, 841–857.
24. Leathers, M. R., Master's thesis, Oregon State University, Corvallis, USA, 1987, p. 228.
25. Baker, D. M., Lillie, R. J., Yeats, R. S., Johnson, G. D., Yousuf, M. and Zamin, A. S. H , *Geology*, 1988, **16**, 3-7.
26. Avouac, J. and Tapponnier, P., *Geophys. Res. Lett.*, 1993, **20**, 895–898.
27. Wesnousky, S. G., Kumar, S., Mohindra, R. and Thakur, V. C., 1998 (unpublished).
28. Lave, J. and Avouac, J. P., *J. Geophys. Res.*, 1998 (submitted).
29. Peltzer, G. and Saucier, F., *J. Geophys. Res.*, 1996, **101**, 27943–27956.
30. Molnar, P. and Deng, Q., *J. Geophys. Res.*, 1984, **89**, 6203-6227.
31. Khattri, K. N., *Curr. Sci* , 1995, **69**, 361–366.

32. Oldham, R., *Mem. Geol. Surv. India*, 1833, **19**, 163–215.
33. Bilham, R., *Curr. Sci.*, 1995, **69**, 101–128.
34. Bilham, R., Blume, R., Bendick, R. and Gaur, V. K., *Curr. Sci.*, 1995, **74**, 213–229.
35. Sukhija, E. S., Rao, M. N., Reddy, D. V., Nagabhushnam, P., Hussain, S., Chadha, R. K. and Gupta, H. K., 1996 (unpublished).
36. WGOCEP (Working Group on California Earthquake Probabilities), US Geol. Surv. Circular 1053, 1990, p. 51.
37. Nishenko, S. P. and Buland, R., *Bull. Seismol. Soc. Am.*, 1987, **77**, 1382–1399.
38. Arya, A. S., *Himalayan Geol.*, 1996, **17**, 33–43.
39. Khattri, K. N., *Natl. Acad. Sci. Lett.*, 1998, **21**, 193–220.

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Do decomposing leaves of mangroves attract fishes?

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The present work proves experimentally that the decomposing leaves of mangroves 'attract' the fishes. Nylon bags containing senescent leaves of the mangrove plants, viz. *Rhizophora apiculata* and *Avicennia marina*, were immersed separately in experimental tanks, along a tropical mangrove estuary in south-east India. Juveniles of prawn, fish, crabs and hermit crabs were collected every two days, from the experimental tanks, and from control tanks. The experiment was conducted for 70 days, separately in four different seasons. It was inferred that there was a greater assemblage of fin- and shell-fishes, with the decomposing leaves of mangroves, in all the seasons. In general, the prawn resources increased with days of decomposition, up to around 30–50 days and declined thereafter. The association of fin- and shell-fishes was greater during premonsoon and postmonsoon than in other seasons and was higher with decomposing leaves of *Avicennia* than in *Rhizophora*.

MANGROVE litter provides an important nutrient base for food webs that support fishes and prawns in tropical estuaries[1–7]. Leaves are the major contributors for mangrove litterfall and to nutrient budget of estuaries[8]. During the decomposition of mangrove litter, a large amount of nutrients are released and detritus food is formed for fishes. The litter would need to be decomposed for about 2 months before it becomes fit for consumption by detritivores[8,9]. The detritus food has low C : N ratios (17 : 1) associated with high nutritional quality[9,10] and it supports various animal communities of the coastal ecosystem[11]. This aspect of the association of faunal communities with the detritus has little been studied[12]. The present study was conducted to examine the fishery resources associated with decomposing leaves of mangroves, and the possibility of enhancing fishery resources in tropical estuaries with mangrove litter.

The present study area of Pichavaram mangrove (lat. 11°27′N; long. 79°47′E) is located about 250 km south of Chennai city on the south-east coast of India. It is one of the typical mangrove swamps of India, with a high productivity of about 8 tonnes of organic plant detritus ha/year. It consists of small and large islets covering an area of 1100 ha. Of the total area, 50% is covered by the forest, 40% by the water ways and the remaining 10% by the sand and mudflats[13]. The tidal level of the study area is semi-diurnal, and the salinity level ranged from 13.2 to 34.6 $\mathrm{g\,l^{-1}}$. The nutrient level varied from 0.03 to 18.2 $\mu\mathrm{g\,l^{-1}}$ for nitrate nitrogen, 0.02 to 2.2 $\mu\mathrm{g\,l^{-1}}$ for nitrite nitrogen, 0.07 to 8.02 $\mu\mathrm{g\,l^{-1}}$ for total phosphate and 0.55 to 85.6 2 $\mu\mathrm{g\,l^{-1}}$ for particulate organic carbon[14].

Senescent leaves of *Rhizophora apiculata* Blume and *Avicennia marina* (Forssk.) Vierh., were collected from the trees of the Pichavaram mangrove forest. For decomposing the leaves, the *in situ* litter bag method[15] was adopted. The litter bags (35 × 35 cm) were made of nylon having a mesh size of 2 mm. Each of the nylon bags having 500 g of senescent leaves, was placed in a tank of 1 m length, 1 m breadth, and 1 m depth constructed in the mid-intertidal zone of the Pichavaram mangrove water. The litter bags were immersed in the tanks throughout the experiment.

Five litter bags of each species were kept in separate tanks and maintained throughout the experiment. To avoid the floatation 500 g of stones were added to each bag. The inner sides of the tanks were covered by nylon nets of mesh size (2 mm) to trap the organisms, which were attracted during litter decomposition. The litter bags were maintained in ten treated tanks – five for *Avicennia marina* and another five for *Rhizophora apiculata*, along with a control tank, which was maintained simultaneously with a bag having 500 g stones without any leaf litter.

The organisms such as juveniles of prawn, fish, crabs and hermit crabs were collected from the experimental tanks every two days, during the low tide by lifting the inner net from the experimental tanks[15]. The organisms were identified and counted, for prawns[16], crabs[17], fish[18] and hermit crabs[19]. To find out the significant difference between species of mangroves and among the days of decomposition the data were treated with analysis of variance (ANOVA). This experiment was repeated during four different seasons in the same site: July–September 1994 (premonsoon), October–December 1994 (monsoon), January–March 1995 (postmonsoon), April–June 1995 (summer). The experiments were carried out for a period of 70 days in each of the four different seasons.

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