32. Kotlia, B. S., *Eiszeitalter Ggw.*, 1990, **40**, 38–52.
33. Ranga Rao, A., Agrawal, R. P., Sharma, V. N., Bhatia, M. S. and Nanda, A. C., *J. Geol. Soc. India*, 1988, **31**, 361–385.
34. Yoshida, M. and Gautam, P., in *Palaeoclimatic and Palaeoenvironmental Changes in Asia During the Last 4 Million Years*, INSA, New Delhi, 1988, pp. 78–85.
35. Ranga Rao, A., *Bull. ONGC*, 1986, **23**, 109–128.
36. Hashimi, N. H., Pathak, M. C., Jauhari, P., Sharma, A. K., Bhakuni, S. S., Bisht, M. K. S. and Valdiya, K. S., *J. Geol. Soc. India*, 1993, **41**, 91–104.
37. Sakai, H., *Mem. Fac. Sci., Kyushu Univ., Japan*, 1986, **26**, 81–93.
38. Wadia, D. N., *Proc. Natl. Inst. Sci. India*, 1938, **4**, 73–94.
39. Seeber, L. and Gornitz, V., *Tectonophysics*, 1983, **92**, 335–367.
40. Madin, I. P., Lawrence, R. D. and Rahman, S. U., in *Tectonics of the Western Himalayas* (eds. Malinconico, L. L. and Lillie, R. J.), Geol. Soc. Am., Boulder, 1989, pp. 169–182.
41. Shroeder, J. F., Khan, M. S., Lawrence, R. D., Madin, I. P. and Higgins, S. M., in *Tectonics of the Western Himalayas* (eds. Malinconico, L. L. and Lillie, R. J.), Geol. Soc. Am., Boulder, 1989, pp. 275–294.
42. Zeitler, P. K., *Tectonics*, 1985, **4**, 127–151.
43. Bhargava, O. N., *Tectonophysics*, 1990, **174**, 315–320.
44. Cronin, V. S. in *Tectonics of the Western Himalayas*, (eds. Malinconico, L. L. and Lillie, R. J.), Geol. Soc. Am., Boulder, 1983, 183–202.
45. Fort, M., Burbank, D. W. and Treget, P., *Quat. Res.*, 1989, **31**, 332–350.
46. Lakhanpal, R. N., Sah, S. C. D., Sharma, K. K. and Guleria, J. S. in *Geology of Indus Suture Zone of Ladakh* (eds. Thakur, V. C. and Sharma K. K.), Wadia Institute of Himalayan Geology, Dehradun, pp. 179–185.
47. Guleria, J. S., Thakur, V. C., Virdi, N. S., and Lakhanpal, R. N., in *Geology of the Indus Suture Zone*, (eds. Thakur, V. C. and Sharma, K. K.), Wadia Institute of Himalayan Geology, Dehradun, 1983, pp. 187–193.
48. Owen, L. A., *Tectonophysics*, 1989, **163**, 227–265.
49. Sharma, K. K., Singh, I. and Joshi M., in *Current Trends in Geology*, (ed. Saklani, R. S.), Today and Tommorrow's, New Delhi, 1989, vol. 12, pp. 397–403.
50. Jalote, P. M, in Proceedings of the Third Symposium on Earthquake Engineering, Roorkee Univ., Roorkee, 1966, pp. 495–510.
51. Nossin, J. J., *Z. Geomorphol.*, 1971, **10**, 18–50.
52. Agrawal, V. K. and Bhattacharya, A., *Photonirvachak*, 1981, **9**, 59–68.
53. Validiya, K. S., Joshi, D. D., Sanwal, R. and Tandon, S. K., *J. Geol. Soc. India*, 1984, **25**, 761–774.
54. Sinvhal, H., Agrawal, P. N., King, G. C. P. and Gaur, V. K., *Geophys. J. R. Astron. Soc.*, 1973, **34**, 381–391.
55. Ansari, A. R., Chugh, R. S., Sinvhal, H., Khattri, K. N. and Gaur, V. K., *Himalayan Geol.*, 1976, **6**, 323–327.
56. Arur, M. G. and Rajal, B. S., *Tectonophysics*, 1981, **71**, 154.
57. Valdiya, K. S., Rana, R. S., Sharma, P. K. and Dey, P., *J. Geol. Soc. India*, 1992, **40**, 509–528.
58. Valdiya, K. S., *Ann. Tect.*, 1993, in press.
59. Nakata, T., *Geomorphic History and Crustal Movements of the Himalaya*, Institute of Geography, Tohuku Univ., Sendai, 1972, p. 77.
60. Rao, D. P., *Photonirvachak*, 1977, **5**, 5–40.
61. Talukdar, S. N. and Sudhakar, R., in Miscellaneous Publication, GSI, Calcutta, 1972, vol. 15, pp. 185–199.
62. Rajal, B. S., Virdi, N. S. and Hasija, N. L. in Proceedings of the International Symposium on Neotectonics in South Asia, Survey of India, Dehradun, 1986, pp. 146–159.
63. Valdiya, K. S., *Indian J. Geol.*, 1989, **61**, 1–13.
64. Thakur, V. C., *Tectonophysics*, 1987, **135**, 127–151.
65. Bürgisser, H. M., Gansser, A. and Pika, J., *Ecol. Geol. Helv.*, 1982, **75**, 51–63.
66. Karunakaran, C. and Ranga Rao, A., *Status of Exploration for Hydrocarbons in the Himalayan Region*, ONGC, Dehradun, 1976, p. 72.

Seismic gaps and likelihood of occurrence of larger earthquakes in Northern India

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On the basis of seismicity pattern in and structural setting of the Himalaya, seismic gaps have been identified. These gaps are the likely locales of future great earthquakes. The extents of the gaps are defined by the structural discontinuities that exist in the subducting Indian crust.

Introduction

NORTHERN India is subject to considerable hazard due to earthquakes, which occur mostly in the Himalaya—the site of collision between the Indian and Eurasian plates. In the past the earthquakes have played considerable havoc in this region[1-8], where there has been a phenomenal increase in population density and also development programmes. It is important that the seismic hazard be assessed realistically in order to provide a sound basis for earthquake hazard reduction to the planners and administrators.

The strain energy release in the form of earthquakes at the plate boundaries is due to the relative motion of the plates. They release from time to time by rupturing and relative slip of the plates in the sections of the plate boundaries with the accompaniment of great earthquakes.

The ruptured section then waits for appreciable period of time for the strain to accumulate to the bearing limit before the next great earthquake occurs. Thus one may anticipate a quasi-periodicity in the occurrence of great earthquakes in the same section of the plate boundary. Indeed studies of great plate-boundary earthquakes (magnitude $M \geqslant 7.75$) have shown that there is such a behaviour which is epitomized in the strain rebound theory of Reid[9]. Another recent model of earthquake recurrence states that they occur when a certain critical strain level has been attained in the focal region. At this state the rocks rupture, causing an earthquake and release of the stored up strain in proportion to the size of the event. The next earthquake will occur when the strain accumulation rises to the rupture threshhold again. Thus a longer time interval will be needed after fuller release of strain such as in a great earthquake. This is known as the time predictable model of earthquakes[10].

Studies of great earthquakes ($M \geqslant 7.75$) have shown that they occur at sections of the plate boundaries which have not ruptured during the past several decades or more[11]. The frequency of such earthquakes depends upon the rate of relative plate motion which governs the rate of strain accumulation. The rupture lengths in such earthquakes appear to be controlled by the extents of the relatively mechanically homogeneous blocks along the plate boundary[12,13].

The sections of the plate boundary which have not ruptured in the past several decades are called seismic gaps. Such gaps may be in various states of preparation for the next gap-filling earthquake, and thus constitute areas of high seismic hazard. In the present article, the Himalaya plate boundary is examined with a view to reassessing its sections which have been identified earlier as seismic gaps[14-19].

Seismicity

The seismicity ($M \geqslant 7$) of Himalaya is shown in Figure 1, also depicting main elements of structure and tectonics. The seismicity is confined mostly to a belt close to the Main Central Thrust. Four great earthquakes since 1897 have ruptured the plate boundary. Their rupture zones are shown by broken lines. Between these rupture zones are sections of the plate boundary that have not ruptured in great earthquakes for at least 160 years but are undoubtedly accumulating strain at the rate of about 5 cm/yr (ref. 20).

It is noteworthy that several major structural elements trending in NE direction of the Indian shield come in abrupt contact with the arcuate trend of the Himalaya. These elements form natural boundaries of sections of the plate boundary that may be behaving mechanically as homogeneous. For example, the 1897

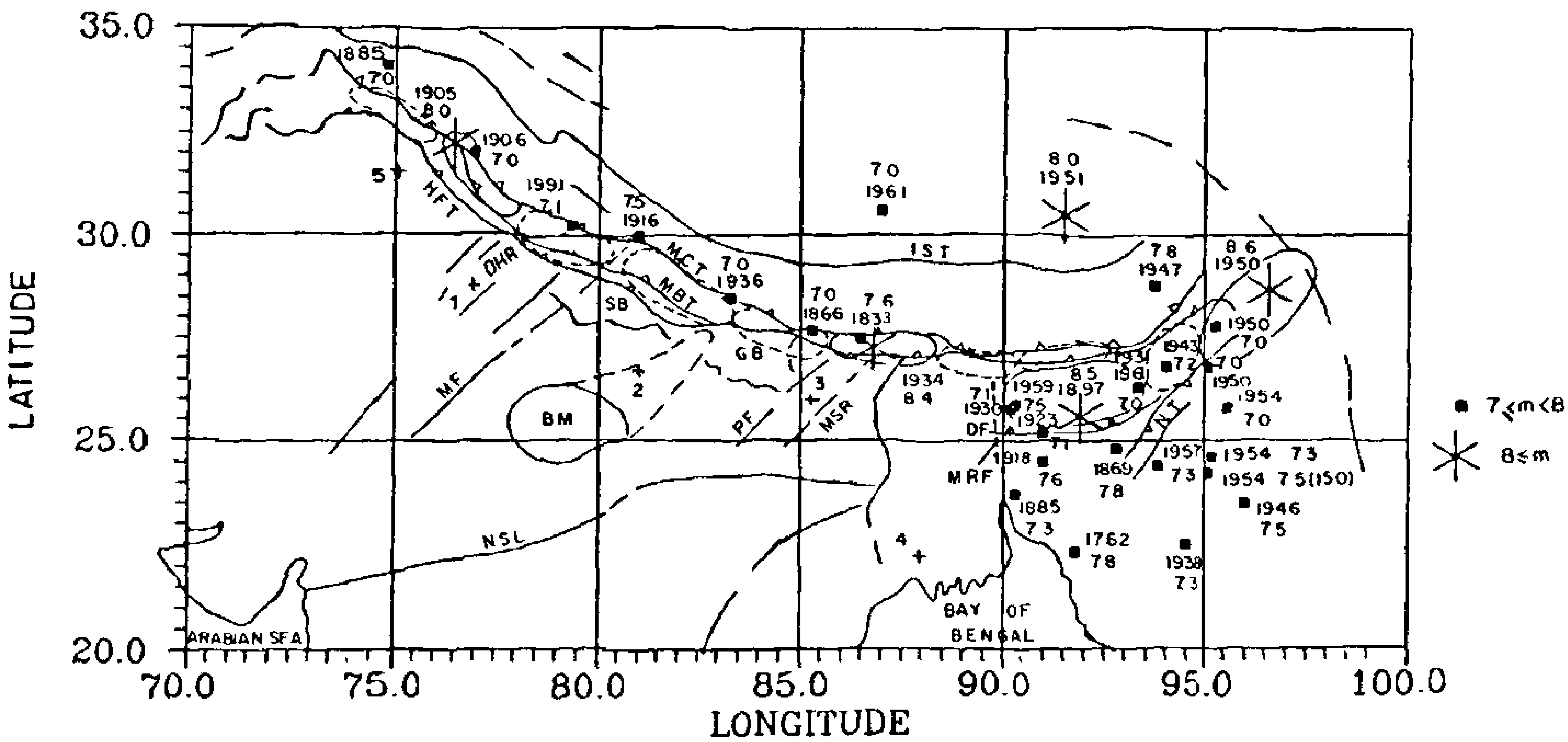

Figure 1. Large earthquake ($M \geqslant 7$) in the Himalaya region, with years and magnitudes of the major earthquakes. 1: New Delhi. 2: Lucknow. 3: Patna. 4: Calcutta. 5: Lahore. BM: Bundelkhand massif. DF: Dauki fault. DHR: Delhi–Hardwar Ridge. GB: Gandak Basin. HFT: Himalayan Frontal Fault. IST: Indus Suture. MBT: Main Boundary Thrust. MCT: Main Central Thrust. MF: Moradabad Fault. MRF: Madhupur Fault. MSR: Munger–Saharsa Ridge. NSL: Narmada–Son Lineament. NT: Naga Thrust. PF: Patna Fault. SB: Sharada Basin.
Continuous lines enclosing oval regions show sections that have ruptured in great earthquakes during the past about 100 years. Broken lines outline the present seismic gaps.

great Assam earthquake occurred in the Shillong massif region which is one such section bounded by the Madhupur Fault on the west and the Kopili graben on the east. The rupture zone of the 1905 great Kangra earthquake is bounded on the east by the Delhi–Hardwar Ridge. The 1934 great Bihar earthquake is bounded on the west by the Patna Fault and on the east it is controlled by the Munger–Saharsa Ridge. These ruptured sections are about 250 to 350 km long and have left unruptured sections between them. These were identified, from west to east, as the Kashmir gap lying to the west of the rupture zone of the 1905 Kangra earthquake, the central gap bounded by the rupture zones of the Kangra and the 1934 Bihar earthquakes, and the Assam gap lying between the 1897 and 1950 Assam earthquakes[14–19]. In addition, there may be a smaller gap between the Bihar and the Assam earthquakes and the section of the Main Central Thrust north of the Shillong massif[17]. The central gap is very long and can rupture in three future great earthquakes (Figure 1).

The basis of the identification of seismic gaps is primarily the major transverse structural features of the subducting Indian shield, and the main governing elements could be the underthrusting rocks. Thus one such section is defined by the rupture zone of the Kangra earthquake and the Moradabad Fault, the next section lies between the Moradabad Fault and the salient of the Bundelkhand massif, followed by the section defined by the Bundelkhand massif and the Patna Fault. Interestingly, the large earthquakes have originated at or near these boundaries which are defined by the structural features. These regions are mechanically more heterogeneous, and therefore became the sites of ruptures. The great earthquakes may start at asperities[21] which may be ridges on top of the underthrusting lithosphere or warps in the thrust planes. Their ruptures stop at barriers defined by the major structural boundaries[22]. This is the case for the Assam, Kangra, and the Bihar earthquakes.

The focal region of a great earthquake sometimes shows drop in the occurrence of small earthquakes[23,24]. This can be studied in a space time plot (Figure 2). The precursory seismic quiescence periods are seen for the Assam, Kangra, and perhaps also for the Bihar great earthquakes. There is also a post-earthquake drop in the small-magnitude earthquake activity due to release of the strain. The central and the Assam gaps are seen to be exhibiting reduced seismic activity, since 1969, in the latter case (Figure 3). Khattri and Wyss[25] have determined that the precursory seismic quiescence occurs for about 30 years prior to the occurrence of the great earthquakes.

The earthquakes sometimes show a migration of their focal regions[11,26,27]. The possible migrating loci are shown in Figure 2, which suggests that the western

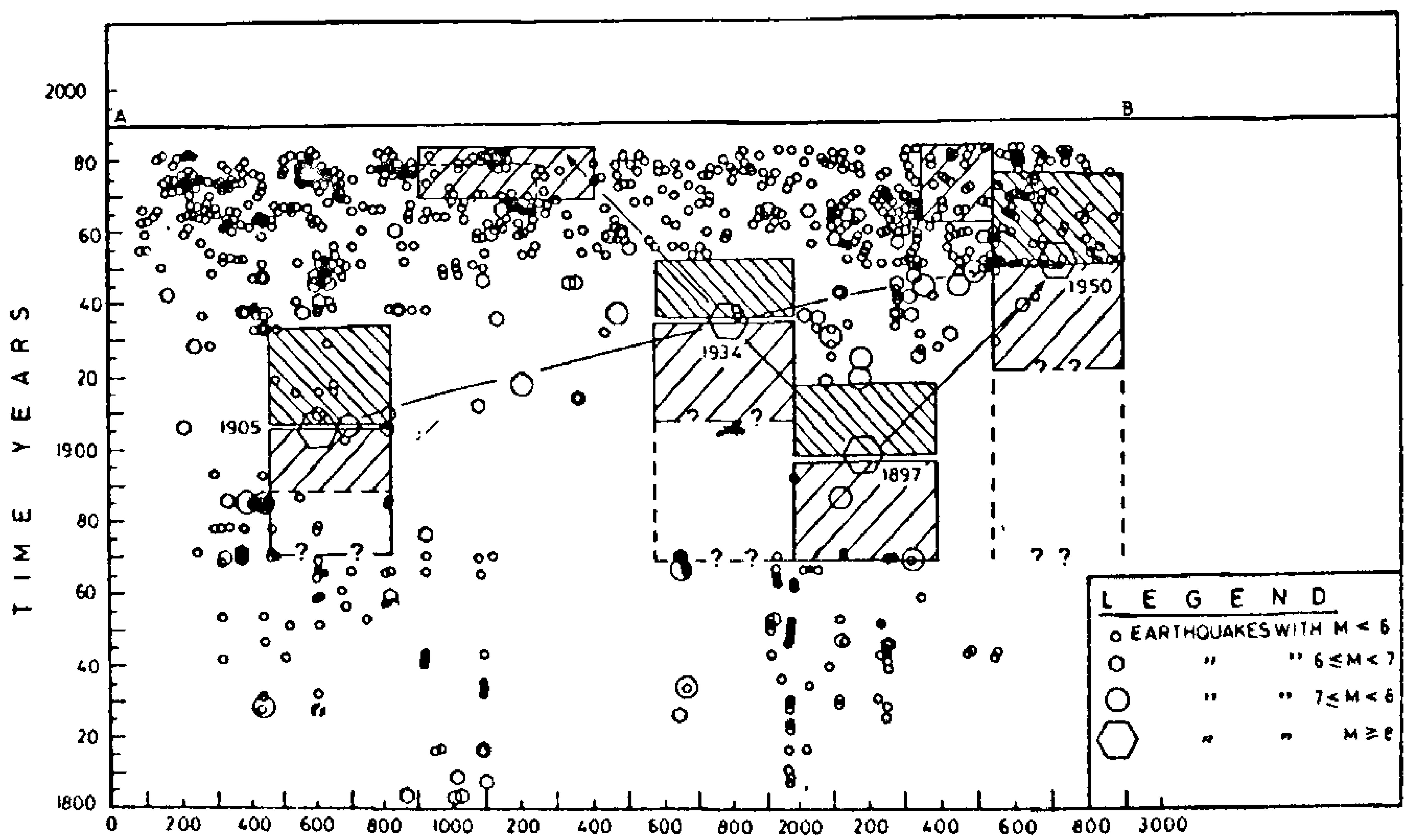

Figure 2. Space time plot of earthquakes in the Himalaya. The areas identified by boxes with left-slanting lines represent precursory quiescence and those with the right-slanting lines represent post great earthquake quiescence of magnitude $M \geq 6$. The boxes with broken lines represent possible alternative interpretations for quiescence periods. Arrows indicate possible migration trajectories of great earthquakes (after Khattri[14]).

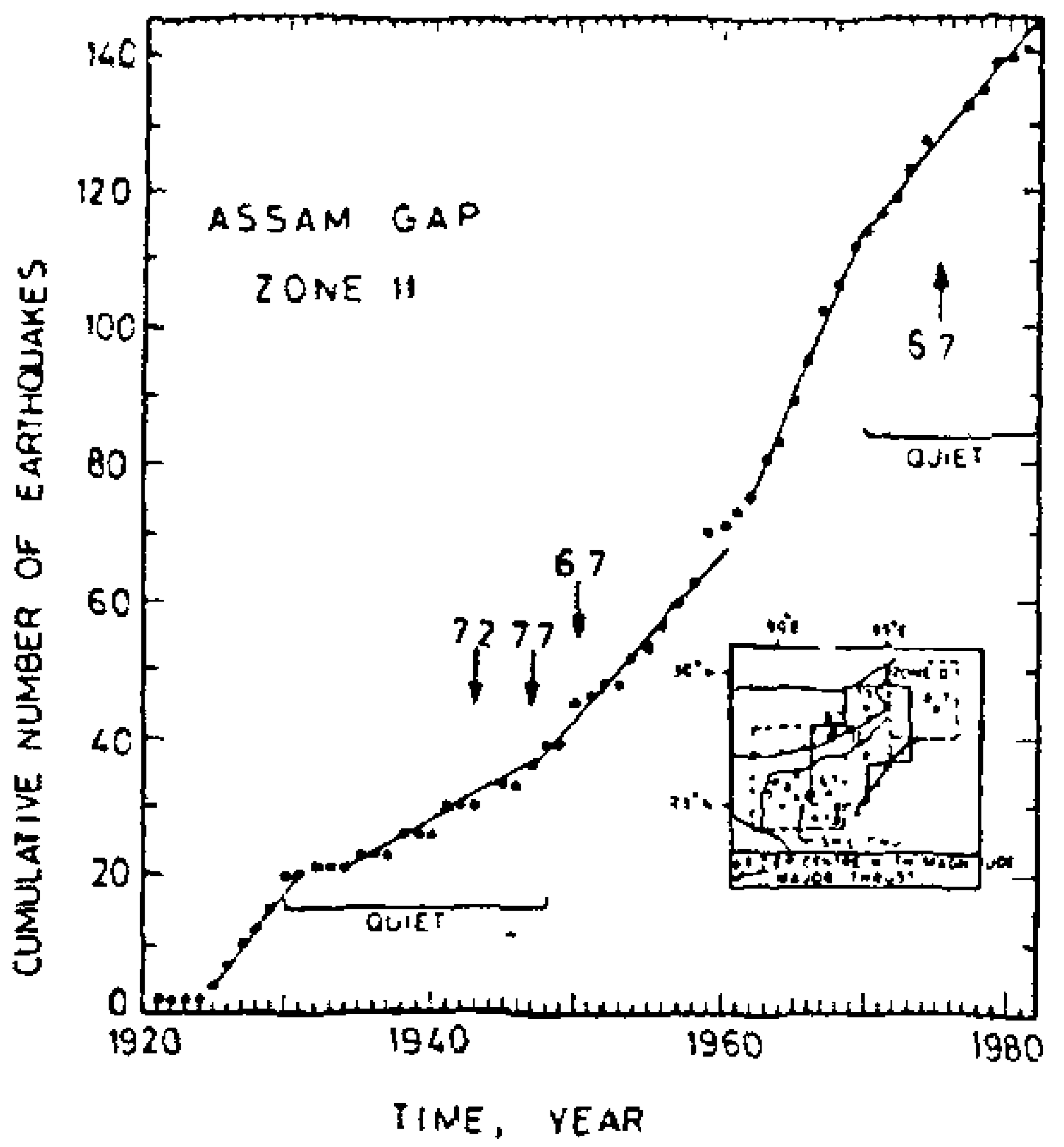

Figure 3. Cumulative number of earthquakes located in a zone encompassing the Assam gap shows decreased rate of seismic activity since about 1969 (after Khattri[14]).

sub-gap in the central gap is among the most likely locales of a major earthquake in future. The Indian lithosphere has been shown to be in a state of very high stress (in the kilobar range) by the modelling of plate motion forces[28]. The 1991 $M > 7.1$ earthquake in Uttarkashi tends to confirm the above findings. The other highly likely candidate for gap-filling earthquake is the Assam gap.

In the yearly release of seismic energy in the Himalaya as a whole, in the matter of release of the largest strains, there is a quasi-cyclicity with some clutter of about 35 to 55 years. A renewal model of earthquake occurrence has been proposed to describe such a feature of seismicity[29]. The last large strain was released in 1950. Since there is plate motion, the likely locales of future earthquakes are clearly identifiable. Although the repeat times of great earthquakes in the same segment are as yet not well constrained, some estimates put them at a few hundred years[17]. The difficulty is that at the present state of our knowledge we do not know when the last gap-filling earthquake was in the present gaps. Since we are dealing with human lives, the most conservative of the estimates must be adopted for earthquake hazard assessment. These may be revised as new knowledge becomes available.

1. Oldham, R. D., *Mem. Geol. Surv. India*, 1899, **26**, 1–379.
2. Middlemiss, C. S., *Mem. Geol. Surv. India*, 1910, **38**, 1–409.
3. Auden, J. B. and Ghosh, A. M. N., *Rec. Geol. Surv. India*, 1934, **68**, 177–239.
4. Gee, E. R., *Mem. Geol. Surv. India*, 1934, **65**, 1–106.
5. Richter, C. F., *Elementary Seismology*, Freeman, San Francisco, 1958, p. 764.
6. Rao, M. B. R., Central Board of Geophysics, Publ., 1953, vol. 1, p. 112.
7. Taft, J. V., U. S. Geol. Surv. Openfile Report, 1988, pp. 88–361, 7–11.
8. Uttarkashi Earthquake (M = 7.1) of October 1991, Newspaper accounts.
9. Reid, H. F., *The Mechanics of Earthquake*, Carnegie Institution, Washington, 1910, vol. 2.
10. Shimazaki, K. and Nakata, T., *Geophys. Res. Lett.*, 1980, **7**, 279–282.
11. Mogi, K., *Earthquake Prediction*, Academic Press, New York, 1985, p. 355.
12. Mogi, K., *J. Phys. Earth.*, 1968, **161**, 30–36.
13. Mogi, K., 1968, *Bull. Earthquake Res. Inst.*, Univ. Tokyo, 1968, **46**, *1225–1236*.
14. Khattri, K. N., *Tectonophysics*, 1987, **138**, 79–92.
15. Khattri, K. N., and Tyagi, A. K., *Tectonophysics*, 1983, **96**, 19–29.
16. Seeber, L. and Armbruster, J. G., in *Earthquake Prediction: An International Review* (eds. Simpson, D. W. and Richards, P. G.), Maurice Ewing Series, 4, Amer. Geophys. Union, Washington, D. C., 1981, pp. 259–277.
17. Molnar, P. and Pandey, M. R., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1989, **98**, 61–70.
18. Chander, R., *J. Sci. Res., Banaras Hindu Univ.*, Varanasi, 1991, **B41**, 1–8.
19. Gahalaut, V. K. and Chander, R., *Tectonophysics*, 1992.
20. Minster, J. B. and Jordan, T. H., *J. Geophys. Res.*, 1978, **83**, 533.
21. Kanamori, H., in *Earthquake Prediction: An International Review* (ed. Simpson, D. W. and Richards, P. G.), Maurice Ewing Series, Amer. Geophys. Union, Washington, D. C., 1981, vol. 4, pp. 1–19.
22. Aki, K., *J. Geophys. Res.*, 1984, **89**, 5867–5872.
23. Habermann, R. E., *Pure Appl. Geophys.*, 1988, **126**, 279–318.
24. Scholz, C. H., *Pure Appl. Geophys.*, 1988, **126**, 701.
25. Khattri, K. N. and Wyss, M., *Geology*, 1978, **6**, 685–688.
26. Toksoz, M. N., Shakal, A. F. and Michael, A. J., *Pure Appl. Geophys.*, 1979, **117**, 1258–1270.
27. Delsemme, J. and Smith, A. T., *Pure Appl. Geophys.*, 1979, **117**, 1271–1285.
28. Cloetingh, S. and Wortel, R., *Tectonophysics*, 1986, **132**, 49–67.
29. Nishenko, S. P. and Buland, R., *Bull. Seismol. Soc. Am.*, 1987, **77**, 1382–1399.