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SEISMIC HAZARD IN INDIAN REGION

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ABSTRACT – *The earthquakes constitute a rapid onset, natural hazard that poses a serious threat of catastrophic disaster in certain parts of India. This paper surveys the inputs required for preparing a well-estimated map of hazard for the country. The rationale for improving the above estimation by the identification of earthquake source processes and areas of high seismic potential are discussed. These include the concept of asperities and barriers, the velocity structure, the nature of rupture process, the geothermal status and the rate of plate convergence. The gaps in the existing knowledge base are identified and mechanisms to generate the missing knowledge, are suggested. The notions of vulnerability and risk posed by earthquakes are presented.*

INTRODUCTION

The earthquakes constitute a major quick-onset disaster. Even today when considerable understanding of the phenomena has been gained and methods of containing them have been evolved the recent earthquakes have caused severe damage and loss of lives.

Thus even with the progress of civilization the earthquake damages have not been reduced upto the desirable levels by the application of modern knowledge. There are two main factors responsible for this situation. Firstly the population centers have become denser with older unsafe structures under continued use and newer ones have not taken into consideration the modern technology. Secondly, there are still no working methods of short range earthquake prediction which could save lives.

It is instructive to compare the localities of earthquakes with the sites of major dams and hydro power plants shown in figure 1. The hydro-electric cum irrigation dams are in close proximity of the zones of severe seismic activity.

Several investigations have addressed the problem of assessing seismic hazard in the Indian region[1,2]. The effects of the earthquake phenomenon is estimated by calculating the probability of occurrence of a parameter representing the ground shaking in a certain exposure time window. These studies are based upon treating the earthquake phenomenon to be a uniform (in time and space) seismogenic process. They give reasonable average accounts of the hazard.

Recent studies of the earthquake processes have however shown that the processes are not stationary in either time or in space. Thus it is possible to refine the seismic hazard assessments by identifying fault sections which may produce characteristic earthquakes in a quasi periodic manner[3]. The recurrence rates, the state of earthquake preparation and the spectral content of the elasto-dynamic radiations, which depend upon the stress levels and the heterogeneity of the fault zone, from such segments may be estimated more objectively.

In the present analysis we address the above questions in respect of the seismic hazard in the Indian sub-continent.

SEISMIC HAZARD

Seismic hazard is taken here to refer to the exposure of any region to the destructive effects of the seismic phenomena. Seismic vulnerability is defined as the anticipated effects of earthquake phenomena on the structures and on human beings. Here the strength of the structures comes into play in addition to the seismic phenomenon. The anticipated loss, either in terms of property (currency) or human life is represented in terms of seismic risk. The seismic risk is a function of seismic hazard and seismic vulnerability and may increase or decrease as a function of time accordingly as an area develops or decays due to population migration or fluctuations in economic activity.

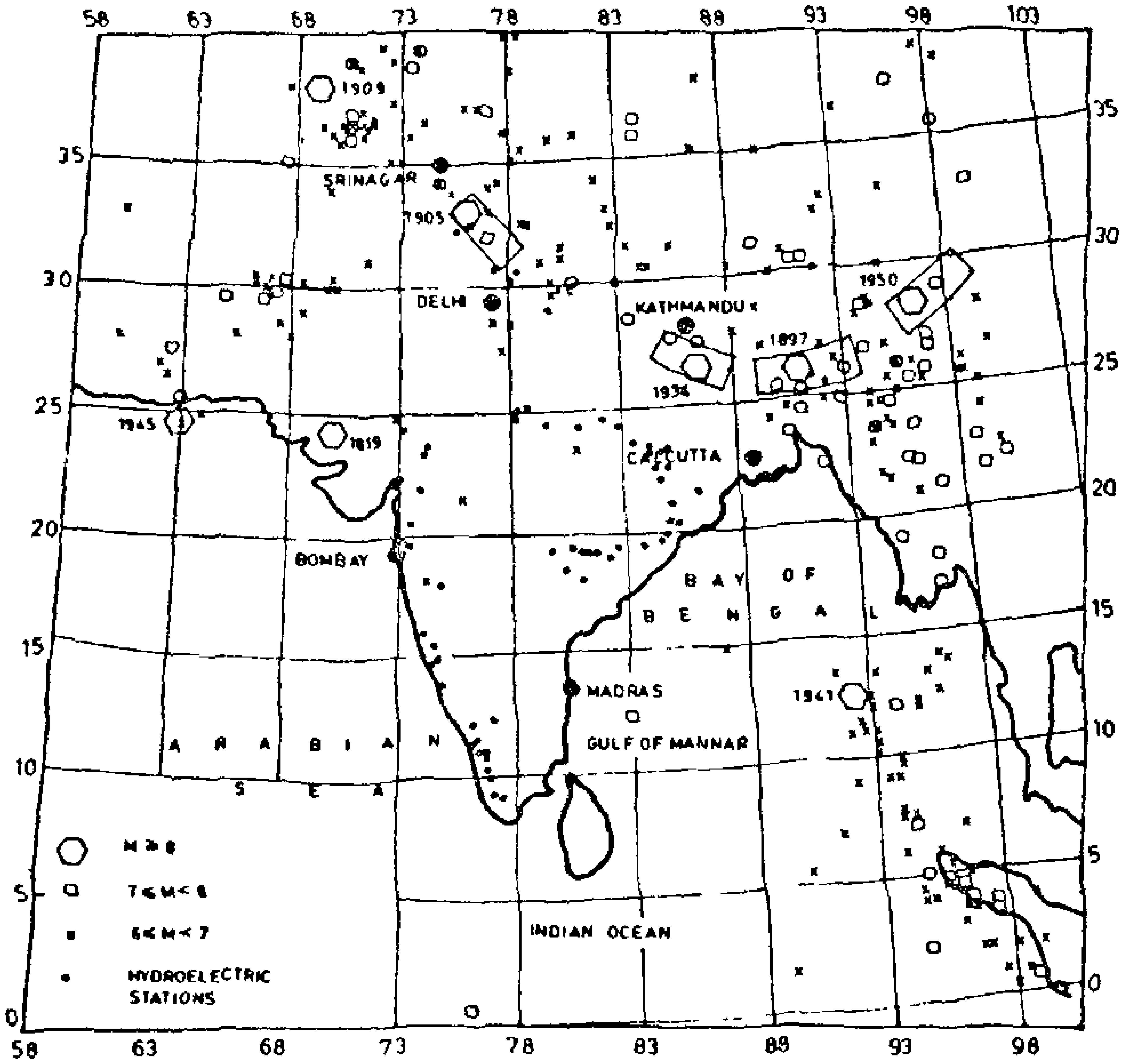


FIGURE 1 The epicentres of earthquakes with magnitude M ≥ 6 (upto the present time) and nearby hydro-electric power plants are shown. The generalised meizoseismal zones of the great earthquakes are shown by boxes.

The damage due to earthquakes is caused by various associated phenomena which may be categorized into those which are caused by the direct effects of faulting such as damage to the foundations of the structures, tilting of ground, damage due to ground shaking caused by seismic waves, tsunamis etc. The land slides, soil liquefaction, ground slumping and cracking, excitement of seiches, fires, breakdown of civic facilities like power, water, communication disruption and destruction of medical facilities are the indirect phenomena.

The seismic hazard mapping begins with the delineation of the seismic source zones. One characterizes the nature of the earthquake processes, the estimation of the recurrence time for various magnitude earthquakes, the selection of the maximum possible *future earthquake*, and the definition of the wave attenuation rate. Using these inputs and representing the earthquake occurrence process usually as a Poisson distribution the estimates of expected ground motion parameters (e.g., peak ground acceleration, or peak ground velocity etc.) in a certain given time window are mapped for a given probability of exceedance[1].

It is now recognised that there are earthquake quasi cycles in convergence zones which depend upon the convergence rates of the lithospheric plates. Sections of the plate boundaries rupture with quasi periodicities[4,5]. The seismic gaps are those sections of a convergent plate boundary which have not ruptured in the most recent tens of years and have accumulated tectonic strain. The strain will be released in the next great gap filling earthquake.

The heterogeneity in the fault zone renders the radiation of elastodynamic field to be characteristic for each zone. This has to be investigated in terms of asperities and barriers[6,7] and to determine, if possible, the characteristic earthquakes for each such zone. Incorporating such details in the analysis will help improve the seismic hazard maps.

SEISMIC MORPHOLOGY

The earthquakes at the plate boundaries occur as a consequence of the accumulation of the strain due to the relative motion of the plates. In this model the plates are assumed to behave as rigid bodies and the strain release takes place at the plate boundaries which behave as brittle material. Thus, it is the plate motion coupled with the heterogeneous behaviour of the crustal material on the plate scale that produces the global earthquake distribution. Not all stress is released at the plate boundaries, however, intraplate earthquakes are evidence that a part of such strain is released outside the plate boundaries and to that extent it also represents the departure of the plates from rigid body assumption[8].

Similarly on a regional scale also we observe rigid blocks which are largely aseismic and are bordered by relatively softer regions having seismic activity representing faulting.

Figure 1 shows the seismicity of the Indian region. One can discern an arcuate belt of seismicity following the Himalaya mountain belt. The Peninsular India presents a relatively quiet picture with fewer earthquakes. The earthquakes are defining block tectonics on a regional scale although their definition is not clear in this figure as only larger earthquakes have been plotted which are relatively few in number.

CHARACTERISTICS OF SEISMIC SOURCE ZONES

We consider here in some depth the seismic source zone associated with the Himalaya as most of the earthquake hazard arises in this zone.

There are a limited number of well-determined earthquake focal mechanism solutions which show a gently dipping nodal (fault) plane towards NE, perpendicular to the local strike of the Himalaya mountain belt, and the other one dipping steeply towards SW[9-13] (figure 2). The depth of focus of these events is about 12–20 km, confining them to the upper crust. The slip vector dips at about 15°–25° in the NW sector whereas at shallower angles of about 5° in the eastern sector. These earthquakes represent the rupturing of the upper surface of the Indian plate as it subducts at the convergent boundary[13-15].

Several focal mechanism solutions displaying strike slip and dip slip faulting have also been presented[11,16,17].

There are strike slip solutions for earthquakes in the source zones in the extreme west. The strike of these fault planes is NW-SE parallel to the strike of the Himalaya and the source zones and depicts right lateral motion[18]. A well determined E-W trending left lateral strike slip zone has been established in Garhwal Himalaya[19]. Besides, several NE or NW trending strike slip solutions have been obtained which are in consonance with similar geological structures and lineaments[17,20,21].

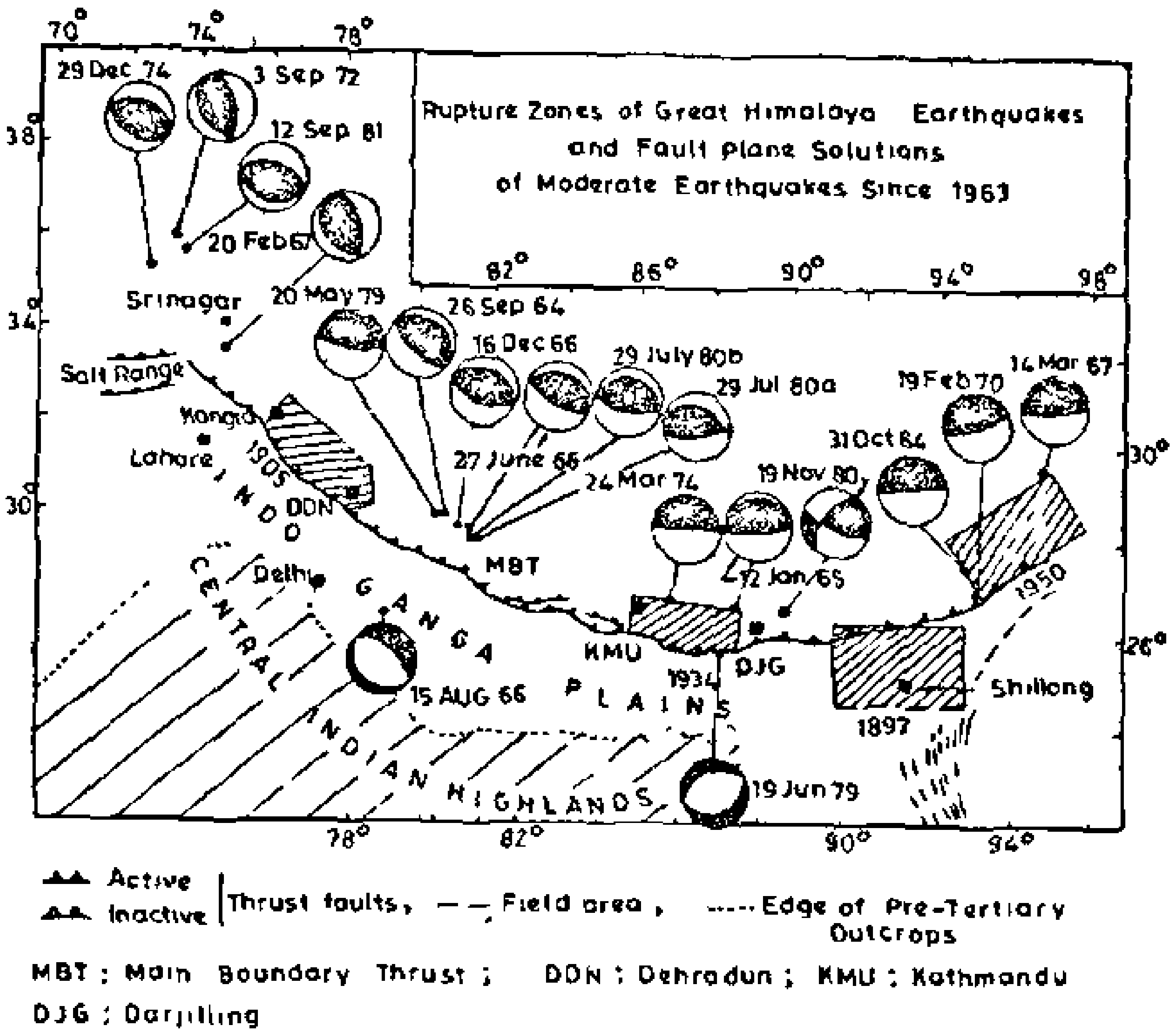


FIGURE 2 Summary of fault plane solutions and the nature of dislocations in the region of Himalaya plate boundary. Hatured areas are the rupture zones of the great earthquakes.

The depths of focus of earthquakes is not confined to the upper about 20 km of the crust everywhere. Figure 3 shows the nature of this variation along the strike of the Himalaya in the western sector. Furthermore, the deeper earthquakes have been located in the north western region (around 73°E, 34.5°N)[18].

Detailed seismological investigations in the Garhwal-Kumaon Himalaya have shown that the small earthquakes there are confined to the upper about 20 km of the crust[22].

Similarly high resolution seismological investigations in the Shillong massif region have demonstrated a complex picture of active tectonics in the upper crust[22,23,24]. However underlying this picture of tectonics in the upper crust, northward underthrusting of the Indian shield takes place giving rise to great plate boundary earthquakes.

Thus there is reliable evidence that the earthquake process which is basically driven by the convergence of the Indian and the Eurasian plates is considerably perturbed to produce a variety of active tectonic signatures along the Himalaya as summarized in figure 4.

CRUSTAL STRUCTURE

Several studies have shown that the crustal structure of the Ganga foredeep is different on the east as compared to the west of the Delhi-Hardwar ridge (Aravallis).

The nature of the uppermost Indian plate in Ganga foredeep is quite heterogeneous[25,26]. The region west of

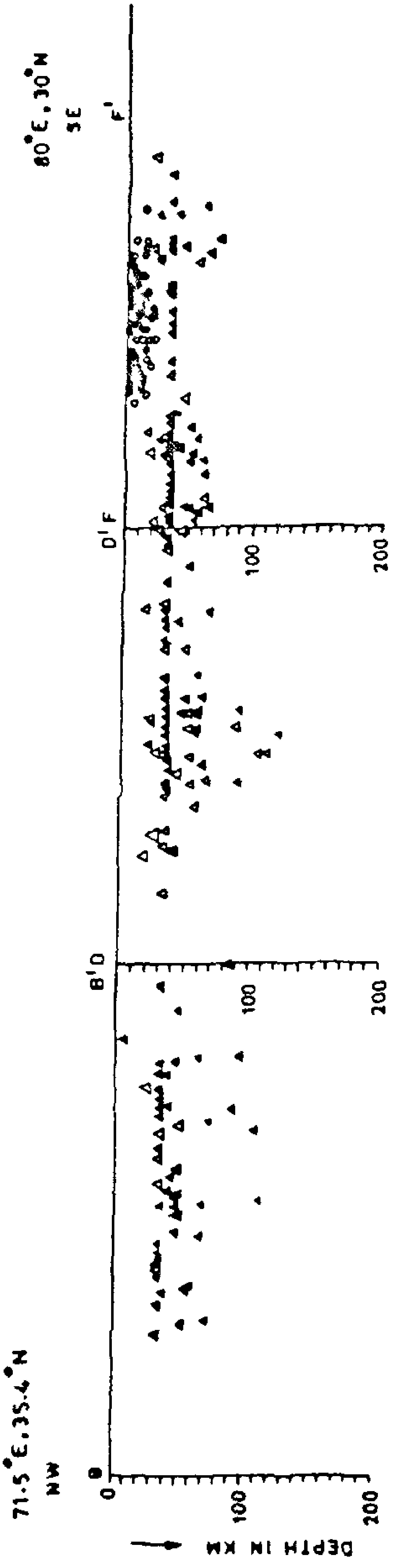


FIGURE 3 The distribution of the depth of focus of earthquakes along the strike of Himalaya in western sector. Triangles represent teleseismically located earthquakes. Circles represent locally recorded earthquakes.

the Delhi–Hardwar line is a gently NE dipping basement supporting a sedimentary pile of about 2 km near the foot hills. The region eastward is a complex aggregate of basins and faulted ridges trending in NE-SW direction. The sedimentary thickness at its maximum exceeds 10 km near the foot hills. The Delhi–Hardwar region itself is a zone that represents a salient of the NE trending Aravalli ranges. This considerable variation of the sedimentary cover is likely to accompany responses in the deeper crustal structure and thickness. One may expect a thinning of the lower crustal layer in the regions of considerable sedimentary thickness[27]. Thus the rheological response at the collision boundary will be expected to have a corresponding perturbation.

The surface wave dispersion studies[28,29] have demonstrated that the average crustal structure of the section of the Ganga foredeep west of the Aravalli (Delhi–Hardwar ridge) is having oceanic affinity whereas on the east it is typically continental.

The magnetic signatures in the western part of the Sindhu–Ganga foredeep are different than in the east of Delhi–Hardwar ridge[25,30]. In the west the contours define elongated 2-D anomalies that locally parallel the Himalaya strike.

A transversely trending zone of high conductivity has been delineated along the Delhi–Hardwar ridge[31,32]. Among the explanations offered for the anomaly are

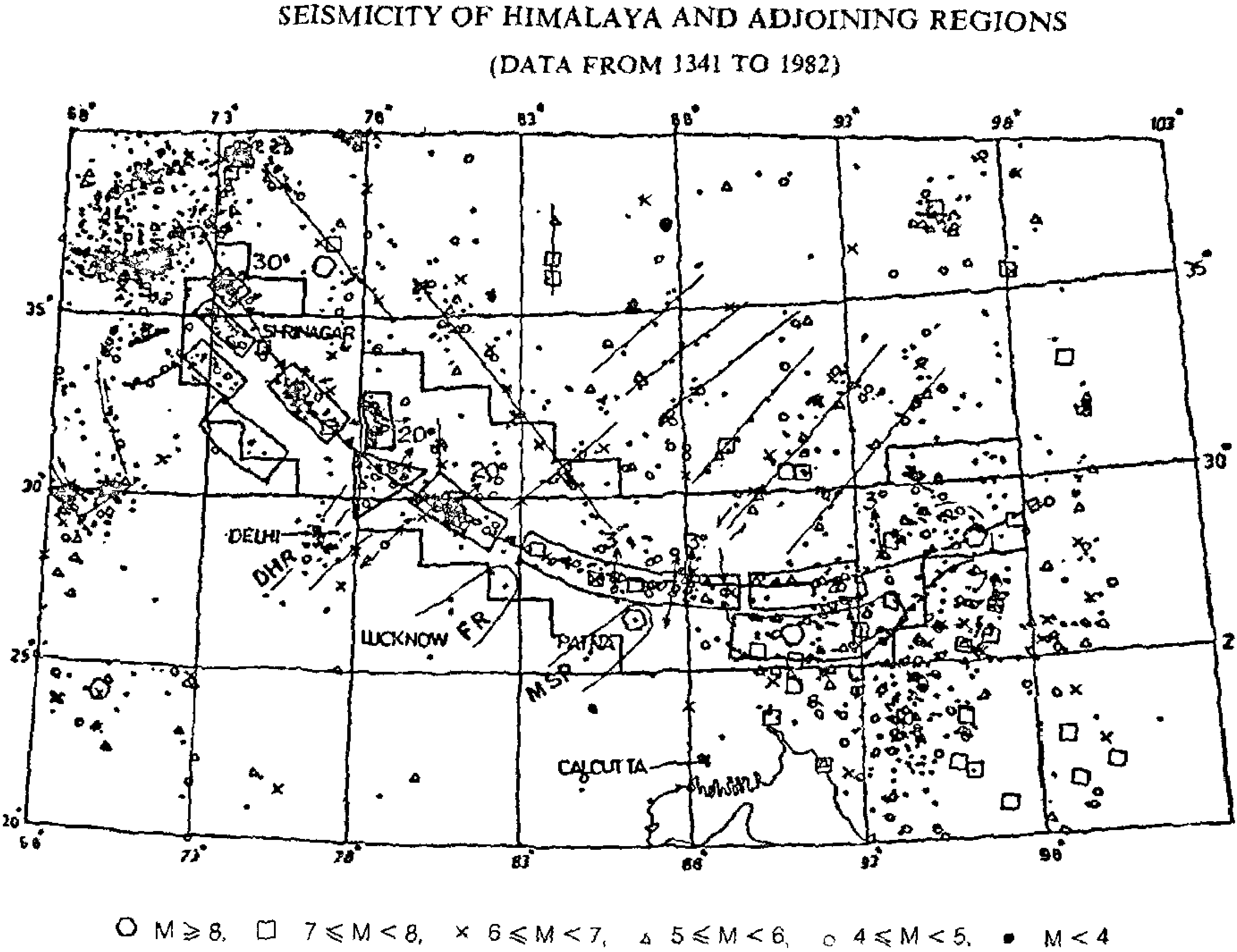
- *Existence of a shear zone*
- Upwelling of a highly conducting asthenosphere
- Layer contrast in electrical conductivity between two sides of the Aravalli ridge.

The deep geomagnetic soundings (GDS)[31,32] have established the presence of elongated high conductivity zones that follow the Lesser Himalaya in the north western sector. The high conductivity zones in Lesser Himalaya may be caused by the hydrous sediments of Ganga foredeep subducted beneath them and along the shear zones[33].

Chun[29] suggested that the higher plunge of earthquake nodal (fault) planes 20°–25° in the western Himalaya as compared to less than 10° in the eastern Himalaya is a reflection of the crustal structure complexity cited above.

Similarly the geological picture of the Himalaya zone shows a considerable variation along arcuate mountain belt. The Main Central thrust (MCT) and the Main Boundary thrust (MBT) are sinuous and come very close to each other in the western side (west of about 78°E). In Garhwal Himalaya they are quite far apart. The bends in the thrusts may be the sites of locking of slip and may serve as asperities. Such sections need to be identified and their role in hazard estimation needs to be included.

The development of systematic frontal folds in the



SEISMICITY OF HIMALAYA AND ADJOINING REGIONS

(DATA FROM 1341 TO 1982)

FIGURE 4 The scheme of dominant active deformation in the Himalaya region. DHR: Delhi Hardwar ridge; FR; Faizabad ridge; MSR: Mongheyr Saharsa ridge. Arrows with numbers represent the slip vectors of thrust earthquakes. Pairs of arrows forming dipoles represent normal earthquakes. Strike slip motion is shown by pairs of oppositely directed arrows. Lines are identifying possible earthquake lineaments. Boxes are representing earthquake source zones.

Siwalik and younger strata is caused by the scrapping action of the overthrusting northern block. The frontal folded belt is the site of considerable neotectonic activity[34,35]. However moderate-sized earthquakes are rare in this domain. The deformation may therefore be largely occurring by creep in the soft upper Tertiary sediments induced by episodic great earthquakes. Such models have to be taken into consideration in hazard estimation.

The seismicity in the Ganga foredeep is not well investigated. A fairly large event occurred near Moradabad which was interpreted to be a tensional earthquake related to the bending of the Indian plate. Some small events have been recorded in this region by a microearthquake network[36]. These could be representing either reactivation of faults in the basement or formation of a new thrust front. There is evidence of north hading thrust in the pre-tertiary formations that may progress upwards into upper Tertiary formations as revealed by reflection seismic surveys (personal communication: V. Raiverman, ONGC). This supports the second possibility mentioned above.

The thermal picture of the region shows very high thermal gradients (twice the normal) existing in the Higher Himalaya north of the MCT. The Lesser Himalaya region between the MCT and MBT also has on an average 130% the normal thermal gradient[37]. However the estimates of S_n velocity in the region implies that the material is not having elevated temperatures[38]. Thus the impact of the thermal data on earthquake processes in the Himalaya will have to await further studies.

RUPTURE ZONES OF GREAT EARTHQUAKES

The estimates of rupture zones of the great Indian earthquakes since 1897 are as follows[13,14,39–45].

1897 Assam $160\,\text{km} < L < 550\,\text{km}$;
1905 Kangra $250\,\text{km} < L < 280\,\text{km}$;
1934 Bihar $100\,\text{km} < L < 300\,\text{km}$;
1950 Assam $200\,\text{km} < L < 450\,\text{km}$,

where L is the length. Oldham[39], Molnar[44,45], Khattri and Tyagi[41], Khattri[42], Chander[43,46], and Molnar and Pandey[13] favour lower estimates, whereas, Seeber and Armsbruster[14] suggested higher estimates.

Khattri and Tyagi[41] and Khattri[42] find that the nucleation of these earthquakes has a correlation with the basement highs in the subducting Indian plate. Thus, major asperities[6] and barriers[7] produced by the geological heterogeneities play a governing role in controlling the location of the initiation and stopping of the faulting and therefore of the fault dimension. The average fault length for an $M > 8.4$ earthquake may be taken to be 270 km.

The rupture zones of the aforementioned great earthquakes have left seismic gaps that have not ruptured for at least the past one hundred years in a great earthquake[42]. These gaps have a higher potential for a future gap filling great earthquake. The Assam seismic gap has an estimated length of 200 km and is capable of generating an $M = 8$ earthquake. The gap between the 1905 and 1934 earthquakes is about 800 km long. This may be divided into two sections by the Faizabad salient forming an asperity. Thus two characteristic great earthquakes can fill the gap in the future[42]. These gaps have also been recognized to have a high probability for large future earthquakes by Bhatia *et al.*[47] on the basis of pattern recognition.

EARTHQUAKE CYCLE

The frequency of occurrence of great earthquakes along a plate boundary is governed by the rate of strain accumulation[48]. As the strain accumulates in a section of the plate boundary the region displays a drop in seismic activity due to strain hardening several tens of years prior to the catastrophic event[5]. Such a quiescence has been recognized to be at present existing in the Garhwal–Kumaon sector of the gap and in the Assam gap[42,49].

The seismological data does not go sufficiently back in time to allow the observation of even one complete cycle in the Himalaya. However the estimates of the average recurrence time of great earthquakes in the Himalaya have been estimated to range between 200 to 270 years[13,14]. The longest time elapsed since a great earthquake ($M > 8$) in the identified gaps is at least 186 years. Thus some gaps may be dangerously close to rupture.

The notion of cycle must be qualified by the fact that earthquakes are a non-linear phenomenon. Thus they will be following a deterministic chaotic behaviour[50] and their predictability as a cycle will be cluttered by chance.

FAULT ZONE HETEROGENEITY

Although the length of coherent rupture determines the largest earthquake in a plate section, in detail the fault zone is also heterogeneous. This implies variability in the strength of the zone as a function of space. The distribution of hard spots determines the spectral content of the elastodynamic radiations[7] which will be critical in estimating the seismic vulnerability of various facilities. In order to map the fault zones a high definition seismological monitoring is needed.

MODELLING EARTHQUAKE SEQUENCES

A pivotal element in the earthquake hazard mapping involves a suitable representation of the occurrence of earthquakes. The most prevalent model is the Poisson process. This model assumes an average rate of occurrence anywhere in a source zone that is stationary in time. This assumption is inadequate in the light of our current understanding of the earthquake phenomenon. Time dependent models have been developed. Another suggestion is to use compound Poisson model wherein the rate of the process itself is a random variable[51].

SITE EFFECTS

The local site geology can play a very significant role in the type of damage caused by earthquake shaking. An example of this is the soil liquifaction observed in the great 1934 Bihar earthquake and subsequently in the 1988 smaller Bihar earthquake. Mapping of the profile of the physical properties, in particular the shear wave speed profile, of the upper one kilometer or so will be useful in quantizing the site effects.

DISCUSSION AND CONCLUSIONS

Some of the scientific issues involved in preparing a well-estimated seismic hazard map of the Indian region have been presented in the foregoing paragraphs. The

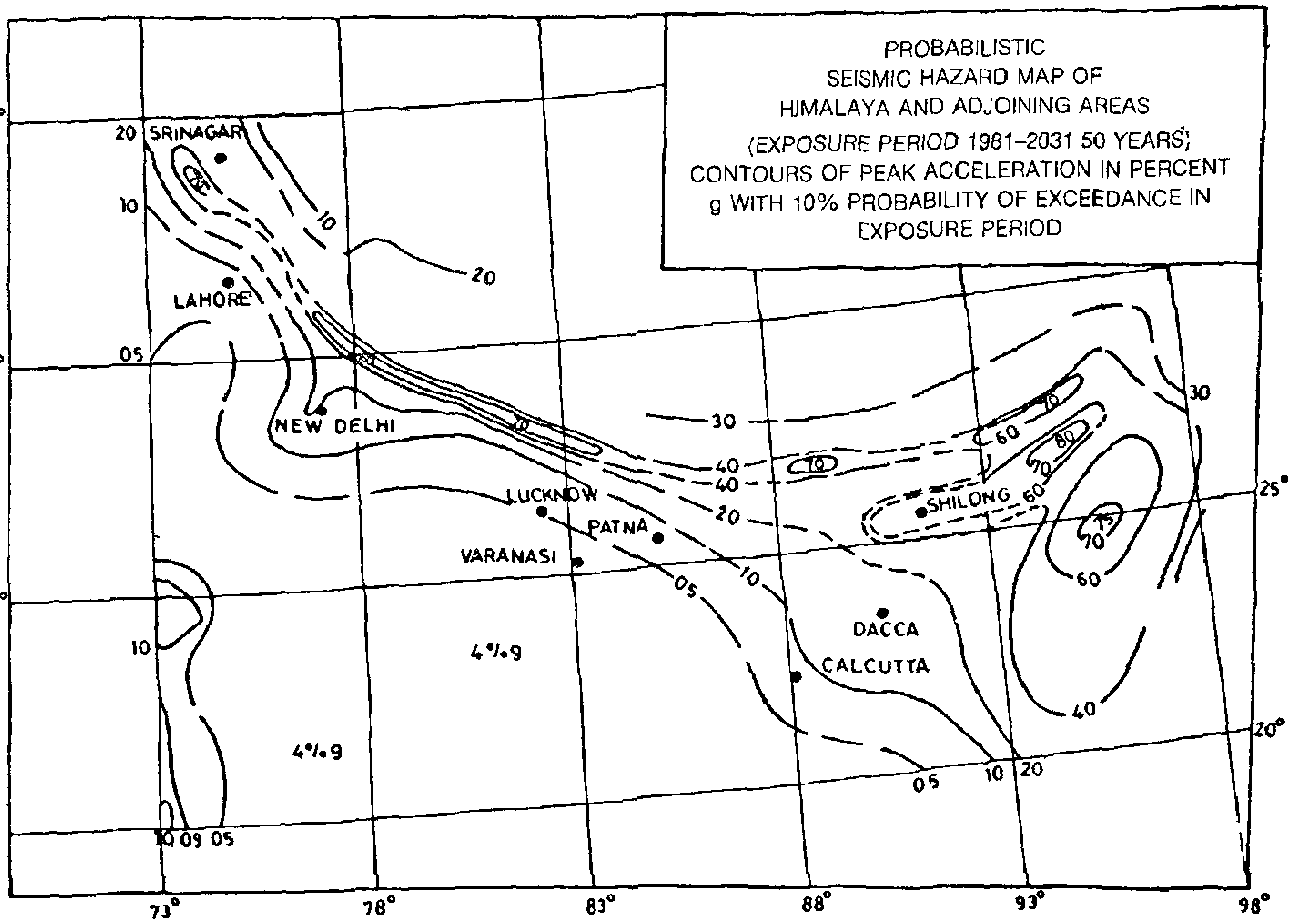


FIGURE 5 Probabilistic seismic hazard map of Himalaya and adjoining areas for exposure period 1981–2031.

present state of knowledge in India is still nebulous in many critical areas to allow a detailed characterization of the seismic hazard.

Questions regarding the influence of local ground response, saturation of ground motion parameters with magnitude, the possibly different attenuation laws for the near field and the far field ground motion are some of the additional difficulties that need to be addressed in improving characterization of the hazard.

Yet another aspect is to take into account particularly high ground accelerations that are expected in convergent plate boundary environment like Himalaya. The Assam earthquake of 1897 recorded vertical accelerations exceeding 1g. Accelerations of over 1g can occur in the near field of moderate earthquakes as has been observed in several cases.

The hazard posed by induced seismicity by man-made reservoirs also needs to be addressed for specific projects. A suitable approach to gain useful information will be to study analogs of seismicity prone zones in various regions to compliment information available in each of them. This may require international cooperation as envisioned in the decade for natural hazard reduction.

Not withstanding the various grey areas in our knowledge a seismic hazard map for the northern region is shown in figure 5 which incorporates the concept of earthquake cycles in a crude way. No attempt is made here to quantify the vulnerability of the region or to prepare the risk map although rough ideas about these parameters can be had from figure 1 and population map. A coordinated program of focussed investigations is needed to refine such maps in this decade.

REFERENCES

1. Khattri, K. N., Rogers, A. M., Perkins, D. M. and Algermissen, S. T., *Tectonophysics*, 1984, **108**, 93.
2. Basu, S. and Srivastava, L. S., Symp. Earthquake Disaster Mitigation, Univ. of Roorkee, Roorkee, 1981, **1**, 99.
3. Schwartz, D. P. and Coppersmith, K. J., *J. Geophys. Res.*, 1984, **89**, 5681–5698.
4. Fedotov, S. A., *Tr. Inst. Fiz. Zemli, Akad Nauk SSSR*, 1965, **36**, 66.

5. Mogi, K., *Bull. Earthquake Res. Inst., Tokyo*, 1968, **46**, 53–74.
6. Kanamori, H., in *Earthquake Prediction. An International Review, Maurice Ewing Ser.*, (ed. Simpson, D. W. and Richards, P. G.) AGU, Washington, D C., 1981, **4**, 1–19.
7. Aki, K., Asperities, barriers, characteristic earthquakes, and strong motion prediction. *J. Geophys. Res.*, 1984, **89**, 5867.
8. Hanks, T. C., *U S Geol. Surv. Bull. 1985*, **40**, *1659*.
9. Fitch, T. J., *J. Geophys. Res.*, 1970, **75**, 2699.
10. Chandra, U., *Phys. Earth Planet. Inter.*, 1978, **16**, 1091.
11. Ni, J. and Barazangi, M., *J. Geophys. Res.*, 1984, **89**(B2), *1147*.
12. Baranowski, J., Armbruster, J., Seeber, L. and Molnar, P., *J. Geophys. Res.*, 1984, **89**(B8), 6918.
13. Molnar, P. and Pandey, M. R., *Proc. Indian Acad. Sci. (Earth and Planet. Sci.)*, 1989, **98**(1), 61.
14. Seeber, L. and Armbruster, J. G., in *Earthquake Prediction: An International Review. Maurice Ewing Ser.*, (ed. Simpson, D. W. and Richards, P. G.) AGU, Washington, D.C., 1981, **4**, 259.
15. Molnar, P., *Philos. Trans. R. Soc. London*, 1988, **A 326**, 33.
16. Mukhopadhyay, M., *Tectonophysics*, 1984, **109**, 227.
17. Dasgupta, S., Mukhopadhyay, M. and Nandy, D. R., *Tectonophysics*, 1987, **136**, 255.
18. Seeber, L. and Armbruster, J., in *Geodynamics of Pakistan* (eds. Farah, A. and Dejong, K. A.) Geol. Surv. Pakistan, Quetta, 1979, p. 131.
19. Khattri, K. N., Chander, R., Gaur, V. K., Sarkar, I. and Kumar, S., *Proc. Indian Acad. Sci. (Earth and Planet. Sci.)*, 1989, **98**(1), 91.
20. Khattri, K. N. and Tyagi, A. K., *Tectonophysics*, 1983, **96**(1/2), 19.
21. Valdiya, K. S., *Tectonophysics*, 1976, **32**, 353.
22. Khattri, K. N., submitted to *Geol. Soc. India*., 1990.
23. *Khattri, K. N., submitted to Geol. Soc. India., 1990.*
24. Mukhopadhyay, Ph. D. Thesis, Roorkee University, Roorkee, 1990, p. 247.
25. Sengupta, S. N. and Khattri, K. N., *Proc. Indian Natl. Sci. Acad.*, 1975, **41**, Pt A, No. 4, 339–357.
26. Agrawal, R. K., in *Geophysical Case Histories of India*, (eds. Bhimsankaram, V. L. S. and Gaur, V. K.) Association of Exploration Geophysicists, Hyderabad, 1978, Vol. 1, p. 22.
27. Matthews, D. H., in *The Nature of Lower Continental Crust*, (eds. Dawson, J. B., Carswell, D. A., Hall, J. and Wedepohl, K. H.) Geol. Soc. Sp. Pub., Blackwell Scientific Publications, 1986, **24**, pp. 11, 394.
28. Chaudhary, H. M., *Ind. J. Meteorol. Geophys.*, 1966, **17**, 385.
29. Chun, K. Y., *Bull. Seismol. Soc. Am.*, 1986, **76**(6), 1687.
30. Querashy, M. N., Kumar, S. and Gupta, G. D., 1989, *Mem. Geol. Soc. India*, 1989, **12**, 207.
31. *Lilley, F. E. M. et al., Phys. Earth Planet. Inter.*, 1981, **25**, 232.
32. Arora, B. R., *Phys. Earth Planet. Inter.*, 1987, **45**, 128.
33. Haak, V. and Hutton, R., in *The Nature of the Lower Continental Crust*, (eds. Dawson, J. B., Carswell, D. A., Hall, J. and Wedepohl, K. H.,) Geol. Soc. Special Publication No. 24, Blackwell Scientific *Publications, 1986*, **35**, p. 393.
34. Valdiya, K. S., *Proc. Intl. Symp. on Neotectonics in South Asia*, Survey of India, Dehradun, 1986, p. 241.
35. Narula, P. L., Shome, S. K., and Nandy, D. R., 1989 in Geology and Tectonics of the Himalaya. *Geol. Surv. India, Spl. Pub.* 26, *1989, 119*.
36. Kumar, A., Ph. D. Thesis, Roorkee University, Roorkee, 1988, p. 276.
37. Shankar, R., *Indian Miner.*, 1988, **42**(2), 89.
38. Ni, J. and Barazangi, M., *Geophys. J. R. Astron. Soc.*, 1983, **72**, *665*.
39. Oldham, R. D., *Mem. Geol. Surv. India*, 1899, **26**, p. 379.
40. Singh, D. D. and Gupta, H. K., *Bull. Seismol. Soc. Am.*, 1980, **70**, 757–773.
41. Khattri, K. N. and Tyagi, A. K., *Tectonophysics*, 1983, **96**(3/4), 281.
42. Khattri, K. N., *Tectonophysics*, 1987, **138**, 79.
43. Chander, R., *Tectonophysics*, 1988, 149, 289.
44. Molnar, P., *J. Geol. Soc. India*, 1987, **29**, 221.
45. Molnar, P., *J. Geol. Soc. India*, 1987, **30**, 13.
46. *Chander, R., Tectonophysics, 1989*, **170**, *115*.
47. Bhatia, S. C., Chalam, S. V., Gaur, V. K., Keilis-Borok, V. I. and Kosobokov, V. G., *Proc. Indian Acad. Sci. (Earth and Planet. Sci.)*, 1989, **98**(1), 111.
48. Reid, H. F., Carnegie Inst., Washington, Publ., 1910, No. 87.
49. Khattri, K. N. and Wyss, M., *Geology*, 1978, *6*, *685–688*.
50. Huang, J. and Turcotte, D. L., *Nature*, 1990, **348**, 234–236.
51. Kapil, S. L., Singh, H., and Moharir, P. S., manuscript.

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