Evaluation of seismic hazard in India towards minimizing earthquake risk

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Earthquakes seem to have inscrutable ways of striking without warning. In this country they also strike at unanticipated sites and surprise us in a state of total unpreparedness. As a result, even moderate earthquakes take a heavy toll of life and property as the recent Khilari earthquake did, in addition to leaving many destitute. Such tragic situations are likely to occur with greater frequency in the future as our burgeoning human family pressed by their subsistence needs unwittingly proceeds to colonize every available ecological niche of the planet, unaware of the slow evolving and therefore unsuspected instabilities which might some day turn into a disaster. In this runaway situation the one effective measure for hazard reduction would be the design and construction of earthquake-resistant structures and retrofitting of existing ones based on a rational evaluation of seismic hazard throughout the country.

Indeed, commendable efforts have been made by some engineers using robust commonsense to produce such designs for human dwellings and utilities in known seismic areas. But this has not benefitted from any serious evaluation of seismic hazard that could have been translated into engineering specifications. Indeed, it is a matter of great public concern that this practice is largely true even for the design of large critical facilities as came to light during a peer scrutiny[1] of the design figures and risk analysis of the Tehri dam. But, whilst we do not yet fully understand the earthquake process, significant leads have been available for quite some time to systematically evaluate the seismic hazard in different parts of the country. As the imperatives of doing so are now being increasingly appreciated, a scientific approach to accomplishing this task and a minimum national programme for underpinning this endeavour is presented below.

Tectonic settings of earthquake zones in India

Figure 1 shows the distribution of earthquakes in the Indian continent which is typical of any epoch. The largest concentration is seen in a northern diffused zone several hundred kilometres wide which progressively broadens towards the east. A few earthquake clusters are also found along the west coast and the east coast. And, then there are quite a few others that occur right in the interior of the continent.

The Indian plate is able to hold aloft the world's highest mountain range on its northern border only by its persistent northward drive into Asia (Figure 2). The pervasive north–south compression so generated throughout the plate ensures that it is at any time under high stress, and provides the basic source for the accumulation of straining energy in its various fracture zones, both old and new. Most of this energy is clearly stored in the rock masses of the detachment faults along which the Himalaya ride over the underthrust Indian plate.

Recognition of the detachment faults (Figures 3 and 4) forming a major inter-continental fracture zone and the locus of all major earthquakes in the Himalaya is based on the convergence of various inferences: the strikingly arcuate shape of the mountain range which argues for a long time coherent regime of strain accumulation and relaxation along the entire boundary, the coincidence of the teleseismically determined[2] depths and fault slips of some moderate earthquakes in the central Himalaya as well as of the best determined locations of the four great earthquakes with a low angle northward dipping plane, the truncation of the source

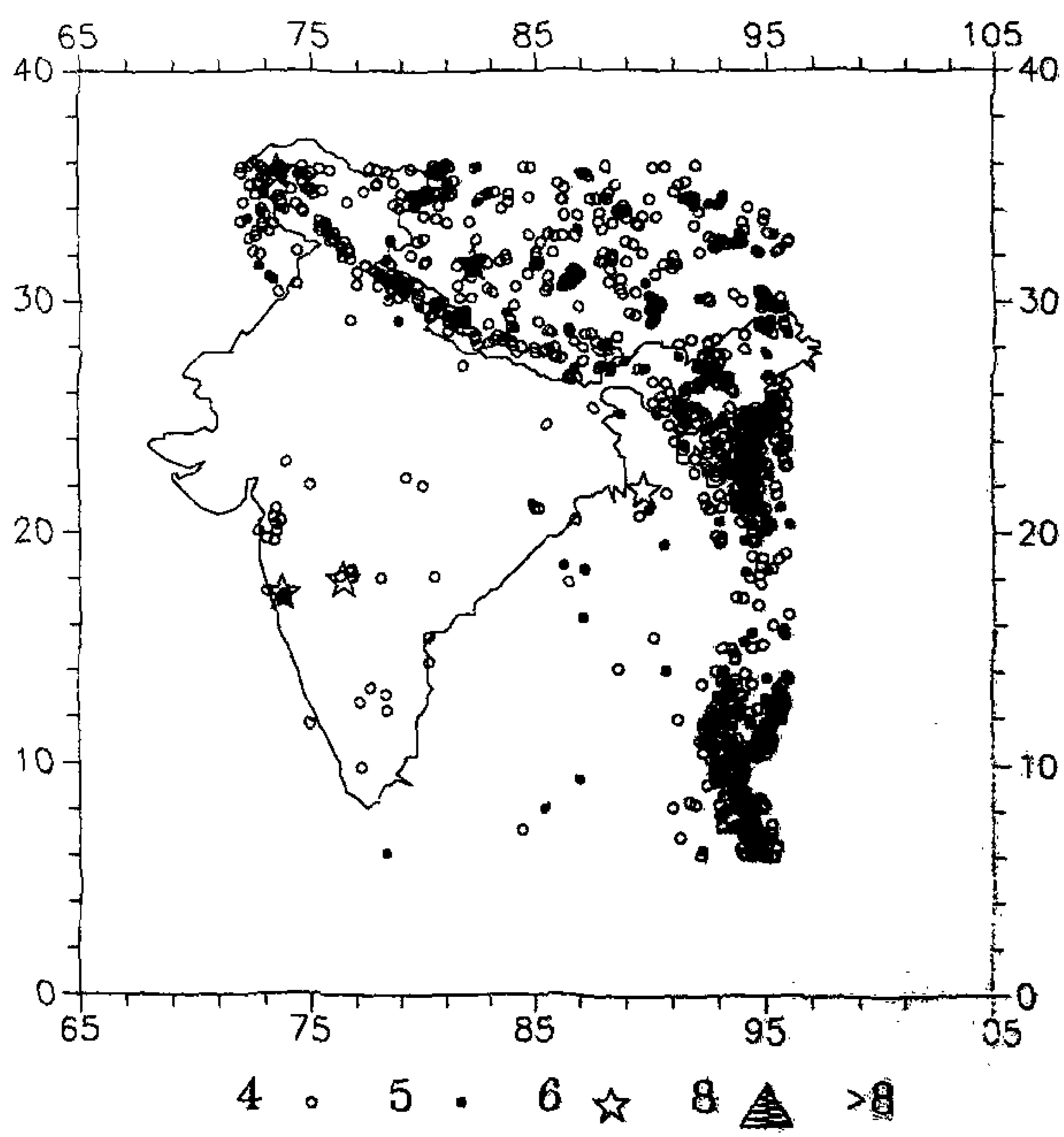

Figure 1. Distribution of earthquakes in India ($M > 4$, period 1981–1983) which is typical of any other epoch.

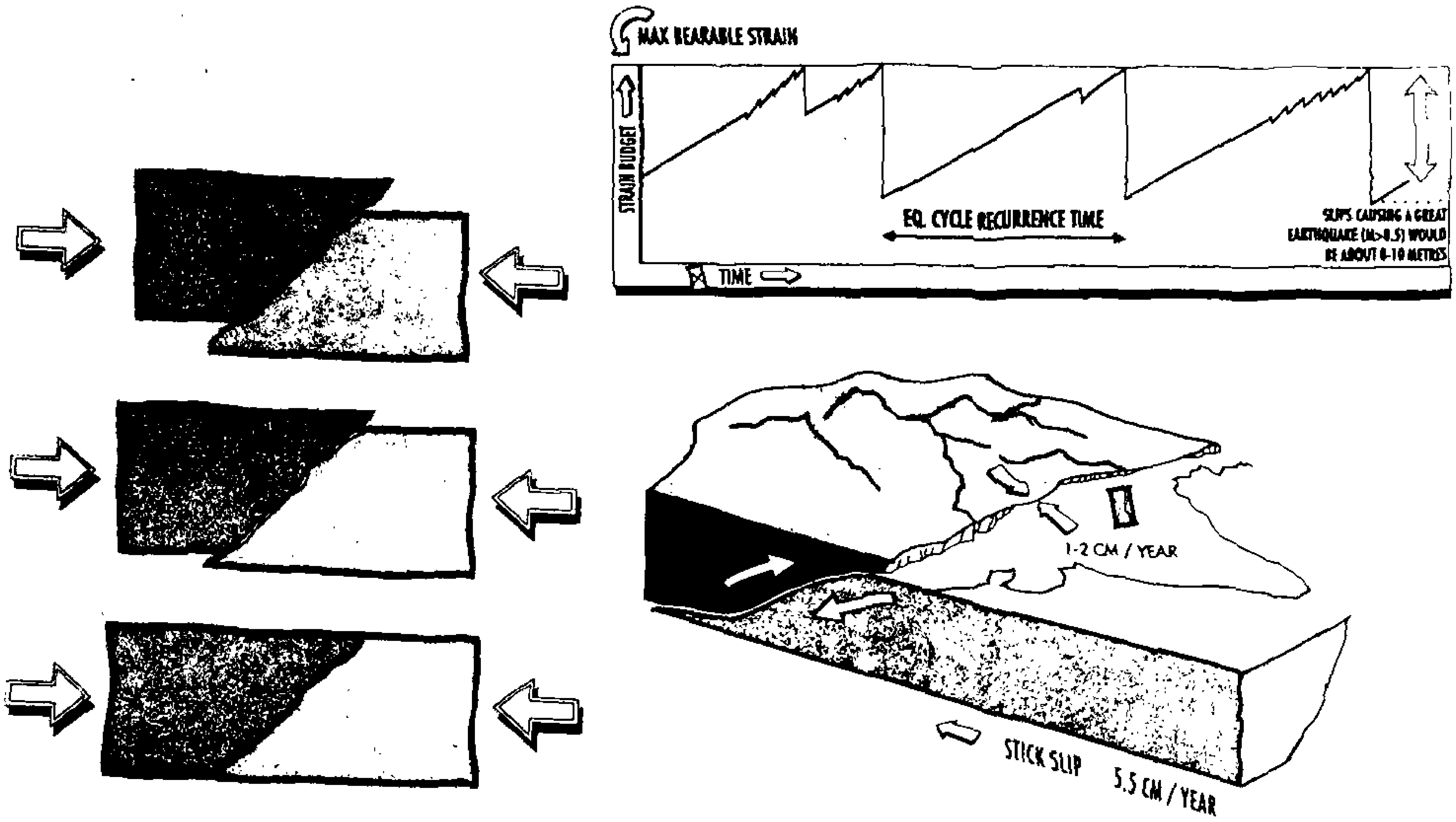

Figure 2. Tectonic setting in which the entire Himalaya made up of the stacked sliced edges of the northward pushing Indian plate, overthrusts the latter in catastrophic slips, creating a series of great earthquakes every few hundred years from one end to the other.

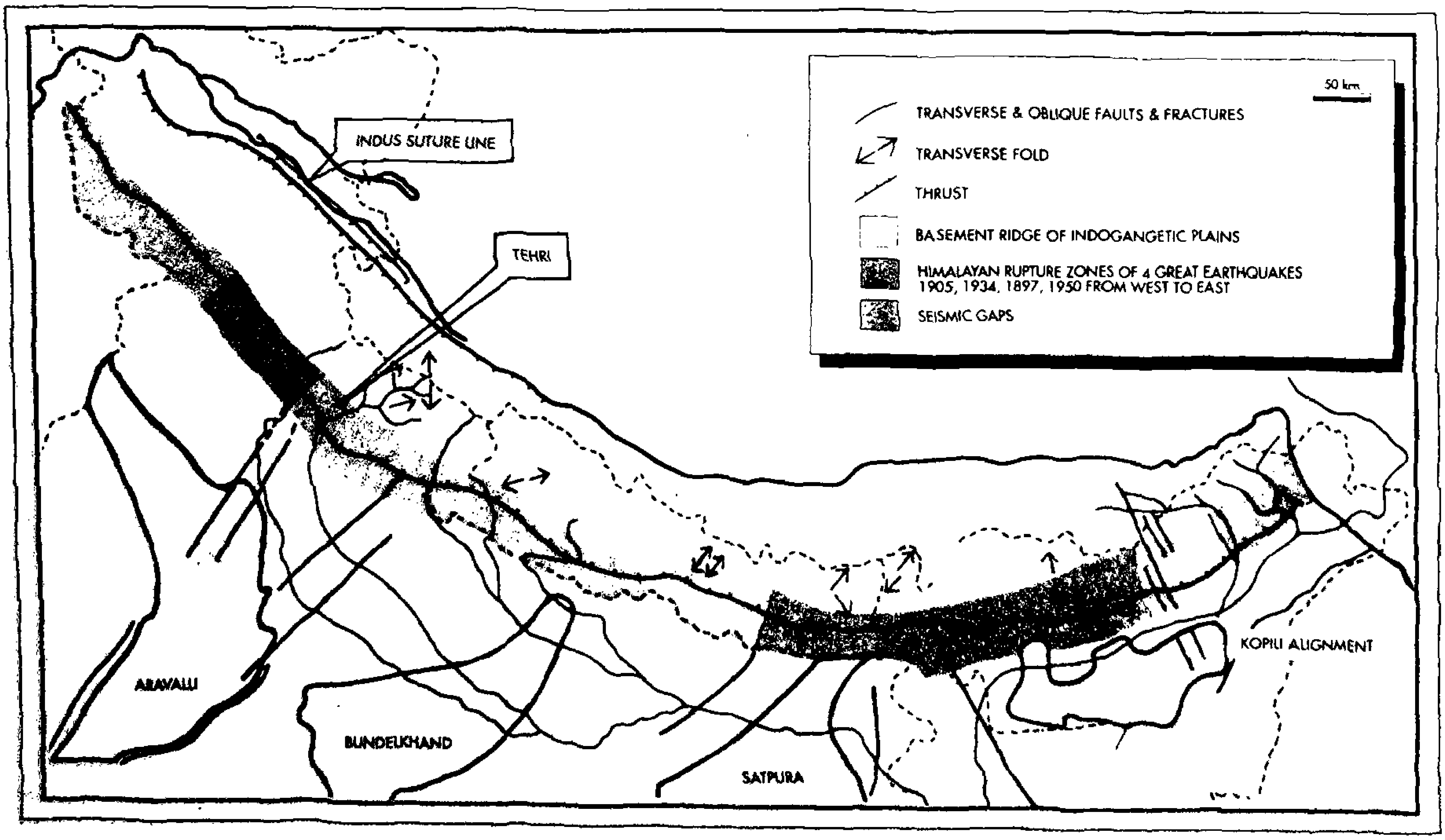

Figure 3. The inferred detachment fault beneath the Himalaya along a N-S section

region of local earthquakes[3] in Garhwal Himalaya by this very plane, and slip modelling by Chander[4]. This recognition constitutes a most crucial element for seismic hazard evaluation in the Himalaya, because a knowledge of its dip and of the fault area(s) likely to rupture in a moderate or major slip together with an estimate of the slip, both of which quantities can be reasonably constrained by systematic seismic investigations, provide the key figures for estimating the strong ground motion parameters in the adjoining region.

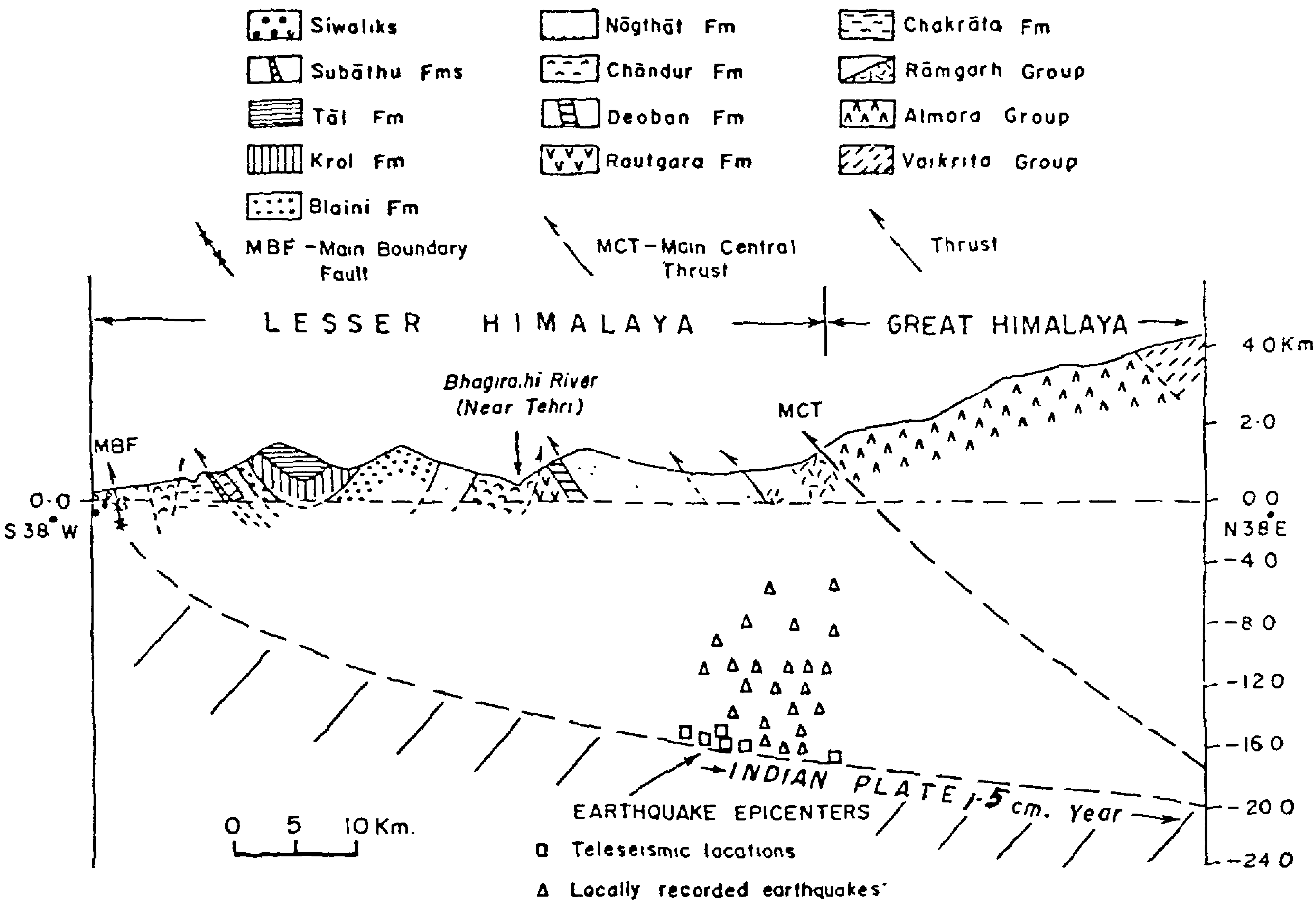

Figure 4. The rupture zones of the four great Himalayan earthquakes, each about 200–300 km long (darker shaded zones), and the intervening seismic gaps (lighter shade) where accumulated strains might be close to rupture.

The earthquakes along the coastal tracts of India, on the other hand manifest strain accumulation and relaxation on buried faults but at a much slower pace, as evidenced by the relatively gentler scale of their tectonic activity. The most likely and the latest tectonic context of the formation of these faults would be that provided by the rifting of the northern Gondwanaland and the subsequent northward drift of the newly carved continent. The east coast thus separated from Antarctica over 130 million years ago, subsequently developing into a passive continental margin, and the west coast about 65 million years ago from Madagascar. These margins of the Indian continent are most likely to have been sliced by a succession of normal faults dipping away from the coast during the long acting extensional stress field that produced the rift. Contemporaneous volcanism and sedimentation would have subsequently invaded and entombed these en-echelon fault sequences even as their fractured interfaces still preserved the scars of initial faulting, with potential for strain accommodation and earthquake generating slips in response to new stress regimes in the future.

Available knowledge of the deep structure of these passive continental margins is too qualitative to shed light on the actual mechanism of earthquake generation along them but this plate tectonic visualization of their latest activity provides an attractive enough model for estimating the seismic hazard associated with coastal earthquakes. However, in order to do so, it would be further necessary to constrain the geometry of these fault systems using definitive tools of seismic imaging, and also determine the distribution of time evolving strain field in the region.

The third group of largely shallow earthquakes that occur in the interior of the continent are not prima facie identifiable with any coherent fracture systems such as those of its active and passive margins, although it is certain that the basic stresses that furnish their strain budgets are the same that move the plates. The first task in the evaluation of hazards associated with these earthquakes therefore, would be to locate their source regions. One characteristic of these regions appears to be their association with lower than average crustal velocity[5], an indirect evidence perhaps of unusually fractured environments and fluid controlled fault mechanics. If this turned out to be the case, there would be a fairly straightforward way of delineating vulnerable areas. But this cannot be settled until their deep structure is studied in detail. Further, not all seismogenic areas in the continental interior may have yet come to light in view of the long return periods of such earthquakes, which may on account of slow strain accumulation be of the order of thousands of years, compared with our rather short historical record. In fact the variegated constituents of the Indian continental plate and long history of their accretion would seem to suggest that over such a vast continental area, there may be other regions like the source region of the Khilari earthquake where slow accumulating strains (>0.01 microstrain) may be quietly building up to failure. One fruitful way to detect such areas would be to launch a countrywide programme for determining the pattern of crustal strains and their variations in time. A network of control points repetitively monitored by Modern Global Positioning System (GPS) receivers which provide sub-centimetre accuracy in the determinations of baselines several hundred kilometres long, offer a most promising tool for accomplishing this task with a fair degree of confidence within a decade or two.

South Indian strain measuring experiment (SISME)

Spurred by these ideas in the aftermath of the tragic Khilari earthquake, scientists of the CSIR Centre for Mathematical Modelling (C-MMACS) at the National Aerospace Laboratories and the Indian Institute of Science, in collaboration with Professor Roger Bilham of the University of Colorado, designed the above crash project. The objective of the project was to distinguish regions undergoing localized deformation from those of relative stability using GPS derived high precision displacement fields at suitably located points in the southern peninsula, by repeating the measurements every year or over a decade or two. It was also decided to select those points for stability and wide angle viewing clearance from amongst those established for the Great Triangulation Survey in the 19th century (Figure 5). For, even though the accuracy of these early measurements was 2 orders lower than that attainable by GPA, a comparison of the two baseline determinations when reduced to a common datum could show statistically significant variations that may have accumulated over the past 150 years.

In order to implement the experiment straightaway, 6 GPS receivers were borrowed for 4 weeks from Bilham's group at the University of Colorado and the GPS processing software simultaneously implemented at C-MMACS with the help of their expert assistance, so that processing of data could progress apace with its generation.

The experiment involved extensive field campaign (Figures 6 and 7) between March 24 and April 16. The GTS mark in the Indian Institute of Science Campus, served as a fixed point where one receiver was operated for 22 hours each day throughout the campaign so as to provide a reference data synchronous with all other measurements. Two other receivers were operated for 22 hours a day for 3 days at two ends of the Bangalore baseline. Three mobile teams travelled, west, east and south of Bangalore, each covering 3 stations, each station being surveyed for 8 hours (9.00–17.00 IST) for 3 days.

Initial results indicated by the data are quite exciting. Indeed, with the supercomputing facilities now available at C-MMACS and the excellent networking, particularly the ftp which permit easy access to delayed time refined orbital parameters available at Scripps, C-MMACS scientists have shown continued repeatability of baseline determinations with a few mm. These facilities are also being exploited to establish longer intercontinental high precision baselines between Bangalore and sites in Canberra, South Africa, Taiwan, Nepal and Japan.

Indeed, an extension of SISME to cover the whole continent for systematic and continued monitoring of its dynamic strain field, as low as 10^{-8} year, offers a most attractive possibility to delineate all the active faults and constrain their lengths and slip rates, at a modest investment of about Rs 10 crores, and annual operating cost of Rs 1 crore. Scores of University groups could be involved to provide both fresh intellectual inputs to the project and exciting new grounds for faculty and students to develop new concepts and ideas. This would, in turn, greatly stimulate the current flagging academic endeavour in earth sciences, and may progressively enrich this whole enterprise with new ideas and new ways of abstracting key figures from natural as well as historical records.

Qualifying earthquake hazard

Once the existence of active faults in and around a region has been delineated and their geometry and slip rates constrained, one may proceed to obtain probabilistic estimates of ground motion at specified sites that may be caused by ruptures on any of these, but would not be exceeded for given percentile values during selected intervals in the future. Both empirical[6] and theoretical (Khattri this volume) approaches are used to accomplish this goal and a comparative analysis of the respective results proves instructive in offsetting the uncertainties involved in either. An important quantity easily determined but necessary for quantifying hazard estimates, is the partitioning of fault slips between different segments of a fault that may rupture at different times.

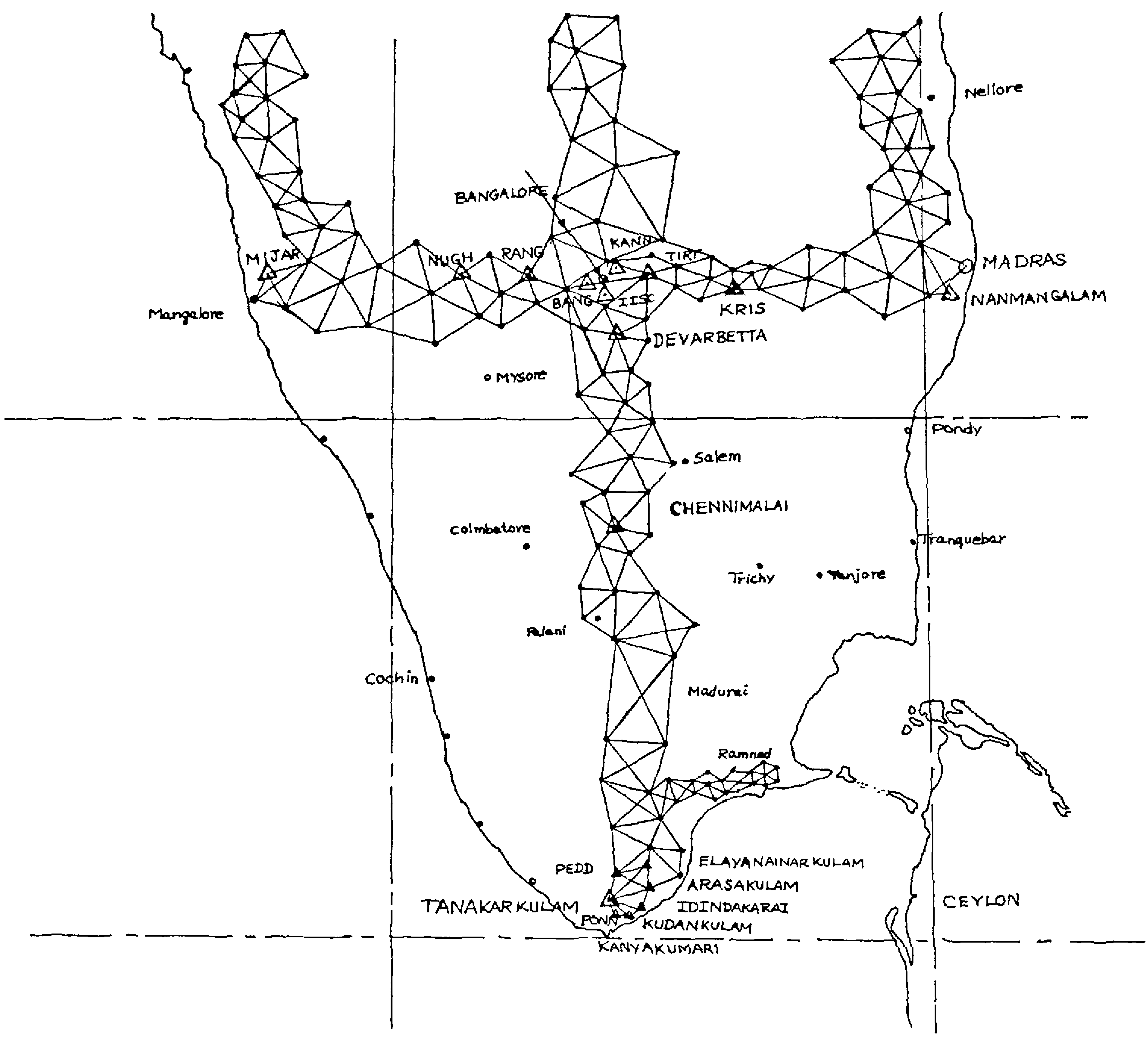

Figure 5. The network of the Great Triangulation Survey established by the Survey of India within the 19th century. Triangles mark the Trig points occupied for GPS monitoring in March 1993.

The notion of the characteristic earthquake that dominates the seismicity of a given fault can of course be quite helpful in settling this question in well investigated environments supported by extended historical record. This approach has gained increasing credence on the evidence of available data. However, other concepts using scale invariance of the faulting process and its fractal dimensions may also be used to develop probability distributions of the maximum area on a fault that would rupture to release the accumulated strains across it.

A minimum national programme for earthquake hazard evaluation

A substantial repertoire of mathematical models, hardware systems and design and software are now globally available to make a dent in the earthquake hazard evaluation and mitigation programme of the country. Substantial skills and expertise also exist to take advantage of these possibilities, if the basic ground motion data (both slow and vibratory) are made available in a digital form and on a fail safe, real-time basis. It

Figure 6. A damaged trig point in Kundankulam near Cape Comorin.

Figure 7. A GPS receiver in operation, centred over the exhumed lower part of the trig point, near Cape Comorin. The upper stone mark has been lost.

is felt that a minimum programme of instituting such an information system, which would have the highest multiplier and take advantage of existing infrastructure in the country to optimize costs, would be to address the following five points on an urgent basis within a short-time frame.

(1) Commissioning of an authentic professionally generated lineament map of the country using space imageries and aerial photographs, and classification of these according to their neotectonic activity based on a rigorous analysis of definitive features and detailed ground truth checks.

(2) Updating of the entire national seismic network maintained by IMD comprising 50 or more stations, by replacing the existing seismographs by new broad-band digital systems and linking them through modern communication systems so as to continuously feed data to a central station where on-line computer hardware and software systems are installed for real time determinations and dissemination of source parameters.

(3) Continual monitoring of the strain field in India. This can be determined over the whole continent through repeat GPS measurements at about 6,000 to 10,000 control points suitably located at intervals of 50–60 km, with the help of 10 or more scientific groups in academic and research institutions acting as a consortium for data generation, archiving analysis, continual refinement of strategies and routine dissemination.

(4) Installation of at least 6 short period tele-linked (using leased telephone lines and VSAT) network of seismographs in the following zones of unusual seismicity to discern the stress field and earthquake potential: Bidar, Ongole, Koyna, Delhi, Tehri and Pithoragarh.

(5) A flying squad of 6 suitably tele-linked digital seismographs, capable of being moved to any area in the country, identified for immediate close surveillance of seismicity within 24 hours. This could be the set of network seismographs normally deployed in one of the nearby areas mentioned above.

1. Introduction in the volume: *Earthquake Hazard and Large Dams in the Himalaya* (ed. Gaur, V. K.) Indian National Trust for Art and Cultural Heritage (INTACH), New Delhi, December 1993.
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