It is observed in the present work that a near-linear speed-up results for each processor that is added. Results from other sources[5] indicate that beyond about 20 processors, the communication overhead assumes large proportions, making further parallelization not very efficient. A recent work[19] shows that incorporating an i860 processor along with transputer networks can further help in increasing the computation speed, thereby enabling us to approach a speed of over 100 Mflops, which is currently available on most of the supercomputers today. The methodology adopted in the present study can be readily extended to processors other than transputers.

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RESEARCH ARTICLES

A hypothesis for the origin of peninsular seismicity

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The seismic activity of the peninsular India has been examined. The seismicity is considerably feeble compared to that of the plate collision boundary (i.e. the Himalayas) towards the northern parts of India. However, several linear seismic zones have been identified. One of these runs along the NW direction and divides the peninsula into two large blocks. Most of the seismic zones are trending along one of the two directions, NW or NE. These directions are consistent with the conjugate system of faults expected to develop in an approximately NS compressive-strain regime. The collision of the Indian plate provides just such a strain environment. Due to the resistance to subduction of the Indian plate, a part of the strain due to plate convergence is released in the peninsula by tectonic escape of the peninsular blocks along the NW-trending faults towards either the NW or the SE direction, giving rise to many of the seismic zones.

THE feebleness of seismicity of the peninsular India in contrast to the high seismicity of the Himalayas had induced a false paradigm of stability and safety from seismic hazard of the former. Lately, the 1967 Koyna and the 1993 Killari (Maharashtra) earthquakes have shattered this paradigm and nudged the earth scientists

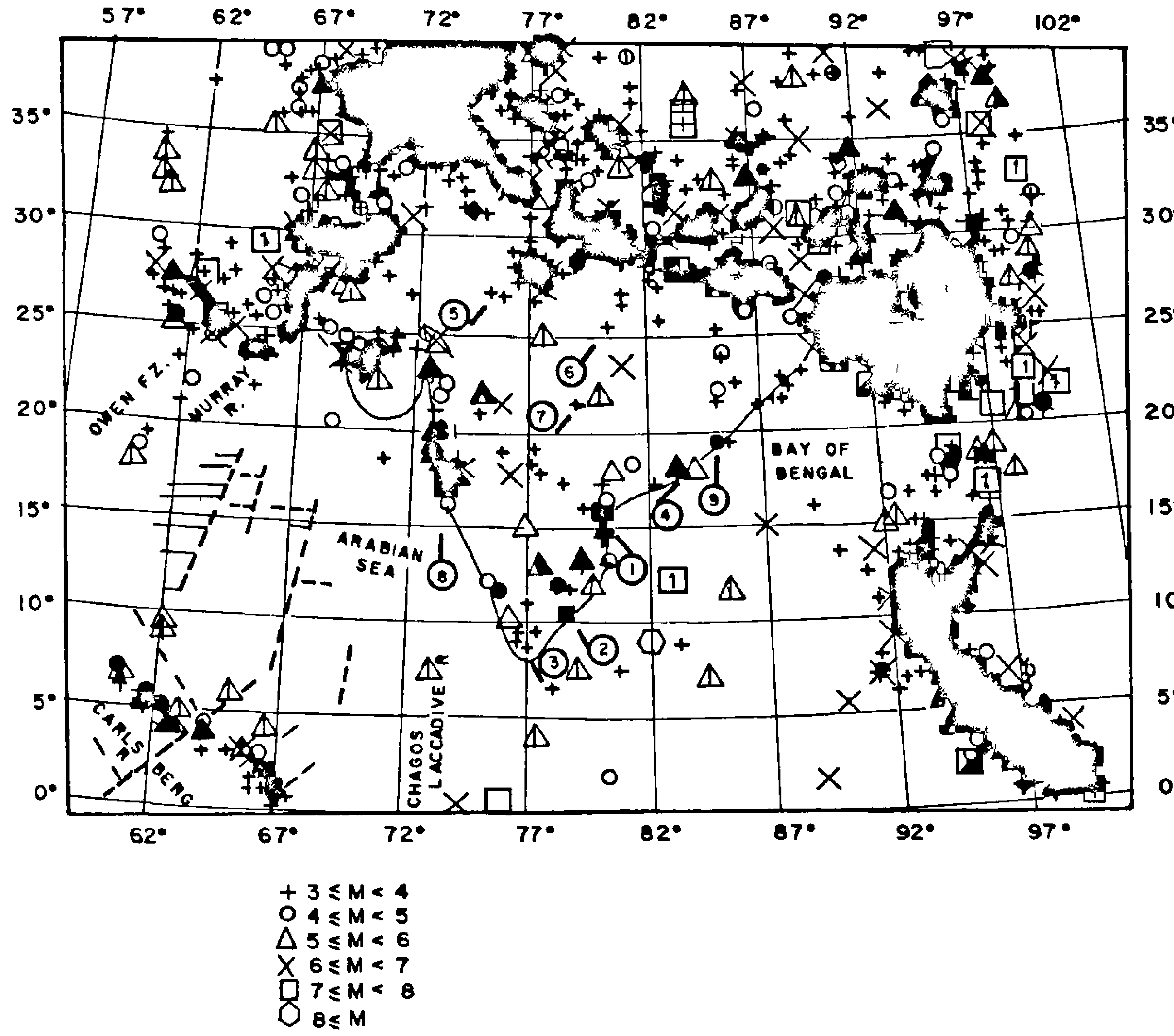

Figure 1. Seismicity of the Indian region The large sizes of the symbols used to plot epicentres is to emphasize the weaker seismicity of the peninsula The resolution is lost in the Himalayas, where the seismicity is profuse The seismic zones in the peninsula have been identified by lines

to take a fresh look at the seismicity of the peninsular India[1-3].

Unlike the seismicity of the Himalayas, which form a plate boundary, for which a generalized model for seismic activity is well developed[4], a similar well-accepted generalized model is not available for peninsular seismicity. Khattri[5] had suggested that the peninsula is subjected to block tectonics, with the strain field being caused by the Indian plate's motion and its collision along the Himalayas. In this paper we develop this hypothesis further and suggest the definition of the blocks on the basis of zones of seismicity. In this scheme, the Killari earthquake was an event that occurred at the boundary of two blocks defined by the earlier seismicity. It has been pointed out by Khattri[5] that, in the absence of a coherent understanding of the cause of peninsular seismicity, much of this boundary zone of seismicity was overlooked in defining the seismic zoning map of India and the region was designated as having the lowest category of seismic severity (seismic zone 1). In the light of the new hypothesis, it will be possible to do experiments for investigating seismicity in a more efficient manner and improve the assessment of seismic hazard in the peninsular India.

The intraplate seismicity in several regions like the eastern North America, eastern China, western Europe and Australia has been found to occur in a compressional-strain environment[6]. Often, the sites of seismicity are the pre-existing weak zones, with clustering occuring sometimes at the intersection of such zones. The peninsular India is smaller in dimensions compared to the continents referred to above. Also, the presence of the Himalayan collision zone to its immediate north will be a critical factor. Thus, both these factors will characterize the seismic behaviour of the peninsula in a special manner. The outpouring of the Deccan Traps and their piling up is expected to have depressed the western region of the peninsular lithosphere. Its isostatic rebound can also be one of the sources of seismic activity. Further, the coastal regions which have been shaped by the sundering of the Gondwanaland will have faults and weak zones which will be possible sites of seismicity.

Seismic morphology

The morphology of seismicity of the Indian region is shown in Figure 1. The symbols in this figure are intentionally kept relatively large to mimic visually the approach of cluster analysis in defining clusters, in order to help define the seismicity zones. Of course, one has to be on the alert towards artificially created seismic alignments in this way. The zones of most significant seismic activity are along the Himalayan plate boundary, as is evident from the dense and wide black zones there. The collision boundary is distinguished by the arcuate distribution of the population of earthquakes. The syntaxial zones in the west and the east are particularly active.

One notices the distinct contrast in seismic activity between the Himalayan collision zone and the peninsular region. The considerably lower level of seismicity of the peninsular India is distinguished by a few relatively narrow zones prone to earthquakes encompassing in between them larger areas with no reported seismicity. We note that the coverage of the region with seismographs is having approximately the same density in the peninsula as in the Himalayas, of about 400 km spacing on an average[7]. Such a network, together with the global network, is expected to locate all earthquakes with m_b of 4 and above. Thus, for the recent times, only the smaller-magnitude ($m_b < 4$) seismicity picture may be somewhat incomplete.

A first-order analysis of the spatial distribution of seismicity can be attempted. A number of seismic zones can be identified. These seismic zones of relatively feeble activity are almost linear and define the boundaries of regions with no seismicity, viz. the *stable blocks*. Lines have been drawn to show these boundaries, by continuous lines where there is a somewhat better visual density of earthquake activity and by dotted lines where it is not so definitively defined. These boundaries as well as blocks have been labelled to facilitate discussion. Nine linear zones of seismicity which define large blocks have been distinguished. The zones of seismicity identified as above are overlaid on the tectonic map of India[8] in Figure 2.

The seismic zones in the peninsula are mostly aligned along the NW or the NE direction. However, three of them are also along the NS direction. The seismic zone 1 runs along the NW direction from near the east coast at 15° latitude and divides the peninsula obliquely into two main blocks. There is no apparent surface expression of tectonic or geologic province identified along this zone except at its NW end, where it coincides with the Jaisalmer arch. Zones 2 and 3, which are of shorter length, run along a similar direction in the southern block. Zone 3 may be related to faults created during the rifting of India which have shaped the southern section of the western coast. Its northwest extension coincides with the shelf break. A couple of earthquakes have been reported in the vicinity of shelf break region on its northern extension. Zones 4–7 form a system of seismic zones running along the NE direction and are located in the northern main block. Zone 4 follows the eastern coast and is most likely related to its creation by rifting of Gondwanaland as well as to strain amplification due to the transition from continental to oceanic crust and upper mantle structure. Zone 5 superposes the Aravalli tectonic zone. Zone 6 is a short one located over the Bundelkhand massif and its subsurface extension into the Ganga foredeep. Zone 7 apparently has no relation with any known geological feature. The most prominent NS-trending seismic zone is zone 8, which corresponds to the west coast fault in the northern half of the west coast. It is noteworthy that the coastline also turns northward around 16° latitude on account of this fault. The shorter NS zone 9 along approximately 85° longitude also does not appear to be related to known geological structures. However, a closer look at the physiography reveals that this zone aligns with the NS-trending Malayagiri–Parasnath hills and with a section of the Kosi river further north. Zone 10 is trending along the NS direction from Madras to about a place where it intersects the Godavari graben. Although known seismicity does not extend further northward, the signature of its continuation further north is seen in the straight NS course of the Wanganga river. Similarly, the straight NS nature of the Madras coast is on account of the same fault.

The above NE- and NW-trending set of seismic zones is a remarkably consistent observation, for in a NS compressive regime, as is present in the peninsula due to collision of the Indian plate, such a set of conjugate system of faults will be expected to develop.

The above concept, however, does not explain the NS-trending zones of seismicity. A possible mode of deformation in some of them is suggested by slip on an en-echelon system of the NW-trending faults aligning to form a north-trending zone of such deformations. This idea is supported by a preferred choice of a single-fault plane solution available in zone 10. However, the characteristics and causes of the associated strain regimes along the NS seismicity zones need to be investigated with further studies of the fault plane solutions and other techniques.

We note that the fault plane solutions of earthquakes in the peninsular India consistently show the direction of the principal axes of strain as nearly NS and horizontal[5, 9–11], which is consistent with the above interpretation (see Figure 2). The directions of maximum horizontal stress obtained from the hydrofracture data are also broadly consistent with the above picture[11]. The fault plane solutions for earthquakes towards the SE end in zone 4 admit strike slip solutions. Towards the NW end of this zone, the earthquakes have a combination of strike and thrust

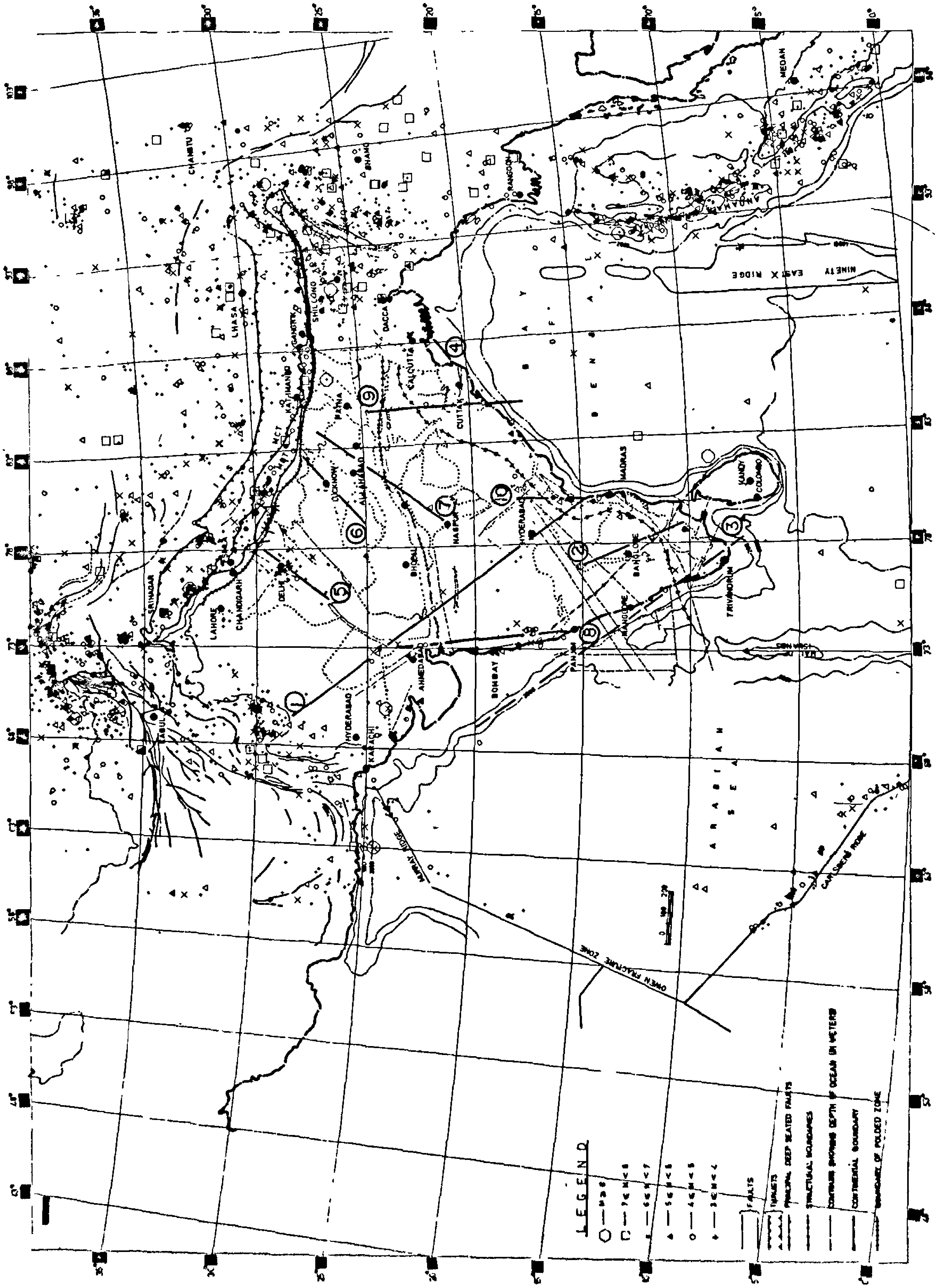

Figure 2. Map showing the main tectonic features of the Indian region. The block boundaries identified in Figure 1 are redrawn here.

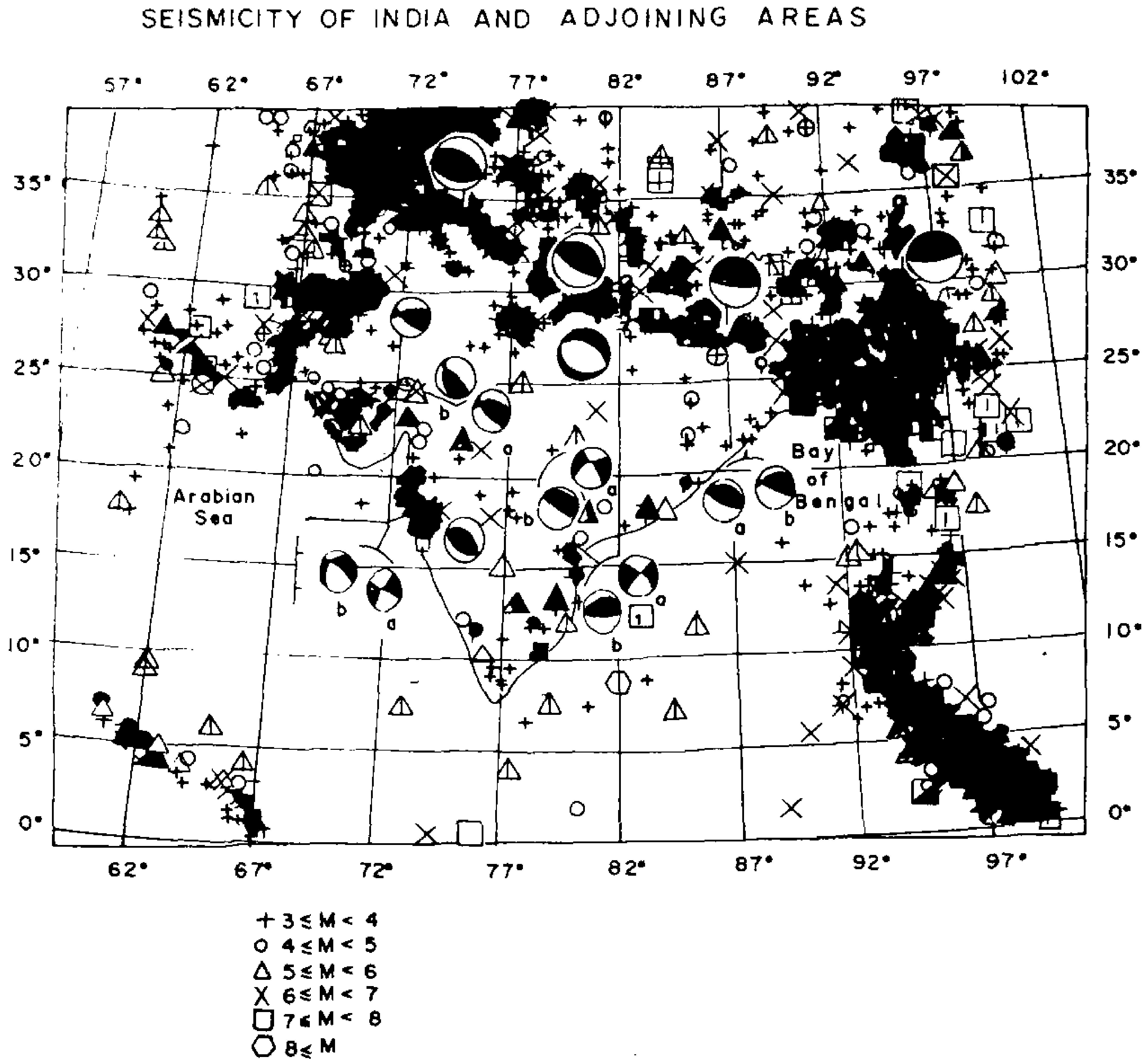

Figure 3. Map showing seismicity and fault plane solutions.

motions, with the thrust motion dominating. However, the Killari (Maharashtra) earthquake, which occurred in zone 1, has a purely thrust solution[12]. The recent Osmansagar, Hyderabad and Sriramsagar earthquakes all fall in zone 1. Their fault plane solutions show right lateral motion along approximately NW-trending strike slip fault planes. However, in the other case it is left lateral[9]. Also, the recent Bangalore and Idduki earthquakes belong to zones 2 and 3, respectively, and show left lateral strike slip motion along the NW-trending fault planes[9].

Discussion

A fault-related weak-zone model has been advocated[6, 13–15] to explain seismicity in continents. Long[15, 16] suggested thermal and fluid control as an alternative reason for the occurrence of major earthquakes. In what follows, we briefly review the geological and geophysical information and discuss the characteristics of seismicity in its light.

Geological and tectonic elements of the peninsular India

The Indian shield is featured by three Archaean subprovinces, namely the NE-trending Aravalli in the NW region, the NNW-trending Dharwar subprovince on the western coast and the NE-trending Eastern Ghats subprovince on the eastern coast. The northern edge is aproned by the Himalayan foredeep. The Proterozoic arcuate-shaped Cuddapa basin is present on the east coast side at 15° parallel. The Narmada–Tapti rift zone trending along almost the EW direction divides the shield into two parts along the 22° parallel. The Godavari and Mahanadi grabens of the Gondwana age trending along the NW direction are present on the east coast side. A large area is covered by the Cretaceous Deccan Trap lava flows on the western coast side, veiling the older geological and tectonic features beneath. The effusion of lava flows in Cretaceous is related to the breaking up of India from Gondwanaland. The coasts are expected to have faults created at that time as also the crust is stretched there.

Geophysical structure

Seismicity is often related to the deeper structure of the lithosphere. Therefore, it will be useful to review briefly the relevant aspects here. Tomographic study has shown the average crustal thickness to be 34–39 km[17]. The mean elastic thickness of the Indian plate under the

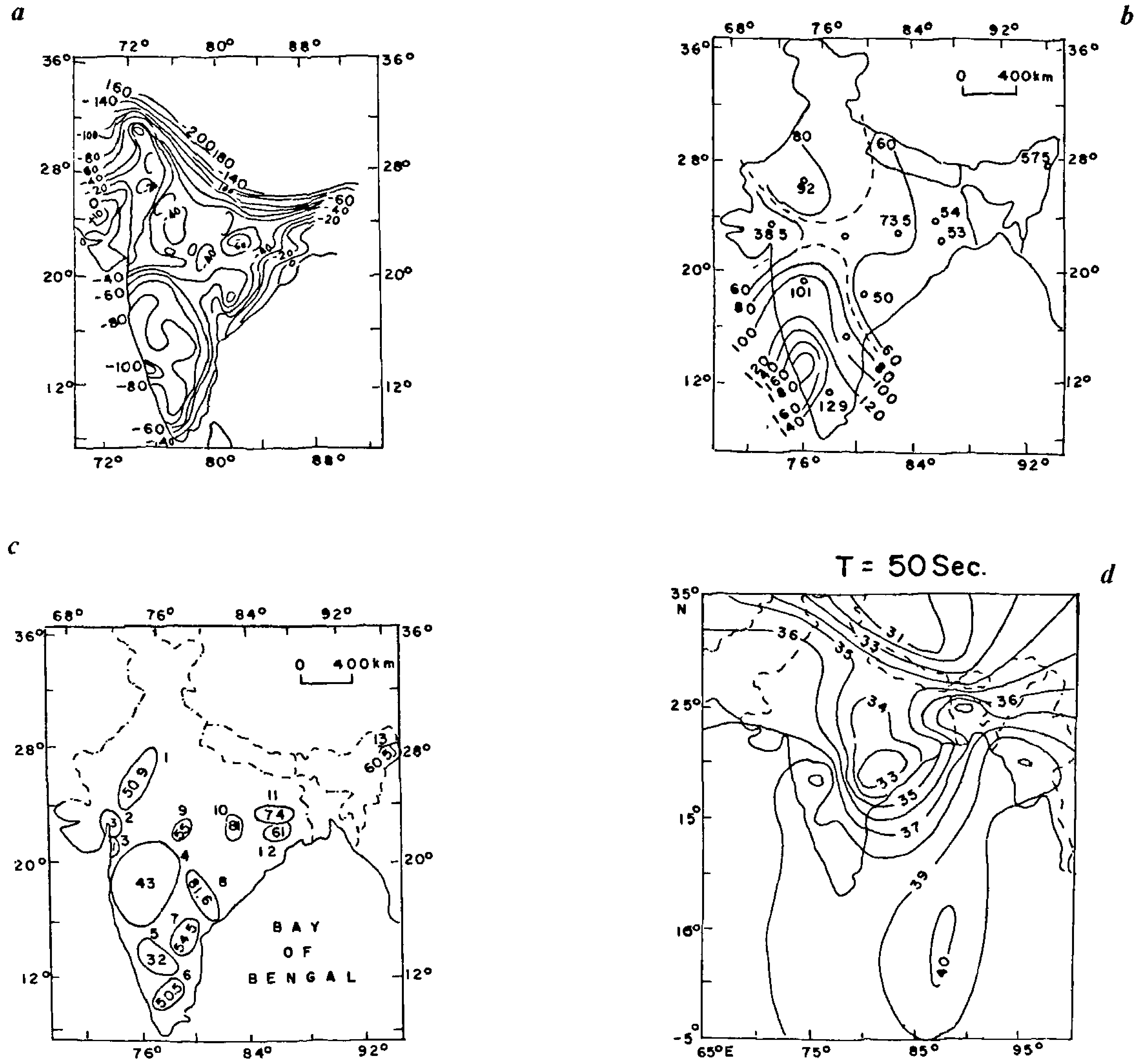

Figure 4. *a*, 1° × 1° Bouguer anomaly map of India[22], *b*, thickness of the thermal lithosphere in km[19]; *c*, heat flow domains[19] 1: Aravallis, 2. Northern Cambay basin, 3 Southern Cambay basin, 4 Deccan Traps, 5. Dharwar schist belt, 6 Peninsular gneiss, 7: Cuddapah basin, 8. Godavari valley, 9 Satpura basin; 10 Son–Mahanadi valley; 11. Damodar valley basins, 12. Singhbhum thrust zone; 13: Assam basin (the mean heat flow values are in mW/m^2), *d*, Rayleigh wave group velocity (km/s) for 50 s period[17].

peninsula has been estimated using surface waves to be around 140 km[18]. The mean thickness of the thermal lithosphere is reported to be 110 km[19]. Iyer *et al.*[20] have found evidence of continental root dipping into the mantle up to about 400 km depth. This would imply a strong coupling between the lithospheric plate and the northward-convecting underlying mantle. The resistance to subduction of the continental lithosphere at the collision boundary along the Himalayas will induce high levels of stress in the Indian plate[21].

The 1° × 1° averaged Bouguer anomalies show a central region of relatively high anomalies compared to the Himalayas in the north and Dharwars in the southwest (Figure 4 *a*). The zone dividing the central region of higher gravity from the Dharwar region of lower gravity is defined by a zone of high gradient with contours running in the northwest direction[22]. Similarly, the thermal lithospheric thickness shows a central zone having a lower thickness (~ 60 km) adjacent to a thicker lithosphere in the Dharwar region[19]. The transition zone between the two runs along the northwest direction and roughly coincides with the similar zone present in the gravity distribution (Figure 4 *b*). This transition zone has elevated mean heat flow[19]. On the other hand, the

Deccan Trap region is colder in comparison[19, 23] (Figure 4 *c*). The Rayleigh wave group velocity at 50 s shows a similarly trending zone of high gradients where group velocities increase from about 3.3 km/s in the central region to 3.8 km/s in the Dharwar region in the southwest[24] (Figure 4 *d*). The above zone, which is characterized by several physical features, interestingly, more or less coincides with the similarly trending zone 1 of seismicity. The heterogeneities implied by the transition zone would help to amplify the strain regime and nucleate rock failure. Thus, even though the seismic zone 1 is feeble and appears sketchy, the above corpus of independent geophysical features are consistent with its existence.

The EW-trending Narmada–Tapti rift zone is a prominent tectonic feature of the peninsular India. The seismic activity in the Narmada rift near Indore has been found to be very low[25]. The upper crust, which usually is the seismogenic layer, has thinned at places to less than 10 km[23, 26, 27]. Also the thermal regime is elevated along this zone[19, 23]. Thus, it is not likely to support significant accumulation of strain which may give rise to larger-magnitude earthquakes. Further, its EW alignment will accommodate thrust faulting only on the EW-trending faults in response to the NS strain regime. There are a few earthquakes that fall along it, albeit in a very sparse spacing. We have not identified it as a seismic zone, in contrast to some opinion to the contrary[23]. The few events located near it have been assigned to the NW- or the NE-trending seismic zones. The locations of these earthquakes are viewed to be at the intersections of two weak zones, i.e. the NE-trending seismic zones and the Narmada–Tapti rift zone. Field mapping has shown the presence of such NE- and NW-trending faults[23].

It is proposed that the Kutch rift originated together with the Narmada–Tapti rift during the Gondwana episode. It forms the north-shifted western end of the Narmada–Tapti rift along the western coast fault, which runs into the Cambay graben. We propose that the west coast fault is a transform fault on which the Chagos Laccadive ridge was formed. As expected, the thermal regime is also elevated along this transform fault[19]. The seismicity of Kutch is related to a NS compressional regime originating in the collision of the Indian plate. The older faults first created in an extensional environment have been reactivated as thrust faults.

The lack of significant seismicity of the Mahanadi and Godavari grabens, which are favourably oriented along the NW direction, is perhaps due to the fact that the upper block is escaping as a whole to the SE. This concept is further elaborated below.

It is conceivable that the seismicities at the NE ends of the NE-trending zones 5–7 and of zone 9 are part of an arcuate zone of seismicity developing in the Ganga foredeep parallel to the main Himalayan arcuate seismic zone. Two types of processes can create such a seismic zone. First, the southwards thrusting and secondly the tensional fracture due to bending of the plate as it subducts under the Himalayas. However, further monitoring of seismicity and its incisive analysis is needed to ascertain this concept.

The Killari earthquake occurred in seismic zone 1. Krishna Bramham and Negi[28], and Valdiya[2] have suggested that the earthquake was related to the

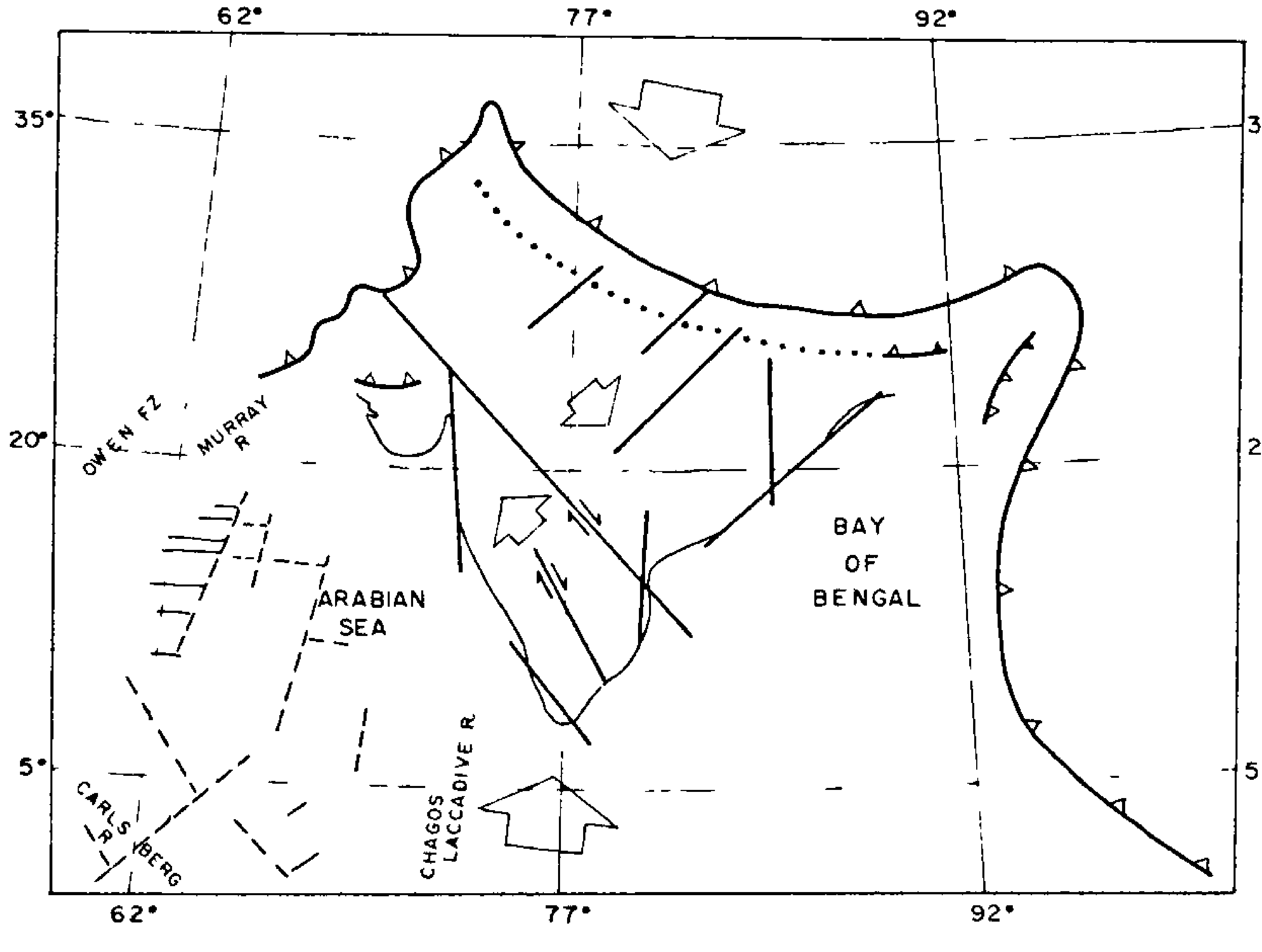

Figure 5. A schematic map showing the global active tectonic deformations taking place in the peninsular India

Kurduvadi graben, as inferred on the basis of gravity anomalies. Kailasam[3], however, has questioned this interpretation. Kaila *et al.*[29] also did not find any evidence in the deep seismic soundings for the existence of the graben.

The load of the Deccan Trap province by the lava effusion and subsequent rebound does not appear to be a significant contributor to seismicity. A diffuse zone of earthquakes is expected to occur under the province, which is not the case.

A model for gross active tectonics of the peninsular India

A schematic view of the gross active tectonics is shown in Figure 5. Khattri[5] envisaged for zone 1 an overall strike slip motion with right lateral slip. The argument offered was that, since the Indian continental lithosphere is unable to subduct at the Himalayan plate boundary easily, the strain has to be partially released by processes such as (i) deformations of the plate interiors on either side of the collision zone, (ii) sideways sliding out of lithosphere sections out of the direction of convergence (*tectonic escape*) as in the Eurasian plate[30], and (iii) thrust faulting and stacking. Thus, it is suggested here that a part of the continued convergence is accommodated by the sliding of the southern part of the Indian plate to the northeast, where the differential motion on account of it will be absorbed by the relative motion of the ocean ridge, possibly also by oceanic plate deformation. Part of it is also taken up by sliding of the northern block eastwards towards the Bay of Bengal, where its oceanic component can subduct under the Andaman arc. The normal direction of slip along the Himalayan arc requires that a left lateral slip also exist at this arc[31]. Furthermore, the deformation of the lithosphere in the Bay of Bengal, which may be caused by such a process, is demonstrated by the existence of seismic activity there.

The above model will be tested according to the Popperian philosophy by a better delineation of seismicity in the course of time. However, a faster approach could be to conduct satellite-based geodectic positioning surveys (GPS) to verify the proposed hypothesis rapidly.

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