Some geodynamic hotspots in India requiring urgent comprehensive studies

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I am a humble foot soldier in the army of the unjustifiably ignored and much undervalued geologists of India, who is impelled to make a fervent plea at the very late evening of his life. The plea is directed to the scientists concerned and to the powers that be in the governance of the country. I urge them to revisit and undertake without delay multidisciplinary, comprehensive studies of some geodynamic hotspots in India, which in the unpredictable future, I believe, would bring about major changes we may not like to happen. The recent catastrophic events of northeastern Honshu island of Japan have impelled me to express my concern on the basis of my extensive fieldwork and studies of published literature. I have been harbouring the concern for years.

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Some inexorable processes

RESTING on the floor of the Indian Ocean, the Indian Peninsula is moving towards mainland Asia at the rate of $58 \pm 4$ mm/yr (ref. 1). The global positioning system (GPS) measurements confirm northeastward as well as eastward velocities of the Indian land mass against Asia$^{2,3}$. The GPS measurements demonstrate that even in northern India the Peninsular Indian crust is slipping under the Himalaya at the rate of 10–20 mm/yr in the Sikkim sector, 10–18 mm/yr in the Uttarakhand sector and 14–20 mm/yr in the western sector$^{4,5}$. Since the immensely large Asian continent is resisting the push, only one-third of the nearly 5 cm/yr convergence is accommodated by tectonic movements in the Himalaya and possibly another one-third in the Tibetan land mass. The remaining one-third of the continental convergence must therefore be affecting the Peninsular India itself – largely stored as elastic strain in its structural framework. The relaxation of accumulated strain is accomplished by reactivation of ancient faults and development of new faults with accompaniment of earthquakes.

Ancient faults are galore all along the western coast of India from Kerala to Kachchh, and in many parts of southern India, including the southeastern coastal belt. Some of these faults are active, registering imperceptibly slow ground movement – sideways or up-and-down. Others have been inactive all through their long lifetime, and many of them are locked. The locked faults are progressively accumulating elastic strain resulting from the stress to which the moving Indian Peninsula is subjected. In many cases the strains after rising to critical points are waiting to be relaxed. Earthquakes would inevitably follow.

And then there are blind faults which are in the process of formation and have yet not reached the surface, and thus have no surface expression. Blind faults have proved to be dangerous.

India does not have large-scale maps showing active and locked faults. There are only research papers describing and illustrating active faults of a few belts and areas, mostly of localized extent. It is ironic that our laws (or regulations) forbid free access to academics of the Survey of India topographic maps on the requisite scale of many crucial regions. Even if one were to delineate the faults in such maps (obtained somehow), these maps cannot be published. The result is that, the maps that are published are simply the tracings on plain papers, lacking details of critically germane topographic features.

The Bay of Bengal part of the Indian Ocean floor, moving eastward at the rate of 30 mm/yr (ref. 6) plunges deep down to the depth of 200 km under the Andaman–Nicobar Island Arc$^2$ – sinking along a deep oceanic trench called the Java Trench. This deep trench is filled up completely by the sediments delivered by the rivers draining the Indian continent.

The Sumatra part of the Java Trench sank 10–15 m along a 1200 km long rupture plane, generating the mega earthquake of 26 December 2004 (ref. 7). The 800-km long rupture in the North Andaman island was accompanied by subsidence and elevation of land$^3$. The world knows what the tsunami originating from the Sumatra part of the Java Trench brought in Indonesia, Malaysia and Thailand, and in the eastern coast of India.

There were a number of tsunami-generating earthquakes in the Andaman Islands – 31 December 1881 and 26 June 1941, for example$^{8,9}$. We have no record of the
destruction brought by the war-time 26 June 1941 tsunami generated by an earthquake of magnitude $M_s$ 8.1 on the eastern coast. And we do not know when the Andaman Trench will suddenly sink again on rupturing of the sea floor.

Cut by a long Owen Fracture, the Arabian Sea floor is moving north and plunging into the Oman Trench (Figures 1 and 2), just south of the Makran coast in Pakistan. This trench is also filled up completely by sediments brought by the River Sindhu. The 27 November 1945, a great earthquake of $Ms$ 8, generated a tsunami that ravaged the west coast as far south as Mumbai.

The floor of the Laxmi Basin in the Arabian Sea, 400–500 km west of the Konkan coast (Figure 1), was created as a result of symmetric east–west spreading of the sea floor at the rate of nearly 0.7 cm/yr to the present 1.2 cm/yr (ref. 11).

I wonder if the eastward stretching of the floor of the Laxmi Basin\textsuperscript{11} is not exerting pressure on the oil pools of Bombay High in the Offshore Bombay Basin\textsuperscript{12} and on the coastal belt stretching from Konkan to Kachchh. The Gujarat coastal belt (including Kachchh) and the Konkan coast are vulnerable even to the formation of blind faults, which can be detected only through highly sophisticated geophysical studies.

The working and pace of natural systems change with time. Man’s reckless activities have hastened the processes of change, and dangerously impacted the nature’s delicate balance as well.

No proper and honest audit is done in India of human activities that have bearing on the functioning of nature. And whenever this is done, the reports are consigned to the burial grounds.

**Western coastal belt**

One of the most significant features all along the Sahyadri, the Western Ghats and the Konkan–Kanara–Malabar coastal belt is the multiplicity of the so-called lineaments. They trend persistently NNW–SSE to NW–SE and N–S. No one would dispute the contention that these lineaments are expressions of the stretching of the Indian crust as it rode over the oceanic Reunion Hotspot.

Many of these lineaments (Figure 3) are associated with hot springs\textsuperscript{13–15}. The large number of hot springs aligned parallel to the coast all along the west coast in Konkan and Kanara (to which may be attributed the high heat flow value varying from $51.5 \pm 4.6$ to $129 \pm 8.3 \text{ mW/m}^2$)\textsuperscript{14} indicate not only the existence of faults, but also the fact that the majority of the faults are quite deep. A hot spring implies that the fault that brought up hot water extends to a depth where the water is heated to its boiling point. The multiplicity of hot springs occurring in linear arrays in the western coastal belt clearly shows that the coastal terrain is cut by deep faults.

Many of the so-called lineaments and fractures are loci of earthquakes. This is evident from the pattern of distribution of epicentres lying in their close proximity, seen noticeably in the Mumbai–Bassien–Panvel sector (upper inset, Figure 4) in the Konkan belt\textsuperscript{15–17}, in the central part of the Sahyadri (inset, Figure 5), that is in the Karnataka sector\textsuperscript{18–20}, and in parts of central Kerala (Figure 6)\textsuperscript{21–24}.

The great depth to which they extend, the earthquakes (Figure 7) that they generate due to slipping on them at depth, the spectacular deflection of streams and the anomalous behaviour including natural blockage or ponding of the present rivers and streams (lower inset, Figure 4 and Figure 5) on their crossing them, imply their reactivation\textsuperscript{19,20,23}. Taken together all these happenings demonstrate unequivocally that the so-called lineaments are faults – rather they are active faults related to the bulging-up of the western part of Peninsular India, and its stretching and breaking by faulting.
Figure 3. Hot springs occur in linear arrays, often along or in the close proximity of the so-called lineaments (which indeed are deeper faults) in the western coastal belt where the heat flow measure is $51.51 \pm 4.6$ to $129 \pm 8.3$ mW/m$^2$ (from: Shanker$^1$).

It must be borne in mind that a fault is not a single plane of rupture; it is a zone of parallel to sub-parallel fractures, some branching off, others joining together. As a consequence, the affected rocks are in a much sheared, shattered and crushed condition. A fault zone is therefore a zone of weakness. Any of, or some of these fractures of the fault zone may become active. Subsidiary fractures are often responsible for foreshocks and aftershocks when reactivated.

Knowing the geodynamic condition described and illustrated above, it should not be difficult to understand why collapse of mountain slopes resulting in endemic landslides, debris flows and mud flows are so common in the Sahyadri domain overlooking the coastal belt. Rainwater playing the triggering effect, all these landslides and associated mass movements are related to fault zones.

Landslides are particularly devastating in the upper reaches of Minachil and Manimala$^{25}$ in Kerala, and east of the Thane, the Raigarh and the Ratnagiri sectors in the Konkan belt$^{26,27}$.

Every rainy season we hear of the Konkan rail track being blocked, sometimes for days, by landslides. These events occur at the spots where the faults (so-called lineaments) cross the rail roads.

Tsunamis or no tsunamis, all structures (such as dams and bridges) and industrial complexes like nuclear power plants, thermal power plants, petrochemical factories, gas
Figure 4. The Mumbai–Bassein–Panvel region in NW Maharashtra is cut by major faults, which have caused vertical uplift of the lava pile, and are locations of epicentres. Hot springs occur in the proximity of some faults (from: Srinivasan15). (Upper inset) Distribution of epicentres and faults of the Mumbai region (based on Srinivasan15). (Lower inset) Abrupt deflection of rivers along the NNW–SSE trending ‘lineaments’, implying strike-slip (sideway) displacement along them (based on Kundu and Matan40).

storage tanks, oil refineries, and so on are vulnerable to the hazards of trembling of the ground and mountain slope failures. Even if the magnitudes of the earthquakes are low, the recurrence of the events will make a difference.

One important point needs to be borne in mind. In the case of currently active faults, slow secular movements causing sinking or rise of the ground or its sideways displacement and sudden spasmodic movements generated by earthquakes have already released the strain of the overstressed Indian crust. They pose less hazard. However, in the case of locked faults, the strain has been and is progressively accumulating; and when the strain build-up
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Exceeds the critical point, a high-magnitude earthquake would occur. Since we have no information about the identification of location and the extent of locked faults, and are almost unaware of the existence of blind faults, the planners of mega projects cannot go simply by the present scale of the seismic zoning map of India based on earthquakes that have occurred so far. Change in the paradigm and methodology of the probabilistic risk assessment that we follow is called for. Buried forest off the dockyard of Mumbai at the depth of 6–12 m indicates sinking, not in a distant past, of a fault block in the Mumbai belt. The occurrence at the elevation of 100 m amsl in the Velas–Bankot belt of beds of more than 40,000-yr-old lignite, formed from the organic matter of coastal marsh and containing near-shore foraminifers implies that the landward fault blocks have risen up in the Late Quaternary.

It would therefore be necessary for the planners of mega projects to commission comprehensive studies related to, among others, identification and delineation of active and locked faults, possibility of the existence of blind faults underground, hill slopes prone to failures, grounds likely to sink or rise up, etc. This also calls for higher level of safety measures, retrofitting of older structures, measures to combat the threats of landslides and ground subsidence and provision of storing adequate volume of water by rainwater harvesting in the vicinity of heat-generating plants.

Sabarmati Plain

North of the Western Ghats coastal belt lies the Sabarmati Plain, concealing underneath a N–S to NNW–SSE trending rift valley characterized by a multiplicity of faults (Figure 8), some trending parallel to the rift valley, and others across it. The Sabarmati Graben (rift valley) hosts a number of oil pools of consequence. Many industrial (including a nuclear) complexes are located on the plain above the graben. The 23 March 1970 Bharuch earthquake of M 5.2 occurred due to the sideways movements on one of the reverse faults. Soft-sediment liquefaction features (seismites) indicate that earthquakes had occurred in the Lower Mahi Valley (near Vadodara) 3320 ± 90 and 2850 ± 90 yrs BP (ref. 30), and in the Dhadar valley 5570 ± 30 yrs BP (ref. 31). The Mw 7.7 event at Bhuj on 26 January 2002 had badly shaken Ahmedabad, among many other places in the Sabarmati Plain. Both the Kachchh and the Sabarmati plains need to be studied for the possibility of developing blind faults.

Southeastern coastal belt

In the coastal stretch of the Palk Bay, occurrence of thermal spring implies deep-seated nature of the east–west trending faults. The faults developed on the Kochi–Ramanathapuram tectonic arc show ongoing movement as borne out by progressive shift of the courses of the rivers Kaveri, Palar, and Ponnaiyar. The morphology of the Kaveri Delta, the pattern of the palaeochannel distributaries, and the sinuosity and arcuate coastline of Tamil Nadu are all attributed to an east-west oriented structural arc.

Now, if the ocean floor of the Bay of Bengal in front of the Andaman–Nicobar Island Arc were to rupture again and sink substantially along the oceanic trench, the effect will be felt by these faults and also the resultant tsunami would cause greater damage than the one that did in 2004, rushing as it did from far off Sumatra.

It is therefore necessary that strong high breakwaters, seawalls and wide belts of forests of fast-growing robust trees are built to diminish the ferocity of surging waves in front of nuclear plants, rocket-launching pads, chemical factories, etc.

Ever-shifting courses of the Kosi River

Many of the rivers in the Indo-Gangetic Plains have been changing their channel laterally. Prominent among them...
are the Gandak and the Kosi in Bihar (Figure 9). The Kosi migrated 112 km westwards in about 238 years (between AD 1735 and 1875), while the Gandak moved 105 km westward in about a hundred years. This is obvious from the abandoned channels that eloquently tell their tales. The Tista used to flow south to meet the Ganga (Figure 9). In AD 1787, it suddenly deflected southeastwards and joined the Brahmaputra. Needless to state that the shifting and deflection of river courses are due primarily to continuing uplift and sinking of the ground through which the rivers flow. In northeastern Uttar Pradesh and adjoining Bihar, the ground has been subsiding at the rate of 0.2–0.3 mm/yr, as indicated by the sinking of the Survey of India benchmarks. The ground subsidence has resulted in impeded flow of rivers, and resultant waterlogging and development of swamps and lakes (jheels).

It happens that the Kosi–Gandaki domain (outlined in Figure 10) occurs in that sector of the Indo-Gangetic Plains which is traversed deep underground by a NE–SW trending ridge, the Munger–Saharsa Ridge, of the basement rocks. The ridge is lined by a long fault—the Patna Fault. There may be many more faults so far unknown.
Figure 7. Epicentres of earthquakes of moderate to low magnitude occur all along the west coast aligned parallel to or in close proximity of the ‘lineaments’. Notice that there is concentration of epicentres in southeastern coastal belt as well (after Rajendran42). (Inset) Focal mechanism solutions of some of these earthquakes indicating that sideways (strike-slip) and up-and-down (normal faulting) movements are responsible for the events (after Rastogi43).

Figure 8. Underneath the thick pile of Sabarmati alluvial plain is a large graben (rift valley) lined and cut by a number of parallel, deep faults. Some faults cut across the graben. The two sections on the right side show the internal structure and location of oil pools (based on works mentioned in Valdiya44).

The Gandak–Kosi region was ravaged by a great earthquake of magnitude $M_{8.4}$ in 1934. The meizoseismal area of this disastrous event has recorded a number of great earthquakes in the past – earlier than 25,000 yrs BP, and during 5300 to 1700 yrs BP, as palaeoseismic studies show36. I believe that this is a belt where blind faults are likely to be forming underground.

In 2008, the then consistently westward-migrating Kosi abruptly and drastically changed its course and flowed through its abandoned channel right through the middle of its mega fan, bringing unimaginable devastation (Figure 9b).

A recent report (The Times of India, dated 3 March 2011) states that the ‘Kosi has suddenly changed the course, drifting eastwards, threatening its embankments, spilling over at places and inundating farmland’.

This fact points to the reversal of the trend of shifting of the Kosi. In my perceptions, deep down under the Kosi Plain another subsurface fault related to the Patna Fault has become active again. This calls for comprehensive...
study incorporating: (1) the study of physiographic changes, including modification of landscape, sinking and uplift of the ground, change in the extent of waterlogging, deflection and blockage (ponding) of streams, sudden acceleration of stream-bed erosion (cutting); (2) monitoring fluctuation of water level in dug wells; (3) measurement of radon gas emission; (4) recording and interpretation of microseismicity and its clustering, and (5) analysis of anomalous behaviour of animals and birds, particularly the burrow-living creatures like snakes, rats, red ants and also of the common frog, *Bufo bufo*.

**Very high seismicity area in NE Uttarakhand and adjoining NW Nepal**

The northeastern part of Kumaun embracing the Kapkot–Dharchula area and adjoining northwestern Nepal (Bajang–Darchula area) are frequently rocked by earthquakes of magnitude $M \geq 5$. The quantitative seismicity map (Figure 10) of the Himalaya shows that this part of the Himalaya exhibits the highest seismicity anywhere in the Himalaya, if one goes by the number of earthquakes of $M \geq 5$. The strain energy release map based on the data for the period 1900–1970 confirmed this fact. The microseismicity shown by the region (Figure 11) is extraordinarily high.

Cut by the multiplicity of long and deep thrusts (including the very active Main Central Thrust) and faults, the rocks are in extremely sheared, shattered and locally pulverized conditions. The high mountain slopes frequently fail, giving rise to large and extremely destructive landslides and debris flows. Rock-falls are the order of the day. Some parts of the slopes crumble in season (during rains) and off-season (drier periods), implying slow, unstoppable movements on some of the very active faults.

To compound the tragedy, excessively heavy rainfall has been lashing the region in the last few years.

Knowing fully well the extremely high seismicity condition in the central sector of the Himalaya, cut as it is by a multiplicity of active faults, a large number of high dams have been built, or are being built, and planned in the immediate future (regardless of the interests of the thousands of people who would be uprooted). The sites chosen are invariably the narrowest parts of the valleys. It happens that an otherwise wide valley becomes suddenly very narrow where the active faults cross the valley. It is the movements on the active fault that are responsible for this development. Reactivation of active faults would pose danger to the stability of the structures built.

This region, to my mind, is another hotspot crying for urgent comprehensive studies embracing all aspects, including (i) trend and pattern of landslides and rock falls; (ii) subsidence and uplift and horizontal displacement of the ground; (iii) blockage (ponding) and sudden acceleration of stream-bed erosion (vertical cutting); (iv) marked and inexplicable changes in the discharges of springs and naulas (shallow wells); (v) emission of radon gas and (vi) pattern, extent and frequency of microseismicity with special emphasis on monitoring the period of seismic quiescence.
Concluding remarks

I know that a large number of specialists are fully aware of what I have written in these pages. However, I have ventured to restate these issues to emphasize the urgency for immediately addressing the problems that I regard as critical. I fervently hope that all my inferences and apprehensions are wrong, and no events that I foresee happen at all. As I write, I cannot help recalling the comments of a veteran of many political and legal battles in India – ‘We are the people who turn our heads and pretend that we do not see anything going wrong and we pretend not to have heard people cry’.

I feel terribly agonized to realize that there are people in our country who do not mind the wilting or even death of the dreams of the generation that would replace us tomorrow. I have a feeling that we, the people of India, are reconciled to the loot of our natural resources (including the very scarce water), and are by and large resigned to the selling of the nation’s future to finance our own present.

3. Jade, Sridevi, Anand, M. B., Dileep Kumar, P. and Banerjee, S., Co-seismic and post-seismic displacements in Andaman and


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