New strides in seismology in India – Pointers to progress and prospects

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The period post-1993 Latur earthquake is an era of renaissance in the field of seismology in India. The post-1993 developments now provide a national network with both broadband and short period and strong motion digital instruments, upgrading many old stations and setting up several new ones, thus generating a seismological infrastructure of high international standards. Matching efforts have also been set in motion to promote researches on several aspects of the vital areas of seismotectonics and earthquake engineering and results accruing are brightening up several dark areas of our understanding. The Department of Science and Technology, Govt. of India is in the forefront of these developments. Memoir 54 of the Geological Society of India[1] provides several aspects of the emerging scientific and infrastructural scenario of earthquake studies. The papers in the volume invite a discussion in terms of their overall impact on seismic source mechanisms, crustal structure and seismogenesis, deformation studies, and the great potential for an organized national effort in future built around the new infrastructure, marrying seismotectonics with state-of-the-art instrumentation, geodesy and engineering seismology.

Seismotectonic memories

The Indian shield cratonized more or less by the middle of the Precambrian (~ 1600 Ma). It then passed into prominent episodic and spatially selective extensional regimes in the Late Precambrian, Mesozoic and the early Cenozoic. Since around 55 Ma, the Indian craton has been overprinted by an all-pervading compressive regime transmitted from the plate boundaries. These forces emerge from the spreading centres of Indian Ocean ridges, the associated transform boundaries, the diffuse seismic boundary in the south that divides the Indo-Australian plate and the Himalayan collision boundary in the north. The evolution of a Precambrian craton through episodes of extensional tectonics has imposed on the continent, an unerasable tectonic fabric of great diversity that responds differentially to the ongoing overprinting of compression. Almost all or any of the palaeo-structures, prominently long belts of rifts, half-grabens and horsts, have the potential to get reactivated in the new field, including rifts in the early to mid-Precambrian pre-cratonization fabric. An anticlockwise rotation of the shield brought about by an earlier collision in the NW could generate relative extension along the western continental margins and compression along the eastern continental margin. Large segments of the shield such as the Sahyadris and the Satpura mountains and the Chotanagpur Plateau are rising, largely due to epeirogenic processes, implying lithosphere–mantle interaction. The Shillong Plateau, a Precambrian outpost in the NE, is also rising, but the processes that bring about the uplift are uncertain. The vertical uplift of large segments may be expected to impose an extensional component on an otherwise compressive regime and rotate the stress fields, as has happened in Tibet Plateau in the Himalaya, perhaps in a much different tectonic milieu. These uplifts then have a profound influence in generating slow strain rates characteristic of the Stable Continental Region (SCR) earthquakes[2]. Several endogenous crustal features, some of which will be referred to later, influence the local rheology and determine the locales of stress accumulation. A slightly enhanced thermal structure prevails in the northern part of the shield and the continental margins, being highest in the Cambay Basin, which can influence their seismic response. These are memories of the earlier continental basalt magmatism and have been related, though debatably, to the continuing influence of a past hot spot tectonics, older than some 65 million years[3]. An approximately ~ 2 km thick Deccan basalt cover in the west overlies a large part of the northern shield and has the potential to strengthen weak faults in a compressive regime. Erosion of the basalt cover or a shift in the stress field towards extension can move the weak faults to failure, thus accounting for thin-skinned tectonism.

Despite the fabric of extensive deformation, seismicity in the Indian shield shares several features of the SCR-earthquakes and is characterized by a variable but generally small strain rate shared by several small faults initiated mostly in shallow depths of less than 10 km, but rarely traced to depths as high as 30 km. In this scenario, aseismic regions may be under steady-state stability outside the seismic zones, where the interaction leaves pockets of resultant stress fields along pre-existing weak zones. Any 'transient' mechanism, such as pore-pressure changes that can upset the steady-state stability of weak faults can generate earthquakes. Therefore, locating seismic centres calls for an approach akin to searching for a needle in a haystack. Signals of such failure, where they are of significant magnitude, are transmitted over large areas and therefore render monitoring of the events possible once the earthquake is generated.

This rather simplified analysis of the deformation scenario of the Indian shield, nevertheless, portrays the problems of understanding its seismicity – how, when and where the all-pervading compressive regimes of plate boundary forces and several interacting endogenous forces would generate stress fields to levels of fault failure in a mosaic of widely varying, pre-existing tectonic trends. The network of seismological stations now built up, aims at locating most of the earthquakes of magnitude equal to or greater than three and has the potential to a real-time monitoring of major seismic events. This is then the first step towards closely monitoring earthquakes and advancing towards a total understanding of seismogenesis in the Indian shield. The lessons learnt will no doubt have global relevance.

Seismotectonic provinces

The contributions in the recent publication[1] (see ref. 1 for details) have to be viewed against a broad characterization of the seismo-tectonic provinces of the shield that evolved in the background of the geological history outlined above. These include (i) the Kachchh and (ii) the Cambay–Mumbai belts along the western continental margin; (iii) the eastern pericontinental Shillong Plateau, (iv) the more interior SONATA–Chotanagpur belt, (iv) the Eastern Continental margin and (v) the Southern Indian shield. The Kachchh and Shillong provinces are distinctive by virtue of the highest and strongest seismic incidence and have to be viewed in the background of a more prominent, youthful Late Mesozoic–Cenozoic involvement in crustal evolution, their geographic position in terms of the NW and NE Himalayan re-entrants and the Makran and Burmese arcs and consequent tectonic relationship to the stress fields generated by plate boundary forces[4]. In the rest of the shield, the Cambay–Mumbai pericontinental belt and the SONATA belt have higher earthquake incidence but differ in their deep continental structure, recurrence patterns and strain rates among themselves[5,6]. The interior provinces of SONATA and South India have recorded events originating at depths of some 30 km, even more in the Shillong province, implying a stronger lower crust/lithosphere than in the western and eastern pericontinental regions. Thus seismicity of the shield, labelled under SCR earthquakes, has widely differing seismo-tectonic characteristics that arise from distinctive tectonic evolution.

Source mechanism

New light has been thrown on the source mechanisms of the Latur earthquake, the ongoing Koyna–Warna quakes and tremors and the Allah Bund 1819 earthquake (Kachchh) (revisited) (see ref. 1). The results illustrate that stress fields in each of the centres of failure are unique, though in all the three areas there is a seismic ancestry and studies confirm reactivation models that have been proposed earlier[7,8]. Data on Latur earthquake are from a rare source of four boreholes drilled in an outcropping co-seismic fault zone; seismic zones are rarely investigated through actual drilling, due to uncertainties of the precise fault locations and the high cost of drilling. A cumulative displacement of 3 to 6 m inferred from the drill-hole data, as against less than a metre of displacement in the outcropping fault that may be assigned to the 1993 event implies a seismic tradition, contradicting earlier suggestions of neo-faulting[9]. The earthquake mechanism is a thrust in Latur. The Allah Bund event also seems to have a seismic ancestry, in which three palaeoevents have been recognized. In Allah Bund, inversion of an ancient gravity fault transformed into a thrust and ending up as a fault-propagated fold, seems to fit well with the affected unconsolidated and rather weak supracrustal Holocene sediments that form the Allah Bund. The Allah Bund fault-fold, in contrast to the surface fracturing of the relatively more brittle Latur Deccan basalt cover, raises the possibility that the absence of surface faulting in at least one class of SCR earthquakes is due to the dissipation of stress by effective flexuring of the overburden driven by deep faulting. The brittle basalt cover in Latur has responded by fracturing. This may explain the rarity of surface faults in many SCR events, though their absence in many cases may also be due to mere dissipation of stress through complex splaying out of the faults as they approach the surface. The Koyna–Warna seismicity is now widely recognized as reservoir-induced and is unique as earthquakes of magnitude > 5.0 continue to occur even three decades after the main spurt of activity. Seismicity is migrating towards the Warna reservoir and provides an excellent example of human intervention that can migrate stress fields. Fault-plane solutions in Koyna–Warna region imply a unique interplay of stress concentration and pore-pressure[10]. Ongoing investigations in Koyna–Warna with closer seismic network, deep drilling, pore-pressure monitoring and nucleation studies can provide deeper insights into the earthquake processes. A cascade model for the Koyna–Warna area generated by the study of eight seismic events of > 4.3 M (see ref. 1) may provide a preliminary insight into how the foreshock patterns in Koyna may have the potential to signal a short-term anticipation of an on-coming event.

In the western margin of the Indian shield as a whole, an extensional strain reported through GPS studies in the Maharashtra region, the modelled presence of extensional elastostatic stresses[11] and the stray gravity faults such as Valsad 1986, imply a larger component of extensional stress in this region[12] compared to other seismotectonic provinces, though the overall expression of these stress fields, when released, continues to be mostly as strike-slip faulting. The foci of most earthquakes in this belt are shallow, being less than say 10 km. Such a stress field may be the effect of memories of earlier rifting of the west coast, the anticlockwise rotation of the shield and the on-going epeirogenic uplift of the whole of the Sahyadris, which may be expected to provide an opposing, thin-skinned extensional regime over the overall compressional field of the shield. Such a rotation tends to neutralize the strengthening influence of the Deccan Trap overburden on weak faults.

The fact that each of the earthquakes is due to reactivation of pre-existing faults but generating restrictive movements over short wavelengths, warns us of a fallacy inherent in the common practice of relating the shield seismicity to long faults running for hundreds of kilometres and characterizing them as 'active faults' in the SCR. On the other hand, seismicity seems related, as in most SCR earthquakes, to several small centres of reactivation due to localized stress build-up. The frame of a large number of continent-scale faults, often built up by joining several disconnected, small fault outcrops, may not be critical to problems of seismogenesis in an ancient intra-plate SCR, as may be relevant to plate boundary seismic regions. They may have a place in determining the overall strength of the crust regionally, but the methodology itself of inferring such long faults, which by implication must extend to great depths, needs a review.

A related problem that needs to be addressed is that an event like the uplift of a geomorphic feature like the Allah Bund in the Rann of Kachchh may change the total stress fields, and lead to their concentration into other centres; for example, in the central part of the Kachchh rift along the Kachchh Mainland Fault (KMF), where we had the 1956 Anjar earthquake ($M = 6.1$) and KMF–North Wagadh Fault depth intersection where the 2001 Bhuj earthquake was focused. Similarly, the incessant, renewed seismic bursts in Koyna–Warna region may be influencing the stress field in the whole of the surrounding region. Is then Latur an aftermath of the reorganization of the stress fields brought about by the 1967 Koyna events? These and similar questions are related to the bigger question being addressed by seismologists, namely whether earthquake-induced static and dynamic stress changes trigger subsequent earthquakes[13]? If this is true, seismotectonics is rendered even more dynamic by the very processes of its manifestations.

Crustal structure and rheological response

Recent publications portray the possible influence of rheological layering in areas of seismogenesis inferred through the application of magneto-telluric investigations and after-shock seismic tomography, heralding a new direction in seismological studies in India (see also ref. 1). Fluid-charged mid-crustal conductors, low-high seismic velocity stratification and the presence of high-velocity dense rift cushions in the Lower Crust are candidates that may control the rheology of the seismogenic layers. Their configuration in relation to the earthquake foci, however, differs in the areas investigated. A crustal electrical conductor in the depth range of 6–10 km coincides with a seismic low-velocity layer (LVL) and underlies the seismogenic layer below Latur[14,15] and adjoining areas. Other LVLs at lower depths in the upper crust and the velocity model are comparable to what has been earlier established in the Koyna area[16], indicating a widespread rheological layering. A conductive zone overlies the seismogenic layer below the meizoseismal area of the 2001 Kachchh earthquake[17]. The underlying seismogenic layer is characterized by high *Vp*, low *Vs* and high Poisson ratio[18]. The velocity structure has also been interpreted as that of a dense rift cushion with an embedded low-velocity band in the base of the Lower Crust[19]. The meizoseismal area of the 1997 Jabalpur earthquake may also be underlain by a rift cushion[20] though, in my view, not firmly established from velocity structure. The preferred source for the conductive zones are enriched zones of fluids and stress accumulation that then influence the rheological response of the crust as a whole in the presence of fluid-charged weak layers. The fluid-enriched layers also have the potential to bring about pore-pressure changes that can lead to the failure of faults. How and why these weakening factors, rather widespread, influence fault failure selectively in specific small locales within a large rift system, is the key to anticipating seismic failure. It remains an enigma, that may be resolved only through a larger database. These concepts offer a fertile field for mathematical modelling.

The manner in which more refined data on crustal structure can flow from the enlarged and modern infrastructure has been illustrated, highlighting the integrated use of the seismic stations for monitoring not only teleseismic but also controlled seismic sources (see ref. 1). A significant recent result is the velocity structure determined using surface-wave dispersion along the paths of the 1997 Jabalpur earthquake and Koyna events that highlight the heterogeneity of the Indian shield. The results are at variance with earlier velocity models in inferring a thinner Upper Crust, a much thicker Lower Crust and lower boundary velocity of the mantle. The new model[21] is consistent with geological events of exhumation of the Lower Crust in the Central Indian region in the Late Proterozoic, and later during the extensional development of the Gondwana basins. The results have a practical importance, as a precise velocity structure permits a more accurate modelling of seismic source distances from the teleseismic records. The earlier models[22,23] of crustal structure may be only generalized models for the seismic wave paths considered in modelling. The old and the new models are not necessarily contradictory, but complementary and apply to different paths of seismic transmission[24].

Another area of relevance to seismicity is the tectonic evolution of the western continental margin. Correspondence between lineament densities, isostatic uplift and earthquake epicentres leads to the conclusion that the NNW-trending fracture lineaments along the Konkan coast are seismogenic. An important consideration is that the fractures may be related to flexural mechanisms involved in rifting. Further, seismogenesis may be related to failure due to rotation of stress fields, as mentioned earlier. Gravity modelling along the Kerala coast provides a tentative model of MOHO depths shallowing from 35 km on land to 16 km farther away, up the Pratap ridge that may be an expression of the initial rift-related faulting along the west coast. The western offshore region needs to be investigated thoroughly by seismic profiling, constrained by the gravity results, to generate reliable velocity models.

Deformation studies

A new dimension has been added to earthquake studies in India by initiating extensive geodetic studies, mainly using GPS. Some of the significant results accruing from these efforts and their long-wave-length results are outlined in a recent publication[25]. Application of GPS studies on a more localized pattern becomes important in evaluating the seismogenesis in the shield, since the rupture areas of the earthquakes are small and deformation has to be inter-related to relatively localized geodetic changes. Results of investigation of GPS studies using smaller networks and on a more localized scale have been exemplified (see ref. 1). The velocity vectors of movement in the Deccan Volcanic Province (western pericontinental tract) give an average of 51 mm/y at N47°E. The average extensional and shear strain is about 0.4 microstrain/year. Results from Central India bring out observations of distension and compression in several sectors that need further confirmation and analysis. GPS geodesy should provide us a picture of the total energy release during the deformation that is only partially expressed in brittle deformation and the resulting seismogenesis.

Seismicity and building safety

Sensors located at the different storeys of the Regional Passport Office at Ahmedabad have generated data useful in designing earthquake-resistant buildings. The study is a singular example of the efforts being channelized by the DST in promoting researches related to structural response to earthquakes in India, an area where outcome of large inputs ploughed in during the last two to three decades, both in the shield and the Himalaya, calls for greater visibility.

Infrastructure and future research

The new seismological infrastructure has already paved the way to drawing up comprehensive programmes of earthquake research. The future task will be to carry forward these integrated multidisciplinary, multi-institutional approaches to larger spheres that will enhance our capabilities of seismic management. The large post-1993 Latur developments in seismology impose on earth scientists, a challenging responsibility of not only proper maintenance but continuous updating of costly and largely imported instrumentation (both seismic and geodetic) and maximizing the utilization of the large data that flow from the network. Development of indigenous instrumentation and software needs a thrust. A larger and a more widely spread participation by the IITs and universities is needed. The new infrastructure built on a healthy consortium mode ensures pooling together all the available expertise in the fields of seismotectonics and earthquake engineering. However, the absence of a single nodal agency to overview and guide such a vast area of scientific infrastructure, would render the task of ensuring scientific progress and accountability quite challenging and demands urgent attention – an aspect emphasized by several national expert committees of the past.

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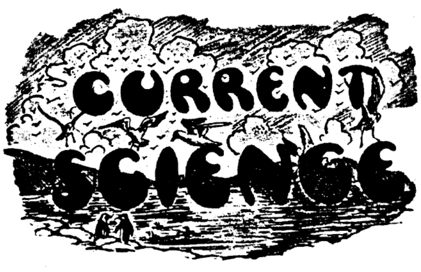

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Problems of post-war agricultural reconstruction

After the war is over and peace is restored, there will arise problems of social and economic repair and reconstruction. Agricultural reconstruction will have to receive prior consideration. Farming will be the first to be re-established in the areas that have suffered from war and being also the occupation of the bulk of the world population, the reconstruction of agriculture is the basis of national reconstruction. These tasks which should be considered well in advance of the need, demand expert knowledge, careful thought, clear vision and planning with foresight.

The lead given by the British Association for the Advancement of Science is, therefore, none too early. Through its Division for the Social and International Relations of Science, the Association arranged, in March this year, a Conference for the discussion of plans for the post-war reconstruction of agriculture in Europe. A large number of experts from the different countries of Europe participated in the Conference and made valuable contributions. Although the discussions were chiefly on plans for the re-establishment of agriculture in the devastated and oppressed areas of Europe and on the alleviation of the effects of famine and disaster, it was recognised that in the general problem of reconstruction the solution of immediate problems were closely interwoven with long-term policies and that, therefore, urgent plans should be linked up with long-term plans.

India, like Europe and the rest of the world, will have her post-war problems. A merciful Providence has so far spared India the horrors and disasters which her less fortunate sister-countries are suffering from. And so, her immediate post-war problems may not be similar to those of Europe and other Eastern countries of Asia. But linked up as she is with the outside world and its affairs, she has to play an important part directly or indirectly in the re-establishment of agriculture in the devastated areas. She has also her own urgent and long-term socio-economic and socio-political problems of reconstruction, special and peculiar to herself and in dealing with these, her plans of reconstruction have to be in consonance with world policies.

The situation arising out of current war conditions such as changes in cropping systems necessitated by loss of export markets for certain crops and by the 'grow more food' campaign, and the effects of inadequate nutrition and disease will need technical examination and practical adjustments as and where necessary. Occupation and instruction in matters of agriculture, village and domestic welfare, will have to be provided for the peasant-soldier returning from war. . . .

The increase in the population and its pressure on land are vitally concerned in