Developments in past hundred years in India in the fields of seismology, tectonics, and geodynamics

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Abstract

In the past 100 years, the most important development in geoscience is the conceptualization of the plate tectonic theory. The concept is revolutionary and can explain earthquake and geodynamic processes globally. As geoscience is a multidisciplinary field, developments in other fields have benefitted geoscience, e.g., the use of digital instruments in place of analog instruments, providing higher accuracy, resolution and dynamic range, real-time data communication through the internet and VSAT, and civilian use of GPS. Worldwide deployment of seismographs has provided the much-needed data on earthquake processes and earth structure. GPS in seismology for time synchronisation of seismographs and for crustal deformation monitoring has revolutionised seismological research. The introduction of high-performance computing (HPC) has allowed geoscientists to take up large scale modelling. In recent times, the divide between geology and geophysical research is virtually non-existent, e.g., the joint analysis of seismological and geochemical data which have helped in understanding deep geodynamic processes. With all these efforts our understanding of earthquakes and the processes involved in their occurrence and crustal and deeper level structures has improved. Despite all these developments, earthquake prediction remains elusive but by studying the impact of earthquakes on the built-up area and by developing the damage scenarios we can mitigate the risk due to future earthquakes.

Keywords: plate tectonics, earthquakes, Himalaya, Tsunami, GPS

Introduction

The conceptualization of plate tectonic theory in the 1960s revolutionised the research in geoscience. By that time, we already had a good understanding of the earth's interior, physical properties, landforms, etc. However, the geoscience in the following years entered a state of supercooling where the smallest input could lead to the simultaneous crystallization of new ideas. The subsequent years were the most happening period in geoscience when scientists were unlearning a few old concepts to learn the concepts of plate tectonics and to apply them in their respective research domains. It led to a great revolution in understanding the earth's behaviours whether in plate boundary or in plate interior regions. This was immediately followed by the global deployment of the World Wide Standardized Seismic Network (WWSSN). Moving from analog instruments to digital instruments in the 1990s was the third revolution which allowed to see the processes over a wide frequency range. The civilian use of GPS and its utility in geoscience was probably the fourth revolution. By that time geoscientists were already integrating data in geophysics and geochemistry and newer techniques of geochemical analysis and geochronology were already in vogue.

In this short note, I intend to bring out the progress and developments in the past 100 years in the field of seismology, tectonics and geodynamics related to the Indian subcontinent. I must admit that this is not an exhaustive compilation, and it is quite possible that I might have missed a few important developments.

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Earthquake processes

Amongst all tectonic plates on the Earth, the Indian plate has made the longest voyage of ~9000 km in ~160 million years after the Gondwanaland breakup. It has undergone several episodes of continental flood volcanism. The northward journey was fast from the late Cretaceous (67 Ma) to early Eocene (50 Ma), at about 20-25 cm/year. However, it slowed down to 5 cm/year during and after its collision with the Eurasian plate. The collision is responsible for the uplift of the Himalayan–Tibetan Plateau. It is responsible for the summer monsoon, precipitation, and fertile soil in the Indo-Gangetic plains. Imagine life without beautiful Himalaya, no topography would mean no or less rainfall in the region, less rainfall and lack of eroded soil from the mountains would make the plains less fertile, which would eventually lead to the loss of the breadbasket of India and civilizations which this region is hosting and have hosted in past. The collision of India and Eurasia plate in the Himalaya causes earthquakes which kill people, but it is the same process which in long term, turns this region into beautiful, scenic, fertile, and inhabitable land that supports life.

Our understanding of the earthquake processes has increased because of keen observations and measurements taken after the occurrence of earthquakes. The earliest such example is probably the 1819 Allah Bund earthquake in the Rann of Kachchh. The occurrence of the earthquake created a fault scarp which is present in the region even now. The earthquake scarp and its effect were so spectacular and profound that Charles Lyell, the famous British geologist, had used it as a classic example to argue for the differential movement of land along a fault. The morphology of the scarp was mapped using levelling observations by the Britishers. After the 1906 San Francisco earthquake, which created several offsets across the fault, H. F. Reid summarised the importance of the Allah Bund and used it to formulate the "Elastic Rebound Theory" which is the basic tenet of seismology and physics of earthquakes. Careful reporting of earthquake measurements during subsequent earthquakes has led to significant improvement in our understanding of earthquake processes. The observations of large boulders being overthrown from their grooves at the time of the 1897 Shillong Plateau earthquake (M 8.1), implied that the acceleration during the earthquake shaking can exceed 1 g. The occurrence of a large but isolated region of damage in and around Dehradun during the 1905 Kangra earthquake highlighted the secondary damage during large earthquakes. The 1934 Nepal-Bihar earthquake (M 8.1) caused large destruction in the Indo-Gangetic plains due to ground failure, and soil liquefaction, while the rupture of the earthquake was confined in the Himalayan region. It highlighted the vulnerability of the adjoining plains to shaking during large earthquakes. The 1950 Assam (now Arunachal) earthquake (M 8.4) which caused extensive landslides and floods, brought the issue of cascading effects of great earthquakes. The occurrence of the 2005 Kashmir earthquake (M 7.6) on steep fault indicated that large earthquakes could occur through out-of-sequence thrusting and it is not necessary that they remained confined on the Main Himalayan Thrust, MHT (the detachment or decollement separating the Himalayan wedge rocks from the under thrusting Indian plate rocks). From the recent 2015 Gorkha earthquake (M 7.8) we learned that the rupture on the MHT of the large earthquakes can be partial and it is not necessary that all great earthquakes extend up to the surface and up to the Himalayan front. All these and several other smaller earthquakes have provided valuable information about the earthquake processes.

In the plate interior regions, also known as stable continental region (SCR), the earliest known and well-documented major earthquake is the 1819 Allah Bund earthquake. In the past 100 years, several strong earthquakes have occurred in the plate interior region, *viz*., the 1897 Shillong plateau, 1956 Anjar, 1967 Koyna, 1970 Bharuch, 1993 Killari, 1997 Jabalpur and 2001 Bhuj earthquake. Most of these earthquakes occur along the paleo structures that formed before the Gondwana land breakup and were subsequently healed. However, after the India-Eurasia collision, many of these structures, primarily the paleo/aborted/failed rifts, got reactivated under the compressional environment. In terms of large magnitude and damage the 2001 Bhuj earthquake is the deadliest. However, some of the earthquakes, like the 1993 Killari, have occurred on structures without any visible geomorphological expression. Through the 1967 Koyna earthquake, we learned that anthropogenic activities, like surface reservoir impoundment for hydroelectricity in this case, can trigger earthquakes.

Earthquake monitoring

The history of instrumental earthquake monitoring in India dates back to 1898, with the first seismological observatory of the country established at Alipore (Calcutta) on December 1, 1898, after the great 1897 Shillong plateau earthquake. By 1950, the number of observatories increased to eight. During the fifties, IMD started indigenous design and development of a few analog seismograph systems and by 1970 the number reached 18. The early sixties marked a very important landmark in the history of global seismic monitoring when the four WWSSN (World Wide Standardized Seismic Network) stations started functioning in India. In 1965, another significant addition was made by installing an L-shaped seismological array at Gauribidanur by Bhabha Atomic Research Centre (BARC), Bombay. Prior to the 1990s, the seismological network primarily consisted of conventional analog type of seismograph systems with photographic/smoke/ink/heat-sensitive paper recording devices. However, the advent of computer-based digital and communication technologies led to the development of high-resolution force balance broadband sensors, large dynamic range digital recording systems and VSAT-based communication facilities for high-speed data transmission. These developments have greatly contributed to improving the country's seismic monitoring and research capabilities. During mid-1990s, 10 analog observatories were converted to the standards of the Global Seismograph Network (GSN), after the Latur earthquake of 1993. Subsequently, 14 more analog observatories of the national network were upgraded with similar digital broadband seismograph systems during 1999-2000. As on today, there are 155 digital broadband seismological observatories of the Indian national network. Several other research and academic institutes operate seismological observatories for research, and most of them are in survey mode.

Tsunami warning centre

The occurrence of tsunami triggered by earthquakes and volcanoes are common in the subduction zones around the Pacific Ocean. Even in the Indian subcontinent, there were a few instances when cases of tsunami were reported in history, e.g., the 1945 Makran earthquake tsunami impacting the western coast and the 1881 Car Nicobar earthquake impacting tsunami in the Andaman and eastern coastal regions of India. But the occurrence of the 2004 Sumatra Andaman earthquake which triggered a devastating tsunami was an eye opener as it killed more than two lakh people. Besides learning several new aspects of earthquakes, e.g., large rupture length of ~1400 km, large magnitude reaching 9.2 ringing the entire earth, a monster tsunami with long reach travelling up to Somalia, large surface displacement of 6 m, long rupture duration of >10 minutes, and realisation of including free oscillations in earthquake magnitude calculation, etc., India established a tsunami warning centre of its own keeping a watch on the Bay of Bengal and Arabian sea for a tsunami.

Crustal deformation monitoring

Studies on crustal deformation in India started by the Survey of India (SOI) using land-based measurements. The Great Trigonometrical Survey (GTS) by Britishers was undertaken during 1802-1871. The main purpose of the survey was to provide accurate maps. Levelling observations were undertaken to measure height. Repeat surveys provided the change in height or coordinates at the benchmark. Probably the first well-documented levelling survey to measure the change in height due to the 1819 Allah Bund earthquake. The triangulation survey in Assam provided the change in angle between the control points due to the 1897 Shillong plateau earthquake. In subsequent years several land-based surveys have been reported and their data have been used to understand the crustal deformation due to earthquake processes. However, in all cases, the corresponding errors in the estimates are large. In the 1990s, the use of the Global Positioning System (GPS) in geoscience revolutionised seismological research. It provided global time synchronization with high accuracy for seismological observatories and accurate coordinates of sites and their temporal variation, for crustal deformation studies. India established its permanent and continuous GPS station at Bangalore and Hyderabad in 1995. This led to the estimation of Indian plate velocity (52 mm/year towards NE at Hyderabad) with unprecedented accuracy with uncertainty in the velocity estimate of less than ±0.5 mm/year. Since then, the use of GPS in crustal deformation has increased and currently, there are more than 250 GPS sites in India tracking the site motion. These measurements have helped in understanding the geodynamics of the Indian plate, in identifying the active faults that can host future large earthquakes, in estimating the fault slip and convergence rate across faults/tectonic units, in accurately assessing the energy (or slip) released during large earthquakes, etc. Because of the GPS measurements, now we know the rate of strain accumulation in various segments of Himalaya (varying from 14 to 20 mm/year), intraplate deformation (less than 1 mm/year). We can also measure the coseismic offsets caused by the strong earthquakes which can be used to estimate rupture parameters of earthquakes.

Himalayan tectonics

In past few decades our understanding of tectonics has increased tremendously. Himalayan region has always attracted geoscientists. Because of extensive geological field work, advent of subsurface imaging geophysical methods, earthquake and deformation monitoring, and the compelling plate tectonics theory, our models of Himalayan collision zones have improved and now we know that the convergence of India and Eurasia in the Himalayan arc region is accommodated on the Main Himalayan Thrust (MHT), the decollement surface between the Himalayan wedge and under-thrusting Indian shield rocks. The MHT beneath the Outer and Lesser Himalaya is seismically active while that beneath the Higher Himalaya and farther north slips aseismically. Thus, the MHT accommodates the convergence in stick and slip manner in which the accretionary prism (Himalayan rocks) deform. The strain accumulates (stick) during the interseismic period and is released (slip) during the coseismic period. Consequently, the efforts of current research are to image the subsurface structures that can host large earthquakes and to quantify the rate of strain accumulation on the identified faults. The deep imaging of structures has led to the identification of subsurface ridges beneath the sediments of Indo-Gangetic plains which extend beneath the Himalaya and probably control the rupture extent of large earthquakes.

Shift from earthquake prediction to the assessment of impact

After practically no success in earthquake prediction, nowadays the focus of research has shifted from understanding the geodynamic processes and complexities involved in it. There is more emphasis on mitigating the hazard, not through prediction but through assessing the impact of earthquakes on the built-up environment. This has led to the generation of earthquake damage scenarios, understanding the behaviour of soil during shaking, strengthening, and retrofitting the structures and finally making the public aware of the hazard. Another important step in this direction is the development of an Earthquake Early Warning system. It is based on the concept that the earthquake waves travel slower (3-5 km/s) than the speed of communication (300,000 km/s). Thus, after the occurrence of a strong earthquake in a region, we can inform people at far-off distances (e.g., ~100 km) where the ground shaking has not reached that an earthquake has occurred here. This will forewarn people at far-off places that they are going to experience shaking in next few seconds. Thus, people of this region will get a lead time of a few seconds (say ~20 seconds in this case) and can take safety measures, e.g., coming out of a building or taking shelter in a safer place of a building.

The entire concept of earthquake occurrence process has been verified from the observations of strong-magnitude earthquakes and is now used in seismic hazard assessment. In fact, a major program called Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 providing hazard maps which in many ways are more objective than the conventional seismic zoning maps. Similarly, a program on World Stress Map was launched in 1986 under the International Lithosphere Program.

Paleoseismology

One of the problems faced in earthquake hazard assessment in the Himalaya is the shorter length of the instrumentally recorded earthquakes. Some earthquakes have been well documented in history but in a more qualitative manner. Realising that the recurrence interval of major and great magnitude earthquakes is large (a few centuries), and for earthquake assessment we need to know about the earthquakes which occurred in past (a few thousand years), a new discipline has come up, which is called as Paleoseismology wherein a datable material from the fault zone is used to estimate the approximate date and size of the earthquake. Other than the known earthquakes of past, now paleoseismologists have unearthed several large magnitude earthquakes in the Himalayan region, e.g., now we have evidence of the 1505 earthquake in western Nepal and part of Kumaun region, the 1344 earthquake in Kumaun and Garhwal, the ~1100 AD earthquake in Nepal, the 1714 earthquake in Bhutan, etc.

Indian Ocean Geoid Low

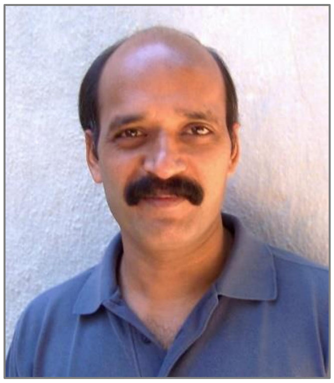
One of the most puzzling aspects of Indian geodynamics is the presence of a large geoid anomaly in the Indian ocean, known as Indian Ocean Geoid Low (IOGL), it is dominated by a significant gravity low where the ocean surface plunges down to 106 m. It has now been found that 'low density anomalies' or the presence of lighter materials in the upper to mid mantle below the IOGL, are responsible for the gravity low in this region which originated from the African superplume.

Deccan volcanism, cartons, dyke swarms

One of the most notable events in earth science in the context of the Indian plate is the Deccan volcanic eruption due to a deep mantle plume. The large area of ~500,000 km^2 and long-term eruption, about 66-65 million years ago, known as the Réunion hotspot, is suspected of causing the Deccan Traps eruption. It is believed that it also caused the mass extinction, the fifth in the past 540 million years. A great amount of work has been done using geochemical analysis to characterise the flows, duration, and extent. In the past few decades, isotopic data on zircons have provided proof for convergence tectonics in place of vertical tectonics operated on the cratons of Indian plate. Thermobarometric, along with the seismological data, have provided constraints on the lithospheric thickness and its variation beneath various cratons. Similar analysis has provided constraints on Singhbum craton to suggest that it is the oldest (~3.5 to 3.2 Ga) rock assemblage so far. Dyke swarms in south India of 2-2.4 Ga age have been studied quite extensively for paleo reconstruction of Indian plate movement, and plume activity.

Closure

Finally, in the end, it turns out that our understanding of the earth's processes improved after the conceptualisation of the plate tectonic theory. Thus, in the true sense, the science of earthquakes is a very young, which started developing < 100 years ago, after the advent of plate tectonic theory. The rapid progress in this field is mainly due to large and quality data acquired in the past few decades. Because of large variations in the natural dynamic processes involved in earthquakes, and the large number of parameters required to characterise the earth's material and processes, we are not able to predict the geological hazards. Nevertheless, efforts have been made to assess the impact of hazards and to mitigate the risk. We are hopeful that with the current pace of progress a day will come when we will be able to minimize the impact of geohazards so that there will be no loss of life and property during their occurrence. At this point of time, we are not able to predict their occurrence, but the agenda of all research efforts is in that direction. *G*



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