Geodetic contributions to the study of seismotectonics in India

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Earthquakes in India are caused by the release of elastic strain energy created and replenished by the stresses resulting from India's collision with Asia. Accumulating strain distorts the surface of the Indian plate, which despite its slow development can now be detected using precision geodesy. The largest and most severe earthquakes occur on the boundaries of the Indian plate to the east, north and west of the subcontinent. Historically, these areas have been somewhat neglected by precise geodesy and it is only recently that suitably dense networks capable of spanning entire plate boundaries have been developed. Earthquakes within the subcontinent, though devastating, have also remained unserved by historical geodesy in India because the rupture areas of these events are small and have tended to occur between networks of adequate precision. Since 1990, the widespread availability of GPS geodesy has resulted in a number of significant findings related to the translation, deformation and rotation of the Indian plate, and to deformation of its margins. The next decade is likely to see the uncertainties of these estimates fall by a factor of 4, permitting estimates of changes of rate in space and time. We discuss these new findings and their historical antecedents, and identify current trends in seismogeodetic research that are likely to contribute to a new understanding of future Indian earthquakes.

Introduction: Seismotectonics and geodesy

The processes of continent–continent plate collision that drive the earthquakes in India have been in progress for several tens of millions of years. The longevity of this process means that our present view of earthquake productivity both within the craton and on its borders is, to a first approximation, representative of 'average' conditions of elastic strain accumulation and release. Quantitative knowledge of the processes involved, however, is based on a fragmentary historic record of seismicity, and a relatively short instrumental seismic record that is inadequate to characterize earthquake processes with cyclic durations exceeding a few hundred years. Thus, it is uncertain whether the earthquakes of the past century are typical of long-term recurrence rates or magnitudes, because we may be viewing a time period insufficient to average random fluctuations in slip on the plate boundary, or strain adjustments within the Indian craton.

By assuming that the processes driving earthquakes are elastic, we may measure the approach of a future earthquake in a given region using geodetic methods (quantitative measures of displacement, tilt and rotation). By further assuming that earthquake processes are linear in time and that failure occurs when frictional stresses are exceeded, we may estimate the renewal time for elastic failure. Geodetic measurements of deformation thus provide an indirect measure of the rate of seismic productivity of a region. The assumption of linear elasticity is clearly inappropriate for a complete description of Indian seismotectonics because folding of strata is ubiquitous in parts of the tectonic system. Moreover, viscous deformation cannot be distinguished from elastic deformation except where the complete elastic cycle is manifest. No unequivocal replications of Indian earthquakes have occurred in the historic record, indicating that the renewal time for these events is much longer than reliable historical data. The application of palaeoseismological methods to historic Indian earthquakes[1] promises to improve our knowledge of these events, but it will be some considerable time before palaeoseismic data are of sufficient density to identify the characteristic styles of slip of Indian faults.

In this review we outline the tectonic setting of India and discuss geodetic contributions to the study of Indian deformation in the past 200 years, and important new findings of the past 5 years. We then identify certain issues whose resolution is critical to understanding the geodynamics of the Indian plate, i.e. the underlying processes responsible for the observed tectonics. Finally, we speculate on some of the interesting issues that will become important as new data become available.

Tectonic overview

The Indian plate is bordered by spreading centres to the SW, by transform boundaries to the east and west and by an unique continental collision boundary to the north

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(Figure 1). An important feature of the northern collision is that volcanoes and deep seismicity are absent. This indicates that the Indian plate does not descend deep into the earth's mantle immediately north of the Himalaya, as the Nazca plate does, for example, to the east of the Andes. Moreover, the absence of a heavy down-going slab means that the forces driving the collision process must largely originate either beneath the Indian plate as

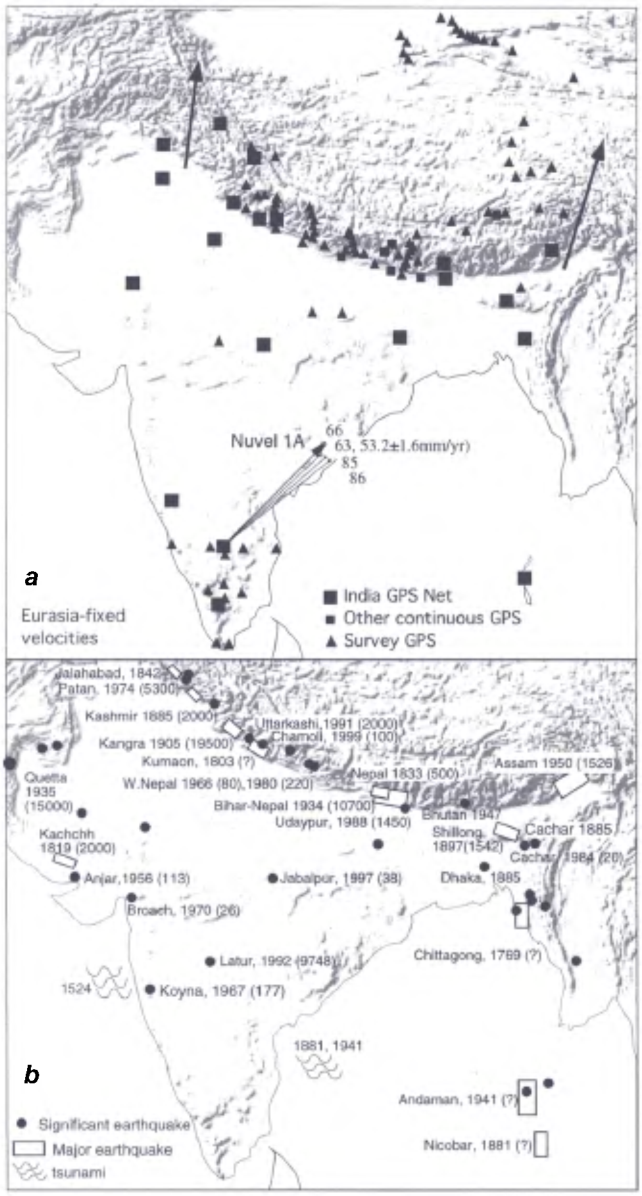

Figure 1. ***a***, GPS measurements in India and Tibet (excluding unpublished Survey of India studies). Existing survey type measurements are indicated with triangles and planned and existing continuous tracking sites by squares. The arrows indicate NUVEL-1A velocity vectors relative to Eurasia, and show four recent estimates of the velocity of IISc, Bangalore[63,66,85,86]. (Uncertainty ellipses are less than 3% of the signal and are almost invisible at the scale shown.); ***b***, Significant earthquakes in India with year of occurrence and fatality count known. Recently revised magnitudes for the Kangra 1905 and Shillong 1897 earthquakes[87,88] have reduced their inferred rupture-areas, leaving large segments of the Himalayan arc unruptured.

basal shear, or at the Indian Ocean spreading centres to the south. These forces subject the Indian plate to NE-directed compressional stresses, which, in consequence, have caused its northern edge to underthrust Tibet.

The convergence vector of India towards Eurasia can be described by the rotation of two rigid plates about a pole near Libya at a rate of ≈ 0.5°/Myr (ref. 2). Geodesy provides both a test of the assumption of plate rigidity and a measure of strain in the intervening zone of deformation. The inferred rate of convergence is unavailable from direct observation of magnetic lineations on the sea floor because Asia and India share no common plate boundary where sea floor is being created. Estimates of this relative motion are instead obtained from global plate reconstructions that continue to be refined as further oceanographic and seismic data become available. The rotation rate of Nuvel-1A (ref. 3) predicts that the collision speed of India relative to Asia increases from ≈ 40 mm/yr in western India and Pakistan to ≈ 52 mm/yr in eastern India and Burma (Figure 1 *a*). Convergence azimuths likewise vary from N4°E in Kashmir to N17°E in Assam. However, these convergence vectors are misleading indicators of true plate-boundary convergence vectors in northern India because the structural units bounding India to the north and east are also moving relative to Asia, and are not rigid plates. Plate boundary slip vectors diverge by more than 50% in speed and by more than 30° in azimuth from Nuvel-1A predictions along the northern and eastern margins of the Indian plate as a result of extensional processes in Tibet and the Andaman Sea.

Early speculation based on the rate of slip of faults in Asia suggested that as little as 30% of the convergence velocity of India with Asia is absorbed across the Himalaya[4]. This has been confirmed by findings of the geological rate of advance of sedimentary facies from the Himalaya over the Indian plate of 18 ± 5 mm/yr (ref. 5), and by reports of a 20 ± 4 mm/yr rate of thrusting on the Main Boundary Faults of the Himalaya[6,7]. The summation of seismic moments for earthquakes since 1897, when divided by the length of the arc and by the time interval for which they have been recorded, results in the derivation of a similar rate of convergence across the Himalaya, suggesting that the current rate of occurrence of these great earthquakes is similar to long-term rates. However, because the great Shillong plateau earthquake did not occur on the main Himalayan thrusts, it is doubtful whether this event should be included in the average seismic moment estimate. Since this event contributes 25% of the moment-release since 1897, a lower rate can be justified (< 15 mm/yr). Moreover, the inclusion of all recorded earthquakes for the past 200 years reduces the rate to less than 10 mm/yr. These inferred low estimates of seismic convergence velocity compared to geological convergence velocity, can be invoked to argue that one or more $M > 8$ earthquakes are overdue along the Himalayan arc. However, the brevity and possible incompleteness of the historic seismic catalogue makes this conclusion rather tentative.

India and Australia were initially considered to form a single large plate, but it is now known that these plates are rotating anticlockwise about a diffuse plate boundary south of the equator. Their angular rotation rate is small and, until the development of space geodesy, was speculative despite the existence of weak microseismicity along their common boundary.

Position and relative-position measurement accuracy 1700–1990

The objective of geodetic measurements is the determination of three components of position (latitude, longitude and height). Their temporal derivatives are commonly used to describe plate motions (two horizontal and one vertical velocity) and several spatial derivatives provide details of tectonic processes (strain, tilt and rotation). These derivatives are rarely measured directly. What is measured instead, are positions (latitude, longitude and height) and/or spatial separations (distance, relative elevation, angular separation) and these are repeated after an elapsed time to determine average velocities that are commonly assumed linear in time.

The latitude of a point on the earth's surface can be measured by determining the angle of the local horizontal to the pole star. Astronomical observatories were constructed in 18th century India at New Delhi, Varanasi, Jaipur, Mathura and Ujjain for astrological observations. These required the erection and alignment of 30-m-high triangles (gnomons) with their hypotenuses parallel to the earth's rotation axis. To obtain timing and prediction accuracy, these large masonry structures were aligned without benefit from optical telescopes to approximately 0.2 minutes of arc (e.g. 1 mm in 30 m), corresponding to a latitude estimation accuracy of ± 300 m. Measurements of latitude were improved by a factor of 20 in the early 19th century[8–10] by the introduction of telescopic survey instruments with angular measurements precise to 1 second of arc (± 30 m) in latitude. Improvements in instrumentation supplemented by statistical analyses and the averaging of the periodic latitude variations[11], resulted in the derivation of latitude with a precision of ± 0.01 seconds of arc (± 0.3 m), and an accuracy better than 0.06 seconds of arc (1.8 m) throughout India.

Triangulation methods were introduced in India 200 years ago to provide a framework for the construction of accurate maps. They required the establishment of a 10 to 20-km-long baseline and its extrapolation outwards as a triangulation network by angular measurements from points on hills or towers spaced at 20–45 km intervals. The scale of the network depended on the length accuracy of the initial baseline. Early methods of distance measurement using iron chains or wooden bars limited the accuracy of these initial triangulation surveys to less than 1 part in 10,000. With the introduction c. 1830, of rigorous procedures and new instruments to overcome systematic errors, length measurements attained an accuracy of 1 part in 100,000 (1 cm/km), and angle measurements of 1 millionth part of the circle (5 μradians). These accuracies were established in 1830 by experimental and theoretical tests, and have been confirmed recently using modern survey methods in southern India[12].

The extension of the triangulation surveys throughout India was to take more than three decades, but by the late 1860s most of the network was in place and was described in great detail in a series of publications that were distributed throughout the world's libraries. These accounts provide site descriptions, and list distance and angle measurements, and their reduction and subsequent adjustment[13,14]. The monuments of the network were installed to endure 'forever', using a combination of surface marks and buried hidden subsurface replicas that would survive vandalism or accidental damage. Marks inscribed on bedrock ridges and summits consisted of a chiselled 1 cm diameter hole surrounded by an engraved 15 cm diameter circle. The original network contained 3706 trigonometrical stations with an average station spacing of approximately 34 km. Of these, 3515 were still intact in 1904 (ref. 11). Since then, however, many of the towers have suffered collapse due to the use of weak masonry, and a number of triangulation points have been lost by accidental damage or vandalism or have been simply swallowed up in the growing expanse of cities. Despite these losses many of the original trigonometrical control points have been repaired and maintained where possible, and the network continues to provide fundamental position control for maps and local surveys.

Estimates of height and changes of height were derived from three methods: vertical-triangulation, spirit-levelling and tide-gauges. Because of large refraction errors in the plains of India vertical-triangulation was of limited accuracy, except in mountainous regions. Spirit levelling yielded height estimates accurate to a few cm over distances of tens of km, but random and systematic errors caused uncertainties to increase to decimetres over transcontinental distances, or areas of significant relief[15]. Measurements of sea level were introduced in 1880 to control propagating errors in precise spirit levelling[16] to mm precision.

Geodetic improvements and the end of the Great Trigonometrical Survey of India

As time progressed and measurement methods improved, it was realized that several of the basic parameters of the Indian survey were inappropriate – the mean latitude and longitude were incorrect, the azimuth of India was slightly skewed, the geoid was more complex than hitherto believed and the spheroid selected to map India was not the most desirable. These imperfections were noted and stored in the developing archives with the assumption that as time progressed they would eventually approach the truth sufficiently closely so as to make future improvements of negligible import. At that future time, it was suggested, a complete revision might be possible. Meanwhile, improvements in accuracy began to shed light on geophysical aspects of Indian tectonics.

The improved accuracy of latitude measurements was responsible before the mid-19th century for the discovery that north-south distances calculated by triangulation methods disagreed with those obtained using astronomical measurements. The reason was that the slope of the geoid was nonlinear. In particular, the geoid was significantly distorted by the mass of the Tibetan Plateau. (The geoid defines the local horizontal to which all theodolites and telescopes were aligned). Horizontal distance measurements were effectively insensitive to this distortion of the geoid. The reconciliation of triangulation and astro-geodetic measurements were eventually to give rise to the theory of isostatic compensation of mountain ranges[17]. Had the Plateau been to the east or west of India rather than to its north, it is doubtful that isostatic compensation of mountain ranges would have been discovered as early as it was. This is because latitude measurements were routinely used from the beginning of the survey in 1805 to constrain propagating errors in triangulation, whereas accurate longitude measurements had to await the development of time transfer using telegraphy c.1880. It is interesting to note that the east-west deflection of the vertical was routinely calculated as soon as telegraphic longitudes became available.

Initial calculations of longitude were made using chronometers or astronomical estimates of time. Their low accuracy (a few km) was caused by timing errors of several seconds. The improved longitude accuracy available using telegraphic time transfer[18] revealed that the initial estimates of longitude for India were 4.5 km too far to the east (a mean chronometer timing error of 10 s in 1830).

Two fundamental assumptions in the computations of the Great Trigonometrical Survey (GTS) were that India was rigid and that it did not rotate or shift in position. These assumptions meant that one could build on the work of previous generations, continually adding to or interpolating precise positions within the survey as it progressed. In the late 19th century, it was discovered that latitude varies slowly because of periodic variations in the earth's spin axis. The early latitude measurements at Madras (now Chennai) in 1860 are north of their current positions, suggesting that secular latitude changes have indeed occurred, causing the net southward motion of India[19,20]. The tectonic approach of India toward Asia in the past 130 years has reduced the amplitude of this southward displacement from about 12 m to approximately 8 m (ref. 12).

Towards the end of the 19th century, at about the time the records of angles and calculations of position were finalized and published, the Great Trigonometrical Survey of India was merged with the topographical survey branch. After that time, the GTS was considered the definitive final measurement of India requiring no major revision.

Earthquakes and geodesy

The first of several 19th century earthquakes to cause measurable surface deformation in India occurred in the Rann of Kachchh (Figure 1 *b*) prior to the establishment of geodetic control. The serendipitous measurement by Baker, a canal engineer, of the bed and bank of the Narra river channel whose flow had been blocked by the creation of the Allah Bund[21,22] permits the slip parameters of this event to be quantified crudely. A $M_w = 7.8 \pm 0.2$ event can be calculated from the 6 m of uplift measured by Baker[23], although recent excavations in the area suggest uplift was significantly less, and a smaller magnitude ($M = 7.6 \pm 0.1$) more plausible[24]. During the subsequent mapping of the Kachchh region by the GTS, 'in January (1857) an earthquake occurred which nearly brought down the tower at Kararho on which the instrument (theodolite) happened to be standing' (ref. 25, page vii). Earthquakes continue in the Kachchh region to this day though not as severe. Had they interrupted the operations of the Survey of India in the period 1830–1860, it is certain that we would know more about mid-continent earthquakes. However, this did not occur. No severe earthquake occurred in the path of the developing Great Trigonometrical Survey of India as it progressed northward and outward, and it is possible that this tectonic silence led to the subsequent effects of earthquakes being largely ignored. George Everest trivialized their potential effects probably because no earthquake occurred during the time that he was responsible for survey accuracy[26]. Earthquakes in the Himalaya in 1803 and 1833 (ref. 27) were far from the growing network that at that time was concentrated south of Madras. Earthquakes occurred in the Nicobar Islands in 1881 (ref. 28) and in Kashmir[29], far from the major triangulation networks. Two exceptions were the severe NE India earthquakes of 1869 (refs 30 and 31) and 1885 (refs 32 and 33) which occurred north and south of the Shillong Plateau close to geodetic networks that had been measured during 1860–1869.

However, in 1897 the foundations of geodetic measurement were shaken by the discovery that the Shillong Plateau earthquake had locally distorted the Assam triangulation network by several meters[34], both vertically and horizontally. 2500 people were killed by this $M_w \geq 8$ event. The Bengal/Assam networks near the epicentre were re-measured incompletely to reveal horizontal angle changes exceeding 90 μradians on and north of the Shillong Plateau[35–37]. As yet no remeasurement of the entire

1860 triangulation has been completed, and current geophysical interpretations of the geodetic data are not well-constrained[38].

In 1905, a second devastating earthquake killed ≈ 20,000 people near Kangra[39,40], shook the headquarters of the Survey of India in Dehra Dun, and re-awakened uneasiness that geographic positions so painstakingly determined were perhaps impermanent. Burrard[11] remarks, 'Before we can take the retrograde view that accurate triangulation is useless, we must first have definitive evidence of the actual effects of earthquakes'. Accordingly, he re-measured the positions of points around Dehra Dun and finding no detectable deformation, and despite cautionary remarks that perhaps points nearer Kangra and south of the Siwalik Hills may have shifted, decided that additional work was too costly to justify further investigation. In contrast, levelling measurements before and after the earthquake suggested that Dehra Dun apparently rose coseismically by 13–15 cm. Burrard was initially reluctant to believe this apparently tectonic result because the signal had all the characteristics of a systematic error in the levelling method, but since it exceeded all known errors, he was emboldened eventually to countenance its reality.

Burrard reasoned that given seismic uplift events exemplified by the Kangra earthquake, it would take 3 million years to raise the summit of Everest from sea level to its present elevation, and 70 million earthquakes to raise the entire Himalayan chain from sea level. On the strength of the Kangra levelling results he initiated a new Survey of India plan to detect the rate of rise of the Himalaya, in the form of seven levelling transects with bench-marks inscribed across the Himalayan foothills on solid rock, speculating that these measurements would yield definitive constraints on the rate of rise of the Himalaya within a century[41]. Ninety years have elapsed but regrettably many of these bench-marks are now lost. Data from one of these lines have led to unsatisfactory conclusions because the re-measurements[42] were published without the constraint of precise locations or uncertainty estimates[43,44].

Burrard's doubts of the validity of the Kangra uplift signal were based on the fact that the levelling signal correlated with elevation. The additional coincidence that the peak uplift occurred exactly at the headquarters of the Survey of India in Dehra Dun, where different levelling surveys started and ended, however, remained unquestioned by him or by subsequent scientists who have used these data to infer the rupture parameters of the Kangra earthquake[43,45–50]. An evaluation of levelling statistics suggests that vertical and horizontal deformation during the Kangra earthquake was insignificant in the Dehra Dun region in 1905 (ref. 51). However, it is quite probable that several GTS trigonometrical stations near the epicentre of the Kangra earthquake, 200 km to the NW of Dehra Dun, were shifted coseismically to new locations that have yet to be re-measured.

In 1934, a great earthquake in Nepal resulted in 10,500 fatalities and widespread damage in Bihar but on this occasion not one of the Great Trigonometrical Horizontal Survey monuments was re-measured. Re-levelling of the first order lines in the Ganga plains was completed to reveal broad regions of liquefaction related subsidence, but the reality of these changes was disputed by Burrard[52] and deGraaff Hunter in a series of articles published in *Nature*. The levelling signal shows subsidence south of the Nepal border, that weakly constrains the spatial dimensions of the rupture zone[53], and GPS measurements of one or two GTS points indicate relatively minor motions[54]. Although the positions of these tower sites were never re-measured systematically, it is likely that the horizontal networks were south of the southern edge of rupture where displacements were small, a conclusion that differs substantially from interpretations made without the benefit of geodetic constraints[55,56]. Everest had argued at length with the British administration to permit him to use the mountains of southern Nepal for survey operations, but Calcutta had rigorously adhered to policies settled at the time of the 1815 Nepal/British war, necessitating the construction of survey towers south of Nepal's 600 km long border[57].

The following year (1935) an earthquake occurred in Baluchistan[58] killing an estimated 15,000 people near Quetta[59]. A 50-cm amplitude vertical deformation signal was recorded[60], that captured vertical deformation in the 1931 Mach and 1935 Quetta events, but no horizontal re-measurements were made. Great earthquakes in the Andamans in 1941 and in Assam in 1950 were ignored by geodesists, the first because it occurred during World War II and the second because existing geodesy in the region was of poor quality[61].

No great earthquake ($M > 7.5$) has occurred in India in the past half century, although severe earthquakes with $6 < M < 7.3$ have occurred both along the Himalaya and on the Indian plate: Koyna, 1967; Bhadrachalam, 1969; Broach, 1970; Udaypur/Nepal 1988; Uttarkashi, 1991; Latur, 1993; Jabalpur, 1997; Chamoli, 1999. The geodetic contribution to the study of these events has been relatively minor because geodetic measurements with appropriate accuracy and density were sparse or non-existent prior to their occurrence.

Geodetic findings 1990–2000

In the past decade GPS measurements have been initiated in several parts of India (Figure 2). GPS geodetic methods are described in several previous texts and are now somewhat routine[62]. They involve the simultaneous recording of broadcast radio phase information from a constellation of NAVSTAR satellites. From a knowledge of the instantaneous positions of these satellites provided in the broadcast message, it is possible to compute terrestrial distances of any length to a precision of 3 mm horizontally and < 20 mm vertically. Their great advantage for seismotectonics in India is that the signals are freely accessible to civilian users and can be used to measure distances and positions across plate boundaries, and within India, unrestricted by distance or terrain (Figure 2).

Plate stability – 5×10^{9}/yr

Re-measurements of numerous points of the Great Trigonometrical Survey (GTS) of India in southern India (far from the deforming margins) using GPS, have confirmed the accuracies claimed by 19th century surveyors. Baselines and angles measured in south India have changed by less than 1 ppm (5 μrad) in angle and by < 10 ppm (10^{-5}) in scale. Since these early measurements were made 130–160 years ago, this null result provides an upper bound to strain instability of the Indian subcontinent. Paul *et al.*[12] determined that the subcontinent south of Madras was stable to < 10^{-8}/yr in shear strain and < 10^{-7}/yr in terms of dilatational strain.

The above estimates were made using the difference between the published GTS and newly observed GPS positions. Repeat measurements of the same points over 5 years, using GPS alone, provide a yet lower threshold for instability of the Indian plate[63]. It now appears that both shear and dilatational strain rates are lower than 5×10^{-9} strain/yr. This is consistent with the anticipated deformation rate for a plate interior. In 2010 we should expect to see the velocity noise threshold of GPS measurements fall to < 10^{-10} strain/yr. The background strain rate from microearthquakes in the shield area of India has been estimated[64] to be < 3×10^{-10}/yr. As the noise threshold of GPS measurements falls, the background strain rate that accompanies this mid-plate seismicity will begin to emerge. It would not be unexpected, for example, to see a northerly or north-easterly contraction rate imposed on the subcontinent. Suggestive of such signals, the distance between Delhi and Kanyakumari between 1994 and 1999 contracted at a rate of 3 ± 1 mm/yr (ref. 63). Additional measurements throughout the craton will be needed to confirm these low rates and to distinguish them from possible local perturbation caused by the viscous relaxation effects of historic Himalayan earthquakes.

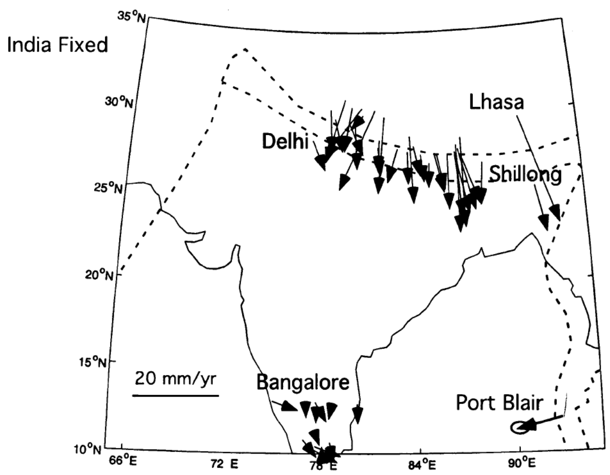

Figure 2. Displacement vectors[63] on an India-fixed frame of reference, 1995–1999. Uncertainties on this plot are 3 to 5 mm/yr and although some of the vectors shown are currently close to noise levels, arc-normal extrusion of the Tibetan Plateau is evident.

Plate boundary deformation of 15–25 mm/yr

As mentioned earlier, few historic GTS survey lines cross the plate boundaries surrounding India. To the north, a line through Gilgit joined the Russian network to the Indian network in 1913, that was partially re-measured in 1980 (ref. 65). Survey lines extend through Assam to Burma, and from Pakistan to Iran but some of these lines were established to second-order accuracy, and their re-measurement is now attended by logistic difficulties given changes in national boundaries that have occurred in the past century.

GPS measurements in the past decade have contributed significantly to our knowledge of plate boundary deformation. The convergence rate between northern India and southern Tibet is central to estimating Himalayan seismic productivity. Until the availability of GPS measurements, this rate had been inferred indirectly from geological and seismic data to lie between 10 and 25 mm/yr. The GPS-derived convergence rate for the central Himalaya in Nepal was initially reported as being 20 ± 3 mm/yr (ref. 19) and revised to 18 ± 2 mm/yr using a slightly enlarged database[66]. A recent evaluation[63] extends the measurements to embrace a 1500 km region of the arc and confirms these rates, although the estimate may increase as more data from southern Tibet are included in the analysis. The recent data provide support for the radial outward-directed pattern of extrusion of the Tibetan Plateau revealed by seismic focal-plane solutions. Thus, it is probable that great earthquakes are driven by arc-normal stresses along the Himalaya, a finding that has great significance to the slip vectors of earthquakes in the western Himalaya and Kashmir.

The encouraging establishment of dense GPS survey networks in the Indian Himalaya should clarify whether strain tensors across the Himalaya are perfectly arc-normal or whether they are perturbed by known or historically unknown earthquakes. A current weakness in refining the closure velocity across the Himalaya lies in the absence of a dense network of GPS sites in southern Tibet. This is currently limited to a few locations (Figure 1). It is likely that the density of these points will increase in the next decade, providing both improved estimates of velocity and improved estimates for the current strain orientation of the principal axes of contraction and tensile strain across the southern edge of the Tibetan plateau.

The eastern plate boundary currently, has a single measurement of the approach of the Andaman Islands towards Bangalore at 16.2 mm/yr[63]. Port Blair is located within the 200-km-wide zone of deformation that characterizes the Indo-Asian plate boundary near the Andaman Islands. The Indian plate dips east at 40° and is defined by epicenters at 35–70 km depth beneath Port Blair[67]. Although the 250° azimuth of approach is probably representative of the motion of the hanging wall of the Andaman plate, its location in the elastic region above the zone of moderate to great earthquakes means that Port Blair may sample < 30% of the total convergence vector. The NUVEL-1A model predicts oblique convergence of the Asian plate along N22°E, at the rate of 54 mm/yr[3], a vector that is modified locally by a back-arc spreading rift system (37.2 mm/yr at 335°) beneath the Andaman Sea[68–71]. A vector diagram of these motions (Figure 3) indicates that Port Blair moves 40% too slow to describe completely the motions at the plate boundary. However, since the azimuths of all three vectors are probably correct to within 5°, vector closure requires either an increase in the Andaman spreading velocity or a reduction in the NUVEL-1A velocity by ≈ 5%.

The plate boundary in NE India remains virtually unstudied geodetically. The region of the eastern syntaxis is likely to be a rewarding area to study, now that the overall velocities of the general plate tectonic setting of India have been established. The same is true of the western syntaxis in Pakistan, although the complexities of international boundaries in this region prohibit the monitoring of this syntaxis in any detail.

The width of the plate boundary between the Salt Ranges and the northern Tien Shan Mountains is of the order of 1500 km, whereas that of the plate boundary in eastern India extends 3500 km northward to the Baikal depression north of Mongolia. For this reason, it was initially expected that continental convergence through the Karakoram Mountains northward would be constrained from GPS measurements at an early stage. As of 2000, only part of this signal has currently been measured with the surprising result that perhaps 50% of the 42 mm/yr Nuvel-1A convergence signal is to be found in the Tien Shan north of the Karakoram Mountains[72]. The distribution of the remaining 21 mm must drive the Karakoram and Himalaya, and slip in the Salt Ranges to their south. If further work reveals that Trans-Himalayan strain contraction vectors continue with arc-normal principal axes beyond 78°E (ref. 63), the north-south component of convergence across the Himalaya at 72°E may be as little as 12 mm/yr. This would leave a 9 mm/yr of N10E directed convergence across the Karakoram and Salt Ranges of Pakistan, consistent with the absence of a clear convergence signal between the years 1880 and 1913, as noted by Chen *et al.*[65].

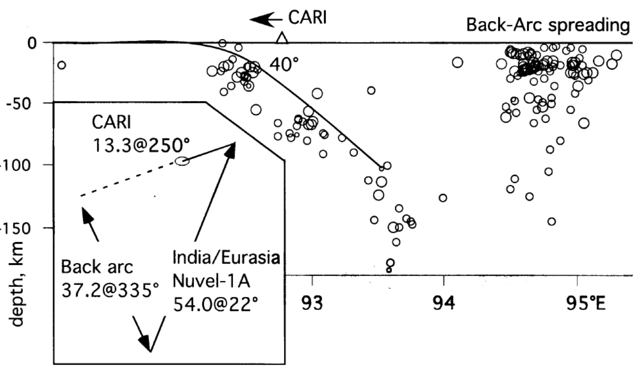

Figure 3. West-east cross-section of micro-seismicity (Engdahl *et al.*[67]) through the Andaman Islands showing location and sense of motion of the Port Blair point, CARI (Paul *et al.*[63]). (Inset) Vector diagram showing the incomplete closure of the Nuvel-1A and back-arc spreading vectors when the Port Blair vector is summed with these. At 13.3 mm/yr CARI apparently samples ≈ 30% of the plate boundary convergence across the Indo-Asian plate boundary.

Outstanding seismo-geodetic problems in India

A number of important parameters describing the motion and stability of the Indian plate remain imperfectly known and these will be briefly discussed. Notably, these include better-constrained values of India's angular rotation vector with respect to Eurasia, and of the relative velocities at its western, eastern and northern boundaries. However, we recognize that these are by no means exhaustive, and that science has a way of raising new issues even as we make progress, and that other issues will soon arise that cannot yet be identified.

Perhaps the first issue that will be resolved soon concerns the rate of rotation of India, relative to Eurasia. As mentioned previously, the global circuit models that have thus far been proposed for India-Eurasian motion appear to indicate a higher velocity than is consistent with GPS rates. The absence of a suite of stable GPS monuments in the shield area of NE Asia is a major drawback to this being accomplished immediately, but this situation is likely to be remedied soon. Recent results suggest[63] that the mean velocity of India is perhaps 5 mm/yr slower than the mean predicted 46 mm/yr velocity of NUVEL-1A. In contrast, a 43 mm/yr approach velocity of northern India towards Urumchi is observed[73] in the northern Tien Shan Mountains, that would require negligible deformation in the NE Tien Shan, Altay Mountains, Mongolia and southern Siberia. Clearly these findings are not easily reconcilable with the extraordinary moment release that has occurred in Mongolia in the past century. Geological trenching across these faults have revealed that the recurrence intervals of these events may be several thousand years and that long-term deformation rates on faults that slipped recently may only be a few mm/yr[74, 75].

Of greatest importance to India is a knowledge of the relative plate velocities at her western, eastern and northern boundaries, because these regions have historically been visited by severe and frequent earthquakes. Relative plate convergence in the central Himalaya is currently well established, but measurements in NW and NE India are needed to examine the distal regions where arc-normal convergence no longer prevails along the arc. A dense Himalayan GPS network would appear eminently desirable for ensuring the integrity of Himalayan seismotectonic studies in the 21st century.

In western India, the plate boundary lies far from India's current border. However, the occurrence of a M_w 7.8 earthquake in 1819 in the Rann of Kachchh and persistent subsequent seismicity requires an underlying tectonic explanation. The Allah Bund is close to the border between India and Pakistan potentially making detailed measurements close to the 1819 epicentre a sensitive issue, but the measurement of deformation in the region of the earthquake is obviously important to the people of both nations. The extension of the Allah Bund westward may be responsible for sinuosity changes in the bed of the River Indus, and if indeed the causal fault extends in this direction, it has serious consequences for earthquake hazard in Karachi. Deformation is clearly higher than normal in the Kachchh region given the Broach and Anjar earthquakes in the mid-20th century and it is certain that GPS measurements in the region will greatly aid our evaluation of the cause of these and future events.

The absence of good spatial coverage of the eastern Indo/Andaman plate boundary south of latitude 14° is likely to hamper efforts to investigate the rate of underthrusting of India below the Andaman plate. A great thrust earthquake occurred in 1941 that is reported to have caused considerable damage to masonry structures in the Andaman Islands and to coastal regions along the Coromandal coast northwards from the resulting tsunami. Tsunami data indicate that the Andaman sea earthquake of 1881 was not on the plate boundary but was an M_w 7.9 crustal submarine event adjoining the East Andaman transform fault, suggesting that no great earthquake has recently occurred west of the Nicobar Islands. Given that a convergence rate exceeding 3 cm/yr may prevail at this latitude, a renewal time of less than 200 years seems likely. Even if this is delayed by the 1881 thrust event, a great earthquake near the Nicobar Islands may be overdue.

The confluence of the convergent units of the Himalaya and Burma in NE India provides a series of fascinating tectonic problems[68]. Although some authors believe that the 1897 earthquake may have been a southward extension of shallow thrusts beneath the Himalaya[43,55], a viable alternative is that the Shillong Plateau represents an isolated block that is being driven wedge-like upwards, by collisional stresses in northern India. In either case, Shillong-type earthquakes may delay great thrust events in Bhutan, but not prevent them[76]. Reports of subsidence north and east of the 1897 epicentre have been interpreted as slip on a SW directed N-dipping thrust[38], yet triangulation data[35,36] favour reverse slip on a steep SE dipping fault. It would appear that a re-evaluation of the historic geodetic data may soon resolve this controversy.

Himalaya

The plate boundary of greatest importance to the people and economy of northern India is of course the Himalaya. Great earthquakes are poorly known in this region prior to the 19th century and even 20th century moderate and major events are not well-studied seismically[77]. Numerous questions can be addressed about the collision process at this plate boundary better, in principle, than at any other convergent plate boundary. This is because, unlike the setting of continent–ocean collisions, the descending footwall is not covered by an ocean and can be instrumented in great detail. The kind of information that is useful here concerns the way in which elastic energy is developed prior to release in earthquakes.

A belt of moderate earthquakes is located south of the edge of the Tibetan Plateau along a small circle with a radius of 1696 km[78]. The 1885 Kashmir, 1905 Kangra, 1991 Uttarkashi and 1994 Chamoli events appear to sequence along this small circle. The great shallow thrust earthquakes that are responsible for translating the Himalaya southward over northern India occur south of these moderate earthquakes. This suggests that the Himalayan foothills experience negligible strain between earthquakes, and that slip in creep or minor seismicity of the Main Boundary Thrust and Main Frontal Thrust may not occur between great earthquakes. This view of Himalayan seismicity requires confirmation, which can be addressed through closely spaced measurements of the horizontal and vertical velocity fields between southern Tibet and the northern plains of India. GPS data acquired in Nepal and in the Central Himalaya appear to confirm that the current deformation field in these areas is limited to the southern edge of the Tibetan Plateau[19,63].

The arc-parallel extension of the Tibetan Plateau that is responsible for its arc-normal radial extrusion over India appears to be occurring at rates of 10–14 nanostrain/yr[53]. The origin of this extensional signal may be gravitational or may be intrinsically related to the collision process[79]. The relation of this extensional signal to great earthquakes south of the line of moderate earthquakes poses interesting kinematic problems for great shallow-dipping ruptures. It is possible that through a process of self-organization contiguous ruptures slip discordantly, and that the arc itself may be formed from a series of overlapping planar ruptures, as suggested by the models of Larson *et al.*[66].

An apparent contradictory pair of results is the recent discovery that the geological rate of extrusion of the Himalaya southward over the Indian plate occurs at approximately 2 cm/yr[6,7], i.e. at the same rate that geodetic measurements estimate that interseismic convergence occurs south of the edge of the Tibetan Plateau. A possible conclusion is that elastic interseismic uplift of the Greater Himalaya is recovered entirely during the seismic cycle and does not contribute to the elevation of the mountains. It is possible that the subsurface geometry of the Himalaya is responsible for this signal[77]. However, Cattin and Avouac[80] show that a viscous model for Himalayan deformation, satisfying both the southward extrusion of the Himalaya over the Indian plate and the interseismic deformation field, results in irreversible uplift. Clearly, spatially denser measurements are required to elucidate the details of the uplift process and its relationship to interseismic strain.

Earthquakes in the subcontinent

Peninsular India has a long history of moderate earthquakes, indicating stresses close to failure throughout the subcontinent. An important result anticipated in the next decade will be the discovery whether the current velocity field throughout India is uniform or whether it shows anomalous strain development in certain areas. As an example, the Kachchh region appears to be one area where above-normal seismicity rates exist. It will be interesting to discover whether a correspondingly higher than normal strain-rate prevails in the region, and if so, why.

One of the problems with mid-plate earthquakes is that they are often associated with epicentral areas measuring only a few tens of km across. The preparation zones preceding these minor though devastating earthquakes are conjectural, and their detection by GPS-geodesy would seem to require a formidable endeavour if we are to demand sufficient resolution to estimate rupture parameters from a pre-seismic geodetic grid. Although it would appear only a matter of time before dense networks of GPS control points are distributed throughout the subcontinent, we foresee that the rigorous development of GPS control throughout India may, in practice, take many decades if a grid spacing of 3–5 km is considered desirable.

Fortunately, Synthetic Aperture Radar interferometry (inSAR) provides an ideal tool for constraining both pre-seismic and co-seismic deformation fields[81]. The method involves the construction of Synthetic Aperture Radar (SAR) images of selected areas by illuminating them with sub-decimetre wavelength microwaves at different times, and forming interferograms from pairs of images. Interferograms with a fringe width of about 56 mm have the potential to reveal the entire deformation field of an earthquake without the installation of any control points. Scenes are typically 100 km on a side with a grid spacing of approximately 10 m, perfectly matched to the strain-fields associated with shallow Indian earthquakes ($5 < M < 6.5$) in the subcontinent. The method is most successful where vegetation is sparse and hill-slopes relatively modest. The method is therefore not applicable to rugged parts of Himalayan terrane or in the agriculturally intense Ganga plain. However, it would appear to be well matched to many terrains in India, and we foresee significant results forthcoming from its application.

Discussion and conclusions

During the 19th century, the Great Trigonometrical Survey of India started as a mapping project and then with the development of new methods and instruments forged ahead to perform at the frontiers of measurement science[82]. Finally, in the period 1880–1905, the Survey consolidated its position with the publication of several dozen volumes of results, analyses and conclusions. These volumes record a great scientific experiment, qualifying as the most basic and rigorous form of science in that every observation was published and testable[83]. In contrast, the period 1910–1947 saw the gradual retreat of geodesy in India from scientific experiment to routine operation. During this time the Geodetic Branch of the Survey of India continued the traditions of enquiry, exploring gravity, magnetics, systematic errors and improved analysis methods, but the published results were increasingly distanced from the raw observations. The World Wars interrupted the direction of the Survey, and budgets for investigative science never seemed to be available for those investigators who were curious about the effects of earthquakes on the Great Trigonometrical Network. Geodetic publications from the Survey Department in the second half of the 20th century are characterized by an absence of raw data. The resulting inability of the scientific community to test or reproduce geodetic results has in turn had the unfortunate consequence that the most recent output from the Survey fails to qualify as science in a Popperian sense.

The availability of GPS and SAR methods means that new geodetic measurements no longer require the vast infrastructure that characterizes map-control based on triangulation and trilateration. Positions are now irrelevant, only changes in position are of interest. GPS geodesy is significantly more versatile, intrinsically higher in accuracy and operationally less expensive to undertake than the line-of-sight measurements of early geodesy. It is moreover a civilian measurement system that, as many nations have discovered, does not require a large government bureaucracy to supervise its operation nor to archive its data. Countries such as New Zealand have decided to replace their National Grid with a GPS-based grid. The great advantage of this approach is that disaster agencies, land surveyors, geographic information systems, public transport systems, etc. may use inexpensive GPS units to obtain position control on maps without referring to local control points. The penalty for such a system is that because of tectonic movements and polar wander, each local GPS coordinate has a velocity attached to it. This velocity varies from place to place and perhaps also with time. However, the correction that must be applied is the signal related to the tectonic deformation and translation of India. New Zealand proposes to provide coordinates with a time-stamp and a velocity, in much the same way the topo-maps are published presently with a magnetic declination at a certain date, and rate-of-change of declination for subsequent users.

The application of GPS control to maps in India is likely to be resisted for military reasons, although the logic upon which these reasons are developed is obscure. The secrecy of control-point information can hardly be justified, thanks to the fastidious accuracy of published coordinates between Afghanistan and Burma by the Survey of India, 1860–1910. Thus the relative positions of points throughout India, Pakistan and Bangladesh are known to sufficient accuracy to render military arguments of secrecy meaningless. The suppression of GPS measurements because they might jeopardize the security of the civilian population is equally specious since it can be argued that more civilian deaths have occurred from earthquakes than in recent wars. The geodetic study of earthquakes is of great importance because future earthquakes can be envisaged to occur near large urban agglomerations that will cause an order of magnitude more fatalities than have occurred in past events[84]. The formal categorization of the gravity field of India (the measurement of which has utility in the estimation of changes of height) as secret is also futile given the open availability of satellite-based geoids and early gravity data published by the Survey of India. Accordingly, we emphasize that we have nothing to lose and everything to gain from a return to a policy of publishing raw data of intrinsic benefit to the people.

Despite almost two centuries of geodesy in India, the geodetic contribution to the study of Indian earthquakes has been relatively minor. The availability of GPS geodesy and SAR interferometry signifies that this is about to change. We have learned more about the deformation processes of the Indian subcontinent in the past decade using GPS methods than in the preceding 190 years. We are optimistic that the next decade will see this knowledge increase ten-fold.

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