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Microstrain stability of Peninsular India 1864–1994

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Abstract. We report the results of the South Indian Strain Measuring Experiment (SISME) designed to determine whether strain related to microseismicity in the past century may have deformed the networks of the 19th century Great Trigonometrical Survey of India (GTS). More than a dozen GTS points were measured between Mangalore, Madras, and Kanyakumari in southernmost India using GPS geodesy to determine regional deformation. Detailed measurements were made near two of the original baselines of the survey to determine the reliability of dilatational strain data for the network. The regional measurements revealed negligible regional dilatational ($+11{\cdot}2 \pm 10$ microstrain) and shear strain changes ($0{\cdot}66 \pm 1{\cdot}2\,\mu$radians) in the southernmost 530 km of India. In addition to these measurements, we determined the rate of northward and eastward motion of a point in Bangalore (1991–1994) in the ITRF92 reference frame to be $39 \pm 3{\cdot}5$ mm/year, and 51 ± 11 mm/year respectively. This is consistent with NUVEL-1A plate motion estimate for India. Simultaneous measurements to a point near Kathmandu reveal that the Indian plate and the Southern Himalaya are moving approximately in unison, placing an upper limit on the rate of creep processes beneath the lesser Himalaya of ≈ 6 mm/year, and suggesting relatively rigid behavior of the Indian plate north of Bangalore. The stability of the Indian plate is confirmed by the absence of significant changes in the lengths of the two baselines at Bangalore and Cape Comorin, which, within the limits of experimental error have not changed since 1869. The measurements place an upper limit for recent deformation in the southern peninsula, and hence a lower limit for the renewal time for intraplate earthquakes in the region of approximately 10,000 years, assuming shear failure strain of approximately $100\,\mu$radians. This, in turn, implies that recurrence intervals for Peninsular Earthquakes far exceed the length of the written historic record, suggesting that the characterisation of seismic recurrence intervals from historical studies is likely to be fruitless. In contrast, the SISME experiment demonstrates that the noise level of geodetic studies based on 19th century GTS data is less than $0{\cdot}02\,\mu$strain/year, providing considerable scope for delineating regions of anomalously high seismogenic strain, by GPS measurements at all available trig points of the 19th century GTS survey.

Keywords. GPS measurements; south Indian trigon; deformation strain rate; plate velocity.

1. Introduction

The application of Global Positioning System (GPS) measurements to precise surveys in seismogenic regions provides opportunities for studying geodynamic processes, and for monitoring the development and release of strain associated with earthquakes. These processes demand measurement accuracies that are typically unobtainable in conventional mapping and control networks (Rajal *et al* 1994), although decimeter control accuracies are of value for monitoring tectonic processes if they were undertaken sufficiently long ago, or if a substantial earthquake occurs near the network. The 19th century Great Trigonometrical Survey of India (GTS) provides potentially an invaluable record of deformation in India in the past 100–150 years, yet few of its original control points have been checked for their current disposition using GPS methods. As a test of the utility of the GTS network in estimating seismic hazards, we designed an experiment to determine the current positions of several points along two of the earliest triangulation chains in India (SISME). The Madras– Mangalore–Cape Comorin measurements were first undertaken in 1805–8, and were repeated with superior instruments in 1864–74. The 1994 experiment was designed to reveal the potential accuracy of dilatational and shear strain in the original networks, and the amplitude of any changes in these values since their mid 19th century measurement.

The experiment was conducted simultaneously with measurements near Kathmandu, Nepal, that had been first undertaken in 1991 by Chris Reigber. The three year interval was associated with GPS–GPS combined errors of the order of 1 cm, permitting deformation rates to be determined with an estimated uncertainty of approximately 3 mm/year. The absolute translation of India relative to the global plate framework was also determined during the 1994 field measurements, and a continuous tracking site implemented at Bangalore to determine rate changes should these exist. The precision of the measurements (3 mm) is such that in theory the motion of India (5 mm/month NE) results in displacements that exceed the measurement noise every 3 weeks. The day-to-day repeatability for the 1994 GPS baselines of 5 km–1800 km in length was examined with the view to implementing special survey networks designed to monitor future seismotectonic deformation.

2. The 19th Century Great Trigonometrical Survey

In March 1994, the South Indian Strain Measuring Experiment (SISME; Gaur 1994) occupied a sparse sampling of original points (figure 1) of the Southern Trigon of the GTS (Walker 1870; Strahan 1890). The points measured are found in two principal triangulation chains that form a large letter 'T'. The vertical arm of the 'T' consists of the north-south Great Arc Series passing through the southern tip of India at 8°N, and the east-west arm of the 'T' is the Madras Longitudinal series that connects Madras with Mangalore at roughly 13°N. The Madras series was measured between 1864 and 1873 with a 24 inch Troughton and Simms Theodolite. The survey progressed westward from Madras, passing through Bangalore, where a 10-km-long baseline was measured in 1867. The Great Arc Series was measured first by Lambton in 1805–1815 with inferior theodolites, and remeasured between 1868 and 1874 using more precise instruments. The 1860 re-measurements of the Great Arc concluded with a measurement of the Cape Comorin baseline in 1868–1869 (we shall retain the GTS name for the Cape Comorin baseline in this article because it is approximately 20 km to the east of Kanyakumari, and is not near any major town). Thus all the points of the survey that we measured in 1994, had been measured precisely between 1864 and 1874, and we have adopted an elapsed time of 125 years for subsequent rate estimates. The southern Trigon was the last of the Indian sub-networks to be adjusted. The adjustment consisted of reconciling the propagating errors of triangulation, with the non-propagating (but possibly systematically biased) errors of astrogeodetic determinations of latitude and longitude. Since the Trigon was the last to be adjusted, the adjustment was extended southward from the already adjusted northern edge of the Southern Trigon where it meets the S.E. Quadrilateral at the latitude of Bombay (Strahan 1890). The adjustment of the southern Trigon included 22 fixed elements (astrogeodetic latitudes, baselines etc.). Between Bangalore and Cape Comorin the adjustment dispersed errors of $-0{\cdot}072''$ in latitude, $0{\cdot}044''$ in longitude, and $1{\cdot}26''$ in azimuth throughout the network. The latitude adjustment corresponds to a 2·2 m reduction of the 529·5 km distance between Cape Comorin and Bangalore, a fractional change of 4·2 ppm. The azimuthal adjustment corresponds to a counter-clockwise rotation of 0·97 microradians, or a sinistral displacement of 0·5 m.

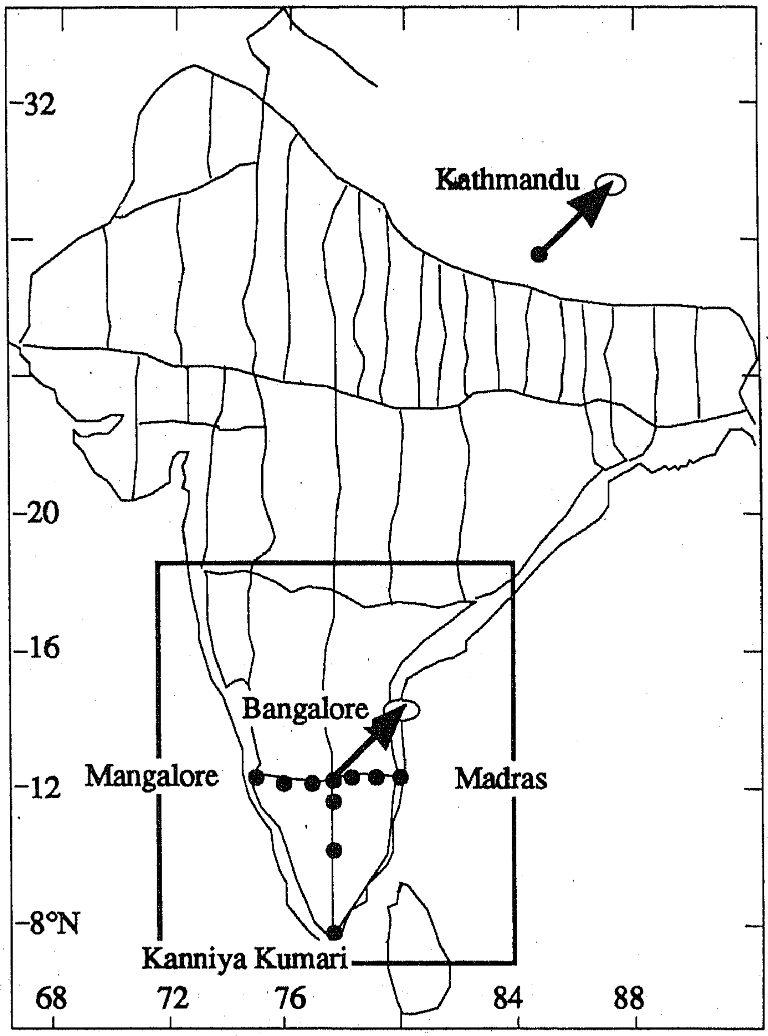

Figure 1. The GTS network in 1874 (Strahan 1890) and locations of GPS measurements discussed in this article. Inset outlines the Southern Trigon. The Kathmandu–Bangalore baseline was measured in 1991 and 1994 to reveal $0 \pm 6{\cdot}5$ mm/year convergence.

Coordinates for the 1890 adjustment are given in terms of the Everest spheroid which has the following parameters (Strahan 1890):

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Estimates of the accuracy of the GTS measurements are based partly on experimental repeatability of data, and partly on estimates of systematic errors in the data. Measurements of angle were tested by closure calculations for different theodolites and for different observers (Strahan 1890, II, p. 116). For the instruments and observers in the part of the survey that we re-measured, the mean square error for observations of angle estimated by Strahan varied from 0·66 to 1·3 seconds of arc (3·2–6·3 μradians). Thus the full circle measurement accuracy was believed to be no worse than 1 ppm.

Measurements of baseline prior to 1890 were believed to contain two errors, a probable error of 1·5 ppm associated with the accuracy of the Colby compensation bars used to successively measure the length of each baseline, and a systematic error associated with the standard of length (the Indian foot) of 2·1 ppm (Walker 1870, p. 96). The combined 1 sigma error assumed in the 1890 adjustment was thus 3·8 ppm and it was assumed that repeated measurements would reduce the overall error by reducing the uncertainty associated with single sequences of measurements using the Colby bars (Strahan 1890, p. 59). However, it is possible that the Colby bar baseline measurements contained unmodeled systematic errors related to imperfect temperature corrections for radiative heating and cooling of the bimetallic Colby bars (Walker 1879).

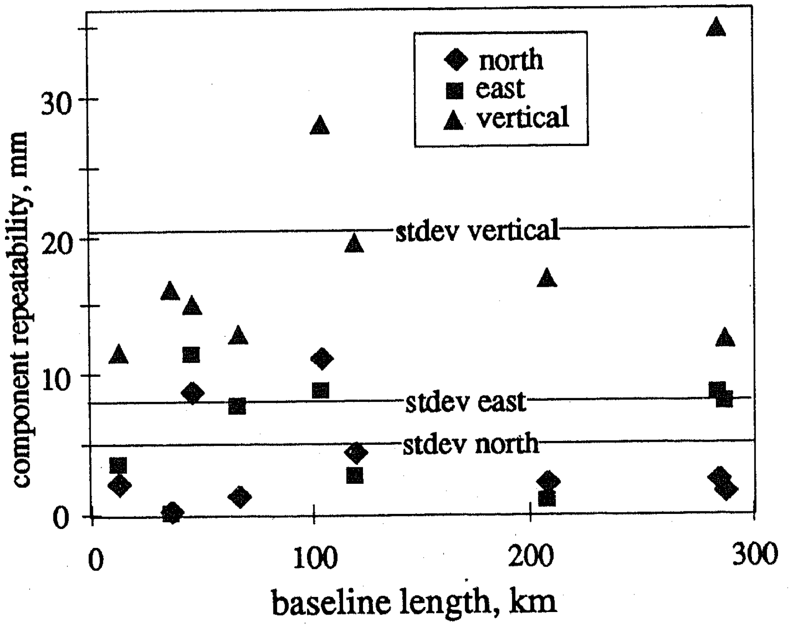
Baseline lengths were measured using horizontal distance measurements (i.e. parallel to a local co-geoid), along the Earth's surface. Each grouping of (normally) six Colby bars were corrected for along-line elevation changes to a synthetic arc at the elevation of the origin (the starting point at one end of the baseline). This was reduced to aninferred sea-level arc length, using estimates for elevation derived from a combination of spirit leveling and vertical triangulation. The sea level baseline lengths reported by Walker (1879) were increased by Strahan (1890) by approximately 0·1 ppm to reflect improved elevations, however, we chose to ignore the revised elevations in our calculations, and our subsequent comparisons are made between GPS and with Walker's computed GTS results.

3. The 1994 GPS observations and their reduction

Six Trimble 4000 SSE receivers were used for the survey. The receivers record up to 9 satellites simultaneously at two separate frequencies (18 channels), and the data were acquired at a sample interval of 15 s down to an elevation mask of 10 degrees. The six units were loaned for the experiment by the University Navstar Consortium (UNAVCO), an NSF-funded US University facility to promote the application of GPS to geodynamic and meteorological studies.

We established a base station at a convenient location on unfractured Peninsular Gneiss in the campus of the Indian Institute of Science (IISC) in Bangalore. The receiver at IISC was operated at this point for 23 hours each day throughout the survey. Not only are all baselines in southern India referred to this point, but points in neighbouring continents, and precise re-computed orbits are also referred to this location. Precise orbital ephemerides are needed to finely constrain baseline lengths derived from GPS data because the orbits broadcast by the GPS satellites (NAVSTAR) in real time are actually estimates of satellite position predicted several hours previously. A geometrical error of 2 m in the orbit of the satellite corresponds to a distance error of 1 cm in a 100 km baseline. Predicted orbits are inferior to the precise orbits that can be calculated after the survey. The longest baseline measured in the Southern Trigon was 530 km, but a 1800-km-long line to Kathmandu, first measured in 1991, was also remeasured in 1994. In order to obtain a precision of 1 cm in the 530 km Bangalore-Cape Comorin distance an orbit accuracy of 20 cm is required, or of 5 cm for a comparable precision in the 1800 km line to Kathmandu. Our subsequent day-to-day repeatability for these long baselines suggest that orbital accuracy of 5 cm was indeed achieved.

We planned to obtain at least 3 days of data from each of the two dozen points measured in the survey. Most sites yielded three days of good quality data (8 hour sessions) butin a few instances some data were lost through operator errors. The 3 days of data provide independent estimates of set-up errors and other forms of noise in the measurements (figure 2). The SISME data were downloaded onto PC's, archived on floppy discs, converted to RINEX format, and processed on Sun computers at CMMACS using Bernese 3·5 software. Data from the fixed station in Bangalore were corrected for cycle slips, time-varying solar radiation pressure and phase ambiguities. The tropospheric delay was estimated using stochastic modeling, and station coordinates were estimated using GYPSY/OASIS II software (Bürgmann *et al* 1994), while site velocities at Bangalore and Kathmandu were computed in a global reference frame (ITRF92) using data from 20 world wide GPS tracking sites of the IGS network. The 1991 distance between Kathmandu (NAGA) and Bangalore was estimated from four 8-hour observing sessions which revealed day-to-day RMS repeatabilities of 8 mm, 20 mm and 8 mm in the north, east, and up components respectively. In 1994 three 23 hour sessions were used to obtain 5 mm, 9 mm and 130 mm repeatabilities for the Bangalore-Kathmandu baseline.



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The day-to-day repeatabilities for < 300 km baselines in the southern Peninsula are shown in figure 2. There is no clear increase of RMS noise with baseline length for horizontal components. North components of baselines yield RMS repeatabilities of ≈ 5 mm, east components ≈ 7 mm. Vertical repeatabilities are typically poor with an RMS value of 20 mm. Baseline length repeatability is observed to be ≈ 6 mm independent of baseline length.

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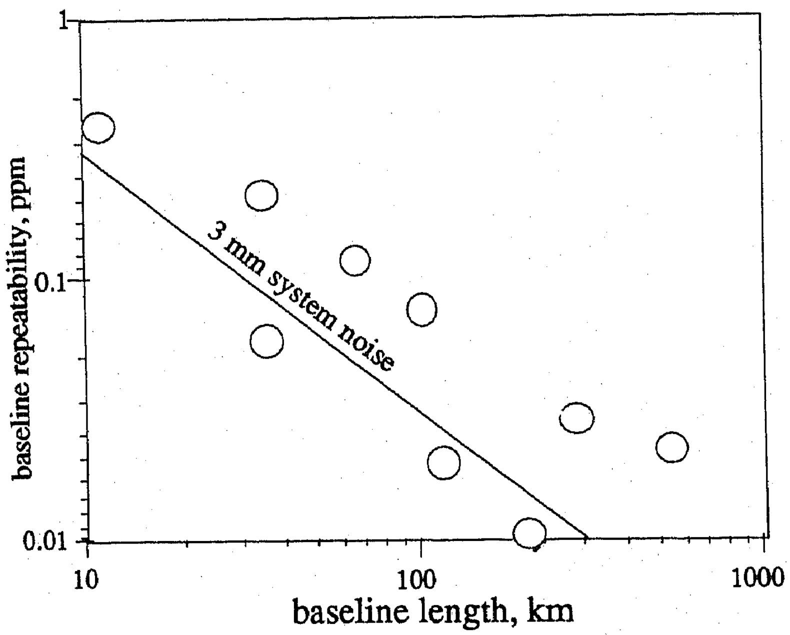

Figure 3. Baseline length repeatability for 1994 southern India GPS data. System noise is believed to be approximately 3 mm.

4. Results

Three distinct data products were obtained from the 1994 SISME survey: translation and rotation information for India between 1991 and 1994, deformation rate estimates between Bangalore and Kathmandu for 1991–1994, and deformation rate estimates for the southern Peninsula for the period 1864–1994. In summary, we found a 5·5 cm/year NE displacement of India relative to the Eurasian plate, which is consistent with inferred plate motion models. We also find less than 0·003 microstrain/year deformation between Bangalore and Kathmandu consistent with assumed plate rigidity, and insignificant strain in southern India. The details of these analyses are discussed below.

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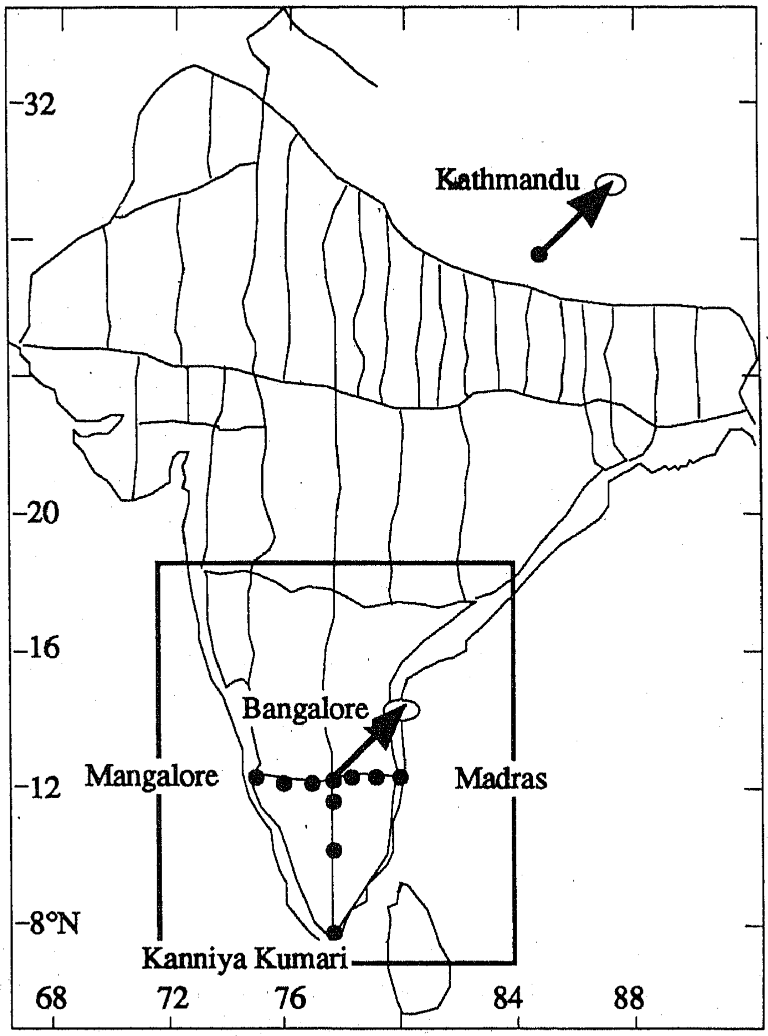

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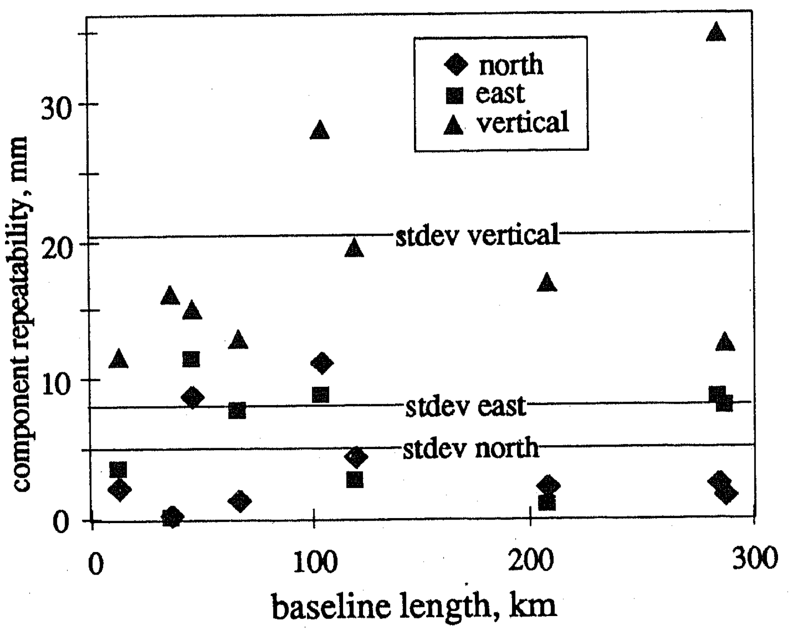

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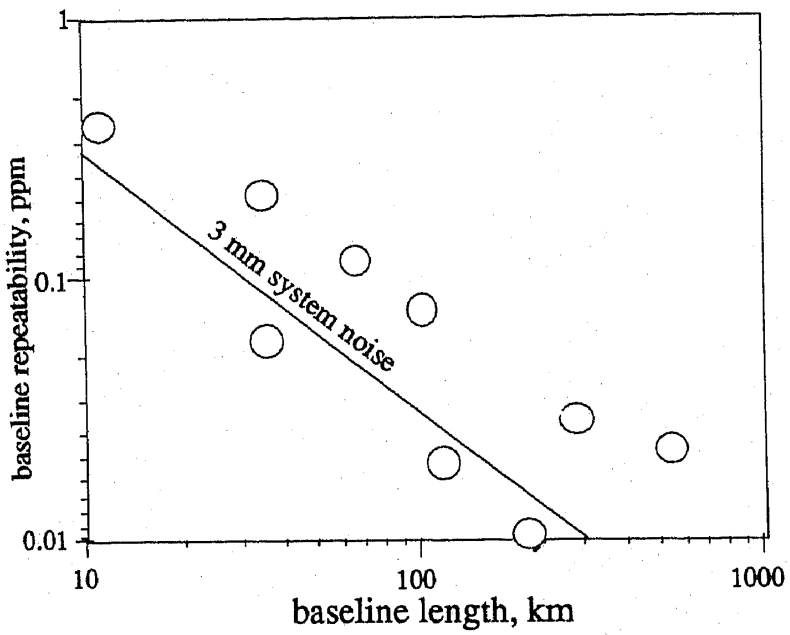

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4.1 *Deformation of India: The Bangalore–Kathmandu baseline 1991–1994*

The precise position of the IISC point in Bangalore was calculated relative to points on the African, Australian, Eurasian, and Pacific plates for 1991 and 1994. The 1991 Kathmandu to Bangalore measurement was made from a different point in Bangalore from the IISC site we have subsequently used, but the two Bangalore points were linked in June 1994 using GPS methods for three days, yielding a repeatability of 1 mm. This permits an indirect comparison between the 1991 and 1994 north-south distances between Bangalore and Kathmandu that has a net uncertainty of 19 mm, corresponding to a velocity uncertainty of 6·5 mm/year. The east west velocities were determined with larger uncertainty (21 mm/year), as also the vertical velocity.

We find this approximately north-south baseline to have shortened $0 \pm 6{\cdot}5$ mm, a result that places an upper limit to creep at the plate boundary between India and the Lesser Himalaya, and intraplate deformation north of Bangalore. The time span of data includes the Latur earthquake and follows the 1988 Udaypur earthquake in southern Nepal, confirming that these two events have had a negligible effect on continent-wide deformation.

4.2 *Translation of India 1991–1994*

In order to examine the observed motions in terms of global plate tectonics, we transform the station coordinates from each GPS station (referred to WGS 84) to the ITRF 92 reference frame (Blewitt 1992), the latter being determined from SLR and VLBI measurements with a 'no net rotation' constraint with respect to the global plate motion model NNR–NUVEL1A (DeMets *et al* 1994). The northward velocity vector for Bangalore (point IISC) so obtained is 39 ± 3 mm/year (figure 4) which agrees to within 2 sigma with the NUVEL-1A global plate motion model. The motion of Kathmandu agrees slightly better than the motion of Bangalore with this model if it is assumed that Kathmandu (point NAGA) is attached to the Indian Plate ($39 \pm 3{\cdot}5$ mm/year). The higher rate of easterly motion for Bangalore suggests that counter-clockwise rotation of the Indian plate may be larger than currently believed. However, this interpretation depends on the reliability of the eastward component of deformation ($\pm$ 11 mm/year for both Kathmandu and Bangalore), that is evidently not as good as the northward estimate. Future measurements from points well within the Indian plate would be of value in resolving this issue. In particular, GPS measurements at northern points of the Indian shield south of the Ganga foredeep should enable us to distinguish between creep and elastic strain in the Lesser Himalaya and Siwalik, as well as plate deformation south of these in Bihar.

4.3 *Baseline changes in the past 125 years*

The scale for the Southern Trigon triangulation chain in 1869 was set by two baselines and we opted to measure these directly to establish how well their present lengths match their published 1869 values. One of the difficulties in measuring these directly using GPS receivers is that many of the early triangulation points are unsuited for direct occupation. The two ends of the Cape Comorin baseline, for example, are surmounted by massive 4 m high brick structures. Their pointed summits resemble shrines, ideal as triangulation targets, but inappropriate as platforms for mounting

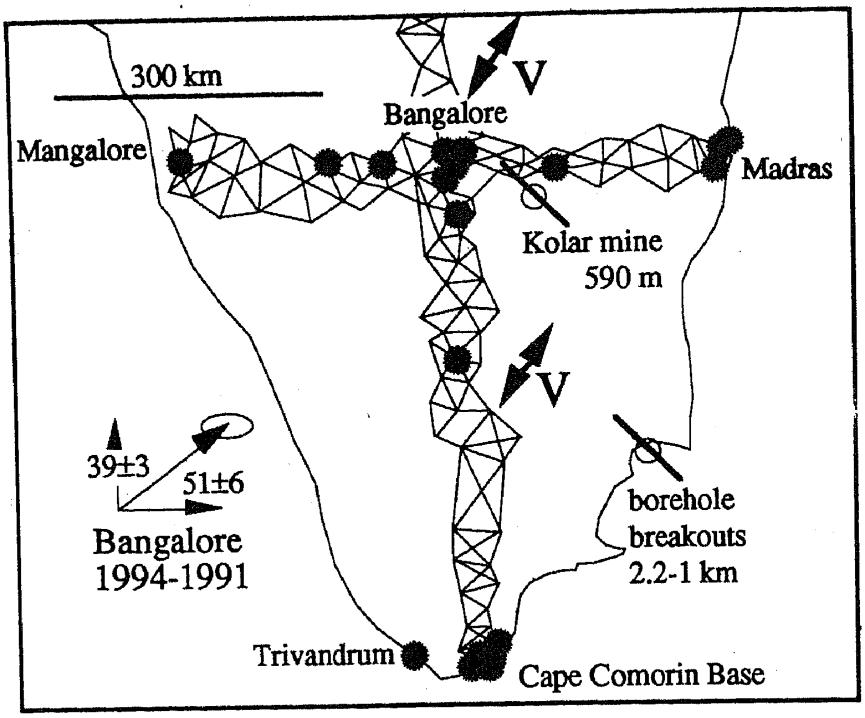

Figure 4. Triangles of the Southern Trigon (Strahan 1890) and GPS points measured in 1994 (Gaur 1994; Gaur *et al* 1994), revealed no significant shear or dilatational strain changes in this 125 year interval. The 1991–4 motion of Bangalore is shown left (Bürgmann *et al* 1994). The fast uppermantle seismic velocity direction (V) are from Rai *et al* (1992), and the stress data are from Gowd *et al* (1992).

a GPS antenna. Thus for the Cape Comorin baseline we occupied the secondary points surrounding the baseline that had been used to extend and verify the baseline in 1869. We occupied 5 of the 6 secondary transfer points, all of which had been repaired relatively recently. The sixth (Erukanderai) was an unusable tower. GTS survey monuments are identified on shallow bedrock, or on a buried stone block at a depth of approximately 1 m, by a dot (1 cm diameter depression) surrounded by a 15 cm diameter circle. A second, similar, reference-mark aligned normal to the lower mark indicates its position on the surface. Vandalism is usually confined to the upper mark. Therefore, whenever they appeared to be in good repair, we assumed that the underlying lower points were precisely located beneath them, as this could not be directly verified in the interest of leaving these marks undisturbed. It is possible, though unlikely, that our vertical offset and horizontal offset may be in error. Disappointingly, the precise reference monuments of the main latitude observatories of Punnae and Kudankulam had been destroyed, and several of the southernmost control points at Cape Comorin on limestone, including Lambton's original mark, had been removed by mining. However, we marked a new GPS point on granite near the Cape Comorin baseline (CAPE) to provide a suitably stable reference point for future measurements.

The GPS measurements for the relatively small Cape Comorin network (figure 5) yielded day-to-day repeatabilities of less than a few mm. To effect the comparison between the 1994 and 1869 measurements we compared line lengths between secondary marks measured directly with GPS in 1994, with lengths calculated from the 1869

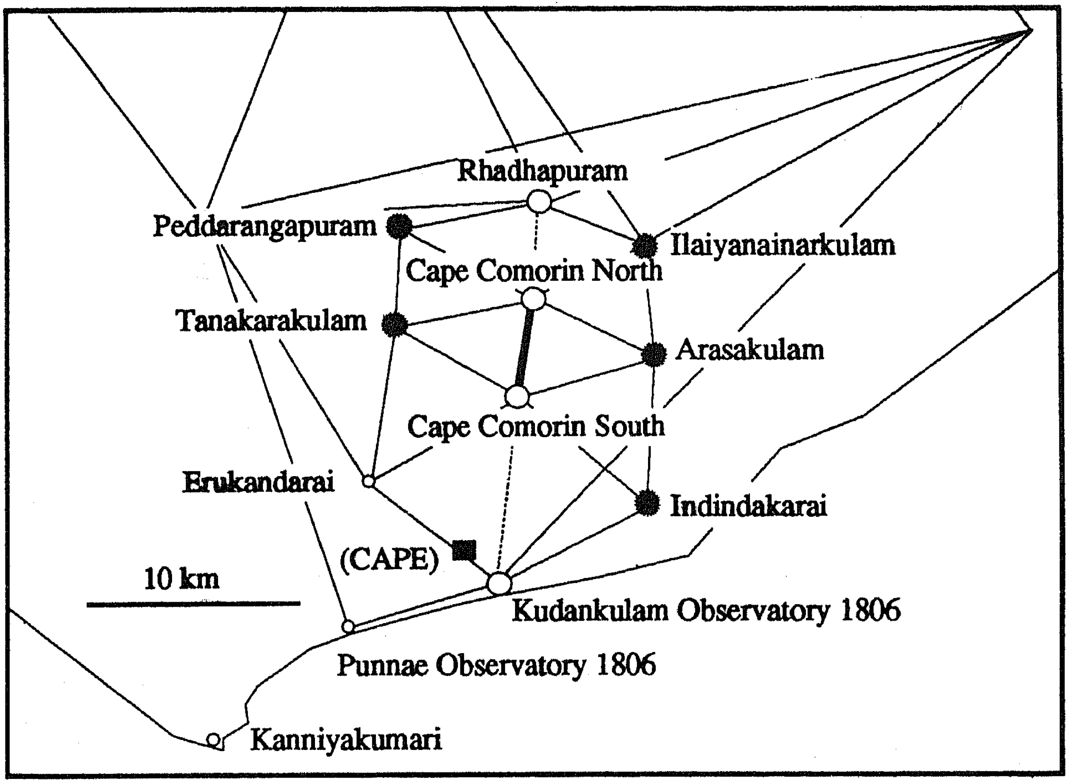

Figure 5. The Cape Comorin baseline (bold line) was extended in 1869 by a factor of 4 in length using six intermediate triangulation stations. The five GPS points (filled circles) were supplemented by a point on a nearby granite outcrop (filled square).

baseline and angle measurements (table 1). As a more informative comparison we used the program DYNAP (discussed below) to determine the areal strain change, rotation, and shear strain change between the original and current positions. The line length comparisons and DYNAP estimates of scale change, rotation, and shear between the 1869 and the 1994 measurements are shown in table 2. The estimated areal dilatational decrease is $(-0{\cdot}62 \pm 8{\cdot}5)$ ppm, within the estimated linear error in the 1869 baseline

Table 1. Comparison of Cape Comorin line changes between 1869 and 1994. Line lengths were calculated from 1869 angles, baseline estimates and elevations.

Baseline	Az. (deg)	Calc. GTS Length (m)	GPS (±0·005 m)	Change (m)	Change (ppm)
PEDD–ELAY	83·4	2749·9110 ± ·0330	2749·9279	0·0169	6·2
PEDD–ARAS	111·7	3225·9719 ± ·0297	3225·9893	0·0174	5·4
TANA–ELAY	64·9	3210·8311 ± ·0385	3210·8239	−0·0072	−2·2
TANA–ARAS	92·7	3176·3348 ± ·0292	3176·3308	−0·0040	−1·3
TANA–IDIN	120·7	3255·3296 ± ·0299	3255·3275	−0·0021	−0·6
ELAY–IDIN	182·1	3024·6010 ± ·0393	3024·6040	0·0030	1·0
ARAS–IDIN	193·9	1556·8990 ± ·0090	1556·8989	−0·0001	−0·1
ARAS–ELAY	350·1	1534·2193 ± ·0089	1534·2229	0·0036	2·3
PEDD–TANA	9·6	1059·8383 ± ·0083	1059·8269	−0·0114	−10·7

Table 2. DYNAP results from the Cape Comorin GTS–GPS comparison (1 μstrain = 1 ppm).

Areal dilatational strain increase 1994–1869	-0.62 ± 8.5 μstrain
Maximum shear strain	5.3 ± 2.4 μradians
Azimuth of maximum compression	N41 $\pm$ 11°E
Contraction at 41 $\pm$ 11°	3.0 ± 4.5 μstrain
Extension at $-49 \pm 11°$	2.3 ± 4.4 μstrain

measurement of 3·8 ppm. If may be noted that the maximum extension and maximum contraction elements of the principal strains from the DYNAP analysis are approximately bisected by the azimuth of the baseline, a numerical result also evident in table 1. The comparison shows that mean extension in the north south component of the baseline is not significantly different from zero indicating that the baseline has evidently remained unchanged in length in the past 125 years.

In contrast to the indirect estimate of the Cape Comorin baseline, the Bangalore baseline could be occupied directly with GPS receivers. The granite-block, astro-geodetic building at the NE end of the baseline was found in good repair, and the upper mark surmounting the building was verified by the Survey of India to be within 4 ± 1 mm of the apparently undisturbed lower mark, 1 m below the observatory floor. This was determined using a pair of Wild T2 theodolites arranged orthogonally to view plumb-bob lines centered on the upper and lower marks. The vertical offset between the lower mark (Gaur 1994, figure 6) and the upper mark was determined to be 4·1 m. The SE end of the Bangalore baseline had been destroyed and rebuilt. We were informed by the Survey of India that the reconstruction of the simple pillar that now marks the SE end of the baseline was undertaken such that there was negligible lateral offset between the buried end point and the current surface point. The vertical offset between this point and the buried point could not be measured and we assumed an offset of 1 m.

For purposes of comparison we first converted the GPS chord measurement to an arc length at the elevation of the 1869 origin (figure 6). We subsequently converted this to a sea level arc length by adopting the same sequence of corrections and the same constants for elevation as described by Walker in 1879. To verify our assumptions and computations we obtained a second comparison by converting the 1869 synthetic arc to the GPS chord length at the measured elevations of the two ends of the baseline. The conversion of the 1994 GPS baseline chord to the inferred 1869 sea level arc was found to be 4.6 ± 0.25 ppm longer than the published sea level arc length of 36083·6258 Indian $feet_{1869}$. The 1994 measurement uncertainty is introduced by a (conservative) 2 m uncertainty in the elevation of the observed SW monument above the buried mark. To confirm our calculations the measured 1869 arc at the height of origin (SW end) was converted to a chord coincident with the 1994 GPS baseline. This yielded an apparent increase of 4·6 ppm between 1869 and 1994. The length increase is within the combined uncertainty of the 1869 (± 3.8 ppm) and 1994 (± 0.25 ppm) measurements confirming that the baseline is essentially unchanged since 1869 (table 3).

As mentioned above, uncertainties in the length of the Indian foot in 1869 are present in our conversions. The Indian foot and the English yard both changed in length by more than 1·2 ppm per decade in the mid 19th century. The measurement of the two

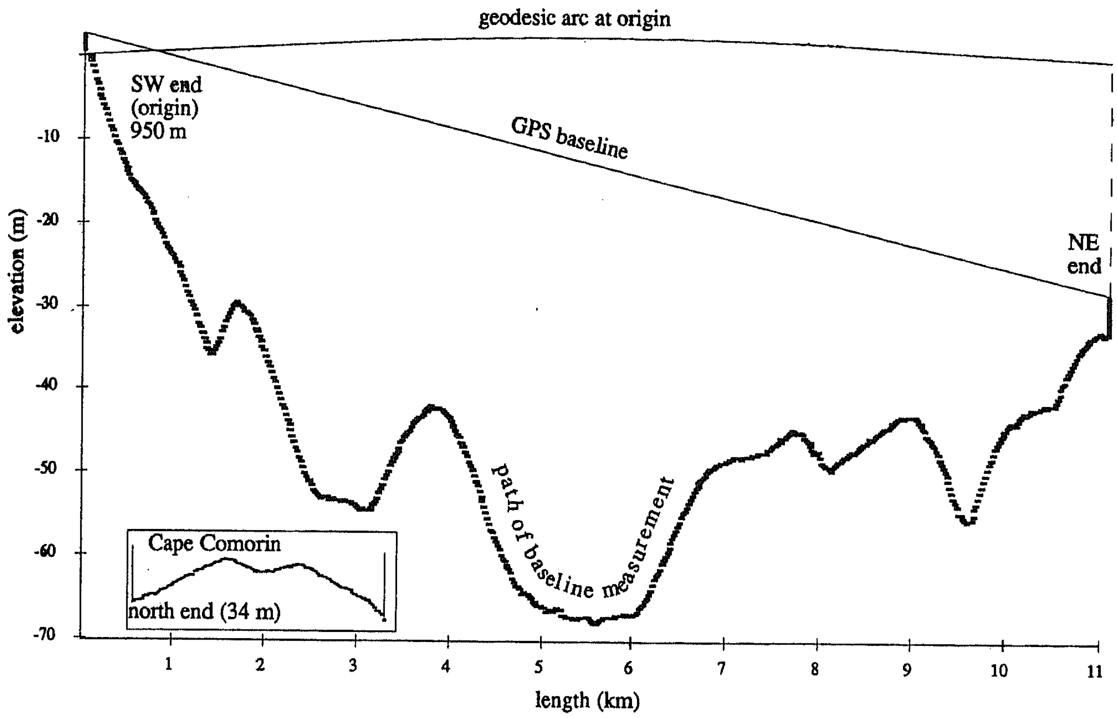

Figure 6. Bangalore and Cape Comorin baseline profiles (to same scale). Each dash represents one of the measurement points of a group of 6 Colby bars. The height of the monuments presently at each end are shown to scale. The separation of the Cape Comorin monuments (bold line in figure 5) was estimated by measuring the present separation of triangulation points installed in 1869 to extend the baseline length from ≈ 3 km to ≈ 12·2 km.

Table 3. Bangalore baseline measurements 1869 and 1994.

Vertical offset at NE End between subsurface mark and top of monument: 12′8″, SW End: 3′1·5″.	
GPS 1994 between uppermost mark of present monuments	10999·9787 ± 0·008 m.
GTS 1869 geodesic arc at origin (36083·6258 + 5·1373) feet	10999·7976 m.
GTS slope distance ($\Delta h = 31{\cdot}9125$ m between sub-surface marks)	10999·8346 m.
GTS slope distance between uppermost marks of present monuments	10999·9273 m.
Increase GPS 1994-GTS 1869	0·0514.
Increase in ppm	4·7 ± 3·8 ppm.

bases occurred within a few years of Clarke's 1866 comparison so that we believe the Bomford's inferred conversion to the meter is applicable. Given this caveat, the two baseline comparisons imply that the scale accuracy of the GTS baselines may be adequate to characterize dilatational deformation to an accuracy of 5 ppm, corresponding to a strain rate accuracy for dilatation in the past 125 years of 0·04 μstrain/year. The equivalent dilatational strain uncertainty is 10 ppm with an areal strain rate uncertainty of 0·08 μstrain/year.

4.4 *Crustal deformation in southern India*

A direct comparison between GTS positions and GPS position (WGS84) is not possible because a precise transformation between coordinates on the spheroid and WGS84 ellipsoid is currently unavailable. The longitude of Madras, to which the Everest datum is referenced, was determined in 1815 before modern time transfer methods were introduced, and it was known before 1860 that all Indian longitudes were in error by at least 2·5 seconds of arc (Walker 1879 p. 135), corresponding to approximately 4·5 km in longitude at the latitude of Madras. Moreover, latitudes in southern India are biased southward by $\approx$ 140 m because of a mean 16 mm/km southward slope of the geoid. A seven-parameter, Helmert transform between the adjusted 1860 positions and the 1994 WGS84 coordinates reveals a substantial translation (4·5 km), and a significant rotation (7·3 $\pm$ 1 μrad), but the scale-change required (+ 1·4 $\pm$ 1·2 ppm) is below the uncertainty in the original baseline determinations. Encouragingly, the RMS residual from the Helmert transform for the subset of points shown in figure 7 is 70 cm (1·3 ppm of the network scale). GPS-GTS residuals are shown graphically in plan view, and the vertical differences are indicated numerically in italics. The residuals imply either position errors in the original GTS determinations of more than a meter, or a heterogeneous strainfield with strains of the order of several μstrain, and wavelengths less than 100 km.

There are several reasons to be cautious of direct comparisons between the two coordinate systems. Localized blunders in the original measurements are distributed as noise throughout the adjusted network, and systematic distortion of the network can be introduced by using astrogeodetic fixes where the local deflection of the vertical remains unmodeled. Moreover, in the presence of ongoing deformation, the different times that data were acquired would distort the resulting network. A more appropriate comparison can be made between the direct GPS positions of all surviving monuments of the original GTS survey, and the raw angle measurements. Astronomical azimuths

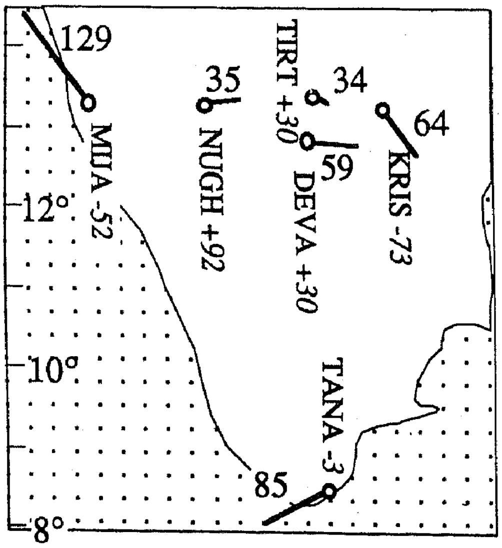

Figure 7. Residuals in mm from a Helmert transformation between adjusted 1860 Everest datum coordinates (Strahan 1890) and WGS84 1994 coordinates at sites indicated. Vertical residuals are indicated numerically in italics.

were generally ignored in the general reduction of the network (xiv, Strahan 1890) and these data can also be utilized to estimate rotation of the network. However, if short period earth orientation signals are to be effectively suppressed, this comparison would require several decades of 19th century astronomical data.

Without the inclusion of these additional data the sparse observations of the 1805–1860 GTS network do not warrant an exhaustive treatment of the 1994 GPS data. Yet there is one signal that should, in principle, be accessible to the comparison, namely the presence of shear strain in the past 130 years. The Helmert transform parameters indicate tangential displacements between the Cape Comorin and Bangalore Baselines that exceed 3·8 m. This rotation signal includes geodynamic rotation of India, errors in the original GTS network orientation, random errors, and tectonic shear strain (table 4).

The Geodynamic Adjustment Program, DYNAP, (Drew and Snay 1989) was applied to the data to extract the shear deformation from the network. The mean date for the initial measurement was assumed to be 1869. Several runs were undertaken to test the sensitivity of the solutions to individual GTS/GPS data. Original triangulation observations were input for 11 GPS sites and 103 intermediate points, as well as the baseline measurements at Bangalore and Cape Comorin. A three dimensional adjustment was performed using the OSU Geoid91 (Pavlis and Rapp 1990; Rapp *et al* 1991) to estimate WGS84 ellipsoid coordinates from the 19th century GTS coordinates and elevations. The astro-geodetic azimuth of the Bangalore baseline was incorporated into the adjustment parameters for the DYNAP GTS/GPS solution (see discussion below). The DYNAP estimate for dilatational strain indicates a cumulative dilatational increase of 11·2 ± 4·8 μstrain, an areal strain increase of 0·090 ± 0·038 μstrain/year. The mean cumulative linear strain was 5·7 ± 2·5 μstrain, in good agreement with our baseline comparison of table 3. To the formal solution uncertainty for the DYNAP result must be added the systematic uncertainty and the random errors of the 19th century determination of the linear dimensions of the baseline. When this is included, the observed dilatation is insignificant at the 1 sigma level (11·2 ± 10 μstrain). Moreover, the DYNAP adjustment indicates that no significant shear strain change has occurred (5·3 ± 9·8 nanoradians per year) with a correspondingly indifferent maximum shear strain contraction direction of 69° ± 52°. A higher shear strain rate was reported by Gaur *et al* 1994 in a preliminary analysis that considered only coordinates and omitted the 1869 angle measurements reported by Strahan (1890), corrections for sea level elevation for the 1869 GTS points, and the estimates for geoid-ellipsoid separations for the 1994 GPS points. We note that the DYNAP solution is somewhat sensitive to

Table 4. DYNAP estimates for the 1869 GTS/1994 GPS SISME network.

	Cumulative 125 years	±	Strain rate/year	±	units
Areal dilatation	+ 11·23	4·76	0·090	0·038	μstrain
Rotation	2·00	2·82	0·016	0·023	μradians (clockwise)
Max shear strain	0·66	1·23	0·005	0·010	μradians
Linear strain at 69 ± 52°	+ 5·42	2·36	0·004	0·019	μstrain
Linear strain at − 21 ± 52°	+ 5·94	2·53	0·005	0·020	μstrain

the astrogeodetic azimuth we adopt for the Bangalore baseline (Strahan 1890, pp. 190–193). The astro-azimuth for the southwest end cited by Strahan agreed with the GPS observations to within 0·01 arc-second, however, the astro-azimuth printed for the NE end differs by 0·1 arc-second. By ignoring the NE astro-azimuth data we obtain the minimum variance in the DYNAP solution. The DYNAP analysis also verifies the 2·5 minute error in the GTS longitudes and the systematic southward bias of latitude due to the regional geoid anomaly.

The net result of the above analysis is that no significant strain changes have occurred in India in the past century. The DYNAP result indicates a cumulative extension at N69 $\pm$ 53E of 5·4 $\pm$ 2·4 μstrain and a cumulative extension normal to this direction of 5·9 $\pm$ 2·5 μstrain. However, if the 3·8 μstrain uncertainty of the original baseline measurement is included in the total uncertainty the changes may be dismissed as insignificant. The apparent increase in linear strain in all azimuths for both detailed and regional comparisons suggests, but does not demand, an error in the 1869 length of the Indian foot by -4 ppm, approximately 2 ppm larger than hitherto believed.

The direction of fast seismic velocities in the upper mantle, and the maximum stress direction indicated by focal mechanism solutions in central India (figure 4) is evidently not reflected by any significant shortening in the direction of plate motion compared to other azimuths. The direction of maximum compressive stress indicated by two stress measurements reported by Gowd *et al* (1992), one from fractures in a gold mine and the other from the mean of several offshore borehole-breakout azimuths is at right angles to these estimates of stress, and has been interpreted to signify a different stress regime from northern India. Although the geodetically determinedshear strain lends no support to any preferred orientation for neotectonic contraction it is possible that strain variability exists at shorter wavelengths than the 530 km scale of the network currently examined.

The theoretical noise level of the 1869 angle measurements corresponds to a shear-strain noise level of 1 ppm and is approximately equal to the shear strain noise level estimated by the DYNAP analysis (1·3 μradians). The observed shear strain rate is consistent with the more precisely determined 1991–1994 GPS strain change determined between Bangalore and Kathmandu (0·002 $\pm$ 0·002 μstrain/year). The approximately 1 μrad per century strain rate noise permits us to estimate a lower limit for the renewal time for earthquakes in southern India. Assuming a failure strain of 100 μradians would require approximately 10,000 years for its release and re-development, this would explain the absence of historically recorded repeating events in Peninsular India. The corollary of this trivial observation has important consequences for the study of future seismic hazards in Peninsular India: regions that have recently experienced an earthquake are unlikely to experience one in the next several thousand years. This conclusion is not necessarily orthogonal to the assumptions currently adopted for the characterization of seismic hazards in southern India, where each new earthquake raises the seismic hazard potential in a region centered on the recent epicenter. Thus, the strain in the region surrounding each new event is perturbed by the recent event, perhaps bringing nearby regions closer to failure. We note, however, that although microseismicity commonly follows each mainshock, no mainshock sequences have clustered around large events in Peninsular India in the past century. Furthermore, although an archival search for historic examples of recent events is unlikely to be successful, an archival search might reveal those areas that have not yet experienced seismicity in recent millennia, possibly highlighting gaps where future seismicity may be pending. These regions may be considered fruitful areas for detailed strain measurements as described in this article.

5. Conclusions

Three years of GPS data confirm a 6 cm/year convergence of India with Asia that has been hitherto inferred indirectly from plate circuit closures. The data permit marginally greater counter-clockwise rotation of the Indian plate than inferred from global plate motions. However, uncertainties in the east-west direction are a factor of two larger than the north component of motion. The northward approach of India toward the Himalaya is evidently accompanied by minor plate deformation, and/or creep processes that cannot exceed 6 mm/year. This finding is consistent with GPS measurements in Nepal that also find creep rates of less than 6 mm/year (Jackson and Bilham 1994). GPS measurement errors in 1994 are characterized by 5–7 mm RMS uncertainties in horizontal components and 1–3 cm uncertainties in vertical components.

Remeasurements of two 19th century GTS baselines reveal that these have not changed in length substantially since 1869. Their original lengths were thought to be accurate to 3·8 ppm and we confirm that they do not now differ substantially from these estimates. Thus, in principle it is possible to detect linear strain rates in the network of larger than 5 ppm should these exist, and areal strain rates larger than 10 ppm. This corresponds to a linear strain rate sensitivity for southern India of 0·04 μstrain per year from measurements of 19th century historical data. The circle measurement accuracy of the original measurements is evidently reliable to 1 ppm providing a shear-strain-rate, noise-threshold of 0·01 μstrain/year since 1869. The southernmost Peninsula of India appears not to have significantly deformed either in dilatation or in shear strain since 1869, providing a lower limit for the renewal time for earthquakes in this region of approximately 10,000 years. Two important conclusions follow from this finding. The first is that we suspect that recent earthquakes do not represent the recurrence of earthquakes that may have occurred since the development of script. That is, a historical search for identical seismic predecessors to ongoing seismicity is likely to be fruitless. The second is that the seismic hazard surrounding recent events is likely to be now reduced compared to areas that have not experienced recent earthquakes in southern India. The latter conclusion is an important consideration for the development of seismic hazard maps for Peninsular India.

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