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Slow tilt reversal of the Lesser Himalaya between 1862 and 1992 at 78°E, and bounds to the southeast rupture of the 1905 Kangra earthquake

Roger Bilham

CIRES and Department of Geological Sciences, University of Colorado, Boulder CO 80309–0399, *USA. E-mail: bilham@colorado.edu*

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SUMMARY

Measurements between 1862 and 1992 of a 77-km-long spirit levelling line that crosses the main frontal thrust of the Himalaya near Dehra Dun (78°E) reveal a slow reversal of tilt in the early part of the last century, unperturbed by the destructive 1905 April 4 Kangra earthquake, 200 km to the northwest. The Lesser Himalaya are inferred to be tilting currently to the northeast at 0.08 μrad yr^{-1}, with similar rate but opposite sign to their tilt in 1862. The absence of co-seismic deformation near Dehra Dun in 1905 indicates that the Kangra rupture terminated short of Dehra Dun, consistent with a revised $M_s = 7.8$ estimate for the size of the Kangra earthquake, but inconsistent with previous analyses of the levelling data that interpret a large slope-dependent systematic error as co-seismic slip. The reversal in tilt corresponds to a linear northeast-down tilt acceleration of 0.0015 ± 0.0004 μrad yr^{-2}.

Key words: earthquake, Himalaya, Kangra, levelling, tilt.

INTRODUCTION

The 1905 April 4 Kangra earthquake was the first of three great 20th century earthquakes to occur in the Himalaya, and was the most severe in terms of lives lost and economic consequences. More than 20 000 people are estimated to have been killed during the event (Middlemiss 1905, 1910; Baduwi 1905), mostly in Himalayan villages surrounding the northern Punjab town of Kangra.

It is generally believed that the earthquake occurred on a shallow thrust fault on the upper surface of the Indian plate beneath the Himalaya (Seeber & Armbruster 1981; Ni & Barazangi 1984). The basal thrust was termed a detachment. Geological reconstructions of the Kangra region by Powers *et al.* (1998) have inferred the presence of a décollement fault at depths of 5 km dipping northeast at 2.5°. Sustained movement on this detachment, or décollement, in great earthquakes along the Himalayan arc permits the advance of India beneath Asia. Although the history of great earthquakes in the Himalaya is incomplete prior to 1900, it is almost certain that no great earthquakes have occurred since 1800, and none are known with any certainty before then. Because the great 1897 Assam earthquake did not rupture Himalayan faults (Bilham & England 2001), more than 70 per cent of the Himalayan arc currently qualifies for the status of a seismic gap (Bilham & Gaur 2000). The identification of the locations of the rupture areas of future great earthquakes contiguous to the 1905 rupture depends on the precise delineation of the size and location of the Kangra rupture zone, yet despite numerous studies of data acquired shortly after the earthquake, the 1905 rupture parameters remain uncertain (Molnar 1987; Molnar & Pandey 1989).

Five methods can be invoked to estimate the rupture parameters of historic earthquakes: teleseismic magnitude, the spatial distribution of the aftershocks, estimates of felt intensity, the extent of surface faulting, and the measurement of surface deformation as recorded by geodetic data. The following is a summary of what is known about the Kangra event.

A surface wave magnitude of $M_s = 7.8 \pm 0.2$ has been derived for the Kangra earthquake from the retrospective calibration of six European seismograms (Ambraseys & Bilham 2000; Ambraseys 2000). Several earlier estimates ($7.5 < M < 8.6$) have been proposed based on uncalibrated or imperfectly calibrated versions of up to 15 seismograms. These earlier estimates are ignored in this article.

No local seismometers were available in 1905, and hence aftershock locations are not known with any accuracy. Similarly, no surface faulting was associated with the 1905 earthquake except for an observed fracture in rock (at 31°40′N, 77°16′E), dismissed by Middlemiss (1910; p. 71, p. 350) as a secondary feature. Thus neither geological nor aftershock data provide constraints on rupture area.

Although reservations have been expressed about the accuracy of the calibration of Middlemiss's (1910) inferred Rossi–Forel contours (Ambraseys & Bilham 2000), his maps of shaking intensity currently provide the best available constraint on the location of the main shock (Fig. 1). The Rossi–Forel intensity IX area drawn by Middlemiss includes the village of Kangra and extends southeast approximately parallel to the Himalaya. The length (120 km) and width (50 km) of this isoseismal contour is similar in area to that anticipated for an $M_s = 7.8$ earthquake, with slip of 3–6 m (an expanded discussion of rupture parameters is found in a later section), and is thus inferred to include much of the 1905 rupture zone.

In contrast, the intensity VIII area appears too large to represent the spatial extent of rupture. The Intensity VIII area is manifest as two areas: one surrounding the Kangra main shock and the other surrounding the town of Dehra Dun, 250 km to the southeast. The presence of this isolated area of intensity VIII shaking has supported speculation that the Kangra rupture may have extended more than 200 km from Kangra, either as a continuous rupture, or as an associated fault that slipped within a few minutes of the main shock. Several authors discuss the possibility that the gap between the two intensity VIII contours is caused by incomplete coverage of the rupture area by post-earthquake investigators (Seeber & Armbruster 1981; Molnar 1987; Molnar & Pandey 1989). However, the intervening region of lower-intensity shaking includes the relatively densely populated town of Simla, which was approached by investigative teams from the northeast and northwest after the earthquake (Middlemiss 1910), suggesting that the observed absence of intense damage there was real. A continuous 250-km-long rupture between Kangra and Dehra Dun is inconsistent with an $M_s = 7.8$ magnitude for the 1905 event. This leaves two explanations for the high-intensity shaking surrounding Dehra Dun: that high intensities were caused

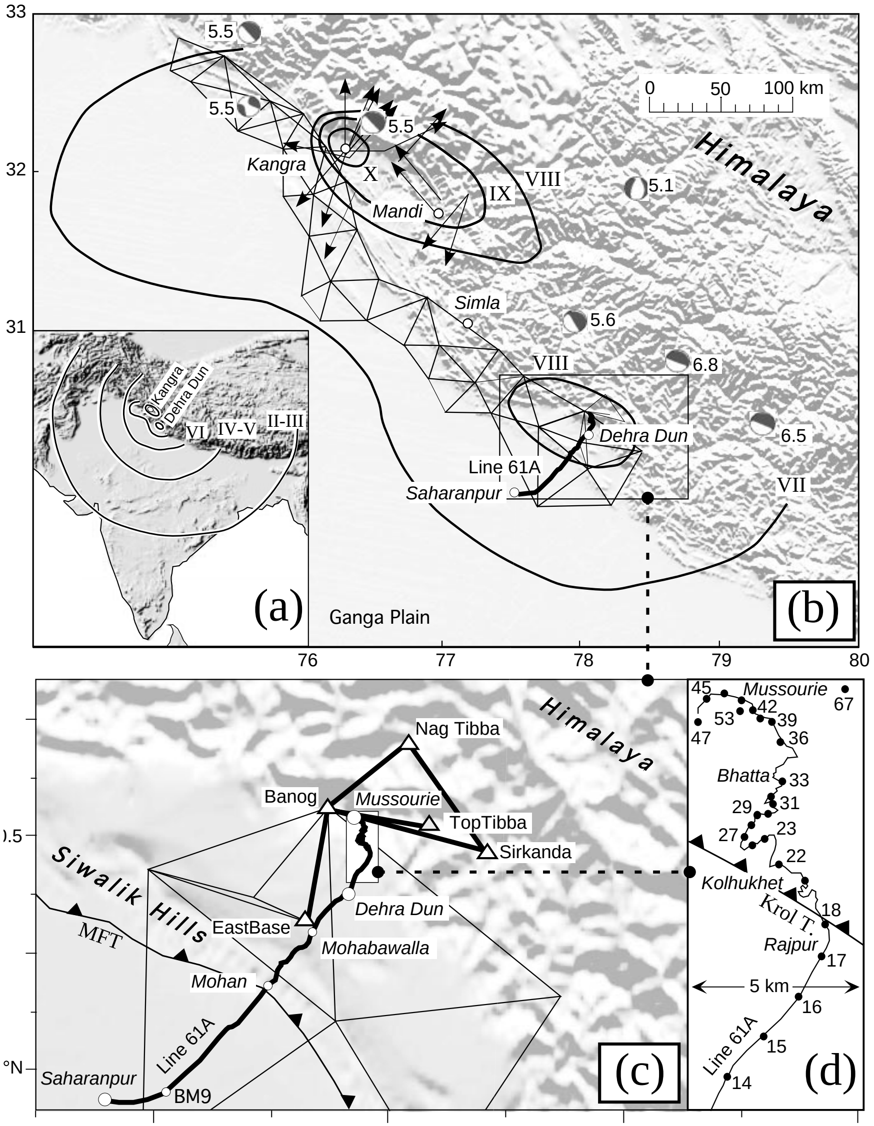

Figure 1. Map of the epicentral region of the 1905 earthquake showing levelling line 61 A and the inferred Rossi–Forel intensity contours from Middlemiss (1905). Positions of benchmarks north of Dehra Dun (d) are from Burrard (1910b, 1915) and Ryder (1919). Positions of trigonometrical points (Δ) remeasured after the earthquake are from Burrard (1909). The topographic DEM is a composite of ETOPO30 and ETOPO5, and the triangulation lines elsewhere are from Walker (1873) and Hennesey (1875). MFT: main frontal thrust. The location of the Krol Thrust (d) is taken from Gulatee (1949). Line vectors with arrows (b) indicate the direction of collapse of objects near Kangra (Middlemiss 1905). Recent focal mechanism solutions for $M > 5$ earthquakes are from the Harvard CMT catalogue.

by local amplification of seismic shaking, or that a local fault slipped near Dehra Dun in a second earthquake triggered by the main shock.

Geodetic coverage of the epicentral region is limited to a line of triangulation stations (Fig. 1) that were measured along the northern edge of the Ganga plain between 1860 and 1880 (Walker 1873), and a sparse set of levelling lines that were measured in the 1860s to provide precise vertical control (Walker 1863). None of the triangulation was remeasured after the earthquake, with the exception of four angles near the town of Mussourie, north of Dehra Dun, which showed that points 10–20 km apart had not moved more than 20 cm (Burrard 1906), the accuracy of resolution of the measurements.

By a fortunate coincidence, a first-order levelling line from Saharanpur to Dehra Dun had been extended northwards to Mussourie in 1904, the year before the earthquake. This line was remeasured immediately after the earthquake to reveal an apparent difference of 15 cm in the height of the town of Dehra Dun relative to Mussourie 15 km to its north.

This apparent uplift of Dehra Dun (or subsidence of Mussourie) has inspired several investigations of the rupture parameters of the Kangra earthquake and subsequent deformation (Chander 1988, 1989; Gahalaut & Chander 1992; Gahalaut *et al.* 1994; Gahalaut & Chander 1997; Yeats *et al.* 1992). Although some of these articles have expressed concern about the quality of the levelling data, none has contemplated the probable absence of deformation presented here.

In the five sections that follow these introductory remarks, I show that the levelling signal contains significant systematic error, most probably caused by unmonitored changes in the lengths of levelling-rods, and that little or no deformation occurred near Dehra Dun. I follow this with three sections in which I show that the absence of significant deformation near Dehra Dun is consistent with the inferred $M_S = 7.8$ magnitude for the Kangra earthquake. Following this is a section in which I estimate arc-normal secular tilt of the levelling line over a 130 year interval and determine that a slow reversal in tilt has occurred unperturbed by the Kangra earthquake.

GEODETIC DATA

In 1897, 7 yr before the 1905 Kangra earthquake, control points of the Survey of India on the Shillong Plateau were shifted by several metres (Oldham 1899), leading to concern that perhaps severe earthquakes might ubiquitously displace control points of the primary network of the Great Trigonometrical Survey of India. Burrard (1906) remarked, ‘To those who are interested in the preservation of these marks for the use of the future, the frequent recurrence of earthquakes in Northern India must necessarily cause uneasiness, but investigation shows that there are no real grounds for despair. Before we can accept the retrograde view that accurate triangulation is useless, we have to have definite evidence of the actual effects of earthquakes.

‘It was therefore important that we should determine whether the terminal stations as fixed by Everest had suffered horizontal displacements from the earthquake, and as this could be done from Dehra Dun without expense, several horizontal angles, which had been observed before were re-observed’.

The four angles that were measured from the hills north of Dehra Dun showed no relative motion greater than the measurement uncertainty and it was therefore concluded that further remeasurement of triangulation points was unjustified. The consequences of this decision, which I discuss in the final section of this article, were to have profound effects on Survey of India policies for the following two great earthquakes in 1935 and 1950.

In contrast to the absence of discernible horizontal motion near Dehra Dun, post-seismic measurement of levelling line 61 A emanating from the Survey Headquarters in Dehra Dun northwards revealed >150 mm of uplift of the town, an amount that far exceeded known errors in spirit levelling. Suspicions that the levelling may have unwittingly included large systematic errors led to remeasurement of part of the line north of Dehra Dun in October 1905, and a remeasurement of the entire line to its south in April/May 1907. These measurements reduced the amplitude of apparent uplift by 18.3 mm (to ≈ 135 mm), but showed that peak uplift occurred in the grounds of headquarters of the Survey of India in Dehra Dun (Fig. 1), precisely at the junction between the two post-seismic surveys (Fig. 2). This rather curious coincidence would normally be cause for concern in any search for a tectonic explanation of the results, but it escaped notice at the time of publication of the data in 1910 and has been ignored subsequently.

The apparent reality of the vertical deformation signal led Burrard (1910b) to speculate that the Himalaya may be actively growing during earthquakes. He reasoned that given seismic uplift events exemplified by the Kangra earthquake, it would take 70 million earthquakes to raise the entire Himalayan chain from sea level, and 3 million years to raise the summit of Everest from sea level to its present elevation. 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 benchmarks 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. 90 yr has elapsed but regrettably many of these benchmarks are now lost.

LEVELLING DATA

Two difficulties attend the unambiguous interpretation of the 1905 re-levelling data. The first is that although the positions of markers south of Dehra Dun are known precisely, the coordinates of those to its north are known only by a series of equivocal descriptions on a road that has been widened and in some cases re-routed (compare Burrard 1915 with Wheeler 1942). Locations in the northernmost 10 km of the line are particularly difficult to identify with certainty. The distribution shown in Fig. 1(d) is obtained from enlarged topographic maps showing the old, now defunct, cart road from Dehra Dun to Mussourie. The locations of some of the benchmarks are approximate (± 50 m), but are adequate for the purposes of this article. The second and more significant problem is that systematic errors are clearly evident in the reported 1904–1905 height changes, especially in the northern 20 km of the levelling line.

Potential errors in the data were first noted by Burrard (1910a) in his original listing of the data, ‘The questions now at issue are the following: Is the rise of 0.4 foot at Dehra Dun a real occurrence and effect of the earthquake of 1905, or is it apparent only and due to the unavoidable errors of levelling over steep ground?’.

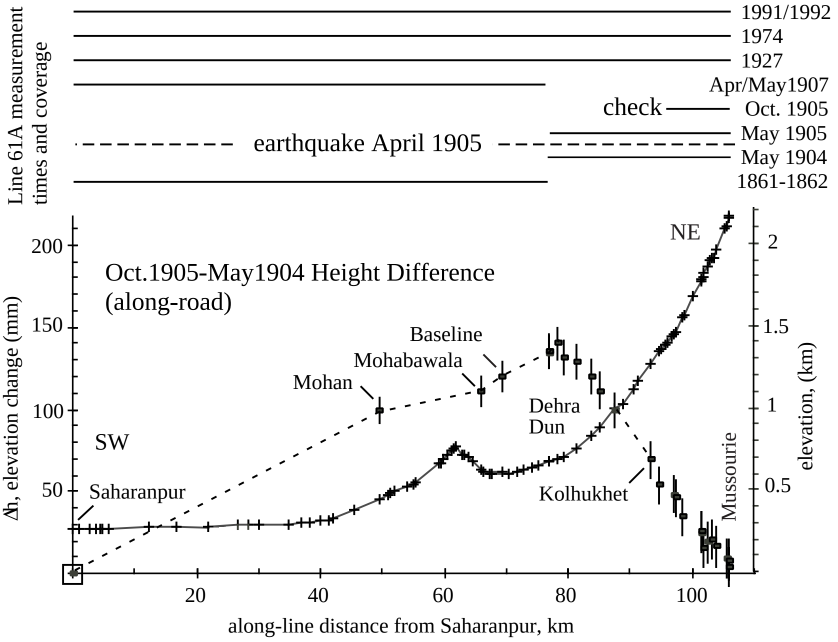

Figure 2. Co-seismic along-line height change, showing all pre-1905 earthquake benchmarks (largely unrecovered) as crosses marked on elevation profile, and growth of random errors in levelling relative to Saharanpur. The spatial coverage of sequential levelling surveys are indicated. Note that peak uplift coincides with the junction between the 1862 and 1904 surveys at the headquarters of the Survey of India in Dehra Dun. The May 1905 levelling between Kolhukhet and Mussourie was single-run. A check on this part of the line was completed as double-run levelling in October 1905, resulting in an 18.3 mm difference in height, and a change in slope in the regression of height change versus elevation (see Fig. 4a).

Burrard (1910b,c) rejected the possibility that the systematic errors may have arisen from levelling-rod miscalibration because although each levelling staff was made of wood, its length was compared occasionally with a steel reference-standard. DeGraaff Hunter (1910) evaluated the possible contribution from refraction errors north of Dehra Dun (but not to its south) and found these to be less than 3 cm. He mentions that closure errors in 48 km of double-run levelling between BM9 (24 km from Saharanpur) and Dehra Dun in 1907 amounted to 17.7 mm (providing a rare glimpse of raw Survey of India levelling data). Gahalaut & Chander (1997) recognized and calculated an approximate correction factor for the systematic error north of Dehra Dun, but failed to identify its full amplitude. Other articles have chosen to ignore the possible error, or to note in defence of the validity of the signal that the 1904–1905 inferred elevation change exceeds all known errors in Survey of India double-run levelling.

In order to examine the reliability of the levelling data it is necessary to examine correlations that may exist between height, slope and spatial azimuth. Two versions of levelling line 61 A data were published (Table 1). The first is an orthometric list of 'corrected elevations' in Burrard (1910c) that have been subsequently repeated in lists of benchmark heights for quadrangle maps of India (Levelling of Precision in India 1912, 1920). The second is a list of 38 heights (h) and changes of height (Δh) before and after the earthquake, with Saharanpur held fixed (Burrard 1910a, p. 342), that have subsequently been reproduced in later re-levelling reports (Rajal *et al.* 1986; Roy & Hasija 1995). The May 1905 double-run measurement was taken only as far as Kolhukhet, and continued as single run to Mussourie. The October 1905 measurement was a double-run survey undertaken to confirm the May 1905 measurement from Kolhukhet to Mussourie. The combined data are listed in post-1906 publications. In addition to averaging the raw double-run field data, some minor adjustments have been incorporated into the data prior to publication. For example, of the 18 pre-1905 data south of Dehra Dun listed by Walker (1863) only four were recovered and listed by Burrard (1910a). The starting point at Saharanpur in 1861 was a point on the 'west side of the south porch' of Saharanpur church, whose vertical separation from the 1904 GTS benchmark at Saharanpur is stated neither by Walker (1863) nor by Burrard (1910c), but which can be inferred from Middlemiss (1910, p. 349) to be 1.378 m lower. The Saharanpur 1863 site description corresponds to neither of the two 1910 site descriptions for benchmarks (7, BM41/53G and 7a, BM42/53G) at Saharanpur Church listed in Burrard (1910c).

The 1904–1905 change in elevation of all 38 points is cited by Burrard (1910a). Reduced subsets of the height change data were listed and plotted by Eccles (1908) and by Middlemiss (1910). The line was remeasured in 1927/1928 (Thomas 1929). A subset of 24 of these data published by Rajal *et al.* (1986) included the 1928 survey (12 points recovered) and a 1974 survey (eight points recovered) and, by presenting the data at a tectonics conference, brought the levelling data to the renewed attention of the seismological community. In 1991 and 1992, eight of the remaining original 38 marks were remeasured by Roy & Hasija (1995).

EVIDENCE FOR SYSTEMATIC ERRORS

The purpose in 1904 for the Survey of India extending levelling line 61 A from Dehra Dun to the triangulation points on the summits of nearby hills was to evaluate errors in vertical triangulation. The plan was to take advantage of the precision believed to be inherent in levelling operations to provide a 'true' relative height between stations in the plains and hilltops 2 km above the plains in order to improve the empirical formulae

Table 1. Data from levelling line 61 A 1862–1908. Column 1 is the assigned benchmark number (geodetic reference number) and columns 5 and 6 are the benchmark numbers on specified quadrants of degree sheet 53 (Ryder 1919). Column 2 is the orthometric listing (Burrard 1910c) and column 4 the listing of benchmark heights holding Saharanpur to be zero (Burrard 1910a). The height in kilometres derived from column 3 is listed in column 7, with the metric equivalent October 1905 minus pre-seismic height listed by Burrard (1910b) (column 8), and the arc-normal distance projected N45°E from Saharanpur (column 9). Column 10 lists the along-line distance in Indian miles from which inter-benchmark slopes and tilt may be calculated, and column 11 lists the site description using the spellings of Burrard (1910c, 1915). Several spellings exist for most locations: the original spelling of Mohan was Mohun and is now referred to as Mohand, as is the nearby village of that name. Mussourie was spelled Masúri in 1872, but has numerous other spellings in subsequent texts.

1 Mark	2 Ortho ht ft Burrard (1910c)	3 Elevation Burrard (1910a)	4 Difference mm +276 m	5 #	6 Map sheet	7 Ht (km)	8 Change Δh (mm)	9 Distance km N45°W	10 Miles along road	11 Description of benchmark from Burrard (1910c)
1	906.323	0	37.186	1	53G	0	0	0	0	Surface of stone slab on west side of south porch of Saharanpur Church.
19	1488.757	582.48	23.165	17	53F	0.178	99.67	43.96	30.91	Mohan near large cairn raised over GTS BM.
37	2095.923	1189.674	14.630	37	53F	0.363	110.6	56.86	40.96	Mohabawala (stone benchmark embedded west side of road).
38/2	1958.463	1052.213	14.935	40	53F	0.321	118.9	57.46	43.06	Ground level markstone, E Dehra Dun base. 1.42 ft above main mark) (30°17′7.35′ N, 77°58′30.74′E).
46/1	2230.563	1324.334	8.534	7	53 J	0.404	135.3	65.96	47.71	Bell platform Trig Office Dehra Dun.
47	2228.556	1322.326	8.839	12	53 J	0.403	134.4	65.96	47.73	Iron Plug, Dehra Dun HQ.
46/2	2236.776	1330.548	8.230	8	53 J	0.406	135	65.96	47.8	Cole's Satellite Sation (Dehra Dun HQ).
48	2282.443	1376.215	8.230	13	53 J	0.419	140.2	65.96	48.65	Near milestone 109 on Rajpur Road.
49	2338.086	1431.875	3.048	14	53 J	0.436	131.4	68.66	49.24	On east side of road near house # 19, Rajpur Road.
50	2515.846	1609.62	7.620	15	53 J	0.491	129.2	70.16	50.65	On top of stone on Rajpur Road near milestone 111 from Meerut.
a/50		1787.749			53 J	0.545	122.8	71.66	51.73	Milestone on Rajpur Road.
51	2748.783	1842.56	6.706	16	53 J	0.562	120.1	73.16	52.06	On top of stone west side of Rajpur Road 32 chains north of Milestone 112.
a/51	2922.149	2015.926	6.706	17	53 J	0.614	111.6	73.86	53.05	Top of stone on north side of road four chains north of Crown Brewery Warehouse at Rajpur
52	3322.605	2416.392	3.658	18	53 J	0.737	99.06	75.16	54.25	Plinth of house, facing road, near water pipe, at upper end of Rajpur Bazar.
53	4201.704	3295.495	2.438	22	53 J	1.004	69.19	75.66	57.99	*In situ* rock at northeast abutment of drain, 60 ft east of lowest step to Kolhukhet water works.
a/53	4425.758	3519.549	2.438	23	53 J	1.073	53.95	75	58.86	*In situ* rock on east margin of road, 67 chains above Kolhukhet water works
54	4497.334	3591.125	2.438	25	53 J	1.095	51.82	74.96	59.1	*In situ* rock on east margin of road, about 1 mile above Kolhukhet water works, and about 2 miles below Bhatta village.
55	4577.137	3670.931	1.524	27	53 J	1.119	45.42	75.56	59.48	*In situ* rock on W. side of road about 2 miles above Kolhukhet water works and 2 miles below Bhata village
56	4630.892	3724.686	1.524	28	53 J	1.135	48.46	75.86	59.68	*In situ* rock on west side of road about 2 miles above Kolhukhet water works and 2 miles below Bhata village.
a/56	4689.38	3783.175	1.219	29	53 J	1.153	49.38	76.36	59.91	*In situ* rock on west side of road about 2 miles below Bhatta village.
57	4739.436	3833.23	1.524	30	53 J	1.168	48.77	76.26	60.08	*In situ* rock on west side of road about 1 mile below Bhatta village.
58	4773.887	3867.682	1.219	31	53 J	1.179	48.46	76.76	60.26	*In situ* rock on west side of road 1 mile below Bhatta village.
59	4837.661	3931.456	1.219	32	53 J	1.198	46.02	77.16	60.5	*In situ* rock on north side of road 72 chains below Bhatta village.
60	5136.917	4230.711	1.524	33	53 J	1.29	34.44	77.06	61.19	On abutment of drain on east margin of road about 20 chains east of Bhatta village.
62	5817.284	4911.084	−0.305	36	53 J	1.497	25.3	78.06	62.98	*In situ* rock four chains south of Oakdene, 42 chains below junction of Kincraig and Library roads.

Table 1. (*Continued.*)

1 Mark	2 Ortho ht ft Burrard (1910c)	3 Elevation Burrard (1910a)	4 Difference mm +276 m	5 #	6 Map sheet	7 Ht (km)	8 Change Δh (mm)	9 Distance km N45°W	10 Miles along road	11 Description of benchmark from Burrard (1910c)
63	5871.066	4964.866	−0.305	37	53 J	1.513	25.91	77.96	63.11	*In situ* rock six chains above Oakdene, 32 chains below junction of Kincraig and Library roads.
64	6001.841	5095.64	0.000	39	53 J	1.553	16.15	77.96	63.44	*In situ* rock east margin of road. Six chains below Kincraig/Library road junction.
65	6146.398	5240.197	0.000	40	53 J	1.597	18.9	77.86	63.8	*In situ* rock on E margin of road 17 chains below Hampton-court/Kincraig road junction, and about 1 mile below library.
66	6281.426	5375.226	−0.305	42	53 J	1.638	21.03	77.76	64.16	*In situ* rock on E margin of road, 23 chains below Falcons nest, and 57 chains below library. Below Falcons nest.
67	6458.616	5552.415	0.000	44	53 J	1.692	16.46	77.86	64.59	*In situ* rock on E margin of road and 23 chains below library.
68	6577.928	5671.727	0.000	45	53 J	1.729	17.07	77.86	64.88	On flooring of verandah of Mussourie library, 11 and 37 ft, respectively, from southeast and northeast corners and a few inches north of librarians door. (30°27′35′N, 78°3′56′E, 6599′).
69	6645.908	5739.707	0.000	50	53 J	1.749	15.54	77.96	65.15	2nd step from bottom of west door of main entrance to Christ Church, Mussourie.
a/69	6740.283	5834.082	0.000	51	53 J	1.778	12.5	77.96	65.31	Cut on rock on outer margin of Evelyn Road about 10 chains above the Church
a/68	6910.091	6003.89	0.000	46	53 J	1.83	10.36	76.66	65.46	*In situ* rock on west margin of the road near southwest end of the bazaar at Vincents Hill, about three chains northwest of the ex Amirs police guard. (30°27′17.4′N, 78°3′29.6′E, 7006′).
71	6934.964	6028.763	0.000	53	53 J	1.838	15.54	77.96	65.59	Markstone of Mussourie Dome Observatory (30°27′40.55′ 78°4′17.41′).
b/68	6923.145	6016.944	0.000	47	53 J	1.834	9.144	77.86	65.61	Upper markstone Eagles nest (30°27/31′ N, 78°3′16′E, 6937′).
c/68	7122.807	6216.606	0.000	48	53 J	1.895	8.534	77.26	65.82	*In situ* rock 3 chains southwest of Dunseverick, and six ft below the level of same.
d/68	7128.282	6222.081	0.000	49	53 J	1.896	3.962	76.76	65.84	Flooring of glazed verandah at Dunseverick on north side of door of southernmost room which contained the pendulum station. (30°2′728′ N, 780°3′33′E, 7129′).

essential to correcting Himalayan summit measurements for refraction errors. However, although the existence of systematic errors in levelling in regions of high relief was known to the Survey of India, slope-related errors were not to receive critical evaluation until after the 1905 earthquake (DeGraaff Hunter 1910; Bomford 1928).

Of the 38 benchmarks of levelling line 61 A for which pre- and post-seismic data were recovered, only four are found south of Dehra Dun: a total of 47 points in the plains from the 1862 survey were lost (8 per cent recovery), and 13 from the 1904 survey (76 per cent recovery). Holding Saharanpur fixed results in the apparent rise of six points at the headquarters of the Survey of India by a maximum of 135 mm (Table 1 & Fig. 2). The change in height between 1862 and 1905 increases monotonically with elevation (351 mm per vertical km), from Saharanpur to Dehra Dun. In contrast, north of this apparent maximum uplift at Survey of India Headquarters, the height change of the 23 benchmarks decreases monotonically with elevation (−118 mm per vertical km; Table 1). This abrupt change in slope at the headquarters of the Survey of India is suspicious because it occurs exactly at the junction of the early 1862 survey and the 1904 survey. Although this may be a real tectonic inflection, it corresponds to no mapped tectonic boundary (Yeats *et al.* 1992; Powers *et al.* 1998) and a simpler explanation is that it is caused by different (and unsuspected) systematic errors in the first two surveys.

Table 2. Relationships between elevation and elevation change for line 61 A. The units are in mm per vertical km, and the shared point at the junction of contiguous surveys is included in the regression analysis of each slope. The number of points included in the regression analysis is listed (#).

Section and benchmark numbers	#	Regression coefficient	Epoch
Saharanpur to Dehra Dun	5	286.0 ± 35.8	1907–1862
Dehra Dun to Kolhukhet	22	−111.1 ± 2.3	May 1905–1904
Kolhukhet to Mussourie	15	−53.0 ± 4.8	October 1905–1904

A second intimation for a systematic error to be present in the data is indicated by the change in slope between the May 1905 and October 1905 levelling data (Table 2; Fig. 4a). This is apparently caused by the revised 18.3 mm height change between the single-run northernmost section in May 1905 and the double-run October 1905 check measurement. Although the details of the May 1905 data are not published, and the data are of lower accuracy because of the absence of double-run procedures, the slope of this northernmost line before correction (dashed line in Fig. 4a) is similar to the slope of the contiguous southern part of the line. This suggests, but does not prove, that systematic errors were different for the two 1905 surveys.

The October 1905 to May 1904 data show a monotonic slope versus height dependence of −54 mm per vertical km for the 22 points north of Kolhukhet, whereas the May 1905 to May 1904 data between Dehra Dun and Kolhukhet show a −111 mm km^{-1} slope, the doubling in slope occurring at the junction between these two surveys (Burrard 1910a,c). DeGraaff Hunter (1910) treated the data on either side of this inflection separately, acknowledging a noticeable difference in mean gradient between the two northern halves of the line.

The abrupt changes in slope and the approximate uniformity in tilt of the three segments of different epochs in Fig. 2 are unlikely to be caused by benchmark instability. Nor is it likely that tectonic signals should produce the observed slope changes. Crustal deformation exhibits gently curved surface changes for subsurface fault slip and discontinuities where faults cut the surface. Neither of these features are evident in the data (Figs 2 and 3). For example, the Krol thrust meets the surface between Rajpur and Bhatta (Raiverman *et al.* 1983: Gulatee 1949), close to Kolhukhet, where the May/October surveys joined (Fig. 1d). No vertical offset occurred in the levelling data, indicating that the fault did not slip. Approximately linear tilts of short segments of the Earth's surface can be generated by slip on subsurface curved surfaces (listric faults). However, abrupt changes in tilt require the activation of surface faults that the levelling data do not reveal, nor do contemporary accounts relate.

Compelling evidence that the observed correlations are not of tectonic origin is available from the geometry of the levelling line (Fig. 1). The levelling line when projected normal (northeast) to the Himalayan Arc shortens from 106 km to 77 km, largely because of hairpin bends and northwest-trending segments of the levelling line between 1000 and 2100 m elevation (Fig. 1 inset), with some additional but minor shortening across the Siwalik Hills. The apparent vertical displacement of the 25 northern points reduces monotonically with elevation (Fig. 2), but when projected normal to the arc (Figs 3 and 4d and e) reduces erratically and inconsistently, exhibiting no simple spatial pattern to vertical motions.

The reduction in height uplift north and south of Dehra Dun evident in Fig. 3, is revealed in Fig. 4(a) to be caused by linear correlations between height and height change. An unequivocal indication that systematic errors dominate the signal is the observation that abrupt changes in the slope of these linear correlations occur precisely at the junctions between surveys of different vintage.

Subsequent studies (Gahalaut & Chander 1997) have analysed the data in Table 1 but have failed to recognize the magnitude of potential systematic errors because the standard procedure devised to identify the presence of these errors yields a poor and somewhat misleading regression coefficient. The conventional

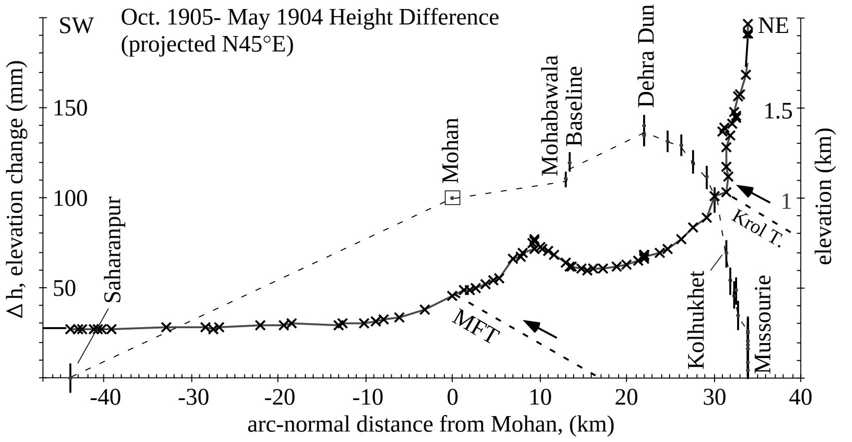

Figure 3. Data from Fig. 2 projected at N40°E, normal to the Himalayan arc. Hair-pin bends and a northerly trend to the line above 1 km elevation foreshorten the line length to 77 km. Data north of Rajpur (Fig. 1d) permit systematic errors to be evaluated independently of arc-normal tectonic deformation.

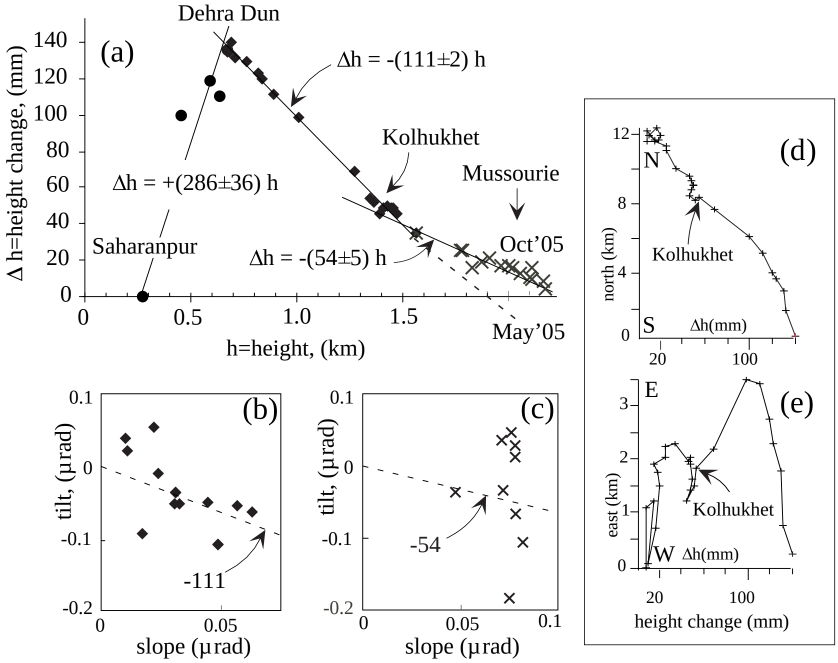

Figure 4. (a) Data from Fig. 2 plotted as elevation change (Δh), versus elevation (h) reveal clear slope breaks between surveys of different epochs. The dashed line in (a) indicates the May 1905 single-run height estimate north of Kolhukhet, which has a similar slope to the earlier part of the May 1905 line (diamonds), suggesting that a common systematic error prevailed. The double-run October data (crosses) show a different slope. The most likely explanation for these changes is that levelling rods changed in length between calibrations in both 1904 and 1905. (b and c) Slope versus tilt plot shows poor correlation for the two northern segments (regression slopes from (a) shown as dashed lines). Height change versus north or east (c and d), or northeast (Fig. 3) distance shows no simple spatial pattern.

test, the pitfalls of which are described by Stein (1981), for the identification of rod-calibration or refraction errors is to regress line slope against observed tilt (Figs 4b and c). Tilt and line slope are calculated between consecutive benchmarks separated by distances of <100 m to several kilometres. Should the resulting plot indicate a random cluster of points with no clear trend, observed changes in height can be assumed to be independent of the differences in height between contiguous benchmarks. A trend in these data, with either negative or positive slope, indicates a systematic correlation between vertical height traversed and the observed change in height. A change in the length of a levelling rod between measurement and remeasurement, for example, would cause such a trend. No trends are clearly evident in the scatter plots of Figs 4(b) and (c).

However, where benchmarks are separated by less than several kilometres, the regression coefficient of slope versus tilt is sensitive to outliers caused both by anomalous benchmark motions and by rounding errors in the measurement of along-line distance. Whereas point-to-point plots of slope versus tilt are sensitive to these random errors (because they are both derived by dividing by the estimated distance between adjacent points), a plot of height change versus elevation for the entire line is less so (Fig. 4a). However, a comparison between height change and elevation will show a linear correspondence in the presence of either a real tectonic signal or a systematic error in levelling measurement. Two special circumstances, if present, permit the two to be distinguished: (i) where the wavelength of the tectonic signal is very large compared to the wavelength of the topography; or (ii) where the spatial path of the levelling line is random compared to the surface tilt vector of the tectonic signal. The data from north of Dehra Dun satisfy criterion (ii) because the bulk of the height-dependent error is concentrated into a tortuous 20-km-long, 1-km-vertical segment oblique to the trend of the Himalayan foothills, and largely normal to the anticipated tectonic signal. It is also possible that this northern segment satisfies criterion (i). The results of applying this procedure are ambiguous south of Dehra Dun, where the levelling line is effectively straight, long, and approximately parallel to the anticipated tectonic signal. The southern line thus fails to satisfy one or both criteria. Fig. 4(a) demonstrates the presence of clear systematic errors north of Dehra Dun. Regression coefficients are listed in Table 2, and are plotted in Figs 4(a), (b) and (c).

The remarkable linear features revealed in Fig. 4(a) indicate that substantial systematic errors are present in the data. Changes in slope occur precisely at spatial or temporal junctions in the levelling line. In the next two sections, I discuss their possible origin in terms of rod calibration errors or refraction errors. Readers who are not interested in the detailed and somewhat inconclusive discussion of these errors may wish to ignore these two sections.

Rod calibration errors

Systematic errors in levelling from all causes rarely exceed 10 mm per vertical km (Bomford 1980; Angus-Leppan 1984). The signals in the 1904–1905 data are 5–30 times larger and are thus apparently beyond dispute, yet the relationships we discuss above make improbable their attribution to crustal deformation. Because these data were of special interest to the Survey of India, every attempt to characterize and correct for errors was made. Burrard (1906, p. 50) asserted, 'When the results were first tabulated, it was perceived that the amount of subsidence increased gradually as the levellers ascended the range. This gave rise to the suspicion that the lengths of the levelling staves may have been in error.

'During the first 6 miles the ascent is 694 feet or 116 feet per mile, and in the last 12 miles it is 4013 feet or 334 feet per mile. A levelling staff being 10 feet long, and the difference of height being 4707 feet, there were contained in the total rise 471 lengths of the staff. If then the 10 foot staves had been 0.001 foot too long, our unit of measurement would have been slightly in error, our measured heights would all have been too small, and the deficiency accumulated at Mussoorree would have been 0.471 of a foot.

'Four different staves are, however, in daily use, and these are periodically compared in the field against a 10 foot steel standard and corrections for each deduced. An examination of the results of the comparisons showed that the apparent subsidence of Mussoorree could not be attributed to errors in the adopted lengths of the four staves.

'The steel standard, against which they were compared was then suspected, and this was subjected to rigorous tests under comparing microscopes at Dehra Dun. Its length, as now determined, accorded with the value previously obtained, and it became clear that the observed change in height of Mussoorree above Dehra Dun between 1904 and 1905 could not be attributed to any error in the adopted standard of reference'.

It is not recorded how frequently 'periodic' comparisons between the wooden levelling staves and the steel standard were undertaken in 1904, although Burrard clearly specifies that the same rods were used for both the 1904 and 1905 surveys. The wooden levelling rods that had just returned from a survey along the River Indus in Sind Province in early 1904 would have to have been only 0.3 mm too long to account for the observed error. To account for the 1862 signal as systematic error, the rods would have to have been 1 mm too short. Although these are large errors to escape detection during calibration, the procedures for calibration permit rod-length changes to occur between the field measurements and the calibration point. Calibration was usually undertaken in the late afternoon after the completion of levelling measurements. In 1929, it was discovered that diurnal changes in the lengths of wooden levelling rods in Dehra Dun exceeded 0.1 mm, with a maximum near midday and a minimum in the late afternoon (Thomas 1930). Thomas intimates that other rods may be less stable than those tested. Rod length changes are caused by thermal expansion and moisture changes. Because the experiments in Dehra Dun may have been performed under less severe conditions than those encountered in the field, it is reasonable to conclude that rod length errors of 0.3 mm could have occurred in 1904 and 1905.

Refraction errors

An alternative source of error prior to 1905 that was not well characterized was the contribution from refraction errors on steep slopes. The cumulative error in Indian levelling prior to 1910 was quoted as $e=\sqrt{(jL+kL^2)}$ (*cf.* Lallemand 1912), where L is the distance in miles, e the error in feet and j and k were constants determined empirically as 1.6×10^{-5} and 1.156×10^{-7}, respectively (Burrard 1910a). The error includes both a systematic error that grows linearly with distance and a random error that grows with the square root of distance, but includes no term dependent on the either slope or the elevation. If Saharanpur in the plains is held fixed, the uncertainty in measured elevation using the stated 1910 error grows to a maximum of 10 mm at Dehra Dun, i.e. 7 per cent of the apparent uplift signal of 140 mm. Relative to Dehra Dun, the height change of Mussourie is apparently even more above the 1910 formula's theoretical uncertainty of 5 mm. Bomford (1928) evaluated refraction effects in the 1928 levelling of the same line using temperature observations of gradient and a newly devised refraction algorithm and concluded that the systematic refraction error between Dehra Dun and Mussourie was no more than 9 mm. However, he pointed out that these temperature measurements were unavailable for the 1905 data.

In 1910, DeGraaff Hunter presented an analysis of levelling data from two independent lines between Saharanpur and Dehra Dun, in which he discussed refraction errors and showed these to be less than a few tens of millimetres. His theoretical analysis of probable errors between Dehra Dun and Mussourie is necessarily tentative because of the absence of measured temperatures, pressures and humidity gradients during the surveys (Table 3). The theoretical vertical errors in the two halves of the line north of Dehra Dun with gradients of 1:31.6 and 1:17.2 are approximately equal because the increased slope results in a shorter set-up length with consequently reduced refraction error. The combined error is 26 mm, or 20 per cent of the measured 133 mm height change.

It is well known that refraction errors tend to be larger in lines of lower gradient, where without cautionary restrictions, surveyors tend to increase sight lengths to improve daily production. In the third column of Table 3, we calculate the possible Saharanpur/Mohan error using Lallemand's formula, assuming similar thermal conditions and empirical terms derived from European gradients, but increasing sight lines to 70 m. The

Table 3. Refraction error calculations from DeGraaff Hunter (1910) for the line north of Dehra Dun (columns 2 and 3) and inferred refraction error using Lallemand's (1896) empirical formula south of the Siwalik (column 4).

Segment	Dehra Dun to Rajpur	Rajpur to Mussourie	Saharanpur/Mohan
Distance	10.515 km	17.088 km	49.730 km
Rise	333 m	992 m	453 m
Number of set-ups	150	458	622
Mean height increment	2.22 m	2.17 m	0.7 m
Mean set-up length	70.1 m	37.3 m	140 m (estimated)
Vertical error per set-up	0.102 mm	0.028 mm	0.050 mm
Vertical error	15.3 mm	12.8 mm	17.0 mm
Error per vertical km	46.0 mm	12.9 mm	37.5 mm

possible error on this 1:110 gradient line remains less than 20 per cent of the observed Saharanpur/Mohan 99.7 mm 1904/1905 signal. Similarly, I calculate an additional 14 mm possible error from Mohan to Dehra Dun across the Siwalik, assuming set-up lengths of 70 m or less, resulting in a cumulative Saharanpur/Dehra Dun error of 31 mm or 30 per cent of the observed signal.

The errors in Table 3 were computed using an empirical formula derived by Lallemand (1896), assuming a logarithmic near-surface thermal gradient for Europe, which DeGraaff Hunter (1910) conceded was unlikely to be appropriate for the Himalaya. Subsequent investigations of thermal gradients suggested that the levelling lines at 30° latitudes should be subject to much larger refraction errors (Holdahl 1981), and since Himalayan slopes face south, insolation is effectively increased to that appropriate for yet lower latitudes. Given that the contribution of refraction to systematic errors is proportional to the square of the set-up lengths (Angus-Leppan 1984), the largest errors are likely to have occurred on the Saharanpur–Mohan segment, where set-ups longer than 140 m were possible. The Dehra Dun to Rajpur segments of the levelling line should be associated with smaller refraction-induced errors, and the northernmost segment of the line should be associated with a yet smaller refraction error. The error is likely to have largely cancelled in the crossing of the Siwalik, where slopes are symmetrical and moderate.

At issue, however, is whether the refraction error was different for the 1862/1904 and 1905/1907 surveys, and whether this could have accounted for the apparent 140 mm signal. Procedural information published by the Survey of India suggests that it was not, but the absence of key physical observations during the surveys in question weakens this conclusion. Claims that the data are validated by the absence of errors of this magnitude detected in other Survey of India levelling investigations are spurious because the 1904 Mussourie measurements are unique in being the first levelling line to rise more than 1.5 km above the plains of India. Recent error estimates for the line calculated from uncertainties in modern survey methods are also inapplicable to the data. For example, Roy & Hasija (1995) estimated random and systematic errors of less than 0.7 mm and 0.1 mm, respectively, for the entire line, implying a random error growth of $0.07\sqrt{(\mathrm{km_h})}$ mm, and an Invar-rod calibration accurate to $0.05(\mathrm{km_v})\times10^{-8}$, where $\mathrm{km_h}$ and $\mathrm{km_v}$ are the horizontal (106 km) and vertical (1.9 km) distances traversed. Although these error estimates appear to be overly optimistic for spirit-levelling procedures that normally attain no better than $0.3\sqrt{\mathrm{km_h}}$ for random errors and $\mathrm{km_v}\times10^{-6}$ for systematic errors under good observing conditions, more realistic estimates of 3 mm and 2 mm, respectively, from such considerations remain negligible compared to the 1905 apparent signal.

I conclude that refraction errors are unlikely to be the cause of the observed systematic error. Changes in lengths of the wooden levelling rods between calibrations, however, have been recorded, and these appear to be a likely source of the errors discussed in this article.

NO 1905 CO-SEISMIC VERTICAL DEFORMATION AT 78°E

Notwithstanding their cause, the linearity of the fit between height and height change in the two northern segments, and the abrupt change in slope between contiguous surveys of different epochs evident in Fig. 4(a), are compelling evidence that systematic errors were present in pre-1905 data and that their removal should be attempted prior to tectonic analysis. Accordingly, adjusted versions of the levelling line are presented in Fig. 5 using the coefficients quantitatively inferred from Fig. 4(a).

The residual levelling signal is essentially featureless after the removal of these systematic errors. No arc-normal tectonic signal remains in the corrected data north of Dehra Dun, although a subdued signal may remain south of Dehra Dun.

This is a somewhat startling result given the historic importance of these venerable data, and their numerous subsequent interpretations. However, whilst the case against co-seismic subsidence of the Himalaya north of Dehra Dun is strong, it remains possible that Dehra Dun rose relative to the Ganga Plain. I now entertain the possibility that the signals shown in Fig. 5(a) or (b) are real, and search for possible subsurface slip on known faults beneath the Siwalik range, in an attempt to explain the isolated intensity VIII contour of Middlemiss (1910) as resulting from a small local earthquake as first suggested by Chander (1988).

Let us suppose that uplift of Dehra Dun is caused by slip on the main frontal thrust fault (MFT in Figs 3 and 5c), which is inferred to dip at 30°NE beneath the Siwalik (Rao *et al.* 1974) and emerge at the surface between the village of Mohand and the benchmark of Mohan (originally Mohun) to its south (Powers *et al.* 1998). Geological fault slip has elevated river terraces north of Mohand with no discernible back-tilting, suggesting that the fault is planar (Wesnousky *et al.* 1999). Slip on a buried planar fault whose surface projection emerges near Mohan will generate little or no uplift or subsidence of Mohan. Using elastic dislocation theory it is possible to show that for there to be less than 14 cm of vertical displacement at Dehra Dun, subsurface slip must be less than 20 cm at depths below 20 km (Fig. 5c) Although a suite of subsurface dislocation models can be contrived to fit the adjusted Fig. 5(a) vertical signal and unadjusted horizontal geodetic data, I refrain from attempting this in view of the uncertainties in the data. Instead I note that the absence of vertical displacement of the Mohan benchmark predicted by these models conflicts with its inferred movement histories depicted in Figs 5(a) and (b). To raise Mohan requires slip on a buried fault below the MFT frontal thrust whose surface projection would emerge in the Ganga Plain south of Mohan. This observation does not of itself render the signal of Fig. 5(a) improbable, but requires *ad hoc* explanations for the location of subsurface rupture.

NO 1905 CO-SEISMIC SHEAR STRAIN AT 78°E

As noted in the previous section, none of the seven articles that has discussed a tectonic interpretation for the levelling data have used horizontal angle changes as a constraint in the calculation of acceptable models. This is because, with the exception of four points near Mussourie whose relative positions were found unchanged, no remeasurements of the triangulation series along the Himalaya were measured (Fig. 1). The measured horizontal data consist of four lines that radiate from Banog, a 2266 m peak 8 km west of Mussourie. The four lines terminate at Nag Tibba (20.4 km at N82°E), Top Tibba (25.5 km at N100°E), Sirkanda (40.8 km at N40°E), and the east end of the Dehra Dun baseline (28 km at N190°E) (Burrard 1906, 1909).

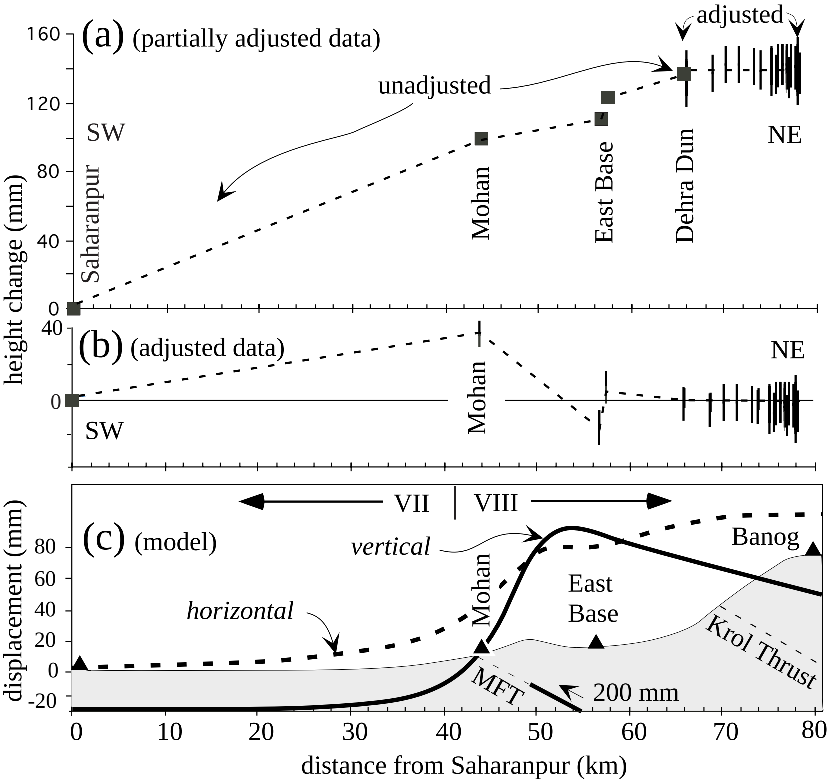

Figure 5. Two alternative versions of the adjusted levelling data compared to surface deformation anticipated from slip on the main frontal thrust (MFT). (a) assumes that no systematic errors are present south of Dehra Dun (dashed line), and (b) applies the regression coefficient derived in Fig. 4(a) for the line south of Dehra Dun. Synthetic contractile strain calculated for a buried dislocation at 10 km depth on the main frontal thrust (MFT) is shown by a dashed curve. Solid curve shows synthetic vertical deformation for same dislocation with zero predicted deformation at Mohan where the MFT meets the surface. The boundary between Middlemiss' Intensity VII and VIII areas is indicated.

'In 1905, after the earthquake which devastated Dharmsála, the triangle Sirkanda, Banog, Nag Tibba was observed with Troughton and Simms 12-inch micrometer theodolites numbers 2 and 3. The results proved conclusively that no relative change had taken place between these stations outside the limit of error of observation' (Burrard 1909, p. xviii).

'Owing partly to the heat and the haze, the revisionary observations were not of the highest order of accuracy; and we are consequently unable to tell whether horizontal movements of six inches or less have taken place or not. A comparison of the results, however, shows (first) that no relative displacement of 8 inches has probably occurred and (second) no relative displacement of 12 inches can have occurred' (Burrard 1906).

Assuming that Burrard's estimated ± 20 cm uncertainty represents the maximum tangential displacement at the ends of the above lines from Banog, the angular measurement uncertainties are 5–10 μrad, with a mean value of 7 μrad, close to the mean error in contemporary triangulation measurements (1.72 arc s or 8.3 μrad). These data indicate that no shear strain occurred larger than 7 μrad within 20 km of Mussourie. This is, of course, an order of magnitude less accurate than first-order levelling accuracies over similar distances. However, the uncertainty is similar in amplitude to the systematic error identified in the levelling data.

In retrospect, it is disappointing that because no significant motions at these points in the Dehra Dun valley were detected, no additional triangulation points were measured, especially those close to the epicentre. Eccles (1907) suggested that the possible motion of points between the Siwalik and the plains should also be observed (Fig. 1), but apparently these measurements were never undertaken.

SOUTHEASTERLY EXTENT OF THE KANGRA 1905 RUPTURE

I now proceed to examine the implications of a maximum 7 μrad shear-strain deformation field in the Dehra Dun region at the time of the Kangra earthquake. Of interest is whether the result provides a useful constraint to the western edge of the rupture.

I first estimate the probable rupture dimensions for a rectangular 3-D rupture centred on the Intensity XI contour rupture area consistent with an inferred $M_s = 7.8$ magnitude (Fig. 6). Wells & Coppersmith (1994) showed that the surface wave magnitude, M_s, approximates the moment magnitude, M_w, for events where $M < 8$, hence we infer an approximate seismic moment $M_0 = 6.3 \times 10^{27}$ dyne-cm from $M_w = 2/3 \log M_0 - 10.73$ (Hanks & Kanamori 1979). Assuming slip of approximately 3 m and $\mu = 3 \times 10^{11}$ dyne-cm^{-2}, an approximate rupture area of 7000 km^2 is estimated from the definition of seismic moment, $M_0 = \mu(\text{area})(\text{slip})$ (Fig. 6). If we now assume that the slip did not extend southwest of the main frontal thrusts, and that its northern extremity did not extend northeast of the small circle noted by Seeber & Gornitz (1983) and inferred from geodetic evidence to define the northern edge of great ruptures at approximately 18 km depth (Bilham *et al.* 1997), we may infer a down-dip width

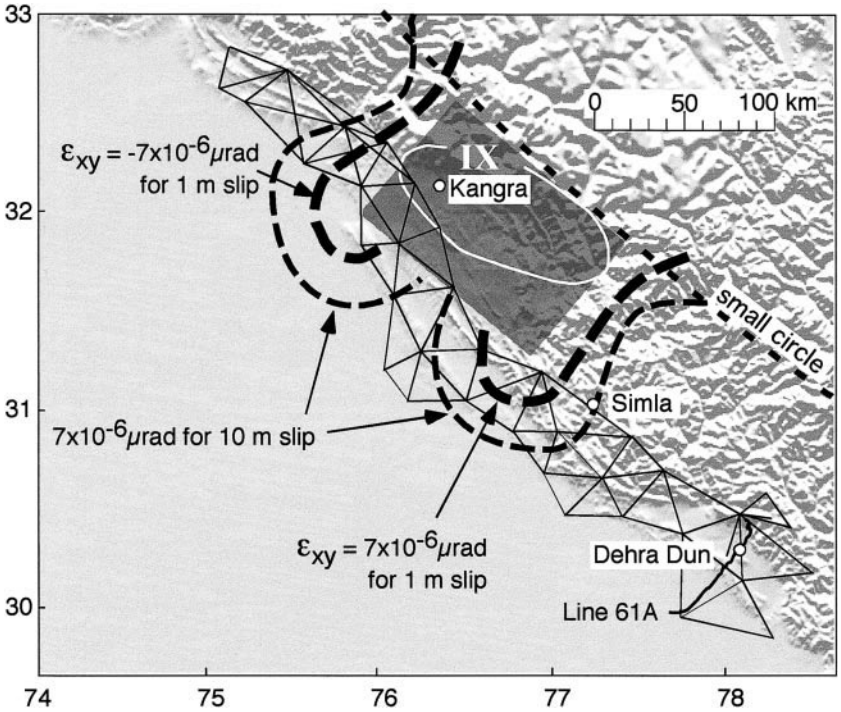

Figure 6. Map of the Kangra epicentral region with triangulation from Walker (1873) and Intensity IX Rossi–Forel intensity contour from Middlemiss (1905). A hypothetical rectangular rupture (dip 3–6°NE, depth 2–4 km, 120 km × 80 km) is centred on this contour equivalent to an $M_s = 7.8$ earthquake. The dashed curves that embrace the southeast and northwest edges of the inferred dislocation indicate $Exy = 7$ μrad shear strain contours for reverse southwest-directed slip of 1 and 10 m. These extend 20–50 km southeast of the rupture zone largely independently of depth or along-arc length. Had triangles along the Himalayan foothills been remeasured, the along-arc length and slip in the Kangra earthquake would have been well constrained. Null deformation at Dehra Dun, however, permits only unreasonably large rupture zones to be excluded. Small circle indicates the locus of moderate earthquakes that follow the southern edge of the Tibetan Plateau (Seeber & Gornitz 1983).

to the 1905 rupture of 60–90 km. For 3 m of slip this corresponds to a fault length of 80–100 km, and for a fault slip of 2 m, this corresponds to a length of 110–170 km. An approximate rupture area is thus 120 km along the arc and 80 km down-dip. We estimate the southeast depth of the rupture to be approximately 5 km using the reconstruction of Powers *et al.* (1998).

The slip vector appropriate for the 1905 earthquake is unknown but the current slip of moderate earthquakes suggests that the current stress direction is normal to the arc (Fig. 1). This corresponds quite well to the observed fall of objects in the zone of highest-intensity shaking recorded by Middlemiss (1905) (Fig. 1). 70 per cent of objects fell towards or away from N45°E in the Kangra region (20 observations). The slip vector is thus assumed to be arc-normal (Fig. 6).

A suite of dislocation models was examined with starting depths of 2–4 km and northeasterly dips of $3° - 9°$. In Fig. 6, the 7 μrad shear strain (εxy) contour is plotted for uniform slip of 1 and 10 m, representing the lower and upper inferred extremes for slip in the Kangra event. The contours were calculated using boundary element coding (King *et al.* 1988; Gomberg & Ellis 1994) appropriate for a dislocation embedded in an elastic half-space (Okada 1985). Shear strain in a uniform slip model is concentrated near the edges of the buried dislocation and its amplitude is largely insensitive to the along-arc length of the dislocation. The southeasterly spatial extent of the shear strain signal is weakly dependent on the down-dip width and the depth of the dislocation, and is linearly dependent on the amount of slip. Thus the shear strain signal provides a good indication of the edges of the rupture, largely independently of the geometrical parameters of depth, dip and length.

From these models it is possible to conclude that the Dehra Dun deformation data provide no useful constraint on the southeast extent or amount of slip during the Kangra rupture other than indicating that it stopped far short of 78°E. More realistic distributions of slip, that is, those that permit tapered slip near the edges of the subsurface dislocation, tend to reduce the compactness of the shear strain field and to reduce its amplitude. The combined effects of tapered slip are to reduce the gradient and peak amplitude of shear strain, which does not alter the principal conclusion that rupture must have stopped far short of Dehra Dun.

An interesting corollary of these models is that the 7 μrad shear-strain contour plotted in Fig. 6, which corresponds to the noise level of remeasurements of Great Trigonometrical Survey angles, suggests that a large number of Survey of India triangles were indeed significantly deformed by the earthquake. Current deformation rates in the region are largely arc-normal contraction (Paul *et al.* 2000), resulting in a deformation field that may be easily extracted from the 1860–2000 strain field. The implication is that the remeasurement of these triangles would even now provide estimates of the slip and along-arc extent of the 1905 earthquake.

SECULAR TILT AT 78°E, 1962–1992

In addition to measurements in 1862, 1904 and 1905, line 61 A was measured in 1927/1928 (Thomas 1930), in 1974–1975 (Rajal *et al.* 1986), and again in 1991 and 1992 (Roy & Hasija 1995). These authors noted that between 1905 and 1974, Dehra Dun rose at approximately 1 mm yr^{-1}, a trend that was reversed in the following 20 years (-3 mm yr^{-1}). The data have been used subsequently to examine aspects of interseismic deformation (Gahalaut & Chander 1992, 1997; Yeats *et al.* 1992), although it is doubtful that benchmark stability is sufficient to defend the details of these analyses. For example, the relative elevation of the east end of the Dehra Dun baseline and the stone marker at Mohabawala vary by more than ± 8 mm, yet they are separated by an arc-normal distance of less than 600 m. The locations of benchmarks in Fig. 5 of Yeats *et al.* (1992) are incorrect.

In contrast to the absence of definitive evidence for localized subsurface aseismic slip near Dehra Dun, the tilt data record a long-wavelength deformation signal that changes systematically over the past century. The time between successive pairs of measurements is used to estimate velocity from the height change data, and the resulting vertical velocity field is plotted holding Saharanpur fixed (Fig. 7a). The 1904 measurement and data north of Dehra Dun for 1905 are ignored in this plot, and the interpretation of data south of Dehra Dun shown in Fig. 5(a) is retained. Least-squares fits to the data are estimated in Fig. 7(a) and their variation as a function of time is plotted in Fig. 7(b).

A feature of Fig. 7(a) is the apparent absence of any clear influence of the 1905 earthquake. Each least-squares fit represents a mean tilt rate, and hence the figure records a change of tilt rate from down to the south in the 19th century to down to the north in the 20th century. This shows itself more clearly in Fig. 7(b) where the tilt rate is seen to vary approximately linearly as a function of time. The absence of any clear disturbance by the 1905 earthquake is clear on this plot.

The change in the tilt rate from 0.07 ± 0.1 µrad yr^{-1} southwards in the 34 yr prior to 1906 to 0.06 ± 0.1 µrad yr^{-1} northwards in the most recent decade (Fig. 7b) corresponds to a secular acceleration of tilt down to the north of 0.0015 ± 0.0004 µrad yr^{-2} and suggests that the current rate of north-down tilt is approaching 0.1 µrad yr^{-1}.

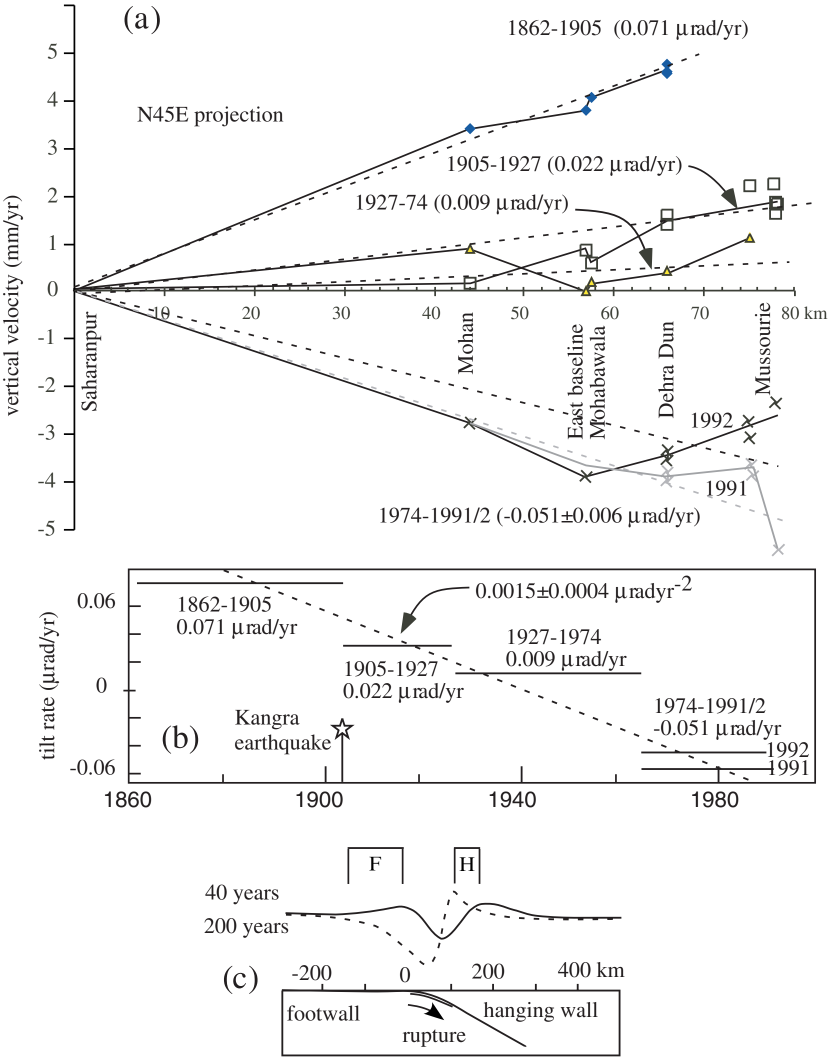

Figure 7. Data from five levelling epochs plotted as arc-normal vertical velocities relative to Saharanpur. A least-squares fit to each epoch (a) yields a tilt rate that shows (b) a progressive tilt acceleration down to the north over the past 130 years. Gahalaut & Chander (1997) noted that the uplift of Mohan is consistent with the region of footwall surface-tilt reversal identified as area F on the surface velocity field (c) (reproduced from Matsu'ura & Sato 1989). The 1905 earthquake has no significant effect on the tilt reversal, although contributions from systematic errors discussed in this article may render data unreliable prior to the 1927 survey. The scale for the vertical surface deformation field in (c) is scaled to co-seismic slip and is omitted from this figure. A second region of retrograde to prograde tilt reversal (H) occurs on the surface on the hangingwall.

A change in the sense of tilt is not anticipated by elastic models of subsurface slip on dislocations of fixed geometry, although it is ubiquitous in the post-seismic setting for viscoelastic models of the earthquake cycle (Pollitz 1997). Gahalaut & Chander (1997) invoked the viscoelastic models of Matsu'ura & Sato (1989) to explain the reversal of vertical displacements of Mohabawala relative to the Ganga Plain to the south. However, the motion of Mohabawala is different if other points are held fixed. For example, relative to Mohan, only 10 km to its south, Mohabawala moves erratically (Fig. 7). The use of spatially averaged levelling data discussed here renders interpretations of long-wavelength viscoelastic fields less sensitive to the problem of these random benchmark motions. In the viscoelastic models of Matsu'ura & Sato (1989), two regions near the tips of the elastic dislocation undergo reversals of tilt in the interseismic period: one in the footwall region fronting a locked thrust and the other near the trailing edge of the dislocation in the hangingwall. The line 61 A levelling data are consistent with $\approx$100-km-long wavelength tilt processes in the footwall (Fig. 7c).

This interpretation assumes that we have treated systematic errors evenly throughout the 130 yr data interval. The estimated errors in these later surveys are much smaller than in the earlier surveys, ostensibly less than 15 mm (a tilt of 0.2 μrad along the entire arc-normal line). Hence the changes in relative elevation in the northernmost 20 km of the line that exceed 61 mm between 1991 and 1992 appear significant. Roy & Hasija (1995) attributed these to deformation associated with the $M_W = 6.8$ Uttarkashi earthquake $\approx$80 km northeast of the line. An inspection of Fig. 7(a) shows that 1991–1992 tilts near Mussourie have the wrong sign, magnitude and spatial wavelength for elastic deformation associated with this event (Gahalaut & Chander 1997). This suggests that the 1991/1992 data are afflicted by systematic height-dependent or slope-dependent errors similar to those discussed for 1904–1905. However, if we assume that the 1991–1992 difference is representative of the magnitude of these uncertainties, the correlation evident in Fig. 7(b) is not substantially altered. Thus the post-1905 tilt changes shown in Fig. 7(b) are apparently larger than estimated artefacts of the levelling process.

The observation of northward tilt acceleration is clearly important for its possible association with deformation prior to a future great earthquake near Dehra Dun, yet attempts to utilize this observation quantitatively face additional difficulties that are outside the scope of the current article. Several essential parameters that are of importance to a realistic viscoelastic model of the earthquake cycle are currently unknown: the date of the last great earthquake and the interval between earthquakes, the geometry and location of the rupture zone and the relevant viscoelastic parameters in the region.

It is of interest to note that the current tilt signal is potentially detectable with newly available geodetic methods with much less difficulty than precise spirit levelling. The inferred current tilt rate of 0.1 μrad yr^{-1} corresponds to a relative vertical displacement between Saharanpur and Mussourie of 7–8 mm yr^{-1}, detectable with annual measurements using continuous GPS or absolute gravity measurements.

CONCLUSIONS

Elevation-change data from the northern end of the Saharanpur to Mussourie levelling line measured before and after the 1905 earthquake show linear correlations between elevation and height change, with distinct and abrupt increments in slope at the junctions between surveys completed at different times. Inferred correlations north of Dehra Dun (i) are highly correlated with elevation, (ii) are uncorrelated with azimuth, and (iii) show inflections between surveys of different epoch, all compelling reasons for suspecting systematic errors. A likely origin for the systematic errors is from temperature- or humidity-induced rod-length changes that escaped detection during regular calibration. I conclude that all or most of the apparent 13.5 cm signal north of Dehra Dun is attributable to systematic error, and that all previous analyses of these data are without foundation (Chander 1988, 1989; Gahalaut & Chander 1992, 1997; Yeats *et al.* 1992; Gahalaut *et al.* 1994).

The data south of Dehra Dun are too sparse to form definitive conclusions concerning systematic errors, and my justification for suggesting that no co-seismic signal exists south of Dehra Dun is circumstantial. The apparent presence of unexplained errors in the levelling data north of Dehra Dun weakens the case for their reality southwards but does not prove it. Assuming that the signal is real, however, leads to two conclusions: that subsurface slip on any local fault cannot exceed 0.3 m; and that the fault that slipped corresponds neither to the Main Frontal Fault nor to the Krol Thrust.

The presence of neither co-seismic horizontal nor vertical deformation near Dehra Dun provides the weak constraint that the 1905 Kangra earthquake, were it caused by southwest-directed slip of 3–5 m, could not have approached closer than 50 km northwest of Dehra Dun. This limits the southeast length of the rupture to approximately 200 km This result is consistent with the recent re-appraisal of the magnitude of the event of $M_S = 7.8 \pm 0.2$ (Ambraseys & Bilham 2000).

Few areas of the world permit us to glimpse the deformation field in the footwall of a convergent plate boundary because they are typically submarine (Zachariasen *et al.* 2000). The slow tilt reversal of the mountain front recorded between 1862 and 1992 is thus of importance in characterizing interseismic behaviour in this unique setting. Measurements of surviving benchmarks subsequent to the 1905 earthquake reveal a progressive tilt acceleration down to the north of 0.0015 ± 0.0004 μrad yr^{-2}, causing an inferred reversal of tilt from down to the south of $\approx$0.1 μrad yr^{-1} in the 19th century to down to the north of $\approx$0.1 μrad yr^{-1} in the 21st century. This >100 km wavelength signal is attributed to viscous adjustment of the mountain front following a previous earthquake of unknown date.

I conclude that thrust faults in the Dehra Dun region have been seismically quiescent for the past century, and for perhaps two or more centuries based on the absence of historic records of previous earthquakes at this longitude. Thus, given a long-term slip rate of 11–17.5 mm yr^{-1} on the main frontal thrust underlying the Siwalik (Wesnousky *et al.* 1999), 2–6 m of slip is currently available for rupture in a future earthquake. Had 20 cm of subsurface slip occurred locally on the Main Frontal Fault in 1905 it would have delayed rupture of the fault by no more than two decades. Because no prediction of the timing of this future earthquake has been proposed, this finding offers no substantial change to the estimate of seismic risk to the region.

Tragically, the absence of horizontal deformation at Dehra Dun in 1905 resulted in the Survey of India's subsequent decision not to measure trigonometrical control points closer to the epicentre after the Kangra earthquake. Moreover, the apparent confirmation that earthquakes caused insignificant displacements of triangulation points, despite clear evidence to the contrary in 1897 (Oldham 1899), influenced the Survey of India decision not to measure points in northern Bihar in 1935 and Assam in 1950 following these great earthquakes (Gulatee 1953). The recovery and re-measurement of Great Trigonometrical Survey markers near Kangra even now, 95 years after the Kangra earthquake, would yet provide constraints on subsurface slip associated with this important earthquake.

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REFERENCES

Ambraseys, N., 2000. Reappraisal of north-Indian earthquakes at the turn of the 20th century, *Current Sci.,* **79,** 1237–1250.

Ambraseys, N. & Bilham, R., 2000. A note on the Kangra earthquake of 4 April 1905, *Current Sci.,* **79,** 46–50.

Angus-Leppan, P.V., 1984. Refraction in Geodetic levelling, in *Geodetic Refraction: Effects of Electromagnetic Wave Propagation Through the Atmosphere,* pp. 213, ed. Brunner, F.K., Springer-Verlag, Berlin.

Baduwi, M., 1905. *In Which the Events of the 4 April 1905 Earthquake in North India and all of India and Other Countries are Described, Simla 1905,* University of Colorado (in Urdu).

Bilham, R. & England, P., 2001. Plateau pop-up in the 1987 Assam earthquake, *Nature,* in press.

Bilham, R. & Gaur, V.K., 2000. Geodetic contribution to seismotectonic studies in India, *Current Sci.,* **79,** 1259–1269.

Bilham, R., Larson, K., Freymueller, J. & Project Idylhim members, 1997. GPS measurements of present-day convergence across the Nepal Himalaya, *Nature,* **386,** 61–64.

Bomford, G., 1928. Three sources of error in precise levelling, *Surv. India Prof. Paper,* **22**.

Bomford, G., 1980. *Geodesy,* 4th edn, Clarendon Press, Oxford.

Burrard, S.G., 1906. Geodesy, in *Annual Rept Board of Scientific Advice for India for the Year 1904–05,* pp. 42–52, Government Central Press, Calcutta.

Burrard, S.G., 1909. *Account of the Operations of the Great Trigonometrical Survey of India,* North East Longitudinal Series, Synoptical Volume **XXXVB,** Survey of India, Dehra Dun.

Burrard, S.G., 1910a. *Account of the Operations of the Great Trigonometrical Survey of India, Descriptions of Heights of Bench Marks of the Northern Lines of Levelling,* **XIX,** Survey of India, Dehra Dun.

Burrard, S.G., 1910b. Memorandum on the steps taken in 1905–10 to enable movements of the Earth's crust to be detected, in *Account of the Operations of the Great Trigonometrical Survey of India,* Appendix No. 3, *Descriptions of Heights of Bench Marks of the Northern Lines of Levelling,* **XIX,** Survey of India, Dehra Dun.

Burrard, S.G., 1910c. *Account of the Operations of the Great Trigonometrical Survey of India, Descriptions of Heights of Bench Marks of the Northern Lines of Levelling,* **XIXB,** Survey of India, Dehra Dun.

Burrard, S.G., 1915. *1:63360 Map of United Provinces 53 J/3 (Dehra Dun),* 1st edn, Survey of India, Dehra Dun.

Chander, R., 1988. Interpretation of observed ground level changes due to the Kangra earthquake, northwest Himalaya, *Tectonophysics,* **149,** 289–298.

Chander, R., 1989. On applying the concept of rupture propagation to deduce the location of the 1905 Kangra earthquake epicenter, *J. geol. Soc. India,* **33,** 150–158.

DeGraaff Hunter, J., 1910. Dynamic and orthometric corrections to the Himalayan levelling lines and circuits; and a consideration of the order of magnitude of possible refraction errors, in *Account of the Operations of the Great Trigonometrical Survey of India,* Appendix No. 4, *Descriptions of Heights of Bench Marks of the Northern Lines of Levelling,* **IXX,** ed. Burrard, S.G., Survey of India, Dehra Dun.

Eccles, J., 1907. Geodesy, in *Ann. Rept Board of Scientific Advice for India for the Year 1905–06,* pp. 36–38, Government Central Press, Calcutta.

Eccles, J., 1908. Geodesy, in *Ann. Rept Board of Scientific Advice for India for the Year 1906–07,* pp. 45–54, Government Central Press, Calcutta..

Gahalaut, V.K. & Chander, R., 1992. On the active tectonics of the Dehra Dun region from observations of ground elevation changes, *J. geol. Soc. India,* **39,** 61–68.

Gahalaut, V.K. & Chander, R., 1997. Evidence for an earthquake cycle in the NW outer Himalaya near 78°E longitude from precision levelling operations, *Geophys. Res. Lett.,* **24,** 225–228.

Gahalaut, V.K., Gupta, P.K., Chander, R. & Gaur, V.K., 1994. Minimum norm inversion of observed ground elevation changes for slips on the causative fault during the 1905 Kangra earthquake, *Proc. Indian Acad. Sci. (Earth Planet. Sci.),* **103,** 401–411.

Gomberg, J. & Ellis, M., 1994. Topography and tectonics of the central New Madrid seismic zone: results of numerical experiments using a three-dimensional boundary-element program, *J. geophys. Res.,* **99,** 20 299–20 310.

Gulatee, B.L., 1949. Levelling, *Survey of India Tech. Rept, Part 3, 1948–1949,* Survey of India Press, Dehra Dun.

Gulatee, B.L., 1953. Geodetic and geophysical aspects of the earthquakes in Assam, 16–25, in *A Compilation of Papers on the Assam Earthquake of August 15, 1950,* ed. Ramachandra Rao, M.B., *Central Board Geophysics Publication,* **1,** 112.

Hanks, T.C. & Kanamori, H., 1994. A moment magnitude scale, *J. geophys. Res.,* **84,** 2348–2350.

Hennesey, J.B.N., 1875. Account of the operations of the great trigonometrical survey of India, *Principal Triangulation of the Great Arc Meridional Series,* **V,** Survey of India, Calcutta.

Holdahl, S., 1981. A model for temperature stratification for correction of levelling refraction, *Bull. Geod.,* **55,** 231–244.

King, G.C.P., Stein, R.S. & Rundle, J.B., 1988. The growth of geological structures by repeated earthquakes, 1, Conceptual framework, *J. geophys. Res.,* **93,** 13 307–13 318.

Lallemand, M.Ch., 1896. Note sur l'erreur de refraction dans le nivellment geometrique, *Comptes Rendues des Seances de la Commission Permanente de L'association Geodesiques Internationale, Lausanne,* 247–276.

Lallemand, M.Ch., 1912. General report on levelling, *Proc. Int. Assoc. Geodesy,* Annex, B, VIII, C, Hamburg.

Levelling of Precision in India, 1912. *Heights of Bench Marks in Sheet 53,* Survey of India, Dehra Dun.

Levelling of Precision in India, 1920. *Heights of Bench Marks in Sheet 53,* 2nd edn, Corrected 1919, Survey of India, Dehra Dun.

Matsu'ura, M. & Sato, T., 1989. A dislocation model for the earthquake cycle at convergent plate boundaries, *Geophys. J. Int.,* **96,** 23–32.

Middlemiss, C.S., 1905. Preliminary account of the Kangra Earthquake of 4th April 1905, *Records geol. Soc. India.,* **32,** 258–294.

Middlemiss, C.S., 1910. The Kangra Earthquake of 4 April 1905, *Mem. geol. Surv. India,* **38,** 405.

Molnar, P., 1987. The distribution of intensity associated with the 1905 Kangra earthquake and bounds on the extent of rupture, *J. geol. Soc. India,* **29,** 221–229.

Molnar, P. & Pandey, M.R., 1989. Rupture zones of great earthquakes in the Himalaya region, *Proc. Indian Acad. Sci. (Earth planet. Sci.),* **98,** 61–70.

Ni, J. & Barazangi, M., 1984. Seismotectonics of the Himalayan collision zone: geometry of the underthrusting Indian Plate beneath the Himalaya, *J. geophys. Res.,* **89,** 1147–1163.

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space, *Bull. seism. Soc. Am.,* **75,** 1135–1154.

Oldham, R.D., 1899. Report on the Earthquake of 12 June 1897, *Mem. geol. Surv. India,* **29,** Calcutta.

Paul, J. *et al.*, 2000. Active deformation across India, *Geophys. Res. Lett.,* in press.

Pollitz, F.F., 1997. Gravitational viscoelastic postseismic relaxation on a layered spherical Earth, *J. geophys. Res.,* **102,** 17 921–17 941.

Powers, P.M., Lillie, R.J. & Yeats, R.S., 1998. Structure and shortening of the Kangra and Dehra Dun reentrants, Sub-Himalaya, India, *Geol. Soc. Am. Bull.,* **110,** 1010–1027.

Raiverman, V., Kunte, S.V. & Mukherjee, A., 1983. Basin geometry, Cenozoic sedimentation, and hydrocarbon prospects in northwestern Himalaya and Indo gangetic plains, *Petrol. Asia J.,* **6,** 67–92.

Rajal, B.S., Virdi, N.S. & Hasija, N.L., 1986. Recent crustal uplift in the Doon Valley, *Proc. Int. Symp. on Neotectonics in S Asia, Dehra Dun, India,* **30,** 146–159.

Rao, Y.S.N., Rahman, A.A. & Rao, D.P., 1974. On the structure of the Siwalik range between rivers Yamuna and Ganga, *Himalayan Geol.,* **4,** 137–150.

Roy, B.C. & Hasija, N.L., 1995. Coseismic and postseismic crustal deformation in the Doon Valley and determined from repeat levelling, *Mem. geol. Soc. India,* **30,** 173–178.

Ryder, C.H., 1919. *1:126,720 map of Punjab,* 53 (1st edn), Survey of India, Dehra Dun.

Seeber, L. & Armbruster, J., 1981. Great detachment earthquakes along the Himalayan Arc and long-term forecasting, in *Earthquake Prediction—an International Review,* eds Simpson, D.W. & Richards, P.G., Maurice Ewing Series, *Am. Geophys. Un.,* **4,** 259–277.

Seeber, L. & Gornitz, V., 1983. River profiles along the Himalayan Arc as indicators of active tectonics, *Tectonophysics,* **92,** 335–367.

Stein, R.S., 1981. Discrimination of tectonic displacement from slope-dependent errors in geodetic levelling from southern California, in *Earthquake Prediction: an International Review,* eds Simpson, D.W. & Richards, P.G., Maurice Ewing Series, *Am. geophys. Un.,* **4,** 441–456,.

Thomas, R.H., 1929. *Survey of India Geodetic Report 1927–1928,* **4,** 102–115.

Thomas, R.H., 1930. *Survey of India Geodetic Report, 1928–1929,* **5,** 94–99.

Walker, J.T., 1863. *Tables of Heights in Sind, the Punjab, NW Provinces and Central India Determined by the Great Trigonometrical Survey of India Trigonometrically and by Spirit Levelling Operations to May 1862, Ambala to Dehra Dun,* pp. 112–113, Public Works Department Press, Calcutta.

Walker, J.T., 1873. *Account of the Operations of the Great Trigonometrical Survey of India,* Principal Triangulation III, 1879, Survey of India, Calcutta.

Wells, D.L. & Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. seism. Soc. Am.,* **84,** 974–1002.

Wesnousky, S.G., Kumar, S., Mohindra, R. & Thakur, V.C., 1999. Holocene slip rate of the Himalayan Frontal Thrust of India, observations near Dehra Dun, *Tectonics,* **18,** 967–976.

Wheeler, E.O., 1942. *1:63.360 Map of Punjab States United Provinces,* 53/J., 5th edn, Survey of India, Dehra Dun.

Yeats, R.S., Nakata, T., Faraj, A., Fort, M., Mirza, M.A., Pandey, M.R. & Stein, R.S., 1992. The Himalayan frontal fault system, *Ann. Tect.,* **6,** 85–98.

Zachariasen, J., Sieh, K., Taylor, F.W. & Hantoro, W.S., 2000. Modern vertical deformation above the Sumatran subduction zone: paleogeodetic insights from coral microatolls, *Bull. seism. Soc. Am.,* **90,** 897–913.