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Contemporary tectonics of the Himalayan frontal fault system—folds, blind thrusts and the 1905 Kangra earthquake: Discussion

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INTRODUCTION

Yeats & Lillie (1991) have recently proposed a source model for the 1905 Kangra earthquake, NW Himalaya (Fig. 1). We discuss here a few points not adequately covered in the review by Yeats and Lillie and remark on some other points, because source models for this earthquake have important implications for estimating the seismic risk to the 260 m high, earth- and rock-fill Tehri dam across the Bhagirathi River in the Garhwal Lesser Himalaya (T in Fig. 1).

According to Yeats & Lillie (1991), the 1905 Kangra earthquake is "the biggest known earthquake on a blind thrust expressed at the surface as a fold". In common with the models proposed by Seeber & Armbruster (1981), Molnar (1987), Chander (1988) and Gahalaut & Chander (1992), Yeats and Lillie ascribe the origin of the 1905 Kangra earthquake to slip on a thrust fault.

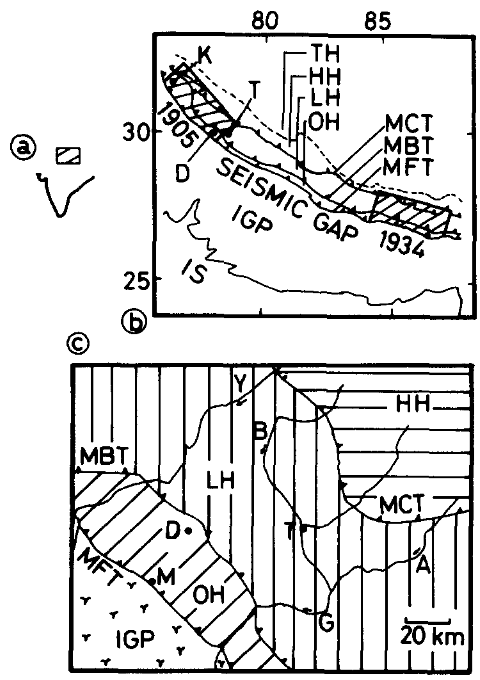

Fig. 1. (a) General location map showing the region of India under discussion. (b) Regions of the NW and Nepal Himalaya. Shaded areas indicate rupture zones of great earthquakes of 1905 and 1934 along the Himalayan seismic belt. The segment of the Himalaya between these zones is a seismic gap. TH, HH, LH and OH indicate the Tethys, Higher, Lesser and Outer Himalaya, respectively. MCT, MBT and MFT indicate the Main Central, Main Boundary and Main Frontal thrusts, respectively. IGP: Indo-Gangetic plains; IS: Indian shield; D: Dehra Dun; K: Kangra and T: Tehri. Background geology is after Gansser (1964). (c) Simplified map of the geology of the Garhwal Himalaya (after Jain 1987). A, B, G and Y indicate the Alakhnanda, Bhagirathi, Ganges and Yamuna rivers, respectively. M marks Mohand. Other abbreviations are as in (b).

BLIND THRUST

Two apparently contradictory observations in connection with the 1905 Kangra earthquake are as follows. First, there is evidence of neotectonic activity on faults in the Outer Himalaya (e.g. Krishnawamy *et al.* 1970, Nakata *et al.* 1990). Second, Middlemiss (1910) reported little evidence of surface faulting during the 1905 Kangra earthquake. Yeats & Lillie (1991) have taken the latter observation as support for their idea that this earthquake occurred on a blind or concealed thrust.

Chander (1988) analysed quantitatively the geodetic data (Rajal *et al.* 1986) that was discussed by Yeats and Lillie qualitatively. Chander also concluded that the 1905 Kangra earthquake occurred on a concealed fault such that the rupture zone (in the sense of Kelleher 1972) of the earthquake lay mainly in the Lesser Himalaya but extended southwestward up to the vicinity of Dehra Dun in the Outer Himalaya (Fig. 1b). Brune (personal communication January 1989 and December 1990) while commenting upon this conclusion suggested that a thrust fault which could be the seat of such a great earthquake as the 1905 Kangra earthquake could not remain concealed and should outcrop because the 1905 earthquake was merely the latest in a long series of earlier great earthquakes on that fault.

There is a need to distinguish between the causative rupture and causative fault of the 1905 earthquake. Oldham (1899) pointed out almost nine decades ago that "it is quite conceivable that (during an earthquake) movement may have taken place along a pre-existent plane of fracture whose whole extent is much larger than the portion over which movement took place". In other words, the 1905 rupture could be concealed while the thrust fault in which it occurred could have an outcrop.

Gahalaut & Chander (1992) re-analysed the geodetic data in an effort to resolve the question. Whereas Chander (1988) had considered a single planar rupture as the cause of the 1905 Kangra earthquake, Gahalaut &

Chander (1992) considered multiple planar ruptures joined end to end to simulate different cross-sectional shapes of the ruptured section of the causative fault. They considered among others a model in which a simple listric thrust had an outcrop and the ruptured section extended up to the surface. They also considered several models of blind thrusts with large nearly flat segments separated by one or more short, steep ramps. The ruptured sections in these cases were necessarily concealed. It was concluded that the rupture zone of the 1905 Kangra earthquake could have extended up to the southwestern limit of the Outer Himalaya. Whether the ruptured segment of the causative fault outcropped near Mohand (Fig. 1c) or was concealed at a depth of up to 3 km beneath Mohand could not be resolved objectively from the available geodetic data.

Thus, if the possibility of surface breaks during the 1905 Kangra earthquake is ruled out, then the available data require only that the rupture should be taken to be concealed.

The remaining slim chance of shedding light on this question is through palaeoseismicity investigations along the outcrop of the Main Frontal Thrust northwest of Mohand (Fig. 1c).

UPLIFT OF THE MOHAND ANTICLINE

The lower part of fig. 9 in Yeats & Lillie (1991) shows a NE–SW geological cross-section through the Outer and Lesser Himalaya in the Dehra Dun region, showing a large asymmetric syncline below the Dehra Dun valley. Much of the section is taken up by the gentler, NE-dipping limb of the syncline. The so called Mohand anticline appears in the section as a small up-dip flattening of sub-surface layering of this limb. The upper part of the same figure is a display of measured ground uplift along the Mohand–Dehra Dun highway during the 1905 Kangra earthquake. Maximum observed uplift was 13.5 cm at a bench mark in Dehra Dun. Uplift was only 10 cm at the Mohand bench mark. Thus it is surprising that Yeats & Lillie (1991) pay less attention to the greater uplift of the Dehra Dun syncline than to the conjectural and relatively minor Mohand anticline. This anticline does not even continue over the entire length of the seriously affected region.

In my opinion, the observed uplift of the surface, including that above the Mohand anticline, is a consequence and not cause of the 1905 Kangra earthquake.

EXTENT OF RUPTURE ZONE NORMAL TO HIMALAYAN STRIKE

The analysis by Yeats & Lillie (1991) deals exclusively with the phenomena near the up-dip end of the buried causative rupture of the 1905 Kangra earthquake. Yet they emphasize the earthquake generation potential of the Outer Himalaya. According to Seeber & Armbruster (1981) and Molnar (1987) as well as on the basis of analysis of geodetic data by Chander (1988) and Gahalaut & Chander (1992), the 1905 rupture extended widthwise to the Main Central Thrust. The rupture zones of the 1934 Bihar-Nepal (Fig. 1c) and 1950 Assam earthquakes similarly extended to the Main Central Thrust (Seeber & Armbruster 1981, Molnar & Pandey 1989). In other words, there is evidence and opinion that rupture zones of great Himalayan earthquakes span both the Outer and Lesser Himalaya (Fig. 1b).

Note added, following the October 1991 *earthquake*
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The rupture zone area in the case of the earthquake of 19 October 1991, with an estimated magnitude of 7.1 and seismic moment of 1.1×10^{19} Nm (U.S. Geological Survey), was approximately 2% of that for the 1905 Kangra earthquake. This small rupture zone coincided with the belt of moderate and small earthquakes astride the Main Central Thrust (Khattri *et al.* 1989) northeast of Dehra Dun (Fig. 1b). This is further demonstration that the seismogenic zone in the Dehra Dun region is in the northern parts of the Garhwal Lesser Himalaya and not, as suggested by Yeats & Lillie (1991), in the Garhwal Outer Himalaya. (End of note.)

IMPLICATIONS FOR THE TEHRI DAM

Estimates of seismic risk to the Tehri dam, located about 50 km east of Dehra Dun in the Garhwal Lesser Himalaya, are a matter of serious and ongoing debate (e.g. Pearce 1991). The dam site (T in Fig. 1) is situated near the boundary between the rupture zone of the 1905 Kangra earthquake and a nearly 700 km long seismic gap along the Himalayan seismic belt (Fig. 1b). The last great earthquake to occur anywhere in this gap was probably in 1833. Thus a great earthquake may possibly affect the Tehri dam within its useful life.

It appears that at present the Tehri dam is designed for a peak ground acceleration of 0.22 **g** (Pearce 1991), where **g** is acceleration due to gravity. However, recent expert opinion, especially outside India (Pearce 1991), is that the dam could be exposed to peak acceleration 10 times higher. Yeats and Lillie's comments on the earthquake potential of the Outer Himalaya could be construed as justification for lower estimates of peak ground acceleration. This has to be countered because, for a project with potential for massive and swift destruction in the event of failure, it is desirable to be conservative by overestimating rather then underestimating seismic risk. For the Tehri dam site, the nearest active fault, for the purposes of estimating peak ground acceleration and other parameters of seismic risk, is not the Main Frontal Thrust about 70 km away horizontally to the southwest but the Himalayan detachment or décollement only about 15 km away vertically down (Seeber & Armbruster 1981, Ni & Barazangi 1984, Chander 1988, Khattri *et al.* 1989, Gahalaut & Chander 1992).

CONCLUSIONS

The following conclusions may be drawn.

(1) Yeats & Lillie's (1991) hypothesis is similar to earlier hypotheses in that the origin of the 1905 Kangra earthquake is ascribed to slip on a thrust fault.

(2) Whether the ruptured section of the causative fault was concealed or had an outcrop cannot be decided objectively from the geodetic data. On the strength of Middlemiss's (1910) report that no major surface break occurred during the 1905 Kangra earthquake, we may conclude at some risk that the ruptured section was concealed entirely. Yeats and Lillie's suggestion that the causative fault was also concealed or blind is neither inconsistent with the observations nor specifically required by them.

(3) Since Yeats & Lillie (1991) admit that uplift of the Mohand anticline was a consequence of slip on the causative thrust fault, their reference to this anticline in the model is a relatively minor detail and an avoidable complication.

(4) Yeats & Lillie's (1991) model of the Kangra earthquake source should not be a basis to scale down estimates of the seismic risk to the Tehri dam.

REFERENCES

Chander, R. 1988. Interpretation of observed ground level changes due to the 1905 Kangra earthquake, NW Himalaya. *Tectonophysics* **149**, 289–298.

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**, 61–69.

Gansser, A. 1964. *Geology of the Himalayas*. Interscience, New York.

Jain, A. K. 1987. Kinematics of transverse lineaments, regional tectonics and Holocene stress field in the Garhwal Himalaya. *J. geol. Soc. India* **30**, 169–186.

Kelleher, J. 1972. Rupture zones of large south American earthquakes and some predictions. *J. geophys. Res.* **77**, 2087–2103.

Khattri, K. N., Chander, R., Gaur, V. K., Sarkar, I. & Kumar, S. 1989. New seismological results on tectonics of the Garhwal Himalaya. *Proc. Indian Acad, Sci. (EPS)* **98**, 91–109.

Krishnaswamy, V. S., Jalote, S. P. & Shome, S. K. 1970. Recent crustal movements in NW Himalaya and the Gangetic foredeep and related patterns of seismicity. *Proc. 4th Symp. Earthquake Engineering*, University of Roorkee, Roorkee. Sarita Prakashan, Meerut.

Middlemiss, C. S. 1910. The Kangra earthquake of 4 April, 1905. *Mem. geol. surv. India* **38**, 1–409.

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

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

Nakata, T., Otsuki, K. & Khan, S. H. 1990. Active faults, stress field and plate motion along Indo-Eurasian plate boundary. *Tectonophysics* **181**, 83–95.

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.

Oldham, R. D. 1899. Report on the great earthquake of 12 June, 1897. *Mem. geol. surv. India* **29**, 1–379.

Pearce, F. 1991. The dam that should not be built. *New Scientist* 26 Jan., 37–41.

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

Seeber, L. & Armbruster, J. G. 1981. Great detachment earthquakes along the Himalayan arc and long term forecasting. In: *Earthquake Prediction: An International Review*. American Geophysics Union, Washington, DC, 259–277.

Yeats, R. S. & Lillie, R. J. 1991. Contemporary tectonics of the Himalayan frontal fault system: folds, blind thrusts and the 1905 Kangra earthquake. *J. Struct. Geol.* **13**, 215–225.