volatilization from black shale materials when processed in the presence of oxygen. They have also found that in Au-bearing black shale ores, PGE are present as organometallic compounds and have suggested the use of selected fluoroxidants for the total and quantitative oxidation of all the Au and PGE, for simultaneous destruction of the organic matrix and to avoid the loss of Au and PGE during open-system digestion procedures. Such specificity of black shales in relation to methods of PGE and Au analyses should be taken into account in the estimation of their PGE–Au potential, as well as in creation of extraction technologies. More work has to be carried out before suggesting a better analytical method for such type of materials.

1. Reimann, P. de C., *Chemical Elements in the Environment*, Springer, Berlin, 1998, pp. 48–51.
2. Jiang Shao-Yong, Jing-Hong Yang, Hong Fei Ling, Yong-Quan Chen, Hong-Zhen Feng, Kui Dong Zhao and Pei, Ni, *Palaeogeogr., Palaeoclimatol., Palaeoecol*., 2007, **254**, 217–228.
3. Pasava J., *Ore Geol. Rev*., 1993, **8**, 425–445.
4. Khanchuk, A. I., Plusnina, L. P., Molchanov, V. P. and Medvedev, E. I., *Tikhookeanskaya Geol*., 2007, **26**(1), 70.
5. Khanchuk, A. I., Molchanov, V. P., Medvedev, E. I. and Plusnina, L. P., In *Nanogeochemistry of Gold*. In Proceedings of the Symposium (Dal'nauka, Vladivostok), 2008, pp. 31–35 (in Russian).
6. Yu, G. and Karabtsov, A., In *Nanogeochemistry of Gold*. In Proceedings of the Symposium (Dal'nauka, Vladivostok), 2008, pp. 122–129 (in Russian).
7. Distler, V. V. *et al*., *Geol. Ore Deposits*, 1996, **38**, 413 (*Geol. Rudn. Mestor-ozhd*, 1996, **38**, 467).
8. Razvozzhaeva, E. A., Spiridonov, A. M. and Tsykhanskii, V. D., *Geol. Geofiz*., 2002, **43**, 286.
9. Balaram, V., Mathur, R., Banakar, V. K., Hein, J. R., Rao, C. R. M., Rao, T. G. and Dasaram, B., *Indian J. Mar. Sci*., 2006, **35**(1), 7–16.
10. Balaram, V. *et al*., *At. Spectrosc*., 1997, **18**, 17–22.
11. Gurskaya, L. I., In *Platinum Mineralization of the Black-Shale Type and Criteria of its Prediction*, VSEGEI, St Petersburg, 2000 (in Russian).
12. Varshall, G. M., Velyukhanova, T. K. and Korochantsev, A. V., *Geokhimiya*, 1995, **8**, 1191.
13. Mitkin, V. N., Galizky, A. A. and Korda, T. M., *Geostand. Newsl. J. Geostand. Geoanal*., 2000, **24**, 227–240.

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Seismic vulnerability and risk in the Himalayan township of Mussoorie, Uttarakhand, India

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Rapid visual screening technique has been resorted to for assessing seismic vulnerability and risk in the Himalayan township of Mussoorie that falls in Zone IV of the Earthquake Zoning Map of India. Damage during an earthquake in this zone is expected to reach MSK intensity VIII. A total of 3344 structures in 11 residential wards of the town were surveyed in the field. Data collected in the field were analysed under GIS environment which suggests that a total of 615 (18%) buildings show high probability of Grade 5 damage and very high probability of Grade 4 damage class. The economic loss likely to be incurred is estimated to be of the order Rs 238.85 crore in the township of Mussoorie alone. Modest estimates suggest that 369 persons might sustain grievous injuries in this event. The study highlights the fact that some of the lifeline buildings are under severe threat and are required to be retrofitted or replaced on priority basis.

Keywords: Damage grade, rapid visual screening, risk, seismicity, vulnerability.

SUBDUCTION of the Indian plate beneath the Eurasian plate has resulted in the consumption of the intervening oceanic plate and eventual collision of the alien land masses. This event caused deformation, upliftment, metamorphism and shearing of the sediments deposited in the hitherto intervening ocean basin together with the rock mass in the vicinity of the collision front. This resulted in the evolution of the Himalayan mountain chain. Since the collision around 55 Ma, India has been underthrusting at a rate of 45–50 mm/yr (refs 1 and 2). GPS measurements indicate that India is moving northeast at a convergence rate of 55 mm/yr, of which 18–22 mm/yr is accommodated within the Himalayas[3] and the remaining convergence is taken up further north in Tibet and Asia[4,5]. The ongoing northward convergence of India produces active deformation in the Himalayas, Tibet and adjoining areas and is responsible for seismic activity in the entire region.

The Himalayan mountain arc together with the adjoining Shillong plateau and western Assam has witnessed four great earthquakes ($M_w \geq 8.0$) in the previous 110 years, i.e. 1897 western Assam earthquake, 1905 Kangra

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earthquake, 1934 Bihar–Nepal earthquake and 1950 eastern Assam (Arunachal) earthquake. Around 18,000 persons were killed in the 1905 Kangra earthquake[6]. Arya[7,8] suggests that around 80,000 persons might be killed if a similar earthquake occurs during daytime. Authenticity of this projection has been verified by the toll of the 2005 Muzaffarabad earthquake and clearly reflects increasing seismic vulnerability of the region due to growth in population and infrastructure.

The entire Himalayan terrain falls in Zones IV and V of the Earthquake Zoning Map of India[9] and is routinely subjected to earthquakes. Uttarakhand has witnessed two moderate magnitude earthquakes in the recent past (Uttarkashi earthquake of 1991 and Chamoli earthquake of 1999). The losses in these events were estimated to be Rs 243 crore and Rs 339 crore respectively. The state is however located in the seismic gap of the 1935 and 1905 great earthquakes. This enhances seismic risk in the region.

Seismic risk is a direct function of the state of the built environment or vulnerability of the building stock. Assessment of the vulnerability of the built environment is therefore important for undertaking any seismic risk reduction exercise. This is all the more important in the urban areas that have a concentration of both infrastructure and population. Such an exercise is intended to pave the way for effective mitigative planning through appropriate structural and non-structural measures.

The present study focuses on the seismic vulnerability and risk evaluation of the Himalayan township of Mussoorie. With fairly good road, train and air connectivity and being located in close vicinity to the state capital (Dehradun), Mussoorie is a famous Himalayan tourist destination situated in the Lesser Himalayas (Figure 1). Mussoorie is located in close proximity to the Main Boundary Thrust (MBT) that is a north–northeast dipping thrust along which the Lesser Himalayan rocks are thrust over the Siwaliks. It falls in Zone IV of the Earthquake Zoning Map of India[9] and has a population of 26,069 (ref. 10). The population of the town is however highly variable and during the peak tourist season (from April/May to September/October) the same witnesses manifold increase. The built environment in Mussoorie is particularly old and the large influx of tourists to the township warrants seismic vulnerability assessment and adoption of suitable mitigative measures for reducing human miseries and toll in the event of an earthquake in the area.

Detailed seismic vulnerability evaluation is a technically complex and expensive procedure and can only be performed on a limited number of buildings. It is therefore important to use simpler procedures that help in rapid evaluation of the vulnerability profile of different types of building. More complex evaluation procedures can thus be limited to the most critical buildings[11].

Rapid Visual Screening (RVS) is one such cost-effective tool for identifying highly vulnerable structures that can subsequently be surveyed in detail for appropriate mitigative action. RVS was first proposed in the US in 1988 and was further modified in 2002 to incorporate latest technological advancements and lessons from earthquake disasters in the 1990s. Though originally developed for typical constructions in the US, this procedure has been widely used in many other countries after suitable modifications. The most important feature of this procedure is that it permits vulnerability assessment based on ‘walking around’ the building by a trained evaluator. The evaluation procedure and system is compatible with

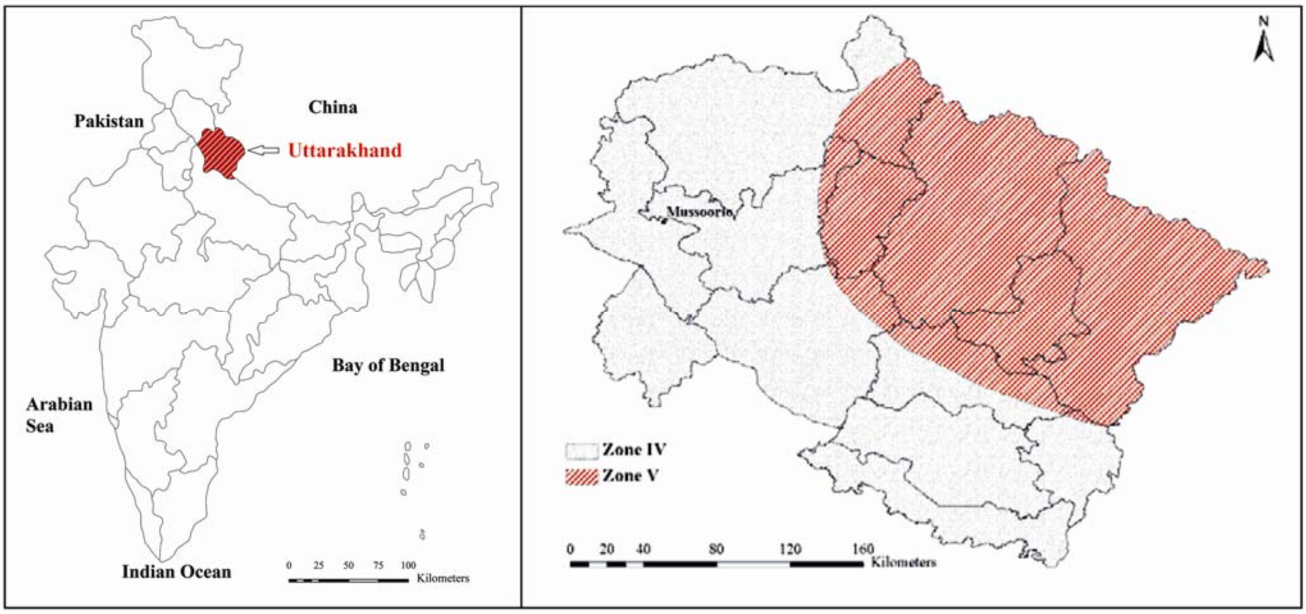

Figure 1. Location map of the study area. (Left) Uttarakhand. (Right) Earthquake Zoning Map of Uttarakhand and the position of Mussoorie.

GIS-based city database and also permits the use of collected building information for a variety of other planning and mitigation purposes.

RVS method is designed to be implemented without performing any structural calculations and utilizes a scoring system that requires the evaluator to identify the primary structural lateral load-resisting system together with the building attributes that modify the seismic performance expected for this lateral load-resisting system. The inspection, data collection and decision-making process typically take place at the building site, and it is expected to take around 30 min for each building. For the actual data collection using the RVS methodology, a modified version of the FEMA-154/ATC-21 based data collection sheet was used[12]. Taking note of the seasonal variation in occupancy, provision was made to account for peak and lean occupancy of the buildings. In order to take the relief of the area into account broad estimation of the slope into three categories (< 15°, 15°–30° and > 30°) was also included. Parameters like building identification number, ward number, owner's name, roof type, accessibility and comment section were added for a broader information spectrum and to make the analysis easier.

When exposed to a particular earthquake intensity, different building types experience different levels of damage depending on their inherent characteristics. Damageability is defined as the level of damage that is likely to be incurred in a seismic event. Sinha and Goyal[11] have developed a methodology of correlating RVS scores of the surveyed structures in different seismic zones with probable seismic losses utilizing the damage grades provided by European Macroseismic Scale[13] (EMS-98). They have suggested only three hazard zones for RVS studies, corresponding to low (Zone II), moderate (Zone III) and high seismic risk (Zones IV and V), as more precise categorization between Zones IV and V is not envisaged to enable better assessment of structural vulnerability using RVS procedure due to the influence of a large number of other factors on the building performance in intense ground-shaking conditions. The same methodology has been used in the present study to assess the likely seismogenic damages.

EMS-98 recommends five damage grades[13]. Among these, Grades 4 and 5 are important for vulnerability and risk assessment as these have the potential of threatening the lives of the occupants and also causing damage to the contents therein. Grade 4 or very heavy damage grade denotes heavy structural damage and very heavy non-structural damage and is characterized by serious failure of walls (gaps in walls) and partial structural failure of roofs and floors. Grade 5 or destruction denotes very heavy structural damage and is characterized by total or near total collapse of the structure.

For translating the seismogenic losses into economic value the cost of reconstruction of the structures falling in high probability of Grade 5 damage and very high probability of Grade 4 damage has been accounted for together with average value of the contents therein. Both the built area of the structures and the number of floors therein have been accounted for while determining the cost of reconstruction and the building usage has been taken into account while calculating the value of the contents therein.

Different buildings have different types of content and therefore in the present exercise economic worth of the contents likely to be lost in a seismic event is estimated to be a function of the replacement value of the structures. For residential buildings the content value is taken as 50% of the replacement cost, whereas for schools, commercial establishments (shops), mixed (shops and residential), hotels, hospitals, religious and office buildings the economic worth of the contents likely to be lost is taken to be 25%, 200%, 100%, 25%, 400%, 10% and 50% of the cost of replacement of the structures respectively.

IKONOS imagery was used for mapping the structures and the database was prepared using ARC INFO GIS software that was also used for analysis and data correlation.

A total of 3344 buildings falling in 11 residential wards of Mussoorie township were surveyed using modified FEMA-154/ATC-21 data collection form[12]. Among these, the oldest was constructed in 1836 and only 282 were constructed in the pre-1900 period, whereas 913 were constructed during 1901–50, 962 in 1951–84 and 881 in the post-1984 periods (Figure 2). Most surveyed structures were observed to be low-rise; 1135 being single storeyed and 1957 being double or triple storeyed (Figure 2). As many as 30 buildings, however, were observed to be more than five-storeyed. Construction (94%) was observed to be unconfined rubble masonry (URM), mostly stone and brick masonry with slate/CGI roofing. The built environment of the town can thus be classified as being non-engineered.

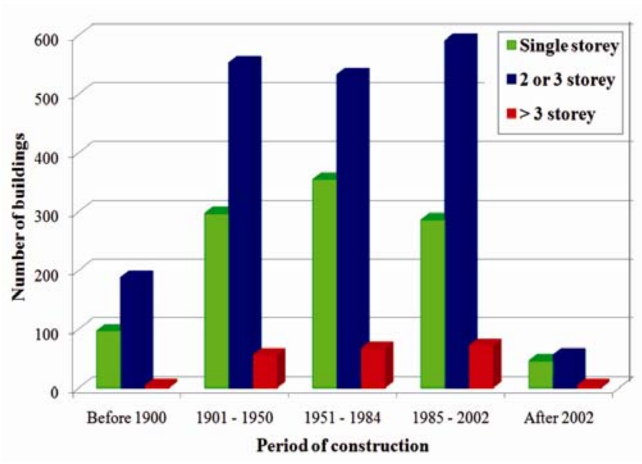

Figure 2. Changing building elevation trend in Mussoorie over time.

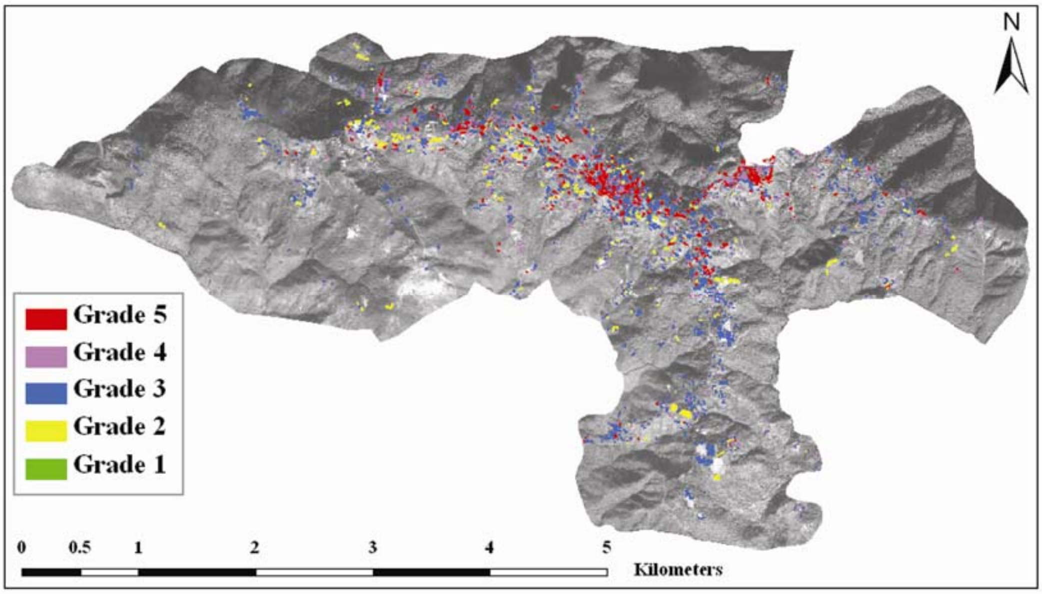

Figure 3. Spatial distribution of the buildings falling under five damage classes. Damage Grade *N* denotes high probability of Grade (*N*) damage and very high probability of Grade (*N* – 1) class.

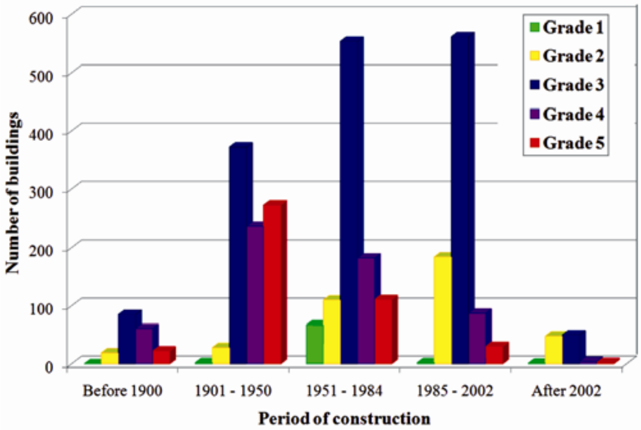

Figure 4. Distribution of buildings falling under different damage grade classes with respect to their period of construction.

Analysis of the data collected for the surveyed structures on the basis of the methodology based on FEMA 154 as given by Sinha and Goyal[11] shows that 18% of the surveyed buildings fall in high probability of Grade 5 damage and very high probability of Grade 4 damage in the case of damage reaching intensity VIII on MSK scale (Figure 3). Majority of the buildings falling in this damage class were reportedly constructed in the pre-1950 phase; 21% in the pre-1900 and 52% between 1901 and 1950. Only 6% of the buildings constructed in the post-1984 phase showed high probability of Grade 5 damage and very high probability of Grade 4 damage (Figure 4). This shows growing compliance of the seismic safety norms with the passage of time. Wards 5 and 7 have maximum number of buildings falling in the high damage grade; 114 and 156 respectively. It is interesting to note that most buildings falling in the high damage grade were low rise; 30% being single-storeyed and 61% being two or three-storeyed. Only 58 buildings falling in more than three-storey class showed high probability of Grade 5 damage and very high probability of Grade 4 damage.

The total built-up area of the buildings falling in high probability of Grade 5 damage and very high probability of Grade 4 damage class in Mussoorie was calculated to be 296,974 m^2 (3,196,598 ft^2). At the standard rate of Rs 450 per ft^2 the replacement cost of these buildings is estimated to be Rs 143.85 crore. This however is a gross underestimate as it does not include the cost of demolition of the structures and the cost of restoration of structures falling in other damage grade classes. Based upon the type of usage of the building, it is estimated that contents worth Rs 92.00 crore would be lost in these structures. Total direct economic loss of Rs 235.85 crore is thus estimated to be incurred due to damage to the surveyed structures in Mussoorie in the event of any seismic activity causing damage reaching intensity VIII on the MSK scale.

On the basis of data on seismogenic losses in India and China, average death rate was estimated to vary between 6% and 18% of the occupants of the collapsed houses. In the present study death rate of 10% is being assumed. The same assumption has been made by Arya[7]. On an average six persons reside in every building in Mussoorie (Census of India, 2001) during the lean season. The population under threat would thus be approximately 3690 and expected casualties (calculated on the basis of 10%) would be around 369 (for high probability of Grade 5 damage and very high probability of Grade 4 damage).

The expected casualties could, however, vary depending upon other factors like time of earthquake, month, etc.

An earthquake is a harsh reality for any tectonically active region. Constraints in earthquake prediction amplify the importance of effective planning, preparedness and mitigative action for saving lives and property. Assessment of seismic risk and vulnerability is a necessary precondition for realistic planning and effective mitigation. RVS, together with GIS and remote-sensing tools, has been utilized in the present study for assessing the seismic vulnerability of Mussoorie that falls in Zone IV of the Earthquake Zoning Map of India. The study attempted to collect data pertaining to all the existing structures and a total of 3344 structures were actually mapped in the field. Majority of the surveyed buildings of the township were observed to be low rise URM structures constructed in the post-1950 period. Among the surveyed buildings, 615 showed high probability of Grade 5 damage and very high probability of Grade 4 damage in the event of a seismic activity reaching intensity VIII on MSK scale. Most of these buildings were constructed in the pre-1950 phase with only 6% being constructed post-1984. This shows growing awareness and compliance of the seismic safety norms with the passage of time.

Fourteen hospitals in Mussoorie were also covered under the study. Most of them were very old, low rise structures with sloping tin roofs. The study indicates that half of the surveyed hospitals are likely to incur serious seismic losses (high probability of Grade 5 damage and very high probability of Grade 4 damage), whereas the essential services in the other five falling in high probability of Grade 4 damage and very high probability of Grade 3 damage class are likely to be disrupted due to heavy non-structural losses. Even though the economic loss likely to be incurred to the hospital buildings in the event of a major seismic event is not significant, disruption of healthcare facilities would immensely aggravate the post-disaster trauma of the victims and add to the human death toll. Intangible losses thus emanating from disruption of this important service on the aftermath of any disaster would be high and are hard to assess. A strategy for immediate detailed vulnerability assessment of all the lifeline structures followed by retrofitting or replacing these structures is thus recommended.

Most construction in Mussoorie dates back to a time when concepts of seismic safety were not well-developed. It would, however, not be practical to recommend the replacement of these structures. Therefore, it is important to undertake a massive awareness drive to popularize retrofitting measures among the masses. People routinely undertake maintenance of their buildings and if made aware and provided implementable technological support, they would be willing to dovetail retrofitting with building maintenance. Tax benefits and soft loans for this cause can further motivate the people to adopt these initiatives. Legislative measures, however, need to be enacted to enforce seismic safety-related provisions in all public buildings.

The study brings out the fact that majority of the structures falling in high damage grade are low-rise; 91% being up to three storeys high. This might lead one to conclude that particular care is being taken while designing and constructing taller structures. This is, however not true and is clarified by the fact that only 16% of the single-storeyed buildings fall in high probability of Grade 5 damage and very high probability of Grade 4 damage class, whereas 19% of two- or three-storeyed buildings and 27% of more than three-storeyed buildings fall in this damage class. It thus becomes clear that the principles of seismic safety are being ignored even while constructing multi-storeyed buildings, which is a cause of serious concern. The message therefore needs to be propagated that all the buildings are required to be constructed with particular care regarding the seismic safety norms and standards. Appropriate changes in the techno-legal regime are therefore required to be introduced together with strict compliance of the same. The present practice of compounding needs to be discontinued immediately as financial penalty alone, without corrective structural measures, cannot guarantee adequate performance from a building that is constructed defying the standards and safety norms. Moreover, one unsafe structure is likely to jeopardize the safety of a number of adequately built structures in its vicinity.

Direct economic losses likely to be incurred have been estimated to be of the order of Rs 235.85 crore in the township of Mussoorie alone. This, however, does not include losses likely to be incurred to public facilities and infrastructure. The estimated economic loss-related figures can be utilized for making an appropriate mitigation strategy as also for putting forth a case for compulsory earthquake insurance of the structures.

The study suggests that 369 persons are likely to sustain life-threatening injuries in Mussoorie alone. This estimate seems staggering, but is modest as no seismic event is likely to affect one particular habitation alone. The realistic economic and life-loss figures might well be manifold. Moreover, recent research indicates likelihood of a major seismic activity in the region[3,14–17]. The magnitude of the losses in the event of these predictions can well be beyond imagination and this warrants gearing up efforts for seismic risk reduction.

1. Besse, J. and Courtillot, V., Palaeogeographic maps of the continents bordering the Indian Ocean since the early Jurassic. *J. Geophys. Res. B*, 1988, **93**, 1791–1808.
2. Dewey, J. F., Cande, S. and Pitman, W. C., Tectonic evolution of the India/Eurasia collision zone. *Ecolgae Geol. Helv.*, 1989, **82**, 717–734.
3. Bilham, R., Larson, L. and Jeffrey, F., GPS measurements of the present day convergence across the Nepal Himalaya. *Nature*, 1997, **386**, 61–64.

4. Avouac, J. and Tapponnier, P., Kinematic model of active deformation in Central Asia. *Geophys. Res. Lett*., 1993, **20**, 895–898.
5. Peltzer, G. and Saucier, F., Present day kinematics of Asia derived from geological fault rates. *J. Geophys. Res.*, 1996, **101**, 27943–27956.
6. Mahajan, A. K., Thakur, V. C., Sharma, M. L. and Chauhan, M., Probabilistic seismic hazard map of NW Himalaya and its adjoining area. *Nat. Hazards*, 2009, **53**, 443–457.
7. Arya, A. S., Damage scenario of a hypothetical 8.0 magnitude earthquake in Kangra region of Himachal Pradesh. *Bull. Indian Soc., Earthq. Tech. Pap.*, 1990, **297**, 121–132.
8. Arya, A. S., Possible effects of a major earthquake in Kangra region of Himachal Pradesh. *Curr. Sci.*, 1992, **62**, 251–256.
9. Indian Standard (IS): 1893, Part 1, Creteria for earthquake resistant design of structures. Bureau of Indian Standards, New Delhi, 2002.
10. Population profiles (India, States and Union Territories). Office of the Registrar General, India, New Delhi, 2004.
11. Sinha, R. and Goyal, A., A national policy for seismic vulnerability assessment of buildings and procedure for rapid visual screening of buildings for potential seismic vulnerability. Report of the Department of Civil Engineering, Indian Institute of Technology, Bombay, 2004, p. 12; http://www.civil.iitb.ac.in/~rsinha/Vulnerability_Assessment.pdf
12. FEMA 154, Rapid visual screening of buildings for potential seismic hazards. ATC, 1988 (updated 2002).
13. Grünthal, G. and Levret, A. (eds), L'Echelle Macrosismique Européenne, European Macroseismic Scale 1998 (EMS-98), Cahiers du Centre Européen de Géodynamique et de Séismologie 19, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 2001, p. 103.
14. Banerjee, P. and Burgmann, R., Convergence along the northwest Himalaya from GPS measurements. *Geophys. Res. Lett.*, 2002, **29**, 13, 1–4.
15. Bettinelli, P., Avouac, J. P., Flouzat, M., Jouanne, F., Bollinger, L., Willis, P. and Chitrakar, G. R., Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and Doris measurements. *J. Geodyn.*, 2006, **80**, 567–589.
16. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
17. Bilham, R. and Wallace, K., Future Mw > 8 earthquake in the Himalaya: Implication from the 26 December 2004 Mw = 9.0 earthquake on India's eastern plate margin. *Geol. Surv. India Spec. Publ*., 2005, **85**, 1–14.

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