Journal of Nepal Geological Society, 2000, Vol. 22, pp. 547–556

Palaeoseismicity in the Koteshwor area of the Kathmandu Valley, Nepal, inferred from the soft sediment deformational structures

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ABSTRACT

Palaeoseisms have left their imprints within the Plio-Pleistocene fluvio-lacustrine soft sediments of the Kathmandu Basin. Recently, a temple foundation excavation at Koteshwor exposed a soft sediment layer with deformational structures. The deformed horizon ranges in thickness from 60 to 90 cm. It can be separated into the following three zones, from top to bottom, respectively: (1) homogenised zone, (2) ball-and-pillow zone, and (3) basal zone. The shaking forces strongly agitated the topmost soft-sediment layer, and in this process, the sediments were mixed-up, producing subsequently the homogenised zone. At Koteshwor, the homogenised zone ranges in thickness from 15 to 20 cm. It is associated in a few places with micro-debris containing carbonised wood fragments. In the ball-and-pillow zone, the ball-and-pillow structures are 35–79 cm long and 11–35 cm high. The laminae of the ball-and-pillow structures are strongly folded or disrupted and recumbent folds are locally observed. The central parts of the ball-and-pillow structures are mostly homogenised and 2–3 cm long wood fragments are accumulated in a few places at the bottom of these structures. In the basal zone (up to 55 cm thick), sediments are upraised and plastically deformed. A marker layer in the basal zone attests to the simultaneity of compression and extension deformational structures, a combination of structures that excludes the slope failure origin for the soft sediment deformation and that is clearly related to ground shaking during an earthquake.

The fluvio-lacustrine sediments of the Kathmandu Basin consist of a thin alternation of weakly consolidated and cohesionless silty and sandy layers exhibiting rather good sorting. These conditions and physical properties make them suitable for hydroplastic deformation, liquefaction, and/or fluidisation. Previous studies showed that earthquake-induced liquefaction and fluidisation deformational structures are connected with seismic shocks of M>5. The soft sediment deformational structures with a thickness varying between 60 and 90 cm in a lacustrine environment are formed in seismic intensity zones greater than IX. It is therefore inferred that the palaeoseism intensity at Koteshwor was larger than the intensities of the 1833 and 1934 historical earthquakes affecting the Kathmandu Basin.

INTRODUCTION

The soft sediment deformational structures (SSDS) such as recumbent folds, convolute laminations, load casts, sand diapirs, and discordant clastic dykes and pipes can be found in many depositional environments due to hydroplastic deformation, liquefaction, and fluidisation (Lowe 1975; Allen 1982; Owen 1987; Plaziat and Poisson 1992; Guiraud and Plaziat 1993). The SSDS interpreted as earthquake-induced liquefaction have been reported in sediments from the lacustrine environment (Sims 1973; Beck et al. 1992; Adams 1996; Hibsch et al. 1997; Lignier et al. 1998) and from the recent and ancient fluvial deposits (Ananda and Jain 1987; Guiraud and Plaziat 1993; Mohindra and Thakur 1998).

Sims (1975) provided keys for identification of liquefaction-induced features from the fluvio-lacustrine deposits in the Norman Lake. During shaking, liquefaction occurs near the sediment/water interface, and any underlying clayey laminated deposits consequently sag or crumple (Sims 1975). The structures are very similar to those obtained in the laboratory experiments (Kuenen 1958; Moretti et al. 1999) by simulating the seismic triggering forces (Fig. 1).

The technique to study the palaeoliquefaction features for the seismic analysis of a basin is new and is being increasingly utilised. Developed only within the past fifteen years, the method of systematically searching for palaeoliquefaction features has been used to interpret the palaeoseismic record at numerous localities (Obermeier and Pond 1999).

This paper describes the synsedimentary deformational structures from Koteshwor (viz. the SW slope of the Tribhuvan International Airport, Kathmandu) and these observations are used to estimate the lower bound for the strength of seismic events in this part of the basin.

TECTONIC SETTING

The study area lies in the Kathmandu Valley. The rocks (Fig. 2 and 3) are represented by the Kathmandu Complex

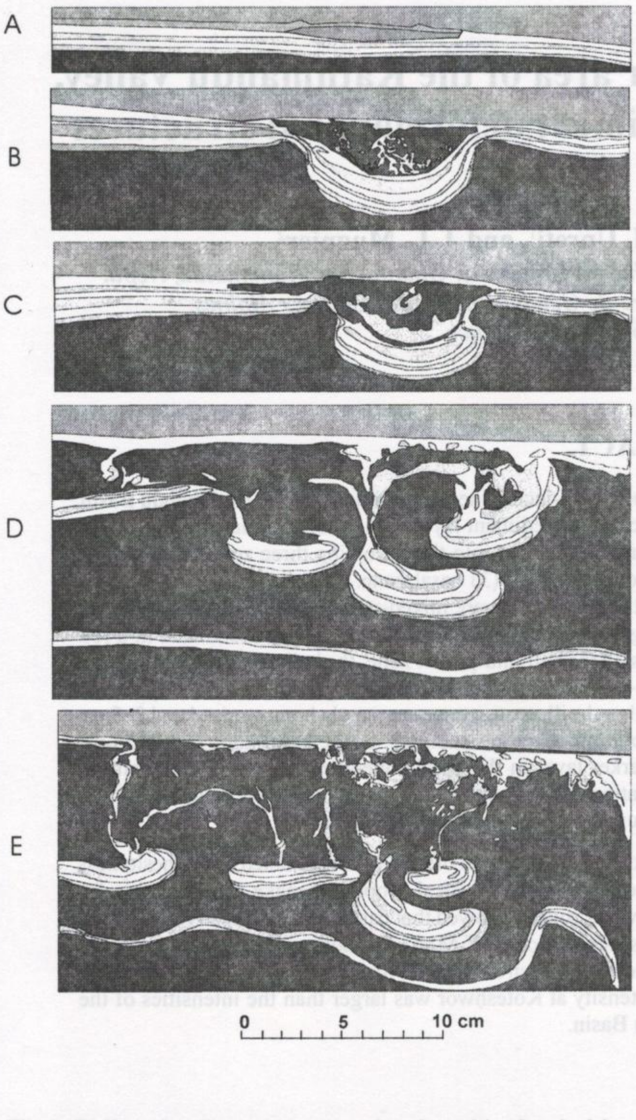

Fig.1: Ball-and-pillow structures developed in the shaking experiment of Kuenen (1965). The structures in the frame D and E are derived from the shaking experiments (Pettijohn et al. 1973, as redrawn from Kuenen 1958) and are very similar to those observed at Koteshwor (see Fig. 6).

(Stöcklin and Bhattarai 1977; Stöcklin 1980) or the Kathmandu Nappe (Hagen 1969; Upreti and Le Fort 1999). The Kathmandu Nappe is thrust over the Lesser Himalayan rocks along the Mahabharat Thrust (MT). Below the MT lies the Main Himalayan Thrust (MHT) and at present, the Kathmandu Nappe is passively transported by it (Harrison et al. 1999). Hence, the Kathmandu Basin is a transported basin lying on the hanging wall of the MHT.

The Sheopuri Range containing gneiss, granite, pegmatite, and schist marks the northern limit of the basin, whereas the Phulchauki–Chandragiri Hills mark the southern limit and are made up of limestone, sandstone, siltstone, and phyllite.

The borehole studies and gravity surveys suggest that the sediments in the basin are up to 600 m thick. They consist mainly of alluvial fan, and deltaic and lacustrine sediments (Yoshida and Igarashi 1984; Gajurel 1998). A few NW–SE trending faults affect the substratum of the basin (Fig. 2).

The SSDS are recorded from the basin deposits of different depositional environment. Folding, pull-apart sand layer, ball-and-pillow structures, and clastic dykes give evidence for deformations (Gajurel et al. 1998). They are observed at various sites including natural cliffs, sand quarries, and foundation excavations.

SEISMICITY

The seismic activity in the Himalayas results from the intracontinental subduction of the Indian Plate beneath the Tibetan Plate. The intense microseismicity and frequent medium-sized earthquakes in the territory of Nepal cluster beneath the topographic front of the Higher Himalaya (Pandey et al. 1995). The Kathmandu Basin is situated very close to the cluster of the micro- and medium-sized (ML <4) seismic events located around the upper part of a deep ramp (Fig. 3). The surroundings of the basin have long been known to be seismically active (Fig. 4) and the area has historically experienced several great earthquakes (Chitrakar and Pandey 1986; DMG 1997). The greatest one was the 1934 Bihar–Nepal earthquake that reached M = 8.3–8.4 and induced destruction estimated at IX MMI (Modified Mercalli Intensity) in the Kathmandu Valley (Pandey and Molnar 1988). Its epicentre was probably located more than 100 km east of Kathmandu, and the seismic rupture probably affected the MHT (Pandey and Molnar 1988). The 1833 Nepal earthquake of IX MMI caused severe destruction in the Kathmandu Valley and reached M 7.7± 0.2 (Bilham et al. 1995). Its epicentre was located either north or northeast of Kathmandu.

GPS measurements have shown a present-day shortening rate of 11 ± 2 mm/year over a 100 km long north–south profile in central Nepal (Flouzat et al. 1999), and indicate that the present-day deformation is locked beneath the Sheopuri Range. It is suggested that the deformation is presently elastically stored and would be released during future great earthquakes (Bilham et al. 1997).

The central part of the Kathmandu Basin contains many silt and fine sand beds, which are very prone to liquefaction. By comparing these liquefaction structures with those published in the literature, it is possible to estimate the palaeoseismic intensities in the Kathmandu Basin. The SSDS observed at Thimi (Fig. 2, 8) evidenced the palaeoseisms (Gajurel et al. 1998) of the same order of intensity as the seismic events recorded by the historical and instrumental data.

SOFT SEDIMENT DEFORMATIONAL STRUCTURES AT KOTESHWOR

The outcrop of the SSDS discussed here is located on the SW cut slope (Fig. 2). The structures were observed

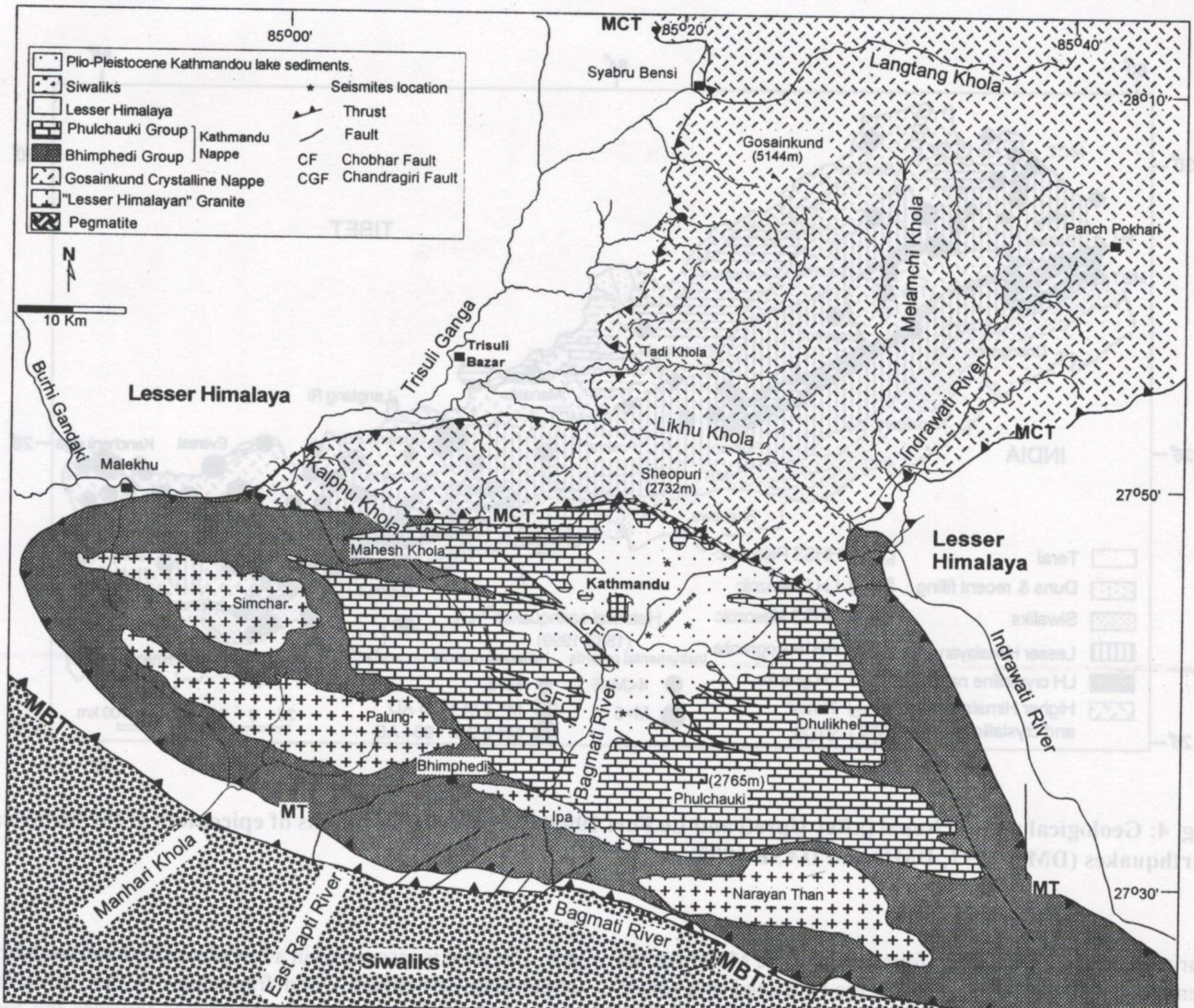

Fig. 2: Geological map of central Nepal showing the study area (modified after Rai et al. 1997)

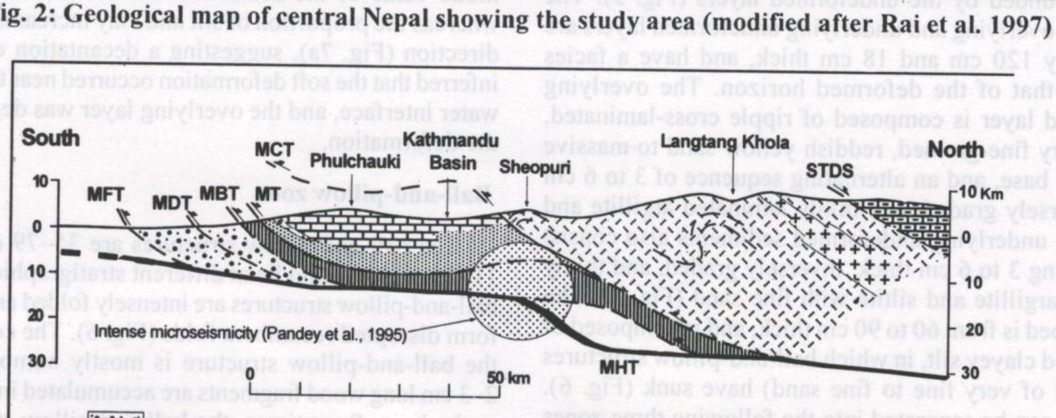

Fig. 3: North-south geological cross-section through the Langtang Valley and Kathmandu showing the position of the Kathmandu Basin (modified after Upreti and Le Fort 1999)

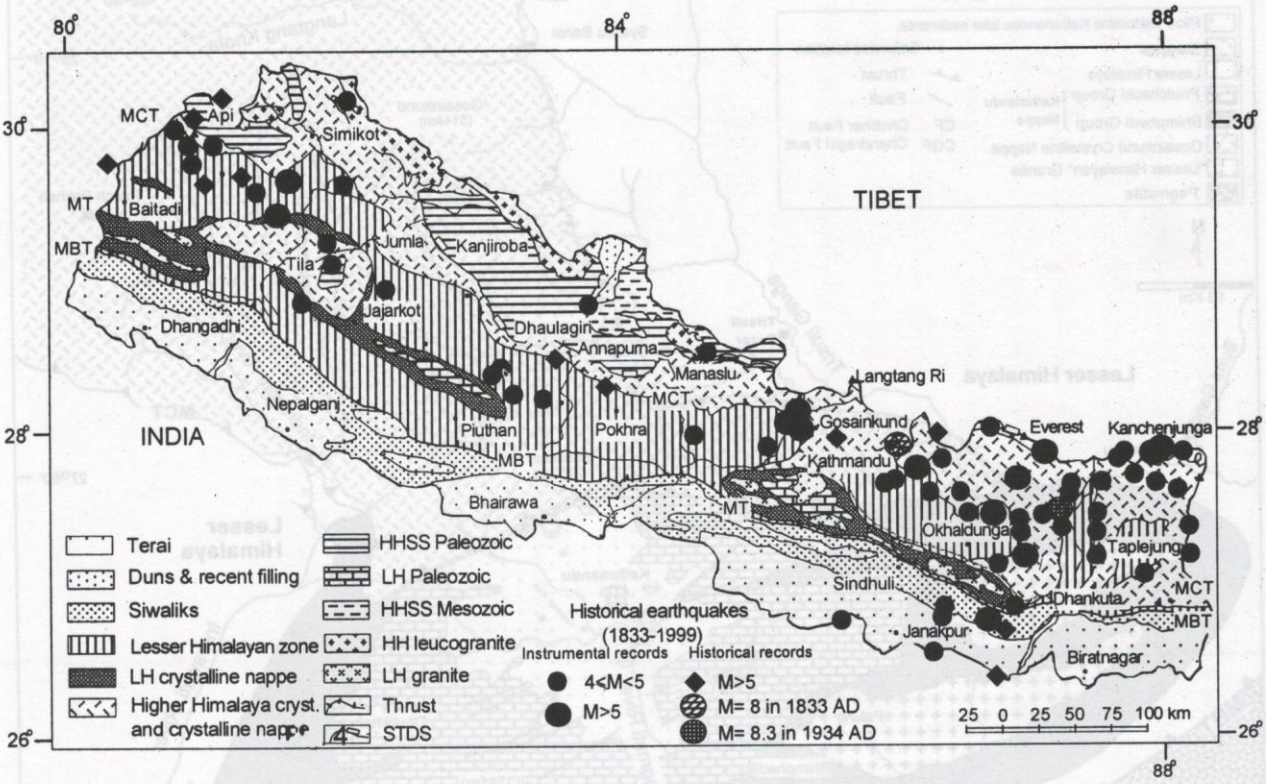

Fig. 4: Geological map of Nepal (after Upreti and Le Fort 1999) depicting the locations of epicenters of the historical earthquakes (DMG 1997; DMG and DASE 1999).

during the excavation of the foundation of the Munibhairab Temple. The deformed structures are restricted to a single horizon bounded by the undeformed layers (Fig. 5). The sub-planar overlying and underlying undeformed layers are respectively 120 cm and 18 cm thick, and have a facies similar to that of the deformed horizon. The overlying undeformed layer is composed of ripple cross-laminated, fine- to very fine-grained, reddish yellow sand to massive sand at the base, and an alternating sequence of 3 to 6 cm thick, inversely graded, and thinly laminated argillite and siltite. The underlying undeformed sediments also consist of alternating 3 to 6 cm thick, inversely graded, and thinly laminated argillite and siltite with fine sand (Fig. 5). The deformed bed is from 60 to 90 cm thick, and is composed of fine-grained clayey silt, in which ball-and-pillow structures (composed of very fine to fine sand) have sunk (Fig. 6). The SSDS can be separated into the following three zones from top to bottom, respectively: (1) the homogenised zone, (2) the ball-and-pillow zone, and (3) the basal zone.

Homogenised zone

The topmost soft sediment layer was strongly agitated by the shaking forces, and in this process, the sediments were mixed-up, producing subsequently the homogenised zone. At Koteshwor, it ranges in thickness from 15 to 20 cm. The zone is associated in a few places with micro-debris containing carbonised wood fragments. In this zone, the mode value of the sediments decreases towards the top, whereas the proportion of silt and clay increases in the same direction (Fig. 7a), suggesting a decantation deposit. It is inferred that the soft deformation occurred near the sediment/water interface, and the overlying layer was deposited after the deformation.

Ball-and-pillow zone

The ball-and-pillow structures are 35–79 cm long and 11–35 cm high, and lie at different stratigraphic levels. The ball-and-pillow structures are intensely folded and frequently form disrupted recumbent folds (Fig. 6). The central part of the ball-and-pillow structure is mostly homogenised and 2–3 cm long wood fragments are accumulated in a few places at the base. Sometimes, the ball-and-pillow structures are oriented obliquely to the bedding (Fig. 6c). In the undeformed area, the same sandy layer without the ball-and-pillow structures is 2–3 cm thick.

Basal zone

In the basal zone, the materials are upraised and plastically deformed. This zone reaches up to 55 cm in thickness. In a few places, the sink materials form structures

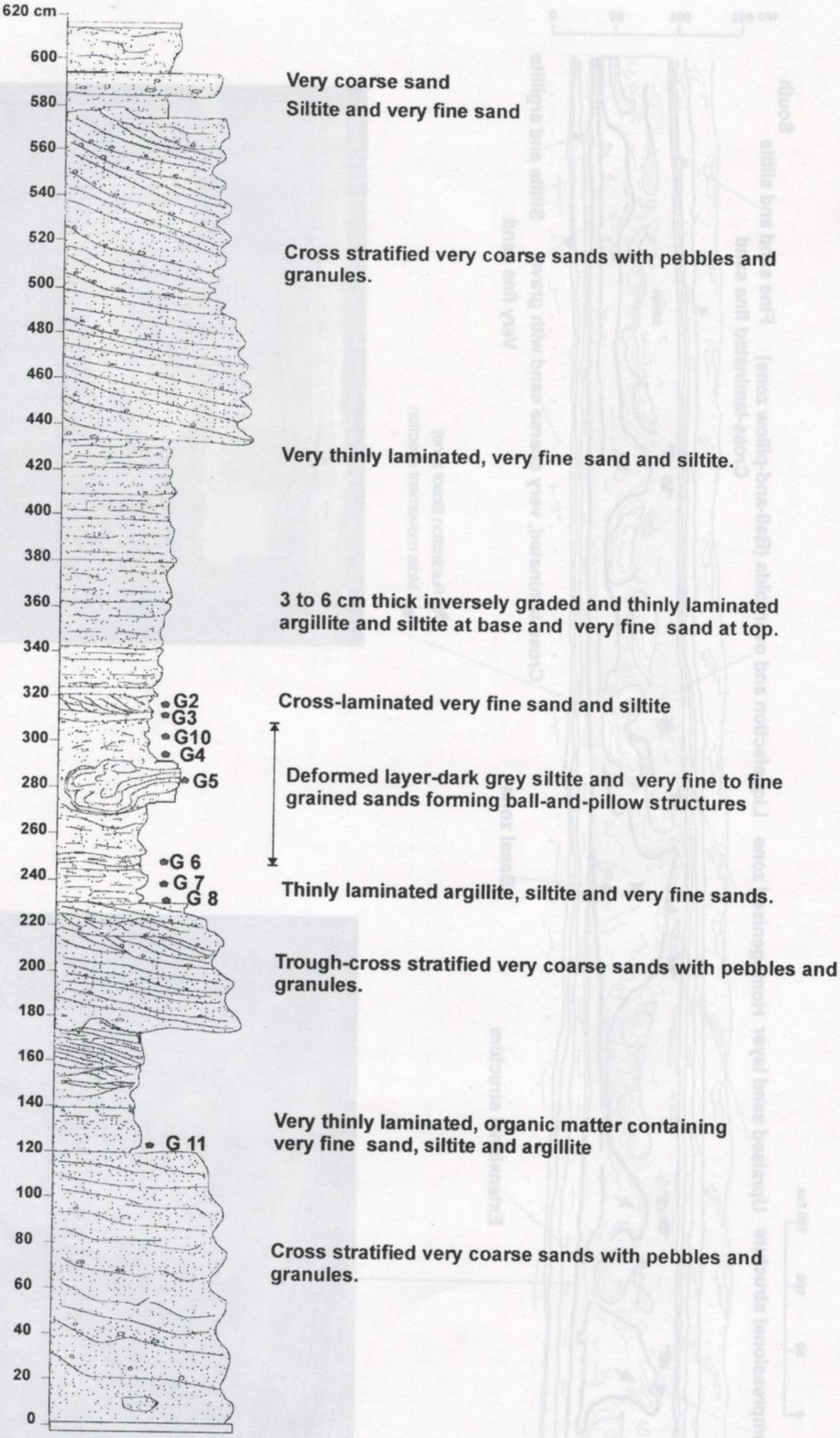

Fig. 5: Litholog of the Koteshwor area showing the position of the seismite horizon and sample locations (G1, G4, etc).

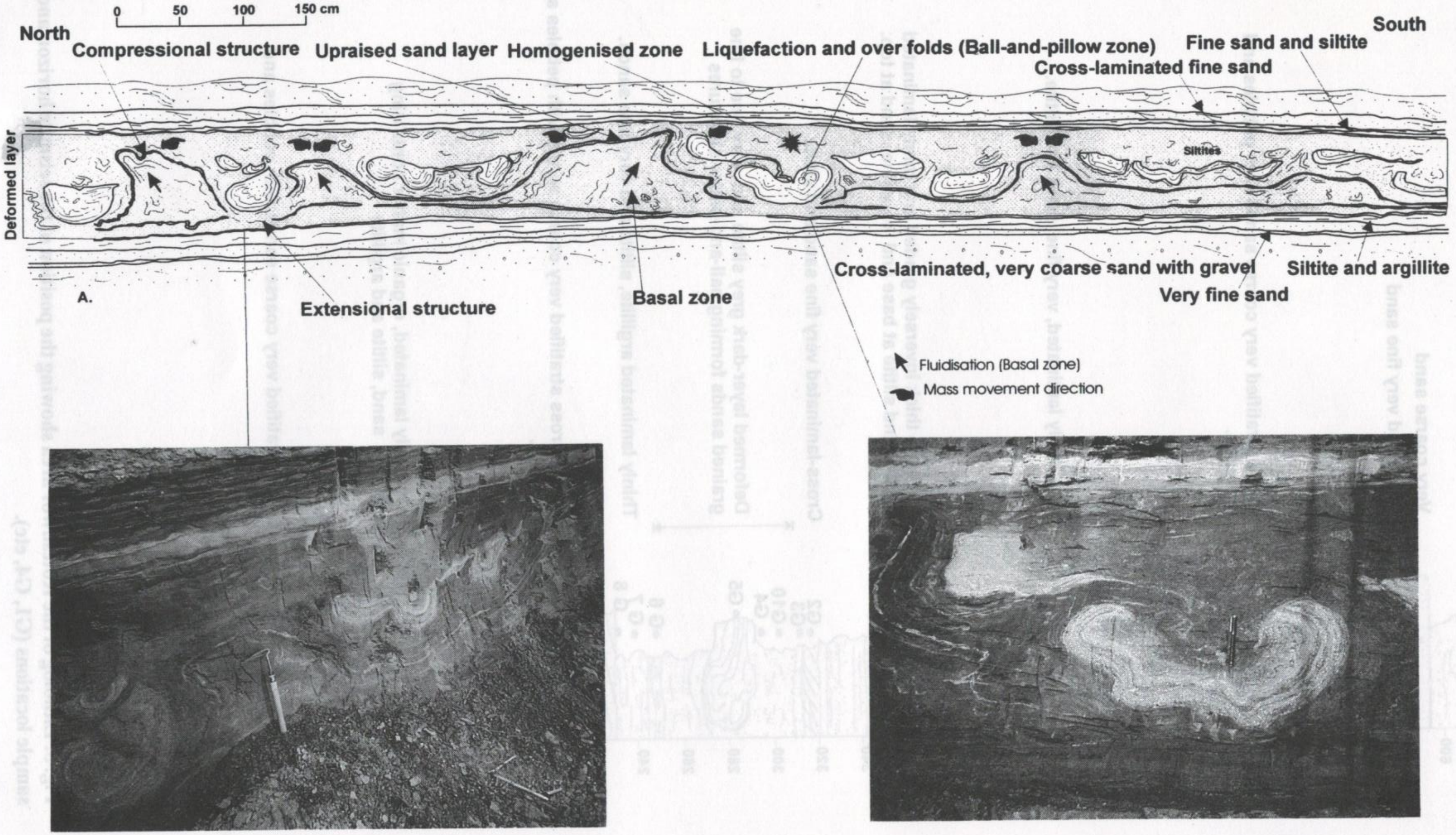

Fig. 6: Details of the seismite horizon at Koteshwor. a. Detailed sketch of the seismite layer; b. photograph of a typical ball-and-pillow structure similar in morphology to a teardrop; and c. photograph of contorted and folded (in two opposite directions) sand laminae due to sinking.

morphologically similar to the shape of a teardrop (Fig. 6b). In the basal zone, a marker layer clearly shows compression and extension deformational structures developed during ground shaking (Fig. 6). The marker layer is composed of about 3 cm thick light yellow-brown fine-grained sand. This layer is intensely folded and torn apart in several places, but has still a rather good lateral continuity, which suggests that the sand layer was well compacted before the deformation and acted as a barrier for the liquefied material. This level forms tight and broad antiforms and wide synforms. The amplitude of the folds varies from 50 to 15 cm. Their axial planes are inclined in different directions. These characteristics exclude the possibility of slope failure during the formation of these structures. Therefore, the folding and sinking events in the deformed layer seem to be co-seismic in origin. The other layers underneath this marker layer are plastically extended and ruptured.

Granulometric analyses were carried out through the seismite structure (Fig. 5) to determine the critical size of sediments that are susceptible to liquefaction and deformation. The liquefiable layers at Koteshwor can be categorised as clean silt and sand with the fine content of less than 6% (Fig. 7b). The low fine content is quite similar to that of the layers that were strongly liquefied in the San Francisco area during the 1989 Loma Prieta earthquake (Pease and O'Rourke 1998). In general, the cohesionless water-saturated material containing less than 20 per cent (by weight) of fines are considered susceptible to liquefaction (Holzer 1998). The difference in fine content between the upraised material (Fig. 7b) and the undeformed layer is very small, suggesting that the fine content is not the only parameter that promotes liquefaction. In the case of the Koteshwor seismite, the deformed silt and sand beds are poorly graded (Fig. 7a) and well sorted (Table 1), a characteristic that still favours liquefaction (Pease and O'Rourke 1998). The mean diameter of the material forming the ball-and-pillow features (D_{50} = 0.206 mm) seems to be more than twice that of the material from liquefiable layer (D_{50} = 0.066 mm), a fact that was also observed at the Thimi section in the Kathmandu Valley (Gajurel et al. 1998).

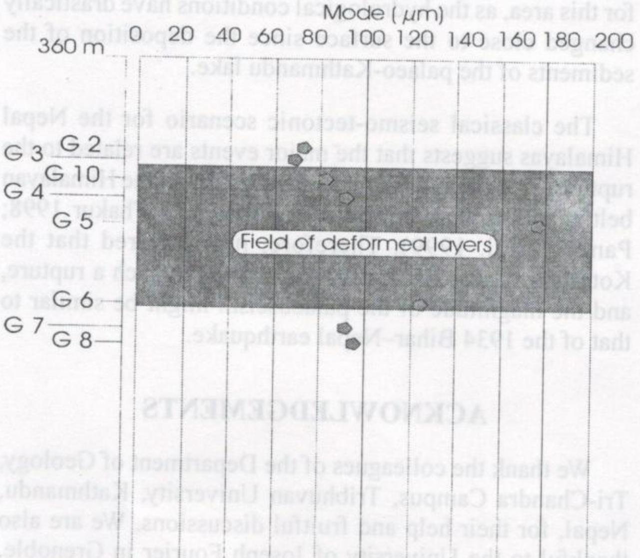

Fig. 7a: Mode value of the samples from the Koteshwor area (see Fig. 5 for the sample locations). Sample number are indicated as G2, G3, G5 etc.

Table 1: Result obtained from grain size analysis

Sample No.	Sorting value (ϕ)
G2	1.96
G3	2.14
G4	2.05
G5	1.83
G6	2.09
G7	1.98
G8	2.01
G11	1.87
G10	1.95

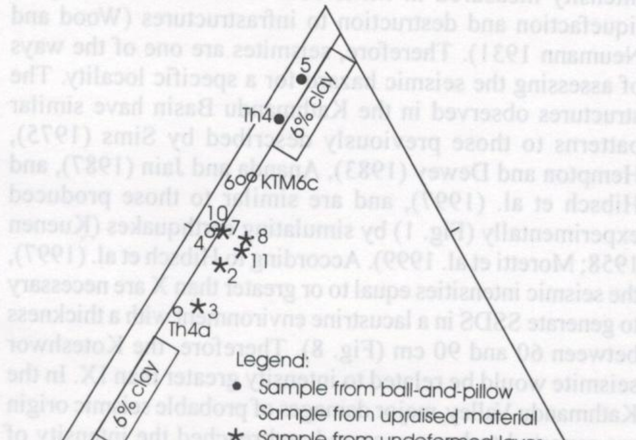

Fig. 7b: Diagram showing sand, silt, and clay proportions from deformed and undeformed layers. The sediments from ball-and-pillow structures and from upraised materials are distributed in two different fields. The samples from the undeformed layers exhibit similar proportions of silt and clay to that of the deformed layer. Th and KTM are samples from the Thimi section and the remaining samples are from the Koteshwor area (see Fig. 5).

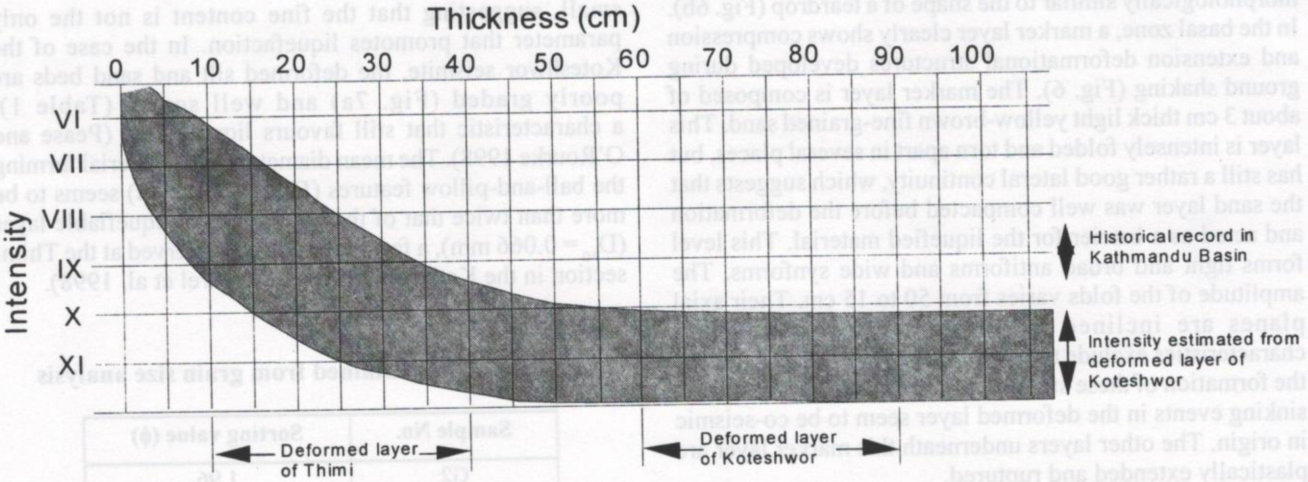

Fig. 8: A comparison of the intensity of the historical earthquakes and the palaeoseisms in the Kathmandu Basin using the diagram of intensity versus thickness of liquefied layer (adapted from Hibsch et al. 1997). The grey area refers to the domain of possible relationships between the thickness of the liquefied layer and the intensity of earthquake.

CONCLUSIONS AND DISCUSSIONS

The ball and pillow features at Koteshwor were formed in the water-saturated clean silt and sand deposits near their sediment/water interface in a deltaic environment. Such liquefaction structures correlate well with the ground shaking intensity measured in MMI both in terms of severity of liquefaction and destruction to infrastructures (Wood and Neumann 1931). Therefore, seismites are one of the ways of assessing the seismic hazard for a specific locality. The structures observed in the Kathmandu Basin have similar patterns to those previously described by Sims (1975), Hempton and Dewey (1983), Ananda and Jain (1987), and Hibsch et al. (1997), and are similar to those produced experimentally (Fig. 1) by simulating earthquakes (Kuenen 1958; Moretti et al. 1999). According to Hibsch et al. (1997), the seismic intensities equal to or greater than X are necessary to generate SSDS in a lacustrine environment with a thickness between 60 and 90 cm (Fig. 8). Therefore, the Koteshwor seismite would be related to intensity greater than IX. In the Kathmandu Valley, major damages of probable seismic origin are reported to have occurred and reached the intensity of IX (Chitrakar and Pandey 1986). Therefore, it is inferred that the palaeoseism recorded by the seismites at Koteshwor had intensity larger than those of the 1833–1934 historical earthquakes affecting the Kathmandu Basin.

The Kathmandu Valley is particularly subject to site effects, as ground motion is greatly amplified when shaking propagates from surrounding and underlying hard rocks to soft rocks (Bard et al. 1985). The variation in destruction in the Kathmandu Valley was great during the Bihar–Nepal earthquake of 1934 (Dunn et al. 1939). The microtremor analysis reveals high peak amplification in the central part of the Kathmandu basin. The amplification zone correlates well with the areas of devastation in the Kathmandu Valley during the Bihar–Nepal earthquake of M = 8.3 (Pandey et al. 1999). Therefore, it is inferred that the site effects are great in the airport area. This assumption does not contradict the modern low liquefaction hazard inferred by DMG (1998) for this area, as the hydrological conditions have drastically changed close to the surface since the deposition of the sediments of the palaeo-Kathmandu lake.

The classical seismo-tectonic scenario for the Nepal Himalayas suggests that the major events are related to the ruptures along the MHT, and each segment of the Himalayan belt should rupture episodically (Yeats and Thakur 1998; Pandey et al. 1999). Therefore, it is inferred that the Koteshwor palaeoseismites were related to such a rupture, and the magnitude of the palaeoseism might be similar to that of the 1934 Bihar–Nepal earthquake.

ACKNOWLEDGEMENTS

We thank the colleagues of the Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal, for their help and fruitful discussions. We are also thankful to the University of Joseph Fourier in Grenoble, France, for the laboratory facilities.

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