Journal of Nepal Geological Society, 1998, Vol. 18, pp. 417-430

Palaeoseismicity in the Siwaliks: occurrence of major seismic events in the Himalayas of west Nepal

Georges H. Mascle[1], Edouard Chalaron[2], A.P. Gajurel[3], Pascale Leturmy and [1]Jean Louis Mugnier

[1]*Laboratoire de Géodynamique des Chaines Alpines (CNRS/UJF Grenoble)*
15 rue Maurice Gignoux, 38041 Grenoble, France
[2]*INRS Georessources, 2535 Boulevard Laurier, Sainte Foy, Quebec, G1V 4C7, Canada*
[3]*Geology Department, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal*

ABSTRACT

The Siwaliks represent both the Neogene-Quaternary foreland thrust belt of the Himalaya and the sedimentary series of fluvial origin that have been deposited in a flexural foreland basin near the mobile front of the Himalayan range and have been successively incorporated by thrusting to the structural edifice. The still active deformation of the Siwalik prism occurs through both the seismic and aseismic regime. Structures of syn-sedimentary liquefaction are observed in the Upper Siwaliks of the well dated Surai Khola section of western Nepal. Two particularly thick liquefied layers occur near the base of the Dobata Formation of around 4.1 Ma in age and are also observed in the Babai Khola section about 120 km west of the Surai Khola. These data are compared with the extension of liquefaction induced by modern earthquakes in the area (mainly the 1934 Bihar-Nepal earthquake) and plotted on two graphs: 1- maximum epicentre distance from liquefied sites versus magnitude of earthquake; 2- thickness of liquefied layers versus earthquake intensity. All the results agree with the occurrence of major paleoearthquakes in the area.

LOCATION AND BULK STRUCTURE OF THE SIWALIKS

The Siwaliks are the foothills of the Himalaya and are made up of the Neogene-Quaternary intracontinental molasse which has been deformed by the Himalayan compression of fairly constant direction. Associated with the Ganga-Indus basin, they form the still in evolution modern Himalayan foreland basin. The Himalayan belt loads the Indian lithosphere (Lyon-Caen and Molnar, 1984) and creates a flexural basin, which traps a part of the detrital supplies provided by the erosion of the belt. Characteristics of the Siwalik system results from three particularities: first, the Precambrian Indian lithosphere is thick and rigid; second, the high belt provides abundant detrital supplies; and third its geographic situation and the associated climate allow this material to be easily removed. The main result is that the flexural basin is filled-up and its superficy is aerial, above sea level (Mascle et al., 1986); in this intracontinental basin an important fluvial sedimentation occurs.

The Siwaliks are made up of a south-verging thrust succession. Even if in detail variations of the structure appear, three main thrust zones are reported and are documented as piggy-back basin type propagation (Hérail and Mascle, 1980; Delcaillau et al., 1987). In the north, the Lesser Himalayan rocks (Pre-Cambrian, Gondwana, Eocene, sometimes Oligocene) overthrust the Siwaliks along the Main Boundary Thrust (MBT, Medlicott, 1864); in the central part the Main Dun Thrust (MDT, Mascle and Hérail, 1982) breaks up two units or group of units of Siwalik facies of different ages. Southward the Siwaliks overthrust the Quaternary deposits of the Gangetic plain by the Main Frontal Thrust (MFT, Gansser, 1964, 1983), or Main Siwalik Thrust (MST, Mascle and Hérail, 1982), or a frontal anticline (Delcaillau, 1986;

Delcaillau et al., 1987; Schelling and Arita, 1991; Mugnier et al., 1992). The seismic surveys (Raiverman et al., 1983; Department of Mines and Geology, 1985) have shown to be a propagation fold over a ramp. The bulk structure results from the deformation of results from the deformation of a sedimentary cover detached along a basal décollement level where Siwalik thrusts branch off and may reach the surface (Delcaillau et al., 1987).

The Himalayan foothills are a place where numerous earthquakes occurred (Molnar et al., 1973; Seeber and Armbruster, 1981; Ni and Barazangi; 1984; Molnar, 1990; Bilham et al., 1995). For the most recent seismic activity, the events of high magnitude that occurred in the region are: 1803 (Kumaon), 1833 (Nepal), 1897 (Assam), 1905 (Kangra), 1934 (Bihar-Nepal), 1950 (Assam). The two last are considered to be more than 8 in magnitude.

SIWALIKS OF WESTERN NEPAL: STRUCTURE AND STRATIGRAPHY

Structure

The studied region (Fig. 1 and 2), is located in western Nepal between two main draining features of the Himalayan belt: the Narayani and Bheri rivers (between 81°E and 84°E). The Siwaliks' lateral structure shows important variations from east to west. Close to Narayangadh (Fig. 3a), at the hanging-wall of the MST, the Chitwan Dun is developed with a maximum of 100 km in length and of 33 km in width. To the north, this dun is overthrust by a tight 5 to 10 km slice of the Lower Siwaliks, which is also overthrust by Precambrian deposits of the Lesser Himalaya along the MBT (Hérail et al., 1986). Ninety kilometers westward, close to Butwal (Fig. 3b), the Siwalik hills comprise a tight 10 km zone of the Siwalik deposits, separated in a north sheet between the MBT and the MDT made up of the Lower Siwaliks, and a south sheet made up of the Middle Siwaliks and which set off a frontal anticline in Butwal (Hérail and Mascle, 1980; Tokuoka et al., 1986, 1990). Further westward, this structure is continuous along 55 km until the Surai Khola valley. Here (Fig. 3c) the Siwalik system enlarges. To the north, the Lesser-Himalaya overthrusts the Siwaliks along the MBT (Nakata, 1982; 1988). Then, this unit overthrusts (thrusts of the Sit Khola or Babai Khola, both MDT) a second one comprising of the Upper Siwaliks, which form the large Dang-Tulsipur Dun (25 km in its maximum width, 100 km in length). This dun is bounded southward by a Siwalik slice, which shows a complex structure. A frontal anticline is covered by a thrust-sheet itself bounded by a double system of thrusts: one at the north is back-thrusting northward (Siling Khola Thrust) and the second (Rangsing thrust) is ovethrusting southward the Deokhuri Dun (Dhital et al., 1995). This dun (16 km in width and 54 in length) is located at the hanging-wall of the most external Siwalik thrust sheet, overthrusting Quaternary deposits. Close to Kanchanpur, this thrust-sheet show an offset of about 12 km due to a tear fault offsets over a lateral ramp and a frontal anticline which disappears 25 km eastward of Nepalganj. There, the Rapti River suddenly curves southward (Fig. 2c). Northernmost structures (Rangsing and Babai thrusts and the MBT) are not affected by the Kanchanpur tear-fault. When the southernmost hills disappear, the Rangsing Thrust becomes the frontal structure (Fig. 3d). Then it also disappears 50 km westward where the Babai Khola curves (Bardiya), and shows a frontal anticline (Mugnier et al., 1992; Chalaron et al., 1995) northward relayed by the MDT (Fig. 2).

Stratigraphy

Usually, the Siwaliks are divided into three main units from lithostratigraphic features (Medlicott, 1864; Auden, 1935): Lower, Middle and Upper Siwaliks according to their detrital components. The detrital components of the Lower Siwaliks come from low metamorphic grade sedimentary formations, and the ones of middle Siwaliks are characterised by removed minerals of amphibolite grade (garnet, staurolite, kyanite, sillimanite; Glennie and Ziegler, 1964; Tandon, 1990). The Upper Siwaliks are characterised by both the presence of leucogranites boulders and Lower Siwaliks pebbles (Hérail and Mascle, 1980). This indicates that: first, with time the erosion affected deeper and deeper zones; and second, older sediments of the Siwaliks basin may have been outcropped and participated to sedimentation of younger ones. This last point agrees with the piggy-back type of faults propagation and

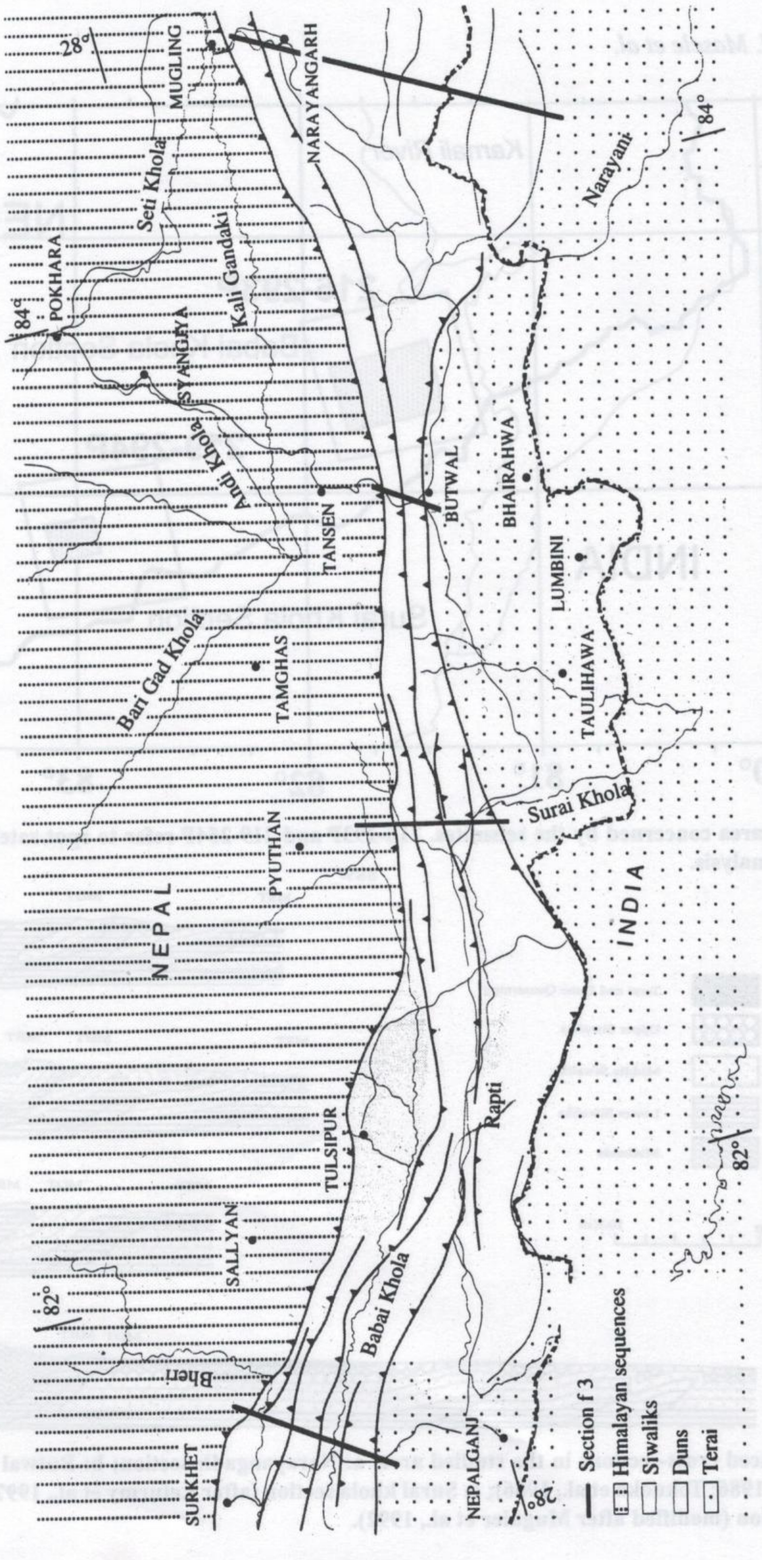

Fig. 1: Location of study area.

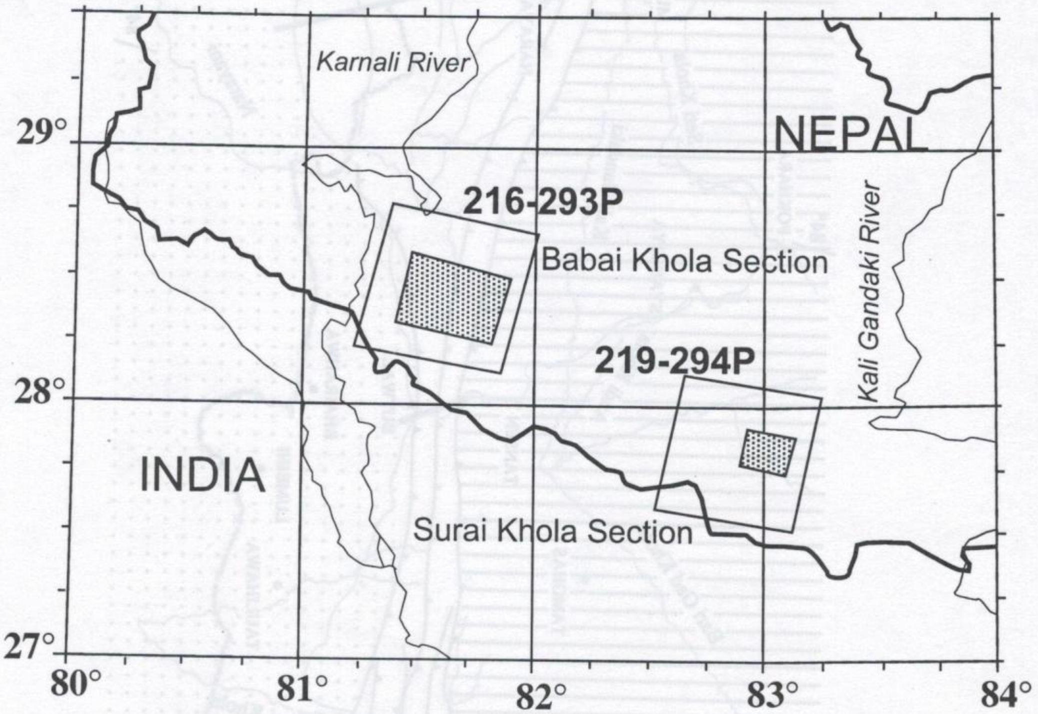

Fig. 2: The area concerned by the seismites. 216-293P and 219-254P refer to spot satellite images used for the structural analysis.

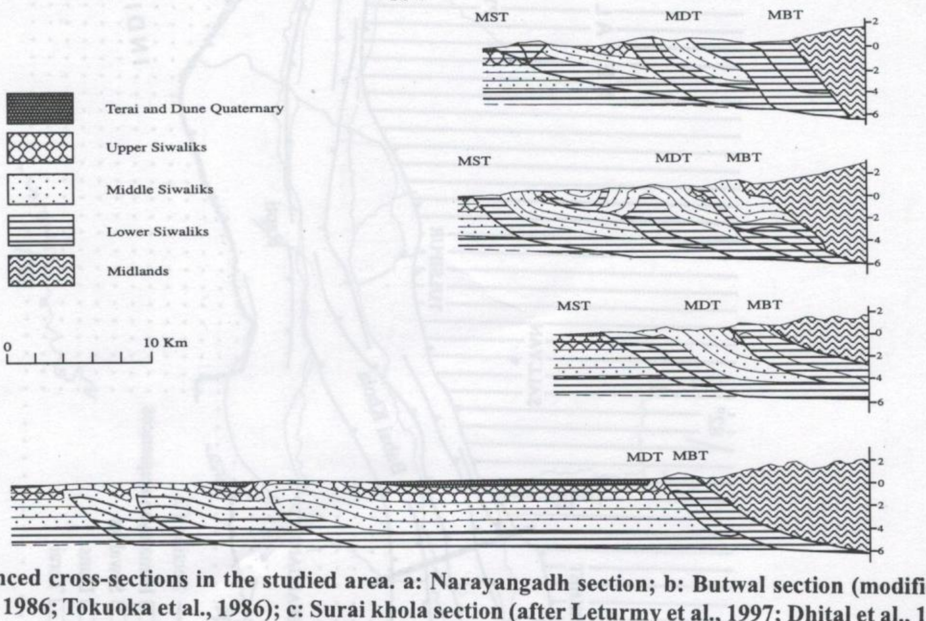

Fig. 3: Balanced cross-sections in the studied area. a: Narayangadh section; b: Butwal section (modified after Hérail et al., 1986; Tokuoka et al., 1986); c: Surai khola section (after Leturmy et al., 1997; Dhital et al., 1995); d: Surkhet section (modified after Mugnier et al., 1992).

with numerical models (Chalaron, 1994; Chalaron et al., 1995).

The construction of the Mahendra Highway in this region facilitated to carry out studies of fossils and magnetostratigraphy (Appel et al., 1991; Appel and Rossler, 1994; Corvinus, 1994; Dhital et al., 1995). Along the Surai Khola section, a complete Siwalik sequence can be observed (Fig. 4) as:

1. The Bankas Formation which outcrops along 585 m, is made up of fine sandstones and brown-purple mudstones sequences that show palaeosoils and plant remains. The environment of deposit is the one of the distal parts of alluvial fans by meandering channels (Delcaillau et al., 1987; Tandon, 1990), under an equatorial climate. A *Gomphoterium* remain agrees with the upper part of the Lower Siwaliks (Chinji stage, Corvinus, 1994);
2. The Chor Khola Formation is made up of medium grained mica rich sandstones, sometimes limestones beds and dark grey mudstones to marly beds (thickness 1235 m) outcrop with abundant leaves prints and ligneous remains transformed into coal. The sequences thicken upward; the environment of deposit corresponds to flood plains ran over by high bed load meandering channels (Delcaillau et al., 1987; Tandon, 1990) under a humid and hot climate and is interpreted to be of the lower part of middle Siwaliks (Nagri stage);
3. The Surai Khola Formation (thickness 1310 m), shows very thick layers of medium to coarse

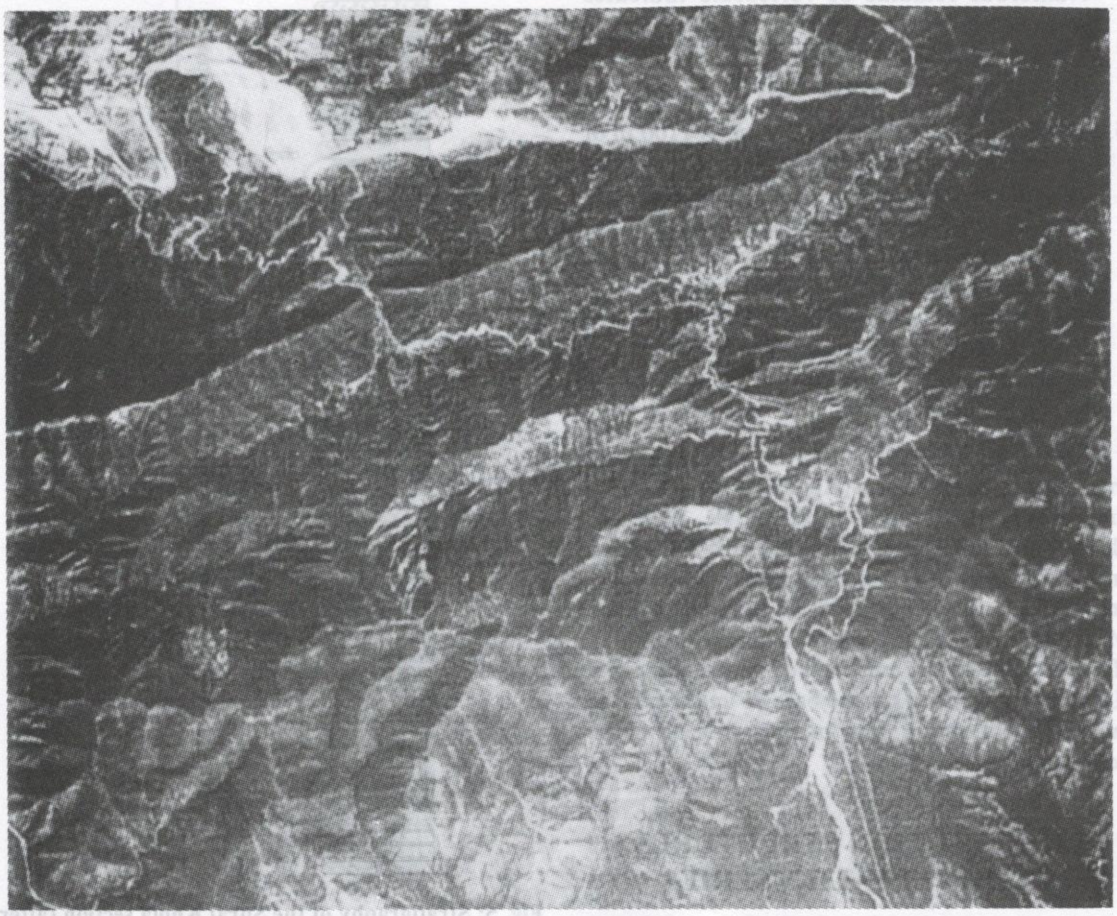

Fig. 4: Situation of the Surai Khola section. The section mainly outcrops along the road that crosses the frontal range.

grained multistoried sandstones, salt and pepper sandstones and siltstones. The upper part exhibits numerous remains of fossils, coal, wood, leaves prints, fresh water molluscs, and vertebrate bones and teeth and allows to correlate with the Middle Siwaliks (Dhok Pathan stage) and Upper Siwaliks (Tatrot stage, Corvinus, 1994; Dhital et al., 1995). The environment of deposit corresponds to high bed load meandering and anastomosing channels (Delcaillau et al., 1987; Tandon, 1990) with a drier climate as indicated by the occurrence of pollens of *Cycadaceae* and *Pinaceae* (Corvinus, 1994).

4. The Dobatta Formation shows 750 m of light coloured to brown mudstones comprising channels filled by coarse sandstones, sometimes boulders. Numerous remains of vertebrate indicates sediments of Upper Siwaliks series (Pinjor stage). The environment of deposit is still of anastomosing channels with high coarse bed load.

5. The Dhan Khola Formation exhibits 1100 m of coarse conglomerate and light-brown sands and volcanic sediments; the top of the sequence is not well consolidated; fossils are rare and do not allow to give an age. The environment of deposit corresponds to proximal alluvial fans with very close sedimentary supply (Delcaillau et. al., 1987; Tandon, 1990). According to Corvinus (1994), pollen records would reflect a climate a little more drier than actual.

Combining biostratigraphic (Corvinus, 1994) and magnetostratigraphic data (Appel and Rosler, 1994) and lithostratigraphy (Dhital et al., 1995), a chronology has been set as following: boundaries 1 and 2 occur around 11 Ma, boundaries 2 and 3 occur around 7 Ma, boundaries 3 and 4 occur around 4.1 Ma, boundaries 4 and 5 occur around 2.3 Ma (Fig. 4). However, due to the evidence of an unconformity (Leturmy et al., 1997) at the base of unit 5 and the lack of chronologic data in the same unit, the boundary is poorly dated.

LIQUEFACTION STRUCTURES WITHIN SIWALIKS SERIES

Liquefaction structures can be observed in these series. They are well developed along the Surai Khola section close to Dobatta along the Mahendra Highway (Fig. 5). Most characteristic structures are located within two thick sandstone layers. One of 15 m thick located 90 m above the base of the formation, the second of 14 m thick is located 80 m higher. The destructuration of the base of each of these layers is observed on 4 to 5 m and appears as convolute lamination structures (Fig. 6) of 1 m in

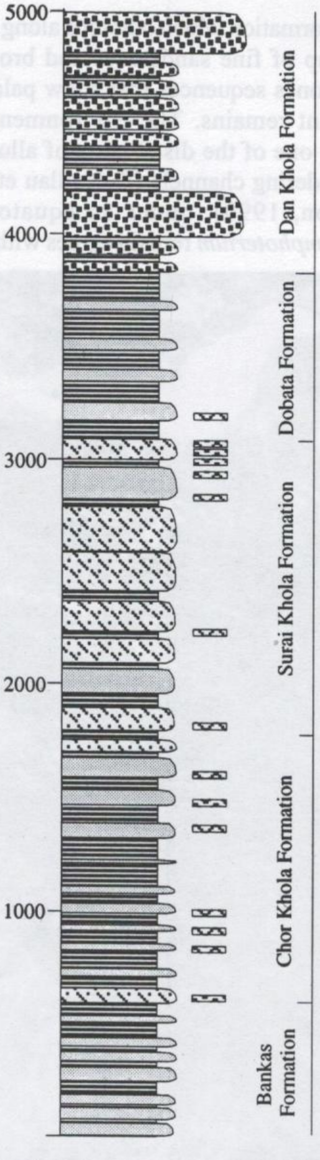

Fig. 5: Stratigraphy of the Surai Khola section (after Appel et al., 1992; Corvinus, 1994; Dhital et al., 1995; s: paleoseismite layers.

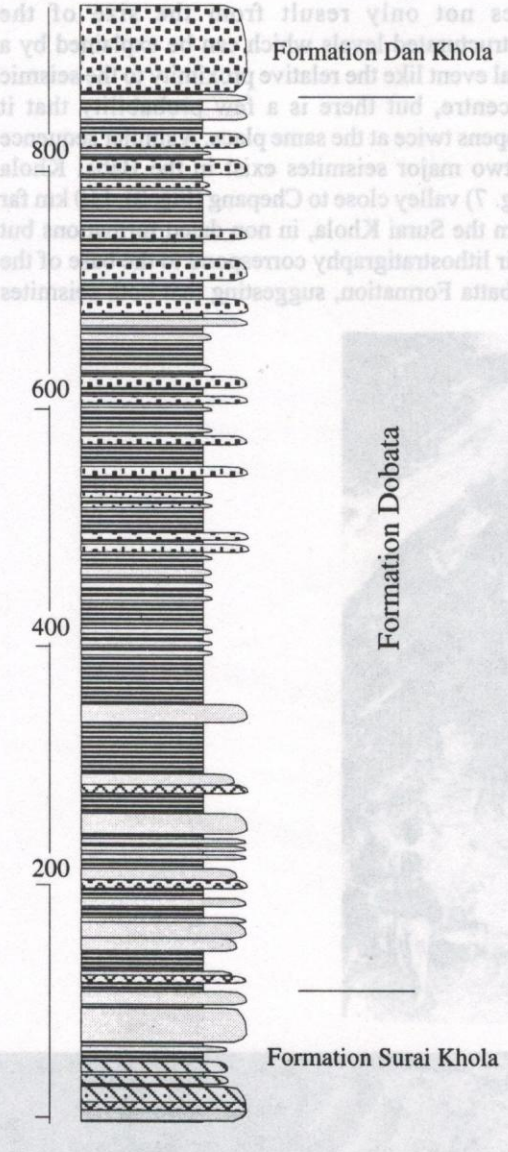

Fig. 6: Details of the formations Surai Khola and Dobatta (after Dhital et al., 1995); s: paleoseismite layers.

diameter in the upper level. They are typical structures of hydroplastic deformation and are commonly interpreted as the result of an increase of fluid-pressure which allows the motion of grains. There is no preferential verging of such structures and by consequence, no mark of shearing. This implies that liquefaction is due to unconsolidated sediments subjected to a vibration. Sims (1975; 1979) and Sieh (1978) have interpreted similar structures as seismites. Smaller equivalent structures occur in underneath levels, especially in a 8 m thick layer located 8 m above the base of the formation and in a 18 m thick layer located in the Surai Khola Formation, 90 m beneath its boundary with the Dobatta Formation. Finally ball and pillow structures fairly frequently occur in lower levels of the Surai Khola Formation and the underneath Chor Khola Formation. Ball and pillow and other dewatering structures have been observed in many other places all along the Siwaliks belt, even if they have not been interpreted as paleosismites; for example some have been reported in eastern Nepal (Mascle and Herail, 1982; Delcaillau et al., 1987) and in Pakistan (Pivnik and Khan, 1996; Durrani, 1997).

Origin of Liquefaction Structures in Sedimentary Sequences

Liquefaction structures can result from different phenomena. Sub-aquatic gravitational outlets supply numerous examples of structures showing a more or less important liquefaction. For directed outlets structures exhibit preferential orientation and verging (Montenat et al., 1993; Hibsch et al., 1997). For example layers of slumps are very frequent in the Berriasian of sub-Alpine belts (Beaudoin, 1977), they indicate that a sediment close to the equilibrium have slid in the basin and the signal sense of the sedimentary slope but does not demonstrate a seismic origin of the motion of the sediments.

Liquefaction also occurs during earthquakes (Sarconi, 1784 in Berardi et al., 1991; Oldham, 1899; Dunn et al., 1939). It takes a lithological system that made up of water-saturated layers covered by an impermeable material. Seismic vibrations promote water expulsion and grains settling; this induces hydraulic fracturation of upper levels (Plaziat et al., 1990; Plaziat and Poisson, 1992; Montenat et al., 1993; Blanc et al., 1997). Typical examples exist in lacustrine deposits (Beck et al., 1992; 1996; Chapron et al., 1996; Hibsch et al.. 1997: Marco et al. 1996; Sims, 1975; Adams, 1996) and have been observed in recent alluvial banks after recent seismic event in Iran (Baltzer and Purser, 1979), in India (Anand and Jain, 1987) or in fluvial Cretaceous sediments in Benoue (Guiraud and Plaziat, 1993). The main characteristic of these structures is that they do not exhibit preferential verging (Montenat et al., 1993; Hibsch et al., 1997). Seilacher (1969) defined them as seismites.

DISCUSSION

Extension

The importance of the seismite sequence in the Dobatta Formation along the Mahendra highway does not only result from the size of the destructurated levels which can be explained by a local event like the relative proximity to the seismic epicentre, but there is a few probability that it happens twice at the same place. A similar sequence of two major seismites exist in the Babai Khola (Fig. 7) valley close to Chepang (Fig. 2), 110 km far from the Surai Khola, in non dated formations but their lithostratigraphy correspond to the base of the Dobatta Formation, suggesting that both seismites

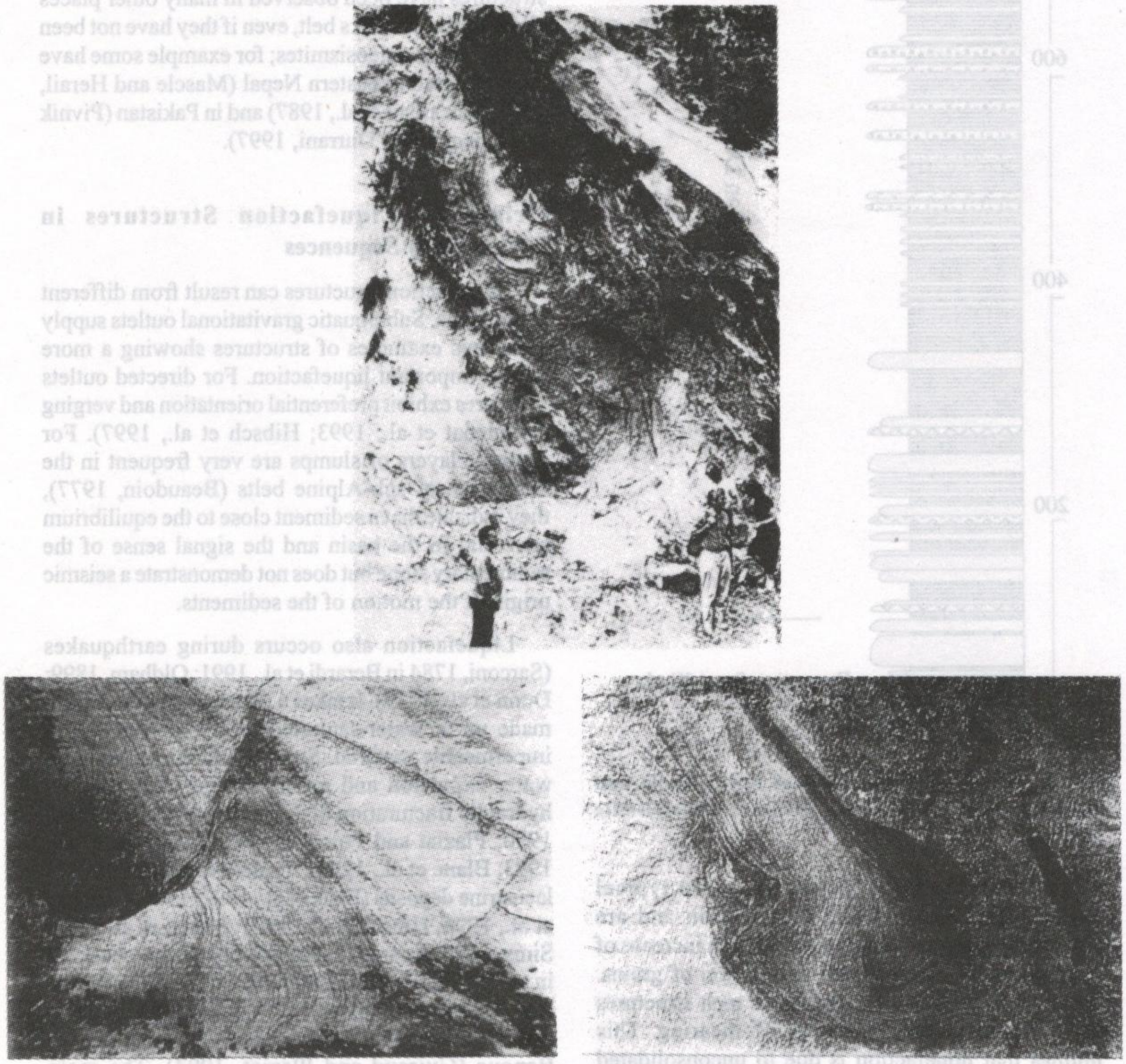

Fig. 7: Liquefied layer of the Dobatta Formation; a: general view; b and c: detail of liquefaction structures.

are the same. Eastward of the Surai Khola valley, the tight structure of the Siwaliks implies that upper levels of the section have been eroded; more eastward, between Butwal and Narayangadh (Fig. 2), the seismites are not observed even if an equivalent of the Dobatta Formation outcrops (Binai Khola upper formation, Tokuoka et al., 1986). They presumably disappear between the Surai Khola and Butwal. This allows to precise that Surai Khola features occur on a distance of at least 110 km.

Intensity and Magnitude

Lot of historical earthquakes of the Himalayan front have promoted major liquefactions in the Terai gangetic Quaternary deposits as related by chronicles. In particular the 1934 earthquake of Bihar-Nepal (Fig. 8), where a 8. 4 magnitude is documented (Molnar et al., 1973); a major liquefaction (intensity domain from IX to X in MSKS) interested an elliptic 12.000 square kilometers band of Terai parallel to the Himalayan front. More occasional events occurred inside an area of about 46,000 km^2 (Dunn et al., 1939) limited by the isoseism VIII in MSKS. Knowing that the modern Terai alluvial and the series of the Dobatta Formation can be compared, physical properties should have been very similar to those actual of the Terai. As the lateral extension of the Surai Khola seismites is of the same order in size as in the area subjected to an important liquefaction during the Bihar-Nepal earthquake (Fig. 8), we can propose a similar intensity scale within the area where Surai Khola paleoseisms occurred, close to IX, and a possibly 8 in magnitude.

Tinsley et al. (1986), Vittori et al. (1991), Guiraud and Plaziat (1993) propose an empirical abacus linking magnitude to the maximal distance separating points where liquefaction is observed; this allows (Fig. 9) a magnitude between 7 and 8 for the Surai Khola paleoseisms to be estimated. Relations have been also proposed linking maximum epicentre distance to liquefaction sites (Re) and the magnitude (M) (Kuribayashi and Tatsuoka, 1975; Youd, 1977; Allen, 1986; Ambrasey, 1988; Papadopoulos and Lefkopoulos, 1993). Making the minimum hypothesis that the epicentre was located within the liquefaction area, Kuribayashi and Tatsuoka's formula ($M = (3.80 + \log Re)/0.77$) gives a lower value of 7. 4, considering Re = 120 km, and of 7 for Re = 60 km (epicentre at the centre of the liquefied zone). Papadopoulos and Lefkopoulos's formula ($M = 3.686 + 1.584 \log Re$) gives the values of 7 and 6. 5 for the same conditions. The Bihar-Nepal earthquake epicentre is located close to Okhaldhunga, outside from the liquefied zone (Fig. 8). The previous formula leads respectively to values of 7. 5 and 7. 1 (Fig. 10), one order lower than those estimated by Molnar et al. (1973).

Hibsch et al. (1997) proposed to evaluate the paleoseismic intensity from the thickness of liquefied layers. After their studies of a serial of lacustrine seismites from historical earthquakes in Equator, these authors propose that a minimum of VI (MSKS) in intensity is necessary to release the liquefaction of silty-sandy sediments and a relation linking seismites thickness to the intensity at the place of observation. This relation applied to the Surai Khola seismites (Fig. 11), leads to propose an intensity from IX to X, which agrees with previous results.

Frequency

The four major Surai Khola seismites are separated by 80 to 100 m. According to the estimated age of the Dobatta Formation, and considering the sedimentation rate to be constant, recurrence time may be about from 200,000 to 250,000 years for a continuous section. This value cannot be compared to the modern frequency of major earthquakes observed in this region (6 in 200 years). But the tectonic context of the region has not changed since 4 Ma. It's not likely that the deformation 4 Ma ago was characterised only by aseismic conditions and that the regional seismicity was very different. Thus, it is possible that all events were not recorded which implies that the section that appears like a continuous one, comprises many gaps. It is also possible to consider that Siwaliks sedimentation has most often removed the paleoseismic records. Favorising the effacement, we will note that the alluvial sedimentation is characterised by an important and fast divagation of rivers over their fan (Mackey and Bridge, 1995); an example in the modern Himalayan front may be the Sun Koshi, which promotes major and fast erosion and sediment

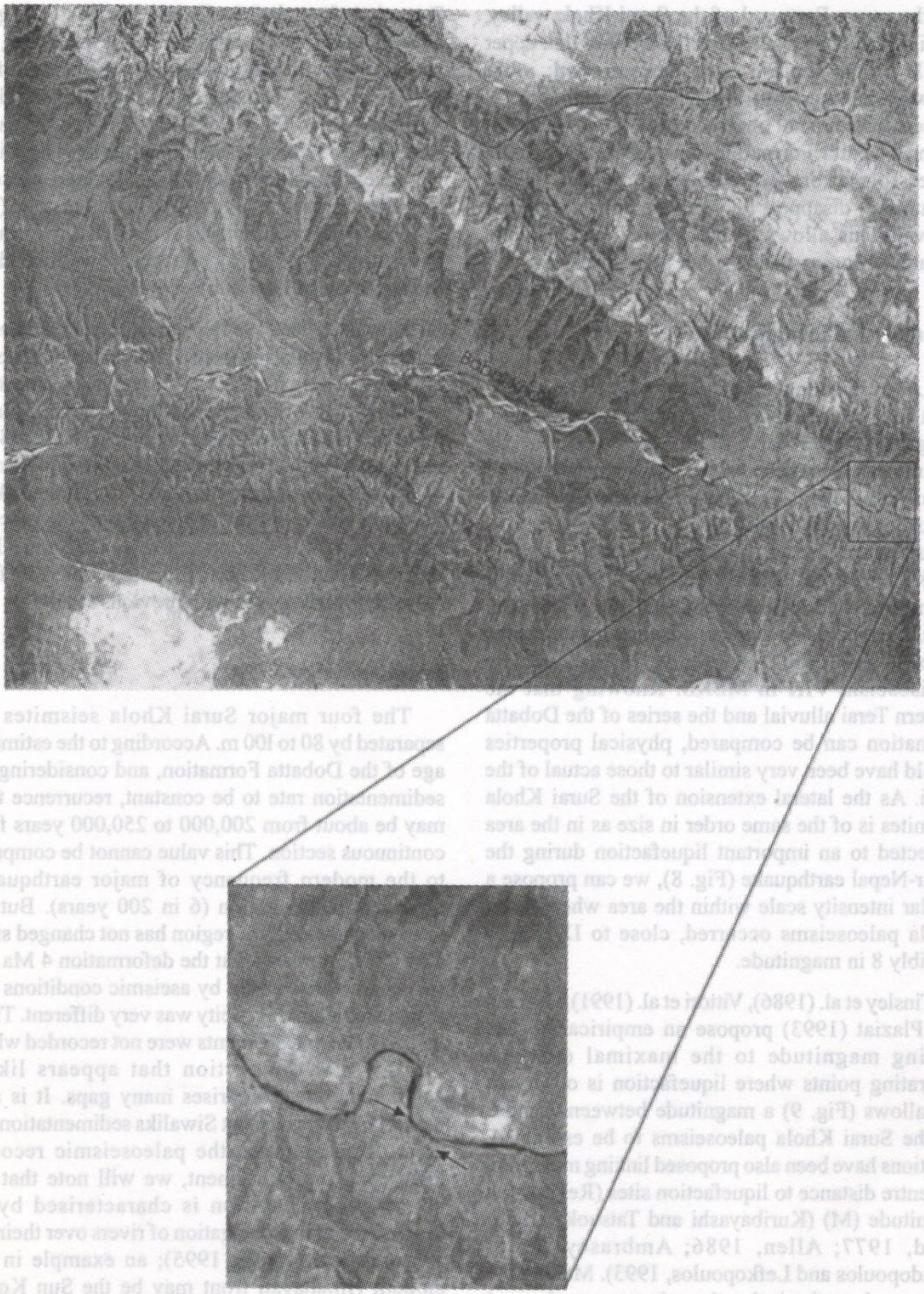

Fig. 8: Occurrences of seismites in the Babai Khola area. Black lines on the satellite image.

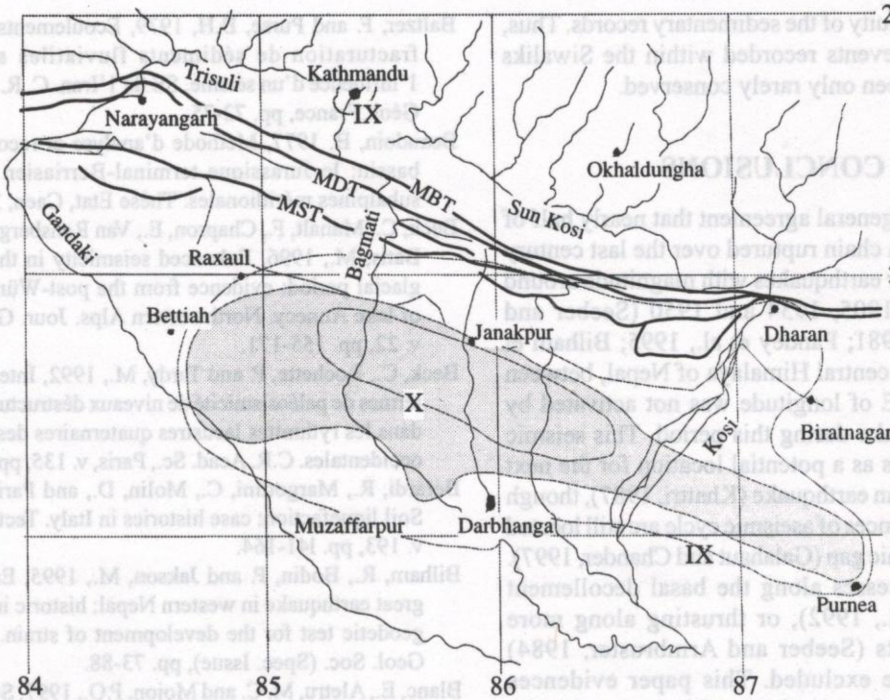

Fig. 9: Evaluation of the magnitude of the paleoseisms of Surai Khola by comparison with the Bihar-Nepal (1934) earthquake; ★: recalculated epicenter after Pandey and Molnar, 1984.

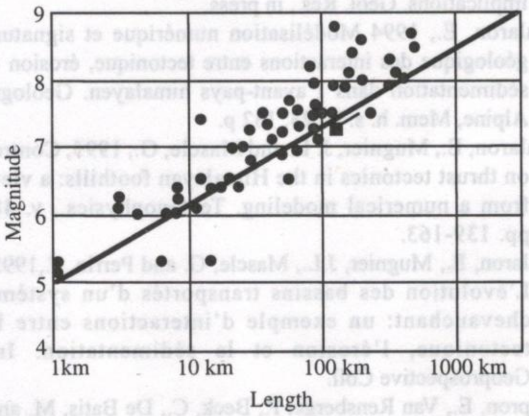

Fig. 10: Evaluation of the magnitude of the paleoseisms of Surai Khola using a diagram magnitude versus maximal distance separating points where liquefaction is observed (after Guiraud and Plaziat, 1993); square: Surai khola paleoseisms.

Favorising the non recording, we will note that numerical modeling results (Chalaron, 1994) suggest that, when deposits occur with a high transport capacity, there are strong reworking of sediments, and frequent lateral transfer of the channels, which implies that, for a stratigraphic succession, more than 50% of the time corresponds to sedimentation gap. Kumar and Nanda (1989) actually show that in the region of Dehra Dun, middle Siwalik layers are characterised by very frequent erosion surfaces, showing the very important small reworking and a consequent high probability to remove fragile structures, like the ones due to the 1934 event.

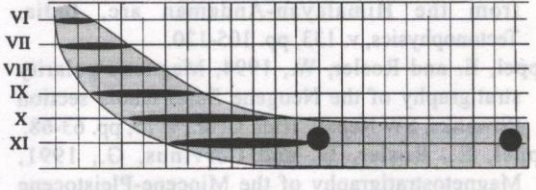

Fig. 11: Evaluation of the intensity of the paleoseisms of Surai Khola using a diagram intensity versus thickness of liquefied layer (after Hibsch et al., 1997); dots: Surai Khola paleoseisms.

scale discontinuity of the sedimentary records. Thus, paleoseismic events recorded within the Siwaliks would have been only rarely conserved.

CONCLUSIONS

There is a general agreement that nearly half of the Himalayan chain ruptured over the last century producing four earthquakes with magnitude around 8.5 in 1897, 1905, 1934 and 1950 (Seeber and Armbruster, 1981; Pandey et al., 1995; Bilham et al., 1995).The central Himalaya of Nepal, between 79°E and 85°E of longitude was not activated by major earthquake during this period. This seismic gap thus stands as a potential location for the next large Himalayan earthquake (Khattri, 1987), though the direct evidences of aseismic cycle arc still located out of the seismic gap (Galahaut and Chander, 1997). Creeping processes along the basal decollement (Jackson et al., 1992), or thrusting along more internal thrusts (Seeber and Armbruster, 1984) cannot still be excluded. This paper evidences paleoseisms in the seismic gap: this suggest that the gap is a gap of historical archives, but not a lack of major seisms.

REFERENCES

Adams, J., 1996, Paleosismology in Canada: a dozen years of progress. Jour. Geoph. Res., v. 101(B3), pp. 6193-6207.

Allen, J.R.L.,1986, Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins. Sedimentary Geology, v. 46, pp. 67-75.

Ambrasey, N.,1988, Engineering Seismology. Int. Jour. Earthquake Eng. Struct. Dyn., v. 7, pp. 1-105.

Anand, A. and Jain, A.K., 1987, Earthquakes and deformed structures (seismites) in Holocene sediments from the Himalayan-Andaman arc, India. Tectonophysics, v. 133, pp. 105-120.

Appel, E. and Rosler, W., 1994, Magnetic polarity stratigraphy of the Neogene Surai Khola section (Siwaliks, SW Nepal). Him. Geol., v. 15, pp. 63-68.

Appel, E., Rosler, W. and Corvinus, G., 1991, Magnetostratigraphy of the Miocene-Pleistocene Surai Khola Siwaliks in west Nepal. Jour. Int. Geophy., v. 105, pp. 191-198.

Auden, J.B., 1935, Traverse in the Himalaya. Geol. Surv. India Rec., v. 69, pp. 123-167.

Baltzer, F. and Purse, B.H, 1979, Ecoulements en masse et fracturation de sédiments fluviatiles actuels sous l'influence d'un séisme, SE de l'Iran. C. R. Somme Soc. Géol. France, pp. 72-75.

Beaudoin, B. 1977, Méthode d'analyse et reconstitution de bassin: le Jurassique terminal-Berriasien des chaînes subalpines méridionales. Thèse Etat, Caen, 339 p.

Beck, C., Manalt, F., Chapron, E., Van Rensbergen, P. and De Batis, M., 1996, Enhanced seismicity in the early post-glacial period: evidence from the post-Würm sediments of lake Annecy. Northwestern Alps. Jour. Geodynamics, v. 22, pp. 155-171.

Beck, C., Rochette, P. and Tardy, M., 1992, Interprétation en termes de paléosismicité de niveaux déstructurés intercalés dans les rythmites lacustres quaternaires des Alpes nord-occidentales. C.R. Acad. Sc., Paris, v. 135, pp. 1525-1532.

Berardi, R., Margottini, C., Molin, D., and Parisi, A., 1991, Soil liquefaction: case histories in Italy. Tectonophysics., v. 193, pp. 141-164.

Bilham, R., Bodin, P. and Jakson, M., 1995, Entertaining a great earthquake in western Nepal: historic inactivity and geodetic test for the development of strain. Jour. Nepal Geol. Soc. (Spec. Issue), pp. 73-88.

Blanc, E., Aletru, M. C. and Mojon, P.O., 1997, Soft-sediment deformation structures interpreted as seismites in the uppermost Aptian to lowermost Albian transgrssive deposits of Chihuahua basin (Mexico): geodynamic implications. Geol. Res., in press.

Chalaron, E., 1994 Modélisation numérique et signature géologique des interactions entre tectonique, érosion et sédimentation dans l'avant-pays himalayen. Geologie Alpine, Mem. h. s. N. 23, 132 p.

Chalaron, E., Mugnier, J. L. and Mascle, G., 1995, Control on thrust tectonics in the Himalayan foothills: a view from a numerical modeling. Tectonophysics., v. 48, pp. 139-163.

Chalaron, E., Mugnier, J.L., Mascle, G. and Perrin, F.,1995, L'évolution des bassins transportés d'un système chevauchant: un exemple d'interactions entre la tectonique, l'érosion et la sédimentation. In: Geoprospective Coll.

Chapron, E., Van Rensberge, P., Beck, C., De Batis, M. and Paillet, A., 1996, Lacustrine sedimentary records of brutal events in lake Le Bourget (norhwestern Alps-southern Jura). Quaternaire, v. 7, pp. 155-168.

Corvinus G., 1994, The Surai Khola and Rato Khola fossiliferous sequences in the Siwalik Group, Nepal. Him. Geol., v. 15, pp. 49-62.

Delcaillau, B., 1986, Dynamique et évolution morphostructurale du piémont frontal de l'Himalaya: les Siwaliks du Népal oriental: Rev. Géol. Dyn. Geograph. Phys., v. 27, pp. 319-337.

Delcaillau, B., Herail, G. and Mascle, G., 1987, Evolution geomorpho-structurale de fronts de chevauchement actifs: le cas des chevauchements intrasiwaliks du Népal central. Z. Geomorph., N. F., v. 31(3), pp. 339-360.

Department of Mines and Geology, 1985, Nepal exploration opportunities. Kathmandu, Nepal, 52 p.

Dhital, M.R., Gajurel, A.P., Pathak, D., Paudel, L.P. and Kizaki, K., 1995, Geology and structure of the Siwaliks and Lesser Himalaya in the Surai Khola-Bardanda area, midwestern Nepal. Bull. Dept. Geol. Tribhuvan Univ. Nepal, v. 4(Spec. Issue), pp. 1-70.

Dunn, J.A., Auden, J.B. and Ghosh, A.M.T., 1939, Earthquake effects in the Bihar-Nepal earthquake of 1934. Mem. Geol. Surv. India, v. 73, pp. 27-48.

Durrani, K.H., 1997, Etude stratigraphique et sédimentologique du "Siwaliks" dans la région de Zarghune. Quetta, Balochistan, Pakistan. Thesis Univ. Orléans, Mem. Orléans-Géoscience, v. 17, 199 p.

Galahaut, V.K. and Chander, R., 1997, Evidence for an earthquake cycle in NW Outer Himalaya near 78°E longitude from precision leveling observations. Geoph. Res. Lett., v. 24, pp. 2-228.

Gansser, A., 1964, Geology of the Himalayas. Interscience Publ. Wiley, London, 289 p.

Gansser, A., 1983, Geology of the Bhutan Himalaya. Denk. Schweiz. Natur. Ges., v. 96, 181 p.

Glennie, K.W. and Ziegler, M.A., 1964, The Siwalik formation in Nepal. C.R. 22nd Cong. Genl. Intern., Delhi, v. 15, pp. 82-95.

Guiraud, M. and Plaziat, J.C., 1993, Seismites in the fluvatile Bima sandstones: identification of paleoseisms and discussion of their magnitudes in a Cretaceous synsedimentary strike-slip basin (Upper Benue, Nigeria). Tectonophysics., v. 225, pp. 493-522.

Hérail, G. and Mascle, G., 1980, Les Siwaliks du Népal central: structure et géomorphologie d'un piémont en cours de déformation. Bull. Assoc. Géogr. Fr., v. 431, pp. 259-267.

Hérail, G., Mascle, G. and Delcaillau, B., 1986, Les Siwaliks de I'Himalaya du Népal: un exemple d'évolution géodynamique d'un prisme d'accretion intracontinental. In: Evolution du domaine orogénique de I'Asie Méridionale (de la Turquie à l'Indonésie). Livre jubilaire en I'honneur de P. BORDET, Sciences de la Terre. Mém. v. 47, pp. 155-182.

Hibsch C., Alvarado A., Yepes, H., Perez, V.H. and Sebrier, M., 1997, Holocene tectonics and liquefaction/soft sediment deformation in Quito (Ecaador): a paleoseismic history recorded in lacustrine sediments. Jour. Geodynamics, v. 24, p. 30.

Jackson, M., Barriento, S., Bilham, R., Kayestha, D. and Shresta, B., 1992, Uplift in the Nepal Himalaya revealed by spirit leveling. Geophys. Res. Let., v. 19, pp. 1539-1542 .

Khattri, K.N., 1987, Great earthquakes, seimic gaps and potential for earthquake disaster along the Himalaya plate boundary. Tectonophysics, v. 138, pp. 79-92.

Kumar, R. and Nanda, A.C., 1989, Sedimentology of the middle-Siwalik Subgroup of Mohand area, Dehra Dun valley, India. Jour. Geol. Soc. India, v. 34, pp. 597-616.

Kuribayashi, E. and Tatsuoka, F, 1975, Brief review of liquefaction during earthquakes in Japan. Soil & Foundations, v. 15, pp. 81-92.

Leturmy, P., Mugnier, J.L., Delcaillau, B., Mascle, G. and Vidal, G., 1997, Uplift rates linked to the propagation and out-of-sequence reactivation of the outer thrust belt of western Nepal. XII Himalayan workshop, Rome, pp. 173-174.

Lyon-Caen, H. and Molnar, P., 1984, Constraints of the structure of the Himalaya from analysis of gravity anomalies and a flexural model of the lithosphere. Jour. Geoph. Res., v. 88(B10), pp. 8171-8191 .

Mackey, S. D. and Bridge J.S., 1995, Three-dimensional model of alluvial stratigraphy : theory and application. Jour. Sediment. Res., v. 65, pp. 7-31.

Marco, S., Stein, M., Agnon, A. and Ron, H., 1996, Long-term earthquake clustering: a 50,000-year paleoseismic record in the Dead Sea graben. Jour. Geoph. Res., v. 101(B3), pp. 6179-6192.

Mascle, G. and Herail, G., 1982, Les Siwalik: le prisme d'accrétion tectonique associé a la subduction intracontinentale himalayenne. Géol. Alpine, v. 58, pp. 95-104.

Mascle, G., Herail, G., Delcaillau, B. and Van Haver, T., 1986, Structure et évolution des bassins d'épisuture et de périsuture liés à la chaîne himalayenne. Bull. Centres Rech. Explor-Prod. Elf-Aquitaine, v. 10, pp. 181-203.

Medlicott, H.B., 1864, On the geological structure and relationship of the southern portion of the Himalayan range between the rivers Ganga and Ravee. Mem. Geol. Surv. India, v. 3, pp. 1-212.

Molnar, P., 1990, A review of the seismicity and the rates of active underthrusting and the deformation of the Himalaya. Him. Geol., v. 1, pp. 131-154.

Molnar, P. Fitch, T.J. and Wu, F.T., 1973, Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia. Earth Planet. Sc. Let., v. 19, pp. 101-112.

Montenat, C., Ott D'estevou, P., Barrier, P. and Paturel, D., 1993 Les séismites: essai de typologie. Géochronique, v. 46, pp. 15-17.

Mugnier, J.L., Mascle, G. and Faucher, T., 1992 La structure des Siwaliks de l'Ouest Népal: un prisme d'accrétion intracontinental. Bull. Soc. Géol. France, v. 163, pp. 585-595.

Nakata, T., 1982, A photogravimetric study on active faults in the Nepal Himalayas. Jour. Nepal Geol. Soc., v. 2, pp. 67-81.

Nakata, T., 1988, Active faults of the Himalayan of India and Nepal. Geol. Soc. Am., v. 218(Spec. Paper), pp. 243-264.

Ni, J. and Barazangi, M., 1984, Seismotectonics of the Himalayan Collision Zone: geometry of the underthrusting Indian plate beneath the Himalaya. Jour. Geoph. Res., v. 89(B2), pp. 1147-1163.

Oldham, R.D., 1899, Report on the great earthquake of l2 June 1897. Mem. Geol. Surv. India, v. 29, pp. 1-379.

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Lavé, J. and Massot, J.P., 1995, Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophys. Res. Lett., v. 22, pp. 751-754.

Papadopoulos, G.A. and Lefkopoulos, G., 1993, Magnitude-distance relations for liquefaction in soil, from earthquakes. Bull. Seism. Soc. Am., v. 83, pp. 925-938.

Pivnik, D.A. and Javed Khan, M., 1996 Transition from foreland- to piggyback basin deposition. Plio-Pleistocene Upper Siwalik group, Shingar range, NW Pakistan. Sedimentology, v. 43, pp. 631-646.

Plaziat, J.C. and Poisson, A., 1992, Mise en évidence de plusieurs séismes majeurs dans le Stampien supérieur continental au Sud de Paris: enregistrements sédimentaires de la tectonique oligocène. Bull. Soc. Geol. France, v. 163, pp. 541-551.

Plaziat, J.C., Purser, B.H. and Philobos, E., 1990, Seismic deformation structures (seismites) in the syn-rift sediments of the NW Red Sea (Egypt). Bull. Soc. Geol. France, v. 8(6), pp. 419-434.

Raiverman, V., Kunte, S.V. and Mukherjee, A., 1983, Basin geometry, Cenozoic sedimentation and hydrocarbon prospects in northwestern Himalaya and Indo-Gangetic plains. In: L.L. Bhandari (eds.), Petroliferous basins of India. Petrol. Asia Jour., v. 6, pp. 67-92.

Schelling, D. and Arita, K., 1991, Thrust tectonics, crustal shortening, and the structure of the far-eastern Himalaya. Tectonics, v. 10, pp. 851-862.

Seeber, L. and Armbruster, J., 1981, Great detachement earthquakes along the Himalayan arc and the long term forecasts. In: Earthquake Prediction: an international review. Maurice Ewing series, v. 4, pp. 259-277.

Seeber, L. and Armbruster, J., 1984, Some elements of continental subduction along the Himalayan front. Tectonophysics., v. 105, pp. 263-278.

Seilacher, A., 1969, Fault-graded beds interpreted as seismites. Sedimentology, v. 13, pp. 155-159.

Sieh, K.E., 1978, Prehistoric large earthquakes produced by slip on the San Andreas fault at Pallett creek, California. Jour. Geoph. Res., v. 83, pp. 3907-3939.

Sims, J.D., 1975, Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. Tectonophysics., v. 29, pp. 141-152.

Sims, J.D., 1979, Records of prehistoric earthquakes in sedimentary deposits in lakes. Earthquake In: Bull. U.S. Geol. Surv., v. 1, pp. 228-233.

Tandon, S.K., 1990, The Himalayan foreland: focus on Siwalik basin. In: S.K. Tandon, C.S. Pant and S.M. Casshyap (eds.), Sedimentary basins of India: tectonic context. Gyanodaya Prakashan print., Nainital, pp. l71-201 .

Tinsley, J. C., Youd, T. L., Perkins, D. M. and Chen, A. T. F., 1986, Evaluating liquefaction potential. U.S. Geol. Surv. Prof. paper, v. 1360, pp. 263-316.

Tokuoka, T., Takayasu, K., Yoshida, M. and Hisatomi, K., 1986, The Churia (Siwalik) Group of the Arung Khola area, west central Nepal. Mem. Fac. Sc. Shimarte Univ., v. 20, pp. 135-210.

Tokuoka, T., Takayasu, K., Hisatomi, K., Yamasaki, H., Tanaka, S., Konomatsu, M., Sah, R. B. and Ray, S., 1990, Stratigraphy and geologic structures of the Churia (Siwalik) Group in the Tinau Khola-Binai Khola area, west central Nepal. Mem. Fac. Sc. Shimane Univ., v. 24 pp. 71-88.

Vittori, E., Sylos Labin, S. and Serva, L., 1991, Paleosismology: review of the state-of-the-art. Tectonoph., v. 193, pp. 9-32.

Youd, T.L., 1977, Discussion of "Brief review of liquefaction during earthquakes in Japan by E. Kuribyashi and F. Tatsuoka". Soil & Foundations, v. 17, pp. 82-85.