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The break-back thrust splay of the Main Dun Thrust (Himalayas of western Nepal): evidence of an intermediate displacement scale between earthquake slip and finite geometry of thrust systems

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Abstract—Numerous studies have shown that development of a forward breaking sequence in a thrust belt is accompanied by reactivation of inner faults and development of break-back thrusts. The partitioning of shortening in the Outer and Lesser Himalayan thrust belt follows these rules. Tectonic and sedimentary relationships in this thrust belt exemplify out-of-sequence thrusts in the Lesser Himalayas and break-back imbricate fans close to the MBT (Main Boundary Thrust) and MDT (Main Dun Thrust) which are transported during their development above the Himalayan basal detachment. The displacement along a single splay of the imbricate fan of the MDT was > 40 m, before abandonment and nucleation of a new inner splay. The development of the break-back imbricate fan is discontinuous in time. Furthermore, superimposition of ultracataclasite, pressure-solution cleavage, extensional crenulation cleavage and tension gashes in the fault zones suggests that the 40 m displacement occurred by discrete slip events, or most probably by a succession of several seismic/aseismic deformations. These data require several scales of sequential displacement in the Outer and Lesser Himalayas consisting of forward propagation of the thrust system, out-of-sequence reactivation, break-back nucleation of thrust splays, and seismic/aseismic fault slip. Our findings require an intermediate period of tectonism between the < 1000 y earthquake cycle and the > 500 Ka deformation of the accretionary sediments of the Himalayas. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Thrust sequence classifications are based on simple kinematic rules. Piggy-back thrust sequences (Boyer and Elliott, 1982; Butler, 1982) are found in most thin-skinned thrust belts, and are associated with deformation which propagates towards the foreland over a period of several million years. Nonetheless, detailed studies show complexities in the sequence of displacement along thrust systems. For example, Burbank and Beck (1989) show kilometric out-of-sequence thrust pulses lasting for 0.5–1 Ma in the Salt Range of Sub-Himalaya (Pakistan), and Jordan *et al.* (1993) show synchronous motion on several thrusts lasting for 1–2 Ma in the Sub-Andean thrust belt. Hectometric displacement along minor splays of a break-back thrust (term defined by McClay, 1991) is also observed in the Southern Pyrenees, where *ca* 1 Ma separated nucleation of each branch (Deramond *et al.*, 1993). These episodic events are on a million-year scale and are between 10^3 and 10^4 longer than seismic/aseismic fault slip cycles (nearly 100–1000 y, Kanamori and Anderson, 1975) or than episodic tilting of blocks during extension (nearly 1000–10000 y, Hooke, 1972). It is suggested in this paper that displacement along a break-back splay may follow an intermediate periodicity. The study (location on Figs 1 & 2) is based on thrust geometry, syn-orogenic depositional pattern and microstructures in the foothills of the Southern Himalayas (western Nepal).

THE OUTER AND LESSER HIMALAYAN BELT

Several thrust sheets form the Outer Himalayas (Fig. 2) and deform the Cenozoic foreland basin sequence between the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). The foreland basin sequence is classically subdivided into three units on the basis of lithostratigraphic criteria (Auden, 1935). These are Lower, Middle and Upper Siwaliks,

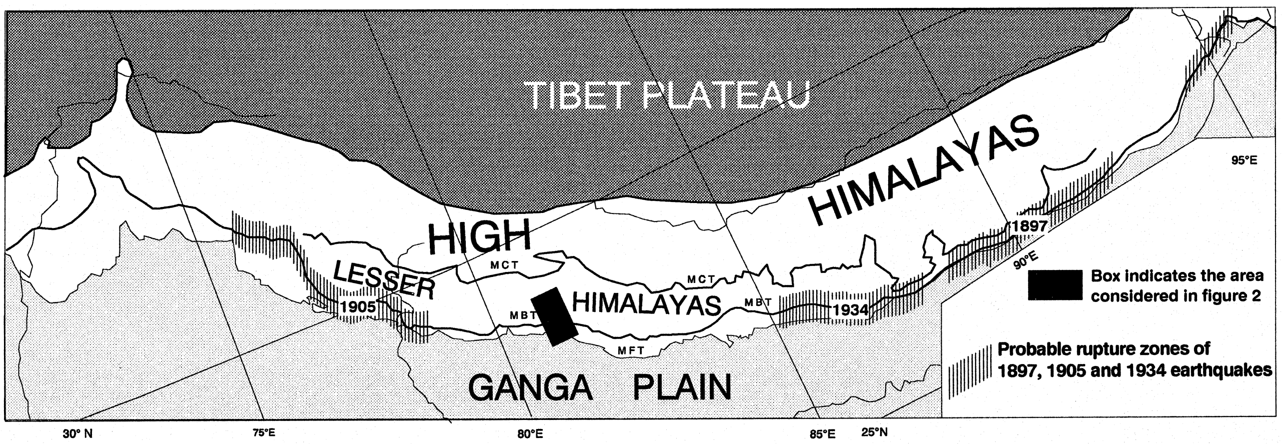

Fig. 1. Structural sketch of the Himalayas with location of the area considered and probable rupture zones of historical earthquakes.

and their ages in western Nepal range, respectively, from 13 to 9 Ma, 9 to 4.8 Ma and 4.8 to 1 Ma (Appel *et al.*, 1991). Over the Upper Siwaliks, Dun Gravels were deposited in the mobile belt (Ranga Rao *et al.*, 1988). A shallow north-dipping detachment (Ni and Barazangi, 1984) links the development of the thin-skinned thrust belt of the Outer and Lesser Himalayas to the deep tectonics beneath the Higher Himalayas. Thrusting, sedimentation and erosion were simultaneous in the Outer Himalayan Belt with hanging walls of thrusts eroded and alluvial plains located above small basins. These basins are fundamentally translated piggy-back (Ori and Friend, 1984) on large thrust sheets above the basal décollement (Delcaillau

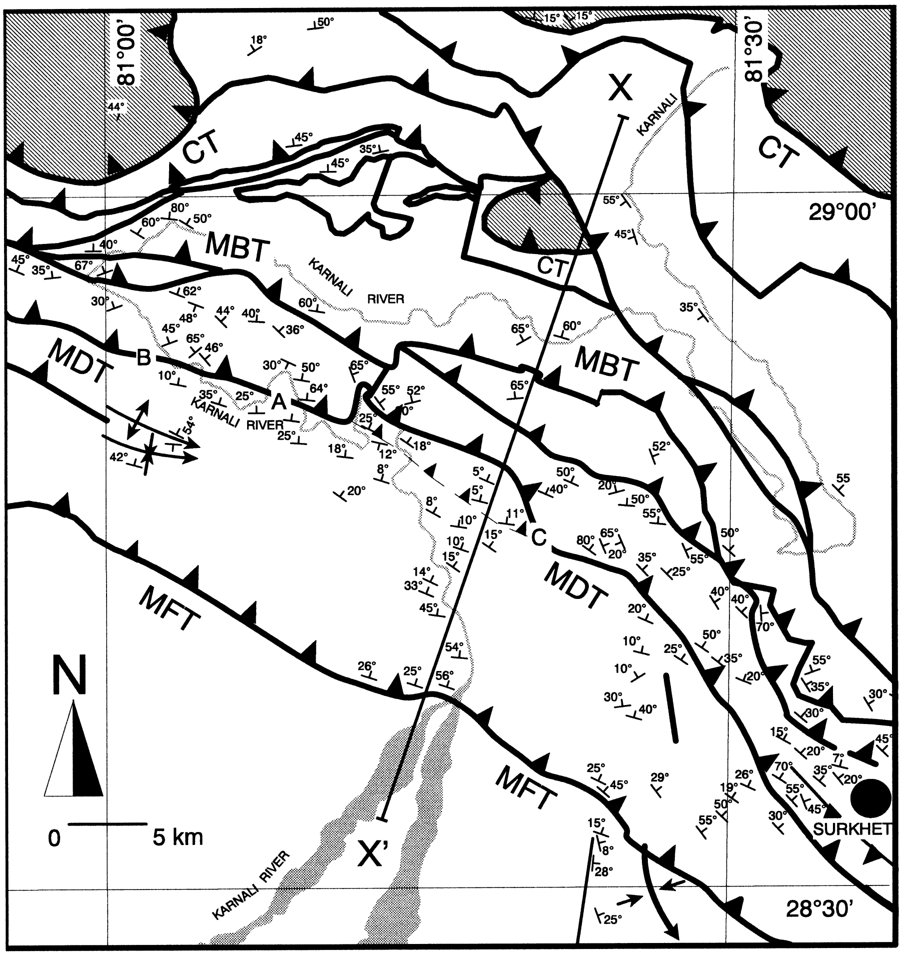

Fig. 2. Structural map of the area considered and location of Fig. 3 (line XX′). MFT is the Main Frontal Thrust, MDT is the Main Dun Thrust, MBT is Main Boundary Thrust and CT is the Mahabharat Thrust. Dark hachured areas are crystalline nappes.

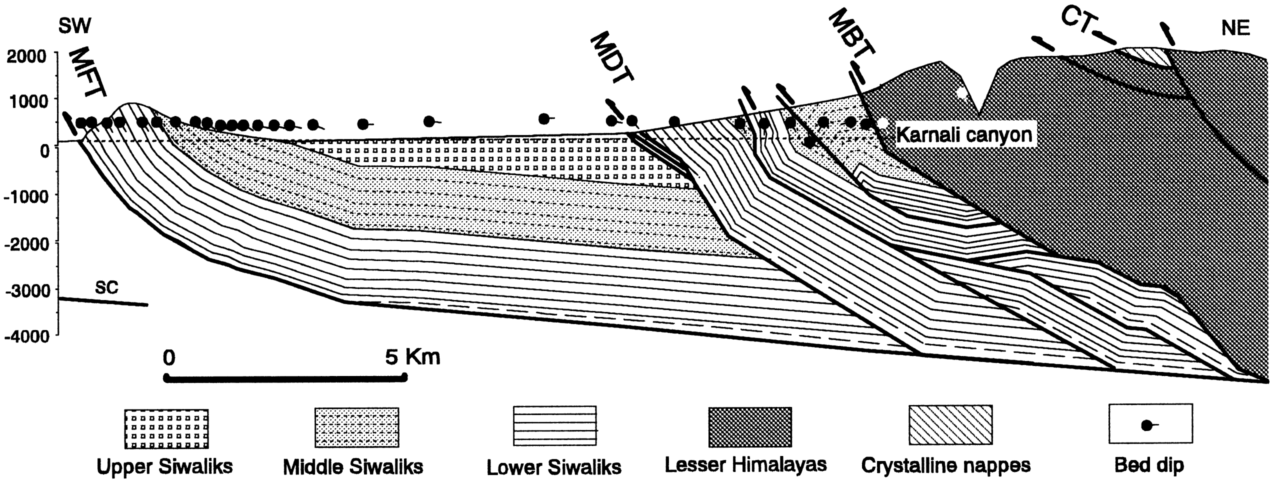

Fig. 3. Balanced cross-section through the Outer and Lesser Himalayan Thrust Belt, Karnali area, western Nepal. (Line XX′ on Fig. 2.) SC refers to the bottom of the foreland sediments from seismic control beneath the Ganga plain (Line 7, HMG Nepal, 1994).

et al., 1987), but are momentarily truncated by motion on faults. Geometric relationships between syn-orogenic sediments and thrusts enable the relative timing of fault motion to be determined.

Mapping recently completed (Mugnier *et al.*, 1995) provides data for the balanced cross-section in Fig. 3 from the Karnali area, western Nepal. The deep trajectory of the MFT was drawn using the kink method (Suppe, 1983) applied to dip and stratigraphic thickness data. The main décollement is located at 3–5 km depth, slightly above the northward prolongation of the acoustic basement recorded by seismic methods in the foreland (HMG Nepal, 1994). The Main Dun Thrust (MDT on Fig. 2) is one of the most laterally extensive structures of the Outer belt. In portions of western Nepal, the imbrications associated with MDT contain several splays that show complex relationships with syn-orogenic sediments (Figs 4 & 5).

The MBT is very steep in the field and forms the boundary between Cenozoic foreland sediments and older rocks of the Lesser Himalayas (Le Fort, 1975). Duplexes, inferred from balancing bed-length, developed in the Outer Himalayan formations at the footwall of the MBT. Break-back thrusts truncate Late Quaternary sediments a few hundred metres north of the MBT in far western Nepal (Bashyal, 1981), whereas strike-slip and normal components are observed on active faults located a few hundred metres north of MBT in mid-western Nepal (Nakata, 1989; Mugnier *et al.*, 1994).

In the Lesser Himalayas of far western Nepal, the geometry and kinematics of the faults are difficult to assess. Nonetheless the remains of Himalayan crystalline nappes above the Mahabharat Thrust (CT on Fig. 2) are locally truncated by faults (Shresta, 1985), involving several kilometres of out-of-sequence motion. This structural situation has already been described by Srivastava and Mitra (1994) in Himalayas of western India or by Schelling and Arita (1991) in eastern Nepal.

SEQUENCE OF EVENTS IN THE IMBRICATE SPLAY OF THE MAIN DUN THRUST

Four key features have been observed and form the basis of our analysis close to the MDT: (a) sediments of the Dun Gravels overlap inactive thrust faults; (b) these sediments onlap erosional surfaces that affect the Lower Siwaliks in the hanging wall of thrusts; (c) these sediments are truncated by younger, inner faults; (d) faults dip less steeply than beds in the hanging wall of the thrusts. These angular relationships suggest that thrusts break through the Lower Siwalik strata that were previously tilted in the hanging wall of the main MDT slip surface.

Figure 4 illustrates an outcrop along the Karnali River (A on Fig. 2), whereas Fig. 5 is a synthetic geometry that basically applies to the segment B–C on Fig. 2 of the MDT. Analysis leads to the following succession for tectonic and sedimentary events: (1) >8 km displacement occurred along thrust Ia (from balancing bed length on Fig. 3); (2) a topographic culmination developed over the hanging wall of the thrust Ia. Thrust Ib, which has a very steep dip and is nearly parallel to the Lower Siwaliks beds and to thrust Ia, was also active at that time; (3) erosion exposed the Lower Siwaliks in the hanging wall; (4) sedimentary sequences (a) and (b) overlapped Lower Siwaliks, thrusts Ia and Ib; (5) thrust II moved more than 40 m through the previously tilted Lower Siwalik strata and through the upper part of sequence (b); (6) erosion affected the hanging wall of thrust II; (7) top of sequence (c) overlapped Lower Siwaliks and thrust II; (8) thrust III moved more than 40 m; (9) recent terrace deposits (e) overlap the hanging wall of thrust III; (10) regional uplift occurred during motion along the basal décollement that extends the Main Frontal Thrust (Fig. 3) and Karnali river incised the present-day outcrops.

Fig. 4. (a) Picture of the break-back thrust splay of the MDT (A on Fig. 2 for location). The complex pattern of the outcrop induces a strong distortion of the thickness of sedimentary bodies on the picture.

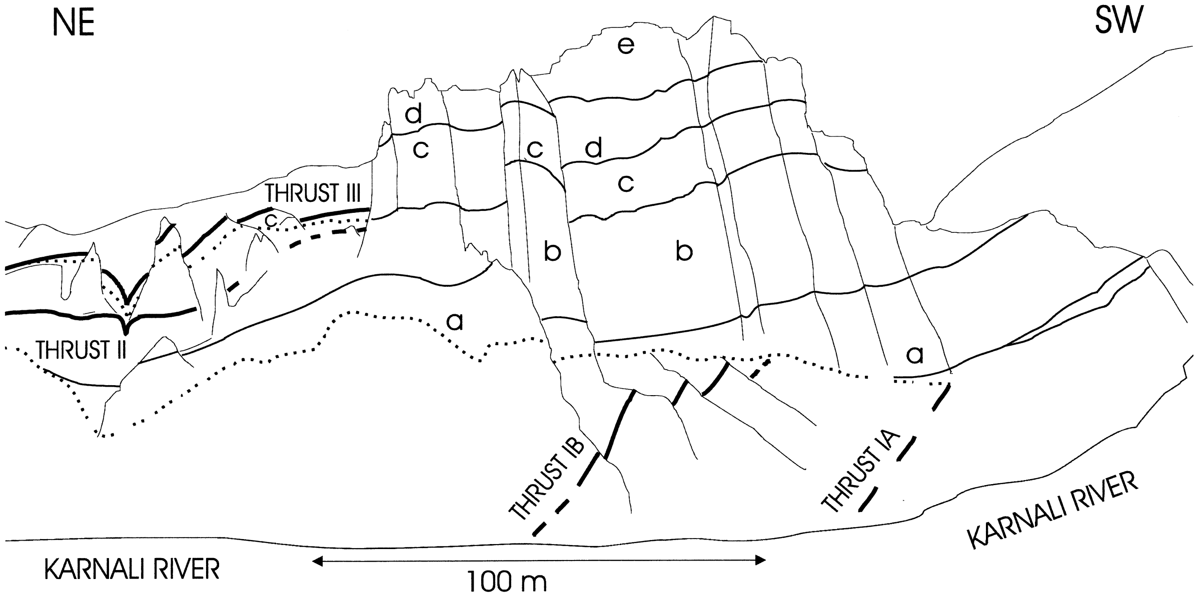

Fig. 4. (b) Interpretation of the picture. Thrusts Ia, Ib, II, III are branches of the Main Dun Thrust (MDT) in the Karnali area. Faults Ia and Ib dip 50–55° to the NE, faults II and III dip 30–34° to the NE. Dotted lines are unconformities, thin lines are boundaries of (a), (b), (c), (d) and (e) sequences, very thin lines are prominent relief features.

The cutting pattern shows that thrusts II and III propagated after tilting of the strata in the hanging wall of the major MDT slip surface. They may have propagated after the deposition of sequence (a) and (b), or alternatively were present in the Lower Siwalik beds prior to the deposition of sequence (a) and (b) and were subsequently reactivated.

The >1 m size Lower Siwalik boulders (locally more than 4 m) in the debris flows (Gms on Fig. 6) at the bottom of sequence (c) and (d) appear to be related to erosion of adjacent hanging wall culminations developed respectively during motion of thrusts II and III. These huge boulders promote the development of erosion columns close to the thrusts (Fig. 4). Their size and the thickness of the debris flow decreases rapidly southwards. Close to the thrust contact, the sediments display the typical pattern of thrust front breccia (Delcaillau *et al.*, 1987) characterised by monogenic Lower Siwalik clasts embedded in a silty matrix without any clear bedding structure. The erosional surfaces that bound sequence (d) are only observed close to the thrust front, and are presumably related to local tectonics. Nonetheless, no attempt was made systematically to correlate facies evolution (Miall, 1978) to local tectonics as sequences alternatively show coarsening upwards of bedsets, fining upwards or a succession of the two trends. Furthermore, numerous unconformities in the Upper Siwaliks and Dun Gravels at the hanging wall of the MFT show that this latter thrust was active for several million years (Leturmy *et al.*, 1995) and partly controlled the deposition of Dun Gravels.

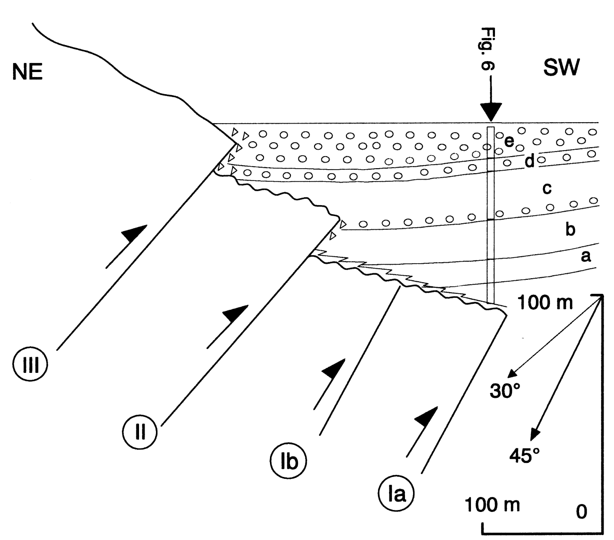

Fig. 5. Simplified cross-section showing the relationships between the sequence boundaries and thrusts forming the Main Dun Thrust (MDT) imbricate (Vertical exaggeration: X2). Vertical column shows the location of the stratigraphic log of Fig. 6.

In short, these data show a break-back sequence of thrust splays. A period of quiescence separated thrust displacement episodes which relayed toward the hinterland. The spacing between thrusts is small (<100 m), and the imbricates join laterally in a single fault trace. Therefore, the displacement along each splay corresponds at depth to the displacement on the MDT. The MDT itself is displaced piggy-back above the basal décollement. Nonetheless, details of the MFT activity compared to thrusts I, II, III cannot be specified. These faults could be either synchronous, or the MFT could be temporarily inactive during motion along the MDT splay.

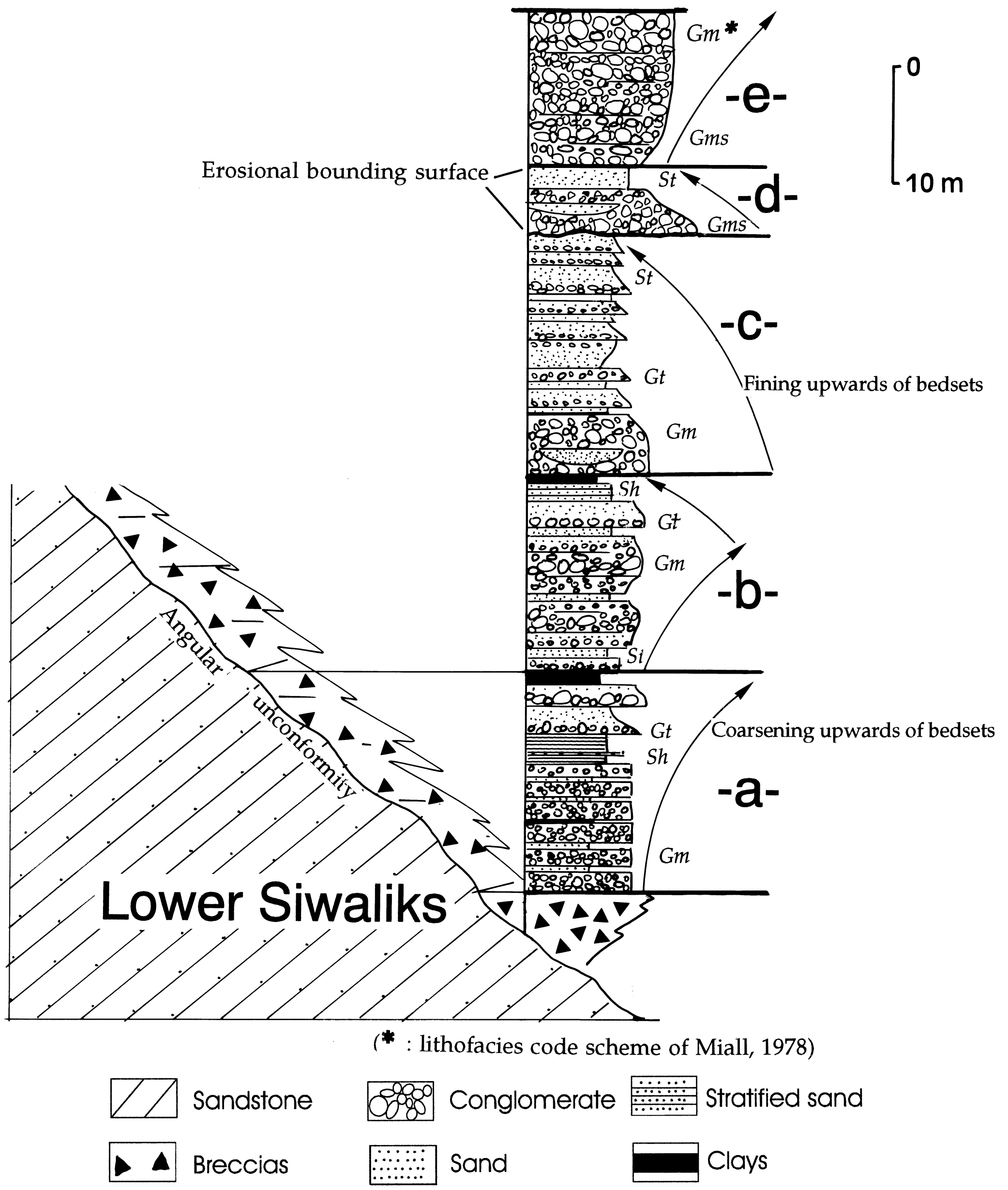

Fig. 6. Lithofacies of sequences which onlap the thrust sheets (A on Fig. 2 for location). Gms, Gm, Gt, Sh, St refer to the Miall nomenclature (1978) and are, respectively, debris flow, sieve deposits, minor channel fills, dunes and planar bed flow. The > 1 m size Lower Siwalik boulders of sequences (c) and (d) are linked to the erosion of hanging-wall culminations of thrusts II and III.

MECHANISM AND RATE OF FAULT-SLIP ALONG THE BREAK-BACK SPLAYS

At least 8 km of displacement occurred along the MDT, the main shear zone of which (thrust Ia on Fig. 5) is < 2 m thick. Two mechanisms may accommodate sliding on the same fault (Gratier and Gamond, 1990) with transitions between cataclastic deformation (possibly seismic slip) and pressure solution deformation (aseismic convergence resulting in aseismic slip). Fabrics within the MDT show superposition of both deformation types: micro-clasts of quartz and calcite (from a few mm to 10 μm in size) are incorporated in a matrix where clay minerals outline a cleavage (S on Fig. 7) and an extensional crenulation cleavage (C′ on Fig. 7) (Platt and Visser, 1980). These fault gouges, with their sharp internal C–C′ shear surfaces (close to 15° on Fig. 7), may be associated with unstable fault motion or seismic slip events (Shimamoto, 1989), whereas micro-breccia probably represents the rock products of frictional wear during seismic slip or aseismic cataclastic flow (Sibson, 1989). Small-scale tension gashes are filled with calcite and quartz (T on Fig. 7) and bisect the acute angle of two conjugate fracture sets (F1–F2 on Fig. 7), indicating a major principal strain direction dipping southwards. This orientation is consistent with a phase of inter-seismic strain accumulation in the Outer Himalayas (Bilham *et al.*, 1995), but not with the typical development of a shear zone pattern, as T is nearly perpendicular to the

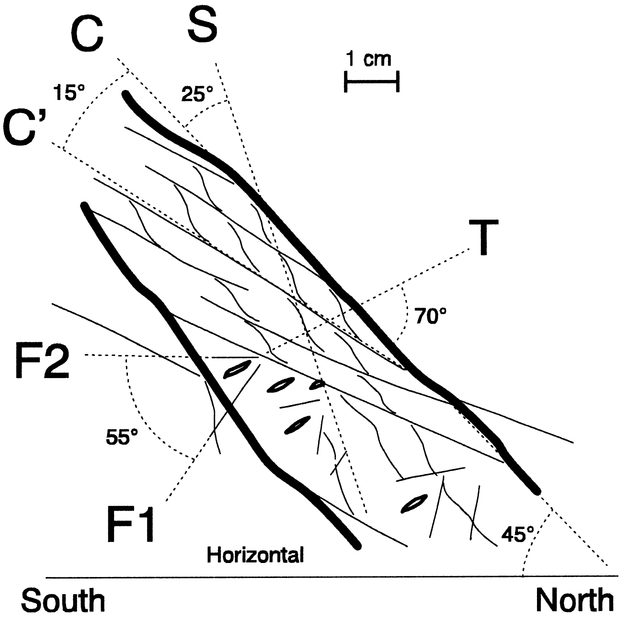

Fig. 7. Typical pattern observed at the outcrop along the main Karnali shear zone (C on Fig. 2 for location). (Thrust Ia on Fig. 5.) C: Shear plane parallel to the shear zone boundary; C′: Extensional crenulation cleavage (Riedel shear fractures), S: Cleavage and T: Tension gashes filled with calcite and quartz; F1–F2: conjugate fractures.

shear zone (C–T angle is more than 70° on Fig. 7). These observations suggest that the MDT splay follows the same type of seismic–aseismic cycle as the MFT in western India (Rajal *et al.*, 1986; Gahalaut and Chander, 1997) or in Eastern Nepal (Pandey *et al.*, 1995). At the very least, the superimposition of the pressure-solution deformation on the cataclastic deformation implies discontinuous slip increments.

A single 40 m seismic motion along one fault of the splay (Fig. 5) is implausible as such a single seismic event would imply, from the relationships between rupture area and mean coseismic slip (Bilham *et al.*, 1995), a rupture zone much greater than the present-day 800 km seismic gap (Fig. 1) evidenced by historical seismicity in Nepal. As the displacement rate (for a time-span longer than the seismic cycle) on any Himalayan ramp cannot be faster than the convergence rate estimated between the High Himalayas and the Indian plate, a value of 20 m/ka (Molnar, 1987; Bilham *et al.*, 1997) is probably a maximum and 40 m displacement requires at least 2 ka of fault slip.

A lower limit for the displacement rate can be estimated from sedimentary records. The total duration of thrust activity is less than the interval between the older hanging wall onlap and the younger footwall cut-off. In the Karnali thrust splay, this interval ranges between 1 and 2 sedimentary sequences. These units belong to the Dun Gravel Formation. Due to the lack of fossils and paleomagnetic signal in the Dun Gravels (Appel *et al.*, 1991), their precise age remains unknown. Nonetheless, the 15–20 m thick sequences (a), (b) and (c) (Fig. 6) do not appear to be separated by erosional surfaces and a first order estimate of the time elapsed can be determined from the sedimentation rates ranging from 0.11 m/ka to 0.83 m/ka (Gautam and Appel, 1994) in the Siwalik area. Considering 0.10 m/ka as a lower limit for the sedimentation rate, a 20 m thick sequence would be deposited in less than 200 ka, and the thrust activity would occur in less than 400 ka. This result should be interpreted with caution due to the lack of direct dating, but agrees with the slip rate in mid western Nepal estimated from Holocene terraces uplifted at the hanging-wall of MDT: if the 6–10 m/ka shortening rate found 200 km eastward (Leturmy *et al.*, 1997) is applied to the MDT Karnali splay, a 40 m displacement would only last from 4 to 7 ka.

DISCUSSION

The above observations are significant for two reasons:

1. The Karnali segment of the MDT is in the ‘seismic gap’ (Fig. 1) between the west (1905 Kangra earthquake) and east (1934 Bihar earthquake), historical ruptures on the basal décollement of the Himalayas. The estimation of seismic hazard needs to be carefully assessed in the Karnali zone where the largest hydraulic projects of Nepal and India are under study. Major dams and galleries are planned across, or close to, the Main Thrusts. Evidence that reactivation of the MDT occurs episodically and that fault slip has been accommodated by seismic and aseismic processes emphasizes the potential hazard in this area. Structural geology clearly appears a relevant approach to assess these hazards.
2. Several cycles of deformation exist with periods intermediate in duration between short seismogenic cycles and the long period finite deformation of a thrust belt. The following tectonic events have already been inferred in thrust belts: (1) forward propagation of the thrust system (Boyer and Elliott, 1982), (2) out-of-sequence reactivation of thrusts (Burbank and Beck, 1989), (3) break-back nucleation of a thrust splay (Deramond *et al.*, 1993), and (4) seismic/aseismic period of convergence (Kanaromi and Anderson, 1975). We do not suggest that these examples provide a general rule in thrust deformation but that the tectonics of far western Nepal involves all these events. Furthermore, the structure of the Karnali MDT splays requires an intermediate scale of incremental sliding, that, to our knowledge, has still to be described: 40 m displacement on thrusts II and III of the imbricate splay of the MDT may have occurred between 2 ka and 400 ka.

Studies of physical processes inducing this order of periodicity already exist. Climatic changes occur within a range of periods that are appropriate to drive erosion cycles of the sort that would result in the observed sequence of tectonics and sedimentation in the Himalayan foothills, and previous studies (Koons, 1990; Beaumont *et al*., 1991; Chalaron *et al*., 1995; Norris and Cooper, 1997) have indicated that erosion has a major influence on the deformation pattern of a thrust belt.

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