Kinematics and Sedimentary Balance of the Sub-Himalayan Zone, Western Nepal

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ABSTRACT

The Sub-Himalayan Zone constitutes a tectonic wedge of synorogenic sediments along the southern edge of the Himalayan Belt. Sediments are incorporated into the prism from the foreland Indo-Gangetic plain, undergo a tectonic cycle within it, and eventually are eroded. The structural sketch map exhibits westward-plunging arcuate structures on the foremost location of the Outer Belt. Investigations from spatial imagery and digital elevation modeling (DEM), together with kinematic data, allow us to calculate velocities for the geomorphologic development. Four velocities rule the general evolution of the wedge. The foremost geomorphic structure (ridge) is the assemblage of elementary structures. The lateral ridge propagation velocity is estimated to be 40 cm/yr, which supports a general cylindrical development of the Outer Belt, in spite of the asymmetrical development of each independent elbow-shaped structure. The sediment’s burial history can be quantified from geometric and kinematic data. We emphasize that because of the cylindrical behavior of the prism, extrapolation of the sediment transfer to the entire western Nepal Siwalik is valid. Burial in the foreland basin takes two times longer than the entire tectonic cycle, which only lasts for about 6.5 m.y. Sediments reaching $6 \times 10^{-5}$ km$^3$ per year and per linear kilometer accrete along the Siwalik range.

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About 21% of the flowing material within the wedge is captured and withdrawn from it as subducted duplexes. Assuming a steady-state development of the wedge, and according to the Coulomb-wedge theory for the Siwalik, mean erosion rates are estimated to be about 1.9 mm/yr, which is in accord with previous estimates. We emphasize that this consistency supports the overall estimates for the general development of the wedge.

INTRODUCTION

The critical taper formed by orogenic belts can be divided into various parts in their front zone. As is the case for the Sub-Himalayan Zone of western Nepal, the most frontal deformed part often corresponds to an accretionary wedge of synorogenic sediments incorporated from the foreland basin into the mountain belt. This unit constitutes an open system of material, because sediments are added to the wedge from the foreland and removed from the wedge by erosion. According to Dahlen and Barr (1989), mature continental synorogenic accretionary wedges display critical-taper angles and can be in a volumetric steady state. As a consequence, to keep a balanced volume of sediments throughout time within the unit, the processes that withdraw material from the wedge (erosion or duplex subduction) must be strong enough to remove sufficient material from the wedge. This statement is implicitly constrained by the global energy budget for mature prisms, because increasing the volume of the prism implies an increase of its activation energy. Material within the wedge undergoes a burial cycle, from the fresh sediment in the foreland being incorporated into the prism, to the free, eroded sediment at the surface. This pattern is generally associated with thin-skinned deformation styles.

The main morphotectonic units of the Himalayas south of Tibet include the High Himalayas, which are made of crystalline rocks and are bounded southward by the Main Central Thrust (MCT); and the Lesser Himalayas, which are made of metasedimentary rocks and are separated to the south by the Main Boundary Thrust (MBT). The last unit is the Sub-Himalayan Zone Fold-and-thrust Belt, which forms a Neogene accretionary wedge on the southern foothills of the Himalayas that is deformed in a thin-skinned style (Héral and Mascle, 1980; Héral et al., 1986; Schelling, 1992; Mugnier et al., 1992, 1999a; Powers et al., 1998).

Characterization of hydrocarbon maturation, migration, and entrapment in fold-and-thrust belts is often limited by poor knowledge of the kinematics of these areas. The burial history and residential time at depth are the key parameters for such problems, which can only be assessed if the global kinematics of the wedge is well understood (Baby et al., 1994; Moretti et al., 1996). Maturation is closely linked to the time span during which kerogen was maintained at depth; migration depends on the fluid paths, which are controlled by the tectonic regime and associated structure; and eventually, entrapment in foreland fold-and-thrust belts is linked to structural buildup. Although the petroleum potential is rather poor in this area (Bashyal, 1998), the Sub-Himalayan Zone is relevant to our general understanding of the deformation schemes of frontal parts of orogenic belts. Most active mountain belts show similar structural sketches, in which tectonic velocities, sedimentation, and erosion rates are in the same range. These parameters are fundamental for the evolution of petroleum systems in fold-and-thrust belts.

The aim of this chapter is to quantify the geometric and kinematic development of the Sub-Himalayan prism in western Nepal. First, we analyze the structural and morphological evolution of the wedge. Second, we estimate the volume of material incorporated from the foreland, the time of residence within the wedge, and the volume of material removed from the prism undergoing erosion, using across-strike geometric and tectonic velocities together with a structural sketch map. The kinematics cannot be restricted to a 2-D forward cycle, because the lateral growth of the structure also controls the sediment-incorporation mechanisms within the wedge. The morphological evolution helps in documenting the global dynamics of the wedge. The overall development of the wedge is best characterized by its frontal and lateral structural and geomorphological velocities.

GEOLOGIC SETTING

The Sub-Himalayan Fold-and-thrust Belt was created by the deformed synorogenic series of the Siwalik Group (Mugnier et al., 1992, 1994; 1999a; Powers et al., 1998), above the northward-subducting Indian plate. The series is located in the foothills of the Himalayas and comprises a succession of east-southeast–west-northwest-trending ridges that are perpendicular to the N10–N30°E compressional axis (Ni and Baraganzi, 1996; Jouanne et al., 1999).

A few ridges are the geomorphological expression of active thrusts. These faults branch off of a gently north-dipping décollement (Raiverman et al., 1994; Galahaut and Chandler, 1992; Biswas, 1994). Therefore, only a few active thrusts beneath south-verging slices accommodate the shortening in the Sub-Himalayan Zone (Figure 1). The fold-and-thrust belt is bounded by the Main Boundary Thrust (MBT) to the north, and the
Main Frontal Thrust (MFT) is the southernmost tectonic feature, characterized by Tertiary sediments overthrusting Quaternary (DeCelles et al., 1998a). Another primary thrust is the Main Dun Thrust (MDT) (Héraill and Mascle, 1980; Delcaillau et al., 1987; Mugnier et al., 1992), which constitutes a succession of laterally relayed thrusts propagating westward as ramp folds. This thrust owes its name to the piggyback basins called duns, which it overthrusts. Previous studies defined the Sub-Himalayan Zone as a fold-and-thrust belt characterized mainly by fault-propagation folds, fault-bend folding, and duplexes (Mascle et al., 1986; Banks and Warburton, 1986; Powers and Lillie, 1996; Powers et al., 1998; Mugnier et al., 1999a).

The prism grows by propagating southward into the foreland Indo-Gangetic plain. The stratigraphic sequence over the Main Décollement (MD) extends from the middle Miocene to the present (Appel and Roesler, 1994; Corvinus, 1994) and consists of a coarsening-upward succession of sandstone and conglomerate as much as 6000 m thick. The Siwalik Group is divided into three informal stratigraphic units. The lower Siwalik unit (middle Miocene) displays paleosols and fluviatile channel deposits, the middle Siwalik unit (upper Miocene) is of a flooded-plain to braided-channel type, and the upper Siwalik unit (Pliocene to Pleistocene) is mainly conglomeratic and of a braided-channel type (Héraill et al., 1986; Delcaillau, 1997). This sequence

**Figure 1.** Top: Mosaic of SPOT satellite scenes and structural interpretation of the western Nepal Siwalik. Labeled dashed lines A–D are location of balanced cross sections shown in Figure 7. (E) is location of the cross section Figure 6. Unlabelled dashed lines are the locations of other available balanced cross sections. Bottom: Sketch map of west-plunging salients. MDT: Main Dun Thrust; MFT: Main Frontal Thrust; FPF: Fault-related fold (mainly fault-propagation folds).
seems to be diachronous in along-strike and across-strike directions (Appel and Roesler, 1994; Corvinus, 1994, DeCelles et al., 1998a, Ohja et al., 2000) and is interpreted to be the Miocene to Holocene sedimentary record of the Himalayan front’s southward migration (Héraill to be the Miocene to Holocene sedimentary record of DeCelles et al., 1998a, Ohja et al., 2000) and is interpreted seems to be diachronous in along-strike and across-strike

**STRUCTURAL VELOCITIES IN THE HIMALAYAN OUTER BELT**

**Structural Development**

A mosaic of six (60 km × 60 km) SPOT satellite pictures (Figure 1) taken between longitudes 80°30’E and 83°00’E was compiled to complete the previous field structural investigations and create the structural sketch map along a 300-km-long segment of the Himalayan foothills. Analysis of spatial imagery brought out a peculiar recurrent set of en echelon arcuate structures (salients) that are convex toward the foreland, above the MFT (Figure 1). Information from satellite imagery includes the westward transition from the hinterland to the foreland location of the same continuous structures. They change laterally, from north-dipping MDT monoclines on a hinterland setting to ramp folds showing emergent faults (MFT type), and end up in blind-thrust ramp folds. Previous theoretical and field work emphasized that the fault length increases with greater forward displacement over the fault (Elliott, 1976; Walsh and Waterson, 1988; Jackson et al., 1996; Leturmy, 1997; Mueller and Talling, 1997). In the Sub-Himalayan Zone of western Nepal, all the aforesaid structures become progressively less mature toward their western tips (evolution of MDT monoclines to MFT ramp folds). Along the eastern salient, an early Pliocene cartographic unconformity on the backlimb of the fold disappears toward the west (Leturmy, 1997; Mugnier et al., 1999a). In the central salient, a wind gap (Mueller and Talling, 1997) used to be a main water gap for the Rapti River. The current water gap of the Rapti River bypasses the anticline to the west (Leturmy, 1997, Leturmy et al., 1999).

Because the structures are always less evolved toward the west, and considering the field observations, we infer that the salients propagate westward asymmetrically (from the monoclines toward the anticlines); on a map, the development of the frontalmost structures is not cylindrical but is westward-plunging. Fault tips migrate laterally, perpendicularly to the main deformation axis, as the width of the fault increases with its displacement (Elliott, 1976; Walsh and Waterson, 1988; Marchal et al., 1998). If these statements and observations are correct, they imply that greater displacement occurs over the MDT than over the MFT anticlines, and faults propagate westward.

**Structural Velocities Over the Fold-and-thrust Belt**

The convergence rate of the Indian plate with the Eurasian plate is about 50–55 mm/yr (De Mets et al., 1990). Only a part of it is accommodated in the Sub-Himalayan Zone. The total shortening rate in this area has been estimated by several methods. To constrain the shortening rate in this area, we review the various published results using various methods. Lyon-Caen and Molnar (1985) used the southward migration of the Tertiary basin depocenter to determine a minimum Indo-Himalayan convergence rate of 10–15 mm/yr and a maximum of as much as 20 mm/yr. By subtracting the shortening accommodated on faults in the High Himalayas from the total Indo-Eurasian convergence, Avouac and Tapponier (1993) arrived at a shortening rate of 18 mm/yr. Peltzer and Saucier’s (1996) global kinematic model of Asia suggests a convergence rate of 18 mm/yr between the High Himalayas and the Indian plate. Schelling (1992) and Schelling and Arita (1991) determined a rate of 8.4 to 18.6 mm/yr using minimum shortening estimates from cross-section balancing between the High Himalayas and the MFT in eastern Nepal. DeCelles et al. (1998b) estimated a southward forebulge migration rate of 14 to 33 mm/yr during Eocene-Oligocene time. Lavé and Avouac (2000) used terrace folding to estimate a minimum shortening rate of 21 mm/yr for the Holocene period. All these estimates indicate an average shortening rate of 18 mm/yr for the area between the MCT and the MFT, and this value corresponds to the Indo-Himalayan convergence following the initiation of the MCT (20–22 Ma, according to Hodges et al., 1996). After initiation of the MBT, the total shortening has been partitioned between the Lesser Himalayas and the Sub-Himalayan Zone.

From cross-section balancing in western Nepal, Mugnier et al. (1999a) determined minimum shortening of 40 km in the Sub-Himalayan Zone between the MBT and the MFT. Because the onset of shortening in the present Sub-Himalayan Zone postdates the Pliocene upper Siwalik member (DeCelles et al., 1998a; Mugnier et al., 1999a), shortening-rate estimates are at least 17–20 mm/yr for the various cross sections. In northwest India, Powers et al. (1998) synthesized shortening rates that also had been deduced from various cross-section balancing in the Sub-Himalayan Zone between the MBT and the MFT, and they are in the same range (14 ± 4 mm/yr). Such shortening rates in the Sub-Himalayan Zone in turn implies current minor shortening rates in the Lesser Himalayas.

It can be argued that geodetic data from spirit-leveling (Jackson and Bilham, 1994) or GPS measurements (Bilham et al., 1997; Larson et al., 1999) indicate little current shortening of the Sub-Himalayan zone, the maximum convergence being accommodated in the
the structures are in a dynamic equilibrium. Erosion com-
and 228 m). Hurtrez et al. (1999) showed that because of
 smoother morphology (standard deviations are 213 m
the two studied ridges), and the MDTs have an even
shape (standard deviations are 145 m and 148 m for
termination of the MFT (FPF of Figure 2) is sharp (stan-
vation densities are concentrated around the mean
of the elevation density characterizes the sharpness of
morphological data are compiled over the ridges over-
30
ridges overlying the thrusts helps to constrain velocities
over the entire wedge. From a 30° arc DEM (Figure 2a),
morphological data are compiled over the ridges over-
lying the thrusts (Figure 2b). The mean elevation corre-
sponds to the average altitude of each particular thrust-
related relief, and the standard deviations of the eleva-
tions characterize the distribution of the elevation around
this mean value. The morphology of the ridges is directly
linked to the tectonic activity (Hurtrez et al., 1999).

The mean elevation increases from the southern
MFT periclinal ridge (fault-propagation fold, FPF) to the
MFT ridges and to the MDT. The gentle hinterland
increase characterizes the average taper geometry
of the wedge; it includes the local tectonic activity
of the thrusts but also the depth and slope of the Main
Décollement, MD, which rules the shape of the wedge
as a whole (Davis et al., 1983). The standard deviation
of the elevation density characterizes the sharpness of
the structures: the lower the standard deviation, the
sharper the overlying ridge. In other words, if the eleva-
tion densities are concentrated around the mean
elevation, the flanks of the ridge are abrupt. The lateral
termination of the MFT (FPF of Figure 2) is sharp (stan-
dard deviation is 100 m), the MFTs have a smoother
shape (standard deviations are 145 m and 148 m for
the two studied ridges), and the MDTs have an even
smoother morphology (standard deviations are 213 m
and 228 m). Hurtrez et al. (1999) showed that because of
the rapid erosive processes in the Sub-Himalayan Zone,
the structures are in a dynamic equilibrium. Erosion com-
ments for uplift (Figure 3), and the topographic pro-
files remain constant through time as long as no tang-
gle change occurs in the tectonic velocities or erosion
rates. The topographic profile relates to the thrust ve-
locity. For one particular thrust velocity and ramp geo-
metry, there is one, and only one, associated topo-
graphic profile for the overlying ridge. This statement
applies to mature ridges when the equilibrium profile is
reached. Hence, the sharpness of the FPF probably re-
lates to the growing structure (for which an equilibrium
profile is not reached, as shown, by its low mean eleva-
tion) rather than to its tectonic activity. If the assump-
tion of a dynamic equilibrium law is correct, the shapes
of the MFT and MDT reflect their tectonic activity.
Because the MFT and MDT ridge morphologies are globally
constant, the previous statement indicates that local
estimations of thrust velocities for the major thrusts
can be extrapolated laterally.

The MBT presently shows major displacement (rocks
of the Lesser Himalayas thrust over the Tertiary sedi-
ments of the Sub-Himalayan wedge, according to Upreti,
1990; Mugnier et al., 1992). However, Holocene acti-
vation of the MBT has locally minor normal sense slip
(0.5 mm/yr; Mugnier et al., 1994), thus suggesting that
taper is overcritical in this area, which implies that the
MBT is not currently accommodating tangible shortening.

As a consequence, the overall shortening is accom-
modated mainly by the MDT and the MFT. According
to the previous discussion on shortening rates, we as-
sume that shortening over the MCT is minor, and that
at least 17–20 mm/yr of shortening occurs within the
Sub-Himalayan Zone. Sparse velocity data are available
for the Sub-Himalayan thrusts: From terrace uplift
inversion, Leturmy et al. (1999) suggested velocities in
the range of 7–10 mm/yr for both the MFT and MDT in
western Nepal, whereas Lavé and Avouac (2000) cal-
culated a velocity of 21 mm/yr for the MFT and found
0 mm/yr for the MDT in eastern Nepal. These differ-
cences can be explained by the distribution of shorten-
ing versus time over these thrusts. The MDT displays
minor out-of-sequence faults that are overlapped by
undeformed sediments (Mugnier et al., 1998; Mugnier
et al., 1999a), which indicate a nonpermanent tectonic
activity. The ratio between faulted sediments and over-
lapping sediments is 1:3. We assume that it reflects the
periods of relative activity to inactivity of the MDT. If
shortening in the Sub-Himalayan Zone is partitioned
only over the MDT and MFT, the tectonic activity time
span reflects the coeval activation of both thrusts (Let-
urmy, 1997), whereas inactivity indicates periods of fast
activation over the MFT alone (Lavé and Avouac, 2000).
Coeval activation exists for a third of the time, hence
the MDT tectonic velocity $V_t^{MFT}$ is one-third of the value
given by Leturmy et al. (1999), that is, 2–3 mm/yr.
Similar calculations for the MFT indicate a tectonic vel-
ocity, $V_t^{MFT}$, of about 17 mm/yr.
Average forward-shortening velocities are available for the main Siwalik thrusts (Figure 4). However, forward velocities do not supply enough information to describe the asymmetrical development of the Sub-Himalayan Zone, and the lateral ramp-fold propagation velocities are needed. Leturmy (1997) calculated lateral-thrust velocities for the structures of the Sub-Himalayan Zone, which are 10 times faster than the forward-thrust velocities. This value is consistent with the observations of average fault displacement versus length given by various authors (Walsh and Watson, 1988). Therefore, lateral velocity ($V_{l\text{MFT}}$) for the MFT is in the range of 170 mm/yr. By analogy, as Elliott (1976) previously suggested, the forward and lateral velocities that control the fault propagation can be compared to the ductile edge and screw dislocations, respectively (Figure 5).

$$V_{f\text{MFT}} = 17 \text{ mm/yr}$$
$$V_{l\text{MFT}} = 170 \text{ mm/yr}$$

For the sake of simplicity, these velocities will further be named $V_1$ and $V_2$, respectively.

These structural velocities rule the westward propagation of the salients, which branch off of the MDT. Such a pattern suggests that the development of the most frontal structures is asymmetrical, because propagation only acts toward the west. The remaining question concerns the cylindrical nature of the overall wedge. How do structures and morphology evolve, over time, in the fold-and-thrust belt of western Nepal, where shortening is perpendicular to the global east-southeast to west-northwest trend of the belt and where structures plunge westward?

**HOLOCENE MORPHOLOGICAL VELOCITIES OF THE HIMALAYAN FRONT**

**Lateral Propagation Velocity of the Morphological Structures**

Evidence for an asymmetric westward growth of the salients was described previously. It includes ancient unconformities that are located on the eastern part of the salients but that vanish toward the west; a westward transition from water gaps to wind gaps; the distribution of the drainage pattern; and the systematic maturation of the structures, from the eastern monoclines maturing to fault-related folds showing emergent ramps, to the western ends of fault-related folds evolving with blind ramps.

We emphasize that the en échelon pattern of the thrust belt of western Nepal is linked to the lateral propagation of the imbricate thrusting (see Shaw et al., 1999), perpendicularly to the thrust-sheet motion (Mugnier et al., 1999a), and does not reflect any dextral strike-slip component of the front. MFT salients branch eastward on the MDT and propagate westward on the foremost position. The subcontinuous trend of the MFT corresponds to the most frontal ridge, composed of the en échelon fault-related folds. In other words, the envelope of the ridges overlying the MFT is the southernmost

![Figure 2](image-url)  
**Figure 2.** (a) 30’ arc DEM of the studied area. Solid white lines represent sampled areas for statistical analysis of elevation. (b) Elevation density histograms of each sampled structure. FPF: fault-propagation fold ridge, MFT1 and 2 : Main Frontal Thrust ridges, MDT1 and 2 : Main Dun Thrust ridges.

![Figure 3](image-url)  
**Figure 3.** Dynamic-equilibrium theory. (a) Topography is too low with respect to the ramp velocity; erosion rates becomes lower than uplift rates. (b) Topography is in a dynamic-equilibrium state, erosion rates balance uplift. (c) Topography is too high, erosion rates become higher than uplift rates. Solid black line is topography, dashed line is equilibrium profile, light gray is the volume input as a result of shortening, dark gray is the erosion response.
morphological feature, elongated along a broad N110°E axis. Each salient is a discrete element belonging to the MFT “chain” (Figure 1).

The salients in the studied area are distributed regularly, with a 75-km spacing (Figure 1), which can be defined as a spatial periodicity of the structures. Over the area, the lengths of the bows (from the beginning of the bend to the tip of the structures) show that they are 30 km shorter on each westward step. On the western side of the area (to the west of 81°20'E), no salient is displayed yet, whereas eastward, although some duns forming arcuate structures are displayed, the system is already too evolved. In the studied area, the easternmost salient (salient 1) is already overmature; that is, there is no more available space for lateral propagation to the west of the fold pericline, because it is bounded by the central salient.

Mugnier et al. (1999c) emphasized that shortening rates have remained constant over the Sub-Himalayan Zone through time. This statement is extended to the MDT and MFT tectonic velocities by assuming that a constant strain has been spread over these thrusts, over time. If this is correct, each frontal salient propagated, over time, with forward and lateral MFT-type velocities, and the relative lengths of the salients provide relative ages for these structures. If the 170 mm/yr lateral velocity is globally constant, salients of the en échelon series grow to the west with a 180,000-yr period, which corresponds to the time required to form a 30-km-long structure (the westward decreased length of these structures). These salients can now be regarded as independent, discrete defects that are gradually emerging westward with an average 180,000-yr period. The MFT ridge is created in this area by the assemblage of these defects. Therefore, this morphological structure propagates laterally with its own velocity, depending only on the

**Figure 4.** Top: Model for fault-propagation fold dynamics (after Suppe and Medwedeff, 1990). \( V_1 \) is the MFT forward velocity, \( V_2 \) is the MFT lateral propagation velocity. Bottom: analogy with ductile strain dislocations. \( V_1 \) is the edge dislocation and \( V_2 \) is the screw dislocation.

**Figure 5.** Structural and morphological velocities for the Sub-Himalayan wedge’s frontal development. \( V_1 \) and \( V_2 \) are respectively the frontal and lateral propagation velocities for structural growth, and \( V_4 \) and \( V_3 \) are frontal and lateral velocities for morphological growth.
period of time (180,000 yr) and the spatial offset (75 km) of the independent elements of which it is made. Again, as an analog to the ductile approach, this phenomenon corresponds to dislocation creep. A rough estimate of the lateral morphological propagation velocity (V₃) is now added to the edge and corner structural velocities mentioned above:

$$V₃ = 420 \text{ mm/yr}$$

The morphological ridge, which is an assemblage of the elementary structural defects, propagates laterally more than twenty times faster than the forward structural-propagation velocity and nearly three times faster than the lateral structural-propagation velocity. This, in turn, implies that, even if the structural pattern is asymmetrical (with westward-propagating salients), the overall development of the wedge can be considered to be cylindrical, because the morphological development can be approximated to be instantaneous with respect to structural propagation velocities. However, the proposed value is considered to be a first-order estimate, because we are uncertain about the local structural velocities.

### Forward Morphological Propagation Velocity

As for the lateral evolution, the morphological propagation to the south can be defined (Figure 6). Lyon-Caen and Molnar (1985) estimated, from the migration of the flexural Indo-Gangetic plain, that the southward progradation of the deformed area is in the range of 10–15 mm/yr (and is as much as 20 mm/yr). DeCelles et al. (1998a) proposed a southward forebulge migration of 14–33 mm/yr. We assume that the wedge is in a volumetric steady state, and that the taper angle is preserved through time (see Davis et al., 1983 or Dahlen and Barr, 1989). Hence we estimate the southward migration of the morphological front of the foothills to have an average rate of about 19 mm/yr, which is the value we previously debated for the convergence between the Lesser Himalayas and Indian plate. This value is the V₄ forward morphological velocity of the front.

Four velocities thus characterize the development of the Himalayan front. Two structural velocities control the development of individual structures: V₁ = 17 mm/yr, and V₂ = 170 mm/yr.

Two morphological velocities control the topographical evolution of the fold-and-thrust belt: V₃ = 420 mm/yr, and V₄ = 19 mm/yr.

The main observation we can infer from these kinematic estimates is that the overall development of the wedge is very fast laterally and is therefore cylindrical on a first-order approximation, in spite of the surface structural pattern displaying west-plunging fault-related folds. As a consequence, an across-strike evaluation of the sediment cycle within the wedge is adapted and is representative of the behavior of the wedge all along its 300-km strike length.

### Burial Cycle of the Sediments Within the Wedge

#### Maximum Residence Time

A set of nine balanced cross sections that were based on surface data has been constructed over the Siwalik (Figure 7) (Letermy, 1997; Mascle et al., 1998; Mugnier et al., 1999a, b). Assuming an “equivalence” hypothesis, lateral along-strike variations observed in the various cross sections represent different stages of the geometric and kinematic history of the analyzed thrust-related fold. This implies that measurement of fold geometries along each cross section can be used to
determine the kinematics (Poblet et al., 1998). The equivalence hypothesis is extended to all frontal folds, because, it is argued, the kinematics are the same for all the structures in a cylindrical setting. Hence, the whole set of cross sections provides various stages of fault-related fold evolution in the Himalayan fold-and-thrust belt, and together with the tectonic velocities described above, an evolutionary sketch can be constructed (Figure 8). Thrust sheets stack one above the other with a synchronous development of foreland fault-related folds. New structures develop southward; however, the reactivation of more hinterland thrusts (MDT) implies that hinterland slices gradually tend to be almost entirely eroded (passive remnants are occasionally preserved—see discussion below). Erosion acts as a major control on the evolution of the fold-and-thrust belt. It actually rules the migration of the foremost structures, because it permanently reorganizes the stress field by unloading (Chalaron et al., 1995). Indeed, erosion controls the permanent activation/reactivation regime shifts of the MDT, yielding an average tectonic velocity of 2–3 mm/yr. As soon as a new structure develops toward the south, the previous, juxtaposed hinterland structures enter a reactivation regime. From the geometric analysis, it is estimated that structural growth switches to a foreland fault-propagation fold as soon as the fault begins to crosscut the fold. Suppe and Medwedeff (1990) define this evolution as the breakthrough fault. At this time, both structures are coeval; hinterland structures evolve at low rates (MDT style, at 2–3 mm/yr), whereas the most frontal structures grow at rapid rates (MFT style, at 17 mm/yr). Hence, for a structure, the fast tectonic regime lasts as long as it remains in the foremost position. From the average geometric data obtained from numerous cross sections, we hypothesize that new structures form southward when the ramp is emergent, because two anticlines never coexist along a cross section in the Sub-Himalayan Zone of western Nepal. At least one of the hinges is totally eroded, and only monoclines are preserved.

The burial cycle in such settings can be divided into various stages (Figure 9a), and the associated burial history through time is synthesized in Figure 9b. The residence time presented in the following section is calculated, using average geometries of cross sections and previously described kinematic data, for the tail of a slice implicated in the wedge. Therefore, it corresponds to the maximum residence time within the wedge, because the hinterland part of a thrust sheet is preserved longer.

The first stage of the cycle is the sedimentation in the subsiding foreland basin (stage 1 in Figure 9b), as the Himalayan front migrates toward the south. The Khutia Khola section (Ohja et al., 2000) and the Surai Khola section (Appel and Roesler, 1994; Corvinus, 1994), on the western edge of the studied area, constitute reference stratigraphic series after the date assignments using magnetostratigraphy (Appel and Roesler, 1994; Ohja et al., 2000) and paleontology (Corvinus, 1994). The sedimentary burial curve used in the present study is derived from the magnetostratigraphic study of Appel.
and Roesler (1994) and Ohja et al. (2000). Although the ages from magnetostratigraphy show strong variations depending on the sampled lithologies (Ohja et al., 2000), it can be estimated that in the Sub-Himalayan Zone, this phenomenon lasts for about 12 m.y. to 13 m.y., and drives sediments to depths as great as 5000 to 6000 m. Next is the tectonic thickening episode at the footwall of the frontal thrust (stage 2, Figure 9b), when this thrust consumes the foreland sedimentary pile. It gradually moves up the hanging-wall of the décollement to the surface, which corresponds to about 5000 m uplift and is partially compensated in this stage by erosion. Beneath the relief of the frontal crest, it subsequently increases the burial depth by as much as 1000–1500 additional meters. Assuming a vertical uplift of the related fold of about 9–12 mm/yr over the ramp (for ramp dips between 30° and 45° and 5000 m total uplift), this phenomenon lasts for 400,000 to 600,000 years. It is considered to be minor with regard to the total cycle. The following stage corresponds to the instant at which the incorporated sediment enters the dynamic part of the cycle, that is, at which the motion of the sediments is governed by faulting and hence undergoes horizontal displacement. In the Sub-Himalayan Belt, most sediments are incorporated below ramp folds and only a very small amount of sediment accumulates on top of growing structures. During this episode, the sediment is transported over the Main Décollement (stage 3, Figure 9b). The total displacement on the Main Décollement is partitioned between the fast MFT (17 mm/yr) and the low MDT (2.5 mm/yr). These velocities are thus given with regard to the thrust-sheet reference. Sliding on this décollement is split into two stages. When the structure is in the foremost position, transportation over the décollement occurs at 17 mm/yr; afterward, displacement undergoes a reactivation regime at 2.5 mm/yr. As we said above, the former episode of transportation lasts from the ramp’s initiation to the breakthrough faulting, and the latter lasts until the slice is totally exhumed on a hinterland location. Average lengths are about 10,500 m for the
ramp and the breakthrough fault, and 15,000 m for the basal décollement. On average, this period initially includes a rapid transportation phase of the tail of the slice at 17 mm/yr over about 10,500 m, and secondly, a slow transportation at 2.5 mm/yr, over 4500 m (15,000 minus 10,500 equals 4500 m). During this episode, the vertical-motion component is very small; the burial depth increases only weakly as a result of piggyback sedimentation, whereas a small uplift component is linked to the slip over the gently dipping basal décollement. Exhumation (stage 4, Figure 9b) of the tail of the slice starts as soon as it begins to climb over the ramp, when sliding over the basal décollement is totally finished and the slice is squeezed between the foremost sheet and the backstop buttress. Average ramp and fault lengths lead to approximately 10,500 m total displacement at that low rate. At that time, new structures have grown forward, and exhumation is realized on both the ramp and the breakthrough fault at low rates of reactivation (2.5 mm/yr). The burial depth subsequently decreases as a function of the ramp and fault angles. An average angle of 45° is used for both the ramp and the fault. The associated vertical displacement gradually leads to the total exhumation and erosion of the thrust sheet. Finally (stage 5 in Figure 9b), surface transportation phenomena are fast enough to be considered instantaneous with respect to the overall cycle.

Therefore, the wedge’s development can be described as a steady-state burial cycle, from the incorporation of the foreland sediments to their exhumation and sedimentation in a more distal foreland.

The major burial phase is sedimentation in the foreland, but it lasts fairly long (the average sedimentary rate is only about 500 m/yr). The tectonic thickening, on the other hand, is faster and still increases the burial depth; whereas exhumation is the fastest process of the internal cycle (about 1700 m/m.y. of vertical motion).

The 12-m.y. sedimentation stage in the foreland is about two times longer than the tectonic stage within the wedge. The calculated short time of residence within the prism supports the idea that only a limited number of active thrust sheets control the development of the wedge. Only short-lived slices constitute the actual prism.

Sediment Transfer Balance Within the Wedge

The previously calculated time for the burial/exhumation cycle is an average for the Sub-Himalayan Zone of western Nepal. Using such a sketch of development, we can calculate the material balance within the wedge.

Sediments incorporated from the foreland into the fold-and-thrust belt constitute the main input of material, because piggyback basins represent a weak volume in the Sub-Himalayan Belt. The total input is estimated from kinematic and geometric data, assuming an average velocity of 19 mm/yr of southward migration of the wedge (V₄). In the studied area, the incorporated volume per linear kilometer of the Indo-Gangetic plain (input I), over time, is given by:

\[ I = V₄ \times T_s \]

where \( T_s \) is the average total thickness of the involved sedimentary pile above the Main Décollement (5000 m).

\[ I = 9.5 \times 10^5 \text{ km}^3/\text{yr} \]

Given a steady-state regime for the wedge (Dahlen and Barr, 1989), the input volume, I, equals the output volume, O. The main output is erosion. However, geometric observations from the structural sketch map and the balanced cross sections (Leturmy, 1997; Mugnier et al., 1999a) imply some restrictions for the material balance. A part of the wedge’s volume is “captured” either as passive remnants of slices, accreted along the footwall of the MBT, or as duplexes, subducted beneath the MBT. Various settings can be distinguished (Figure 10). The lower Siwalik Formation, at the base of the thrust sedimentary pile, often shows duplexes. If duplex horses are located at the hanging-wall of the Main Internal Décollement ID (Figure 10a), they are unrelentingly eroded as normal stacked slices; on the contrary, if the duplex is located on the footwall of this décollement, it is subducted and consumed by the Lesser Himalayas (Figure 10b) and eventually withdrawn from the prism.

Finally, local passive remnants of middle to upper Siwalik sheets are stacked beneath the MBT (Figure 10c) and incorporated into the Lesser Himalayan wedge. Inferences from geometric data (structural sketch map and balanced cross sections) suggest that only subducted duplexes may constitute a significant volume of captured material. On a first-order approximation from geometric data, remnants of slices comprise less than 5% of the total volume of the wedge. On the whole, it can be estimated from the structural sketch map that, within the 300-km length of the studied area, about 55% of the lower Siwalik unit does not reach the surface. In order to keep a balanced structure in the wedge, this unit has to form duplexes, subducted beneath the Lesser Himalayas and subsequently withdrawn from the wedge. Per linear kilometer along the belt, the captured volume (CV) from lower Siwalik duplexes is in the range of:

\[ CV = 55\% \times t \times V₄ \]

where \( t \) is the average stratigraphic thickness of the lower Siwalik unit (2000 m),

\[ CV = 2.1 \times 10^5 \text{ km}^3/\text{yr} \]
and hence, the current withdrawn material from subduing duplexes, CV, is therefore approximated to be about 21% of the total volume of the Sub-Himalayan Zone of western Nepal. Again, according to a volumetric steady state (see Dahlen and Barr, 1989) and a critical taper angle (Davis et al., 1983; Mugnier et al. 1992; DeCelles and Mitra, 1995) for the prism, the output has to be equivalent to the input I, as topography remains constant versus time. Hence erosion accounts for about 79% of the input I. Sediments totaling $7.5 \times 10^5 \text{ km}^3$ flow through the wedge per year and per linear kilometer along the belt, in western Nepal.

The average width of the Sub-Himalayan Zone in the studied area is 35–40 km. The average erosion rate for the whole wedge is thus in the range of 1.8 to 2.1 mm/yr.

Previous estimates of erosion from the sediment load in rivers are in the range of 1.5 to 2 mm/yr (Delcaillau, 1997), therefore, they support our estimate of erosion. According to an average density of 2.65, the corresponding eroded mass is about 5000 t/km$^2$/yr. Delcaillau (1997) calculated specific erosion rates for various drainage areas of the Siwalik in the very wide range of 400 to 9500 t/km/yr, that is, 0.1 to 3.5 mm/yr of erosion. This consistency supports the hypothesis of a steady-state regime for the Siwalik wedge and in turn validates the calculated balance (Figure 11).

**CONCLUSIONS**

The sediment burial cycle was the main focus of our study. However, across-strike estimates for the Sub-Himalayan Zone’s sediment cycle are significant if the behavior of the wedge is similar laterally. Structural
data inferred from balanced cross sections, a structural sketch map, and spatial imagery reveal a laterally orientated development. Further investigations, including geomorphological observations, allowed us to calculate the velocities of the wedge buildup. We see from this study that the lateral morphological growth is much faster than the lateral propagation of the fault-related folds. Morphological structures are the assemblage of independent structures coalescing with time. These structures propagate laterally in an asymmetric pattern, and the envelope of these elementary “defects” propagates fast enough laterally (in the range of 40 cm/yr) to assume an overall cylindrical development on a wedge scale. Hence, estimates of the sediment burial cycle are justified in such a setting. Accretion is the only input of scale. Hence, estimates of the sediment burial cycle are consistent with previous studies and not only supports the erosion rates presently propounded, but also the overall cycle, and hence, the proposed sketch of the wedge’s development.

The evolution of foreland petroleum systems is ruled primarily by these parameters (burial, erosion, and tectonic rates), because they control the thermal regime. According to previous studies (Stüwe et al., 1994; Mancktelow and Grasemann, 1997), sedimentation rates such as those found in the Sub-Himalayan Zone would lower the thermal gradient by about 15% at a 5-km depth, whereas erosion rates in the range of those of the Sub-Himalayan Zone would increase the thermal gradient by about 30%. On the other hand, tectonic velocities are not fast enough to induce perturbations on the thermal field. In such settings, the oil window lies at greater depth in the sedimentary basin than it does in the folded belt, where it is significantly shallower. Given these parameters, one can therefore make general assumptions for kerogen maturation in such settings.

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