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Structural and Thermal Evolution of the Siwaliks of Western Nepal

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ABSTRACT

The piedmont of the Himalayas is formed in Western Nepal by: a) Siwalik sediments affected by folds, thrust and back-thrust structures and b) intra-belt basins (Duns) that are displaced piggyback above the thrust sheets. Vitrinite reflectance values (VRo) are found between 0.3% and 0.5% in Middle Siwalik sediments and between 0.6 and 1% in Lower Siwaliks. The thermal maturity of the organic matter agrees with maximum burial depth (3500 m for Middle Siwaliks and 6000 m for Lower Siwaliks) that do not strongly exceed the stratigraphic thickness of the Siwaliks Group. Intense erosion concomitant with deformation balances closely tectonic thickening and prevent burial of the Siwalik sediments at great depth. Nonetheless, Duns developed above the steeper part of the basal decollement and/or ahead of back-thrusts prevent the exhumation of rock and could lead to greater burial depth.

INTRODUCTION

The active piedmont of the Himalayas consists of the Siwaliks, which form the southern border of the orogen for more than 2000 Km and constitute the deformed part of the foreland basin situated above a flexure of the Indian plate (Lyon-Caen andMolnar 1984). The morphology of the Siwaliks is characterised by several hill ranges parallel to the southern border of the Himalayas (Hérail and Mascle 1980). This paper deals mainly with the structural and thermal evolution of the Siwaliks of Western Nepal in the area located between the Karnali river and the Dun valley of Dang (Fig. 1). It is based on field mapping, on aerial photo studies and measurement of vitrinite reflectance of the organic matter.

STRUCTURAL PATTERN

The Siwalik Group is classically subdivided into three units on the basis of lithostratigraphic criteria (Auden 1935). These are Lower, Middle and Upper Siwaliks. The total thickness of the sediments is on the order of 5000 to 6000 m. These lithological units do not necessarily correspond to synchronous deposits along the whole Himalayan front. However, palaeontological (Corvinus 1994) and magnetostratigraphic studies (Appel and Rosler 1994) along the Surai Khola, Western Nepal, suggest dates for the bases of major lithological units that do not strongly differ from those found in Pakistan by Johnson et al. (1982, 1985) and in Western India by Ranga Rao et al. (1988). For the Lower Siwaliks, the bottom of the sections in western Nepal refers only to the bottom of thrust sheets, and the comparison of the age could therefore be meaningless.

Several thrusts delineate in the field the boundaries between Upper and Lower Siwaliks. Along a section close to Surkhet (Fig. 2), north dipping thrusts form the major structures. They are successively the Main Frontal Thrust (MFT), the Babai Thrust, and the Bheri-Karnali Thrust and an inner steep thrust (Fig. 1). The Babai and Bheri-Karnali Thrusts can be considered as lateral prolongation of the Dun Thrusts (MDT) defined in Eastern Nepal by Delcaillau et al. (1987) or of the Dobhan fault de-

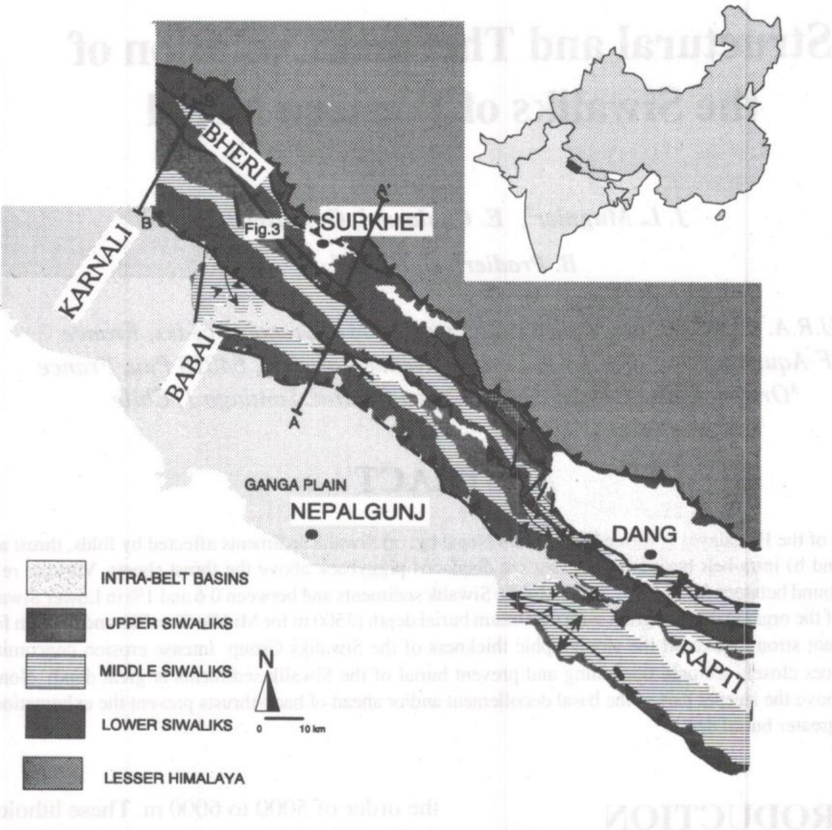

Fig. 1 Simplified structural map of the Siwalik area of Western Nepal

fined in central Nepal by Yoshida and Arita (1982). In some places, back-thrusts are also observed (Mugnier et al. 1994) (Fig. 1). In the southeastern part of the study area, back-thrust structures form the southwestern boundary of the Dun valley of Dang.

In numerous places, displacement between the thrust sheets is localized in less than 1 meter thick shear zones (Fig. 3a) and generally separate Upper from Lower Siwaliks. In these shear zones, cleavage and Riedel fractures clearly indicate thrust motion (Fig. 3b). Nonetheless, these structures locally indicate dextral oblique slip, for example where the Karnali river crosses the Bheri/Karnali Thrust. The gouge within the shear zone is formed by broken clasts in a clay matrix (Fig. 3c). Recrystallisation occurs around the clasts, suggesting a strong influence of fluids during pressure-solution deformation. The hanging-wall beds are closely parallel to the major thrusts, an observation that implies a bedding parallel decollement level within the lower Siwaliks, at the bottom of the thrust sheets, and a displacement value that exceeds the length of ramps crossing the whole sedimentary pile.

The Main Frontal Thrust outcrops only in few places. This is due to the poor quality of outcrops; nonetheless in numerous places the Main Frontal Thrust is a blind thrust in a stage of fault propagation. In these latter places, the more external range of Siwaliks is constituted of an anticline cut across by numerous minor thrust faults.

In the study area, two major North-South transfer zones affect the thrust pattern. One is located West of Surkhet, the other one is located West of the Dun valley of Dang (Fig. 1). They are complex zones formed by: (i) lateral ramps that laterally bound the thrust sheets, (ii) tear faults that develop in the transported sheets, (iii) en-echelon folds and (iii) Riedel faults oblique to the tear faults. These zones induce

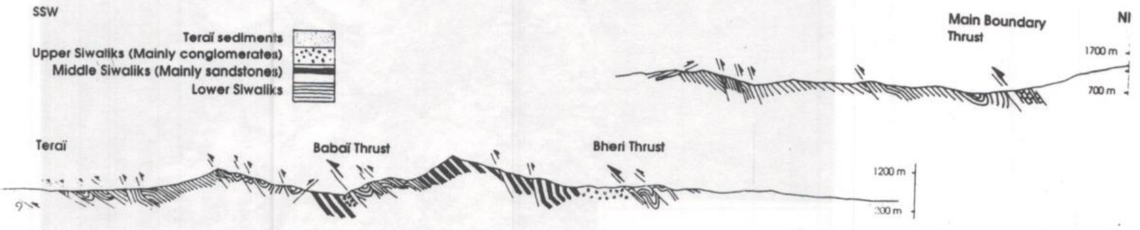

Fig. 2 A cross-section across the Siwalik belt (AA' on Fig. 1), horizontal and vertical scale same as in Fig. 1

bends of the structural trend, and they could be localized above lateral steps along the basal decollement and/or above faults that affect the top of the pre-Tertiary basement (Raiverman et al. 1983).

At the scale of the whole belt, the thrusts presumably branch along a major decollement (Seeber et al. 1981; Raiverman et al., 1983; Gahalant andChander 1992, Biswas 1994). In western Nepal, this decollement is located close to the base of the Siwalik Group, but in some places of Eastern Nepal, slices of pre-Siwalik beds are also incorporated within the thrust sheets above the decollement (Hérail and Mascle 1980). Construction of the basal decollement by the use of the kink method has been performed in an area where the horizontal spacing between thrusts is much greater than the thickness of thrust sheets (Fig. 4); this suggests a gently dipping basal decollement located close to 6 Km (Fig. 4). This result agrees with the depth of the top of the basement beneath the Surkhet area (Department of Mines and Geology; Ministry of Industry, His Majesty's Government of Nepal, 1985), and the position of seismically active gentle faults beneath the Outer and Lesser Himalayas (Ni and Barazangi 1984).

The amount of shortening that affects the whole Siwalik range is very difficult to estimate, due to the lack of subsurface data allowing the determination of the footwall cutoff and due to the intense erosion that in most cases totally affects the hanging wall anticlines. Nonetheless, a minimum estimation can be proposed. Along the section of Fig. 2, a minimum of 4 Km shortening affects the frontal anticline structure, a minimum displacement of 7 Km acts along the Babai Thrust; 7 Km along Bheri Thrust, and 7 Km along the inner thrust beneath the Surkhet area are also inferred. This implies more than 25 Km shortening for a section presently 38 Km long, i.e. a bulk shortening exceeding 40%. These values are in the range of those proposed by Schelling andArita (1991) in Eastern Nepal (i.e. 20 Km shortening for a section presently 30 Km long). In the Siwalik of northwestern India, a section constrained by several subsurface data shows 70 Km shortening along a section presently 80 Km long (Biswas 1994), also implying a bulk shortening greater than 40%.

If a shortening rate of 6 to 12 mm/yr is considered (Sinhval et al. 1973, Mugnier et al. 1992) for the present-day shortened Siwaliks area, the beginning of the thrust activity can be estimated between 4 Ma (25 Km/6mm/Yr) and 2 Ma, i.e. during the deposition of Upper Siwaliks. Furthermore syn-sedimentary deformation is locally observed in the Middle Siwaliks (Chalaron 1994), and evidences the lack of stability of this area at this time. Therefore the top of the Upper Siwaliks cannot be used as a reference for line length balancing. The concept of piggyback basin for these sediments deposited above moving thrust sheets (Johnson et al. 1985) is useful in the understanding of the sedimentary evolution of the area. The intra-belt basins (Duns) filled with Post-Siwalik sediments can also be considered as present-day piggyback basins (Mugnier et al. 1992). From numerical modelling, it is inferred that piggyback basins preferentially develop, if the geometry of the thrust sheets varies along strike, above the steeper parts of the basal decollement (Chalaron et al., in press).

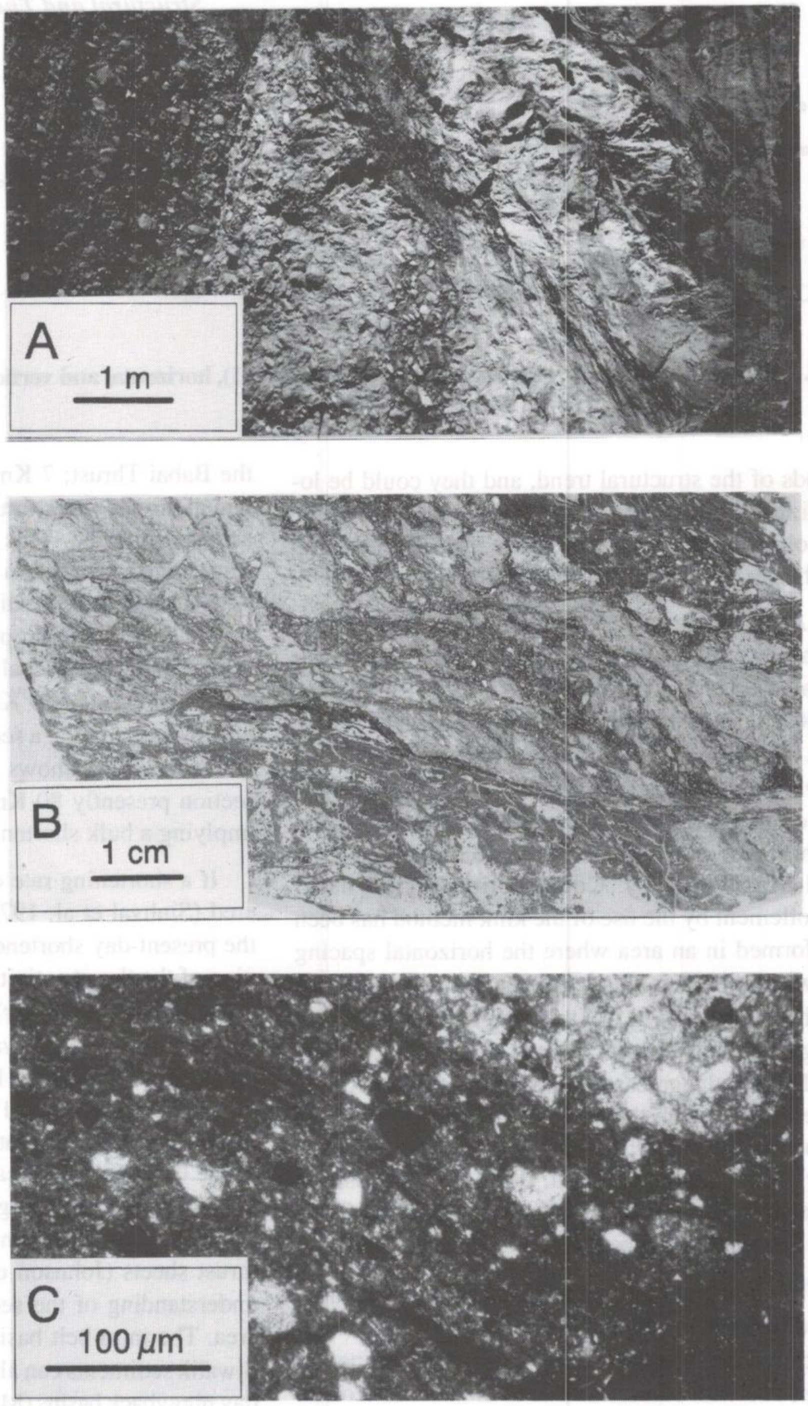

Fig. 3A The Bheri Thrust outcrop (Location on Fig. 1)
Fig. 3B A hand specimen from the shear zone
Fig. 3C Microscopic view of the gouge in the shear zone

VITRINITE REFLECTANCE OF THE ORGANIC MATTER

Vitrinite reflectance of the organic matter were measured in the laboratory of Elf-Aquitaine. The method is described by Bertrand andPradier (1993).

The wooden pieces preserved in Middle and Lower Siwaliks, and black shales from Lesser Himalayan formations (Dhital and Kizaki 1987) were used for the vitrinite reflectance. It is found that the vitrinite reflectance values (VRo) range between 0.3 and 0.5 in the Middle Siwaliks of Western Nepal (Fig. 5). In Eastern Nepal (Fig. 6), values as great as 1 are found in Lower Siwaliks at the footwall of the MBT.

The unexpected small value found in the Lesser Himalayas (VRo = 0.48) is due to the peculiar form of the organic matter (Bituminous form), implying the use of the "Jacob" formulae to estimate a vitrinite reflectance equivalent value.

The vitrinite reflectance gives an estimation of the maturity of organic matter (Fig. 7). In the Middle Siwalik formation, the values are characteristic of the lignite, and are in an immature stage for hydrocarbon generation. In Eastern Nepal, Lower Siwaliks at the footwall of the MBT show values characteristic of coals, and are in the peak of oil generation.

The vitrinite reflectance is a function of thermal evolution through time. Therefore the estimation of maximum temperature from vitrinite reflectance implies to infer a whole temperature story. A first attempt to estimate depth and maximum temperature has nonetheless been performed by comparing the field samples with data provided by wells located in the Siwaliks of West India (Agarwal et al. 1994).

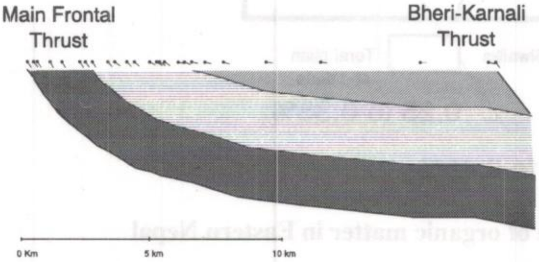

Fig. 4 Cross-section of the Siwalik area along the Karnali River (BB' on Fig. 1); the deep structures are formed by the kink method (same horizontal and vertical scale, same symbols as in Fig. 1).

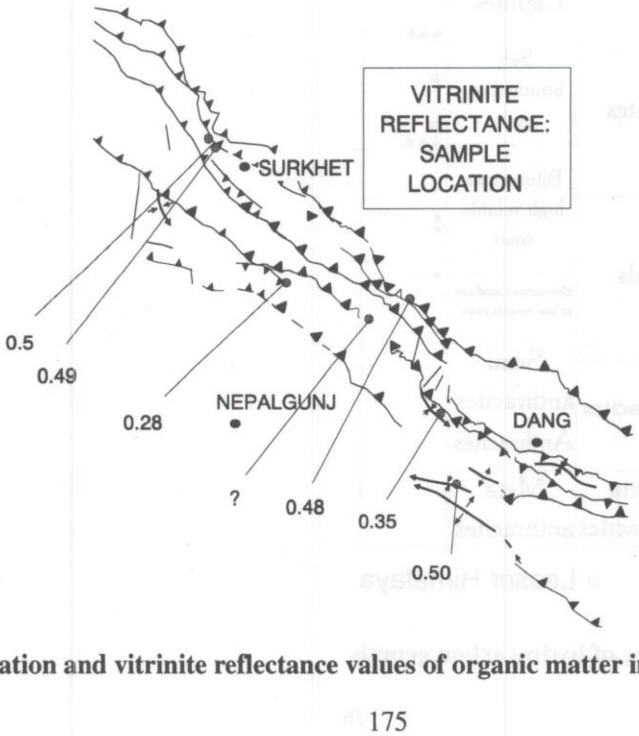

Fig. 5 Sample location and vitrinite reflectance values of organic matter in Western Nepal

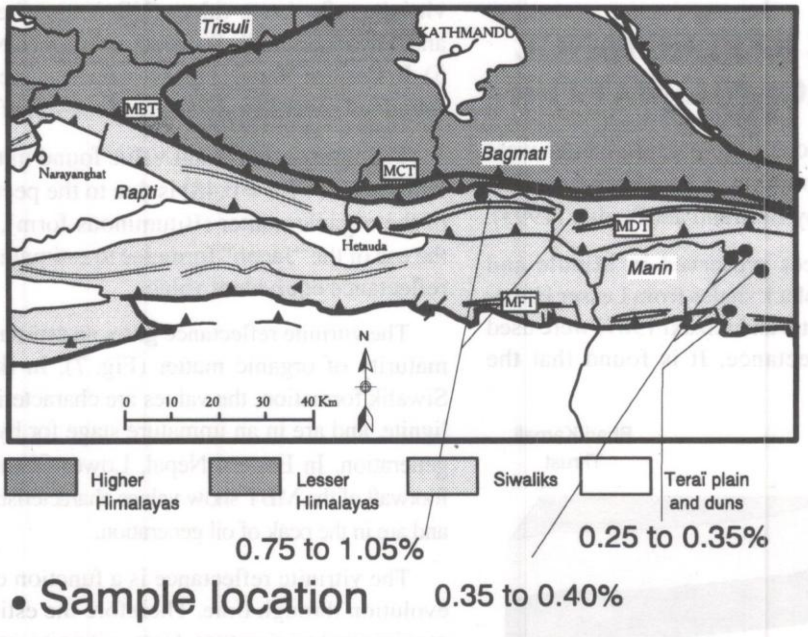

Fig. 6 Sample location and vitrinite reflectance value of organic matter in Eastern Nepal

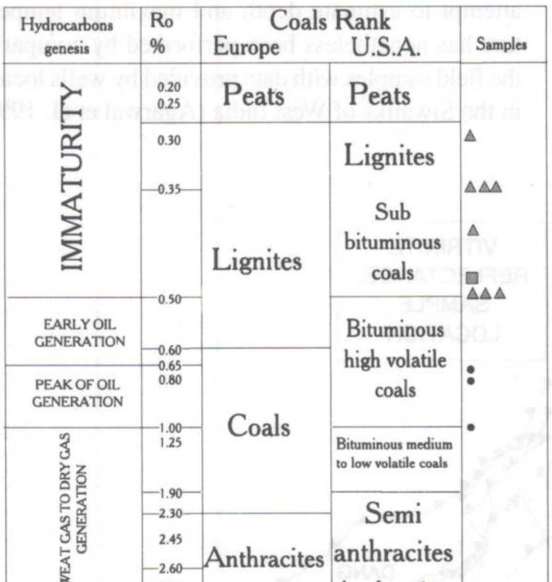

Fig. 7 Coal range and stage of hydrocarbon genesis

These wells show that the thermal gradient is near 20°/Km, and the early phase of hydrocarbon generation (i.e. VRo = 0.5) is found close to 3500 m. (temperature : 100°C) at the bottom of middle Siwaliks, and the peak of oil maturation (i.e. VRo = 1) is found between 5500-6000 m (temperature: 150°) in bed older than Lower Siwaliks.

Let us consider that the past thermal gradient was not very different because the same Indian crust was the substratum of the actually deformed Siwaliks. Thus our field samples indicate that the layers have been submitted to rapid exhumation and reached their maximum burial a long time before the still buried levels of the same stratigraphic age reached by the wells. Therefore, the maximum depth and temperature of the samples collected in Middle Siwaliks of Nepal have reached in a time shorter than for the Middle Siwalik beds found in the Indian wells, though they show the same VRo. This comparison suggests that the Middle Siwalik samples collected in the field reached a depth of the same order or only slightly exceeding those of the Indian wells, i.e. 3500 m. For the Lower Siwalik field samples, the same reasoning also suggests that a burial depth slightly exceeding 6000 m has been reached.

This evolution where deep sediments of the foreland basin are incorporated in the thrust belt and exhumed at a fast rate by erosion in the inner zones of the accretionary wedge is well documented in the Taiwan thrust belt (Dahlen and Barr 1989).

CONCLUSIONS

The present-day Siwaliks consist of continental molasses, the material of which was produced by erosion of the Himalayan belt and was deposited in a flexural foreland basin. The persistence of shortening between India and Asia involves their deformation and incorporation into the growing mountain since at least 4 Ma This deformation is caused by the operation of a series of thrusts which succeed one another in both space and time. Intense erosion concomitant with deformation balances closely tectonic shortening and prevents burials of the Siwalik sediments at great depth. Furthermore, thrust tectonics and erosion could have totally destroyed inner parts, presently unknown, of the foreland basin. Due to this weak tectonic burial and to a weak thermal gradient, weak metamorphism affects the Siwalik sediments, and the highest metamorphism that has been found, located in lower Siwaliks at the footwall of the Main Boundary Thrust seems just enough to allow organic matter maturity. Nonetheless piggyback basins (Duns) develop preferentially above the steeper part of the basal decollement and/ or hinterward to back-thrusts affecting the Siwaliks. These piggyback basins prevent the exhumation of rocks and could induce greater burial depth for Siwalik beds located beneath these areas than those recorded from field samples.

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