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Micro-structures, mineralogy and geochemistry of clay size fraction (< 2 µm) of thrust zones of western Nepal Siwaliks (Karnali area)

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ABSTRACT

Shear zones of the Main Dun Thrust (MDT) of the Siwaliks of western Nepal have been investigated in order to specify the deformation mechanisms and mineral transformations. The Riedel fractures and cleavage are developed. They are responsible for the scaly fabric of the fault zones and generate a "tectonic mixture" of both the Upper and Lower Siwaliks at the footwall and hangingwall of the MDT. Grain-size analysis of samples from the shear zones indicates a strong cataclastic deformation. Clay mineralogy varies significantly within the shear zone. However, the smectites abundance is higher in the shear zone than in the Upper and Lower Siwaliks and may exceed 40% of the <2 µm clay fraction.

The isotopic oxygen composition of clay fractions in the shear zone gives $\delta^{18}O$ of smectites that implies neoformation. The temperature of smectite neoformation is 40 to 60°C higher than pedogenic smectites present in the borders. δD of fluid inclusion of calcite associated to deformation show values consistent with water similar to the actual surface water and $\delta^{18}O$ of mineral implies temperature of crystallisation around 50°C. These low temperatures are in good agreement with the precipitation of smectites and kaolinites. Fluids sampled in hot springs of the Siwaliks of western Nepal have a meteoric origin with respect to the stable isotopes but are enriched in Na and depleted in K. The chemistry suggests the partial dissolution of feldspar and neoformation of smectites induced by fluid circulation.

It is presumed that shearing and crushing take place during seismic slip increasing the exchanging mineral surfaces whereas mineralogical reactions occur during interseismic periods.

INTRODUCTION

Numerous studies have shown the occurrence of fluids during tectonic deformation (Sibson, 1981; Karig, 1986; Sibson et al., 1988; Shi and Wang, 1988). In oceanic prisms, the main décollement level could be a path for fluids to the surface (Westbrook and Smith, 1983; Brown and Westbrook, 1988; Moore, 1989; Le Pichon et al., 1990). These fluids may be representative of deep processes. Pore fluid overpressure is thought to facilitate thrust faulting (Hubbert and Rubey, 1959) and controls thrust-fold belt and accressionary prism mechanics (Dalhen, 1990). Thus, mineralogy of shear zone is affected by the characteristics of fluids during deformation process.

This paper presents the fluid characteristics along the major thrusts of the Himalayan thrust system. The major thrusts affecting the Siwaliks of western Nepal may be considered as frontal field outcrops of the Himalayan thrust system. A branch on a shallow north dipping detachment (Ni and Barazanghi, 1984) links the development of the outer thin-skinned thrust belt (intra-continental prism of the Siwaliks) to the deep tectonics beneath the Higher Himalaya.

The main shear zones of the intra-Siwalik thrusts have been investigated with a multidisciplinary approach. Analysis of micro-structures within the main shear zones was performed to identify the deformation mechanisms. Grain-size analysis of the <1mm fraction was performed across the fault zones.

Special care was taken for clay mineralogy and especially clay transformations and neoformations. Clay mineralogy could be a marker for fluids running along the faults. Oxygen isotopes of clayey material is used to determine the source and temperature of these fluids. Geochemistry and temperature of "hot springs" are also considered and integrated in the results.

THRUST-FAULTS OF OUTER HIMALAYAN BELT

Several thrust sheets deform the Cenozoic foreland basin sequence between the Lesser Himalaya to the north and the Gangetic Plain to the south (Fig.1). From north to south, the main thrusts are the Main Boundary Thrust (MBT), the Main Dun Thrust (MDT) and the Main Frontal Thrust (MFT). These thrusts have a mean N120°-N140° trending direction with steep northward dip varying from 35° to 85°. The foreland basin sequence is classically subdivided into three units on the basis of lithostratigraphic criteria. These are Lower, Middle and Upper Siwaliks. The lower member consists of fluvial channel sandstones alternating with oxidised calcitic palaeosols. The Middle Siwaliks are composed of very thick channel sandstones and drab-coloured histosols, and the upper member comprises of mainly gravely braided river deposits. The Siwalik Group of western Nepal exhibits an overall upward coarsening trend. The sandstones contain various grain types from the major lithotectonic zones of the Himalaya. The main grain types are plagioclase, K-feldspar, quartz and rock fragments of quartzite, schist, phyllite, gneiss, limestone and dolostone. Cements are mainly calcite, kaolinite, quartz, and anhydrite (Dhital et al., 1995).

The Main Dun Thrust (Fig. 1) is one of the most laterally extensive structures and at least eight kilometres of displacement occurred along its main shear zone. From balancing methods, Mugnier et al. (1994) estimated the depth of the décollement at about 4-5 km as inferred from seismic methods for the main décollement in the Siwaliks of western Nepal (DMG, 1994). The Lower Siwaliks form the hangingwall of the thrust and the Upper Siwaliks

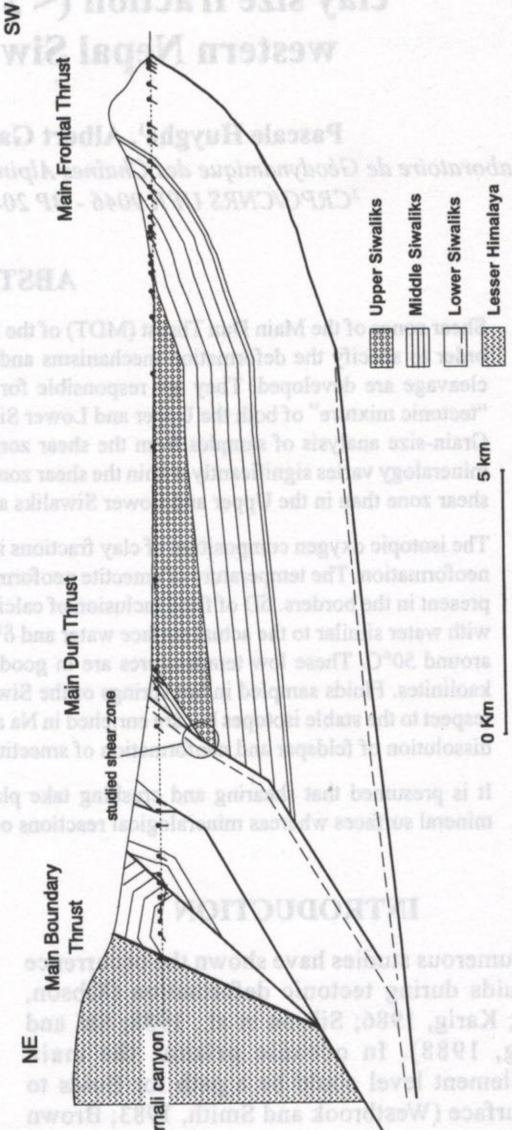

Fig. 1: Balanced cross-section through the Outer and Lesser Himalayan Thrust belt, Karnali area, western Nepal. Location of the studied shear zone.

occur at the footwall. Shear zones of the MDT are several metres thick. In outcrop, they are evidenced by coloured alteration bands of muddy material that outline complex tectonic fabrics.

The shear zones are mainly composed of clayey material and micro-clasts of quartz and calcite from a few mm to a few μm in size. At the outcrop, the shear zone is often characterised by a network of faults ranging from cm to m scale. At the m scale, the faults interpreted as Riedel fractures often enclose rock lenses of different lithologies. The acute angle between the main thrust surface and faults bounding lenses indicates unambiguously the shear sense from north to south. At a cm scale, statistical analysis of the distribution of both the fractures and cleavage within the shear zone of the MDT along the Bheri River at Kummekhot (Fig. 2) also shows a north to south shear sense. Small-scale tension gashes (T on Fig. 2a) filled with quartz and automorphic calcite crystals may develop around the quartz crystals in the fault gouge (Baille-Bareille, 1997).

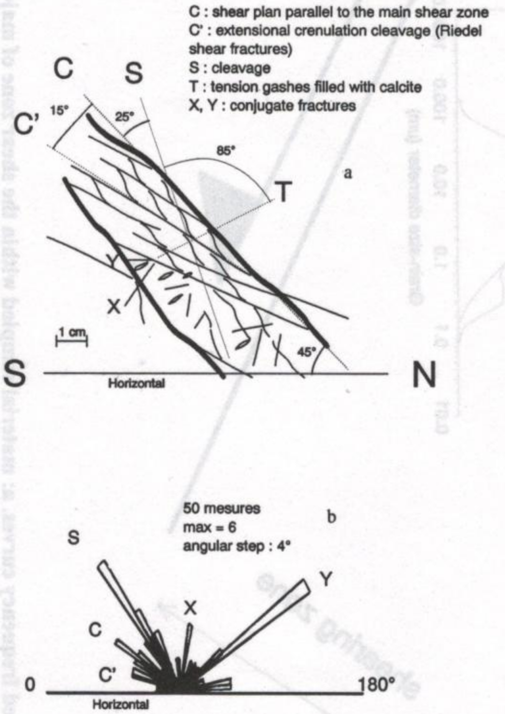

Fig. 2: Typical pattern observed at outcrop along the main Karnali shear zone. (a): main tectonic features; (C): shear plane parallel to the shear zone boundary; (C'): Extensional crenulation cleavage (Riedel shear fractures), (S): cleavage and (T): tension gashes filled with calcite. b: statistical analysis of the distribution of the fractures and cleavage.

The network of Riedel fractures and cleavage are responsible for the scaly fabric of the shear zones. One of the major characteristics is a "tectonic mixture" of both the Upper and Lower Siwaliks at the footwall and hanging wall of the major thrusts.

CLAY MINERALOGY AND GEOCHEMISTRY WITHIN THE SHEAR ZONES

Methods

Grain size analysis was performed by laser diffraction using Malvern particle sizer model 215 FR at the University of Chambéry. Analysis of clay was carried out by X-ray diffraction at the University of Grenoble, using a Philips PW 1120/90 diffractometer. The <2 μm and <0.4 μm fractions were collected by decantation after settling and oriented aggregates were made on glass slides. The semiquantitative estimation is based on the peak heights of clay mineral peaks.

Oxygen from silicate sites on clays was extracted by fluorination using BrF_5 following the technique of Clayton and Mayeda (1963). Oxygen was converted to CO_2 gas that was analysed on a VG 602D mass spectrometer. Average reproducibility was ±0.12‰ on clay duplicates. Isotopic ratios ($\delta^{13}C$) and ($\delta^{18}O$) of carbonates were determined following the method of McCrea (1950).

Results

Grain Size Analysis

Grain size of material sampled within the shear zones generally varies between 0.1 μm and 100 μm. It mainly consists of clays, silts and very fine sands (Fig. 3). There is no particles with a size ranging from 100 μm to 1000 μm (Fig. 3b). The <100 μm grade mainly consists of quartz, feldspar, goethite and clay minerals. No significant lateral variation of grain-size or sorting may be noted towards the 2 m thick shearing zone.

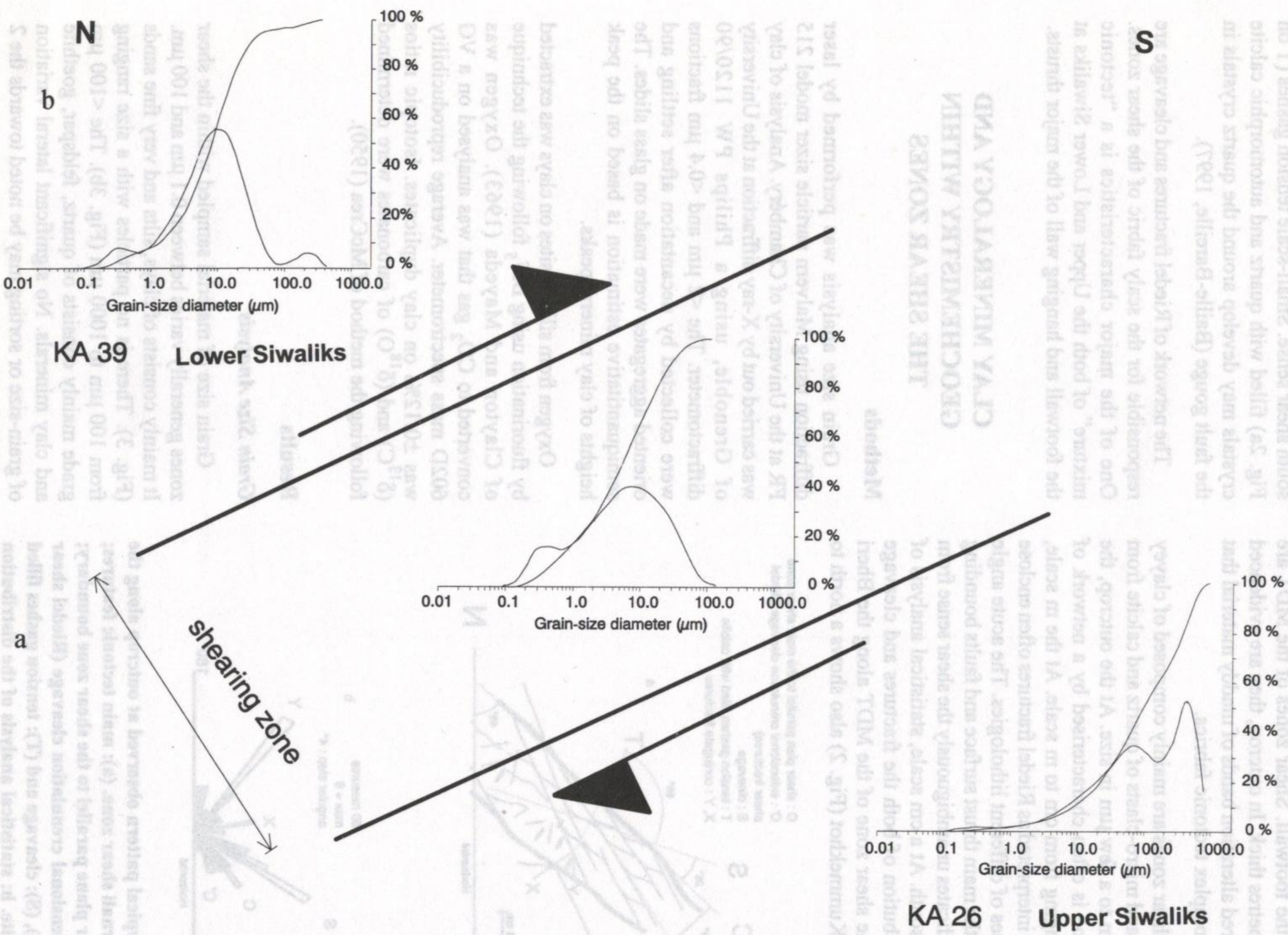

Fig. 3: Selected smoothed frequency curves. a: material sampled within the shear zone of major thrusts; b: at the thrust hangingwall (Lower Siwalik sediments); c: at the thrust footwall (Upper Siwalik sediments).

Clay Mineralogy

In all samples, the fraction <2 µm generally contains illite, chlorite, kaolinite, smectites and mixed-layers (Fig. 5) and small amounts of quartz, feldspar (mainly plagioclases) and goethite or hematite. Illite is the dominant clay mineral with a mean proportion of about 45%. Smectite is especially increasing within the shearing zone up to 40% of the <2 µm clay fraction, wherea sillite, chlorite and kaolinite contents decrease (Fig. 6).

Mixed-layer clay minerals consist of illite-smectites and chlorite-smectites. Their proportion is rather constant of about 10% in the hangingwall and footwall of the fault. Within the shear zone itself, an increase of the proportion of mixed-layers up to 25% is also noted.

In the <0.4 µm fraction, proportions of smectites is 1.5 higher than in the <2 µm fraction and contents of mixed-layers may be twice what it was in the <2 µm fraction. Correlatively, chlorite content decreases (Fig. 4b).

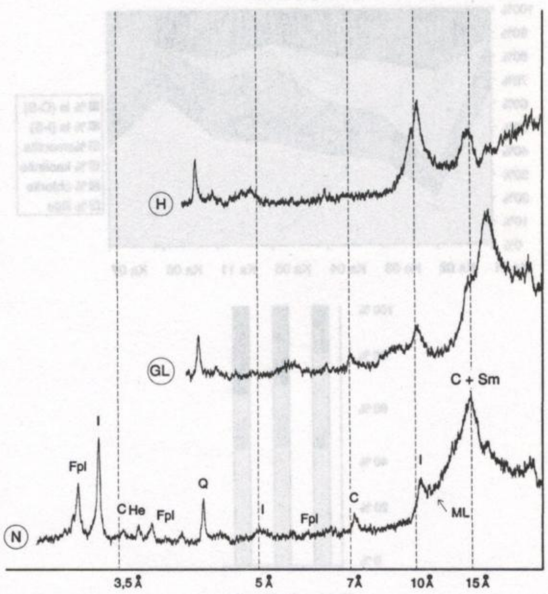

Fig.5: Diffractogram of sample KA02. N : natural unheated test ; GL : glycolated test ; H : heated test ; I : illite ; C : chlorite ; Sm : smectites ; Q : quartz ; Fpl : feldspars

Oxygen Geochemistry of Clay Fraction and Carbonate Geochemistry

The $\delta^{18}O$ of clayey fraction ranges from 12.4 to 14.4‰ in the Siwalik rocks while it ranges from 12.4 to 17.0‰ in the shear zone (Table 1). These values are relatively low for clay minerals and similar to results obtained for the other parts of the Siwaliks (Stern et al., 1997). Variations in isotopic composition of the shearing zone samples were correlated with their smectite contents (Fig. 7). Two distinct populations appear, one representative of the <2 µm fraction and the other one representative of the <0.4 µm fraction. This implies that $\delta^{18}O$ is controlled by mixing proportions of different minerals showing very distinct isotopic signature. Smectites in the <2 µm fraction have, therefore, a

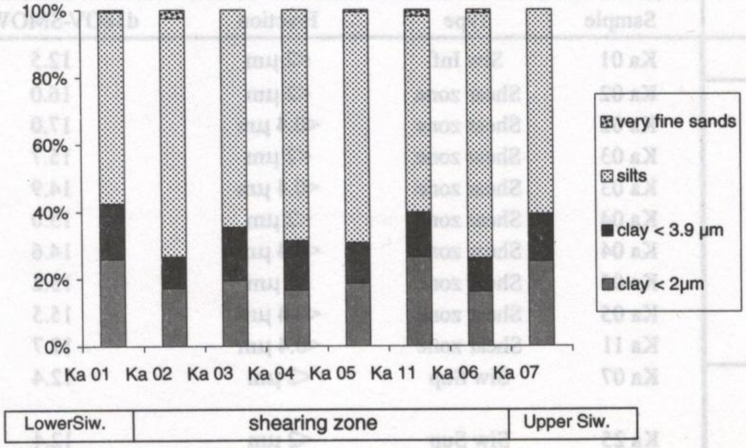

Fig. 4: Grain-size analysis through the shear zone.

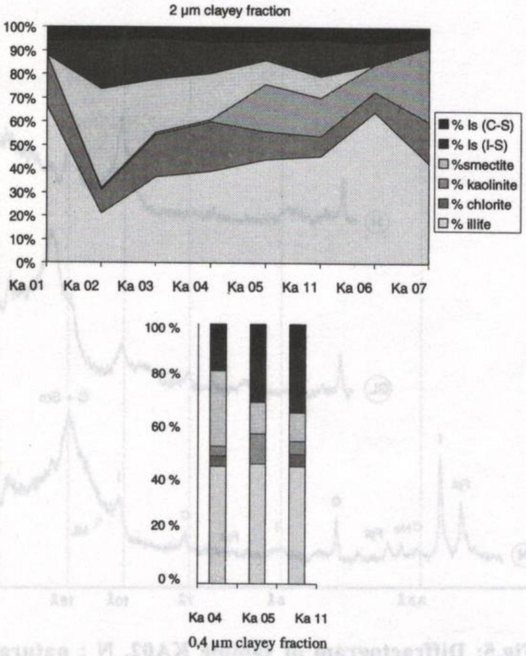

Fig. 6: Clay mineralogy through the shear zone. a : for the < 2 µm fraction; b : for the < 0,4 µm fraction.

$\delta^{18}O$= 25±3‰ while those in the <0.4 µm fraction have a $\delta^{18}O$=19±1‰.

A single calcite slickenslide along the bedding was sampled at the hangingwall of the MFT and was analysed for carbon, oxygen and strontium isotope composition of calcite and for hydrogen isotope composition of fluid inclusions. The $\delta^{18}O$ value of the calcite slickenslide is 12.6‰ (Table 1), that is lower than values usually shown by detrital or pedogenic carbonates of the Siwaliks (Quade et al., 1995; Quade et al., 1997). The $\delta^{13}C$ value of the calcite is low, whereas the $^{87}Sr/^{86}Sr$ ratio is high. These characteristics are similar to C and Sr isotopic ratios of "hot springs" (Table 2) and modern rivers (Galy and France-Lanord, 1998).

More than 99% of fluid inclusions found in the calcite slickenslide consist of H_2O and the rest corresponds to CO_2 suggesting a pure water inclusion. The δD values for fluid inclusions are relatively low (-83‰) corresponding to the composition of the lower part of local surfacial water.

DISCUSSION

Comparison with the Siwalik Series of Karnali Section

The Karnali River offers a stratigraphic section of about 4000 m thick Lower to Upper Siwaliks. The clay fraction and grain size of this section were analysed using the same method as for material sampled within the shear zones. Changes of clay mineral proportions and grain size parameters

Table 1: Oxygen isotopic composition of silicate.

	Sample	Type	Fraction	d18OV-SMOW %	N
Lower Siwaliks	Ka 01	Siw Inf	<2 µm	12.5	1
Shear Zone	Ka 02	Shear zone	<2 µm	16.0	2
	Ka 02	Shear zone	<0.4 µm	17.0	1
	Ka 03	Shear zone	<2 µm	15.7	2
	Ka 03	Shear zone	<0.4 µm	14.9	1
	Ka 04	Shear zone	<2 µm	15.0	2
	Ka 04	Shear zone	<0.4 µm	14.6	1
	Ka 05	Shear zone	<2 µm	13.2	2
	Ka 05	Shear zone	<0.4 µm	15.5	1
	Ka 11	Shear zone	<0.4 µm	12.7	1
Upper Siwaliks	Ka 07	Siw Sup	<2 µm	12.4	2
	Ka 25	Siw Sup	<2 µm	12.4	1
	Ka 27	Siw Sup	<2 µm	14.3	1

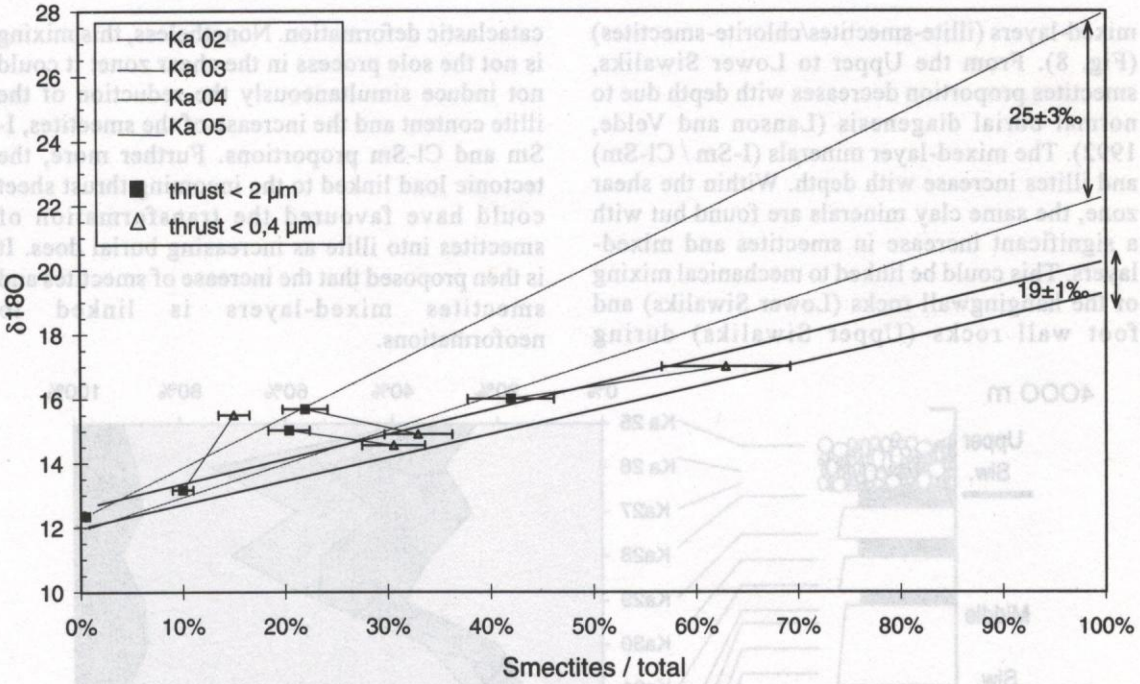

Fig. 7: $\delta^{18}O$ versus smectites abundance of clays sampled within a major thrust shearing zone of the Siwaliks.

Table 2: Chemistry of "hot springs" and carbonates data.

Sample		NH 2	NAG 17	KAR
Type		S	S	C
Place		Surai	Reare	
Date		3.11.95	11.21.95	
Temperature	°C	35	30	
pH			7.45	7.95
TDS	mg/l	825	1094	
HCO_3	µmol/l	9820[§]	16846	
F	µmol/l	35	137	
Cl	µmol/l	67	347	
SO_4^{2-}	µmol/l	201	781	
NO_3	µmol/l	8	bdl	
Na^+	µmol/l	5942	17180	
K^+	µ,ol/l	120	827	
Mg^{2+}	µmol/l	782	131	
Ca^{2+}	µmol/l	1275	309	
Si	µmol/l	1057	442	
Sr^{2+}	µmol/l	4.79[#]	1.12	551[•]
$^{87}Sr/^{86}Sr$		-	0.7336	0.72968
δD	V-SMOW	-48	-44	-83[¶]
$\delta^{18}O$	V-SMOW	-7.8	-6.5	12.56
$\delta^{13}C$	PDB	-9.5[‡]	-5.0[‡]	-9.11

[#]: AA analysis calibrated with MSID;
[§]: alkalinity field titration; [‡]: Dissolved inorganic carbon;
[•]: ppm; [¶]: Fluid inclusion.

between the shear zone samples and the undisturbed sediments are valid and their significance is discussed in terms of deformation mechanisms.

Grain Size

The Siwalik sediments sampled along the Karnali River have a systematic trimodal distribution (Fig. 3b). Every grain-size fraction is present (clay, silt and sand fractions). In the shearing zone, fine and medium sands disappear whereas the silt fraction increases. The very poor sorting found within the shearing zone is interpreted as the result of cataclastic deformation. The cataclastic deformation involves all mineral species even the quartz crystals are broken (Baille-Bareille, 1997). Cataclastic deformation affects a wider zone up to 3-4 m away from the shear zone itself.

Clay Mineralogy

The clay fraction of the Siwaliks along the Karnali River shows a classic detritic micaceous series with illite, chlorite, kaolinite, smectites and mixed-layers (illite-smectites/chlorite-smectites) (Fig. 8). From the Upper to Lower Siwaliks, smectites proportion decreases with depth due to normal burial diagenesis (Lanson and Velde, 1992). The mixed-layer minerals (I-Sm / Cl-Sm) and illites increase with depth. Within the shear zone, the same clay minerals are found but with a significant increase in smectites and mixed-layers. This could be linked to mechanical mixing of the hangingwall rocks (Lower Siwaliks) and foot wall rocks (Upper Siwaliks) during cataclastic deformation. Nonetheless, this mixing is not the sole process in the shear zone: it could not induce simultaneously the reduction of the illite content and the increase of the smectites, I-Sm and Cl-Sm proportions. Further more, the tectonic load linked to the incoming thrust sheet could have favoured the transformation of smectites into illite as increasing burial does. It is then proposed that the increase of smectites and smectites mixed-layers is linked to neoformations.

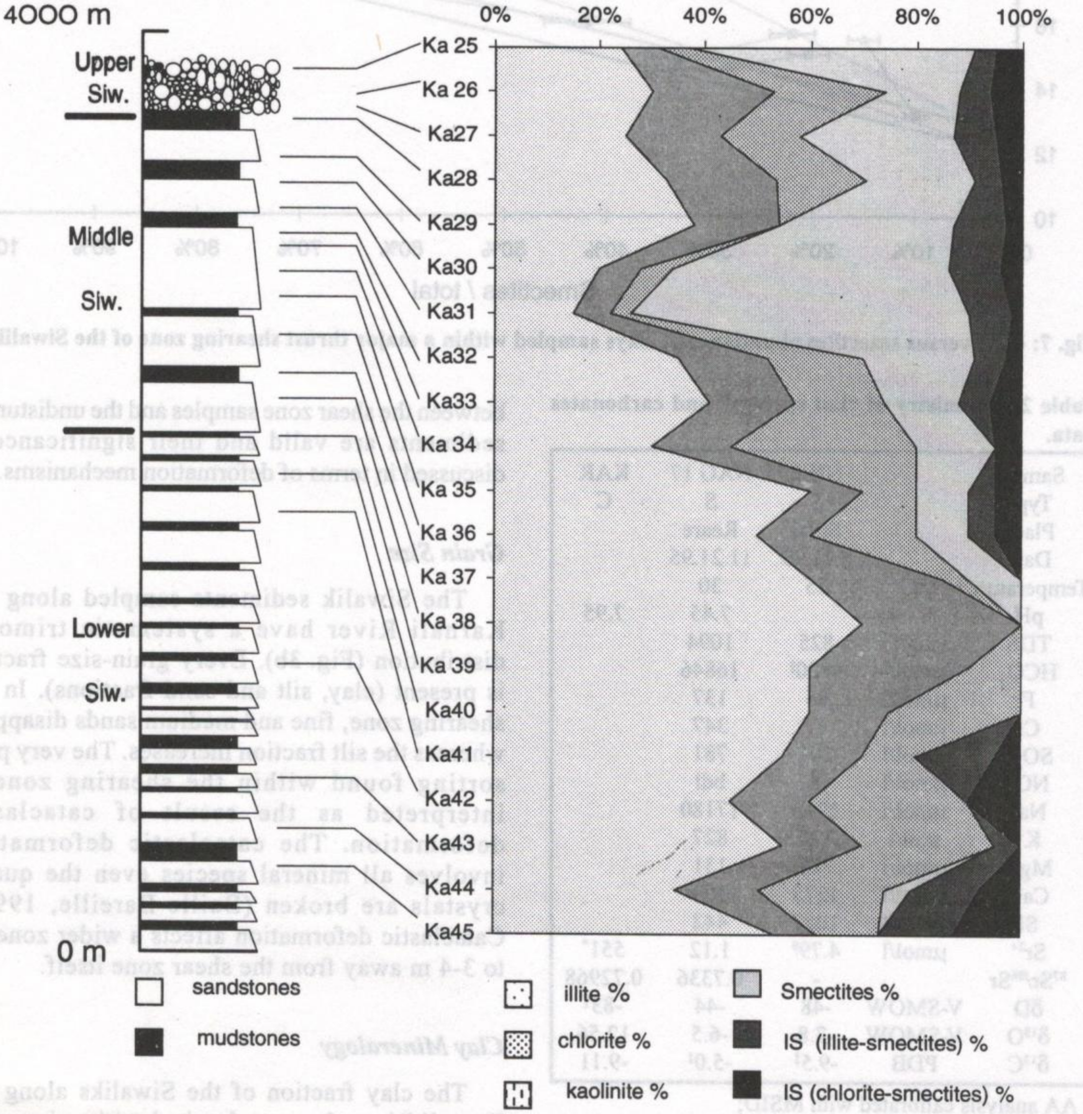

Fig. 8: Clay mineralogy for the Siwalik sediments sampled along the Karnali River.

Oxygen Isotopes and Carbonate Geochemistry

As fault planes are preferential drains for fluids to the surface (Brown and Westbrook, 1988; Moore, 1989), it is proposed that the neoformations and transformations would be induced by fluid circulation. More over, the strong crushing that occurs during thrusting increases the potential exchanging surfaces of particles within the shear zone. Geochemistry corroborates this hypothesis. Extrapolation of oxygen isotopic composition of clay fractions in the shear zones gives $\delta^{18}O$ of smectites that does not fit with formation in pedogenic conditions. It is then proposed that the $\delta^{18}O$ values of clays are associated to neoformations within the shear zone and reflect the $\delta^{18}O_{fluids}$ and $T_{crystallisation}$ conditions. The temperature for smectites neoformation is 40°C to 60°C higher than pedogenic smectites present in the borders. δD (-83 ‰) of fluid inclusions of calcite associated to the deformation is consistent with the present-day surface water and the $\delta^{18}O$ of mineral implies a temperature of crystallisation around 50°C. These low temperatures are in good agreement with mineral transformations of feldspars or detrital clays and micas into smectites and kaolinite rather than formation of illite.

Comparison with Fluids From "Hot-Springs"

Fluids have been sampled in two "hot-springs" of the Siwaliks. They have been analysed in CRPG, Nancy. (δD - $\delta^{18}O$) lies on the local meteoric water line defined by surface running water. Sr isotopic tracers are insensitive to the temperature of crystallisation.The fractionation factor between dissolved inorganic carbon and calcite is less than 2‰ for $T>20°C$ (Faure, 1986; Emrich et al., 1970). Sr and C isotopic compositionsare in the same range for springs and shear zone fluids than for calcite in slickenside. Their high Total Dissolved Solid (TDS) is carried by bicarbonate and sodium, in large excess of chlorine. While carbonate occurred in the percolated formations, $[Ca^{2+}]$ is in the same range as in surface water. The high $[Na^{+}]$ correlated with [Si] and associated with low $[Ca^{2+}]$ suggests an enhanced incongruent dissolution of Na-silicates. We suggest the partial dissolution of feldspar and the neoformation of smectites. The $^{87}Sr/^{86}Sr$ is largely higher than that of carbonate in the Siwaliks of western Nepal (0.718-0.722) and corresponds to detrital Himalayan feldspar (Galy et al., 1996). The isotopic composition of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) and its covariation with $[SO_4^{2-}]/([SO_4^{2}]+[HCO_3^{-}]$ ratio are similar to those found in surface water (Galy and France-Lanord, 1998). Sulphate is therefore provided by the oxidation of sulphide and bicarbonate comes from the dissolution of carbonate.The dissolved CO_2 may also react with silicate but in this case the $\delta^{13}C_{DIC}$ would be much lower (around –16‰). This suggests that dissolved CO_2 is not a reactant for the neoformation of smectites. Since these spring waters lie not far away the albite-kaolinite and kaolinite-Na montmorillonite lines (in Na_2O-Al_2O_3-SiO_2-H_2O after Garrels and Christ, 1965), we propose :

$$2NaAlSi_3O_8+2H^++4H_2O=Al_2Si_4O_{10}(OH)_2+3H_4SiO_4+2Na^+$$

as the main neoformation reaction.

CONCLUSION

From this study of the shear zones, it seems that the increase of smectites and smectite mixed-layers could be a good marker for thrusting in the Siwaliks.We propose that their abundance is essentially linked to clay neoformations from feldspars. The $\delta^{18}O$ of clays within the shear zone and the geochemistry of carbonate associated to the deformation show that these neoformations take place at relatively low temperatures. They are induced by fluid circulation running along the thrust planes to the surface. Moreover crushing within the shear zones increases the exchanging mineral surfaces helping the partial dissolution of feldspars and then their transformations into clays. Chemical analysis of "hot-springs" corroborates these reactions.

These results are preliminary ones but they suggest that clay minerals could record fluid circulation associated with tectonics, as they are sensitive to changing chemical and physical conditions. These mineralogical reactions occur during interseismic periods, whereas crushing takes place during seismic slip.

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REFERENCES

Baille-Bareille, B., 1997, Mécanismes de la déformation dans les zones de failles situées au front du système chevauchant himalayen. Unpublished Master's Memoir, Grenoble University, 23 p.

Brown, K.M. and Westbrook, G.K., 1988, Mud diapirism and subcretion in the Barbados Ridge Accretionary Complex–the role of fluids in accretionary processes. Tectonics, v. 7(3), pp. 613-640.

Clayton, R.N. and Mayeda, T.D., 1963, The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. Geochim. Cosmochim. Acta, v. 27, pp. 43-52.

Dalhen, F.A., 1990, Critical taper model of fold and thrust belts and accretionary wedges. Annu. Rev. Earth and Planet. Sc., v. 18, pp. 55-99.

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, mid western Nepal. Bull. Dept. Geology, Tribhuvan Univ., Kathmandu, Nepal, v. 4(Special Issue), pp. 1-70.

Emrich, K., Ehhalt, D.H. and Vogel, J.C., 1970, Carbon isotope fractionation during precipitation of calcium carbonate. Earth and Planet. Sc. Lett., v. 8, pp. 363-371.

Faure, G., 1986, Principles of isotope geology. Second Edition, John Wiley and Sons, New York, 589 p.

Galy, A. and France-Lanord, C., 1998, Processes of weathering in the Himalaya and the riverine alkalinity budget. GERM Workshop, 10-13 March. La Jolla.

Galy, A., France-Lanord, C. and Derry, L. A., 1996, The late Oligocene-early Miocene Himalayan belt Constraints deduced from isotopic compositions of early Miocene turbidites in the Bengal Fan. Tectonophysics, v. 260, pp. 109-118.

Garrels, R.M. and Christ, C.L.,1965, Solutions, Minerals and Equilibra. Harper and Row.

DMG, 1994, The Kingdom of Nepal exploration opportunities. Department of Mines and Geology, Katmandu, 16 p.

Hubbert, M.K. and Rubey, W.W., 1959, Role of fluid pressure in the mechanics of overthrust faulting. In: Mechanics of fluid-filled porous solids and its application to overthrust faulting, Bull. Geol. Soc. Am., v. 70, pp. 115-166.

Karig, D.E., 1986, Physical properties and mechanical state of accreted sediments in the Nankai Trough, Southwest Japan Arc, Geol. Soc. Am. Mem., v. 166, pp. 117-133.

Lanson, B. and Velde, B., 1992, Decomposition of X-ray patterns: a convenient way to describe complex diagenetic smectite-to-illite evolution, Clays and clay Miner., v. 40, pp. 629-643.

Le Pichon, X., Foucher, J.P., Boulegue, J., Henry, P., Lallemant, S., Benedetti, M., Avedix, F. and Mariotti, A., 1990, Mud volcano field seaward of the Barbados accretionary complex: a submersible survey. Jour. Geoph. Res., v. 95(B6), pp. 8931-8943.

McCrea, J.M., 1950, On the isotopic chemistry of carbonates and a palaeotemperature scale. Jour. Chem. Phys., v. 18, pp. 849-857.

Moore, J.C., 1989, Tectonics and hydrogeology of accretionary prisms: role of décollement zone. Jour. Struc. Geol., v. 11, pp. 95-106.

Mugnier, J.L., Mascle, G.H. and Faucher, T., 1994, The structures of the frontal belt of Himalaya (Siwaliks of western Nepal). In: R. Kumar, S. K. Ghosh, and N. R. Phadtare (eds.). Siwalik foreland basin of himalaya. Oxford, Himalayan Geology, v. 15, pp. 245-261.

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

Quade, J., Cater, J.M.L., Ojha, T.P., Adam, J. and Harrison, T. M., 1995, Late Miocene environmental change in Nepal and the northern Indian subcontinent: stable isotopic evidence from paleosols. Geol. Soc. Am. Bull., v. 107, pp. 1381-1397.

Quade, J., Roe, L., DeCelles, P.G. and Ojha, T.P., 1997, The late Neogene 87Sr/86Sr record of lowland Himalayan rivers. Science, v. 276, pp. 1828-1831.

Shi, Y. and Wang, C., 1988, Generation of high pore fluid pressures in accretioary prisms: inferences from the Barbados subduction complex. Jour. Geophys. Res., v. 93, pp. 8893-8910.

Sibson, R.H., 1981, Fluid flow accompagnying faulting : field evidence and models. In: D. Simpson, P. Richard (eds.), Earthquake Prediction: An International Review, Maurice Ewing Series, Am. Geophys. Monogr., v. 4, pp. 593-603.

Sibson, R.H., Robert, F. and Poulsen, H., 1988, High angle reverse faults, fluid pressure cycling and mesothermal gold quartz deposits. Geology, v. 16, pp. 551-555.

Stern, L.A., Chamberlain, C.P., Reynolds, R.C. and Johnson, G.D., 1997, Oxygen isotope evidence of climate change from pedogenic clay minerals in the Himalayan molasse. Geochim. and Cosmochim. Acta, v. 61, pp. 731-744.

Westbrook, G.K. and Smith, M.J., 1983, Long décollements and mud volcanoes: evidence from the Barbados Ridge Complex for the role of high pore fluid pressure in the development of an accretionary complex. Geology, v. 11, pp. 279-283.