Mountain building in the Nepal Himalaya: Thermal and kinematic model from 20 My to present

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Abstract

We describe a model of crustal deformation and thermal structure across the Nepal Himalaya over the last 20Myr. The model assumes that, throughout this period, shortening across the range has been entirely taken up by slip along a single thrust fault, the Main Himalayan Thrust (MHT) Fault, and that the growth of the Himalayan wedge has resulted from the development of a duplex at mid-crustal scale. We show that this process explains the inverse thermal gradient documented throughout the Lesser Himalaya, the discontinuity of peak metamorphic temperatures across the MCT, as well as the age gradient of exhumation across the range. This study shows that the Himalayan range has primarily grown by underplating through the development of a mid-crustal duplex straddling the brittle-ductile transition on the MHT.

1 Introduction

The Himalaya is often quoted as a case example of a mountain range that would fit the critical wedge model [*Davis et al.*, 1983]. According to such a model, crustal thickening in the Himalayas results from frontal accretion combined with internal deformation so as to maintain a topographic slope at equilibrium with frictional stresses along the basal thrust fault. The

Holocene kinematics of deformation along the Himalaya of central Nepal suggests a different kinematics since all the shortening across the range is presently taken up by slip along a single major thrust fault, the Main Himalayan Thrust (MHT), while erosion would have maintained a topography at dynamic equilibrium [*Lavé and Avouac*, 2001; *Lavé and Avouac*, 2000]. On the other hand the structural evolution and chronology of exhumation over the last about 20 Myr of this part of the Himalaya has been relatively well documented from a number of structural and thermochronological studies (e.g. [*Catlos et al.*, 2001; *Robinson et al.*, 2001]) , and might suggest a deformation more consistent with the prediction of a critical wedge model.

Hereafter, we show that the evolution of the range over the Holocene and over the last 20Myr can be reconciled from a model in which the Himalayan wedge would have developed primarily by underplating. We show that this model predicts PT-t paths and a thermal structure consistent with the inverse thermal gradient recently documented throughout the Lesser Himalaya from RSCM thermometry [*Beyssac et al.*, submitted; *Bollinger et al.*, submitted] as well as with the available thermochronological data collected in Central Nepal .

2 Constraints on the structure and kinematic evolution of the range

To the first order, the structure of the range consists of imbricated sheets separated by major thrust faults (Figure 1). The sub-Himalaya is bounded to the south by the Main Frontal Thrust fault (MFT). This fold-and-thrust belt involves Tertiary molasses detached from the underthrusting Indian basement. North of it, the Main Boundary Thrust fault (MBT) places the meta-sediments of the Lesser Himalaya on top of the Tertiary foreland deposits. These faults most probably branch from a single thrust fault at depth, the MHT which would root into a mid-crustal ductile shear zone beneath southern Tibet [*Alsdorf et al.*, 1996; *Makovsky et al.*, 1996].

The Holocene kinematics of deformation along the Himalayan front in central Nepal was constrained from the study of deformed alluvial terraces [*Lavé and Avouac*, 2000] and from the pattern of river incision across the range [*Lavé and Avouac*, 2001]. It indicates a thrusting rate along the MHT of 21 +/- 1.5 mm/yr, close to the shortening rate across the whole Himalaya estimated from GPS measurements [*Bilham et al.*, 1997; *Larson et al.*, 1999], implying negligible internal shortening of the Himalayan wedge. This finding seems at odd with the structure of the Himalaya which implies some accretion as well as some internal deformation with possibly out of sequence thrusting. The various units in the Lesser Himalaya consist of proterozoic sediments of Indian affinity that were accreted to the High Himalayan crystallines (e.g. [*DeCelles et al.*, 2001; *Robinson et al.*, 2001]). These units have a well developed foliation which depicts a broad antiform [*Pêcher*, 1989], interpreted as the result of a duplex [*DeCelles et al.*, 2001; *Schelling and Arita*, 1991] (Figure 1), that would have developed mainly over the last 10 Myr [*DeCelles et al.*, 2001; *Robinson et al.*, 2001]. Relatively young exhumation ages along the front of the High range, were interpreted as evidence for late, out-of-sequence reactivation of the MCT zone [*Catlos et al.*, 2001; *Harrison et al.*, 1998].

Here, we contend that a simple way to reconcile the long term structural evolution of the range is to assume that the MHT has always been the only major active thrust fault, but that it has migrated southward incorporating some slivers detached from the underthrusting Indian crust (Figure 1). Accordingly the Himalayan wedge would have grown by underplating rather than by frontal accretion. In the following section, we test such a model in view of its prediction with regards to the chronology of exhumation and metamorphic temperatures.

3 Constraints on the Kinematics of exhumation and petro-metamorphic structure.

The distribution of peak metamorphic temperatures in the Lesser Himalaya of Central Nepal has been recently documented from RSCM thermometry [*Beyssac et al.*, submitted]. Temperatures in the LH vary typically between 550°C near the MCT to about 350°C at deeper structural levels. The combination of these data with local structural measurements indicate that the inversed thermal gradient first documented near the MCT zone actually encompasses the 7-8 kilometres topmost Lesser Himalayan units [*Bollinger et al.*, submitted]. About 50km north of the MBT these data show that the peak temperatures decreases by about 30°C/km on average with a break in slope about 4-5 km from the MCT. Closer to the MCT, the thermometric data show primarily a 200°C discontinuity at the MCT.

The most complete picture of the chronology of exhumation in central Nepal comes from ^{39}Ar/^{40}Ar ages on muscovites (Figure 4). This technique provides an estimate of the age of cooling of the rock sample through the muscovite blocking temperature ~350°C. These data indicate that the trailing edge of the Katmandu thrust sheet cooled below 350°C about 20-22Myr ago, an age consistent with the onset of deformation and anatexis in the MCT zone [*Hodges et al.*, 1996; *Hubbard*, 1989]. The ages from the klippe and the LH decrease gradually northwards to about 5 Myr at the front of the high range, following a nearly linear trend corresponding to a slope of about 0.24 Myr/km (figure 3). Sparser cooling ages from apatite and zircon fission track also depict ages decreasing northward from the MBT to the front of the Himalayan range.

4 Modeling

Although it is highly probable that the duplex has resulted from discrete events of migration of the MHT, we model accretion as a continuous process. We choose the position of the active MHT to be the reference, and define the underthrusting rate, v1, and overthrusting rate, v2, as pictured in Figure 4. The rate of slip on the MHT is then v1+v2. If the topography is assumed steady-state, the hanging wall moves up across the steady-state thermal structure in such a way that the cooling ages should decrease linearly as a function of distance from the front the range, the gradient of ages being 1/v2 [*Avouac*, 2003; *Bollinger et al.*, submitted]. The various cooling ages do indicate such a trend (figure 4). The 0.24Ma/km gradient defined from the muscovites Ar/Ar ages implies a value for v2 of about 4mm/yr. The understhrusting rate can be estimated from the rate of sediment progradation in the foreland over the last 20-25Myr, assuming a steady state geometry of the flexural foreland [*Avouac*, 2003]. These data suggest a poorly constrained underthrusting rate between 10 and 20 mm/yr. Here, we assume that the underthrusting rate has remained constant over the last 20Myr, as well as the slip rate on the MHT taken to 21mm/yr, so that v1=17mm/yr.

The location of the zone of accretion was adjusted by trial and error so as to get peak metamorphic temperatures in the range of observed values (300 to 550°C). Given the parameters used to compute the thermal structure, this range of temperatures implies that the zone of accretion extends from about 80km to 150km from the MBT.

The thermal structure is computed from a finite elements formulation [*Henry et al.*, 1997; *Zienkiewicz and Taylor*, 1989]. Following [*Henry et al.*, 1997], frictional heating along the MHT is taken into account and 5 mediums are considered each being ascribed a radiogenic heat production and conductivity based on lithology (figure 4).

The total volume of accreted material was estimated from the structural section. The model preserves the HHC thrust sheet, as observed in Central Nepal, but would make it possible to produce a LH window by increasing only slightly the amount of material accreted. The rate of underplating was adjusted so as to imply denudation rates (assumed equal to uplift rates) consistent with the youngest exhumation ages at front of the High range. The Ar/Ar ages on muscovite of the order of 7Ma, as well as apatite fission track ages of around 2Ma requires a denudation rate of the order of 1.5mm/yr. This kinematics implies an underplating flux of 54km^3/km. By comparing this flux with the total volume of accreted LH, it makes it necessary that it has varied over the last 20 Myr. The break-in-slope in the inverse thermal gradient also suggests that some change in the regime of accretion has occurred. To keep the model simple, we have decomposed the accretion flux in two terms. One term is considered to have been constant over the last 20Myr and corresponds to the development of the so-called MCT zone, and the other term accounts for the development of the LH duplex over the last 8Myr. Because metamorphism is higher in the MCT zone we have therefore assumed that the corresponding zone of accretion extends to deeper depths than the zone of development of the LH duplex over the last 8Myr (figure 4). It implies a flux of 24km3/Ma/km since 20 Ma through the entire underplating window (80-150km), with an additional 30 km3/Ma/km across the shallower window (80-120km) over the last 8Myr. The geometry and total amount of material accreted, around 750km^3/km, is relatively consistent with the structural section across the Kathmandu klippe in central Nepal (Figure 4).

5 Discussion-Conclusion

The calculated isotherms show large deflections and are locally inverted (figure 5). This thermal structure results from the thrusting of a hot and highly radiogenic high Himalayan crystalline over the cold Lesser Himalaya (e.g. [*Le Fort*, 1975]), combined with the effect of erosion [*Huerta et al.*, 1999] and frictional shear heating (e.g. [*England*, 1993]).

In itself, the calculated thermal structure does not explain the steep inverse gradient of temperatures across the Lesser Himalaya. Actually, as the rocks move up along the MHT, colder rocks are gradually underplated leading to a gradient of peak metamophic temperatures much steeper than the one predicted from passive advection of the steady-state isotherm. This mechanism is alike post metamorphic shearing of the thermal isograds [*Brunel and Andrieux*, 1980].

The range of temperatures along the midcrustal zone of accretion matches with the peak temperatures deduced from RSCM thermometry. The peak temperatures calculated fits correctly the inverse apparent gradients estimated 50km from the MBT, with some break-in-slope at about 5km from the MCT due to the change in mode and rate of accretion around 8Myr, as well as the discontinuity of peak temperatures across the MCT (figure 2).

The model predicts cooling ages below 350°C consistent with the Ar/Ar ages on muscovites (figure 3). The cooling ages through 200°C and 100°C are also relatively consistent with the sparse fission tracks ages on zircon and apatite. It should be noted that the model predicts peak temperatures less than 350°C isotherm in the core of the anticlinorium at structural distances as short as 5km from the top of the LH, consistent with non reset muscovites as reported by [*Copeland et al.*, 1991].

The model implies that the Himalayan wedge would have grown essentially as a result of underplating. Given the range of temperature at these depths this process likely occurs in the transition zone between the brittle, seismogenic, and ductile portions of the MHT. The similar kinematics inferred from exhumed thrust fault system [*Dunlap et al.*, 1997] suggests that this process might be a common mode of crustal thickening. The data requires a major increase of the flux of accretion about 8Myr ago corresponding to the development of the LH mid-crustal duplex. The model presented here is based on some questionable crude hypothesis: the topography is assumed steady-state and underplating is modelled as a continuous process. Nonetheless, we believe it provides a first order kinematic description of the evolution of the Himalaya over the last Million years, which brings together a variety of structural, geochronological and petrological data. The discussion of the mechanisms controlling the mode and flux of accretion is deferred to further investigations that could be achieved from thermomechanical modelling.

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Figures

Fig. 1 : Simplified N18E section across the Himalaya of Central Nepal. Boxes A and B show structural location of the sections of figure 2 where inverse thermal gradients were documented.

Fig. 2 : Peak temperatures estimated from RSCM thermometry at respectively 80km (A) and 50 km (B) from the front of the range in central Western Nepal [*Bollinger et al.*, submitted]. Circles show the prediction of our model (KTM11). These data suggest an inverse thermal gradient which encompasses the topmost 7-8km of Lesser Himalayan units.

Fig. 3 : Synthesis of thermochronological ages from the Lesser Himalaya and HHC across the Himalaya of Central Nepal [*Arita et al.*, 1997; *Arita and Ganzawa*, 1997; *Bollinger et al.*,

submitted; *Macfarlane*, 1993; *Rai*, 1998]. All data are reported along a N18E section together with the predicted cooling ages from model KTM11.

Fig. 4 : Model geometry, kinematic and thermal parameters used in model KTM11. We have also reported the amount of HHC eroded over the last 20 Myr. Thermal diffusivity is taken to $10^{-6} m^2.s^{-1}$. The crust and mantle thermal conductivities are respectively 2.5 and 3 W.m-1.K-1. Surface temperature is 0°C. Shear stress along the MHT is assumed to be the minimum between the ductile and brittle shear stresses, for an effective friction μ=0.1 [*Henry et al.*, 1997]. Here it does not exceed 50 MPa. The width of the ductile shear zone is taken to 100m.

Fig. 5 : Steady state thermal structure (present day estimate) and velocity field predicted from model KTM11 over the last 8 Myr.

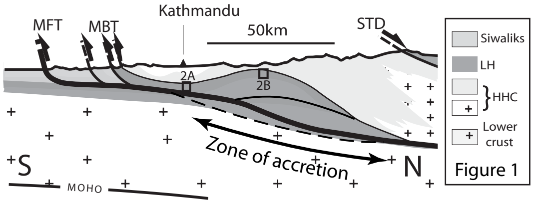
MFT
MBT
Kathmandu
50km
STD
2A
2B
Zone of accretion
S
N
MOHO
Siwaliks
LH
HHC
Lower crust

Figure 1

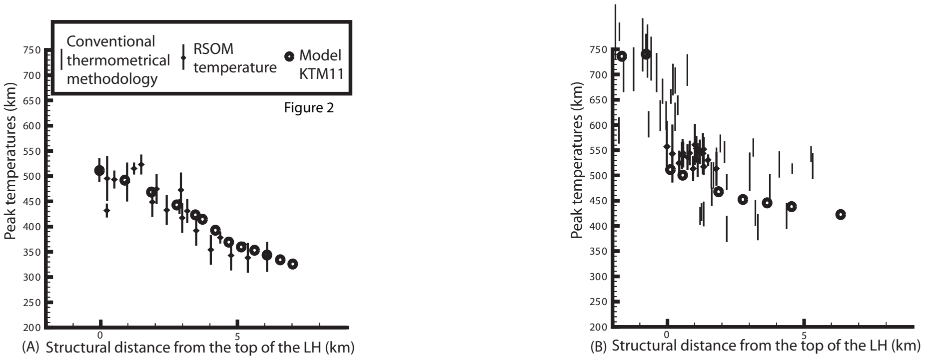

Figure 2

Conventional thermometrical methodology
RSOM temperature
Model KTM11
Peak temperatures (km)
750
700
650
600
550
500
450
400
350
300
250
200
0
5
(A) Structural distance from the top of the LH (km)
Peak temperatures (km)
750
700
650
600
550
500
450
400
350
300
250
200
0
5
(B) Structural distance from the top of the LH (km)

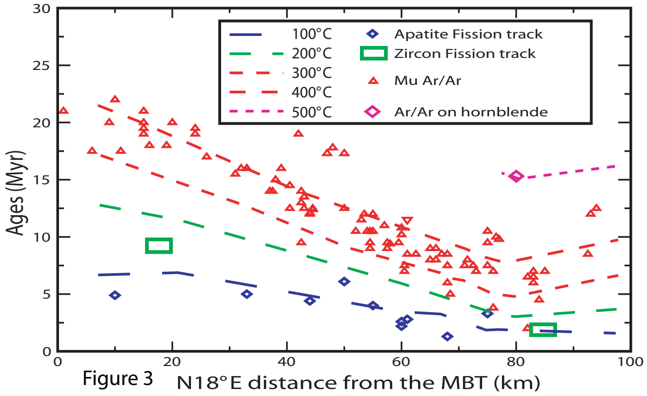
100°C
200°C
300°C
400°C
500°C
Apatite Fission track
Zircon Fission track
Mu Ar/Ar
Ar/Ar on hornblende
Ages (Myr)
0
5
10
15
20
25
30
0
20
40
60
80
100
N18°E distance from the MBT (km)

Figure 3

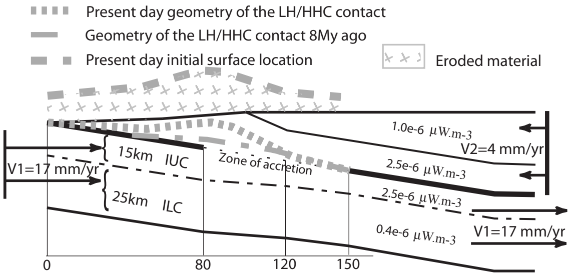
Present day geometry of the LH/HHC contact
Geometry of the LH/HHC contact 8My ago
Present day initial surface location
Eroded material
1.0e-6 μW.m-3
V2=4 mm/yr
15km IUC
Zone of accretion
2.5e-6 μW.m-3
V1=17 mm/yr
25km ILC
2.5e-6 μW.m-3
0.4e-6 μW.m-3
V1=17 mm/yr
0
80
120
150
Distance to the MBT (km)

Figure 4

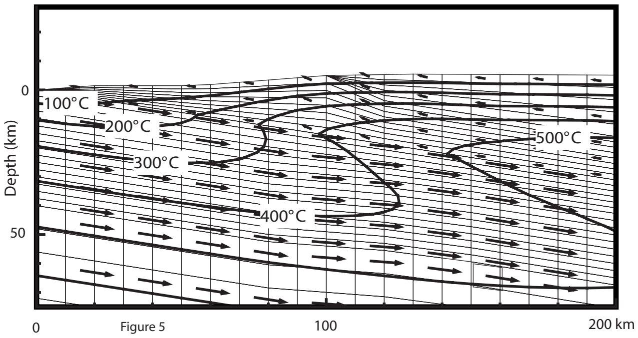

Figure 5