Is rapid exhumation of the High Himalaya driven by ramp overthrusting, the formation of mid-crustal duplex, or out-of-sequence thrusting associated with channel flow?

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A number of studies of river incision and exhumation across the Nepal Himalaya indicate that uplift rates must increase abruptly from the Lesser Himalaya to the High Himalaya. A zone with enhanced uplift rates is also needed to explain the high relief and the straightness of the front of the High Himalaya (Figure 1). Locally high uplift rates could relate to: 1- thrusting over a mid-crustal ramp (Lave and Avouac, 2001); 2- mid-crustal duplex growth (Bollinger et al, 2004, 2006); or 3- out-of-sequence thrusting along the front of the High Himalaya. (Harrisson et al, 1998; Hodges et al, 2004)

Rampoverthrusting can be a viable mechanism only over a short period of time since, considered alone, this mechanism fails to account for the growth of the orogenic wedge. The same problem arises with out-of-sequence thrusting, if considered alone. Thus an additional mechanism is needed to account for the transfer of material from the underthrusting Indian crust to the Himalayan wedge. The structure of the Himalayan wedge as well as the pattern of active deformation across the range suggests that underplating, through the development of a duplex system at mid-crustal depth, has been the dominant mechanism of accretion over the last ~15Myr. In an attempt at determining plausible kinematic models of the Himalaya of central Nepal over this period, we have applied a formal inverse approach based on the Neighbourhood Algorithm. The forward models consider the possibility of either thrusting localized along a single major thrust fault (the MHT) with non-uniform underplating due to duplexing, or out-of sequence thrusting in addition to thrusting along the MHT and with uniform underplating rate. The models are computed using the thermokinematic FEM model PECUBE (Braun 2003, Herman et al 2007), and tested against thermochronological, thermometric and thermobarometric data (Figure 2, compiled from the literature (Beyssac et al, 2004; Bollinger et al, 2004; Blythe 2007; Burbank 2003; Kohn et al 2004; Catlos et al 2001; Harrison et al 1998) and complemented with some new (U-Th)/He data.

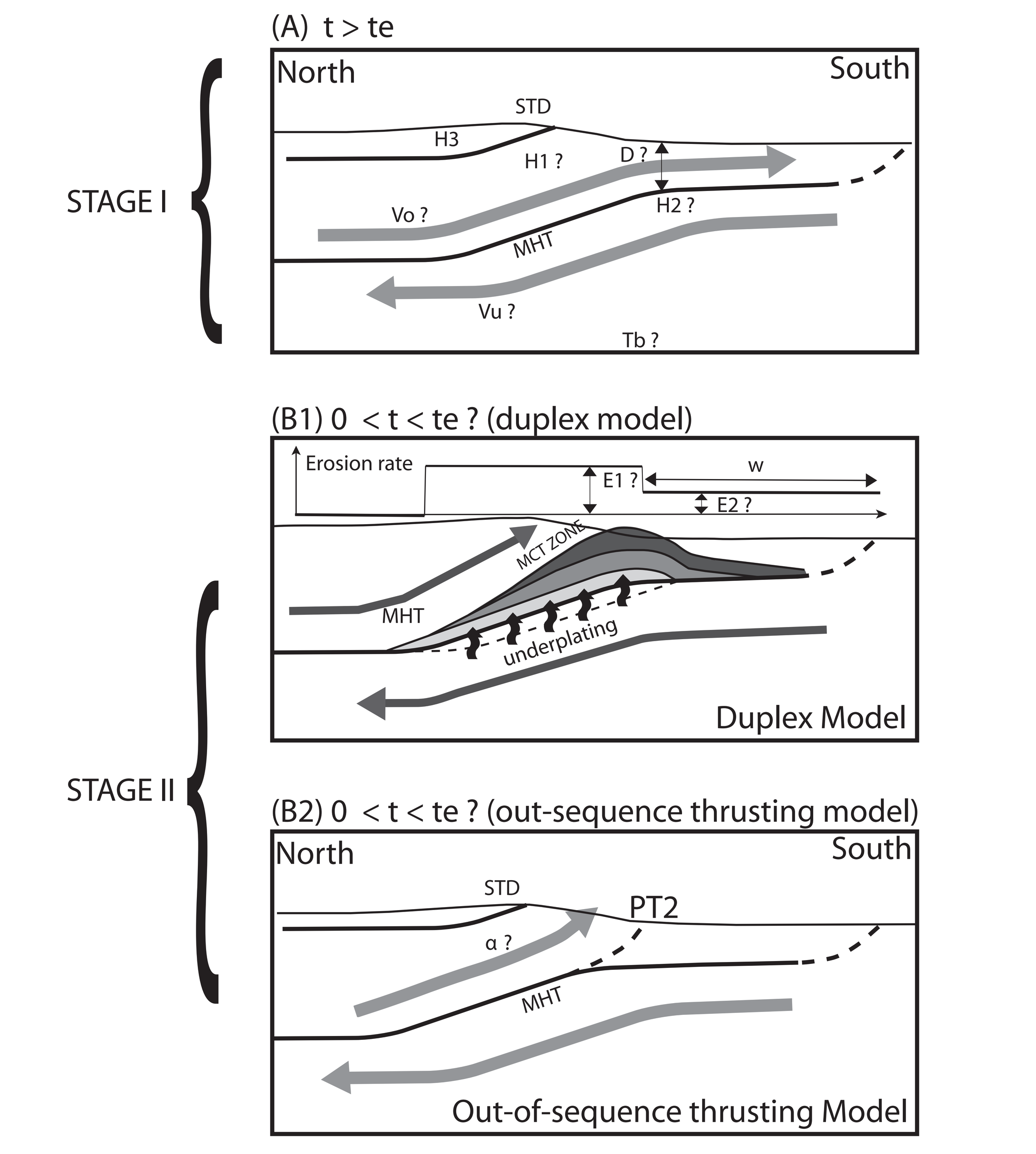

Figure 1: Kinematic models tested in Pecube. (A) Both models are identical during the first stage (STAGE 1). (B1) Second stage of the Duplex Model. (B2) Second stage of Out-of-sequence thrusting model

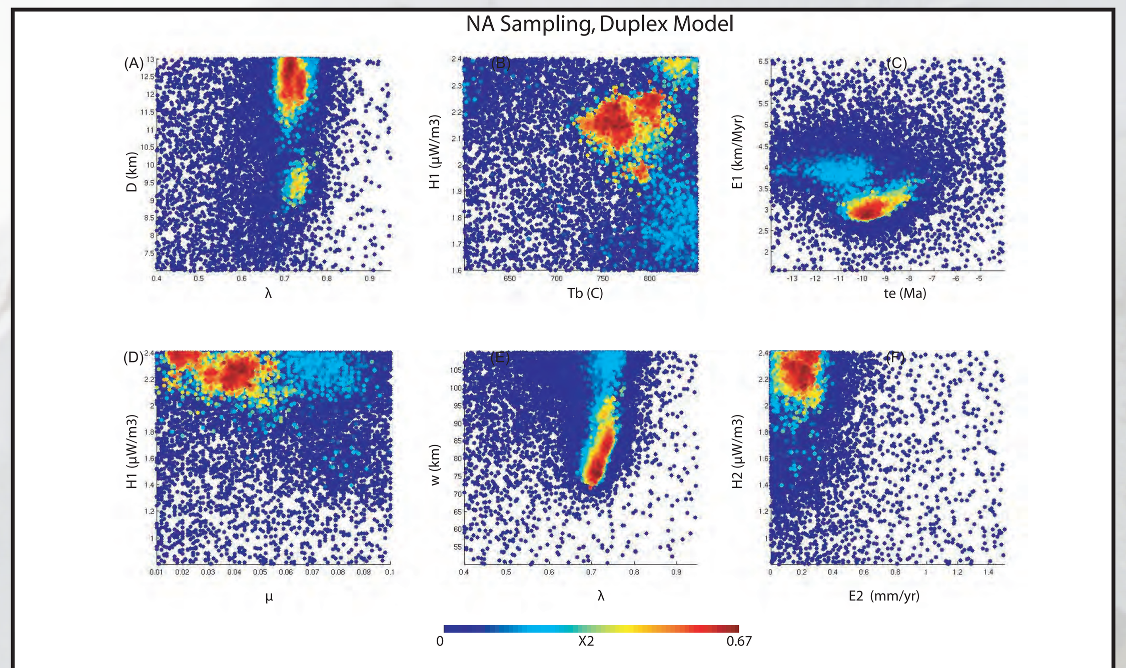

Figure 3: NA sampling stage for the Duplex Model. Definition of each parameter is shown in Table 1.

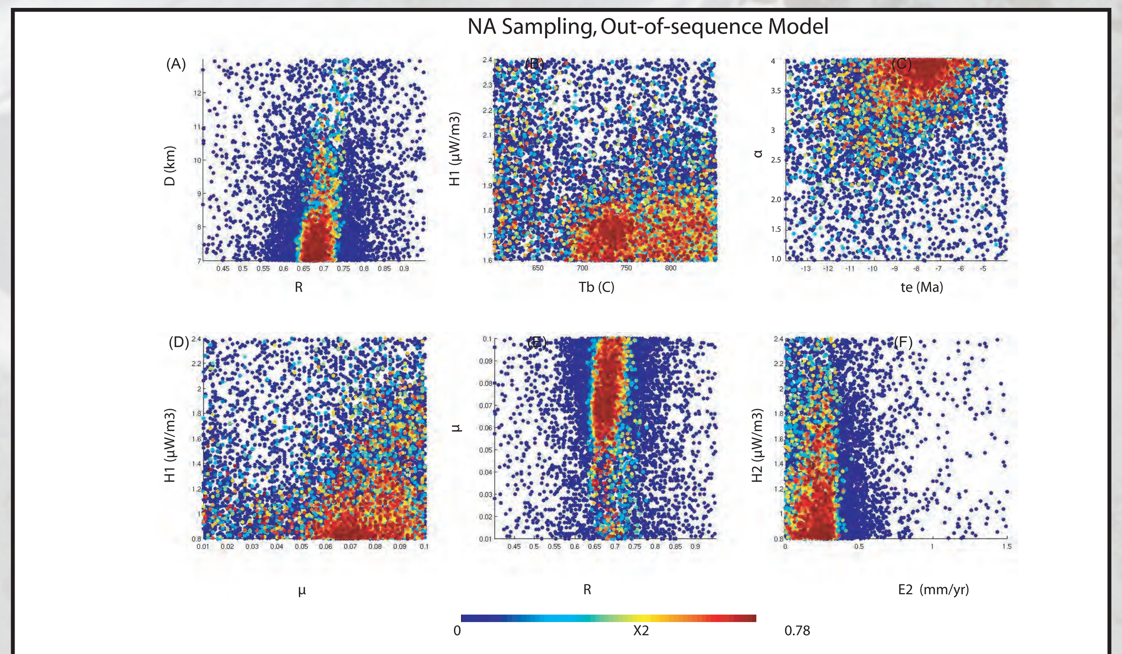

Figure 4: NA sampling stage for the Out-of-sequence thrusting model. Definition of each parameter is shown in Table 1.

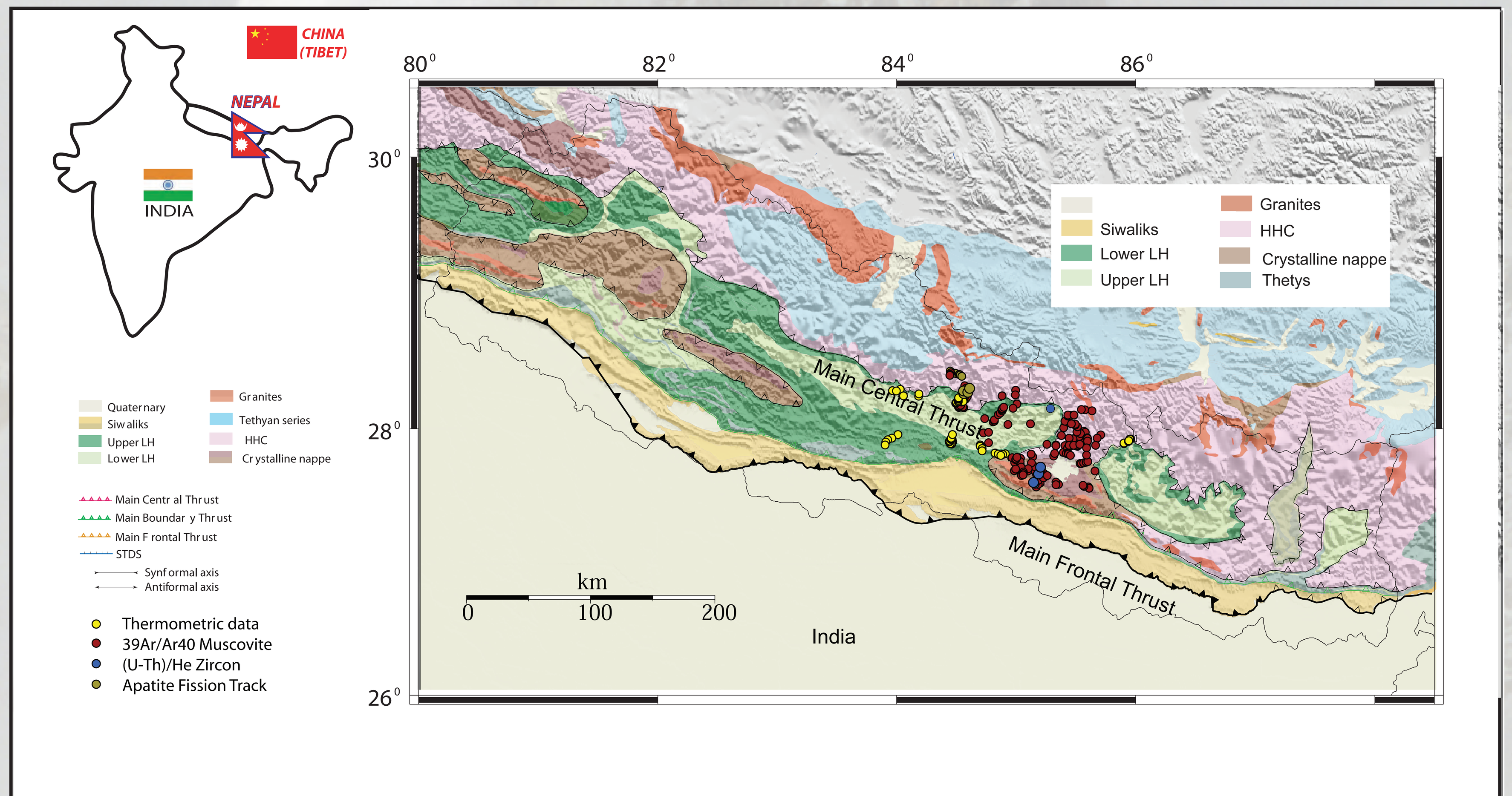

Figure 2: Geological map of Central Nepal Himalaya and location of thermochonometric and thermobarometric data used in this study.

A formal inversion approach based on the Neighbourhood Algorithm (Sambridge 1999) allows definition of best fitting values of model parameters from a parameter search (Figure 3-4) and their estimated uncertainties from the computed Probability Density functions (Figure 5-6, Table 1). In addition to the geometric parameters, model variables include overthrusting rates; radiogenic heat production in the High Himalayan Crystalline (HHC) sequence; the timing of enhanced rock uplift/exhumation rates corresponding to the formation of the duplex or out-of-sequence thrustre-activation. The inverted paremeters a summarized in Table 1. The duplex model, with a minimum reduced X2 of 0.67, is more consistent with observation. According to this model the 20 mm/yr convergence rate is partitionned between an overthrusting rate of 5 +-1 mm/yr and an underthrusting rate of 15 +- 1 mm/yr. Modern uplift rates are estimated to increase from about 0.8+-0.2 mm/yr in the Lesser Himalaya to 3.5 +- 0.5 mm/yr at the front of the high range, 95 +- 5 km from the MFT. The effective friction coefficient is estimated to be 0.09 +- 0.01 and the radiogenic heat production of HHC units is estimated 2.2 +- 0.1 μW/m3. The mid-crustal duplex initiated at 10 +-2 Ma, leading to an increase of uplift rate at front of the High Himalaya from ~0.8 to 3.5 mm/yr. A model with out-of-sequence thrusting can provide a satisfactory fit to the data (with a minimum reduced X2 of 0.78) but requires a large overthrusting rate of 11 +- 1mm/yr and implies a total convergence rate >30 mm/yr. Thus the analyzed dataset appears more consistent with a duplex model than to out-of-sequence thrusting.

In Figure 7, we present an example of a forward duplex model that leads to a good fit to the data. The parameters correspond to the best fitting parameters summarized in Table 1.

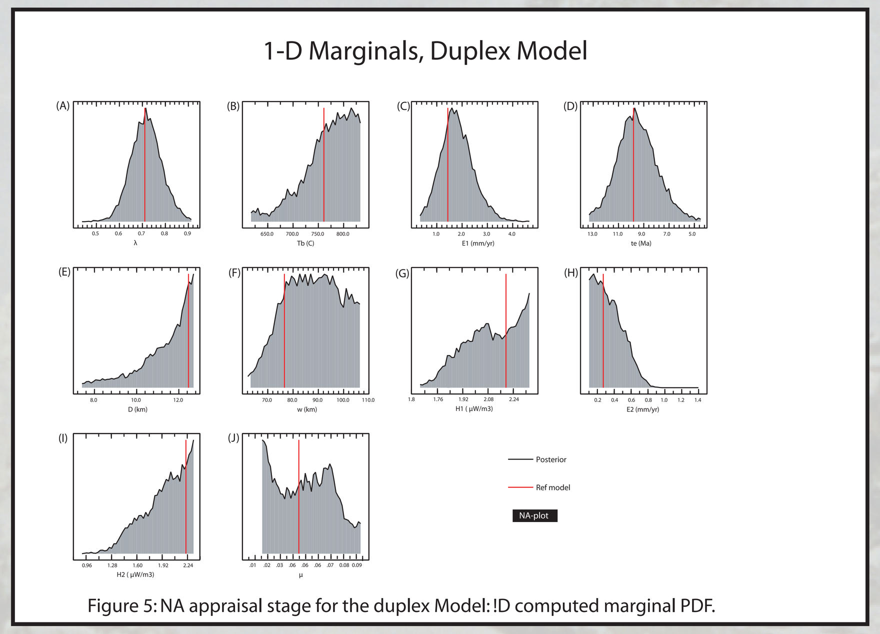

Figure 5: NA appraisal stage for the duplex Model: 1D computed marginal PDF.

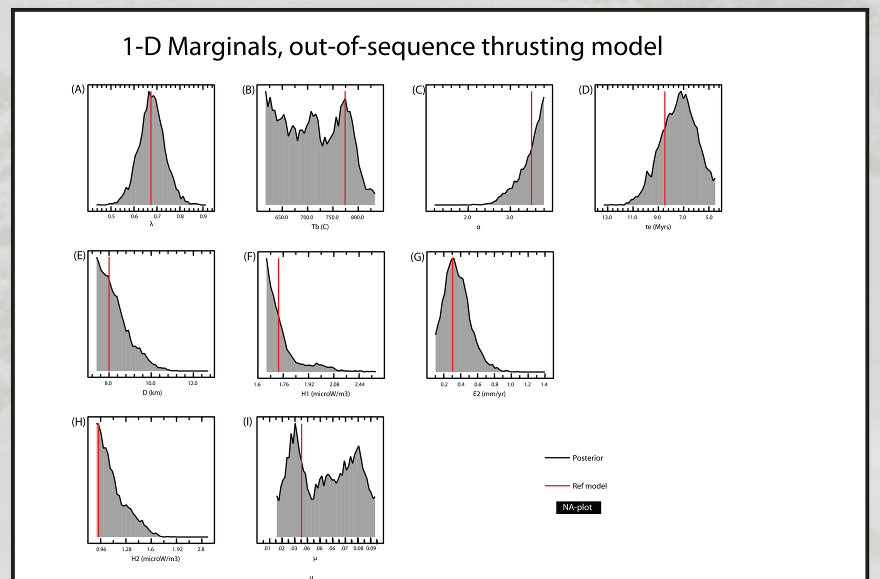

Figure 6: NA appraisal stage for the OOS Model: 1D computed marginal PDF.

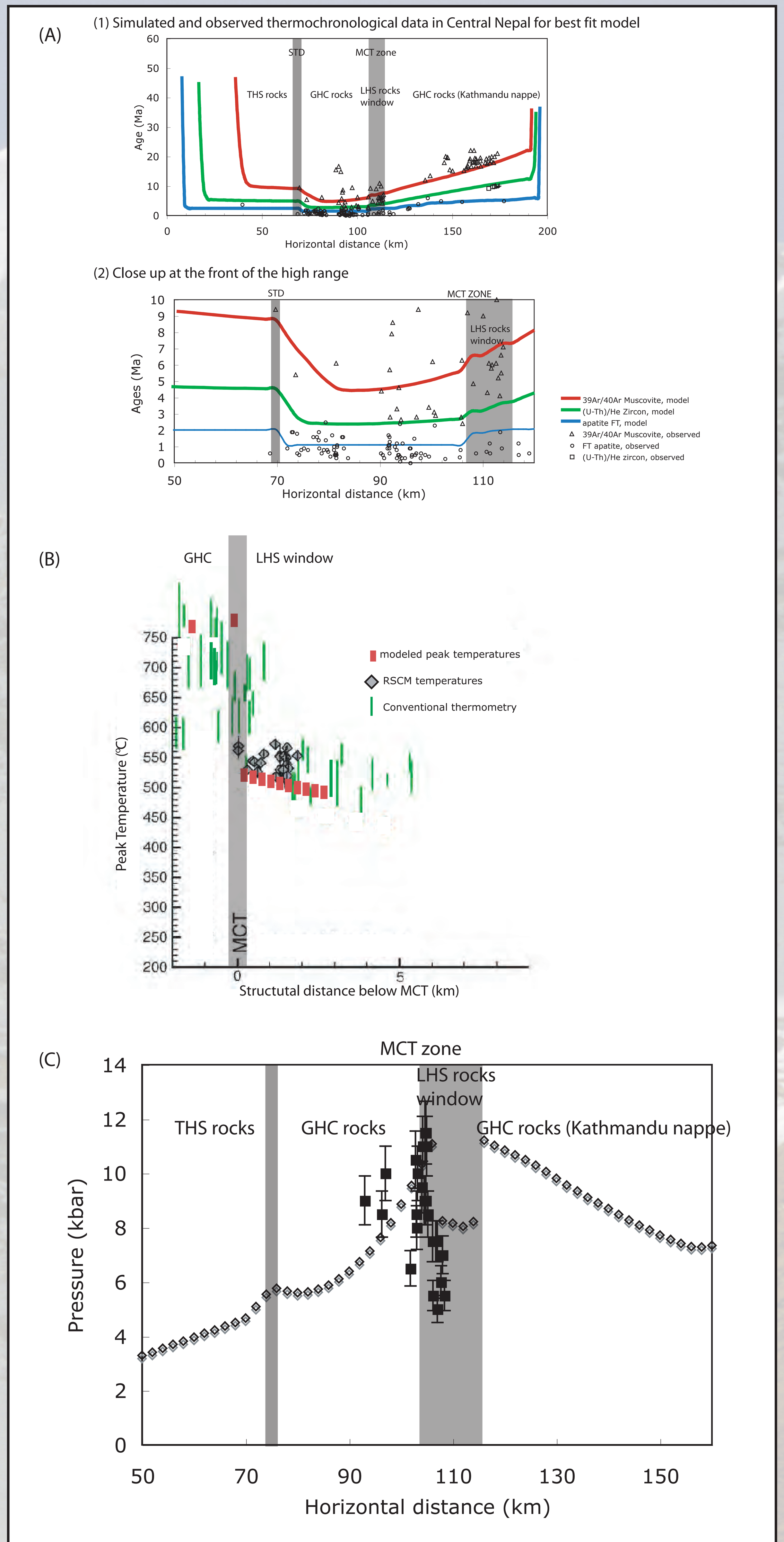

Figure 7: Example of a good fitting model for the Duplex scenario. (A) Observed and predicted thermochronollogical data. (B) Observed and predicted peak metamorphic temperature Modified from Bollinger et al 2006. (C) Observed and predicted peak metamorphic pressure.

Parameter	Prior information	Posterior value duplex	Error	Posterior value out-of-sequence	Error	units	Kinematic model	comment
λ	0.4-0.95	0.71	0.07	0.67	0.1		DM/OOS	Partioning between overthrusting and underthrusting
Tb	600-850	776	54	706	144	C	DM/OOS	Temperature ate the base of the model
D	7-13	11.45	1.38	8.01	0.07	km	DM/OOS	Depth of kink-fault
w	50-110	86	13	n/a	n/a	km	DM	Distance of high exhumation window from trace of MHT
E1	1.0-6.5	3.4	0.9	n/a	n/a	mm/yr	DM	Enhanced exhumation of underplating window
E2	0.0-1.5	0.25	0.18	0.3	0.21	mm/yr	DM/OOS	Vertcial accretion rate
μ	0.01-0.1	0.05	0.03	0.06	0.04		DM/OOS	effective friction coefficient
H1	1.6-2.4	2.1	0.16	1.7	0.4	μW/m3	DM/OOS	Radiogenic heat production in GHC
H2	0.8-2.4	1.9	0.24	1.04	0.4	μW/m3	DM/OOS	Radiogenic heat production below MHT
te	14-4	9.8	1.7	7.3	1.6	Ma	DM/OOS	timing of formation of duplex
α	1-4	n/a	n/a	2.8	0.8		OOS	increase of motion along the MCT

Table 1: Parameters set free for inversion with NA. DM stands Duplex Model amd OOS for out of sequence reactivation

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