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Key Points:

- Thermo-kinematic modeling of Muli thrust, a major thrust fault of SE Tibetan Plateau
- 15 km crust exhumation in 50 Ma on a high-angle ($>70^\circ$) ramp—décollement fault linked to thickening of SE Tibetan crust
- Fault related to significant Moho step and shear wave velocity contrast in deep crust suggests entire crust implication

Supporting Information:

Supporting Information may be found in the online version of this article.

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Exhumation History Along the Muli Thrust—Implication for Crustal Thickening Mechanism in Eastern Tibet

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Abstract Thrusting implication in the crustal thickening history of eastern Tibet is highly debated. The ~250 km-long Muli thrust of the Yalong thrust belt in SE Tibet is a major Miocene structure with a pronounced topographic step (~2,000 m). Using thermo-kinematic modeling based on thermochronology data, we constrain the crustal geometry of the thrust as being steep ($>70^\circ$) at the surface, in agreement with field observations, and flattening at depth (≥ 20 km) on an intra-crustal décollement. Thrusting motion on the fault shows a velocity of 0.2 ± 0.06 km/Ma since 50 Ma, followed by an acceleration at a rate of 0.6 ± 0.08 km/Ma starting at 12.5 ± 1 Ma, yielding a total of ~15 km of exhumed crust. Deeper, deformation may be localized through a ductile shear zone, and be related to the ~15 km Moho step and shear wave velocity contrast imaged by tomography beneath the Yalong thrust belt.

Plain Language Summary The India-Eurasia collision (~50 million years ago [Ma]) led to the formation of the Tibetan Plateau, the world's largest and highest orogenic plateau. The formation and evolution of such a unique geological feature has been one of the main controversies in Earth Sciences for decades, especially regarding the role of faulting in the thickening of the crust. Here, we present 3D thermo-kinematic models of thermochronology data allowing to constrain the exhumation history of the Muli thrust fault, a ~250 km-long major structure of the SE Tibetan margin, linked to significant steps in surface topography and in crustal boundary at depth (Moho). We constrain a steep fault ($>70^\circ$) within the upper crust, consistent with field observations, that flattens at depth (≥ 20 km). The Muli thrust presents rapid thrusting motion (0.6 ± 0.08 km/Ma) that initiated at ~12.5 Ma, following a slower phase (0.2 ± 0.06 km/Ma) since 50 Ma, with total rock exhumation of ~15 km. This underlines the important role of thrust faulting in the thickening of the SE Tibetan crust.

1. Introduction

The eastern margin of the world's largest and highest orogenic plateau, the Tibetan Plateau, shows contrasted edges, with a steep topographic gradient along the Longmen Shan (LMS) north of the Xianshuihe strike-slip fault (XF), and gentler slopes across the Yalong margin to the south (Figure 1a). The driving mechanism(s) leading to such contrasts between margins are still poorly understood and have given rise to end-member models of plateau growth with different crustal structures: either a weak lower crust localizing crustal thickening (“channel flow model,” e.g., Clark & Royden, 2000), or a more rigid crust, with thickening that includes the upper crust, in a brittle manner (“stepwise model,” Tapponnier et al., 2001). Those two end-member models can be tested by investigating the role of thrusting mechanisms in SE Tibet.

At present, upper crustal deformation of the LMS is dominated by reverse faulting with a small component of right-lateral motion, as shown by recent earthquake focal mechanisms such as that of the 2008 Mw7.9 Wenchuan earthquake (e.g., de Michele et al., 2010; Fielding et al., 2013). This event ruptured two subparallel reverse structures, the Guanxian and Beichuan thrusts (Figure 1b), with steep shallow ramps (up to 70°) which root between 15 and 25 km-depth on a sub-horizontal décollement zone (e.g., Airaghi et al., 2017; Fielding et al., 2013; Hubbard & Shaw, 2009; Li et al., 2013; Qi et al., 2011) corresponding to the brittle-ductile transition (Feng et al., 2016). In addition, receiver function profiles (Robert et al., 2010) and regional shear waves tomography images (Yao et al., 2008) show a ~20 km step of the Moho depth between the

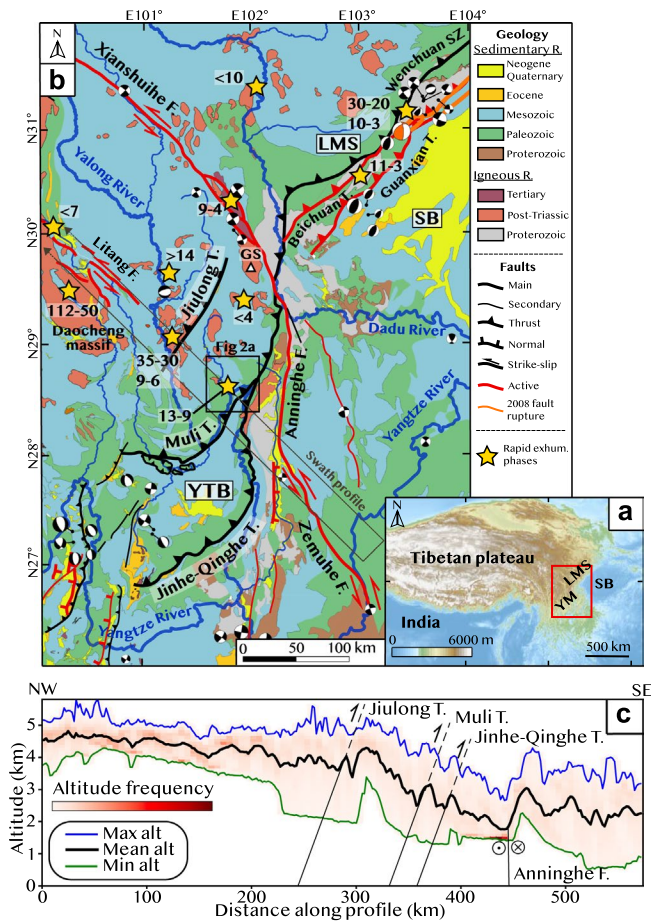


Figure 1. (a) Topographic map of Tibet (YM: Yalong Margin, LMS: Longmen Shan, SB: Sichuan Basin). (b) Geologic map of SE Tibet (CIGMR, 2004) with $M_w > 5$ earthquake focal mechanisms, including 2008 Wenchuan earthquake ($M_w 7.9$) in orange (Global CMT catalog). YTB: Yalong thrust belt, SZ: shear zone, GS: Gongga Shan. (c) Swath elevation profile across YTB.

plateau (~60–63 km) and the Sichuan craton (~40 km) at the apex of the Wenchuan shear zone. This has been interpreted either as a lower crustal ductile continuation of the shear zone (Robert et al., 2010), or as the halt of the lower crustal flow by the rigid Sichuan craton, hence inducing upward motion along the thrusts (Burchfiel et al., 2008).

By contrast, the Yalong margin only shows normal and strike-slip focal mechanisms, as well as two active left-lateral strike-slip fault systems: XF (Allen et al., 1991) and Litang (Chevalier et al., 2016; Wang & Burchfiel, 2000). Major geologic discontinuities attest, however, to the presence of the NE to EW-trending Yalong thrust belt (YTB) along the margin (e.g., Clark et al., 2005; Liu-Zeng et al., 2008; Perrineau, 2010; Wang & Burchfiel, 2000), consisting of the Muli and Jinhe-Qinghe thrusts that merge south of the XF (Figure 1b). Being most likely currently inactive considering regional seismicity, these thrusts were however active during the Miocene, as shown by thermochronology ages (Clark et al., 2005) as well as by the significant topographic step (~2,000 m) (Figure 1c). The YTB has been identified as the SW continuation of the LMS (Yan & Lin, 2015) prior to activation of the XF at ~9 Ma (Y.-Z. Zhang et al., 2017), although the amount of thrusting remains controversial. Similarly to what has been observed in the LMS, tomography images (Yao et al., 2008) reveal a ~15 km vertical jump in crustal thickness across the YTB between the plateau (~60–63 km) and the Yalong margin (45–50 km) (Figure S5), coinciding with the limit of a low shear velocity layer in the middle and lower crusts (Figure S6), suggesting that the YTB plays a major role in thickening of the Yalong margin. By contrast, the channel flow model predicts a mainly horizontal flow at depth across the Yalong margin, generating a smooth topographic gradient with no spatial discontinuity and no thickening of the upper crust (Clark & Royden, 2000).

Whether the Yalong margin has been uplifted by major thrusts or has only been passively uplifted, is therefore key to understand the processes involved in the formation of SE Tibet and distinguish between these models. In this paper, we focus on the structure, amount and timing of exhumation of the Muli thrust, the northernmost segment of the YTB. We use thermo-kinematic modeling of low-temperature thermochronology data with apatite and zircon (U-Th)/He (AHe and ZHe respectively), and apatite fission-track (AFT) ages, as well as high-temperature systems with $^{40}\text{Ar}/^{39}\text{Ar}$ on biotite (BAr) and muscovite (MAr) from the hanging wall.

2. Geological Setting and Timing of Exhumation

The NW-dipping Muli thrust runs southward for ~250 km from the XF, with mainly Paleozoic resting atop Mesozoic rocks (Figure 1b). The thrust corresponds to a large topographic step bounding to the east the low-relief, high (>4,000 m) Tibetan Plateau, as well as a sharp bend of the Yalong River (Figure 1). There, the hanging wall consists of schists and marbles, mapped as Paleozoic and Triassic, with NNW to W-trending folds, with N70–130°-trending schistosity, intruded by numerous Cretaceous granites such as that of Datan (Figure 2a). Along the mapped trace of the thrust, schists and marbles have a strong schistosity and foliation trending N30° and steeply dipping 76°W on average, within a ~2 km-wide zone. Locally, the schistosity has a sigmoid geometry with slightly shallower (74°W) shear planes indicative of reverse shear (Figure 2b). In the footwall, sediments are mapped as Triassic and Upper Paleozoic and are only intruded by one small Mesozoic granite (Figure 1b).

Published AHe and AFT ages in the hanging wall of the Muli thrust have been interpreted as indicating fast exhumation between 9 and 13 Ma (Clark et al., 2005), while 80 km NW of the Muli thrust, AHe and ZHe

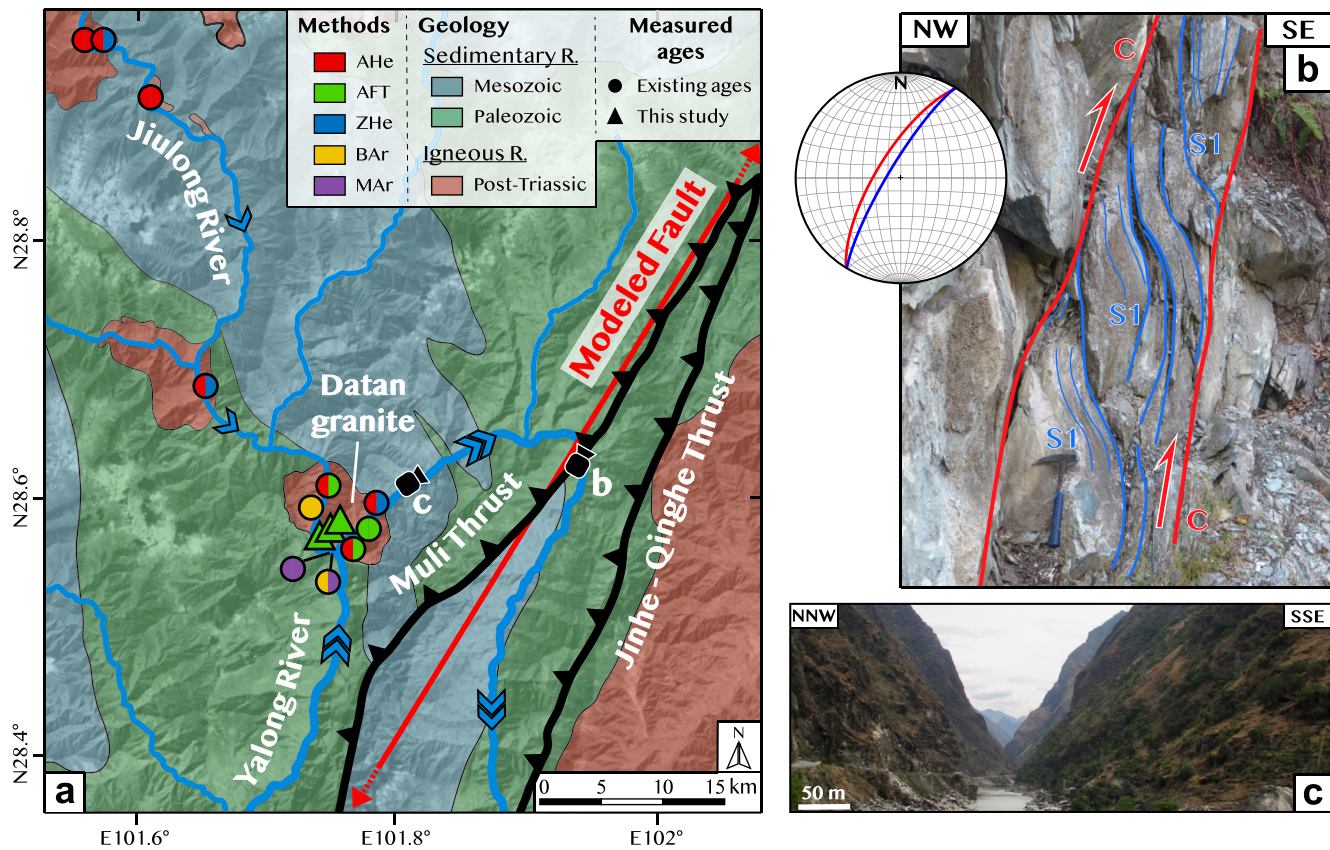


Figure 2. (a) Geologic map of Yalong River bend region (CIGMR, 2004), atop Landsat image, with sample locations. (b) Outcrop along Muli fault and stereographic plot (inset) showing sigmoidal schistosity (S1) between steep shear planes (c) indicating reverse shear. (c) Photo of deeply incised Yalong River.

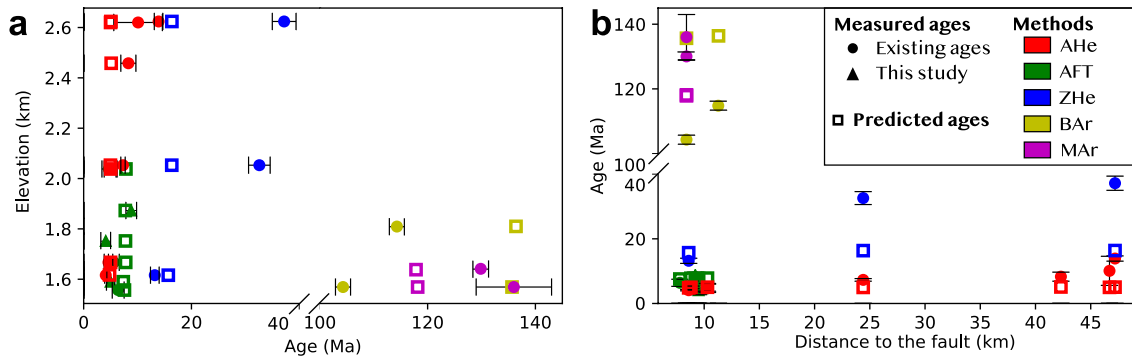
ages have been interpreted to indicate the reactivation of the Jiulong thrust between 6 and 9 Ma, after an initial rapid exhumation phase between 35 and 30 Ma (H. Zhang et al., 2016). In the Gongga Shan massif, AFT and ZFT ages have been interpreted as representing the local activation of the XF at 9 Ma and its southward propagation along the Anninghe/Zemuhe fault at ~4 Ma (Y.-Z. Zhang et al., 2017).

3. Results

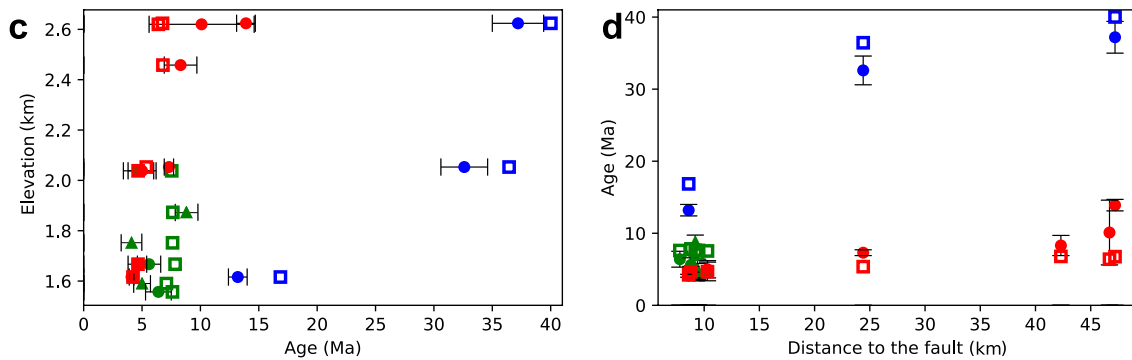
3.1. Thermochronology Data

Because of the steep banks of the Yalong River (Figure 2c), and the lack of granite outcrops in the footwall, the existing data set is limited to valley bottoms in the hanging wall of the Muli thrust. We here add three samples along a steep profile between 1,590 and 1,873 m of elevation within the Datan granite (Figure 2a), which yield AFT ages of 4.1 ± 0.9 , 5.0 ± 0.6 , and 8.8 ± 0.9 Ma (Figure 3, Table S1 and Text S1). To best constrain the crust's cooling history using thermochronology dating, one needs an adequate spatial distribution of the data and the use of several distinct thermochronology systems. We, therefore, compile all available ages (seven AHe, three AFT, three ZHe, two BAr, and two MAr) from previous studies (Clark et al., 2005; Perrineau, 2010; Wallis et al., 2003) (Table S2 and Text S2). Samples are ideally distributed along a 50 km-long transect perpendicular to the Muli thrust following the Jiulong River, at elevations between 1,557 and 2,624 m (Figure 2a). AHe (4.1 ± 0.2 to 13.9 ± 0.8 Ma) and ZHe ages (13.2 ± 0.8 to 37.2 ± 2.2 Ma) show a positive correlation with elevation and distance away from the fault (Figure 3). AFT ages are all located close to the junction between the Jiulong and Yalong Rivers (Figure 2a) and are tightly distributed between 4.7 ± 1.3 and 6.4 ± 1.1 Ma (Figure 3). BAr and MAr ages are Cretaceous, ranging from 104.3 ± 1.4 to 136 ± 7 Ma.

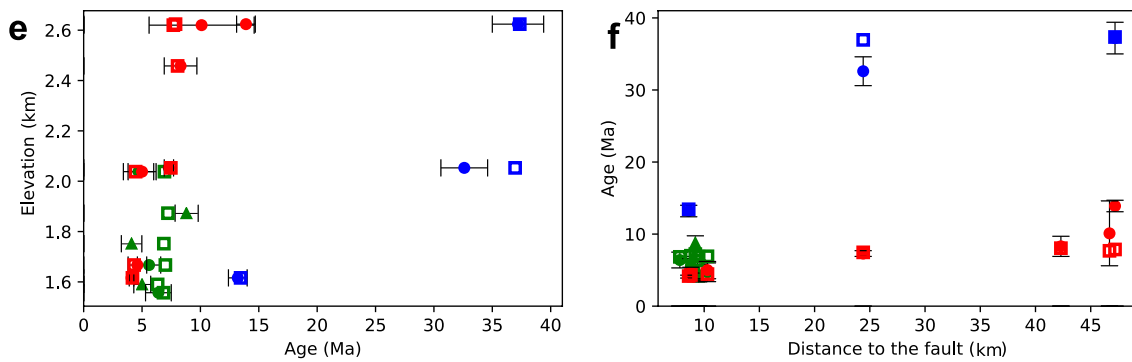
Vertical uplift (misfit = 7.76 ; nb of inverted parameters = 3 ; Time range = 140 - 0 Ma)



20km-depth fault (misfit = 3.06 ; nb of inverted parameters = 6 ; Time range = 50 - 0 Ma)



30km-depth fault (misfit = 2.12 ; nb of inverted parameters = 6 ; Time range = 50 - 0 Ma)



50km-depth fault (misfit = 2.02 ; nb of inverted parameters = 6 ; Time range = 50 - 0 Ma)

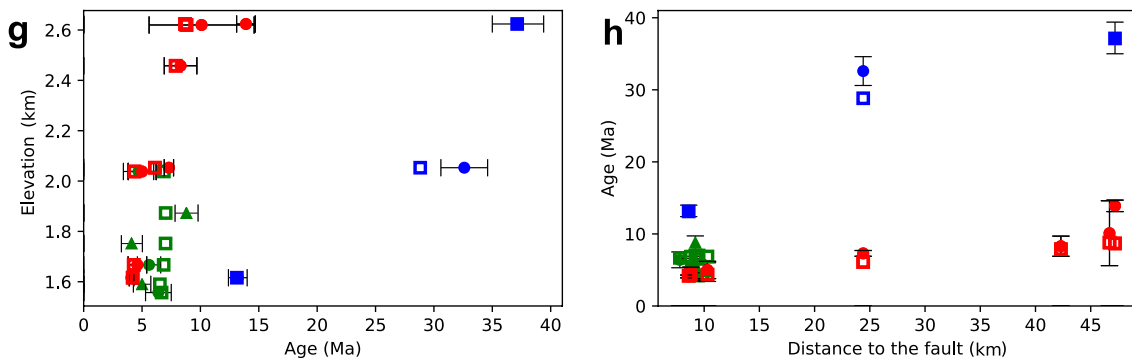


Figure 3. Comparison between measured and predicted ages on vertical (a, c, e, and g) and horizontal (b, d, f, and h) profiles perpendicular to the Muli fault for different scenarios.

3.2. Thermo-Kinematic Modeling

We use the code PECUBE (Braun, 2003; Braun et al., 2012) to unravel the 3D temporal evolution of the crust's thermal history. This code was designed to calculate theoretical ages for various thermochronometers, yielding the misfit value (Equation S1) with the measured ages for different scenarios, and to use an inversion method to find the model with the lowest misfit value. We define a $\sim 100 \times 100 \times 50$ km block with present-day surface topography and set a basal temperature of 800°C, corresponding to a geothermal gradient of $\sim 35^\circ\text{C}/\text{km}$ (Clark et al., 2005; Y.-Z. Zhang et al., 2015) (Tables S3, S4, and Text S3).

3.3. Crustal Thermal History Driven by Vertical Exhumation

We first conduct an inversion with more than 3,000 models (Table S3) to find the best fitting model that constrains the exhumation history for a scenario with a homogeneous vertical rock uplift. Our model starts at 140 Ma, slightly earlier than our oldest $^{40}\text{Ar}/^{39}\text{Ar}$ age. The best fitting exhumation scenario (misfit = 7.76) is a two-stages history with a first stage having a denudation rate of 0.033 km/Ma, followed at 14 Ma by a second stage with a faster rate of 0.47 km/Ma (Figure S1). This yields a total exhumation of 10.7 km since 140 Ma, including 6.5 km since 14 Ma. Predicted AHe ages are consistent with those measured for the low-elevation samples located <10 km away from the fault trace, while the four samples located at higher altitude, that is, farther away from the fault, show predicted AHe ages that are much younger (up to ~ 5 Ma) than the measured ones (Figures 3a and 3b). The difference is even higher for the three ZHe predicted ages, that is, up to ~ 15 Ma younger for samples farther from the fault. Those large differences suggest that a scenario with a homogeneous vertical uplift, and thus no fault, cannot fit the spatial distribution of our thermochronology data set (Figures 4a and 4b).

3.4. Crustal Thermal History Driven by the Muli Thrust

To simulate a more complex uplift velocity field, we implement a fault with exhumation of a hanging wall with respect to a stable footwall. The fault trace at the surface follows that of the Muli thrust (Figure 2a), and the number of segments defining the fault geometry at depth is set to three, which appears sufficient to get a satisfying velocity field. Given the lack of geophysical data constraining the deeper part of the fault, we run three distinct inversions in which we fix the deepest segment to be horizontal at depths of 20, 30, and 50 km. We add three variables to invert, in order to define the Muli thrust geometry, and only consider the low-temperature data (AHe, AFT, ZHe, ages <40 Ma), removing $^{40}\text{Ar}/^{39}\text{Ar}$ ages to reduce the number of thermochronometers used, and the time window of 50 Ma, which allows to reach a well-constrained inversion by running twice as many models ($>6,000$) than in our previous vertical exhumation setting.

The lowest misfit (2.02) inversion model is obtained for a steep ($\sim 80^\circ$) shallow fault segment down to 46 km-depth and a transitional segment from 46 to 50 km-depth dipping at $\sim 10^\circ$, which joins the deep horizontal segment at 50 km-depth (Figures 4g and 4h). With this geometry, we find that the best fitting exhumation scenario occurred in two stages: a first stage with a fault velocity rate of 0.26 km/Ma, followed at 11.5 Ma by a second stage with a faster rate of 0.52 km/Ma (Figure S4). The modeled fault geometry yields an age zonation parallel to the fault, with young ages close to the fault, rapidly becoming older away from it (Figure 4). Young ages result from rapid vertical rock uplift above the steeply dipping fault plane, while away from the fault, older ages result from a slower rock uplift above the gently-dipping fault plane at depth. This thermo-kinematic model successfully reproduces the positive correlation between AHe and ZHe ages and distance to the fault (Figures 3g and 3h), with predicted AHe ages falling within uncertainty of the measured ones, and predicted ZHe ages evolving almost linearly with distance to the fault, reproducing well the measured ages. This spatial distribution is not obtained in our vertical exhumation scenario, and highlights the mandatory role of a listric Muli thrust.

Nevertheless, while the first order geometry of the fault is well constrained, the depth of the deep, flatter segment (equivalent to a basal décollement) is not. Indeed, running a model with a basal décollement at 30 km results in a misfit value being only slightly higher (2.12) than in our previous model using a basal décollement of 50 km (2.02). In that case, the shallow fault segment is dipping at 68° , the transitional segment is sub-horizontal (dip of 3°) (Figures 4e and 4f), and the transition time occurs 2 Ma earlier (13.5 Ma), separating two exhumation phases with velocity rates on the fault nearly identical to those in our previous

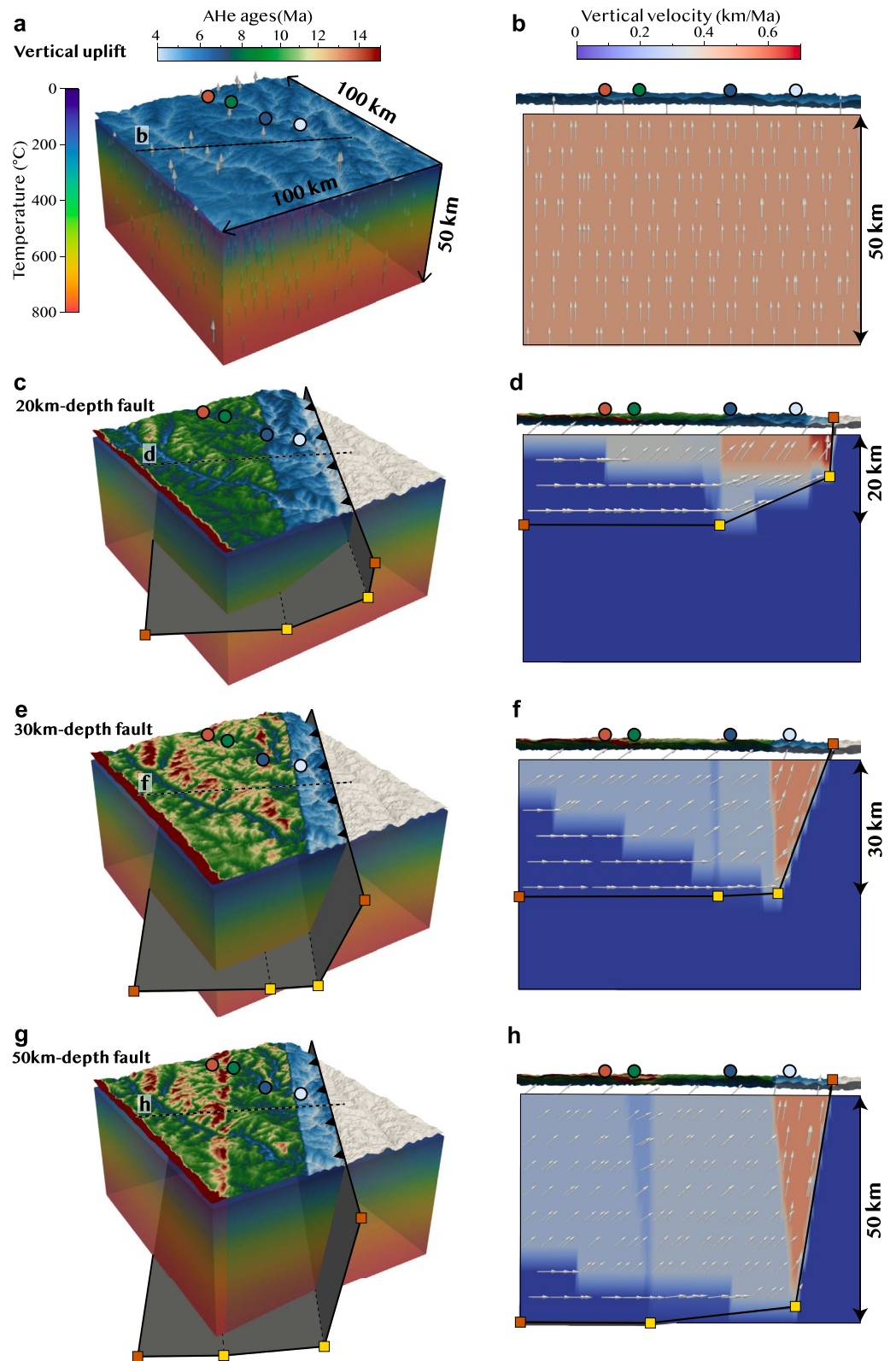


Figure 4. Crustal thermal models for different scenarios overlaid by predicted present-day AHe ages wrapped on topography, with circles showing measured ages. Squares represent inflexion points defining fault geometry (yellow: inverted points; orange: fixed points): (a, c, e, and g) 3D view, (b, d, f, and h) 2D rock particle velocities (arrows) along middle section during most recent exhumation phase.

model (0.24 and 0.54 km/Ma) (Figure S3). The predicted AHe ages in such a scenario are slightly younger than those predicted for the 50-km basal depth model, while the ZHe ages show a more pronounced break in slope with distance to the fault, also consistent with the measured ages (Figures 3e and 3f). The misfit value (3.06) significantly increases for a model with a basal décollement depth of 20 km. In that case, the shallow fault segment is sub-vertical ($\sim 85^\circ$) down to 9 km-depth, the transitional segment is less steep (25°) from 9 to 20 km-depth (Figures 4c and 4d), and the transition time is 12.7 Ma, with a more pronounced rate jump from 0.14 to 0.67 km/Ma (Figure S2). The predicted AHe ages are ~ 2 Ma younger than the measured ones, and the predicted ZHe ages are up to 4 Ma older than the measured ages, leading to a higher misfit than in the previous models (Figures 3c and 3d).

4. Implication for the Crustal Thickening History of Eastern Tibet

Using both vertical and horizontal thermochronology data profiles in the hanging wall of the Muli thrust, we show that a scenario with a spatially homogeneous vertical uplift is incompatible with the currently available thermochronology data set. A more complex velocity field driven by a high-angle ramp–flat décollement fault geometry is required (Figure 4). Using data inversion, we obtain a ramp that dips between 85° and 68° , in agreement with surface field observations (Figure 2b), as well as with the high-angle (70°) ramp imaged in the LMS, for décollement depths of 20, 30 and 50 km that we test in agreement with LMS observations (Feng et al., 2016; Fielding et al., 2013; Li et al., 2013; Qi et al., 2011; Robert et al., 2010). The upper crustal velocity field in all three models show similar general kinematics with nearly vertical motion close to the fault leading to young predicted ages, and a more oblique, slower velocity farther away from the fault yielding older predicted ages, consistent with the measured ages (Figure 3). The exhumation evolution is also very similar between the three models, with a slow velocity rate on the fault between ~ 0.14 and ~ 0.25 km/Ma from 50 to 12.5 ± 1 Ma, followed by a rapid phase between ~ 0.53 and ~ 0.67 km/Ma. The early exhumation phase may be related to that recorded in the hanging wall of the Jiulong thrust between 35 and 30 Ma (H. Zhang et al., 2016), and to that in the LMS between 30 and 20 Ma (Tan et al., 2014; Wang et al., 2012). In the LMS, a second phase of rapid exhumation started at ~ 11 Ma at a rate of ~ 0.65 km/Ma (Godard et al., 2009), similar to the fast exhumation we document here along the Muli thrust. This would confirm a continuity between the YTB and LMS prior to the activation of the XF at ~ 9 Ma, having since then offset them by ~ 60 km (Yan & Lin, 2015; Y.-Z. Zhang et al., 2017) (Figure 1b).

For a thrust rooted at 20 km-depth, predicted ages are slightly diverging from the measured ages (younger predicted AHe ages, older ZHe ages, Figures 3c and 3d), leading to a slightly higher misfit (3.06) than for deeper décollements (2.02–2.12). Nevertheless, considering the simplicity of the kinematics modeling associated to fault displacement rates, such higher misfit is insufficient to reject this model, and mostly shows that low-temperature thermochronology data are more adequate to constrain the upper crust thermal evolution than that of the lower crust. To further discuss the structure of the Muli thrust in the lower crust, we then compare our results with geophysical data and crustal structures proposed for the LMS. The 20-km depth model agrees with the depth of the brittle-ductile transition (Feng et al., 2016), considering that thickening during the Cenozoic collision is limited to the brittle upper crust (Airaghi et al., 2017). The 50 km-depth model agrees with the thickening of the entire crust in the hanging wall of the Muli thrust fault (Figure 4h), as proposed for the Wenchuan shear zone in the LMS (Robert et al., 2010). This scenario is the only one compatible with an abrupt step of the Moho depth observed beneath the Yalong margin (Yao et al., 2008) (Figure 5). Indeed, for the Yalong margin, such step cannot be explained by a rheological contrast, as invoked in the LMS between the rigid Sichuan craton and the weak Tibetan crust, inducing a strong thickening of the Tibetan lower crust halted by the craton (e.g., Burchfiel et al., 2008). Beneath the Yalong margin, only a listric geometry of the Muli thrust rooting deep into the lower crust may induce a Moho step, the eastward limit of a low velocity crustal layer (Figure 5), and the thickening of the entire crust (Figure 4h). Below 20 km-depth, deformation has to be more ductile and localized in a ductile shear zone aligned with the upper crustal Muli thrust, which, since 50 Ma, exhumed a total of ~ 15 km of crust along its high-angle ramp and ~ 8 km above its sub-horizontal deep décollement, forming a significant topographic step of ~ 2 km (Figures 1c and 5).

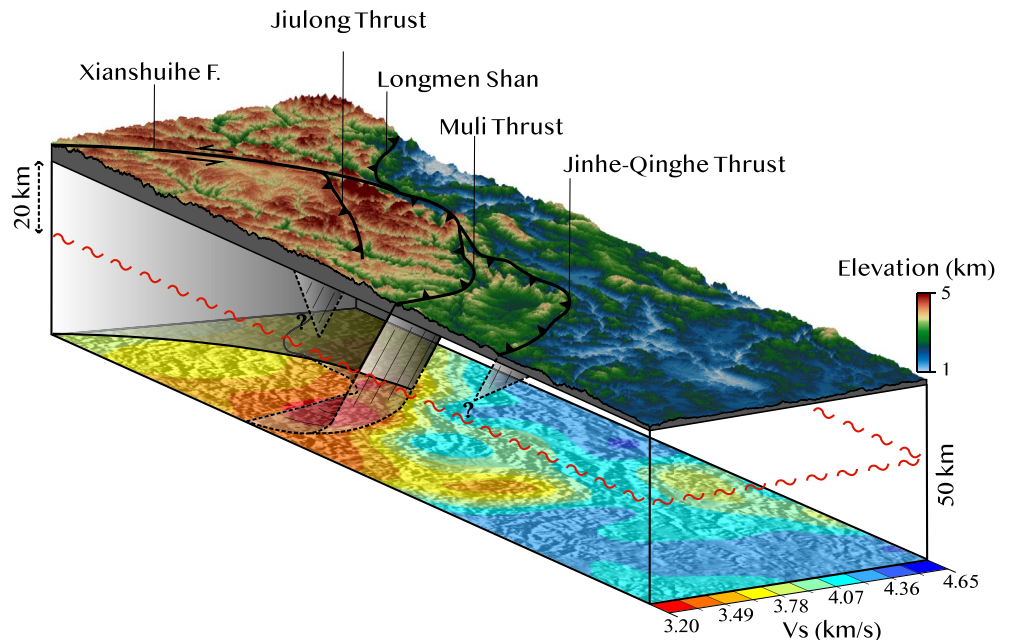


Figure 5. 3D block diagram of Muli crustal fault geometry showing surface topography (2X vertical exaggeration), 20 km-depth brittle-ductile transition (“~” symbol), and tomography section at 50 km-depth (Yao et al., 2008).

5. Conclusions

We present 3D crustal models of different cooling scenarios using a wide spatial distribution of thermochronology ages from the Muli fault’s hanging wall. We show that such a data set can only be related to a complex velocity field generated along a high-angle ($>70^\circ$) ramp thrust fault at the tip of a horizontal décollement. In such a scenario, we obtain a total exhumation of ~ 15 km since ~ 50 Ma, including ~ 7.5 km since 12.5 Ma. Our results show that the upper crust is strongly involved in the thickening of the Tibetan crust in this part of Tibet, and that it is not passively uplifted as assumed in channel flow models. Even if the rooting depth of the Muli fault remains difficult to constrain using such thermal modeling, tomography images reveal a Moho step and a shear wave velocity contrast in the deep lower crust at the apex of the YTB, which cannot be related to rheological contrast as proposed beneath the LMS. We, therefore, interpret such discontinuities as evidence of the listric nature of the Muli thrust rooting deep into the lower crust, behaving as a ductile shear zone below 20 km-depth, allowing the thickening of the whole crust.

Data Availability Statement

Supplementary data reported in this study are given in the Supporting Information and all apatite fission tracks data are stored in Figshare repository: <https://doi.org/10.6084/m9.figshare.14770752>. Supplementary thermochronology data used in this study can be found in Clark et al. (2005) (<https://doi.org/10.1130/G21265.1>) and Perrineau (2010) (<http://www.theses.fr/2010GLOB0007>).

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