

*Tectonics*

Supporting Information for

**Along-strike variation in the initiation timing of the north-trending rifts in southern Tibet as revealed from the Yadong-Gulu rift**

Shuang Bian1,2,3, Junfeng Gong2,3\*, Andrew V. Zuza4, Rong Yang2,3, Lin Chen5, Jianqing Ji6, Xiangjiang Yu7, Yihong Tian8, Zhiquan Yu2,3, Xiaogan Cheng2,3, Xiubin Lin2,3, Hanlin Chen2,3

1 State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

2 Key Laboratory of Geoscience Big Data and Deep Resource of Zhejiang Province, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China

3 Research Center for Structures in Oil and Gas Bearing Basins, Ministry of Education, Hangzhou 310027, China

4 Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada 89557, USA

5 Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

6 School of Earth and Space Sciences, Peking University, Beijing 100871, China

7 College of Earth Sciences, Jilin University, Changchun 130061, China

8 Key Laboratory of Deep-Earth Dynamics, Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

\* Corresponding author: Junfeng Gong (jfgong@zju.edu.cn)

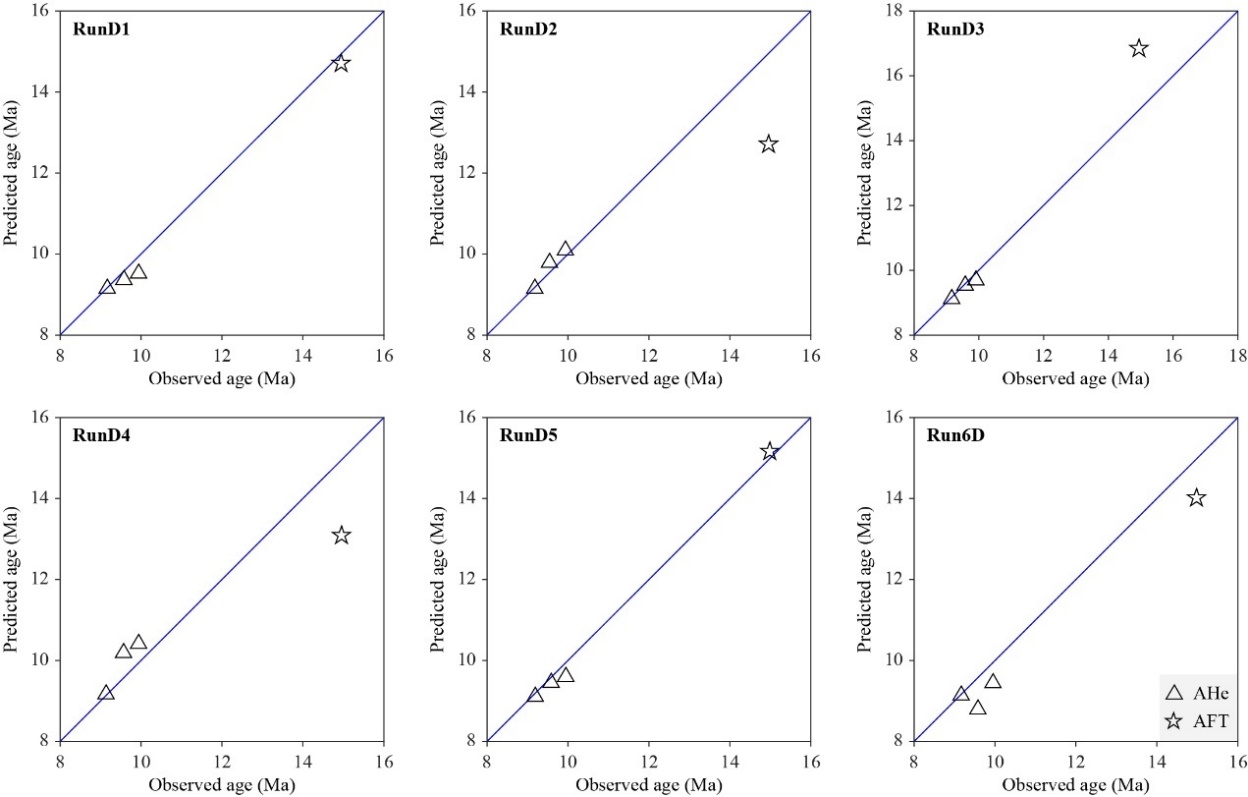
**Contents of this file**

*Text S1*

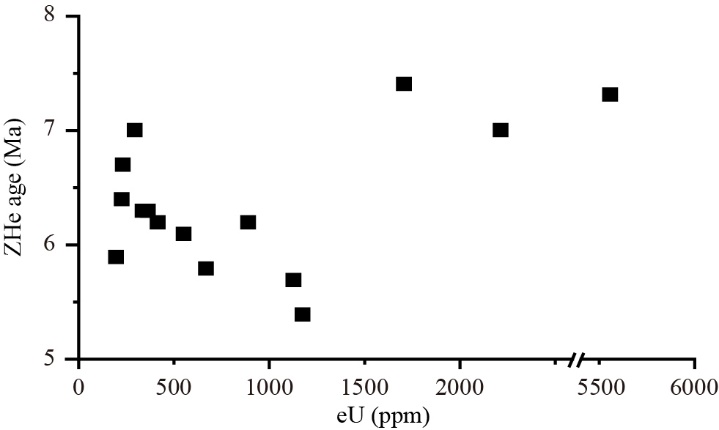
*Figures S1 to S6*

*Tables S1 to S7*

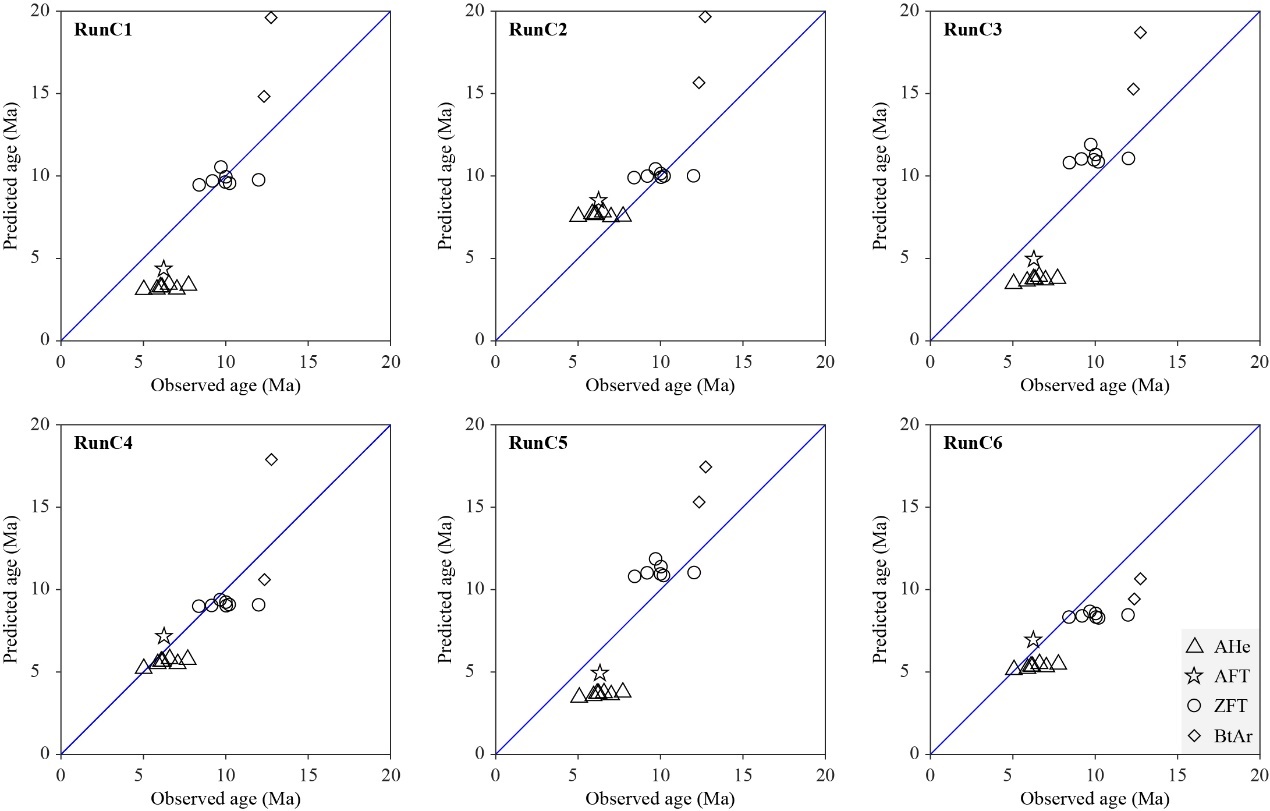
Figures S1 to S3 are cited in the main text.



**Fig. S1**. Comparison of predicted and observed data of profile DD’ for each forward model in the Table S4.



**Fig. S2**. Individual zircon (U-Th)/He dates versus [eU] for samples from Dong et al. (2020). Three grains contain high eU concentration above 1500 ppm, and others show negative date vs eU correlation, which suggests that these grains might be damaged.



**Fig. S3**. Comparison of predicted and observed data of profile CC’ for each forward model in the Table S5.

**1 Introduction**

This document contains further information on the 2D thermo-mechanical simulations used to analyze the deformation after slab detachment. This section covers the model setup and results.

**1.1 Model Setup**

The 2D thermo-mechanical numerical models are conducted with I2VIS (Gerya and Yuen, 2003). The model domain is 4500 km in width and 820 km in depth, which consists of Indian plate (2000-km-wide), Tethys Ocean (500-km-wide) and proto-southern Asia (2000-km-wide) from left (north) to right (south) (Fig. S4).

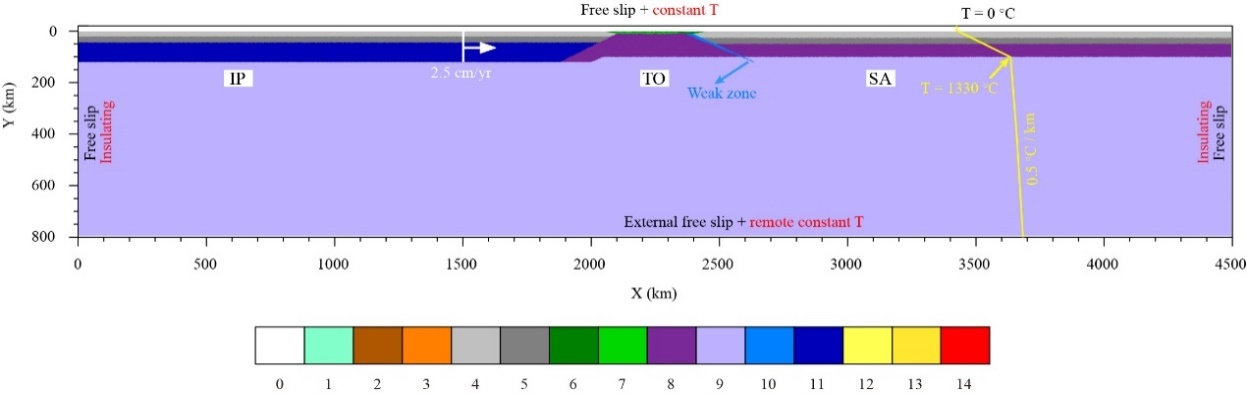
The lithosphere is nonuniform in the entire model domain. A layer of “stick air” is applied to allow deformation of the crustal surface, which is 20-km-thick at the top of the model. For the Indian continental lithosphere, a 20-km-thick upper crust and a 25-km-thick lower crust are configured above the 75-km-thick lithospheric mantle. The proto-southern Asia is assumed to have a pre-thickened crust composed of 25-km-thick upper crust and 25-km-thick lower crust (Murphy et al., 1997; Kapp et al., 2005), which overlies the 50-km-thick lithospheric mantle. The oceanic lithosphere is composed of a 3-km-thick upper crust, a 5-km-thick lower crust, and a 90-km-thick lithospheric mantle layer. The initial geotherm linearly increases from 0 °C at the surface to 1330 °C at the base of the lithosphere beneath all the tectonic units, and adiabatic gradient of 0.5 °C/km is used for the sub-lithospheric mantle. The thermal and velocity boundary conditions are illustrated in Fig. S4.

**1.2. Results**

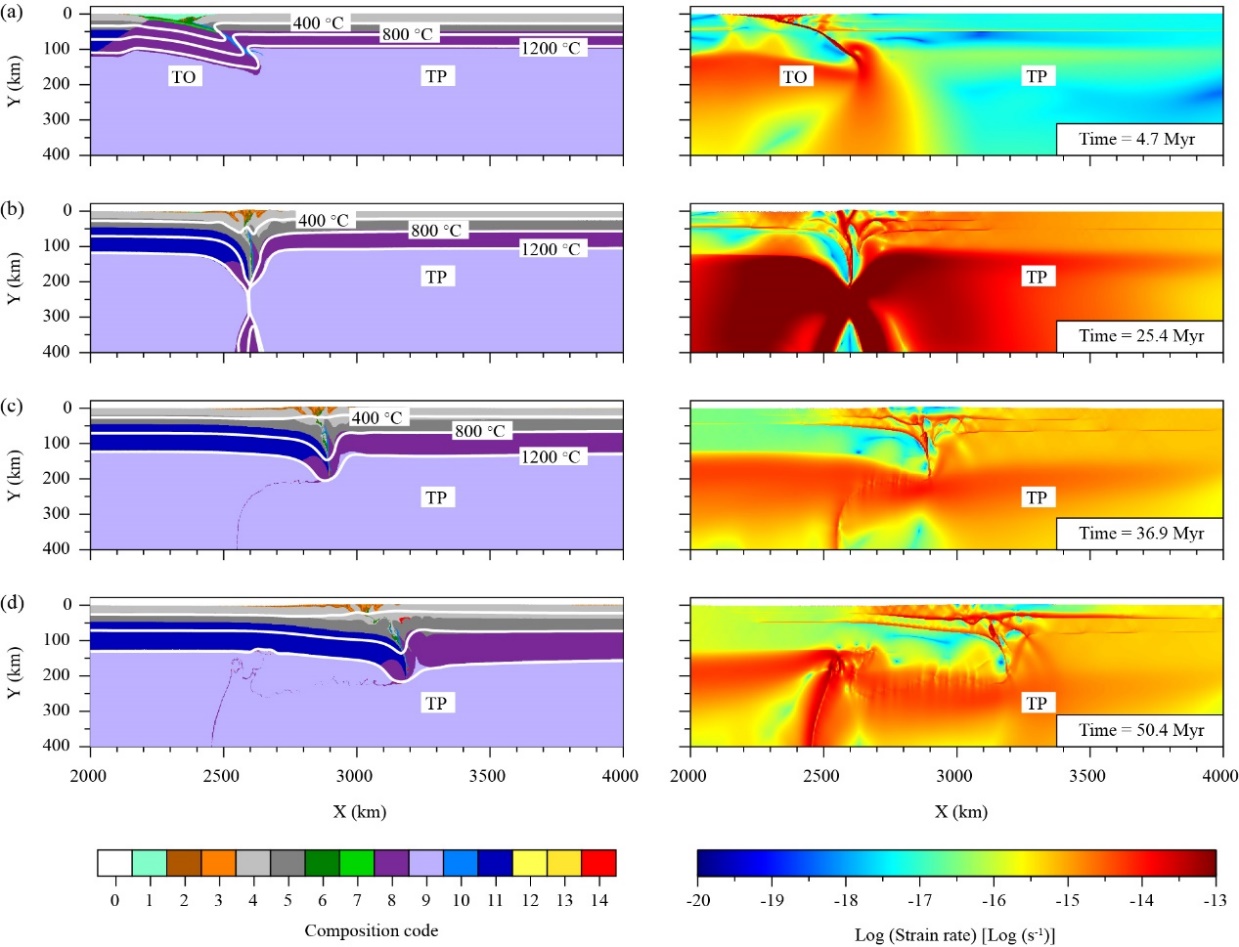
Fig. S5 shows the evolution of this model. At the initial stage, the Tethys Ocean subducts underneath the proto-southern Asia, where the deformation is negligible and strain rate is generally slow (Fig. S5a). As convergence continues, subducted slab experienced the necking and breakoff after ~25.4 Myr (Fig. S5b), which transfers compression to the overlying crust. This process would favor the strong increase in coupling of the subducting plates and the overriding plate, which leads to the deformation of the Tibetan plateau and significantly increases the upper-plate compressional stress. The deformation of the upper plate becomes faster relative to the initial stage, and significant strain localizes at the Tibetan plateau (Figs. S5c, d). A fold-and-thrust structure is formed within the upper crust at the conjunction zone between the two plates. The crust on the right side is visibly thickened by ~30 km and reached a value of ∼80 km in deep (Fig. S6a).

This crustal deformation leads to high topography areas (Fig. S6b). In response to the slab breakoff, an abrupt topographic uplift takes place on the subducted plate. As the push exerted on the left side moves forward, slab underthrusting further results in the topographic uplift. The topography grows continuously and propagates to the right. An uplift of ~4 km related to underthrusting is recorded in southern Tibet.

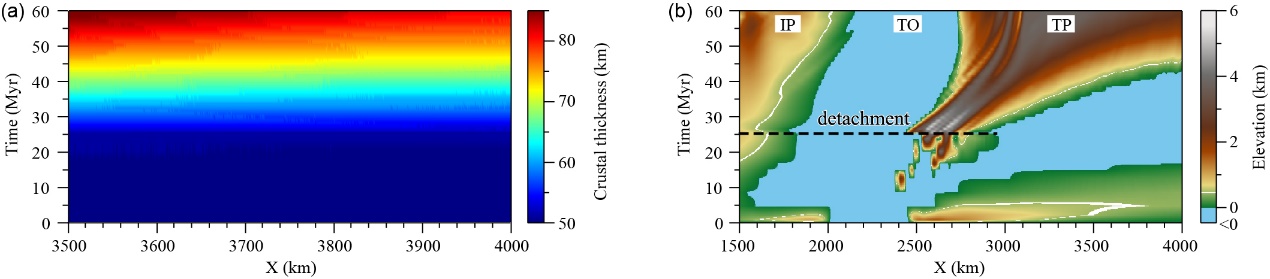
In general, slab underthrusting can significantly increase upper-plate compressional stress and favor the strong coupling with the overlying plate. This process can thicken the Tibetan crust and lead to the topographic uplift. The lower crustal thickening would be balanced by crustal thinning, among which rifting play an important role (e.g., Styron et al., 2015).



**Fig. S4** Initial model configuration and thermal-mechanical boundary conditions. Yellow line indicates the initial temperature profile. Abbreviations: IP: Indian plate; TO: Tethys Ocean; SA, Proto-southern Asia; The color code shows different rock types, with: 0-air; 1-water; 2 and 3-sediment; 4-upper continental crust; 5-lower continental crust; 6-upper oceanic crust; 7-lower oceanic crust; 8 and 11-lithospheric mantle; 9-athenospheric mantle; 10-weak zone mantle; 12 and 13-partially molten sediment; 14, partially molten continental crust.



**Fig. S5.** Temporal evolution of the model at four different stages. The composition fields (left) illustrate deformation features at each stage, with white lines representing the isotherms with a 400 °C increment. The strain rate distribution fields (right) present that strain is localized after slab breakoff. Abbreviations: TO: Tethys Ocean; TP, Tibetan plateau.



**Fig. S6.** Evolution processes of the crustal thickness (a) and surface topography (b). Abbreviations: IP: Indian plate; TO: Tethys Ocean; TP, Tibetan plateau.

Table S1. Full summary of compiled thermochronological results

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Longitude (°) | Latitude (°) | Elevation  (m) | AHe  (Ma) | error | AFT  (Ma) | error | ZHe  (Ma) | error | ZFT  (Ma) | error | BtAr  (Ma) | error | Reference |
| Y2 | 88.9331 | 27.4209 | 2841 | 5.9 | 1 |  |  |  |  | 8.4 | 0.9 |  |  | Wang et al., 2019 |
| Y3 | 88.9239 | 27.4378 | 2868 | 6.6 | 0.7 |  |  |  |  | 10 | 0.9 |  |  | Wang et al., 2019 |
| Y4 | 88.9098 | 27.4344 | 3495 |  |  |  |  |  |  | 9.7 | 1.3 |  |  | Wang et al., 2019 |
| Y5 | 88.9118 | 27.4291 | 3401 | 7.7 | 0.4 |  |  |  |  | 10 | 0.7 |  |  | Wang et al., 2019 |
| Y6 | 88.9147 | 27.4275 | 3240 | 7 | 0.5 |  |  |  |  | 12 | 1.2 |  |  | Wang et al., 2019 |
| Y7 | 88.9184 | 27.4359 | 3067 | 6.4 | 1.6 |  |  |  |  | 9.2 | 1 |  |  | Wang et al., 2019 |
| Y8 | 88.9164 | 27.4526 | 2910 | 6.2 | 2.3 |  |  |  |  | 10.2 | 1 |  |  | Wang et al., 2019 |
| Y9 | 88.9063 | 27.4860 | 2955 | 7.0 | 0.4 |  |  |  |  | 9.4 | 0.8 |  |  | Wang et al., 2019 |
| Y10 | 88.9032 | 27.5038 | 3028 | 4.2 | 0.4 |  |  |  |  | 9.4 | 1.4 |  |  | Wang et al., 2019 |
| Y11 | 88.9147 | 27.5224 | 3129 | 5.5 | 0.7 |  |  |  |  | 11.5 | 1.4 |  |  | Wang et al., 2019 |
| Y12 | 88.9266 | 27.5384 | 3181 |  |  |  |  |  |  | 9.1 | 1.3 |  |  | Wang et al., 2019 |
| Y13 | 88.9305 | 27.5551 | 3258 |  |  |  |  |  |  | 8.2 | 0.7 |  |  | Wang et al., 2019 |
| Y14 | 88.9150 | 27.5699 | 3296 |  |  |  |  |  |  | 9.0 | 0.7 |  |  | Wang et al., 2019 |
| Y15 | 88.9090 | 27.5884 | 3413 | 4.5 | 1.5 |  |  |  |  | 8.8 | 1.1 |  |  | Wang et al., 2019 |
| Y17 | 88.9229 | 27.6302 | 3752 | 7.3 | 0.6 |  |  |  |  | 12.1 | 0.9 |  |  | Wang et al., 2019 |
| Y18-2 | 88.9766 | 27.7534 | 3990 | 10.6 | 0.4 |  |  |  |  | 13.4 | 1 |  |  | Wang et al., 2019 |
| Y19 | 88.9993 | 27.7912 | 4256 | 11.1 | 0.7 |  |  |  |  | 14 | 1.7 |  |  | Wang et al., 2019 |
| Y20 | 88.9882 | 27.8343 | 4513 |  |  |  |  |  |  | 11.9 | 1.1 |  |  | Wang et al., 2019 |
| Q25 | 88.9250 | 27.4633 | 3333 |  |  |  |  |  |  |  |  | 12.75 | 0.74 | Xu et al., 2013 |
| Q56 | 88.9200 | 27.4417 | 2964 |  |  |  |  |  |  |  |  | 12.33 | 0.48 | Xu et al., 2013 |
| Q42 | 88.8867 | 27.4300 | 3695 |  |  |  |  |  |  |  |  | 10.85 | 0.56 | Xu et al., 2013 |

Continued Table S1

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Longitude (°) | Latitude (°) | Elevation  (m) | AHe  (Ma) | error | AFT  (Ma) | error | ZHe  (Ma) | error | ZFT  (Ma) | error | BtAr  (Ma) | error | Reference |
| KY4-4 | 88.9766 | 27.7517 | 4039 |  |  |  |  |  |  |  |  | 14.9 | 0.1 | Dong et al., 2020 |
| KY2-2 | 88.9025 | 27.5075 | 2872 |  |  |  |  |  |  |  |  | 11.7 | 0.1 | Dong et al., 2020 |
| KY1-5 | 88.8828 | 27.4273 | 3854 | 7.4 | 0.4 | 5.8 | 0.4 | 6.3 | 0.3 |  |  |  |  | Dong et al., 2020 |
| KY1-7 | 88.9013 | 27.4381 | 3639 |  |  |  |  | 6.8 | 0.3 |  |  |  |  | Dong et al., 2020 |
| KY1-9 | 88.9097 | 27.4377 | 3464 |  |  |  |  | 6.8 | 0.3 |  |  |  |  | Dong et al., 2020 |
| KY1-11 | 88.9134 | 27.4309 | 3219 |  |  | 5.9 | 0.3 |  |  |  |  |  |  | Dong et al., 2020 |
| KY1-12 | 88.9147 | 27.4339 | 3112 | 5.3 | 0.3 | 4.5 | 0.2 | 5.6 | 0.3 |  |  |  |  | Dong et al., 2020 |
| KY1-13 | 88.9185 | 27.4403 | 3031 | 5.8 | 0.5 | 4.3 | 0.1 |  |  |  |  |  |  | Dong et al., 2020 |
| KY1-14 | 88.9229 | 27.4433 | 2874 |  |  |  |  | 6.4 | 0.4 |  |  |  |  | Dong et al., 2020 |
| 05YD-3 | 88.9548 | 27.3687 | 3149 | 6.5 | 0.6 |  |  |  |  |  |  | 11.3 | 0.6 | Gong et al, 2012 |
| 05YD-8 | 88.9762 | 27.3769 | 2721 | 8 | 1 |  |  |  |  |  |  | 11 | 0.4 | Gong et al, 2012 |

AHe: Apatite (U-Th)/He; AFT: Apatite fission track; ZHe: Zircon (U-Th)/He; ZFT: Zircon fission track; BtAr: Biotite 40Ar/39Ar.

Table S2. Full summary of apatite (U-Th)/He thermochronology

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Mass (μg) | ar (μm) | bl  (μm) | U (ppm) | Th (ppm) | Sm (ppm) | He (ppm) | c[eU] (ppm) | 4He (ncc) | dFt | Corrected age (Ma) | Error (±1**σ)** | Mean Age (Ma) | Standard Error |
|
| JG042116-3-1 | 2.84 | 42.55 | 194.95 | 530.97 | 57.69 | 1121.56 | 5.47 | 45.89 | 0.12 | 0.84 | 9.15 | 0.04 | 9.15 | 0.04 |
| JG042116-4-1 | 3.19 | 43.26 | 211.78 | 330.02 | 40.48 | 405.91 | 2.48 | 25.48 | 0.06 | 0.82 | 6.88 | 0.03 | 9.92 | 1.75 |
| JG042116-4-2 | 2.09 | 35.04 | 211.78 | 346.55 | 51.17 | 431.21 | 4.73 | 41.01 | 0.11 | 0.78 | 12.94 | 0.05 |
| JG042116-4-3 | 2.55 | 38.66 | 211.78 | 336.26 | 31.23 | 412.76 | 3.56 | 41.01 | 0.08 | 0.80 | 9.93 | 0.04 |
| JG042116-7-1 | 2.17 | 44.86 | 133.57 | 492.13 | 37.35 | 612.92 | 5.29 | 55.44 | 0.12 | 0.80 | 10.15 | 0.08 | 9.57 | 0.93 |
| JG042116-7-2 | 3.47 | 42.46 | 239.16 | 655.01 | 67.87 | 634.95 | 4.97 | 46.29 | 0.11 | 0.81 | 7.07 | 0.04 |
| JG042116-7-3 | 4.91 | 51.66 | 228.31 | 1391.98 | 118.94 | 1370.09 | 14.66 | 69.33 | 0.33 | 0.84 | 9.51 | 0.04 |
| JG042116-7-4 | 3.51 | 49.90 | 174.85 | 135.09 | 30.93 | 512.90 | 1.88 | 9.72 | 0.04 | 0.87 | 11.55 | 0.17 |
| JG042316-2-1 | 2.65 | 43.98 | 169.95 | 180.02 | 21.25 | 430.26 | 0.86 | 16.74 | 0.02 | 0.84 | 4.22 | 0.13 | 5.84 | 0.89 |
| JG042316-2-2 | 2.01 | 36.24 | 190.24 | 219.31 | 7.55 | 500.06 | 1.84 | 26.34 | 0.04 | 0.83 | 7.66 | 0.11 |
| JG042316-2-3 | 1.44 | 33.72 | 157.73 | 225.94 | 7.29 | 438.59 | 1.71 | 37.77 | 0.04 | 0.81 | 7.08 | 0.19 |
| JG042316-2-4 | 2.70 | 47.76 | 147.16 | 99.22 | 4.61 | 409.28 | 0.50 | 8.89 | 0.01 | 0.87 | 4.38 | 0.23 |
| JG042316-5-1 | 3.12 | 51.37 | 146.84 | 453.14 | 171.30 | 2236.37 | 2.92 | 37.81 | 0.07 | 0.87 | 5.18 | 0.02 | 5.05 | 0.13 |
| JG042316-5-2 | 5.19 | 56.40 | 202.48 | 976.46 | 291.84 | 1840.55 | 5.73 | 48.21 | 0.13 | 0.86 | 4.92 | 0.02 |
| JG042316-9-1 | 4.23 | 49.81 | 211.78 | 604.61 | 226.27 | 1069.11 | 5.41 | 41.01 | 0.12 | 0.84 | 7.50 | 0.02 | 5.65 | 1.17 |
| JG042316-9-2 | 3.33 | 44.21 | 211.78 | 476.55 | 184.82 | 966.39 | 3.36 | 37.29 | 0.08 | 0.83 | 5.98 | 0.02 |
| JG042316-9-3 | 1.21 | 31.08 | 155.66 | 250.00 | 156.45 | 404.02 | 0.95 | 56.55 | 0.02 | 0.73 | 3.48 | 0.10 |
| JG042416-3-1 | 1.15 | 35.60 | 112.65 | 225.62 | 350.97 | 387.42 | 2.61 | 63.71 | 0.06 | 0.70 | 9.36 | 0.10 | 11.18 | 0.96 |
| JG042416-3-2 | 1.93 | 38.46 | 162.29 | 436.61 | 17.07 | 764.09 | 5.41 | 54.62 | 0.12 | 0.81 | 11.58 | 0.07 |
| JG042416-3-3 | 1.97 | 36.67 | 182.31 | 260.16 | 15.92 | 844.37 | 3.68 | 32.04 | 0.08 | 0.84 | 12.61 | 0.10 |

ar - radius; bl - length; c[eU] - effective uranium concentration (U ppm+0.235 Th ppm); dFt - alpha ejection correction of Ketcham et al., 2011.

Table S3. Results of apatite fission track thermochronology

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Nc | ρs (×105 cm–2) | Ns | ρi  (×106 cm–2) | Ni | ρd (×105 cm–2) | Nd | P(χ2) | Central age (Ma) | Error |
|
| JG042116-4 | 20 | 1.18 | 100 | 2.00 | 1693 | 1.48 | 2672 | 79.6 | 14.94 | 1.71 |
| JG042216-8 | 20 | 1.11 | 151 | 3.46 | 4720 | 1.46 | 2629 | 39.12 | 8.00 | 0.78 |
| JG042216-9 | 21 | 0.59 | 97 | 1.29 | 2104 | 1.20 | 2155 | 50.06 | 9.41 | 1.09 |
| JG042316-4 | 22 | 0.64 | 115 | 2.21 | 3954 | 1.56 | 2801 | 91.34 | 7.73 | 0.83 |
| JG042316-5 | 20 | 0.64 | 119 | 2.23 | 4139 | 1.25 | 2241 | 77.04 | 6.27 | 0.79 |
| JG042316-7 | 22 | 0.99 | 127 | 1.94 | 2492 | 1.53 | 2759 | 38.97 | 13.22 | 1.48 |
| JG042416-4 | 22 | 1.09 | 122 | 2.11 | 2363 | 1.67 | 3001 | 79.75 | 14.18 | 1.48 |
| JG042416-6 | 20 | 1.27 | 181 | 1.65 | 2354 | 1.17 | 2112 | 76.69 | 15.37 | 1.43 |

Nc, number of apatite crystals analysed;

ρs, ρi and ρd are spontaneous track density, induced track density and standard track density, respectively.

Ns, Ni and Nd are spontaneous track number, induced track number and standard track number, respectively.

P(χ2) is chi-squared probability that all single-crystal ages represent a single population.

Table S4 Inversion results for the profile DD’

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inversion | free parameters | vertical offset | R | T1  (Ma) | E1  (mm/yr) | T2  (Ma) | E2  (mm/yr) | BIC |
| Range |  |  | 1–0 | 20–8 | 5–0 | 8–0 | 5–0 |  |
| **RunD1** | **2** | **0a** | **1a** | **11.01** | **1.14** | **-** | **-** | **5.85** |
| RunD2 | 4 | 0a | 1a | 9.64 | 1.28 | 2.73 | 1.07 | 10.27 |
| RunD3 | 2 | 5a | 0.1a | 10.97 | 1.11 | - | - | 6.99 |
| RunD4 | 4 | 5a | 0.1a | 15.40 | 1.49 | 1.90 | 1.02 | 10.19 |
| RunD5 | 3 | 5a | 0.2E-05 | 11.20 | 1.13 | - | - | 7.20 |
| RunD6 | 5 | 5a | 0.78 | 8.84 | 2.71 | 2.94 | 0.03 | 10.90 |

a The fixed value imposed in the model.

Table S5 Inversion results for the profile CC’

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inversion | free parameters | vertical offset | R | T1  (Ma) | E1  (mm/yr) | T2  (Ma) | E2  (mm/yr) | BIC |
| Range |  |  | 1–0 | 20–10 | 5–0 | 15–0 | 5–0 |  |
| RunC1 | 2 | 0a | 1a | 14.77 | 0.69 | - | - | 406.29 |
| RunC2 | 4 | 0a | 1a | 11.84 | 1.89 | 7.61 | 0.17 | 260.94 |
| RunC3 | 2 | 5a | 0.1a | 19.99 | 0.46 | - | - | 342.31 |
| **RunC4** | **4** | **5a** | **0.1a** | **12.00** | **2.10** | **4.40** | **0.20** | **146.86** |
| RunC5 | 3 | 5a | 0.23 | 19.65 | 0.43 | - | - | 323.57 |
| RunC6 | 5 | 5a | 0.13 | 14.08 | 1.86 | 7.14 | 0.14 | 148.98 |

a The fixed value imposed in the model.

Table S6. Thermal-kinematic and elastic parameters used in PECUBE modeling

|  |  |
| --- | --- |
| Parameter (unit) | Value |
| Crustal density (kg/m3) | 2700 |
| Mantle density (kg/m3) | 3200 |
| Young's modulua (Pa) | 1.1011 |
| Poisson ratio | 0.25 |
| Elastic plate thichness (km) | 28.8 |
| Crustal thickness (km) | 50 |
| Thermal diffusivity (km2/Myr) | 25 |
| Basal crustal temperature (C) | 1250 |
| Sea-level temperature (C) | 5 |
| Atmospheric lapse rate（C/km） | 0 |
| Crustal heat production (C/Myr) | 0 |

Table S7. Summary of the initiation and acceleration timing of E-W extension across the Himalayan-Tibetan orogen

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Number in Fig. 1 | Rift | Initiation timing (Ma) | Method | Constrain type | Initiation  stage (Ma) | Initiation rate (mm/yr) | Acceleration stage (Ma) | Acceleration rate (mm/yr) | References |
| (a) | Leo Pargil | ~23 | monazite U-Pb in syn-deformation leucogranite | approximation | 23-16 | 2 | 16-10 | 3 | Langille et al., 2012 |
|  |  | 16-14 | muscovite 40Ar/39Ar |  |  |  |  |  | Thiede et al., 2006 |
|  |  | 16 | muscovite 40Ar/39Ar |  |  |  |  |  | Hintersberger et al., 2010 |
| (b) | Gurla Mandhata | ~15 | monazite Th-Pb in syn-deformation leucogranite | approximation | 15-7 |  |  |  | Murphy and Copeland, 2005 |
|  |  | North: 14-11 Central: 14-11 South: 15-8 | Pecube modeling, zircon (U-Th)/He | precise constraint | North: (14-11)-6 Central:(14-11)-(13-11) South:(15-8)-(6-3) | North: 8-11 Central: 2-4 South: 1-2 | North: 6-0 Central:(13-11)-0 South: (6-3)-0 | North: 1-2 Central: 3 South: 2-4 | McCallister et al., 2014 |
|  |  | 9 | mica 40Ar/39Ar |  |  |  |  |  | Murphy et al., 2002 |
|  |  | ~9 | magnetostratigraphy |  |  |  |  |  | Saylor et al., 2009; 2010 |
| (c) | South Lunggar | 16-12 | Pecube modeling, zircon (U-Th)/He | precise constraint | (16-12)-8 | 1.1-1.4 | 8-0 | 3-3.6 | Styron et al., 2013 |
| (d) | North Lunggar | ~15 | zircon U-Pb in syn-deformation leucogranite | approximation |  |  |  |  | Kapp et al., 2008 |
|  |  | >10 | apatite, zircon (U-Th)/He | minimum | >10-5 | <2 | 5-2 | 8-20 | Sundell et al., 2013; Styron et al., 2015 |
|  |  | 10-8 | apatite, zircon (U-Th)/He | minimum |  |  |  |  | Woodruff et al., 2013 |
| (e) | Thakkhola | 17 | muscovite 40Ar/39Ar in syn-deformation rock | approximation |  |  |  |  | Larson et al., 2020 |
|  |  | >14 | muscovite 40Ar/39Ar in fractures | minimum |  |  |  |  | Coleman and Hodges, 1995 |
|  |  | ~11-10 | magnetostratigraphy, growth strata |  |  |  |  |  | Garzione et al., 2000; 2003 |
| (f) | Lopukangri | ~15-14 | mica 40Ar/39Ar of footwall rocks | minimum | 15-14 |  | <5 |  | Sanchez et al., 2010, 2013; Murphy et al., 2010 |
|  |  | 17-15 | zircon U-Pb | approximation |  |  |  |  | Laskowski et al., 2017 |
| (g) | Kung Co | 13-12 | He MP modeling, apatite, zircon (U-Th)/He | precise constraint | 13-10 | 0.9-3.1 | 10 | 6.9-21.9 | Lee et al., 2011 |
|  |  | <4 | apatite (U-Th)/He |  |  |  |  |  | Mahéo et al., 2007 |
|  |  | 19 | zircon U-Pb |  |  |  |  |  | Mitsuishi et al., 2012 |
| (h) | Tangra Yum Co | 14.5 | Pecube modeling, zircon (U-Th)/He | precise constraint | 14.5-3 | 0.3 | 3-0 | 0.8 | Wolff et al., 2019 |
|  |  | 13 | apatite, zircon (U-Th)/He |  | 13 |  | 6 |  | Dewane et al., 2006 |
| (i) | Dinggye | ~13 | biotite 40Ar/39Ar in syn-deformation rock | approximation |  |  |  |  | Zhang and Guo, 2007 |
|  |  | >11 | biotite 40Ar/39Ar | minimum | 12-9 | 5.7 | 6-4 | 1.4 | Kali et al., 2010 |

Continued Table S7

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Number in Fig. 1 | Rift | Initiation timing (Ma) | Method | Constrain type | Initiation  stage (Ma) | Initiation  rate (mm/yr) | Acceleration stage (Ma) | Acceleration rate (mm/yr) | References |
| (j) | Xainza | 14 | zircon U-Pb, apatite, zircon (U-Th)/He | estimation |  |  |  |  | Hager et al., 2009; Sundell et al., 2013 |
| (k) | Shuanghu | >13.5 | Rb-Sr and 40Ar/39Ar of mineralized vein | minimum |  |  |  |  | Blisniuk et al., 2001 |
|  |  | <4 | assumed from the rate and magnitude of extension |  |  |  |  |  | Yin et al., 1999 |
| (l) | Yadong | 13-11 | Pecube modeling, apatite and zircon FT and (U-Th)/He | precise constraint |  |  |  |  | this study |
|  |  | <10 | monazite Th-Pb |  |  |  |  |  | Edwards and Harrison, 1997 |
|  |  | <11.5 | monazite Th-Pb |  |  |  |  |  | Ratschbacher et al., 2011 |
|  |  | 13-11 | mica 40Ar/39Ar |  |  |  |  |  | Xu et al., 2013 |
|  |  | 7 | apatite FT, apatite and zircon (U-Th)/He |  |  |  |  |  | Dong et al., 2020 |
| (m) | Gyanze | >10.8 | Dike emplacement | minimum |  |  |  |  | Ratschbacher et al., 2011 |
| (n) | Ringbung | >7 | zircon U-Pb in leucogranite | minimum |  |  |  |  | Ratschbacher et al., 2011 |
| (o) | Nyainqentanghla | 8 | MDD modeling of mica, K-feldspar 40Ar/39Ar | precise constraint |  |  |  |  | Harrison et al., 1995 |
|  |  | 8.7 | Dike emplacement |  |  |  |  |  | Kapp et al., 2005 |
|  |  | 8-6.8 | apatite FT |  |  |  |  |  | Wu et al., 2002 |
| (p) | Gulu | 7-5 | apatite (U-Th)/He |  |  |  |  |  | Stockli et al., 2002 |
| (q) | Cona | ~3 | biotite and K-feldspar 40Ar/39Ar, zircon and apatite (U-Th)/He | precise constraint | 2.7-2.4 | 4.4 | 2-1 | 1.8 | Bian et al., 2020a |

**References**

Bian, S., Gong, J.F., Zuza, A.V., Yang, R., Tian, Y.T., Ji, J.Q., et al. (2020a). Late Pliocene onset of the Cona rift, eastern Himalaya, confirms eastward propagation of extension in Himalayan-Tibetan orogen. *Earth and Planetary Science Letters*, 544(15), 116383. https://doi.org/10.1016/j.epsl.2020.116383

Blisniuk, P.M., Hacker, B.R., Glodny, J., Ratschbacher, L., Bi, S.W., Wu, Z.H., et al. (2001). Normal faulting in central Tibet since at least 13.5 Myr ago. *Nature*, 412, 628-632. https://doi.org/10.1038/35088045

Coleman, M., & Hodges, K. (1995). Evidence for Tibetan plateau uplift before 14 Myr ago from a new minimum age for east-west extension. *Nature*, 374, 49–52. https://doi.org/10.1038/374049a0

Dewane, T.J., Stockli, D.F., Hager, C., & Taylor, M.H. (2006). Timing of Cenozic E-W extension in the Tangra Yum Co-Kung Co rift, south-central Tibet. *American Geophysical Union fall Metting*, abstract with program.

Dong, H.W., Larson, K.P., Kellett, D.A., Xu, Z.Q., Li, G.W., Cao, H., et al. (2020). Timing of slip across the South Tibetan detachment system and Yadong-Gulu graben, Eastern Himalaya. *Journal of the Geological Society*, 178, 1–15. https://doi.org/10.1144/jgs2019-197

Edwards, M.A., & Harrison, T.M. (1997). When did the roof collapse? Late Miocene north-south extension in the high Himalaya revealed by Th-Pb monazite dating of the Khula Kangri granite. *Geology*, 25, 543–546. https://doi.org/10.1130/0091-7613(1997)0252.3.CO;2

Garzione, C.N., DeCelles, P.G., Hodkinson, D.G., Ojha, T.P., & Upreti, B.N. (2003). East-west extension and Miocene environmental change in the southern Tibetan Plateau, Thakkhola Graben, central Nepal. *Geological Society of America Bulletin*, 115, 3–20. https://doi.org/10.1130/0016-7606(2003)1152.0.CO;2

Garzione, C.N., Dettman, D.L., Quade, J., DeCelles, P.G., & Butler, R.F. (2000). High times on the Tibetan Plateau: Paleoelevation of the Thakkhola graben, Nepal. *Geology*, 28, 339–342. https://doi.org/10.1130/0091-7613(2000)28<339:HTOTTP>2.0.CO;2

Gerya, T.V., & Yuen, D.A. (2003). Characteristics-based marker-in-cell method with conservative finite-differences schemes for modeling geological flows with strongly variable transport properties. Phys. Earth Planet. Inter. 140, 295–320. https://doi.org/10.1016/j.pepi.2003.09.006.

Gong, J.F., Ji, J.Q., Han, B.F., Chen, J.J., Sun, D.X., Li, B.L., et al. (2012). Early subduction-exhumation and late channel flow of the Greater Himalayan Sequence: implications from the Yadong section in the eastern Himalaya. *International Geology Review*, 54(10), 1184–1202. https://doi.org/10.1080/00206814.2011.626604

Hager, C., Stockli, D.F., Dewane, T.J., Gehrels, G., & Ding, L. (2009). Anatomy and crustal evolution of the central Lhasa terrane (S-Tibet) revealed by investigations in the Xainza rift. *Geophysical Research Abstracts*, EGU General Assembly, 11, EGU2009-11346-11341.

Harrison, T.M., Copeland, P., Kidd, W.S.F., & Lovera, O.M. (1995). Activation of the Nyainqentanghla Shear Zone: Implications for uplift of the southern Tibetan Plateau. *Tectonics*, 14, 658–676. https://doi.org/10.1029/95tc00608

Hintersberger, E., Thiede, R.C., Strecker, M.R., & Hacker, B.R. (2010). East-west extension in the NW Indian Himalaya. *Geological Society of America Bulletin*, 122, 1499-1515. https://doi.org/10.1130/B26589.1

Kali, E., Leloup, P.H., Arnaud, N., Maheo, G., Liu, D.Y., Boutonnet, E., et al. (2010). Exhumation history of the deepest central Himalayan rocks Ama Drime range: Key pressure-temperature-deformation-time constraints on orogenic models. *Tectonics*, 29, TC2014. https://doi.org/10.1029/2009TC002551.

Kapp, J.L.D., Harrison, T.M., Kapp, P., Grove, M., Lovera, O.M., & Ding, L. (2005). Nyainqentanglha Shan: A window into the tectonic, thermal, and geochemical evolution of the Lhasa block, southern Tibet. *Journal of Geophysical Research: Solid Earth*, 110, 653–669. https://doi.org/10.1029/2004JB003330

Kapp, P., Taylor, M., Stockli, D., & Ding, L. (2008). Development of active low-angle normal fault systems during orogenic collapse: Insight from Tibet. *Geology*, 36(1), 7–10. https://doi.org/10.1130/G24054A.1

Langille, J.M., Jessup, M.J., Cottle, J.M., Lederer, G., & Ahmad, T. (2012). Timing of metamorphism, melting and exhumation of the Leo Pargil dome, northwest India. *Journal of Metamorphic Geology*, 30(8), 769–791. https://doi.org/10.1111/j.1525-1314.2012.00998.x

Larson, K.P., Kellett, D.A., Cottle, J.M., Camacho, A., & Brubacher, A.D. (2020). Mid-Miocene initiation of E-W extension and recoupling of the Himalaya. *Terra Nova*, 32(2), 151–158. https://doi.org/10.1111/ter.12443

Laskowski, A.K., Kapp, P., Ding, L., Campbell, C., & Liu, X.H. (2017). Tectonic evolution of the Yarlung suture zone, Lopu Range region, southern Tibet. *Tectonics*, 36, 108–136. https://doi.org/10.10022016TC004334

Lee, J., Hager, C., Wallis, S.R., Stockli, D.F., Whitehouse, M.J., Aoya, M., et al. (2011). Middle to late Miocene extremely rapid exhumation and thermal reequilibration in the Kung Co rift, southern Tibet. *Tectonics*, 30(2), TC2007. https://doi.org/10.1029/2010TC002745

Mahéo, G., Leloup, P. H., Valli, F., Lacassin, R., Arnaud, N., Paquette, J.L., et al. (2007). Post 4 Ma initiation of normal faulting in southern Tibet. Constraints from the Kung Co half graben. *Earth and Planetary Science Letters*, 256, 233-243. https://doi.org/10.1016/j.epsl.2007.01.029.

McCallister, A.T., Taylor, M.H., Murphy, M.A., Styron, R.H., & Stockli, D.F. (2014). Thermochronologic constraints on the late Cenozoic exhumation history of the Gurla Mandhata metamorphic core complex, Southwestern Tibet. *Tectonics*, 33, 27–52. https://doi.org/10.1002/2013TC003302

Mitsuishi, M., Wallis, S.R., Aoya, M., Lee, J., & Wang, Y. (2012). E-W extension at 19 Ma in the Kung Co area, S. Tibet: Evidence for contemporaneous E–W and N–S extension in the Himalayan orogen. *Earth and Planetary Science Letters*, 325-326:10-20. https://doi.org/10.1016/j.epsl.2011.11.013

Murphy, M.A., & Copeland, P. (2005). Transtensional deformation in the central Himalaya and its role in accommodating growth of the Himalayan orogen. *Tectonics*, 24(4), TC4012. https://doi.org/10.1029/2004TC001659

Murphy, M.A., Yin, A., Harrison, T.M., Dürr, S.B., Chen, Z., Ryerson, F.J., et al. (1997). Did the Indo-Asian collision alone create the Tibetan plateau? Geology 25 (8), 719–722. https://doi.org/10.1130/0091-7613(1997) 025<0719:DTIACA>2.3.CO;2.

Murphy, M.A., Yin, A., Kapp, P., Harrison, T.M., Manning, C.E., Ryerson, F.J., et al. (2002). Structural evolution of the Gurla Mandhata detachment system, southwest Tibet: Implications for the eastward extent of the Karakoram fault system. *Geological Society of America Bulletin*, 114, 428-447. https://doi.org/10.1130/0016-7606(2002)1142.0.CO;2

Ratschbacher, L., Krumrei, I., Blumenwitz, M., Staiger, M., Gloaguen, R., Miller, B.V., et al. (2011). Rifting and strike-slip shear in central Tibet and the geometry, age and kinematics of upper crustal extension in Tibet. *Geological Society London Special Publications*, 353, 127-163. https://doi.org/10.1144/SP353.8

Sanchez, V.I., Murphy, M.A., Robinson, A.C., Lapen, T.J., & Heizler, M.T. (2013). Tectonic evolution of the India-Asia suture zone since Middle Eocene time, Lopukangri area, south-central Tibet. *Journal of Southeast Asian Earth Sciences*, 62, 205–220. https://doi.org/10.1016/j.jseaes.2012.09.004

Sanchez, V.I., Murphy, M.A.R., Robinson, A.C., Lapen, T.J., Heizler, M.T., & Taylor, M.H. (2010). Onset of Oblique Extension in South-Central Tibet by 15 Ma: implications for Diachronous Extension of the Tibetan Plateau. *American Geophysical Union*, San Francisco.

Saylor, J.E., De Celles, P.G., & Quade, J. (2010). Climate-driven environmental change in the Zhada basin, southwestern Tibet Plateau. *Geosphere*, 6, 74–92. https://doi.org/10.1130/GES00507.S2

Saylor, J.E., Quade, J., Dellman, D.L., DeCelles, P.G., Kapp, P.A., & Ding, L. (2009). The late Miocene through present paleoelevation history of southwestern Tibet. *American Journal of Science*, 309, 1–42. https://doi.org/10.2475/01.2009.01

Stockli, D., Taylor, M., Yin, A., Harrison, T.M., D'Andrea, J., Kapp, P., et al. (2002). Late Miocene-Pliocene inception of E-W extension in Tibet as evidenced by apatite (U-Th)/He data. *Geological Society of America, Abstracts with Programs*, 34, 411.

Styron, R., Taylor, M., & Sundell, K. (2015). Accelerated extension of Tibet linked to the northward underthrusting of Indian crust. *Nature Geoscience*, 8, 131–134. https://doi.org/10.1038/ngeo2336

Styron, R.H., Taylor, M.H., Sundell, K.E., Stockli, D.F, Oalmann, J.A.G., Möller, A., et al. (2013). Miocene initiation and acceleration of extension in the South Lunggar rift, western Tibet: Evolution of an active detachment system from structural mapping and (U-Th)/He thermochronology. *Tectonics*, 32(4), 880–907. https://doi.org/10.1002/tect.20053

Sundell, K.E., Taylor, M.H., Styron, R.H., Stockli, D.F., Kapp, P., Hager, C., et al. (2013). Evidence for constriction and Pliocene acceleration of east-west extension in the North Lunggar rift region of west central Tibet. *Tectonics*, 32(5), 1454–1479. https://doi.org/10.1002/tect.20086

Sundell, K.E., Taylor, M.H., Styron, R.H., Stockli, D.F., Kapp, P., Hager, C., et al. (2013). Evidence for constriction and Pliocene acceleration of east-west extension in the North Lunggar rift region of west central Tibet. *Tectonics*, 32(5), 1454–1479. https://doi.org/10.1002/tect.20086

Thiede, R.C., Arrowsmith, J.R., Bookhagen, B., McWilliams, M., Sobel, E.R., & Strecker, M.R. (2006). Dome formation and extension in the Tethyan Himalaya, Leo Pargil, northwest India. *Geological Society of America Bulletin*, 118(5–6), 635–650. https://doi.org/10.1130/B25872.1

Wang, A., Min, K., Wang, G.C., Cao, K., Shen, T.Y., Jiang, P.F., et al. (2019). Slow exhumation of the Greater Himalaya in the Yadong region, the transition between the Central and Eastern Himalaya, during the Late Neogene. *Journal of the Geological Society*, 176, 1207–1217. https://doi.org/10.1144/jgs2018-186

Wolff, R., Hetzel, R., Dunkl, I., Xu, Q., Bröcker, M., & Anczkiewicz, A.A. (2019). High-Angle Normal Faulting at the Tangra Yumco Graben (Southern Tibet) since ~15 Ma. *Journal of Geology*, 127, 15–36. https://doi.org/10.1086/700406

Woodruff, W.H., Horton, B.K., Kapp, P., & Stockli, D.F. (2013). Late Cenozoic evolution of the Lunggar extensional basin, Tibet: Implications for basin growth and exhumation in hinterland plateaus. *Geological Society of America Bulletin*, 125(3/4), 343–358. https://doi.org/10.1130/B30664.1

Wu, Z.H., Hu, D.G., Liu, Q.S., Xia, H.D., & Yan, X.L. (2002). The Formation and Evolution of Tectonic Landform of Damxung Area in Central Tibetan Plateau. *Acta Geoscientia Sinica*, 5(23), 423-428.

Xu, Z.Q., Wang, Q., Pêcher, A., Liang, F.H., Qi, X.X., Cai, Z.H., et al. (2013). Orogen-parallel ductile extension and extrusion of the Greater Himalaya in the late Oligocene and Miocene. *Tectonics*, 32, 191–215. https://doi.org/191-215.10.1002/tect.20021

Yin, A., Kapp, P.A., Murphy, M.A., Manning, C.E., Harrison, T.M., Grove, M., et al. (1999). Significant late Neogene east-west extension in northern Tibet. *Geology*, 27, 787-790. https://doi.org/10.1130/0091-7613(1999)027<0787:SLNEWE>2.3.CO;2.

Zhang, J.J., & Guo, L. (2007). Structure and geochronology of the southern Xainza-Dinggye rift and its relationship to the south Tibetan detachment system. *Journal of Southeast Asian Earth Sciences*, 29, 722–736. https://doi.org/10.1016/j.jseaes.2006.05.003