nature geoscience

LETTERS

PUBLISHED ONLINE: 12 JANUARY 2015 | DOI: 10.1038/NGEO2336

Accelerated extension of Tibet linked to the northward underthrusting of Indian crust

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The Tibetan Plateau is undergoing eastward extension on north-trending rifts, but the cause is unclear. The extension is commonly thought to represent gravitational collapse and outward spreading of the plateau[1–5], a view based on observations of the synchronous onset of regional extension during the middle to late Miocene[4,6–13]. However, rifting in southern Tibet occurs at a faster rate and is more developed than in the north, implying that rifting could instead be caused by progressive underthrusting of the Indian Plate beneath the southern plateau[14–17]. Here we use three-dimensional numerical models, constrained by structural and thermochronological data sets, to simulate extension of the Lunggar rift in southern Tibet as the orogenic system evolves. Our simulations reveal slow extension beginning in the Miocene, synchronously throughout the rift, followed by a wave of rapid extension that sweeps northwards along the rift, slightly ahead of the underthrusting Indian slab. Although the initial period of slow extension is consistent with orogen-scale gravitational collapse, we suggest that the subsequent extension at a high rate and magnitude in southern Tibet reflects thinning of the upper crust in response to thickening of the lower crust as the Indian plate is underthrust. Our results demonstrate that large-magnitude upper-crustal extension can occur during peak orogenic events, as well as during post-orogenic collapse.

The elevation of an orogenic plateau or mountain belt is limited in part by the tectonic compressive stresses at the orogen's margins that support the high elevations and consequent high gravitational potential energy[1,5,18]. In an actively deforming orogen at this equilibrium, either a sudden increase in elevation or a decrease in tectonic compressive forces will lead to orogen-wide crustal extension and thinning as the orogen collapses under gravitational force to regain equilibrium at lower elevation[1,5,18]. Gravitational collapse is thought to have widespread occurrence in space and time, particularly during the waning phases of orogeny[1,18,19], and modern extension of the Tibetan plateau is considered a canonical example[2–5]. This interpretation of Tibetan extension is largely based on observations of widespread normal faulting at high elevations throughout the plateau, which probably began relatively synchronously in the Miocene[4,6–13] (Fig. 1a). This ostensibly simultaneous onset of east-directed extension throughout the plateau has lead to explanations invoking a sudden, orogen-wide forcing, such as the convective removal of mantle lithosphere[2–5] or changes in plate convergence rates that decrease horizontal compression across Tibet[20,21].

However, explanations for Tibetan extension due to orogen-wide changes in elevation or boundary forces do not predict the observations of faster rifting with more cumulative extension in southern Tibet than farther to the north[7–18]. Therefore, some workers have proposed alternative hypotheses incorporating the underthrusting of the Indian plate to explain Tibetan extension[14–17]. These models invoke various combinations of shear tractions on the subduction interface between the top of the underthrusting Indian plate and the base of the overriding Eurasian plate[15–17], an increase in buoyancy due to the displacement of denser mantle by the Indian plate[6,14], and eastward displacement of Tibetan lower crust[6,14]. Although variation exists, these models predict extension in south Tibet and strike-slip faulting to the north; therefore, the boundary between the deformation styles should migrate northwards with the Indian plate. However, because extension began simultaneously[4,6–13] and is ongoing throughout the plateau[22], these models are also problematic.

Further development of our understanding of Tibetan rifting has been hindered by a lack of data. In the handful of studied rifts (Fig. 1a), the onset of extension may be constrained by as little as a single dated cross-cutting relationship[8], and very few constraints on net extension or rate exist. To gain more insight into the dynamics of Tibetan rifting, we have conducted the first north–south geologic transect across southern Tibet at the Lunggar rift[9,11,12] (Fig. 1). We have collected an unprecedented amount of geochronological and structural data, specifically apatite and zircon (U–Th)/He thermochronometric data (which date the cooling of rocks through 40–70 °C and 160–200 °C thermal windows, respectively); these temperature ranges are well suited to characterize the deformational and exhumational history of rifting through the cooling history of exhumed fault blocks. Data from the footwalls of major normal faults in the Lunggar rift document late Miocene to Pliocene cooling, consistent with extension beginning in the Miocene[9,11–13]. The large number of zircon (U–Th)/He cooling ages of 3 to 4 Myr (Fig. 2a) from samples now hundreds of metres above the hanging wall basins indicates extremely rapid Pliocene exhumation and cooling of the footwall blocks[9,11,12].

To more rigorously constrain the extensional history of the Lunggar rift, we have made six E–W oriented three-dimensional thermokinematic models corresponding to (U–Th)/He sample transects across the uplifted detachment footwalls, spanning 80 km along a N–S strike (Fig. 1b), incorporating 46 zircon and 13 apatite (U–Th)/He samples. For each model, we have run 1,500–15,000 numerical simulations, searching over a wide range of deformational histories that produce net extension in agreement with structural estimates at that location (see Methods and Supplementary Methods for more information). We have allowed rift initiation to begin at any time in the middle Miocene to early Pliocene, and have allowed for (although not enforced) a later increase or decrease in extension rate.

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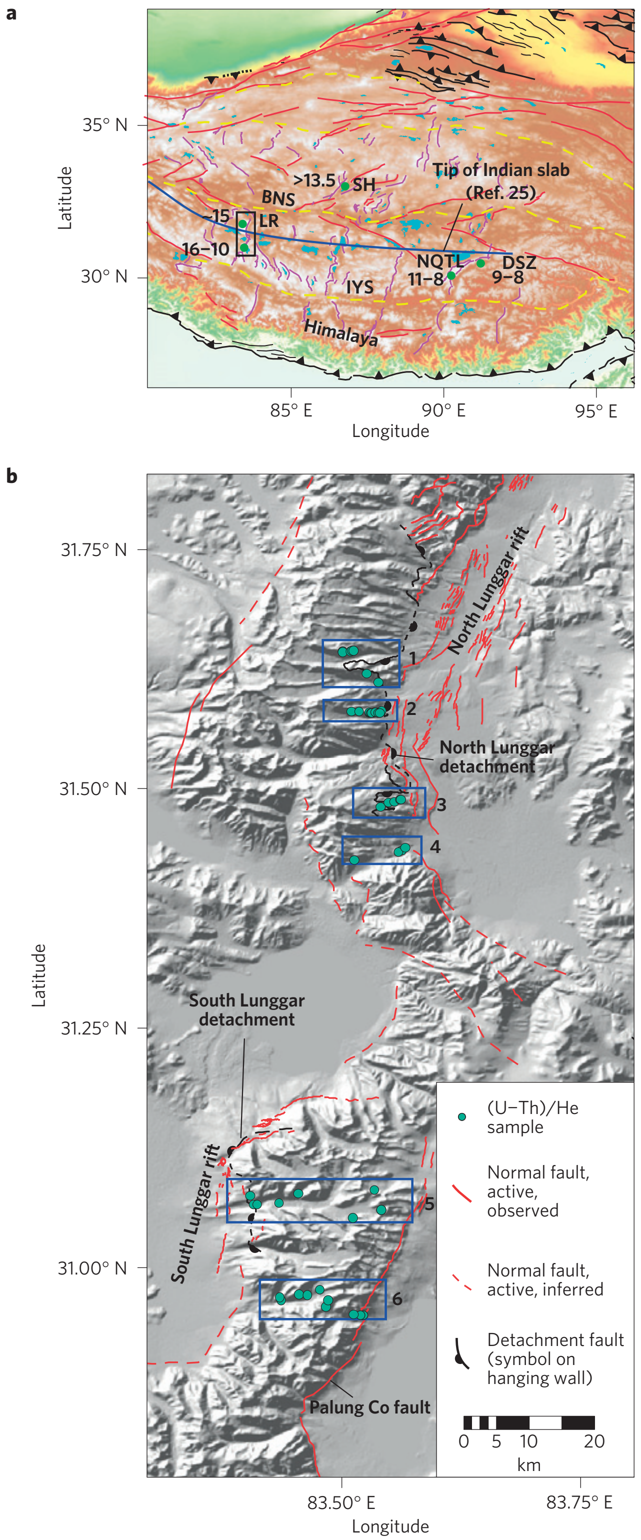

Figure 1 | Topography and active faulting in Tibet. a, Central Tibet, with thrust faults and folds (black) strike-slip faults (red), normal faults (magenta) and sutures (yellow). The green dots indicate the timing of initiation of rifts north of the Himalaya. The blue line indicates the modern northern tip of the underthrusting Indian slab[25]. Black box indicates the area shown in **b**. LR, Lunggar rift[9,11–13]. SH, Shuang Hu graben[8]. NQTL, Nyainqentanghla rift[7]. DSZ, Damxung shear zone[10]. BNS, Bangong-Nujiang suture zone. IYS, Indus-Yarlung suture zone. **b**, Topographic hillshade of the Lunggar rift showing active normal faults[9,11–13] and (U–Th)/He samples used in this study. Numbered blue boxes indicate sample transects.

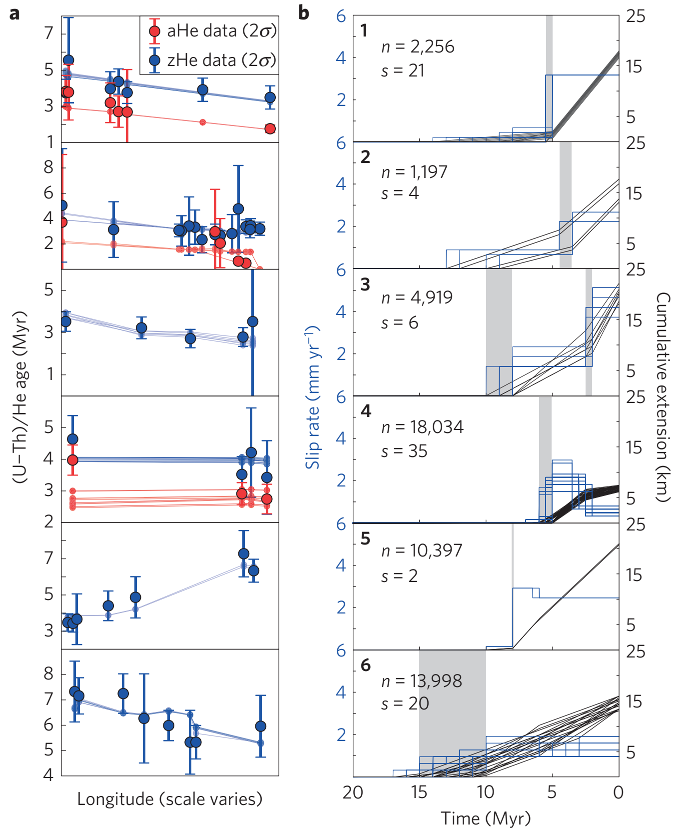

Figure 2 | Thermokinematic modelling results. a, Age–longitude plots of thermochronological data (large circles, with 2σ error bars) and model fits (small circles, with lines joining results from each model) for each model transect. See **b** for transect number and Fig. 1b for transect location. **b**, Plots of horizontal extension rate (blue lines, left *y*-axis) and cumulative extension (black lines, right *y*-axis) for each model transect. Numbers in bold indicate transect number. Grey boxes indicate onset of rapid extension. *n*, number of models run. *s*, number of 'successful' models.

Our model results show that extension began in the Miocene throughout the Lunggar rift (Fig. 2b), consistent with previous work on the structure and syn-extensional sedimentary basins in the rift[9,11,13]. Initial extension rates are low, with only one transect above 1 mm yr^{-1}. Consequently, cumulative extension during this phase of rifting is also low, below 5 km for four of the six transects and below 10 km for all. These timing results are similar to other estimates from the orogen, consistent with arguments that Tibetan extension began after a hypothesized orogen-wide event[2–5,20,21].

All modelled transects show strong evidence for an increase in extension rate in the late Miocene to Pliocene. Post-acceleration rates are ~1.5–5 mm yr^{-1} for all transects, substantially higher than the earlier rates. This acceleration, following slow extension, is required to fit the geologic constraints on extension initiation age[9,11,13] and magnitude[11,12] with the young observed cooling ages in the footwall. Rapid extension is ongoing at all transects but Transect 4, which is located in an accommodation zone between the two main rift segments. This faster rifting phase is responsible for the majority of the cumulative extension across the Lunggar rift.

Strikingly, the timing of rift acceleration youngs to the north. This is consistent with structural observations indicating less extension from Transect 5 northwards, and with (U–Th)/He cooling ages that generally young northwards, indicating more rapid exhumation. North of our transects, supracrustal rocks with Mesozoic cooling ages are exposed in the footwall[12], evincing <6 km exhumation. This rifting pattern resembles the predictions made by Indian

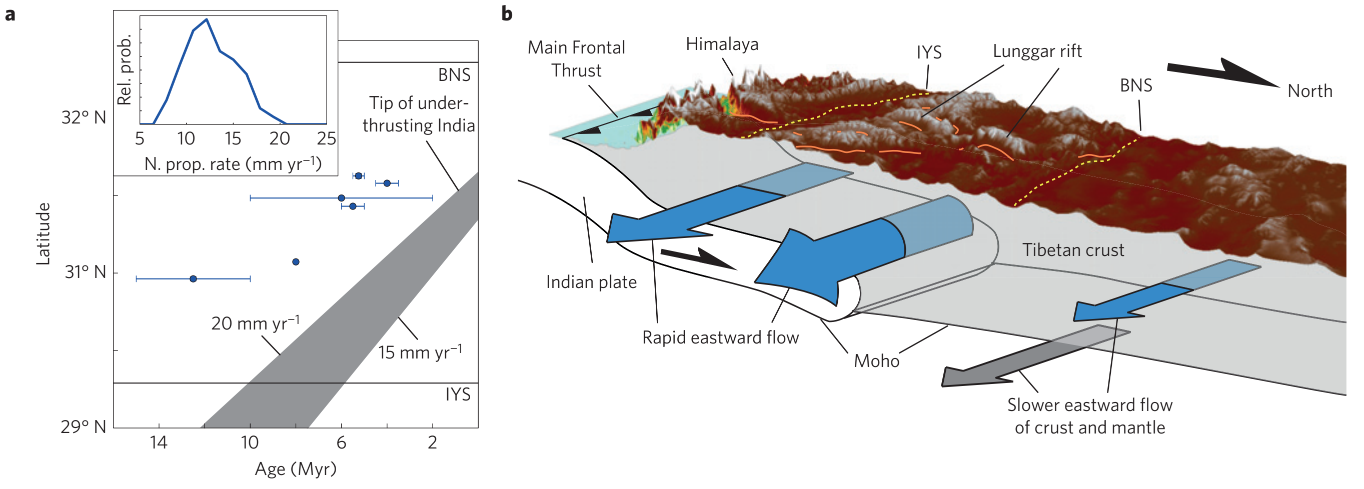

Figure 3 | Rift acceleration and Indian underthrusting. a, Age of rift acceleration versus longitude for all models (blue circles). Error bars indicate complete range. Grey polygon indicates the latitude of the northern tip of India through time. Inset shows the relative probability of northward propagation rate of rapid extension. **b**, Three-dimensional perspective view of topography and conceptual model of south-central Tibet in the Lunggar region. Rapid extension and crustal flow (blue arrows) occurs above and in front of the underthrusting Indian plate. Active normal faults in orange. IYS, Indus–Yarlung suture. BNS, Bangong–Nujiang suture.

underthrusting hypotheses, where the northern front of rifting migrates northwards with the Indian plate.

If rapid extension in the Lunggar rift is caused by the underthrusting Indian plate, we would expect that the northern front of rapid extension should sweep northwards with a rate and position similar to that of the tip of India (in the case of flat-slab subduction) or a northward-migrating hinge line (if subduction steepens northwards). The flat-slab subduction hypothesis predicts the northward sweep of extension to proceed at the rate of Indian underthrusting; the subduction hinge-line hypothesis predicts the sweep to migrate northwards more slowly than, and behind, the advancing tip of India. We test these hypotheses by calculating the northward progression of rapid extension in a Monte Carlo simulation where we iteratively fit 100,000 regression lines to samples drawn from the probability distributions for the age of onset of rapid extension from the thermokinematic modelling results. The slope of the line equals the rate of the northward sweep of extension. The simulation yields rates from 7 to 20 mm yr^{-1}, with a mode at ∼12 mm yr^{-1} (Fig. 3a). This compares well to Indian underthrusting rates (overthrusting minus convergence rates), estimated at ∼15 mm yr^{-1} based on geodetic and neotectonic studies[23,24]. The northern tip of India has been located under the North Lunggar rift[25], although no spatial uncertainty is given. We reconstruct its past location with an *ad hoc* uncertainty of 0.3° latitude (Fig. 3a), and observe that the onset of rapid extension sweeps northwards ahead of India by about 50 km. Because of the agreement among the rates of Indian underthrusting and this extensional 'sweep', our results support the hypothesis that flat-slab subduction of Indian crust drives rapid extension. They are less supportive of the hypothesis that extension tracks a subduction hinge line, which must lie to the south of the tip of the Indian plate; furthermore, seismic images of the Indian crust do not show steeply dipping subduction under southern Tibet[25].

These results elucidate the tectonic evolution of southern Tibet in a wider framework. The initial slow phase of rifting accounts for a small fraction of the total extension. If this phase was ongoing, the rift would have 5–10 km of extension over much of its length. This is similar to extension estimates for rifts in north-central Tibet[26], which show no evidence for accelerated rifting. Therefore, our results are consistent with theories in which extension begins in response to a significant orogen-wide event. Widespread middle Miocene magmatism and volcanism in the Lunggar rift[9,11,12] and elsewhere throughout southern Tibet[6,7,10], particularly volcanic rocks with upper mantle xenoliths indicating temperatures of ∼1,100 °C at 50–65 km depth[27], provide independent evidence of significant crustal heating, as would be expected following removal of the mantle lithosphere.

However, the majority of extension in the Lunggar rift is probably caused by the underthrusting of Indian crust beneath southern Tibet. This process thickens the crust at depth, displacing high-density upper mantle with low-density continental crust, which would typically lead to the uplift of southern Tibet, as has been suggested in the India-centric rifting hypotheses[6,14]. Early Miocene mantle xenoliths sourced from 5–20 km above the present Moho[27] indicate that significant crustal thickening has occurred since then. Similarly, seismic tomography illuminates an approximately 15-km-thick slab, plausibly Indian lower crust, at the base of the Tibetan crust[25]. But because Tibet was already extending, and therefore at its maximum possible elevation given the magnitude of horizontal compression, lower crustal thickening has to be balanced by upper and middle crustal thinning. Thinning is accommodated by normal faulting in the upper crust, and probably by distributed crustal flow in the middle to lower crust above the stronger Indian slab, given that highly extended areas in southern Tibet maintain the same crustal thickness as less extended regions[28], as well as evidence for eastward flow into southeast Tibet[29]. Displacement of 15 km of Tibetan asthenosphere by Indian lower crust would add up to approximately 10 MPa of vertical (buoyancy) stresses to the base of the Tibetan crust, given reasonable values for the densities of both[28]; integrated over the whole of southern Tibet, this is ample force to accelerate eastward crustal flow or directly load normal faults.

The similarities in rift morphology and published thermochronometric data between the Lunggar rift and other major south Tibetan rifts[6,7], compared to much smaller, scattered rifts to the north[26], suggests that southern Tibet has experienced a rapid late Miocene to Pliocene rift acceleration. Although Tibet is considered a textbook example of gravitational collapse (as indicated by the plateau-wide onset of rifting), the majority of extension in the plateau is not directly related to collapse but instead to the maintenance of its current elevation by shallow crustal thinning balancing deep crustal thickening. However, previous work focused on the onset of rifting has masked this conclusion. Our work considers the full history of rifting and unites both sets of hypotheses for east-directed extension of Tibet by showing that minor gravitational collapse precedes more significant rifting related to Indian underthrusting. Our work also shows that rapid, large-magnitude normal faulting does not necessarily indicate bulk crustal thinning, wholesale collapse, or other late- to post-orogenic processes, as is commonly inferred[1,2,5,18,19]; it may be instead a re-equilibration to changing (not waning) orogenic conditions.

Methods

The modelling strategy uses a two-stage inversion scheme following ref. 11, incorporating both geologic estimates of rift geometry, kinematics and extension magnitude, as well as thermal histories obtained from the apatite and zircon (U–Th)/He thermochronological data. The thermokinematic modelling is conducted using Pecube[30] and accounts for radiogenic heating, heat advection due to rock uplift, heat flux through both the Moho and the earth's surface, and structural complexities such as fault interaction, down-dip changes in fault geometry, and isostatic flexure of the rift flanks. See the Supplementary Methods for a full description of the model geometry and modelling strategy. All data used in the paper is published[11,12] and all code is publicly available online at https://github.com/cossatot/lunggar_thermochron.

Received 1 July 2014; accepted 28 November 2014; published online 12 January 2015; corrected online 20 January 2015

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Acknowledgements

We thank P. Kapp, A. McCallister, B. Horton, W. Woodruff and D. Liu for collaboration in the field, and D. Stockli and R. Kislitsyn for laboratory collaboration and assistance. We thank P. DeCelles and J-P. Avouac for reviews. This work was supported in part by the Tectonics Division of the National Science Foundation. We thank T. Becker for feedback on a previous version of the manuscript.

Author contributions

R.S. performed the thermal modelling. R.S. and K.S. created the data sets. All authors participated in field mapping, sample collection, conceptual model development and manuscript preparation.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.S.

Competing financial interests

The authors declare no competing financial interests.