Thermochronologic constraints on the slip history of the South Tibetan detachment system in the Everest region, southern Tibet

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24

25 **Abstract**

26 North-dipping, low-angle normal faults of the South Tibetan detachment system (STDS)
27 are tectonically important features of the Himalayan-Tibetan orogenic system. The STDS
28 is best exposed in the N-S-trending Rongbuk Valley in southern Tibet, where the primary
29 strand of the system – the Qomolangma detachment – can be traced down dip from the
30 summit of Everest for a distance of over 30 km. The metamorphic discontinuity across
31 this detachment implies a large net displacement, with previous studies suggesting >200
32 km of slip. Here we refine those estimates through thermal-kinematic modeling of new
33 (U-Th)/He and $^{40}\text{Ar}/^{39}\text{Ar}$ data from deformed footwall leucogranites. While previous
34 studies focused on the early ductile history of deformation along the detachment, our data
35 provide new insights regarding the brittle-ductile to brittle slip history. Thermal modeling
36 results generated with the program *QTQt* indicate rapid, monotonic cooling from
37 muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ closure (ca. 15.4 – 14.4 Ma at ca. 490°C) to zircon (U-Th)/He
38 closure (ca. 14.3 – 11.0 Ma at ca. 200°C), followed by slower cooling to apatite (U-
39 Th)/He closure at ca. 9 – 8 Ma (at ca. 70°C). Although previous work has suggested that
40 ductile slip on the detachment lasted only until ca. 15.6 Ma, thermal-kinematic modeling
41 of our new data suggests that rapid (ca. 3-4 km/Ma) tectonic exhumation by brittle-
42 ductile to brittle fault slip continued to at least ca. 13.0 Ma. Much lower modeled
43 exhumation rates (≤ 0.5 km/Ma) after ca. 13 Ma are interpreted to reflect erosional
44 denudation rather than tectonic exhumation. Projection of fault-related exhumation rates
45 backward through time suggests total slip of ca. 61 to 289 km on the Qomolangma

detachment, with slightly more than a third of that slip occurring under brittle-ductile to brittle conditions.

1. Introduction

Regional-scale, low-angle normal fault (‘detachment’) systems are common features of extensional tectonic regimes such as the Basin and Range province of the North American Cordillera, but similar features are also found in convergent settings and their significance has proved to be controversial. One of the most impressive confirmed structures of this type is the South Tibetan detachment system (STDS), which crops out near the crest of the Himalaya in Bhutan, India, and Nepal over a distance of well over 1000 km along strike [Burchfiel *et al.*, 1992; Hodges, 2000]. Some researchers have argued that normal-sense displacement along the STDS has been one of the defining structural events of Himalayan evolution, enabling the southward extrusion of a thick, mid-crustal channel, over distances of well over 100 km, during the Miocene [Nelson *et al.*, 1996; Beaumont *et al.*, 2001; Hodges *et al.*, 2001; Grujic *et al.*, 2002]. Others have instead argued that this structure is comparatively minor and was initiated simply as the upper bounding thrust fault of a tectonic wedge that subsequently accommodated at most a few tens of kilometers of normal-sense offset [Yin, 2006; Webb *et al.*, 2007; Webb, 2013].

One way to objectively evaluate these competing hypotheses is to establish robust constraints on the total normal-sense offset across the STDS. Here we report the results of a study designed to contribute to this effort through medium- and low-temperature thermochronometry and thermal-kinematic modeling of the results. Specifically, we

present new $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite (MsAr), (U-Th)/He zircon (ZrnHe), and (U-Th)/He apatite (ApHe) data for samples collected in the Rongbuk Valley, 28.063159°N 86.865197°E to 28.273212°N 86.805560°E, north of the Everest massif, in southern Tibet (Figure 1). In this region, the principal strand of the STDS is called the Qomolangma detachment [Burchfiel *et al.*, 1992]. Exposures of Qomolangma detachment footwall metamorphic and igneous rocks in this valley are among the best and most continuous examples discovered thus far in the orogen. As a consequence, there have been many detailed studies of the structural, metamorphic, and igneous processes that took place in these rocks during an early (ductile) phase of Qomolangma detachment displacement in the early to middle Miocene [Hodges *et al.*, 1992; 1998; Murphy and Harrison, 1999; Law *et al.*, 2004; 2011; Jessup *et al.*, 2006, 2008; Cottle *et al.*, 2015a; Corthouts *et al.*, 2016]. The goal of this study has been to build upon these efforts by examining the younger exhumation history of the detachment footwall during the waning stages of fault slip.

2. The South Tibetan Detachment System in Rongbuk Valley

The structural architecture of the Himalaya is a south-facing orogenic wedge that developed subsequent to the initial collision between Greater India and Eurasia at ~50-55 Ma [Najman *et al.*, 2010; van Hinsbergen *et al.*, 2012]. Its basic geology and structural development were reviewed by Hodges [2000], to which interested readers might turn for additional information. In the context of the wedge, the shallowly north-dipping STDS is an anomalous, topographically high structural feature, typically cropping out near the crest of the Himalaya and marking the top of the metamorphic core of the range. The core

92 – referred to here as the Greater Himalayan sequence (GHS) – includes high-grade
93 metasedimentary and metaigneous gneisses with lowermost Paleozoic-Neoproterozoic
94 protolith ages and Indian provenance [*Parrish and Hodges, 1996*]. In some places,
95 particularly at high structural levels, the intensity of Oligocene-Miocene amphibolite-
96 granulite facies metamorphism was such that anatexis melting occurred [*Le Fort, 1987*],
97 and mobilization of this melt led to the intrusion of leucogranitic bodies of a variety of
98 sizes [*Searle et al., 2010*]. In contrast, the STDS hanging wall comprises Cambrian and
99 younger, unmetamorphosed or weakly metamorphosed strata deposited along the thinned
100 northern continental margin of India prior to collision [*Gaetani and Garzanti, 1991*;
101 *Myrow et al., 2009*].

102 Hanging wall and footwall rocks of the STDS are spectacularly exposed in the
103 Rongbuk Valley of southern Tibet, which extends north from the foot of Mount Everest
104 for about 35 km before opening to the more subdued topography of the Dzaka Chu
105 drainage (Figure 1). Exposures of the STDS, while present on both the eastern and
106 western sides of the valley, are more obvious on the east [*Burchfiel et al., 1992*]. As part
107 of the first reconnaissance work on the STDS in the Rongbuk Valley in the mid-1980's,
108 Burchfiel and colleagues identified the principle strand of the detachment system as a
109 low-angle ($< 15^\circ$ NE) brittle fault that they named the Qomolangma detachment. In the
110 northern part of the valley, where it dips into the valley floor and is most accessible, the
111 Qomolangma detachment is marked by a zone of fault breccia and gouge several meters
112 thick and juxtaposes weakly metamorphosed to unmetamorphosed hanging wall rocks on
113 mylonitized amphibolite facies metamorphic rocks and leucogranitic dikes and sills.
114 Noting that descriptions of rocks making up the summit pyramid of Everest by *Yin and*

115 *Kuo*, [1978] suggested a similarity with rocks above the detachment in the northern
116 Rongbuk Valley, *Burchfiel et al.* [1992] postulated that the fault projected to the south
117 from the floor of the Rongbuk Valley, up dip, to the summit pyramid, a distance of
118 roughly 34 km. Subsequent work confirmed that the Qomolangma detachment is indeed
119 exposed on the north face of Everest at an elevation of ~ 8520 m [*Sakai et al.*, 2005]. In
120 the Rongbuk Valley exposures, the immediate hanging wall rocks are fossiliferous, silty
121 to relatively pure limestones of the Lower-Middle Ordovician Mt. Qomolangma
122 Formation [*Myrow et al.*, 2009], and similar lithologies dominate rock exposures on the
123 summit pyramid of Everest [*Searle et al.*, 2003; *Sakai et al.*, 2005; *Jessup et al.*, 2006;
124 *Corthouts et al.*, 2016]. Brecciated hanging wall rocks above the detachment are cut by
125 minor, high-angle, NNE-dipping normal faults that are truncated down dip by the
126 detachment, while footwall rocks in the brittlely deformed zone contain numerous shear
127 bands separating asymmetric boudins of footwall rocks [*Burchfiel et al.*, 1992; *Carosi et*
128 *al.*, 1998]. The asymmetry of these features indicates hanging wall-to-the-NNE brittle
129 displacement on the Qomolangma detachment.

130 Although hanging wall rocks display similar characteristics all along the roughly
131 displacement-parallel cross section of the Qomolangma detachment between Everest and
132 the northern end of Rongbuk Valley, the same is not true of the footwall. On Everest, the
133 immediate footwall of the Qomolangma detachment comprises marbles, as well as
134 calcareous metapsammites and metapelites, of the ‘Yellow Band’, a distinctive unit
135 frequently described in the mountaineering literature (Figure 1). The rocks of the Yellow
136 Band and underlying schists, metapsammites, and metaquartzites of the North Col
137 Formation – sometimes less formally referred to as the Everest Series – are part of a

coherent Cambrian stratigraphic sequence recognized along most of the length of the Himalaya [Myrow *et al.*, 2009]. The Mt. Qomolangma Formation and North Col Formation locally represent the structurally and stratigraphically lowest components of the succession often referred to throughout the Himalaya as the Tibetan sedimentary sequence [e.g., Hodges, 2000]. On Everest, the North Col Formation units overlay Precambrian high-grade metasedimentary units (pelitic, psammitic, and carbonaceous) that have been intruded by a complicated network of predominantly Miocene leucogranitic dikes, sills, and plutons [Yin and Kuo, 1978; Burchfiel *et al.*, 1992; Carosi *et al.*, 1998, 1999; Searle, 1999; Searle *et al.*, 2003]. Here as elsewhere in the Himalaya, these rocks are typically assigned to the Greater Himalayan tectonostratigraphic sequence [e.g., Hodges, 2000]. In this contribution, we follow the convention of Burchfiel *et al.* [1992] in referring to these rocks as exposed in the Rongbuk Valley collectively as an ‘injection complex’ (Figure 1).

Several authors [e.g., Lombardo *et al.*, 1993; Pognante and Benna, 1993; Carosi *et al.*, 1998, 1999; Searle, 1999] have interpreted the sharp, N-dipping contact at the base of the North Col Formation as a second, structurally deeper extensional shear zone. In the interpretation of Searle [1999], this inferred structure – which he referred to as the Lhotse detachment – is the basal strand of the South Tibetan detachment system in the Everest area, and the Qomolangma detachment is a hanging wall splay from it. However, the contact at the base of the North Col Formation has not been studied in detail on the Everest massif and has not been confirmed to have ductile or brittle fabrics along it that would support its interpretation as a detachment. Observations on the north side of Everest have shown that this contact – whatever its structural significance – dips

northward more shallowly than the Qomolangma detachment, such that the Qomolangma detachment cuts out the North Col Formation rocks entirely near the northern end of the Rongbuk Valley and places Mt. Qomolangma Formation carbonates directly on to the injection complex as mapped by *Burchfiel et al.* [1992], *Carosi et al.* [1998], and *Jessup et al.* [2008]. Although we follow *Searle* [1999] and *Jessup et al.* [2008] in showing exposures of the Lhotse detachment in the upper Rongbuk Valley on Figure 1 for the sake of consistency with earlier published maps, direct evidence for the existence of the Lhotse detachment has not been found in the Rongbuk Valley.

Wherever the structural geology of the North Col Formation or injection complex beneath the brittle Qomolangma detachment has been studied in the valley, both units display conspicuous mylonitic fabrics up to at least 1000 m-thick [*Carosi et al.*, 1998]; these fabrics are universally interpreted as having developed as a consequence of STDS extensional displacement (Figure 3). They include well-developed mineral and stretching lineations and S-C fabrics indicative of a significant component of top-to-the-NNE simple shear deformation [*Burchfiel et al.*, 1992], although subsequent, more detailed studies have shown that these rocks were deformed through general shear during tectonic denudation related to slip on the STDS [*Law et al.*, 2004; *Jessup et al.*, 2006]. *Law et al.* [2011] presented the results of a detailed study of microstructures and quartz c-axis fabrics in which they inferred a substantial, extension-related telescoping of isotherms in the footwall based on quartz fabric opening angles.

Of particular significance for interpreting the thermochronologic data presented below, *Law et al.* [2011] estimated a deformation temperature of 625 ± 50 °C for one mylonitized sample collected ~ 420 m beneath the detachment near the mouth of

Hermit's Gorge (Figure 1). This is the same locality where a sillimanite-grade pelitic schist sample was collected that has yielded the only published quantitative pressure and temperature estimates for Qomolangma detachment footwall rocks in the Rongbuk Valley [Hodges *et al.*, 1992] based on major element partitioning thermobarometry: ca. 630°C and 460 MPa. Collectively, these data suggest that the mylonitic fabrics found beneath the Qomolangma detachment near Hermit's Gorge developed at paleodepths of roughly 17 km [Hodges *et al.*, 1992].

The initiation age and duration of slip on the Qomolangma detachment in the Everest region are actively debated. Most estimates are based on (U-Th)/Pb dates obtained for accessory minerals in the leucogranites of the injection complex, which exhibit field relationships suggesting that their intrusions into the detachment footwall occurred before, during, and after the development of mylonitic fabrics [Copeland *et al.*, 1988; Hodges *et al.*, 1992; 1998; Murphy and Harrison, 1999; Cottle *et al.*, 2007; 2015b]. Unfortunately, obtaining easily interpretable ages for these leucogranites based on their accessory mineral (U-Th)/Pb systematics has proven extremely difficult. These leucogranites are products of local anatexis of the Greater Himalayan sequence, and many contain accessory minerals, inherited from their proximal sources that are only a few million years older. Published dates range from ca. 20 Ma to ca. 15 Ma, with the most dominant population ranging from 16.8 ± 0.8 to 16.4 ± 0.1 Ma [Hodges *et al.*, 1998; Murphy and Harrison, 1999; Cottle *et al.*, 2015b]. (Note that throughout this contribution, we cite geochronologic and thermochronologic uncertainties at 2σ .) A second important population of leucogranites, some of which contain mylonitic fabrics and some of which are undeformed and cut the mylonitic fabrics at high angles, yields

dates from 15.6 ± 0.1 to 15.3 ± 0.1 Ma, which *Cottle et al.* [2015b] interpreted as indicating that cessation of ductile deformational activity on the STDS in the Rongbuk Valley occurred before 15.6 Ma. However, none of these young granites obviously crosscut the brittle Qomolangma detachment, leaving open the possibility of significant brittle displacement on the detachment after intrusion of the youngest of this population of granites.

3. Exploring the Late-Stage Slip History of the Qomolangma Detachment

The juxtaposition of unmetamorphosed and weakly metamorphosed hanging wall rocks and amphibolite facies footwall rocks across the Qomolangma detachment suggests that the total displacement across the structure is much greater than the minimum of ~ 34 km required by the total hanging wall-footwall overlap observed in cross section [Burchfiel *et al.*, 1992]. The stratigraphic level of the Mt. Qomolangma Formation exposed in the immediate hanging wall of the detachment is essentially the same on Everest and at the northernmost outcrops of the detachment in the Rongbuk Valley. Similarly, although the detachment does cut out the North Col Formation down dip, prograde metamorphic pressures and temperatures of the detachment footwall constrained by thermobarometry are similar on Everest and at the mouth of Hermit's Gorge, roughly 18 km to the north [Figure 1; Hodges *et al.*, 1992; Jessup *et al.*, 2008]. Such observations demonstrate that the detachment occupies approximately the same structural level in both the hanging wall and footwall wherever it is exposed. Coupled with the present-day low ($\leq 15^\circ$) dip of the detachment, this means that the structure has not been appreciably rotated since its development (Figure 2). Thus, the net displacement

on the structure can be estimated from trigonometry from its current dip and its tectonostratigraphic throw, the latter of which is calculated using the amount of vertical exhumation of the footwall during detachment slip.

One example of such an estimate was obtained by *Searle et al.* [2003], who calculated total slip amounts between 90 and 216 km (depending on different assumptions for the regional dip on the detachment: 10° and 5°, respectively) based on thermobarometrically constrained metamorphic depths of the footwall rocks. Subsequently, *Law et al.* [2011] estimated slip of between 25 and 170 km using particle path models based on the apparent telescoping of synkinematic isotherms during ductile deformation. As noted by *Law et al.* [2011], the latter set of estimates largely refer to the portion of offset accommodated by ductile deformation, whereas the higher values estimated by *Searle et al.* [2003] refer to the total offset and include both ductile and brittle deformation. An important goal of our low-temperature thermochronometric work has been to determine to what extent the differences between these estimates might be explained by transitional ductile-brittle and brittle faulting along the Qomolangma detachment.

3.1. Research Strategy

One of the most effective ways to explore the thermal history of an orogenic environment is the application of isotopic thermochronometers to a single sample or a single structural horizon. Many lithologies from the Qomolangma footwall are amenable to such studies, particularly the leucogranites, which contain a wide variety of major and accessory minerals. For this study, we collected eight deformed and undeformed

leucogranite samples along a transect east of, and just above, the valley floor, over a distance of ~ 8.7 km roughly parallel to the dip direction of the Qomolangma detachment (Figure 2). The southernmost sample (R01), collected near the mouth of Hermit's Gorge (Figures 1 and 2), is from an outcrop roughly 800 m beneath the projection of the Qomolangma detachment, whereas the northernmost sample (R08) is from roughly 300 m beneath the fault. Our strategy was to determine dates for the MsAr, ZrnHe, and ApHe thermochronometric systems, which have nominal closure temperatures (assuming a cooling rate of 10°C/Ma) of ca. 490°C [Harrison *et al.*, 2009], ca. 170°C [Reiners *et al.*, 2004], and 70°C [Farley, 2000] respectively. We then used this information to constrain the cooling and exhumation history of the detachment footwall. We were particularly interested in whether or not we would find down-dip variations in the dating results because such variations have been found in thermochronologic datasets from detachment footwalls in other tectonic settings [e.g., John and Foster, 1993; Stockli *et al.*, 2001; Brady, 2002; Brichau, 2004; Stockli, 2005; Evans *et al.*, 2015]. For our highest-temperature thermochronometer, we chose MsAr because the nominal closure temperature range for this chronometer overlaps with the low end of the 680-480°C range of deformation temperatures estimated for the Rongbuk mylonites by Law *et al.* [2011] based on quartz fabric opening angles. Collectively, the Law *et al.* [2011] dataset implies that our MsAr closure dates might roughly reflect the timing of the waning stages of ductile deformation. Lower-temperature ZrnHe and ApHe thermochronometers were anticipated to provide constraints on the thermal and kinematic evolution of these rocks subsequent to the cessation of ductile deformation. Unfortunately, when the mineral separates for all samples were examined, most were found to contain only very small (60

µm) apatites with abundant inclusions, which were thus not suitable for ApHe dating due to concerns regarding the large alpha ejection corrections needed for such small grain sizes [Farley *et al.*, 1996] and the effects of inclusions on the (U-Th)/He systematics [Vermeesch *et al.*, 2007]. As a consequence, we dated muscovite and zircon from all eight samples, but apatite from only two samples, R01 and R02. $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th)/He analyses were performed at the Group 18 Laboratories at Arizona State University using procedures outlined in the Supplementary Materials.

4. Thermochronology Results and Age Interpretations

Muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ laser step-heating age spectra data for the Rongbuk samples can be found in Figures 4 and A1 and Table A1. All samples exhibited uncomplicated behavior and yielded statistically defined plateau dates ranging from 15.420 ± 0.050 Ma (R04) to 14.400 ± 0.060 (R05) Ma. There is no obvious correlation between the MsAr cooling age of a sample and the latitude at which it was collected or its structural distance below the detachment (Table 1).

As noted in the Supplementary Materials (Tables A2 and A3), several of our samples yielded (U-Th)/He zircon and apatite age datasets that are ‘over-dispersed’, meaning that their dispersion is greater than would be expected from analytical imprecision alone. For example, only two samples (R04 and R08) yielded inverse-variance weighted mean ZrnHe dates that are not overdispersed (Table 1 and Table A2). The remainder of the samples yielded over-dispersed (U-Th)/He results as defined by the mean squared weighted deviation (MSWD) of each dataset [Wendt and Carl, 1991]. For those datasets, we tried to identify obvious outliers using the Hampel identifier method

with a threshold value of four [Pearson, 2011], but unfortunately, no outliers were identified. As a consequence, we conservatively report uncertainties for the ZrnHe inverse-variance weighted mean dates of the six over-dispersed datasets using twice the standard deviation of the population of ZrnHe dates for the sample (Table 1 and A2). The complete set of ZrnHe mean dates range from 14.32 ± 0.28 Ma (sample R04) to 11.0 ± 1.1 Ma for sample R06. We noted no correlation between individual ZrnHe dates and effective uranium (eU) values [Guenther *et al.*, 2013], calculated from the U and Th concentrations for the dated grains as $eU = 0.235[Th] + [U]$, where the brackets indicate mass concentrations. Inasmuch as such values are sometimes used as a proxy for radiation damage [Guenther *et al.*, 2013], we see no evidence that radiation damage played a major role in the dispersion of observed ZrnHe dates. As was the case for the MsAr dates from the same samples, the ZrnHe dates show no clear pattern geographically or with structural depth (Table 1).

Apatite (U-Th)/He dates for samples R01 and R02 are summarized in Table 1 and presented in detail in Table A3. For sample R01, one ApHe date (4.09 ± 0.26 Ma) was identified as an outlier by the Hampel identifier method and remaining six dates ranged from 10.99 ± 0.34 Ma to 7.38 ± 0.42 Ma. Even after removal of the 4.09 Ma outlier date, the remaining R01 sample dates were still over-dispersed, with an inverse-variance weighted mean date of 9.3 ± 2.8 Ma, with the 2σ uncertainty again reported as twice the standard deviation of the population distribution. Only three datable apatite crystals were found in sample R02, and one of them – with an apparent age of 11.96 ± 0.62 Ma – was identified as an outlier using the Hampel identifier method. The other two yielded a mean ApHe date of 7.76 ± 0.52 Ma, younger than, but statistically indistinguishable from, the

mean ApHe date for sample R01. If the apparent outlier is not excluded, the inverse-variance weighted mean date for all three R02 apatites would be 9.5 ± 5.0 Ma. For both R01 and R02, the ApHe dates are predictably younger than the ZrnHe dates.

We interpret the MsAr, ZrnHe, and ApHe dates (Table 1) as indicative of the ages of cooling of the samples through nominal closure conditions for the applied thermochronometers. Our new MsAr data indicate that the temperature of the Qomolangma detachment footwall did not cool below amphibolite facies temperatures until after at least 15.420 ± 0.050 Ma, consistent with the interpretation of *Cottle et al.* [2015b], based on U/Pb monazite ages of different generations of leucogranites, that ductile activity on the Qomolangma detachment, recorded by its high-temperature footwall mylonites, was largely over by ca. 15.6 Ma. There are two previously published $^{40}\text{Ar}/^{39}\text{Ar}$ mica dates for a sample collected in 1986 from the approximate location of our sample R05, which yielded a MsAr plateau date of 16.56 ± 0.23 Ma and a biotite plateau date of 16.51 ± 0.30 Ma [*Hodges et al.*, 1998]. The inconsistency of these previous results with our new data – as well as the *Cottle et al.* [2015b] inference regarding the cooling history – is interpreted as a reflection of the much higher analytical precision of the new MsAr data, and the fact that the *Hodges et al.* [1998] data were obtained for large, multigrain aliquots rather than single mica crystals.

5. Reconstructions of the Thermal and Exhumation History of the Qomolangma Detachment Footwall

We present here the results of two different, but complimentary, approaches to modeling the thermal and thermal-kinematic history of the Qomolangma detachment

footwall during its exhumation, and we use the results to infer the late-stage slip history of the structure.

5.1. Temperature-Time Trajectories from QTQt Modeling

Many recent attempts to model time-temperature histories of rocks from thermochronologic data have taken advantage of one of two, freely available software packages: *HeFTy* [Ketcham, 2005] and *QTQt* [Gallagher, 2012]. Here we apply the *QTQt* software because of its capacity to simulate the three mineral-isotopic systems measured in the Rongbuk Valley samples.

Employing a Bayesian transdimensional Markov chain Monte Carlo (MCMC) inversion scheme, *QTQt* constrains a set of best-fit temperature-time paths given a posterior probability distribution [Gallagher, 2012]. Essential input parameters for models using this program are diffusion parameters for the mineral-isotopic systems, diffusion domain sizes, diffusion geometry, apparent ages, and uncertainties in these apparent ages.

We assumed diffusion parameters for MsAr as determined by *Harrison et al.* [2009] for MsAr and corrected to a pressure of 500 MPa, which is within uncertainty of the thermobarometrically estimated pressure for amphibolite facies metamorphism in the Rongbuk Valley as determined by *Hodges et al.* [1992]. We employed the diffusion parameters of *Reiners et al.* [2004] for ZrnHe and *Farley* [2000] for ApHe. We made no attempt to adjust these helium diffusion parameters to account for radiation damage as suggested by *Shuster et al.* [2006], *Flowers et al.* [2009], and *Guenther et al.* [2013] for two reasons. First, as noted above, there is no clear correlation between eU and apparent

age for our sample set. Second, these samples experienced amphibolite facies metamorphism in the Miocene, only a few million years prior to ZrnHe and ApHe closure. That metamorphism was of sufficiently high grade to have effectively annealed any pre-Miocene radiation damage, such that we would expect any radiation damage accumulated between metamorphism and ZrnHe and ApHe closure to be negligible. We assumed a spherical geometry for He and Ar diffusion, consistent with the experimental interpretations of *Farley* [2000], *Harrison et al.* [2009], and *Reiners et al.* [2004] of their experimental results. We then calculated equivalent spherical radii from grain sizes using the equations of *Reiners and Brandon* [2006]. Our sieved muscovite grains had a mean equivalent spherical radius of 375 μm ; for zircon and apatite, we used the average of the spherical radii for all the crystals in each sample (Tables A2 and A3) for *QTQt* modeling purposes.

QTQt also requires the input of certain characteristics of the inversion search protocol (usually determined by trial-and-error, as outlined by *Gallagher*, 2012), and it permits the specification of certain temperature-time constraints to narrow the search space. For our models, we specified that the modeled cooling trajectories pass through: 1) the 17-15 Ma time window at temperatures between 750 and 550°C; and 2) the 0.38-0.28 Ma time window at temperatures between 10 and 0°C. The first specification reflects the presumption that these samples had temperatures near that of the muscovite- or biotite-dehydration melting reactions at ca. 500 MPa [*Le Breton and Thompson*, 1988; *Patiño-Douce and Harris*, 1998] in the age range of most leucogranites in the injection complex. The second reflects the requirement that these samples had to be at the surface by at least the time of deposition of the oldest known glacial deposits in the valley [*Owen et al.*,

2009]. All models represent 20,000 iterations: 10,000 used to stabilize or ‘burn-in’ the inversion process, and the second 10,000 used for the inversion itself; see *Gallagher*, 2012). Exploratory runs using larger numbers did not appreciably change model outcomes.

The resulting models for samples R01 and R02 (which include ApHe constraints) are presented in Figure 5, along with the models for R05 and R08 to illustrate results for samples for which ApHe are unavailable; the figures for all other samples may be found in the Supplementary Materials Figure A2. In the figures, we illustrate the expected model from *QTQt* (the weighted mean of all best-fitting thermal histories) as well as the 95% credible confidence intervals for that model.

Overall, this modeling exercise suggests that the thermochronologic data for the Rongbuk Valley imply a simple, monotonic cooling history, with a progressive decrease in cooling rate since ductile deformation on the Qomolangma detachment. Specifically, they indicate rapid cooling from ambient temperatures of ca. 500°C at ca. 15.4 to 14.4 Ma to ca. 170°C by no later than ca. 12 Ma. Although the model output for sample R01 suggests that it cooled less rapidly compared to the other samples, we note that the uncertainties of the ZrnHe dates for this sample are large, which permits greater variability in possible cooling trajectories. The output for this sample still shows rapid cooling from ca. 15 to 13 Ma followed by cooling to ca. 70°C by ca. 9 Ma, similar to R02.

5.2. Exhumation Rates Through Time from Thermal-Kinematic Modeling

Calculation of transient exhumation histories that could produce the previous thermal histories is best done through thermal-kinematic modeling in which the advection-diffusion equation is solved for a range of temporally varying exhumation rates. For this we use a modified version of the *Pecube* software originally presented by Braun, [2003] and Braun *et al.*, [2012]. The modified version used here [Thiede and Ehlers, 2013; Adams *et al.*, 2015] assumes one-dimensional heat transport (from depth toward Earth's surface, by both advection and conduction) and applies a smart-search Monte Carlo method to identify the range of all possible exhumation rates that could produce the observed cooling ages. Modeling parameters for our study follow those used by Thiede and Ehlers [2013] and Adams *et al.*, [2015]; see the Supplementary Materials for details.

Because many published applications of *Pecube* to problems in tectonics and landscape evolution employ two- or three-dimensional heat transport, our choice to use the 1D approach of Thiede and Ehlers [2013] merits further explanation. While large-displacement normal faulting on moderately to steeply dipping structures can lead to significant lateral heat advection [Ruppel *et al.*, 1988; Campani *et al.*, 2010; Braun *et al.*, 2012], which might be an argument for our using at least a 2D model, these effects are actually minor for extremely low-angle structures like the Qomolangma detachment. For example, we can compare the nearly uniform ZrnHe dates obtained along the Rongbuk Valley transect with ZrnHe dates for samples collected over a similar distance along a dip-parallel transect beneath the more steeply dipping Snake Range detachment in Nevada [Evans *et al.*, 2015]. Those authors reported that ZrnHe apparent ages decreased from ca. 41 Ma to ca. 21 Ma in the dip direction of dip, roughly a factor of two. Had there

436 been considerable lateral heat advection during slip on the Qomolangma detachment
437 faulting, we likely would have detected evidence for it in the form of a progressive
438 younging of closure ages. In addition, previous work comparing the outcomes of 1D and
439 3D thermal-kinematic models suggest that rapid exhumation regardless of mechanism
440 largely results in a vertical compression of isotherms and an essentially 1D thermal field
441 at the shallow depths where ZrnHe and ApHe chronometers pass through their partial
442 retention zones; compare, for example, 1D, 2D, and 3D modelling results reported by
443 *Thiede and Ehlers* [2013]. Concerns regarding the suitability of 1D techniques for
444 thermal-kinematic modeling of thermochronologic data are generally more valid for
445 regions that experience low (<1 mm/a) exhumation rates, where lateral heat advection
446 rates due to faulting may exceed vertical heat advection rates, especially for higher
447 temperature chronometers like MsAr, as noted by *Thiede and Ehlers* [2013]. As we show
448 below, modeled exhumation rates for the Rongbuk samples at the time of MsAr closure
449 are much higher. Due to its relative computational simplicity, a 1D version of Pecube
450 modeling has an important advantage of over multidimensional modeling: it permits the
451 rapid testing of hundreds of thousands of theoretical exhumation histories for
452 compatibility with observed cooling ages with relative computational ease and speed.

453 Our thermal-kinematic models for the Rongbuk samples show two general types
454 of behavior (Figures 6 and A3). Models for six of the eight samples indicate high
455 exhumation rates (≥ 3.5 mm/a) persisting to as recently as 14.0-13.0 Ma and a rapid
456 decrease in exhumation rate to ≤ 0.5 mm/a thereafter. Models for two samples (R01 and
457 R06) also show a factor of two or more decrease in exhumation rate at 13.0 Ma, but

indicate moderate (ca. 1.0-1.5 mm/a) exhumation rates from 13.0 to 8.0 Ma that then decrease to ≤ 0.5 mm/a thereafter.

6. Tectonic Interpretations

The MsAr dates reported here indicate that the Qomolangma detachment footwall exposed in Rongbuk Valley maintained relatively high temperatures (ca. 450-500 °C) well after 15.6 Ma, the timing of the end of ductile activity on the structure as inferred from U/Pb monazite dates of *Cottle et al.* [2015b]. Our thermal models indicate rapid cooling (ca. 262 - 72°C/Ma) of the footwall commencing after MsAr closure at 15.420 ± 0.050 to 14.40 ± 0.060 Ma (Figures 5 and A2). The thermal-kinematic models imply that this cooling was accompanied by exhumation at rates of ca. 3-4 mm/a prior to ca. 13.0 Ma (Figures 6 and A3). Those rates are a factor of 3 higher than erosional exhumation rates during that same period as deduced from thermochronological data for the southern flank of the Himalaya [e.g., *Thiede and Ehlers*, 2013]. It is improbable that the high 3 – 4 mm/a exhumation rates implied by our data reflect high precipitation-driven erosion, given that Mount Everest was near its present-day elevation in the Miocene, with the southern Tibetan Plateau likely already established and the current monsoonal precipitation pattern probably in place by 15.4-13.0 Ma [*Coleman and Hodges*, 1995; *Blisniuk et al.*, 2001; *Spicer et al.*, 2003; *Harris*, 2006; *Clift et al.*, 2008; *Gébelin et al.*, 2013]. As a consequence, we might expect dryer, rather than wetter, conditions to have prevailed north of the Himalayan crest where our samples under study would have been at the time. We interpret the high modeled exhumation rates prior to ca. 13 Ma to be related to rapid slip on the Qomolangma detachment.

Our thermal-kinematic models further suggest that this early period of very rapid tectonic denudation ended at ca. 13 Ma. Modeling of two of our eight samples (R01 and R06) indicate at least a factor of two lowering of the exhumation rates from ca. 2.2-3.4 mm/a to 1.0-1.2 mm/a at this time, and the other six samples indicate an even higher (order of magnitude) decrease from 1.5-4 mm/a to <0.5 mm/a (Figures 6 and A3). The most reasonable interpretation of this behavior is that slip on the Qomolangma detachment effectively terminated or drastically slowed at ca. 13 Ma (within the ± 1 Ma resolution of our models). By no later than 8 Ma, the exhumation rate of ca. <1 mm/a, indicated by our models was sufficiently low to be explained exclusively by erosional denudation similar to that currently operating on the Tibetan Plateau [e.g., *Rades et al.*, 2015; *Strobl et al.*, 2012].

6.1. Fault displacement estimations based on exhumation

Our thermal-kinematic modeling results inform a reconstruction of Qomolangma detachment footwall exhumation since the inferred cessation of ductile deformation at ca. 15.6 Ma. This reconstruction, along with a little simple trigonometry, permits an estimation of the displacement history of the fault.

For these calculations, we assumed that total exhumation was constant during each of the time steps shown in Figures 6 and A3. For example, we assumed that the total exhumation between 15.6 Ma and 15.0 Ma for sample R01 was 2.0 km based on the ca. 3 – 4 mm/a exhumation rate estimated by our 1D thermo-kinematic model for this interval. From 15.0 to 14.0 Ma, a comparable calculation indicated an additional 2.8 km of exhumation. Continuing this process for all of the modeled increments from 15.6 through

the 13.0 Ma interval indicated 7.7 km of cumulative exhumation. Modeled cumulative exhumation for the other seven samples ranged from 10.4 km for R05 to 6.3 km for R03 and the average for all eight samples is 8.3 km.

Given that we have no indication that the Qomolangma detachment has rotated significantly since it was active, or that its dip changes significantly between the summit pyramid of Everest and the north end of Rongbuk Valley where it disappears between the valley floor (over 30 km down dip), we estimate displacement values using a simple geometrical model: $\text{displacement} = \text{exhumation} / (\sin \alpha)$, where α is fault dip (Figure 2). The detachment surface is not easily accessible for direct measurement in Rongbuk Valley, so its regional dip – between 5 and 10° – is estimated from its intersection with topography along the valley (Figure 1; Figure 2). Figure 7 illustrates detachment displacement histories over the 15.6 to 13.0 Ma time period as calculated from our exhumation histories (based on the alternative assumptions of a 5° or 10° dip) for the two samples with the most complete thermochronologic datasets (R01 and R02). By the cessation of fault slip (presumed to be ca. 13.0 Ma), data from both samples indicate a consistent 44 ± 11 km of slip assuming a 10° dip. If the dip is assumed to be 5°, the amount of slip doubles to 88 ± 22 km. (In both cases, uncertainties reflect the cumulative effects of propagating the 2σ uncertainties in the *Pecube* models for successive time steps.) Calculations for all eight samples yielded average 10° fault slip estimates ranging from 60 ± 8 km (R05) to 36 ± 11 km (R03). For an assumed 5° dip, the range was from 119 ± 17 km to 72 ± 22 km.

The modeling results are most consistent with the cessation of slip by ca. 13.0 Ma, but we cannot completely rule out an alternative interpretation: that minor slip may

have persisted into the 13.0-8.0 Ma timeframe. Unfortunately, the lack of apatite crystals suitable for ApHe thermochronology in most samples precluded our examining this possibility in more detail. Smaller step thermal-kinematic modeling increments between 13.0 and 8.0 Ma would not have yielded robust results given the lack of quantitative constraints on temperature-time paths. The dotted lines in Figure 7 show modeled projections of the slip history for our R01 and R02 samples if we assume that detachment activity continued until 8.0 Ma. Of all the models, sample R01 would imply the most total slip in this case: 78 ± 21 km (for $\alpha = 10^\circ$) or 156 ± 42 km (for $\alpha = 5^\circ$).

7. Discussion

7.1 Comparisons with previous work

On the same timeframe as – but independent of – our thermochronologic work in the Rongbuk Valley, another team [Orme *et al.*, 2015; Carrapa *et al.*, 2016] also conducted low-temperature thermochronologic studies in the Rongbuk Valley. They reported ZrnHe, ApHe, and apatite fission-track (ApFT) dates for seven different bedrock samples (mostly leucogranites) from outcrops close to the collection localities for our samples. While providing more detailed insights, our analytical results and modeling generally support the interpretation of the other team that the injection complex cooled rapidly during the middle Miocene [Carrapa *et al.*, 2016]. However, neither our new data nor the monazite U/Pb data of Cottle *et al.* [2015b] are consistent with the contention of Orme *et al.* [2015] that the footwall of the Qomolangma detachment has not experienced temperatures greater than the nominal ApFT closure temperature (ca. 110-120°C; [Reiners and Brandon, 2006]) since 16 Ma.

The ApFT results in *Carrapa et al.* [2016] are particularly challenging to interpret in a robust way. In theory, the ApFT chronometer should provide constraints on the timeframe of cooling of a sample through the partial annealing zone for apatite; a nominal closure temperature range for ApFT assuming a cooling rate of 10°C/Ma is ca. 100-120°C [Reiners and Brandon, 2006]. The Rongbuk ApFT dates reported by *Carrapa et al.* [2016] were significantly over-dispersed in individual samples, and showed a sample-to-sample range of weighted mean dates from 12.7 ± 3.0 Ma to 15.6 ± 5.6 Ma, with a mean for all samples of 14.8 ± 6.4 Ma (uncertainties reported at the 2σ level). Some of the ApFT dates seem impossibly old, approaching or exceeding the U/Pb crystallization ages of leucogranite dikes in these collection outcrops [Cottle *et al.*, 2015b]. Five of the seven samples yielded mean ApFT dates as old or older than the MsAr dates reported here, even though the closure temperature range for MsAr is several hundred degrees higher than that for ApFT. Given that the ApFT dates reported by *Carrapa et al.* [2016] have low precision and are highly over-dispersed regardless, they do not provide very useful constraints on the thermal history of Rongbuk Valley.

Analyzing their zircons using methods essentially identical to ours, including the assumption of homogeneous U+Th in the crystals, *Orme et al.* [2015] obtained 25 single-crystal ZrnHe dates ranging from 14.70 ± 0.46 Ma to 9.87 ± 0.29 Ma, with all but two dates between ca. 12.8 and 9.9 Ma. Noting that *Sakai et al.* [2005] obtained 14-15 Ma ApFT and zircon fission track (ZrnFT) dates for a sample collected beneath the Qomolangma detachment near the summit of Everest and likely mindful of the team's own ApFT data from the Rongbuk Valley that would be published in *Carrapa et al.* [2016], *Orme et al.* [2015] questioned the reliability of their own ZrnHe dates since the

closure temperature for the ZrnHe chronometer is higher than that of the ApFT
chronometer. *Orme et al.* [2015] also presented laser ablation ICPMS depth profiling data
for five of their dated crystals, showing evidence for significant U and Th zonation, often
featuring rims highly enriched in uranium. This sort of zoning, if not recognized and
properly accounted for during the data reduction procedure, can result in improper alpha
ejection corrections leading to substantial underestimates of the true ZrnHe ages
[*Hourigan et al.*, 2005]. However, U-Th zoning in zircon is typically complex in three
dimensions and can vary widely among zircons from the same sample [*Corfu et al.*,
2003]. This is why most (U-Th)/He researchers, without *a priori* comprehensive
knowledge of zoning in a zircon, choose the simplifying assumption that the U-Th
element distribution is homogeneous within the crystal as they correct raw (U-Th)/He
zircon dates for alpha-particle ejection [*Farley et al.*, 1996]. Given their knowledge of
zoning in at least one dimension at one place beneath the rims of the five profiled zircons,
Orme et al. [2015] attempted a correction of their original ZrnHe dates for the five
crystals, obtaining new estimates ranging from 17.00 ± 0.36 to 14.82 ± 0.31 Ma. These
corrections assumed that the single 1D profiles they obtained for each crystal could be
extrapolated concentrically around the zircon.

As noted by *Orme et al.* [2015] and *Bargnesi et al.* [2016], such a correction
exercise is not an exact science. Some knowledge of the magnitude of chemical zoning,
such as that obtained by one-dimensional depth profiling measurements of U and Th, can
provide useful information regarding the likelihood that the homogeneity assumption
yields alpha ejection corrections that are too large or too small, but quantitative
adjustments based on such data can be misleading. In the case of the samples analyzed by

Orme *et al.* [2015], it appears that the correction procedure used led to an over-correction of most or all of their ZrnHe dates. All of their corrected ZrnHe dates are as old as or older than our MsAr dates for the same structural horizons, which is inconsistent with published kinetic data indicating that the MsAr chronometer has a much higher nominal closure temperature than the ZrnHe thermochronometer. Our ZrnHe analytical procedures, like those used by Orme *et al.*, [2015] for most of their samples, did not permit evaluation of parent element zoning, but we note that our dates are generally older than original dates obtained by Orme *et al.* [2015] (assuming parent element homogeneity), while still being appropriately younger than MsAr dates for the same samples.

In contrast to the low-temperature thermochronometry results published by Orme *et al.* [2015] and Carrapa *et al.* [2016], our ZrnHe and ApHe dates are appropriately younger than the higher-precision MsAr dates obtained for Rongbuk Valley samples. Moreover, our thermochronologic dataset is consistent with previously published data indicating that amphibolite facies metamorphic conditions were maintained in the Qomolangma detachment footwall until at least 15.6 Ma [Law *et al.*, 2011; Cottle *et al.*, 2015b]. Thus, we regard our dataset and the thermal and thermal-kinematic models derived from it as robust indicators of the thermal evolution of the Qomolangma detachment footwall in Rongbuk Valley.

7.2. Tectonic ramifications of this Rongbuk Valley study

One popular model for the development and evolution of the South Tibetan detachment is that it represents a fundamental structural boundary at the top of a

southward extruding metamorphic infrastructure, the Greater Himalayan sequence [Nelson *et al.*, 1996; Beaumont *et al.*, 2001; Hodges *et al.*, 2001; Grujic *et al.*, 2002; Hodges, 2006; Cottle *et al.*, 2015a]. If correct, this interpretation would predict the compression of isotherms within the detachment-related mylonites of the detachment footwall. Indeed, Law *et al.* [2011] presented evidence of this having accompanied the development of mylonitic fabrics in the Qomolangma detachment footwall in Rongbuk Valley: a systematic variation in quartz c-axis fabric opening angles that serves as a proxy for geothermal gradient [Law, 2014]. Law *et al.* [2011] used two particle-path geometric models, with one particle assigned to the 475°C isotherm and another to the 675°C isotherm, to infer displacement on the detachment of 25-170 km during mylonite development, with estimates toward the low and high ends of this range derived assuming a 10° or 5° detachment dip, respectively.

Importantly, Law *et al.* [2011] also estimated the range of mylonitization temperatures in the Hermit's Gorge area as increasing from ca. 480-490 °C immediately near the detachment to ca. 625-680°C at a structural level ca. 480 m beneath the brittle fault trace. The fact that this entire temperature range is at or above the nominal closure temperature of MsAr indicates strongly that the cooling history reported in this paper reflects footwall exhumation subsequent to the ductile deformation responsible for the footwall mylonites. Thus, an important – and somewhat unanticipated – finding of our work is that the amount of brittle-ductile to brittle displacement on the Qomolangma detachment (36 ± 11 to 119 ± 17 km) was similar to the amount of ductile displacement when the mylonites predominantly developed [Law *et al.*, 2011]. Our estimates (ca. 36 to ca. 119 km) and those of Law *et al.* [2011] (25 to 170 km) can be combined to arrive at

an estimate for the total STDS offset in the Everest area of ca. 61 to 289 km. This total compares reasonably well with the very rough estimate of 90 to 216 km calculated by *Searle et al.* [2006] based in the inference that such displacements (varying depending on fault dip) were necessary to juxtapose high-grade rocks from the detachment footwall to the upper crust.

Our preferred interpretation that slip on the Qomolangma detachment terminated at ca. 13 Ma is consistent with an emerging consensus estimate for the end of STDS displacement from the Everest region eastward to Sikkim, India [*Leloup et al.*, 2010; *Cottle et al.*, 2011; *Kellett et al.*, 2013; *Braun*, 2016]. Farther east – across the Yadong cross-structure (Figure 1) in Bhutan and adjacent areas of Tibet – STDS activity appears to have continued for another 1-2 Ma; whether or not this inconsistency is tectonically significant remains unclear [*Cooper et al.*, 2015]. Our estimate of many tens to perhaps more than two hundred kilometers of total slip on the Qomolangma detachment adds to a growing body of evidence [e.g., *Cooper et al.*, 2012; 2013] that the South Tibetan detachment system played a major role in the Miocene tectonic evolution of the Himalaya.

8. Conclusions

Multisystem, medium- to low-temperature thermochronology (MsAr, ZrnHe, and ApHe) of samples collected along a footwall transect parallel to the displacement direction of the Qomolangma detachment have been used to constrain the brittle-ductile and brittle slip history of this important strand of the South Tibetan detachment system. Collectively, the thermochronologic data indicate cooling from the $\geq 480^{\circ}\text{C}$ temperatures

that pertained during ductile deformation on the detachment as recently as 15.6 Ma, followed by cooling through MsAr closure (ca. 15.4 – 14.4 Ma), ZrnHe closure (14.3 – 11.0 Ma), and lastly ApHe closure (ca. 9.3 – 7.8 Ma).

QTQt thermal modeling of the data suggests monotonic rapid cooling from MsAr closure at ca. 490°C and 15.4-14.4 Ma to ZrnHe closure at ca. 200°C (closure temperatures re-calculated from the resulting *QTQt* cooling histories) by no later than 12 Ma. Thermal-kinematic (1D *Pecube*) modeling indicates that this rapid cooling accompanied rapid exhumation from at least ca. 15.6 (nominally the end of ductile deformation on the detachment; [Cottle *et al.*, 2015b]) to ca. 13.0 Ma. We interpret this exhumation to have been caused by brittle-ductile to brittle slip on the detachment subsequent to footwall mylonitization. Our preferred interpretation of the models is that Qomolangma detachment activity effectively ceased ca. 13.0 Ma, but we cannot completely rule out the possibility of minor displacements as recently as ca. 8 Ma.

Reconstructions of the exhumation history between ca. 15.6 Ma and 13.0 Ma for two samples containing all three thermochronometers indicate brittle-ductile to brittle displacements of 44 ± 11 km assuming a 10° fault dip and 88 ± 11 km assuming a 5° fault dip. Six other samples are consistent with fault offsets between 36 ± 11 km and 119 ± 17 km with fault dips of 5 and 10°. When added to previously published estimates for ductile displacement on the detachment [Law *et al.*, 2011], these model results indicate total displacements of ca. 61 to 289 km.

STDS displacements of this magnitude appear to favor tectonic models that feature significant channel flow of the Greater Himalayan metamorphic infrastructure of the range, with the STDS as the upper bounding structure of the core. This interpretation

seems inconsistent, however, with models that assign small displacements to the STDS and relegate the structure to a minor role in Himalayan tectonics [Yin, 2006; Webb *et al.*, 2007; Webb, 2013; Kohn, 2008; He *et al.*, 2015].

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1003 **Figure Captions**

1004 **Figure 1.** A) Map showing the position of the STDS along the crest of the Himalaya. The
 1005 bold shaded box indicates the location of Fig. 1B and the boxes to the east indicate
 1006 regions where the STDS has been previously studied [*Cottle et al.*, 2011; *Cooper et al.*,
 1007 2012; 2013; *Kellett et al.*, 2013]. The map is based on *Cooper et al.*, [2012]. B) Regional
 1008 map of the Rongbuk Valley in the Everest region of Tibet. Geologic units are mapped
 1009 after *Searle et al.*, [2003]. Sample localities are shown with blue and red circles and the
 1010 different colors represent different chronometric systems measured for each sample. See
 1011 inset map for sample names. The base map is taken from the ArcGIS World Imagery
 1012 catalogue.

Figure 2. Geologic cross-section of the Rongbuk Valley showing major geologic units and sample localities. The map is after *Jessup et al.*, [2008]. This figure highlights the structural position of the samples in the footwall of the Qomolangma detachment. MsAr, ZrnHe, and ApHe ages of samples R01 and R02 are shown. All other age data can be found in Table 1.

Figure 3. Field photograph taken in the Rongbuk Valley looking east into the mouth of Hermit's Gorge. The photo clearly shows the leucogranitic dikes and sills of the injection complex, which makes up the immediate footwall of the STDS in this area. The large leucogranite sill near the base of the photo is about 2 m tall. The high-grade sillimanite gneisses are the surrounding dark-colored layers. The photo also highlights the mylonitic fabric and shows how thick the zone is, as the trace of the brittle, low-dipping Qomolangma detachment can be observed near the top of the northern gorge wall.

Figure 4. Muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ release spectra for samples R01, R02, R05, and R08. All eight samples have well-defined plateau ages. See Table 1 for the rest of the plateau ages and the Supplementary Material for the individual heating steps.

Figure 5. Time-temperature histories output from the 1D thermal model $QTQt$ for samples R01 and R02 (with ApHe constraints) and R05 and R08 (without). The bold black line is the “Expected Model,” which is the weighted mean of all best-fit thermal histories [Gallagher, 2012]. Grey shading indicates the 95% credible confidence intervals. The input chronometer data (along with their 2σ uncertainties) are shown on the cooling curve.

Figure 6. Exhumation rate histories from thermal-kinematic modeling using a 1D version of *Pecube* for samples R01 and R02 (with MsAr, ZrnHe, and ApHe constraints) and R05

and R08 (MsAr and ZrnHe only). The bold black lines indicate the mean exhumation rate history, and the horizontal grey boxes indicate two standard deviations from the mean. The input chronometer data (along with their 2σ uncertainties) are presented at the top of each figure pane. The number of acceptable fits to the data is noted. See Figures 1 and 2 for sample locality information. The dashed vertical line at ~ 15.6 Ma indicates the timing of transition from ductile shearing to ductile-brittle slip on the detachment according to Cottle et al. (2015).

Figure 7. Estimates of displacement on the Qomolangma detachment between 15.6 and 13.0 Ma for samples R01 and R02, which have the most thermochronometric information. These detachment displacement histories were calculated from *Pecube* exhumation history results (see Figure 4) and presume either a 5° or 10° dip on the detachment. The shaded areas represent the uncertainties that reflect the propagation of the 2σ uncertainties in the *Pecube* models for successive time steps.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Table 1

Table 1. Thermochronologic data for Qomolangma detachment footwall samples, Rongbuk Valley, Tibet								
Sample number	Latitude	Longitude	Elevation (m)	Structural depth beneath Qomolangma detachment (m)	Rock Type	MsAr (Ma) ¹	ZrnHe (Ma) ²	ApHe (Ma) ²
R01	28.14056° N	86.85194° E	5157	800	Leucogranite	15.37 ± 0.16 (98.8)	11.4 ± 2.4 (4)	9.3 ± 2.8 (6)
R02	28.17328° N	86.84003° E	5114	700	Mylonitized leucogranite	15.000 ± 0.060 (100)	13.0 ± 1.5 (4)	7.76 ± 0.52 (2)
R03	28.17300° N	86.84297° E	5089	600	Mylonitized leucogranite	15.25 ± 0.11 (99)	12.9 ± 1.7 (2)	-
R04	28.18148° N	86.83585° E	5025	600	Mylonitized leucogranite	15.420 ± 0.050 (99.8)	14.32 ± 0.21 (4)	-
R05	28.19000° N	86.83243° E	5019	500	Leucogranite	14.400 ± 0.060 (100)	13.1 ± 1.7 (4)	-
R06	28.20502° N	86.82913° E	5128	450	Mylonitized leucogranite	14.770 ± 0.070 (100)	11.0 ± 1.1 (4)	-
R07	28.20610° N	86.82580° E	4997	400	Leucogranite	14.450 ± 0.070 (99.9)	12.9 ± 1.9 (7)	-
R08	28.21285° N	86.82395° E	4961	300	Leucogranite	14.930 ± 0.080 (99)	13.66 ± 0.17 (5)	-

All uncertainties quoted at 2σ
¹Numbers in parentheses indicates the total %³⁹Ar making up the plateau Ar-Ar age.
²Numbers in parentheses designates number of analyses contributing to the mean