Muscovite $^{40}$Ar/$^{39}$Ar ages help reveal the Neogene tectonic evolution of the southern Annapurna Range, central Nepal

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Abstract: We present new muscovite $^{40}$Ar/$^{39}$Ar ages from thirteen Greater Himalayan rocks and one Lesser Himalayan rock collected from four north-trending transects across the southern Annapurna Range. Combining the new data with previously published ages leads to the following new insight into the tectonic development of the southern Annapurna. Muscovite cooling ages from Greater Himalayan rocks are c. 16–10 Ma in the western Annapurna and c. 6–2 Ma in the eastern Annapurna, revealing a decrease of 4–14 Ma from west to east. Similarly, the muscovite cooling age from one Lesser Himalayan rock in the west is c. 7 Ma and ages from several samples in the east are c. 5–2 Ma, indicating a decline of 2–5 Ma towards the east. Earlier cooling in the western Annapurna can be explained by along-strike differences in the geometry of the frontal ramp on the underlying thrust that carries these Greater and Lesser Himalayan rocks and/or by a NE-striking fault that cut these rocks. In Greater Himalayan rocks from the Modi river valley, one sample yielded muscovite $^{40}$Ar/$^{39}$Ar ages of 18.0 ± 0.7 and 16.2 ± 0.5 Ma for grain sizes of approximately 750 and 200 μm, respectively. In contrast, a sample collected 200 m structurally lower produced ages of 12.6 ± 0.2 and 9.9 ± 0.1 Ma for these two grain sizes. The north-dipping Bhanuwa fault has been proposed between these samples, with different authors arguing for normal or thrust-sense motion. Our newfound pattern of an older muscovite $^{40}$Ar/$^{39}$Ar age pair in the hanging wall supports arguments for the existence of the Bhanuwa fault and suggests normal sense motion.

Supplementary material: Analytical methods, thin section observations, data tables, and plots of argon data for each sample are available at http://www.geolsoc.org.uk/SUP18774

Muscovite $^{40}$Ar/$^{39}$Ar ages are important for understanding the tectonic evolution of fold–thrust belts because they provide constraints on exhumation history. The first study to date minerals from Himalayan rocks by an isotopic technique used the K–Ar system (Krummenacher 1961), and in the following 50 years many authors published K–Ar or $^{40}$Ar/$^{39}$Ar ages for Himalayan muscovites. These studies illuminated the details of two fundamental orogenic processes. The first was exhumation driven by motion on faults below the sampled rocks (Coleman & Hodges 1995; Edwards 1995; Vannay & Hodges 1996; Catlos et al. 2001; Godin et al. 2001; Wobus et al. 2003, 2006; Bollinger et al. 2004; Huntington & Hodges 2006; Robinson et al. 2006; Crouzet et al. 2007). Several studies modelled these and other types of data and showed that erosion tied either to late surface subsidence or to rock uplift above a buried frontal thrust ramp can explain the cooling recorded by the muscovite $^{40}$Ar/$^{39}$Ar ages (Bollinger et al. 2006; Brewer & Burbank 2006; Whipp et al. 2007; Herman et al. 2010). The second process was changes in erosion rate caused by climatic shifts (Huntington & Hodges 2006; Huntington et al. 2006). These authors argued for a five-fold increase in erosion rate in part of the Marsyangdi river valley between 2.5 and 0.9 Ma principally driven by climate change, not changes in geometries and kinematics of faults or other structures.

In west-central Nepal, there are many muscovite $^{40}$Ar/$^{39}$Ar ages available from the ends of the Annapurna Range in the Kali Gandaki and Marsyangdi river valleys (Copeland et al. 1990; Coleman & Hodges 1995; Edwards 1995; Vannay & Hodges 1996; Godin et al. 2001; Bollinger et al. 2004; Huntington & Hodges 2006; Robinson et al. 2006; Crouzet et al. 2007), but no published argon ages from the rocks in the intervening 80 km (Figs 1 & 2). In this paper we fill this data gap with $^{40}$Ar/$^{39}$Ar ages of muscovite in Greater
and Lesser Himalayan rocks from four north-trending transects. The increased spatial resolution achieved by combining our new data with previously published ages allows us to address the following questions across the southern Annapurna.

What is the tectonic significance of large along- and cross-strike age differences, particularly in Greater Himalayan rocks? Computational models presented by Herman et al. (2010) showed that evolving surface topography produces temporal changes in isotherm geometries that alone result in both along- and cross-strike variability in muscovite $^{40}$Ar/$^{39}$Ar ages. These models predicted muscovite age variations of no more than 1.5 myr in transects through Greater Himalayan rocks that covered 80 and 20 km in the along- and cross-strike directions, respectively. In contrast, we find muscovite $^{40}$Ar/$^{39}$Ar age differences of 10 and 6 myr, respectively, in transects through Greater Himalayan rocks that cover 80 km in the along-strike direction and as little as 400 m across-strike.

Are there detectable differences in muscovite $^{40}$Ar/$^{39}$Ar ages across the South Tibet detachment or the Main Central thrust (MCT) throughout the Annapurna? Coleman & Hodges (1998) showed differences in biotite and phlogopite $^{40}$Ar/$^{39}$Ar ages across part of the South Tibet detachment and Huntington et al. (2006) and Huntington & Hodges (2006) argued for differences in muscovite $^{40}$Ar/$^{39}$Ar ages across younger thrusts near the older MCT, in both cases on the east side of the Annapurna.

**Geological setting**

Lesser and Greater Himalayan rocks are exposed in a broad swath across the centre of the Himalayan fold–thrust belt. In this paper we use the terms ‘Lesser’, ‘Greater’ and ‘Tethyan’ to denote structural position and metamorphic grade. However, in this section we also include discussion of
Fig. 2. Simplified geological map of the Annapurna Range. Greater and Lesser Himalayan muscovite $^{40}$Ar/$^{39}$Ar ages decrease to the east. The structural thicknesses of both the Greater Himalayan succession as a whole and its individual constituents increase towards the east. Only K–Ar or $^{40}$Ar/$^{39}$Ar ages interpreted to represent cooling through the closure temperature for Ar loss are shown; ages interpreted to result from white mica growth below the closure temperature are not shown. The location of the MCT is from Martin et al. (2005) and new mapping, and is placed at the approximate location of highest strain in the ductile high strain zone. The mapped location of the South Tibet detachment connects the structurally lowest strands of the system in the Kali Gandaki (Vannay & Hodges 1996; Godin 2003), Modi (Hodges et al. 1996), and Marsyangdi (Coleman 1996) drainages. The boundaries of the Manaslu granite are from Bordet et al. (1981).
the stratigraphy of these rocks. In the remainder of this section we place the Lesser and Greater Himalayan rocks in structural context, beginning to the south with the structurally lowest rocks in the orogen.

Middle Miocene to Upper Pliocene clastic foreland basin strata comprise the Siwalik Group (Ojha et al. 2009). These rocks are bounded at their structural base by the Main Frontal thrust, which juxtaposes them against upper Quaternary alluvium. The Main Frontal thrust and related faults are the active, frontal thrust system in the Himalayan fold–thrust belt (Lave & Avouac 2001; Bettinelli et al. 2006).

Lesser Himalayan rocks structurally overlie the Siwalik Group along the Main Boundary thrust, which was active at or slightly after c. 5 Ma (Robinson et al. 2006). In and near the Annapurna Range, many major thrust faults repeat Lesser Himalayan rocks (Paudel & Arita 2000; Pearson & DeCelles 2005; Khanal & Robinson 2013). In Nepal, the Lesser Himalayan succession is divided into two parts: the Nawakot Unit and the stratigraphically overlying Tansen Unit (Upreti 1996, 1999). The Nawakot Unit primarily consists of metasedimentary rocks deposited in the late Paleoproterozoic (Martin et al. 2011). Clastic rocks dominate the lower formations of the Nawakot Unit, giving way to thick carbonates near the stratigraphic top. The lowermost formation, called the Kuncha Formation in central Nepal, was intruded by multiple granite bodies between c. 1880 and 1780 Ma, and along with a few meta-mafic bodies, these intrusive rocks also are included in the Lesser Himalayan assemblage (Kohn et al. 2010). In all outcrops, the Nawakot Unit is found to have experienced sub-greenschist to lower amphibolite facies conditions, depending on location (Paudel & Arita 2000; Beyssac et al. 2004; Martin et al. 2010). The Nawakot Unit rock sampled for this study reached peak metamorphic conditions of about 9 kbar at 580 °C (Beyssac et al. 2004; Martin et al. 2010; Corrie & Kohn 2011).

The Tansen Unit stratigraphically overlies the Nawakot Unit across an unconformity that spans at least 900 myr (Upreti 1996, 1999; Martin et al. 2011). The lower part of the Tansen Unit consists of the Gondwanan Unit, clastic rocks deposited between the Carboniferous–Permain and the Paleocene (Stocklin 1980; Sakai 1983, 1985; Upreti 1996, 1999). The upper part of the Tansen Unit is composed of the Eocene–Bhainskati Formation and the lower to middle Miocene–Dumri Formation, both of which are clastic Himalayan foreland basin deposits (DeCelles et al. 2004; Ojha et al. 2009). In structurally lower outcrops, Tansen Unit rocks are un- or very weakly-metamorphosed, whereas structurally higher, such as in the middle Modhi Khola valley, exposed Tansen Unit rocks reached lower amphibolite facies conditions (Martin et al. 2010).

The MCT is the structural top of the Lesser Himalayan rocks. The MCT is a several kilometre-thick, top-to-the-south ductile shear zone that placed Greater Himalayan on Lesser Himalayan rocks; in the Annapurna Range this motion occurred between c. 22 and 15 Ma (Hodges et al. 1996; Martin et al. 2005; Corrie & Kohn 2011). The MCT accommodated at least 120 km of offset (Robinson 2008; Khanal & Robinson 2013). In this paper we use the location of the MCT given by Martin et al. (2005), which is the position of maximum strain in the shear zone for most transects (also see discussion in Martin et al. (2010)). In some transects across the shear zone, Martin et al. (2005) used the contact between Greater and Lesser Himalayan rocks, identified with the aid of isotopic analysis, as a proxy for the position of maximum strain in the shear zone.

In the Annapurna Range, the Greater Himalayan succession is divided into a lower pelitic and psammitic accumulation, called Unit I, and an upper calcareous succession, Unit II (Le Fort 1975; Searle 2010). Individual Unit I samples contain detrital zircons with U–Pb isotopic ages as young as 780–540 Ma (Gehrels et al. 2003, 2011; Martin et al. 2005). Unit III, a meta-granite, intruded Unit II at c. 500 Ma (Hodges et al. 1996), constraining deposition of at least part of the Greater Himalayan succession to c. 780–500 Ma. In the Annapurna, Greater Himalayan rocks reached peak metamorphic conditions of about 10–15 kbar at 600–800 °C (Vannay & Hodges 1996; Catlos et al. 2001; Martin et al. 2010; Corrie & Kohn 2011). Like Lesser Himalayan rocks, in the Annapurna there are multiple faults internal to Greater Himalayan rocks (Hodges et al. 1996; Martin et al. 2010; Corrie & Kohn 2011; see review in Mukherjee, this volume, in prep.).

The Bhanuwa fault is one such intra-Greater Himalaya fault that cuts Unit I pelitic schists (Fig. 3). Martin et al. (2010) first recognized this fault based on a difference in near-peak pressures attained by the rocks from either side: approximately 15 kbar to the south and 11 kbar to the north. If the fault dips north like the main tectonic foliation in these rocks, this pressure difference suggests normal sense motion. In contrast, Corrie & Kohn (2011) did not find a pressure difference across this region but did infer a difference in peak temperatures: approximately 650 °C to the south and 735 °C to the north. Again assuming a northward dip, this temperature difference led Corrie & Kohn to conclude that the Bhanuwa fault accommodated thrust-sense motion. The reasons for the conflicting interpretations of peak metamorphic
Map Units

Tethyan Himalayan Rocks
- Undivided Tethyan metasedimentary rocks. Neoproterozoic(?)-Ordovician (Hodges et al. 1996).

Greater Himalayan Rocks
- Unit III. Granitic augen gneiss. Intrudes Unit II. ~500 Ma (Hodges et al. 1996).
- Unit II. Calc-silicate schist, calc-silicate gneiss, and marble.
- Unit I. Pelitic and psammitic gneiss and schist and interbedded quartzite. Neoproterozoic-Cambrian (?) (Gehebals et al. 2010).

Lesser Himalayan Rocks
- Lower Foreland Basin unit. Includes Bhainskati formation. Mostly sandstone. Eocene - Oligocene (DeCelles et al. 2004).
- Malekhu Formation. Calcitic and dolomitic marble, phyllitic in places.
- Dhading Formation. Black slate and phyllite.
- Gondwanan unit, undivided. Black shale and slate, especially at base, more sandstones toward top of unit. Carboniferous (?) - Paleocene (Upreti 1996).
- Malung Formation. Micaceous quartzite, sandy phyllite, phyllite, and slate. Often distinctly pink or lavender.
- Syangja Formation. Compositely and texturally mature white quartzite, medium- to very fine-grained. Minor interbedded green phyllite.
- Kuncha Formation. Micaceous quartzite and sandy phyllite. Minor interbedded carbonate. Includes intrusives: 1780 Ma Ulleri granitic gneiss and unnamed amphibolite (Kohn et al. 2010).

Fig. 3. Geological map of part of the Modi Khola valley showing multi-grain 40Ar/39Ar ages for c. 200 µm muscovite grains. We interpret the date from sample 502056 to represent the time of crystallization of muscovite at a temperature below its closure temperature, whereas the dates from the other samples are cooling ages. The pattern of c. 16–15 Ma ages structurally above c. 10 Ma ages in the Greater Himalayan rocks suggests normal sense motion on the Bhanuwa fault. Corrie & Kohn (2011) interpreted the structurally lower granite mapped here as Cambrian Unit III to be a late Cenozoic granite instead. Contour interval 200 m. BF, Bhanuwa fault; DD, Deorali detachment; GF, Ghandruk fault; MCT, Main Central thrust; MD, Macchapucchare detachment; RF, Romi fault; ST, Sinuwa thrust; TF, Tobro fault.
conditions are not fully resolved. Monazite Th–Pb isotopic dates suggest thrusting, if it occurred, at 23–19 Ma (Corrie & Kohn 2011). Corrie & Kohn (2011) treat the Bhanuwa fault as one thrust in a series of southward-younging, in-sequence thrusts. Because Martin et al. (2010) and Corrie & Kohn (2011) identified the Bhanuwa fault based on thermobarometric results acquired after the completion of fieldwork, these workers did not examine the surrounding rocks in the field to search for indicators of fault orientation, sense of motion, or brittle v. ductile behaviour.

The South Tibet detachment is the structural top of the Greater Himalayan rocks. A widely accepted interpretation of the detachment is that this set of two to three moderately north-dipping structures accommodated tens of kilometres of top-north offset as normal faults (Burchfiel et al. 1992; Searle 2010). In contrast, Webb et al. (2011) interpreted the South Tibet detachment as a backthrust that branched from a southern segment of the MCT (see also Yin 2006; Mukherjee 2013). In the Annapurna Range, slip on this fault system occurred between c. 23 and 18 Ma, and possibly later (Hodges et al. 1996; Searle 2010).

The South Tibet detachment placed lower-grade Tethyan Himalayan metasedimentary rocks on higher-grade Greater Himalayan strata. Deposition of the Tethyan Himalayan succession began in the late Neoproterozoic or Cambrian and continued into the Cretaceous (Bordet et al. 1981; Garzanti 1999). Lowermost Tethyan formations are interpreted to have been the protoliths for Greater Himalayan Units I and II (Le Fort 1975; Gehrels et al. 2003; Myrow et al. 2003; Searle 2010). The Tethyan Himalayan rocks stretch north to the Indus–Yarlung suture zone, which marks the surface location of the former subduction zone between the Indian and Eurasian plates (Burg & Chen 1984; Ratschbacher et al. 1994; Murphy & Yin 2003; Hebert et al. 2012).

### Methods

We collected samples from outcrops of Lesser and Greater Himalayan rocks across the central portion of the southern Annapurna Range (Fig. 2). Within each transect, samples from Greater Himalayan rocks were collected at similar elevations (Table 1). We obtained multi-grain aliquot $^{40}\text{Ar}/^{39}\text{Ar}$ dates of muscovite grains with diameters of about 200 μm from each sample. From samples 502067 and 406042 we also obtained $^{40}\text{Ar}/^{39}\text{Ar}$ dates of single muscovite crystals with diameters of about 750 μm as well as multi-grain aliquot $^{40}\text{Ar}/^{39}\text{Ar}$ dates of biotite grains with diameters of about 200 μm. Micas from samples 502067 and 406042 were dated at

### Table 1. Sample locations and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages used for tectonic interpretations

| Sample ID | Rock ID | Latitude* N | Longitude* E | Elevation (m) | $^{40}\text{Ar}/^{39}\text{Ar}$ age (Ma) | ± (Ma) 2σ |
|-----------|---------|-------------|--------------|---------------|---------------------------------|---------|
| Modi river valley | | | | | | |
| 502056 | Unit III | 28.47078 | 83.86903 | 2550 | 9.7 | 1.4 |
| 502050 | Unit I | 28.44343 | 83.84626 | 2420 | 15 | 3.8 |
| 502067 | Unit I | 28.43072 | 83.83379 | 2150 | 16† | 0.5 |
| 406042 | Unit I | 28.42823 | 83.82610 | 1970 | 9.9† | 0.1 |
| 502071 | Unit I | 28.41742 | 83.82075 | 2240 | 9.6 | 1.5 |
| 502079 | LHS | 28.39588 | 83.79992 | 2220 | 7.2 | 1.3 |
| Seti river valley | | | | | | |
| 502102 | Unit I | 28.38749 | 83.98079 | 1480 | 7.0 | 0.2 |
| 502107 | Unit I | 28.36896 | 83.96693 | 1320 | 4.3 | 0.1 |
| 502112 | Unit I | 28.34251 | 84.00661 | 1920 | 4.8 | 0.4 |
| Madi river valley | | | | | | |
| 502121 | Unit I | 28.39211 | 84.11944 | 1800 | 6.0 | 0.7 |
| 502127 | Unit I | 28.32365 | 84.09097 | 1070 | 11 | 1.3 |
| 502132 | Unit I | 28.30601 | 84.09038 | 1010 | 5.8 | 1.6 |
| Nayu ridge transect | | | | | | |
| 502150 | Unit I | 28.32031 | 84.28823 | 2490 | 4.7 | 0.1 |
| 502147 | Unit I | 28.30042 | 84.30199 | 2250 | 3.2 | 0.1 |

*Map datum: India Bangladesh.
†grain size: 150–250 μm. Grain size for all other samples: 177–250 μm.
LHS, Lesser Himalayan Series.
the University of Alaska Fairbanks Geochronology Facility (Benowitz et al. 2013) and muscovite from the other samples was dated at the New Mexico Geochronology Research Laboratory (Sanders et al. 2006).

Argon isotopic data are presented in Table 2. We identify an age plateau in the release spectra from the step heating experiments if the mean square weighted deviation (MSWD) is less than 2.5 for at least three consecutive steps that together comprise at least 50% of the total argon released. If the MSWD is greater than 2.5 or the combined fraction of $^{39}$Ar released is less than 50% we report a weighted mean age, calculated by weighting the apparent age of each heating step by the fraction of $^{39}$Ar released. For all muscovite analyses we prefer to use the plateau or weighted mean age rather than the inverse isochron age because in most cases the former provided higher precision. Further, the initial $^{40}$Ar/$^{36}$Ar ratio derived from inverse isochron regression had large errors for most samples because the majority of the plateau gas release occurred over steps with a homogeneous radiogenic Ar content (Table 2). We refer to these inverse isochron age determinations as errorchrons. For the biotite $^{40}$Ar/$^{39}$Ar analyses we use the integrated age because age spectra from biotite have been shown to be a potentially unreliable means to evaluate Ar concentration gradients because of instability during heating in vacuo (Gaber et al. 1988). We report all uncertainties at the two standard deviation level.

The closure temperature for Ar loss from muscovite by volume diffusion is a critical part of tectonic interpretations of $^{40}$Ar/$^{39}$Ar ages but currently is the subject of debate. Using data from laboratory experiments, Harrison et al. (2009) showed that the range of closure temperatures for muscovite cooling at rates and pressures found in typical continental fold–thrust belts is about 380–450 °C. In contrast, Villa (1998, 2006) summarized dating of white micas from rocks cooled in nature to conclude that intra-granular diffusive loss of argon effectively stops at 550–600 °C (Hammerschmidt & Frank 1991; Di Vincenzo et al. 2004). Villa also emphasized the importance of age resetting by recrystallization, not volume diffusion. We use the experimental data of Harrison et al. (2009) for our interpretations. Our conclusions would require only minor modifications if the actual closure temperature were higher than 450 °C because the Greater Himalayan samples reached peak temperatures higher than 650 °C and the Lesser Himalayan sample reached a peak temperature of about 580 °C (Catlos et al. 2001; Martin et al. 2010; Corrie & Kohn 2011), in all cases as high or higher than the range of closure temperatures proposed by Villa (1998, 2006).

**Results**

**Greater Himalayan rocks**

We report new $^{40}$Ar/$^{39}$Ar ages for muscovite from thirteen Greater Himalayan rocks collected between the Modi Khola valley and the Nayu ridge in the Annapurna Range (Figs 2–4; Tables 1 & 2). We also present new $^{40}$Ar/$^{39}$Ar ages for biotite from samples 502067 and 406042 from the Modi Khola valley (Tables 1 & 2). All samples were collected from Unit I pelites except for Modi Khola transect sample 502056, which was taken from an outcrop of Unit III meta-granite.

**Modi Khola transect.** Sample 502071 was collected directly above the MCT, and step heating of a muscovite separate yielded a weighted mean age of 9.6 ± 1.5 Ma and an inverse isochron age of 9.7 ± 2.0 Ma from four steps that comprised 57% of the $^{39}$Ar released. The integrated age was indistinguishable at 10.0 ± 0.1 Ma. The approximately 200 μm muscovite fraction from structurally higher sample 406042 generated a plateau age of 9.9 ± 0.1 Ma and an inverse isochron age of 9.5 ± 0.5 Ma from 10 steps that comprised 99% of the released $^{39}$Ar (Fig. 4). The integrated age was nearly identical to the plateau age at 9.9 ± 0.2 Ma. The approximately 750 μm muscovite fraction from sample 406042 produced a plateau at 12.6 ± 0.2 Ma and an inverse errorchron age of 12.4 ± 0.9 Ma from 82% of the $^{39}$Ar released in three steps (Fig. 4). Again, the integrated age was almost identical at 12.9 ± 0.4 Ma. The inverse isochron regression to initial $^{40}$Ar/$^{36}$Ar had large errors because the vast majority of the gas release (82%) occurred during three steps with a homogeneous radiogenic content. The integrated age of biotite from this sample was 14.5 ± 0.3 Ma. The approximately 200 μm muscovite fraction from sample 502067 yielded a plateau at 16.2 ± 0.5 Ma and an inverse isochron age of 17.0 ± 1.7 Ma from seven steps that comprised 71% of the released $^{39}$Ar (Fig. 4). The integrated age was older, 23.0 ± 0.7 Ma. This older integrated age resulted from anomalously old ages from the initial and final heating steps. The approximately 750 μm muscovite fraction gave indistinguishable plateau, inverse isochron, and integrated ages of 18.0 ± 0.7, 18.2 ± 0.9, and 18.8 ± 0.9 Ma, respectively, with the first two age types from 97% of the $^{39}$Ar released in four steps (Fig. 4). The inverse isochron regression to initial $^{40}$Ar/$^{36}$Ar had large errors because the vast majority of the gas release (97%) occurred during four steps with a homogeneous radiogenic content. The integrated age of biotite from sample 502067 was 59.9 ± 1.7 Ma. Muscovite from sample 502050 generated a weighted mean age of 15.3 ± 3.8 Ma and an inverse errorchron
Table 2. Mica $^{40}$Ar/$^{39}$Ar results

| Sample         | Mineral | Integrated age (Ma) | ± (Ma) $^{2\sigma}$ | Plateau age (Ma) | Weighted mean age (Ma) | ± (Ma) $^{2\sigma}$ | No. steps used | $^{39}$Ar released (%) | MSWD | Inverse isochron age (Ma) | ± (Ma) $^{2\sigma}$ | No. steps used | MSWD | Initial $^{40}$Ar/$^{36}$Ar | ± 2σ |
|----------------|---------|---------------------|---------------------|------------------|------------------------|---------------------|---------------|------------------------|------|---------------------------|---------------------|---------------|------|---------------------------|------|
| Modi river valley |         |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 502056         | Muscovite | 10.6                | 0.1                 | –                 | 9.7                    | 1.4                 | 4/12          | 56.5                  | 14   | 9.6                       | 0.8                 | 4/12          | 15   | 302                       | 44   |
| 502050         | Muscovite | 16.2                | 0.1                 | –                 | 15.3                   | 3.8                 | 3/12          | 61.8                  | 32   | 14.2                      | 0.7                 | 3/12          | 22   | 407                       | 1200 |
| 502067         | Musc      | 23.0                | 0.7                 | 16.2              | –                      | 0.5                 | 7/13          | 71.2                  | 0.51 | 17.0                      | 1.7                 | 7/13          | 0.40 | 271                       | 70   |
|                | 200 µm    |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 502067         | Musc      | 18.8                | 0.9                 | 18.0              | –                      | 0.7                 | 4/7           | 97.1                  | 0.47 | 18.2                      | 0.9                 | 4/7           | 0.67 | 311                       | 94   |
|                | 750 µm    |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 502067         | Biotite   | 59.9                | 1.7                 | –                 | –                      | –                   | –             | –                     | –    | –                         | –                   | –             | –    | –                         | –    |
| 406042         | Musc      | 9.9                 | 0.2                 | 9.9               | 0.1                    | 10/13              | 98.8          | 1.2                   | 9.5  | 0.5                       | 10/13               | 0.47          | 354  | 58                        |      |
|                | 200 µm    |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 406042         | Musc      | 12.9                | 0.4                 | 12.6              | –                      | 0.2                 | 3/13          | 82.4                  | 0.27 | 12.4                      | 0.9                 | 3/13          | 0.08 | 360                       | 210  |
|                | 750 µm    |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 406042         | Biotite   | 14.5                | 0.3                 | –                 | –                      | –                   | –             | –                     | –    | –                         | –                   | –             | –    | –                         | –    |
| 502071         | Muscovite | 10.0                | 0.1                 | –                 | 9.6                    | 1.5                 | 4/12          | 56.6                  | 14   | 9.7                       | 2.0                 | 4/12          | 17   | 288                       | 90   |
| 502079         | Muscovite | 8.0                 | 0.1                 | –                 | 7.2                    | 1.3                 | 4/9           | 63.4                  | 12   | 5.2                       | 1.3                 | 4/9           | 0.46 | 1725                      | 2200 |
| Seti river valley |         |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 502102         | Muscovite | 7.3                 | 0.1                 | –                 | 7.0                    | 0.2                 | 4/10          | 48.2                  | 3.3  | 7.0                       | 0.8                 | 4/10          | 3.7  | 301                       | 57   |
| 502107         | Muscovite | 4.5                 | 0.1                 | –                 | 4.3                    | 0.1                 | 3/10          | 41.5                  | 2.7  | 4.4                       | 0.03                | 3/10          | 5.1  | 266                       | 2100 |
| 502112         | Muscovite | 6.1                 | 0.1                 | –                 | 4.8                    | 0.4                 | 5/9           | 60.7                  | 4.0  | 4.8                       | 3.2                 | 5/9           | 4.9  | 302                       | 270  |
| Nayu ridge transect |       |                     |                     |                  |                        |                     |               |                        |      |                           |                     |               |      |                           |      |
| 502150         | Muscovite | 4.8                 | 0.1                 | 4.7               | –                      | 0.1                 | 6/12          | 77.4                  | 2.0  | 4.6                       | 0.2                 | 6/12          | 2    | 322                       | 41   |
| 502147         | Muscovite | 3.3                 | 0.1                 | 3.2               | –                      | 0.1                 | 5/10          | 64.1                  | 2.3  | 3.2                       | 0.4                 | 5/10          | 3    | 295                       | 56   |

MSWD, mean square weighted deviation.
Micas from samples 502067 and 406042 were analysed at the University of Alaska Fairbanks. Muscovite from the remaining samples was analysed at the New Mexico Institute of Mining and Technology.
age of 14.2 ± 0.7 Ma from three steps that comprised 62% of the 39Ar released. The integrated age was similar at 16.2 ± 0.1 Ma. The structurally highest sample, 502056, was collected from Unit III meta-granite and its muscovite yielded a weighted mean age of 9.7 ± 1.4 Ma and an inverse isochron age of 9.6 ± 0.8 Ma from four steps that comprised 57% of the released 39Ar. The integrated age was similar at 10.6 ± 0.1 Ma.

**Seti–Sardi Kholas transect.** We analysed two Unit I samples from the Seti Khola valley and one from the west side of the Sardi Khola valley directly to the east of the Seti. Samples 502107 and 502112 were collected at approximately the same structural position, directly above the MCT. Step heating of muscovite from sample 502107 yielded a weighted mean age of 4.3 ± 0.1 Ma and an inverse isochron age of 4.4 ± 0.03 Ma from three steps that comprised 42% of the released 39Ar. The integrated age was indistinguishable at 4.5 ± 0.1 Ma. Muscovite from sample 502112 gave a weighted mean age of 4.8 ± 0.4 Ma and an inverse errorchron age of 4.8 ± 3.2 Ma from 61% of the 39Ar released in five steps. The integrated age was slightly older at 6.1 ± 0.1 Ma due to anomalously old ages from the final heating steps. The structurally higher sample, 502102, produced indistinguishable weighted mean, inverse isochron, and integrated ages of 7.0 ± 0.2, 7.0 ± 0.8, and 7.3 ± 0.1 Ma, with the first two age types from 48% of the 39Ar released in four steps.

**Madi Khola transect.** Step heating of muscovite from sample 502132, collected directly above the MCT, yielded indistinguishable weighted mean, inverse errorchron and integrated ages of 5.8 ± 1.6, 6.0 ± 5.3, and 6.2 ± 0.1 Ma, with the first two age types from 50% of the 39Ar released in four steps. The structurally intermediate sample, 502127, gave weighted mean and inverse errorchron ages of 11.3 ± 1.3 and 11.2 ± 1.3 Ma from four steps that comprised 52% of the released 39Ar. The integrated age was slightly older at 12.5 ± 0.1 Ma due to anomalously old ages for steps at the beginning and end of the step heating experiment. The structurally highest sample, 502121, produced a weighted mean age of 6.0 ± 0.7 Ma and an inverse isochron age of 5.8 ± 0.2 Ma from 66% of the 39Ar released in five steps. The integrated age was similar at 6.8 ± 0.2 Ma.

**Nayu ridge transect.** Sample 502147 was collected directly above the MCT, and step heating of its muscovite yielded a plateau at 3.2 ± 0.1 Ma and an inverse isochron age of 3.2 ± 0.4 Ma from five steps that comprised 64% of the total 39Ar released. The integrated age was indistinguishable at 3.3 ± 0.1 Ma. Muscovite from the structurally higher sample, 502150, produced an indistinguishable plateau, inverse isochron and integrated ages of 4.7 ± 0.1, 4.6 ± 0.2, and 4.8 ± 0.1 Ma, with the first two age types from 77% of the 39Ar released in six steps.

**Lesser Himalayan rock**

We dated muscovite from one Nawakot Unit rock collected in the Modi river valley, sample 502079 (Fig. 3; Tables 1 & 2). This sample produced a weighted mean age of 7.2 ± 1.3 Ma and an inverse isochron age of 5.2 ± 1.3 Ma from 64% of the 39Ar released in four steps. The integrated age of 8.0 ± 0.1 Ma was indistinguishable from the weighted mean age.

**Geological significance of the ages**

In this section we describe how we assign geological significance to the mica 40Ar/39Ar ages. We
consider three possible explanations for the ages: extraneous argon, crystallization below the closure temperature for argon loss by volume diffusion, and cooling through the closure temperature.

**Extraneous argon**

Both of the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages are older than the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the same sample (Table 2). This situation is common for Himalayan biotite and typically is ascribed to extraneous $^{40}\text{Ar}$ (Copeland et al. 1991; Stuwe & Foster 2001; Kelley 2002; Herman et al. 2010; Warren et al. 2014). We follow these interpretations and likewise conclude that our new biotite ages were contaminated by abundant extraneous $^{40}\text{Ar}$. If this interpretation is correct, the ages have no geological meaning, so we do not further consider the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

In contrast, we conclude that extraneous $^{40}\text{Ar}$ did not compromise our muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages. The large error on the regression to the initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio for nearly all samples precludes using isochrons to evaluate if the muscovite age determinations were affected by extraneous $^{40}\text{Ar}$ (Table 2). Most of the analysed muscovite samples produced anomalous older ages during the first and/or last heating steps. These older age steps are associated with high Cl–K ratios, high Ca–K ratios, and/or high errors. This association leads us to infer that the anomalous older ages may result from gas inclusions (Harrison et al. 1994). Although extraneous $^{40}\text{Ar}$ likely is present in such inclusions, this extraneous $^{40}\text{Ar}$ did not affect our age determinations because we did not use these heating steps to determine the reported age. Further, the identification of significant extraneous $^{40}\text{Ar}$ in muscovite from central Nepal is not common and the systematic spatial variation in cooling ages in this study and others (Herman et al. 2010) argues against the presence of significant extraneous $^{40}\text{Ar}$ in our dated muscovite crystals.

**Cooling v. muscovite crystallization below the closure temperature**

Crystallization of muscovite below the closure temperature for argon loss by volume diffusion sets the $^{40}\text{Ar}/^{39}\text{Ar}$ age at the time of crystallization. To assess this possibility for our samples, we measured grain sizes for each apparent generation of muscovite in thin sections from the Modi and Madi transects. We then compared the measured grain sizes in the thin sections with the sizes of the dated grains, which were established by careful crushing and sieving. We caution, however, that tying the growth of an individual muscovite grain to a particular temperature is challenging and there is no evidence that apparently late-growing muscovite identified in the thin sections crystallized below the diffusive closure temperature.

In all samples, we found that the vast majority of muscovite is parallel to the foliation in the rock and has a range of grain sizes that completely overlaps the sizes of the dated grains. We infer that these muscovite crystals experienced temperatures near the peak metamorphic temperature, which in all cases was higher than the closure temperature for muscovite (Harrison et al. 2009). Every sample also contains muscovite crystals that unambiguously cut across the foliation and did not react with the grains that define the foliation. We discuss these neoblastic crystals for different samples in the following two paragraphs.

Sample 502056 contains many large muscovite (and biotite) grains that cut across foliation. Many of the muscovite neoblasts have the same size as the dated grains, 177–250 μm. Furthermore, we collected this sample very near sample AS01-25 from Corrie & Kohn (2011). In the caption to their figure DR4, these authors argued that monazite rims grew at low temperature during retrograde metamorphism of this rock at c. 10 Ma. The similarity of the muscovite and monazite dates suggests that the same thermal or hydrothermal event may have produced both dates. This explanation may involve c. 10 Ma crystallization of muscovite below its closure temperature, implying cooling through the closure temperature before this time. The textural and grain size data combined with the monazite dates lead us to prefer the interpretation of crystallization below the muscovite closure temperature for the origin of the c. 10 Ma muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ date from sample 502056.

In sample 502071, neoblastic muscovite is rare. All but one of the measured neoblasts was smaller than the dated grain size, 177–250 μm. The lone exception was 190 μm long. In sample 502121, neoblastic muscovite also is uncommon but it is larger than in sample 502071, up to 300 μm long. In the remaining samples, muscovite neoblasts are rare and smaller than the dated grain sizes. The small neoblastic grain size in most samples indicates that these crystals did not affect our age determinations because they were too small to be included in our analysed aliquots, regardless of whether the neoblasts crystallized below the closure temperature. The paucity of neoblastic muscovite in all samples and its small grain size in most samples suggest that, except for sample 502056, our muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages reflect cooling through the closure temperature rather than crystallization of muscovite below the closure temperature.

Several other types of data support this interpretation. In the Nayu ridge transect, muscovite $^{40}\text{Ar}/$
$^{39}$Ar ages are 4.7 ± 0.1 and 3.2 ± 0.1 Ma, one to three million years older than the 1.8 ± 0.4 Ma zircon fission track ages from nearby samples collected at similar elevations (all uncertainties at 2-sigma) (Blythe et al. 2007). We expect older muscovite $^{40}$Ar/$^{39}$Ar ages if they resulted from cooling through the muscovite closure temperature because the temperature at which zircon fission track annealing effectively stops, approximately 350–250 °C, is lower than the closure temperature for volume diffusion of argon from muscovite (Rahn et al. 2004; Harrison et al. 2009). However, the pattern of muscovite $^{40}$Ar/$^{39}$Ar ages older than zircon fission track ages would not necessarily hold if the $^{40}$Ar/$^{39}$Ar ages resulted from muscovite crystallization below the closure temperature.

In the Modi transect, six lines of evidence further our argument that the muscovite $^{40}$Ar/$^{39}$Ar ages resulted from cooling through the closure temperature, except for the age from sample 502056. First, the Modi transect c. 16 and 15 Ma ages are identical to the Greater Himalayan ages from the Kali Gandaki valley 20 km to the west, demonstrating regional consistency of these ages (Figs 2 & 5). Second, neither Martin et al. (2007) nor Corrie & Kohn (2011) found c. 10 Ma monazite in any Modi transect sample except AS01-25 (collected near our sample 502056) despite dating spots in monazites from many samples across the transect. Third, the (hydro) thermal event that affected the structurally highest sample 502056 at c. 10 Ma did not reset the muscovite $^{40}$Ar/$^{39}$Ar ages in the spatially nearest samples (502050 and 502067) to c. 10 Ma, requiring that a c. 10 Ma resetting event, if it existed in the structurally lower rocks, fortuitously skipped these spatially intervening samples to reset the ages in the structurally lowest samples 406042 and 502071 (Fig. 3). Such an explanation necessitates resetting in sample 406042 but not in sample 502067, which was located only 200 m structurally above sample 406042. Fourth, the approximately 750 µm muscovite fraction from samples 502067 and 406042 yielded $^{40}$Ar/$^{39}$Ar ages 2–3 myr older than the approximately 200 µm muscovite fraction (Table 2), as expected for simple cooling (Harrison et al. 2009). Resetting by a (hydro) thermal event therefore demands either a fortuitous temperature–time path that reset the $^{40}$Ar/$^{39}$Ar ages of the approximately 200 µm but not the approximately 750 µm muscovite grains in each sample or metamorphic reactions that fortuitously recrystallized all of the approximately 200 µm but none of the approximately 750 µm muscovite grains. Fifth, the age spectra from all grain sizes analysed from samples 502067 and 406042 produced mostly flat age spectra, not

![Fig. 5. Muscovite $^{40}$Ar/$^{39}$Ar cooling ages for Greater Himalayan rocks from the Annapurna range plotted by sample longitude. There is a prominent decrease in cooling ages from west to east across the range. A NE-striking fault could explain the jump in ages between the Modi and Seti river valleys. The plot does not include a structurally high sample from directly beneath the South Tibet detachment in the Marsyangdi river valley (Coleman & Hodges 1995). Symbol type indicates sample elevation in metres above sea level. The length scale bar is approximate because the samples were collected at different latitudes.](image-url)
stair-stepped or jagged age spectra as expected if the muscovite aliquots were composed of multi-generation populations. Sixth, if neocrystallization or reheating due to either brittle or ductile deformation on the Bhanuwa fault affected the muscovite Ar/39Ar ages (e.g. Dunlap 1997; Cosca et al. 2011), we would expect similar ages in the hanging wall and foothill, not the observed 6 myr jump in ages across the fault.

**Tectonic implications**

**Eastward decrease in cooling ages across the Annapurna Range**

Plotting our new and previously published muscovite Ar/39Ar cooling ages v. longitude reveals a significant decrease in the cooling ages of Greater Himalayan muscovite from west to east (Figs 2 & 5). In the western Annapurna, most Greater Himalayan rocks cooled through the muscovite Ar closure temperature between c. 16 and 13 Ma, and one fault-bounded block in the Modi Khola valley cooled at c. 10 Ma. Modi valley Lesser Himalayan sample 502079 cooled at c. 7 Ma. In the central part of the range, muscovite ages from all but one Greater Himalayan sample are c. 7–4 Ma. In the eastern Annapurna, structurally low Greater Himalayan rocks cooled through the closure temperature between c. 6 and 2 Ma and Lesser Himalayan rocks likewise cooled between c. 6 and 2 Ma.

The eastward decrease in muscovite Ar/39Ar ages across the Annapurna Range mirrors an eastward decline in the youngest (U–Th)–Pb dates of monazite inclusions in Greater Himalayan garnets detected by Martin et al. (2007). These authors found Greater Himalayan monazite inclusions with concordant 232Th–208Pb ages as young as c. 19 Ma in the Modi transect and c. 14 Ma in the Seti valley, but discordant 232Th–208Pb dates as young as c. 13 Ma in the Madi river valley, c. 6 Ma in the Nayu ridge transect, and c. 8 Ma in the Marsyandi river valley. From these dates the authors inferred that growth of retrograde monazite in Greater Himalayan rocks ended by c. 19 Ma in the Modi Khola transect and by c. 13 Ma in the central Annapurna but continued after 6 Ma in the eastern Annapurna. Martin et al. (2007) also found monazite inclusions in Lesser Himalayan garnets from the Nayu ridge transect in the eastern Annapurna but not in Lesser Himalayan garnets from any other transect.

In summary, muscovite Ar/39Ar ages indicate much earlier cooling of Greater Himalayan rocks of the western Annapurna through the closure temperature for Ar in muscovite, and spatial trends in monazite (U–Th)–Pb ages support this interpretation. The presence of only one cooling age of Lesser Himalayan muscovite from the western Annapurna hampers interpretation, but the oldest eastern analyses overlap the western age within uncertainty. In contrast, the youngest Lesser Himalayan sample from the eastern Annapurna is about 5 myr younger than the western sample, which is outside uncertainty. For Greater Himalayan rocks, cooling occurred 7–14 myr earlier in the western Annapurna than in the eastern Annapurna (excluding the c. 10 Ma ages from the Modi transect; including these ages the cooling was 4–14 myr earlier). There are many conceivable explanations for this trend, and in the remainder of this section we discuss five possibilities. The final two explanations seem less likely than the first three. None of the scenarios is mutually exclusive.

**Regional tilting caused by different frontal ramp heights.** One way to explain earlier cooling in the western Annapurna is tilting of a crustal scale block relative to the temperature field at c. 16–13 Ma. Rotation about an approximately north-trending horizontal axis that drove earlier cooling of the western Annapurna through the muscovite Ar closure temperature can explain the observed eastward younging of muscovite Ar/39Ar cooling ages across the range. The edges of the tilting block need not be the bounds of the Annapurna Range.

Figure 6a shows one means of accomplishing this tilting. Thrusting of the hanging wall up a frontal ramp that has a smaller vertical distance from the base to the top of the ramp on the east side of the range would cause more cooling of the western Annapurna. For this scenario to explain the older muscovite Ar/39Ar ages in the west, the frontal ramp must cut the isotherm that corresponds to muscovite closure (420°C on Fig. 6a) in the western but not the eastern Annapurna. Following this thrusting, continued cooling eventually causes the eastern Annapurna to pass through the muscovite closure temperature. This later cooling could result from growth of a duplex beneath the thrust shown in Figure 6a (Robinson 2008; Khanal & Robinson 2013), though the validity of the tilting model does not depend on the mechanism for later cooling. The Greater and Lesser Himalayan rocks that record the eastward younging ages all must be in the hanging wall of the thrust shown in Figure 6a.

**Regional tilting caused by temporal differences in thrusting up an oblique ramp.** Figure 6b depicts another way to produce earlier cooling in the western Annapurna via regional tilting. In this model, motion of the hanging wall up the frontal ramp in the thrust occurs later in the eastern Annapurna because the base of the frontal ramp is located...
Fig. 6. Conceptual models of two mechanisms to produce block tilting of the entire Annapurna range. In the diagrams, the hanging wall of a thrust with a prominent frontal ramp was removed to allow visualization of the thrust geometry. (a) The frontal ramp is higher in the west than the east, so movement up the ramp causes the hanging wall to cool more in the west than the east. This scenario can explain the observed older muscovite $^{40}$Ar/$^{39}$Ar ages in the western Annapurna if the frontal ramp cuts the isotherm that corresponds to the muscovite closure temperature in the west but not the east. The closure temperature was chosen to be 420 °C for illustrative purposes only. (b) Alternatively, if the base of the frontal ramp is located farther south in the eastern Annapurna, south-directed thrusting will result in earlier cooling of along-strike-equivalent rocks in the hanging wall on the west side of the range. This geometry results in a frontal ramp that is oblique to the transport direction.

farther south in the eastern Annapurna. This geometry results in conversion of the frontal ramp into an oblique ramp for south-directed thrusting. As for the situation shown in Figure 6a, the frontal ramp must cut the isotherm that corresponds to the muscovite closure temperature for this model to explain older
muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the western Annapurna. Subduction of the Faizabad ridge, a buried horst in the incoming Indian upper crust, may have caused the frontal ramp geometries shown in Figure 6a and b (cf. Bollinger et al. 2004).

If either method to produce regional tilting is correct, we might expect to find formerly deeper rocks exposed in the western Annapurna. Formerly deeper rocks may crop out in the Modi Khola transect: Martin et al. (2010) estimated pressures of about 15 kbar for rocks between the MCT and Bhanuwa fault whereas Catlos et al. (2001) estimated pressures of 9–10 kbar for Greater Himalayan rocks from the Marsyangdi valley. A challenge to the tilting explanation, however, is that Corrie & Kohn (2011) estimated pressures for those same Modi Khola rocks of about 12 kbar and Vannay & Hodges (1996) estimated that Greater Himalayan rocks from the Kali Gandaki valley experienced pressures of 7–11 kbar, and these pressure estimates are not distinguishable from the estimates from the Marsyangdi valley. Methods of further investigating the regional tilting interpretation include determining whether muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ closure in Greater Himalayan rocks occurred progressively earlier towards the west, in the Dhaulagiri Range, and using palaeomagnetic data to investigate possible horizontal axis rotation.

The upper reaches of the Kali Gandaki river occupy the Thakkhola graben (Fig. 1). East–west extension in and near the Thakkhola graben likely began before c. 14 Ma (Coleman & Hodges 1995) and basin-bounding faults became active by c. 11 Ma (Garzione et al. 2003). These dates overlap the range of Greater Himalayan muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from the Kali Gandaki and Modi Khola transects, so the ages permit a relationship between the causes of cooling of west–east extension in the upper crust at this time.

**NE-striking fault.** Greater Himalayan muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from the western Annapurna are c. 16–13 Ma except for the two c. 10 Ma ages between the Bhanuwa fault and the MCT in the Modi river transect (Figs 2, 3 & 5). In the central to eastern Annapurna, from the Seti river transect east, most ages are c. 7–4 Ma, extending to c. 3 Ma on Nayu ridge and to c. 2 Ma in the Marsyangdi river valley. The lone exception is the c. 11 Ma analysis from the Madi river transect. Ignoring this outlier, our data show a spatially sharp transition between the c. 16–13 (or c. 16–10) Ma ages in the western Annapurna and the c. 7–4 (or c. 7–2) Ma ages from the central to eastern part of the range. A fault that strikes NE, at a high angle to the MCT, is one explanation for this jump in ages (Figs 2 & 5). We do not have other evidence for such a fault, so we do not speculate about its dip or sense of slip except to note that it must have a significant component of dip–slip to produce a difference of several myr in the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages. More Greater Himalayan muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages between the Modi and Seti river valleys would test the interpretation of a spatially sharp break in ages between the western and central Annapurna.

**Long-term differences in erosion rate.** Huntington & Hodges (2006) and Huntington et al. (2006) argued that temporal climate variability produced differences in muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages between Greater Himalayan samples from a small part of the Marsyangdi valley (note that Herman et al. (2010) explained the age differences by an alternative mechanism). Similarly, sustained spatial differences in climate conceivably could cause disparities in $^{40}\text{Ar}/^{39}\text{Ar}$ ages across a region. More rapid erosion, and thus more rapid exhumation, of the eastern Annapurna would yield younger cooling ages in the east than in the west. Such differential erosion would need to be sustained for at least 7 myr to explain the age differences (13 Ma or older cooling in the Kali Gandaki valley v. 6 Ma or younger cooling in the Marsyangdi valley). This spatially varying erosion rate likely would be caused by spatially variable precipitation such as that found for the period 1998–2007 by Bookenhagen & Burbank (2010). A challenge to this explanation is that it seems difficult to maintain a sharp east–west precipitation gradient in one place (in this case in the middle of the Annapurna Range) for times on the order of 7 myr while both regional climate (Clift et al. 2008; Cai et al. 2012) and local and regional topography were changing, for example due to growth of structures to the south (Paudel & Arita 2000; Robinson et al. 2006; Khanal & Robinson 2013).

**Slip on Thakkhola graben-related faults.** Although cooling of the western Annapurna through muscovite closure occurred at broadly the same time as initial slip on faults related to opening the Thakkhola graben (Coleman & Hodges 1995; Garzione et al. 2003), it seems unlikely that slip on these faults directly caused the cooling recorded by the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages. All workers map the southern terminations of the graben-related faults near or north of the South Tibet detachment (Hurtado et al. 2001, and references therein), and dip–slip on the main graben-bounding fault system decreased from a maximum of about 4 km at its centre to zero at its southern end (Fort et al.
1982). It is difficult to envision how faults that ended 10 or more kilometres to the north caused cooling of structurally low Greater Himalayan rocks, especially considering that dip–slip directly north of the fault terminations was limited to a few metres or tens of metres.

**Comparison of Lesser and Greater Himalayan muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages**

In the eastern Annapurna, the range of $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of muscovite from structurally low Greater Himalayan rocks overlaps completely the range of ages from Lesser Himalayan rocks directly beneath the MCT: both are $6–2$ Ma (Fig. 2). The lone exception is the $18$ Ma age from Marsyangdi Greater Himalayan rocks directly beneath the South Tibet detachment (Coleman & Hodges 1995). We do not group this much older age with the younger ages from structurally low Greater Himalayan rocks because different tectonic events probably caused cooling of the two rock packages: motion on structurally higher faults likely caused the older cooling of the structurally higher rocks whereas structurally lower processes produced cooling of the Greater Himalayan rocks far to the south. The $18–15$ Ma muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from the Manaslu granite, structurally above the lowest strand of the South Tibet detachment, support this interpretation (Fig. 2) (Copeland et al. 1990). Our conclusion that there is no significant difference in $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of muscovites from Greater and Lesser Himalayan rocks in the eastern Annapurna contrasts with that reached by Huntington & Hodges (2006) because unlike those authors, we include in our analysis the $6$ Ma age from Greater Himalayan rocks at low elevation along the Marsyangdi river (Edwards 1995), the $2$ Ma age from Lesser Himalayan rocks south of Probi (Bollinger et al. 2004), and our new $5$ and $3$ Ma ages from Greater Himalayan rocks on Nayu ridge.

The similarity of the ages in the eastern Annapurna suggests cooling of both Greater Himalayan rocks and those Lesser Himalayan rocks within a few kilometres of the MCT as a single package not cut by a major active fault. This conclusion supports the interpretation that these rocks cooled through the muscovite closure temperature only as a result of exhumation caused by slip on one or more structurally underlying thrusts (Robinson et al. 2003, 2006; Herman et al. 2010), not as a result of late Miocene–Pliocene slip on a thrust near the MCT (Huntington et al. 2006; Huntington & Hodges 2006).

In contrast, in the Modi river valley in the western Annapurna, the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age from Lesser Himalayan sample 502079 is $7.2 \pm 1.3$ Ma, different outside uncertainty from the age from structurally low Greater Himalayan sample 406042 at $9.9 \pm 0.1$ Ma. The presence of only one Lesser Himalayan cooling age, as well as the large uncertainty on this age, impedes detailed interpretation. Nevertheless, one allowable interpretation is that these rock packages cooled through the muscovite Ar closure temperature at different times because of $10–7$ Ma motion on a fault between them. Nadin & Martin (2012) and Walsh et al. (2012) showed that any such fault was not active within the past 1 myr. It is important to note that without samples that are more closely spaced, we cannot rule out the possibility of older muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages at structurally higher positions simply because of top-down cooling of an intact block.

**Near-synchronicity of Greater and Tethyan Himalayan cooling**

Our compilation of white mica cooling ages from the Kali Gandaki valley shows that the range of ages from Tethyan Himalayan rocks, $13–12$ Ma, overlaps the young end of the range of ages from Greater Himalayan rocks, which is $16–13$ Ma (Fig. 2). Assuming similar closure temperatures for the muscovites near the detachment, the near-synchronicity of cooling in the hanging and footwalls means that motion on the detachment cannot have caused most of that cooling. This recognition requires that either the South Tibet detachment was at most minimally active in the Kali Gandaki valley at $13$ Ma or the currently exposed parts of the detachment were nearly horizontal during slip at $13$ Ma so that at most they cut gently across isotherms. Note that our argument is valid for the muscovite cooling ages most proximal to the structurally lowest strand of the detachment and need not, but could, include consideration of the structurally higher white mica cooling ages near the town of Jomsom. Vannay et al. (2004) found a similar result in the Sutlej valley of NW India: muscovite on both sides of the South Tibet detachment yielded $^{40}\text{Ar}/^{39}\text{Ar}$ Ar cooling ages of $18–16$ Ma.

A similar pattern in cooling ages is present in the hanging wall and footwall of the lowest strand of the South Tibet detachment in the Marsyangdi valley (Fig. 2). A single analysis of footwall Greater Himalayan muscovite yielded $18$ Ma and muscovite from the hanging wall Manaslu granite closed to argon loss between $18$ and $15$ Ma. More analyses of Greater Himalayan rocks are needed to ensure that the single $18$ Ma age is representative of rocks from the footwall, but we tentatively conclude that in the Marsyangdi valley the lowest strand of the South Tibet detachment either was, at
most, minimally active or that currently exposed parts were nearly horizontal at c. 18 Ma. This interpretation conflicts with the main conclusion from Coleman & Hodges (1998). These authors obtained biotite $^{40}$Ar/$^{39}$Ar ages of 17–15 Ma from three footwall rocks, c. 30 and 17 Ma from two hanging-wall rocks, and phlogopite $^{40}$Ar/$^{39}$Ar dates of c. 30 and 27 Ma from two hanging-wall rocks. One of the two hanging-wall biotite ages overlaps with the footwall biotite ages, but the c. 30 Ma hanging-wall biotite and phlogopite dates not only are older than the footwall biotite ages, they are older than hanging-wall muscovite $^{40}$Ar/$^{39}$Ar ages from the Manaslu granite (Fig. 2).

We suggest the c. 30 Ma biotite and phlogopite ages may result from extraneous argon and thus may be geologically meaningless, similar to the biotite we analysed from the Modi Khola transect (Copeland et al. 1991; Stuwe & Foster 2001; Kelley 2002; Warren et al. 2014). Inactivity of the South Tibet detachment at c. 13, and even c. 18 Ma, is expected because the main detachment fault in the Annapurna is thought to have been active between c. 22 and 18 Ma (Searle 2010), with some deformation earlier and perhaps later (Hodges et al. 1996).

Spatial patterns of $^{40}$Ar/$^{39}$Ar cooling ages in Modi Khola transect Greater Himalayan rocks

In the Modi Khola transect, the only Ar analyses that yielded age plateaus were the muscovite fractions from samples 502067 and 406042 (Table 2). Accordingly, for the Modi transect we mostly base our tectonic interpretations on the ages from these two samples. We also include the analyses from the other samples as supplemental ages for our tectonic interpretations in order to provide a wider spatial context.

In the Modi river valley, the structurally central Greater Himalayan samples yielded muscovite $^{40}$Ar/$^{39}$Ar ages of c. 16–15 Ma whereas rocks nearer the structural base and top of the succession gave ages of c. 10 Ma (Fig. 3; Table 1). As discussed in the previous section, we interpret the c. 10 Ma age from structurally highest sample 502056 to reflect muscovite crystallization below the closure temperature, probably due to a localized (hydro) thermal event at this time. In the remainder of this subsection we focus on explanations for the older-on-younger pattern at structurally lower levels in the Greater Himalayan series.

No more than 300 m separated each successive sample vertically, too little to explain the 5–6 myr age difference between them. For comparison, in the Marsyangdi river valley Huntington & Hodges (2006) found differences in muscovite $^{40}$Ar/$^{39}$Ar ages of only 0.3–1.6 myr between samples with about 300 m of elevation difference and an elevation difference of 1300 m produced an age difference of 2.5 myr.

Likewise, cooling represented by these ages is too young to have been caused by motion on the thrusts that cut these rocks. By combining monazite Th–Pb dating and thermobarometric estimates with other age constraints, Corrie & Kohn (2011) argued that offset on two thrusts entirely within Modi Khola Greater Himalayan rocks occurred between c. 27 and 19 Ma and that the MCT was active at c. 22 Ma with thrusting continuing perhaps as late as 15 Ma. These ages are consistent with the conclusion by Hodges et al. (1996) that thrust-sense ductile deformation of Modi Khola Greater Himalayan rocks was ongoing at 23 Ma. Although the inferred end of thrusting on the MCT overlaps with our two oldest muscovite $^{40}$Ar/$^{39}$Ar ages, it seems unlikely that motion on the MCT is responsible for the cooling to produce those ages because spatially intervening samples 406042 and 502071 cooled at c. 10 Ma, at least 5 myr after the probable end of motion on the MCT.

Transport of rocks relative to isotherms with geometries that change through time produces along- and cross-strike variability in muscovite $^{40}$Ar/$^{39}$Ar ages (Herman et al. 2010). However, the computational models of Herman et al. (2010) predict cross-strike differences no greater than 1.5 myr for Greater Himalayan rocks (Herman et al. 2010, figs 5 & 22), much smaller than the 5–6 myr differences present in the Modi transect. We therefore conclude that this effect likely does not explain the full 5–6 myr age differences between Modi valley samples.

Top-down cooling of an intact block seems an unlikely explanation for the older-on-younger ages at structurally low levels because c. 16 Ma sample 502067 is separated from c. 10 Ma sample 406042 by only 200 m of structural distance, which would imply an extremely slow cooling rate between 16 and 10 Ma of 0.8–1.5 °C Ma$^{-1}$ for thermal gradients of 25–45 °C km$^{-1}$ (Nadin & Martin 2012). Even a very high thermal gradient of 100 °C km$^{-1}$ results in a slow cooling rate of 3.3 °C Ma$^{-1}$. In contrast, the cooling rates implied by the differences in muscovite $^{40}$Ar/$^{39}$Ar ages between the approximately 750 and 200 μm fractions are an order of magnitude higher, approximately 22 °C Ma$^{-1}$ for cooling of sample 502067 between 18.0 and 16.2 Ma and 15 °C Ma$^{-1}$ for cooling of sample 406042 between 12.6 and 9.9 Ma (this calculation uses the fact that the closure temperature difference between these grain sizes is approximately 40 °C for any set of geologically reasonable pressures and cooling rates) (Dodson 1973; Harrison et al. 2009).
Tabular Normal Faults

| Earth's surface (held fixed) | A | B | C | D | E | F |
|-----------------------------|---|---|---|---|---|---|
| Exhumation                  |   |   |   |   |   |   |
| Hanging                     |   |   |   |   |   |   |

not a normal fault

Listric Normal Faults

| Earth's surface (held fixed) | G | H | I | J | K |
|-----------------------------|---|---|---|---|---|
| Exhumation                  |   |   |   |   |   |
| Hanging                     |   |   |   |   |   |

position of fault after slip

Tabular Thrust Faults

| Earth's surface (held fixed) | L | M | N | O | P | Q |
|-----------------------------|---|---|---|---|---|---|
| Exhumation                  |   |   |   |   |   |   |
| Hanging                     |   |   |   |   |   |   |

not a thrust fault

Flat-Ramp-Flat Thrust Faults

| Earth's surface (held fixed) | R | S | T | U | V |
|-----------------------------|---|---|---|---|---|
| Exhumation                  |   |   |   |   |   |
| Hanging                     |   |   |   |   |   |

| □ | Hanging wall and footwall rocks that will be juxtaposed by fault slip |
|   | Net motion of a rock relative to Earth's surface due to fault slip |
|   | Vertical component of arrow length is exhumation/burial magnitude and rate |

Fig. 7. Cross-sections through dip-slip faults (thick lines) showing all possible combinations of motions relative to the surface of the Earth. In each case, denoted by a different letter, the square and circle indicate the position of hanging-wall and footwall rocks prior to fault slip and the arrowheads designate their locations after slip; the absence of an arrow signifies no movement relative to Earth's surface during faulting. The y-axis is the vertical direction; the x-axis is any arbitrary horizontal direction. Holding Earth's surface fixed allows direct visualization of exhumation and burial. Throughout motion on normal faults, hanging-wall rocks remain shallower than the footwall counterparts against which they are ultimately juxtaposed (parts A–E and G–K), whereas thrusts move originally deeper hanging-wall rocks to a position shallower than their footwall counterparts after slip (parts L–P and R–V). It is not possible for rocks in the hanging wall of a normal fault to exhume more rapidly than those in the footwall (part F); conversely, it is not possible for rocks in the hanging wall of a thrust to exhume more slowly than those in the footwall (part Q). Tree sizes do not indicate scale (palm trees from freedesignmagazine.com; others from freeda.deviantart.com).
Motion on a fault is one possible explanation for the c. 6 myr offset in muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages between samples 406042 and 502067 (Fig. 3). The Bhanuwa fault lies between these samples (Martin et al. 2010; Corrie & Kohn 2011). The age from sample 502071 is similar to that from sample 406042 and the age from sample 502050 is similar to that from sample 502067, suggesting the presence of blocks of similar age on either side of the fault.

Nadin & Martin (2012) used apatite fission track data to show that rocks on both sides of the Bhanuwa fault cooled through about 140 °C at c. 1 Ma. If the closure temperatures for argon loss from muscovite for each sample were similar to each other, the time-averaged cooling rate for c. 16 Ma sample 502067 must have been significantly slower than that for c. 10 Ma sample 406042 for cooling between the muscovite closure temperature and 140 °C. Assuming that the same relation between cooling rate and exhumation rate existed for the hanging wall and the footwall over most of this temperature range, the slower cooling of the structurally higher sample implies slower exhumation of this sample during some period between peak metamorphism at c. 23 and 1 Ma. Only normal sense offset can explain slower exhumation in the hanging wall compared to the footwall of a fault; thrust-sense offset alone can never result in slower hanging-wall exhumation (Fig. 7). That is, the pattern of an older $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age structurally above a younger one implies normal sense slip on the Bhanuwa fault after c. 23 Ma. Normal sense offset after 19 Ma would reconcile the conflicting interpretations about the sense of movement on the Bhanuwa fault by Corrie & Kohn (2011) and Martin et al. (2010): it accommodated thrusting between c. 23 and 19 Ma followed by later normal sense motion. By a similar analysis, significantly later cooling of structurally higher rocks near sample 502056 relative to those near sample 502050, were it to be found, would imply thrust-sense motion between these samples (Fig. 7). More muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages as well as cooling ages from different thermochronometers would test the interpretation of active faults in the middle to late Miocene.

Our muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages near the Bhanuwa fault are remarkably similar to ages near the Karcham normal fault in the Sutlej river valley, NW India (Janda et al. 2002; Vannay et al. 2004). This fault is parallel to the MCT and cuts Greater Himalayan rocks a few hundred metres above their structural base. Karcham fault hanging-wall and footwall muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages are c. 15 and 10 Ma, respectively, nearly identical to the c. 16–15 and 10 Ma ages from the hanging wall and footwall of the Bhanuwa fault.

Spatial patterns of $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages in transects through Greater Himalayan rocks across the Annapurna Range

As in the Modi Khola valley, the spatial pattern of an older muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age sandwiched between two younger ages is present in Greater Himalayan rocks of the Madi river valley 25 km to the east, although the cooling ages are different than those from the Modi valley (Fig. 2). It is also possible to interpret a spatial alternation of the topographically low Greater Himalayan ages from the Marsyangdi valley: 4–2 Ma to the south, 6 Ma in the middle, and 3 Ma to the north. By analogy with the arguments for the Modi transect rocks, it is possible that in the Madi and Marsyangdi valleys a normal fault separates the structurally lowest and middle samples and a thrust juxtaposes the structurally middle and highest samples. In the Madi transect there currently is no other evidence for faults in Greater Himalayan rocks. In the Marsyangdi valley, Huntington & Hodges (2006) tentatively suggested the presence of a thrust at a position consistent with a location between the northern (3 Ma) and middle (6 Ma) samples. If present, the faults in the Madi, Madi and Marsyangdi transects must have experienced significant slip at different times because of the small or non-existent overlap of the muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages from the three transects. There is no alternation of ages in the Seti river valley nor on Nayu ridge, although it is important to note that we might not have samples from far enough north to detect this pattern (Fig. 2). A greater number of major thrusts within Greater Himalayan rocks could explain the eastward increase in the structural thickness of the components of the Greater Himalayan rocks (Fig. 2).

Conclusions

We interpret all but one of our new muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages to date the time of cooling through the closure temperature for diffusive argon loss. The lone exception is the c. 10 Ma date from Modi river valley sample 502056, which we interpret to reflect the time of crystallization of muscovite below its closure temperature due to a (hydro) thermal event.

Combining our new ages with previously published data reveals that muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages in Greater and Lesser Himalayan rocks decrease by 4–14 myr and 2–5 myr, respectively, from the western to the eastern Annapurna (Figs 2 & 5). The likely causes of this trend are tilting due to the geometry of a frontal ramp in the thrust that underlies these rocks and/or motion on a cross-cutting, NE-trending fault. If thrusting up a frontal
ramp explains the decrease in ages, the ramp must be higher in the west and/or oriented oblique to the hanging-wall transport direction (Fig. 6). The drop in Greater Himalayan muscovite cooling ages between the Modi and Seti river valleys raises the possibility that a heretofore unrecognized cross-fault cut the rocks between these valleys (Figs 2 & 5). Subduction of the Faizabad ridge, a Palaeoproterozoic horst in the incoming Indian upper crust, could explain the along-strike changes in the geometry of the frontal ramp as well as the presence of the cross-fault.

In the Modi river valley, two samples separated by only 200 m structural distance yielded a northward, up-section increase in muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from c. 13 and 10 Ma to c. 18 and 16 Ma for grain sizes of approximately 750 and 200 μm, respectively (Figs 3 & 4). The large age differences across such a small distance confirm the existence of the Bhanuwa fault between these two samples. If the fault dips north, as suggested by previous workers, the older ages indicate slower cooling of the hanging wall, which suggests normal sense motion on the Bhanuwa fault (Fig. 7).

Unlike for the Bhanuwa fault, our compilation of previously published muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ and white mica K–Ar ages reveals no jump in ages across the South Tibet detachment (Fig. 2). In the Kali Gandaki valley in the western Annapurna the cooling ages overlap at c. 13 Ma, whereas in the Marsyangdi valley in the eastern Annapurna the cooling ages overlap at c. 18 Ma. The age similarity across the detachment indicates that either it was nearly horizontal during slip at this time or it was at most minimally active.

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