Online supplement for Martin et al.

Methods

Martin collected samples from outcrops of Lesser and Greater Himalayan rocks across the center portion of the Annapurna Range (Fig. 2). For samples from the Modi and Madi river valleys, thin sections were cut perpendicular to foliation and parallel to lineation if present. We did not make thin sections from the samples from the Seti and Nayu ridge transects. Micas from samples 502067 and 406042 were analyzed at the University of Alaska Fairbanks Geochronology Facility. Muscovite from the remaining samples was processed at the University of Houston and analyzed at the New Mexico Geochronology Research Laboratory at the New Mexico Institute of Mining and Technology.

The micas analyzed from the Modi Khola transect were found to be muscovite and biotite by Martin et al. (2010) and Corrie and Kohn (2011). Because non-muscovite white mica is rare in Unit I and Unit III Greater Himalayan rocks in the Annapurna Range (Vannay and Hodges, 1996; Catlos et al., 2001; Martin et al., 2010; Corrie and Kohn, 2011), for convenience we use the term "muscovite" for all analyzed white mica from all samples.

All samples except 502067 and 406042

Each sample was crushed and muscovite was separated using standard dense liquid, magnetic, and hand picking techniques at the University of Houston. Analyzed muscovite grains passed through a 60 mesh (250 μm) sieve but were retained in an 80 mesh (177 μm) sieve. For convenience, in the main text we refer to this grain size as approximately 200 μm. Our samples were separated, irradiated, and analyzed as part of a batch that included the samples discussed in Robinson et al. (2006). Multiple grains comprised the aliquots for all samples; the mass of each aliquot was 4-10 mg. Muscovite separates were loaded into aluminum disks and irradiated for nine hours in the D-3 position in the 1 MW reactor at the Nuclear Science Center at Texas A&M University in College Station, Texas, USA (NM-174). Grains of Fish Canyon Tuff sanidine (FC-2) with an assigned age of 28.02 Ma (Renne et al., 1998) were included with the unknowns to monitor neutron flux. The irradiation parameter (J) for each sample was determined to a precision of 0.3% (1-sigma) by carbon dioxide laser fusion of six single sanidine crystals from each of six radial positions around the sample tray. Shards of K-glass and CaF_2 were used to measure correction factors for interfering nuclear reactions. These factors were: $(^{40}Ar/^{39}Ar)_K$ = 0 ± 0.0004, $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00028 ± 0.00001, and $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070 ± 0.00005.

During analysis at the New Mexico Institute of Mining and Technology, each sample was heated in a molybdenum resistance furnace with a temperature precision of 5 °C (Sanders et al., 2006). Reactive gases were removed during a nine-minute heating period with an SAES GP-50 getter operated at about 450 °C. Isotopic ratios were measured on line with a Mass Analyzer Products 215-50 mass spectrometer equipped with an automated all-metal extraction system. The mean electron multiplier sensitivity was 2.80 x 10^{-16} moles/pA and total system blank plus background was 360, 1.5, 0.28, 0.015, and 1.2 x 10^{-17} moles for masses 40, 39, 38, 37, and 36, respectively. The one mass unit discrimination value was 1.0037 ± 0.0005 (1-sigma). Following heating, five minutes of cleanup removed residual gas prior to heating the next sample. This cleanup step used two SAES GP-50 getters, one at about 450 °C and the other at 20 °C. The integrated age is the age given by the total gas measured and is equivalent to a potassium/argon (K/Ar) age.

Samples 502067 and 406042

Samples 502067 and 406042 were crushed and sieved by hand at the University of Alaska Fairbanks geochronology facility. To preserve natural grain sizes, we first crushed the sample via gentle hammering in a stainless steel crucible, then we gently sieved the crushate. We separated micas following standard techniques. Three mica fractions were produced from each sample: muscovite that passed a 60 but not a 100 mesh (250-150 µm) sieve, muscovite that passed an 18 but not a 32 mesh (1000-500 µm) sieve, and biotite that passed a 60 but not a 100 mesh (250-150 µm) sieve. For convenience when discussing these size fractions we refer to them as approximately 200 and 750 µm. Each muscovite grain was picked by hand under a stereo-microscope to avoid biotite inclusions; further, the two approximately 200 µm aliquots were run through a Frantz magnetic separator at 1.1 amps numerous times to remove grains with biotite inclusions.

Each of the analyzed mica aliquots consisted of many grains (cumulatively about 0.1 mg per aliquot analyzed) except the approximately 750 µm muscovite separate from each sample; single, approximately 0.1 mg muscovite crystals were analyzed for these two aliquots. All six mica separates were wrapped in aluminum foil and loaded into aluminum cans with diameter 2.5

cm and height 6 cm. Then the samples were irradiated in position 5c of the uranium enriched research reactor of McMaster University in Hamilton, Ontario, Canada for 20 megawatt-hours. Neutron fluence was monitored using the mineral MMhb-1 (Samson and Alexander, 1987) with an age of 513.9 Ma (Lanphere and Dalrymple, 2000) for sample 502067 whereas the monitor mineral TCR-2 with an age of 27.87 Ma was used for sample 406042. TCR-2 sanidine is from the Taylor Creek Rhyolite (Duffield and Dalrymple, 1990). This monitor is a secondary standard calibrated against the primary intralaboratory standard, SB-3, with an age of 162.9 Ma (Lanphere and Dalrymple, 2000).

Upon their return from the reactor, the samples and monitors were loaded into 2 mm diameter holes in a copper tray that was then loaded in an ultra-high vacuum extraction line. The monitors were fused, and samples heated, using a 6-watt argon-ion laser following the technique described in York et al. (1981), Layer et al. (1987) and Layer (2000). Argon purification was achieved using a liquid nitrogen cold trap and a SAES Zr-Al getter at 400 °C. The samples were analyzed in a VG-3600 mass spectrometer at the Geophysical Institute, University of Alaska Fairbanks (Benowitz et al., 2013). The argon isotopes measured were corrected for system blank and mass discrimination, as well as calcium, potassium and chlorine interference reactions following procedures outlined in McDougall and Harrison (1999). Typical full-system 8 min laser blank values were generally $2x10^{-16}$ mol ^{40}Ar, $3x10^{-18}$ mol ^{39}Ar, $9x10^{-18}$ mol ^{38}Ar, and $2x10^{-18}$ mol ^{36}Ar, which are 10–50 times smaller than the sample/standard volume fractions. Correction factors for nucleogenic interferences during irradiation were determined from irradiated CaF_2 and K_2SO_4 as follows: $(^{39}Ar/^{37}Ar)_{Ca} = 7.06 \times 10^{24}$, $(^{36}Ar/^{37}Ar)_{Ca} = 2.79 \times 10^{24}$ and $(^{40}Ar/^{39}Ar)_K = 0.0297$. Mass discrimination was monitored by running calibrated air shots. The University of Alaska Fairbanks VG3600 has a positive bias toward measuring lighter isotopes. The one mass unit discrimination value was 0.9842 ± 0.0012 (1-sigma). While doing our experiments, calibration measurements were made on a weekly to monthly basis to check for changes in mass discrimination with no significant variation seen during these intervals.

The $^{40}Ar/^{39}Ar$ results are given in Table S1, with all uncertainties quoted at the ± 1 sigma level. Ages were calculated using the constants of Steiger and Jaeger (1977). The integrated age is the age given by the total gas measured and is equivalent to a potassium-argon (K/Ar) age.

Muscovite grain sizes observed in thin sections

Sample 502056: Muscovite and especially biotite define the foliation in this sample; many muscovite grains cut across the foliation (Fig. S1A). In some areas of the thin section, several crosscutting muscovite grains each have different orientations. The lengths of the crosscutting muscovite grains range from less than 100 μm to 240 μm.

Sample 502050: Biotite and muscovite define the foliation in this sample. Muscovite grains parallel to foliation have lengths of 100 μm to 5 mm; most muscovite crystals follow foliation. The very few muscovite crystals that unambiguously cut across foliation have lengths from 20 to 150 μm.

Sample 502067: Muscovite and biotite define the foliation in this sample. Most muscovite crystals are parallel to foliation; these grains have lengths of 100 μm to 2 mm (Fig. S1B). Rarely, the external shapes of muscovite grains cut across foliation; the lengths of these grains range from 200 to 700 μm. However, the internal cleavage in nearly all such grains appears crenulated, and in some cases the muscovite grain edges match these crenulations. The axial surfaces of these micro-folds are sub-parallel to the main foliation in the sample. We conclude that the formation of foliation in this rock deformed these grains. Finally, there are aggregates of muscovite composed of individual grains 20 to 60 μm long (arrows in Fig. S1B). These individual grains have a wide range of orientations and very few are sub-parallel to the foliation. In some cases the aggregates of fine muscovite are spatially associated with chlorite.

Sample 406042: Muscovite and biotite define the foliation in this sample. The vast majority of the muscovite grains are parallel to foliation; the lengths of these muscovites range from 100 μm to 3 mm (Fig. S1C). All except one of the muscovite grains that unambiguously cut across the foliation have lengths that range from 30 to 100 μm. The one exception is 140 μm long.

Sample 502071: Biotite and especially muscovite define the foliation in this sample. Most muscovite crystals are parallel to foliation; these grains are 100 μm to 5 mm long. There are also rare, up to 330 μm-long muscovite grains that cut across foliation and reacted with neighboring foliation-defining biotite and muscovite grains. Finally, unambiguously cross-cutting muscovite grains that did not obviously react with neighboring grains are rare and measure 40-190 μm long.

Sample 502079: Muscovite defines the foliation in this sample. The vast majority of muscovite crystals are parallel to the foliation; these grains have lengths of 50 to 500 µm. Muscovite grains that unambiguously cut across the foliation are 40 to 110 µm long; such grains are rare.

Sample 502121: Muscovite and especially biotite define the foliation in this sample. Muscovite grains parallel to the foliation are 100 µm to 1 mm long; these grains comprise the vast majority of muscovite in the sample. Rare muscovite crystals unambiguously cut across the foliation; these grains have lengths of 50 to 300 µm.

Sample 502127: Muscovite and biotite define the foliation in this sample. Most muscovite grains are parallel to the foliation; these grains have lengths of 100 µm to 2 mm. Rare muscovite crystals unambiguously cut across foliation; these grains are 50 to 150 µm long.

Sample 502132: Muscovite and biotite define the foliation in this sample. Most muscovite grains are parallel to the foliation; these grains are 100 µm to 2 mm long. Muscovite crystals that unambiguously cut across the foliation are very rare and range from 100 to 170 µm long.

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Supplemental figure captions

Figure S1. Photomicrographs in cross-polarized light of thin sections from Modi valley samples (A) 502056, (B) 502067 and (C) 406042. In all images the main foliation is oriented east-west. In A, a 240-µm long muscovite grain cuts across the foliation whereas other muscovite grains are parallel to the foliation. In B, 100- to 1000-µm long muscovite grains define the foliation, along with biotite. The arrows point to aggregates of muscovite grains that are not parallel to foliation. These grains have lengths of 20 to 60 µm. In C, the white arrow points to a 30-µm long muscovite grain that cuts across the foliation and the red arrow points to a 100-µm long intergrowth of biotite and muscovite that also cuts across the foliation. Muscovite grains larger than 140 µm invariably are parallel to the foliation. Mineral abbreviations: bt-biotite, kfs-potassium feldspar, ky-kyanite, ms-muscovite, pl-plagioclase feldspar, q-quartz.

Figures S2-S19. Plots showing ^{40}Ar/^{39}Ar, Ca/K, and Cl/K data from the micas analyzed in this study.