Summary of the $^{40}Ar/^{39}Ar$ Analysis

For $^{40}Ar/^{39}Ar$ analysis, samples were submitted to the Geochronology laboratory at UAF where they were crushed, sieved, washed and hand-picked for mineral phases. The monitor mineral MMhb-1 (Samson and Alexander, 1987) with an age of 513.9 Ma (Lanphere and Dalrymple, 2000) was used to monitor neutron flux (and calculate the irradiation parameter, J). The samples and standards were wrapped in aluminum foil and loaded into aluminum cans of 2.5 cm diameter and 6 cm height. The samples were irradiated in position 5c of the uranium enriched research reactor of McMaster University in Hamilton, Ontario, Canada for 30 megawatt-hours. 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 a 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). Bulk furnace-run samples were loaded in aluminum packets and step-heated in a Modifications Ltd. low-blank furnace connected on-line to the mass spectrometer. Temperature is calibrated by means of a thermocouple and a maximum temperature in excess of 1,600°C is achievable. Duplicated isothermal step-heating schedules were conducted on K-feldspar in order to retrieve diffusion characteristics, to apply diffusion models, and to calculate model thermal histories (Harrison et al., 1994; e.g. Lovera et al., 1993). Argon purification was achieved using a liquid nitrogen cold trap and a SAES Zr-Al getter at 400C. The samples were analyzed in a VG-3600 mass spectrometer at the Geophysical Institute, University of Alaska Fairbanks. 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 Harrision (1999). System blanks generally were $2x10^{-16}$ mol ^{40}Ar and $2x10^{-18}$ mol ^{36}Ar which are 10 to 50 times smaller than fraction volumes. Mass discrimination was monitored by running both calibrated air shots and a zero-age glass sample. These measurements were made on a weekly to monthly basis to check for changes in mass discrimination. A summary of all the $^{40}Ar/^{39}Ar$ results is given in repository Table A1, A2, and A5 with all ages quoted to the +/- 1 sigma level and 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. The spectrum provides a true plateau age if three or more consecutive gas fractions represent at least 50% of the total gas release and are within two standard deviations of each other (Mean Square Weighted Deviation less than ~2.7). Isochron ages are obtained on an inverse isochron diagram of $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ (Roddick, 1978; Roddick et al., 1980), which often allows homogeneous excess components to be identified. Errors on age and intercept age include individual errors on each point and linear regression by York's (1969) method. The goodness of fit relative to individual errors is measured by mean square weighted deviation (MSWD).

Minimum K-Spar Ages

K-spar data is shown in table A1. For most K-feldspars, plateau ages cannot be defined, but since we wish to compare and discuss a series of steps with similar ages we use minimum age isochron populations. This is similar to the minima potassium feldspar age used in bulk analysis by Copeland and Harrison (1990) using minimum age spectra steps. A similar isochron approach was also used to examine deformation along the Karakorum

Fault (Valli et al., 2007). We use the more robust isochron minimum population age, but show the pseudo simple-mean minimum age plateau for comparison. In summary the youngest isochron age grouping derived from either single grain K-spar laser runs (3) or bulk furnace runs (10) were considered to be the age of closure for the smallest domain (e.g. McDougall and Harrison, 1999; Valli et al., 2007).

MDD Models

MDD data is shown in figures A38 to A43. MDD thermochronology has proven a useful tool to examine orogenic development because of the wide closure temperature window (~350 °C to ~150 °C) of the system (McDougall and Harrison, 1999). K-spar MDD thermochronology is also useful due to the deep depth for closure (~5 km) of the system minimizing the affect of topography influencing the temperature field of the upper crust (Ehlers, 2005). MDD thermal models were created using software developed by Lovera et al. (1993). Low temperature steps were adjusted to account for the likely presence of fluid-inclusion hosted excess Ar leading to older apparent ages. In many cases, the first step of an isothermal duplicate yielded a significantly older age than the second step, consistent with the presence of fluid-inclusion hosted excess Ar (Harrison et al., 1994). Although this pattern is consistent with the presence of fluid-inclusion hosted excess Ar, corrections using the equations from Harrison et al. (1994) did not yield usable results as was the case for Sanders et al., (2006). We used the isothermal correction technique outlined in Sanders et al., (2006) whereas they took the average age of the step before and the step after an apparent old age as an estimate of the excess Ar correction.

See, GSA Data Repository item 2006190 (Sanders et al., 2006) for a detailed and extensive discussion on MDD modeling.

<u>Fission-track analyses</u>: Apatite fission-track (AFT) data are shown in Table A3. All the fission-track ages measured with external detector method in Armstrong's fission track lab at Cal State Fullerton. Apatite grains were mounted in epoxy and ground/polished to reveal internal parts of the grains. Apatite grain mounts were etched in 5 M HNO_3 for 20 s at 21 ^{o}C. Grain mounts were affixed with low-uranium muscovite micas and irradiated at the TRIGA reactor facility at Oregon State University. After irradiation, track densities were measured at 1250x and track length and Dpar measured at 2000x. See Table 2 for additional measurement parameters.

Between 18 and 40 grains were measured per sample. P(□^{2}) is > 23% in all samples indicating that the individual grain ages show little age dispersion. Track lengths were difficult to find in these young samples, thus the length data may be statistically insignificant for most of the samples. Nonetheless, track lengths are ~12 – 14 □m. Dpar was measured on each age-dated grain. The average sample Dpar varies from 1.36 to 2.02 □m with the largest Dpar measured on the oldest AFT age sample. The highest Dpar value is on for the sample (05PH003A) with the largest AFT age indicating that the apatites in this sample may be more resistant to annealing and hence give a higher age. However, the Dpar difference between the samples (1.36 – 2.02 □m) is great enough to account for only a very small part of the 3- to 5-fold age difference between the samples.

Apatite (U-Th)/He and fission-track age data

Methods and results

The apatites for this study were separated using standard mineral separation techniques including crushing, sieving, water table, magnetic separator, and heavy liquids.

(U-Th)/He analyses: AHe data is shown in Tabe A4. Euhedral, inclusion-free apatite crystals were hand-picked in alcohol under cross-polars at 110x. Grain dimensions were measured for a-emission correction (Farley et al., 1996) and each grain was individually loaded into Pt tube for He extraction. Samples were outgassed under a laser at 1100°C. After spiking with 3He, the 4He/3He ratio was measured on a quadrapole mass spectometer. Grains were then dissolved in nitric acid and analyzed for Th, U, and Sm isotope ratios by ICPMS. All analytical work was completed at in Ken Farley’s lab at Caltech.

Analytical uncertainties on individual (U-Th)/He age is ~2%. However, the actual age uncertainty based on replicate analyses of individual grains from same samples is higher. In three of the samples, three individual grain ages were determined per sample (Table 1); in these replicate samples, the average standard error is about 12% of the mean (at 1 □). In the sample with only one grain age (PH-06A), the mean uncertainty of 12% is used.

AHe/AFT closure temperatures

The AHe ages represent the time since the samples cooled through a closure temperature of 60-70 °C (Farley, 2000). The AFT ages represent the time since the samples cooled through a closure temperatures of about 100 – 120 °C (e.g., Ketcham et al., 1999), for typical apatites and monotonic cooling at rates typical of active mountain belts (Reiners and Brandon, 2006).

Supplemental References:

Copeland, P., Harrison, T.M., 1990, Episoidic rapid uplift in the Himalaya revealed by $^{40}Ar/^{39}Ar$ analysis of detrtial K-feldspar and muscovite, Bengal fan: Geology, v. 18, p. 354-357.

Ehlers T (2005), Crustal thermal processes and the interpretation of thermochronometer data. Rev Mineral Geochem 58:315-350

Farley, K.A., 2000, Helium diffusion from apatite: General behavior as illustrated by Durango apatite: Journal of Geophysical Research, v. 105, p. 2903–2914, doi: 10.1029/1999JB900348.

Farley, K.A., R.A. Wolf, and L.T. Silver, 1996, The effects of long alpha-stopping distances on (U-Th)/He ages, Geochimica et Cosmochimica Acta, 60, 4223-4229.

Galbraith, R.F., 1981, On statistical methods of fission track counts, Mathematical Geology, 13, 471-478.

Galbraith, R.F., and G.M. Laslett, 1993, Statistical models for mixed fission track ages, Nuclear Tracks and Radiation Measurements, 21, 459-470.

Harrison, T.M., M.T. Heizler, O.M. Lovera, Wenji Chen, and M.A. Grove (1994), Chlorine disinfectant for excess argon released from K-feldspar during step heating, Earth Planet. Sci. Lett., 123, 95-104.

Ketcham, R.A., Donelick, R.A., Carlson, W.D., 1999, Variability of apatite fission-track annealing kinetics. III. Extrapolation to geological time scales, American Mineralogist, v. 84, 1235-1255.

Lanphere, M.A., and Dalrymple, G.B., 2000, First-principles calibration of ^{38}Ar tracers: Implications for the ages of $^{40}Ar/^{39}Ar$ fluence monitors, U.S. Geological Survey Professional Paper 1621, 10 p.

Layer, P.W., 2000, Argon-40/argon-39 age of the El'gygytgyn impact event, Chukotka, Russia, Meteroitics and Planatary Science, v. 35, 591-599.

Layer, P.W., Hall, C.M. & York, D., 1987. The derivation of ^{40}Ar/^{39}Ar age spectra of single grains of hornblende and biotite by laser step heating, *Geophys. Res. Lett.,* **14**, 757-760.

Lovera, O.M., Heizler, M.T., and Harrison, T.M., 1993, Argon diffusion domains in K-feldspar 11: Kinetic properties of MH-10: Contributions to Mineralogy and Petrology, v. 1 13, p. 381-393.

McDougall, I. and Harrison, T.M., 1999, Geochronology and Thermochronology by the 40Ar/39Ar method-2nd ed, Oxford University Press, New York, 269pp.

Reiners PW, Ehlers TA, eds. 2005. Low-Temperature Thermochronology: Techniques, Interpretations, Applications. Reviews in Mineralogy and Geochemistry, Vol. 58. Chantilly, VA: Mineral. Soc. Am., Geochem. Soc. pp. 622

Reiners, PW., Brandon, M.T., 2006, Using thermochronology to understand orogenic erosion, Annual Review of Earth and Planetary Science, v. 34, 419-466.

Roddick, J. C. (1978), The application of isochron diagrams in 40Ar_39Ar dating, a discussion, Earth Planet. Sci. Lett., 41, 233 – 244.

Roddick, J. C., R. A. Cliff, and D. C. Rex (1980), The evolution of excess argon in alpine biotites, a 40Ar/39Ar analysis, Earth Planet. Sci. Lett., 48, 185 – 208

Samson S. D., and Alexander E. C. (1987) Calibration of the interlaboratory 40Ar/39Ar dating standard, MMhb1. Chem. Geol. **66**, 27-34.

Sanders, R.E., Heizler, M.T., and Goodwin, L.B., 2006, 40Ar/39Ar thermochronology constraints on the timing of Proterozoic basement exhumation and fault ancestry, southern Sangre de Cristo Range, New Mexico: Geological Society of America Bulletin, v. 118, no. 11–12, p. 1489–1506, doi: 10.1130/B25857.1.

Steiger, R.H. and Jaeger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo and cosmochronology, Earth and Planet Science Letters, v. 36, p. 359-362.

Spotila, J.A., Niemi, N., Brady, R., House, M., and Buscher, J., 2007, Long-term continental deformation associated with transpressive plate motion: The San Andreas fault: Geology, v. 35, p. 967–970, doi: 10.1130/G23816A.1.

Valli, F., Arnaud, N., Leloup, P., Sobel, E., Mahéo, G., Lacassin, R., Guillot, S., Li, H., Tapponnier, P., and Xu, Z., 2007, Twenty million years of continuous deformation along the Karakorum fault, western Tibet: a thermochronological analysis, Tectonics 26 10.1029/2005TC001913.

York, D. (1969), Least squares fitting of a straight line with correlated errors, Earth Planet. Sci. Lett., 5, 320 – 324.

York, D., Hall, C.M., Yanase, Y., Hanes, J.A. & Kenyon, W.J., 1981. $^{40}Ar/^{39}Ar$ dating of terrestrial minerals with a continuous laser, *Geophys. Res. Lett.*, **8**, 1136-1138.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms and aberrations in global climate 65 Ma to Present: Science, v. 292, p. 686–693.

Supplemental Figure File

Figures A1 to A19: $^{40}Ar/^{39}Ar$ age spectra, K/Ca ratios and Cl/K ratios for all hornblende, muscovite and biotite analyses.

Figures A20 to A37: $^{40}Ar/^{39}Ar$ age spectra and inverse isochron plots for all K-spar analyses.

Figures A38 to A43: Arrhenius plot, measured, Cl corrected and modeled $^{40}Ar/^{39}Ar$ age spectra, monotonic multiple diffusion domain (MDD) thermal models generated for K-feldspar from samples 32NEN, 22DEB, 03BAL, 26BAL, 18BAL and 03RAP.

Supplemental Tables

Supplemental Table 1. $^{40}Ar/^{39}Ar$ data from Potassium Feldspar
Supplemental Table 2. $^{40}Ar/^{39}Ar$ and K-Ar data from biotite, muscovite and hornblende
Supplemental Table 3. Apatite Fission Track Analysis
Supplemental Table 4. Apatite U-Th/He data
Supplemental Table 5. $^{40}Ar/^{39}Ar$ data for biotitie, muscovite, hornblende and K-spar.