<u>DATA REPOSITORY:</u> Jessup et al., in rev., "Orogen-parallel extension and exhumation enhanced by denudation in the trans-Himalayan Arun River gorge, Ama Drime Massif, Tibet-Nepal"

APPENDIX DR-1: Thermochronologic methods and results

Low-temperature thermochronometry was used to constrain the exhumation pattern across the Ama Drime Massif. New (U-Th)/He ages of apatite (AHe) were obtained from bedrock samples collected along two east-west transects across the range. Samples used consisted mainly of leucogranite and gneiss. (U-Th)/He dating is based on the radiogenic production and thermally-controlled diffusion of ^{4}He within host minerals. Apparent AHe cooling ages typically correspond to closure temperatures of ~70 ˚C, but closure temperature is cooling-rate and grain-size dependent (Wolf et al., 1996; Farley, 2000; Ehlers and Farley, 2003).

AHe ages were measured at Virginia Tech on 2-25 grain, ~0.01-0.08 mg aliquots (Table DR-1). Apatite grains dated were ≥70 μm in diameter and were screened for micro-inclusions and other crystal defects at 100x magnification. To counter the potential effect of U- and Th-bearing micro-inclusions (i.e. zircon and monazite (House et al., 1997)), fluid inclusions, or parent nuclide zonation on measured ages (Fitzgerald et al., 2006), we analyzed multiple (~4) replicates per sample (a total of 39 analyses for 11 samples). This enabled evaluation of sample reproducibility and identification of anomalously old outliers that likely have ^{4}He contamination. Samples were outgassed in Pt tubes in a resistance furnace at 940 ˚C for 20 minutes (followed by a 20-minute reextraction test) and analyzed for ^{4}He by isotope dilution utilizing a ^{3}He spike and quadrupole mass spectrometry. Blank levels for ^{4}He detection using current procedures at Virginia Tech are ~0.2 femtomoles. Radiogenic parent isotopes (^{238}U, ^{235}U, and ^{232}Th) were measured at the University of Arizona using isotope dilution (^{235}U and ^{230}Th spike) and ICP mass spectrometry. Although ^{4}He is also produced by ^{147}Sm decay, it was not routinely measured because it should produce <1% of radiogenic ^{4}He in typical apatite and should only be a factor in AHe ages when U concentrations are <5 ppm (which applies to none of our samples; Table DR1) (Farley and Stockli, 2002; Reiners and Nicolescu, in press).

Routine 1σ uncertainties due to instrument precision are ±1-2% for U and Th content, ±2-3% for He content, and ±4-5% for alpha ejection correction factor based on grain dimension and shape. Cumulative analytical uncertainty is thus approximately ±10% (2σ). Age accuracy was cross-checked by measurements of known standards, such as Durango fluorapatite (30.9±1.53 Ma (1σ; n=40)), with a known age of 31.4 Ma (McDowell et al., 2005)). These measurements on Durango show that reproducibility on some natural samples is comparable to that expected from analytical errors. Uncertainties for samples are reported as the observed standard deviation from the mean of individual age determinations (Table DR-1). The average AHe reproducibility on well-reproduced average ages is ~11% (1σ), which is worse than that obtained from Durango apatite. This excludes two individual age determinations for MJAD19, which were considerably older than other replicates and thus considered to be outliers. These may have been affected by excess ^{4}He associated with micro-inclusions.

Average AHe ages for two samples appear too old given other regional cooling age data. AHe ages for MJAD26 and MJAD19 are 17.3 and 32.8 Ma, respectively, and exceed regional ^{40}Ar/^{39}Ar muscovite, biotite, and K-feldspar ages (~19-10 Ma) from both the footwall and hangingwall of the normal fault bounding the eastern flank of the Ama Drime Massif (Hodges et al., 1994; Zhang and Guo, 2007). Given the higher closure temperature for ^{40}Ar/^{39}Ar in these minerals, we would expect AHe ages to be considerably younger. MJAD19 reproduced poorly, and may be affected by ^{4}He contamination associated with micro-inclusions (Table DR-1). We thus disregard this AHe age and do not use it in our interpretations. MJAD26 reproduced better, and is closer to fitting the ^{40}Ar/^{39}Ar constraints. If the youngest AHe age determination from this sample (13.8 Ma) is more accurate than the two older replicates (Table DR-1), it would fit with the Ar^{40}/Ar^{39} ages and suggest that cooling was rapid through ^{40}Ar/^{39}Ar and AHe closure temperatures in the Middle Miocene. It would also suggest that AHe ages become older towards the eastern edge of the massif. This would imply that the massif is a tilted normal fault block and that the increase in AHe age with elevation (Fig. 3) is due in part to an increase in AHe age to the east associated with eastward isochron tilting. Although this could place an important constraint on the kinematics of block uplift, additional data are required to document this apparent tilting.

Ignoring the suspect average ages for MJAD19 and MJAD26, AHe ages increase roughly with elevation (Fig. 3). The farthest outlier from this relationship is MJAD40 (3.29 Ma), which reproduced poorly (Table DR-1). The AHe ages of the five lowest samples excluding MJAD40 define an elevation-age trend of ~1 mm/yr (R^2 = 0.95) (Fig. 3). This elevation-age gradient may represent the exhumation rate for the Ama Drime Massif for the past few Myr. This rate is not corrected for isochron tilting, however, and would be higher if the massif has tilted significantly to the east since AHe closure. The

AHe ages from the three highest samples do not fit the elevation-age trend very well, although their large error bars are nearly intersected by the projected line. It is possible that the elevation-age gradient flattens to intersect these higher samples, such that the exhumation rate prior to ~2-3 Ma was slower (illustrated by the dashed line, Fig. 3). A slightly higher recent exhumation rate is obtained assuming a closure temperature approach. Assuming a geothermal gradient of ~30 ˚C/km and a closure temperature of ~80 ˚C (Farley, 2000) for MJAD1 (1.44 Ma), the recent exhumation rate may have been as high as ~2 mm/yr. Given the limited sample coverage, potential eastward isochron tilting, and potential effects of topography and advection on shallow isotherms (Mancktelow and Grasemann, 1997; Reiners and Brandon, 2006), however, more data and analysis are required to better constrain the exhumation history of the Ama Drime Massif.

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<u>Table DR-1:</u> AHe data.

Sample	Elev. (m)	Latitude	Longitude	Lithology	# Grains	Mass (mg)	Ft	U ppm	Th ppm	MWAR	He pmol	Age (Ma)	Avg. (Ma)	% SD
MJAD1-1	3435	28.1000°	87.3665°	felsic granite	2	0.0228	0.828	51.3	5.4	83.0	0.0062	**1.19**	**1.44±0.15**	±10.4%
-2					10	0.0223	0.731	46.2	10.7	49.2	0.0059	**1.44**		
-3					10	0.0196	0.703	55.0	6.3	46.5	0.0063	**1.55**		
-4					10	0.0215	0.732	66.4	7.2	51.2	0.0087	**1.56**		
MJAD10-1	4418	28.0886°	87.4830°	leucogranite	11	0.0177	0.692	42.9	3.3	44.7	0.0059	**2.10**	**2.34±0.21**	±9.1%
-2					10	0.0152	0.710	57.9	3.4	42.3	0.0072	**2.18**		
-3					10	0.0164	0.702	56.6	3.8	44.2	0.0091	**2.64**		
-4					9	0.0211	0.782	50.7	4.3	55.8	0.0109	**2.44**		
MJAD13-1	5024	28.1176°	87.5673°	leucogranite	9	0.0279	0.771	8.7	18.5	50.9	0.0092	**6.23**	**4.79±1.10**	±23.0%
-2				dike	2	0.0242	0.854	4.9	19.8	84.6	0.0037	**3.56**		
-3					11	0.0258	0.762	7.7	27.6	50.2	0.0068	**4.58**		
MJAD14-1	5104	28.1334°	87.5864°	gneiss	11	0.0839	0.816	33.0	2.2	77.6	0.0441	**3.69**	**4.50±0.51**	±11.4%
-2					25	0.0505	0.706	37.4	3.0	44.9	0.0320	**4.50**		
-3					15	0.0467	0.758	31.7	2.3	54.3	0.0282	**4.72**		
-4					15	0.0599	0.760	33.1	2.1	57.1	0.0406	**5.09**		
MJAD19-1	4950	28.1190°	87.6449°	gneiss	7	0.0183	0.770	12.6	8.0	55.5	0.0359	**33.5**	**32.8±0.75***	±2.3%
-2					6	0.0211	0.794	10.1	8.1	59.4	0.0336	**32.0**		
-3					20	0.0269	0.691	4.9	5.1	42.5	0.0559	*94.1*		
-4					14	0.0325	0.744	5.7	4.3	51.9	0.0531	*62.4*		
MJAD26-1	5108	28.1181°	87.6322°	leucogranite	10	0.0106	0.693	17.9	2.6	38.9	0.0098	**13.8**	**17.3±2.44***	±14.1%
-2					9	0.0109	0.719	15.4	1.9	40.3	0.0122	**18.9**		
-3					5	0.0090	0.741	14.6	1.3	49.6	0.0099	**19.1**		
MJAD28-1	5580	28.1637°	87.5661°	leucogranite	13	0.0229	0.709	79.1	4.3	46.9	0.0285	**4.20**	**4.16±0.22**	±5.3%
-2					11	0.0215	0.719	59.9	4.1	47.4	0.0190	**3.87**		
-3					11	0.0172	0.701	70.9	5.1	43.6	0.0200	**4.41**		
MJAD29-1	4814	28.1991°	87.5043°	gneiss	13	0.0290	0.734	56.2	3.0	50.3	0.0175	**2.77**	**2.73±0.04**	±1.4%
-2					11	0.0262	0.740	53.8	2.9	50.8	0.0150	**2.73**		
-3					11	0.0293	0.753	55.4	2.8	51.9	0.0172	**2.67**		
-4					9	0.0228	0.732	51.6	7.6	50.0	0.0128	**2.76**		
MJAD30-1	4813	28.2169°	87.4693°	leucogranite	10	0.0258	0.755	65.2	21.4	47.5	0.0182	**2.54**	**2.62±0.11**	±4.1%
-2				dike	10	0.0255	0.773	59.6	20.5	51.9	0.0184	**2.78**		
-3					9	0.0281	0.795	68.1	21.1	59.0	0.0225	**2.64**		
-4					7	0.0255	0.785	66.6	22.0	56.2	0.0187	**2.50**		
MJAD36-1	4602	28.2254°	87.4334°	gneiss	7	0.0088	0.676	71.1	1.6	40.5	0.0081	**3.62**	**2.77±0.62**	±22.4%
-3					8	0.0082	0.664	85.5	2.1	38.2	0.0062	**2.53**		
-4					3	0.0063	0.740	64.7	0.6	52.0	0.0034	**2.16**		
MJAD40-1	3959	28.2380°	87.3828°	leucogranite	13	0.0145	0.709	119	4.5	37.5	0.0248	**3.85**	**3.29±0.55**	±16.7%
-2				dike	9	0.0106	0.700	155	8.3	39.0	0.0211	**3.47**		
-3					10	0.0123	0.710	160	3.1	38.8	0.0185	**2.54**		

Ages in italics were considered outliers and not used for average age calculation.
Elev. (m) – sample elevation
MWAR – mass weighted average radius of sample (μm)
% SD – standard deviation of average age as percentage of the average age
Ft – alpha ejection correction after Farley et al. (1996)
Avg. – average AHe age (Ma)
* – denotes poorly constrained age not used in interpretatio