Persistent long-term (c. 24 Ma) exhumation in the Eastern Alaska Range constrained by stacked thermochronology

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Abstract: To address Miocene–present episodic v. persistent exhumation, we utilize a simple graphical procedure that vertically stacks spatially diverse K-feldspar 40Ar/39Ar multi-domain diffusion (MDD) models from the length of the approximately 100 km-long high-peak region of the Eastern Alaska Range. We supply additional constraints with 40Ar/39Ar mica dating because the higher closure-temperature-window places limits on the initiation of rapid Eastern Alaska Range exhumation. We also provide a broad 40Ar/39Ar K-feldspar minimum closure age data set to add more detail on spatial patterns in the regional exhumation history for the Eastern Alaska Range. We find that rapid and persistent exhumation has occurred in the Eastern Alaska Range since about 24 Ma at a long-term rate of approximately 0.9 km/Ma, but that this rapid exhumation is spatially variable through time. Onset of rapid Eastern Alaska Range exhumation is coincident with the initiation of rapid exhumation in SW Alaska, the Western Alaska Range and the Chugach–Saint Elias Range at around 25 Ma, implying a region-wide deformational response to a change in tectonic forcing. The initiation of highly coupled flat-slab subduction of the Yakutat microplate is probably responsible for this prolonged period of rapid exhumation in southern Alaska.

Supplementary material: Sample locations from the Eastern Alaska Range, and 40Ar/39Ar data tables and age spectrum figures are available at www.geolsoc.org.uk/SUP18603.

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Thermochronology has now been used for over 30 years (see Reiners et al. 2005) to study orogenic development. Many data interpretation methods regarding orogenic tectonothermal histories have been standardized; including the time-averaged time–temperature (T–t) plots of one sample (McAleer et al. 2009) or numerous samples from one vertical mountain transect (Fitzgerald et al. 1993). Typically, any significant changes in time-averaged cooling rates (i.e. breaks in slope in T–t plots) based on these results combined with other geological evidence of unroofing are interpreted to indicate changes in exhumation rate (Batt et al. 2004). These changes in exhumation rate, also known as ‘events’ or ‘episodes’, are usually interpreted to reflect either large-scale changes in tectonic forcing or variations in near-field (local) conditions that may influence exhumation (e.g. climate, fault geometry, lithology: Buscher & Spotila 2007). Yet, tectonic processes (e.g. continental collision) produce exhumation that can occur over long timescales (10–50 Ma) and great distances (hundreds to thousands of km: e.g. Zhu et al. 2005). In addition, along-strike variations in the focus of exhumation are seen across the world (e.g. Little et al. 2005; Yin 2006; Tricart et al. 2007; Seeber et al. 2010). Thus, orogen-scale interpretations of tectonic processes based on thermochronological analyses of a single vertical transect (Fitzgerald et al. 1993; O’Sullivan & Currie 1996; Haeussler et al. 2008) or a single rock sample (Richter et al. 1990) may not capture the spatial and temporal variability inherent to broad-scale orogenesis. Although spatially restricted sampling for thermochronology can provide first-order information on the timing of orogenesis, can the total exhumation history of an orogen be constrained by such a practice? In addition, a single traverse, vertical profile or sample may contain biased or no information regarding orogenesis due to one or more thermochronometers not being in record mode during crustal movement.

One approach for capturing along- and across-strike variations in deformation response in complicated tectonic settings is to apply a ‘shotgun’ sampling strategy (Spotila 2005). Interpreting
cooling age data from shotgun sampling strategy in terms of episodic or persistent exhumation is critical to correlating an orogen’s exhumation history to far-field tectonic processes. Thus, a need remains for developing approaches that capture the ‘big-picture’ tectonic development of orogens that have experienced subregional-varying exhumation histories.

We have investigated these orogenic development/plate-tectonic reconstruction difficulties along the continental-scale transpressional Denali Fault in the topographically high Eastern Alaska Range (Figs 1 & 2), and use a simple graphical procedure to view an orogen’s exhumation history through time and space. Thermochronological research on the Neogene tectonic history of southern Alaska has led to the interpretation of exhumation pulses at approximately 25, 23, 20, 18, 16, 11, 6, 4 and 1 Ma (Plafker et al. 1992; Fitzgerald et al. 1995; O’Sullivan & Currie 1996; Berger et al. 2008; Enkelmann et al. 2008; Haeussler et al. 2008; Spotila & Berger 2010). Palaeo-environmental analysis of Alaska’s sedimentary basins also suggests that pulses of exhumation occurred during the Miocene–present (Lagoe et al. 1993; Thoms 2000; Ridgway et al. 2007; Haeussler et al. 2008; Finzel et al. 2009). What is still not clear is whether the Neogene exhumation history of southern Alaska is a series of discrete events or part of a continuum related to on-going long-term tectonic processes such as the progressive highly coupled flat-slab subduction of the Yakutat microplate into the North American plate (Fig. 1).

To address the continuous v. episodic nature of exhumation in southern Alaska, we employ $^{40}$Ar/$^{39}$Ar K-feldspar (K-spar) thermochronology combined with $^{40}$Ar/$^{39}$Ar muscovite and $^{40}$Ar/$^{39}$Ar biotite analysis of 50 samples collected across and along the Eastern Alaska Range. These thermo-chronometers span a closure temperature range of approximately 150–450 °C. Thus, muscovite, biotite and K-spar record exhumation from a broad range of crustal depths, thereby providing a large amount of $T$–$t$ information to allow us to assess whether orogenesis was persistent or episodic. We vertically stack numerous best-fit K-spar MDD thermal models (Lovera et al. 2002) (herein referred to as ‘vertical stacking’ or ‘stacked thermochronology’) to account for spatial variations in the focus of exhumation of an orogen.

![Fig. 1. Tectonic map of southern Alaska (modified from Haeussler et al. 2000). Major faults, tectonic plates and tectonic blocks are labelled. Yakutat–North America plate motion (solid arrow) is from Fletcher & Freymueller (2003). The present location of the subducted Yakutat slab beneath the continental margin is denoted (after Eberhart-Phillips et al. 2006). A detailed digital elevation model of the segmented Alaska Range flooded to 1000 m to emphasize topography. The main topography of the Western and Central Alaska Range is south of the Denali Fault. The main topography in the Eastern Alaska Range is north of the Denali Fault. The rectangle delineates the study area in the Eastern Alaska Range along the Denali Fault shown in Figure 2. WAR, Western Alaska Range; CAR, Central Alaska Range; EAR, Eastern Alaska Range; DF, Denali Fault; NR, Nenana River; DR, Delta River; TR, Tok River; WVF, Wrangell volcanic field. Mount McKinley (Denali) and Mount Kimball locations are noted. The small digital elevation model includes all of Alaska. SW, SW Alaska samples; CW, Cottonwood Metamorphic Complex.](image)
We show that rapid exhumation in the Eastern Alaska Range began by the late Oligocene and that it continues to the present. At the regional scale, our data indicate that, at any snapshot in time, rapid exhumation was occurring somewhere in the orogen throughout the Neogene at a relatively consistent rate of about 0.9 km/Ma. However, at the local scale, the focus of rapid exhumation varied in timing depending on the location. We infer that deformation and exhumation have been occurring in southern Alaska for at least about 25 Ma, and are related to the progressive collision via highly coupled flat-slab subduction of the Yakutat microplate with North America.

Tectonics and exhumation in southern Alaska

The Alaska Range lies along the continental-scale dextral strike-slip Denali Fault (Figs 1 & 2). This intraplate region is located approximately 500 km inboard from the active subduction zone of southern Alaska. Suggested drivers for Neogene deformation in the Alaska Range are changes in Pacific plate motion relative to stable North America (Fitzgerald et al. 1995; Enkelmann et al. 2008), Yakutat microplate collision in the Gulf of Alaska (Plafker et al. 1992) and block rotation associated with the Yakutat microplate flat-slab subduction/collision (Fig. 1) (Cross & Freymueller 2008; Haeussler 2008). A variety of studies have used thermochronology to examine the possibility of these as the drivers of Alaska Range exhumation, and we summarize them to provide context for the debate about continuous v. episodic exhumation. We discuss them in terms of the western, central and eastern parts of the Alaska Range (Fig. 1).

Western Alaska Range

The Tordrillo Mountains contain the area of high peaks in the Western Alaska Range (Fig. 1), and the rocks preserve evidence of rapid exhumation at approximately 23 and 6 Ma based on apatite fission track (AFT) thermochronology and an earlier Eocene exhumation event based on $^{40}$Ar/$^{39}$Ar K-feldspar thermochronology (Haeussler et al. 2008; Benowitz et al. 2012a). The approximately 23 Ma exhumation pulse is thought to be controlled by regional uplift and is corroborated by the high-energy depositional environment of the early Miocene Tyonek Formation of Cook Inlet (Stricker & Flores 1996). The approximately 6 Ma exhumation pulse is also thought to be controlled by regional uplift and is corroborated by the eustatic Pliocene Sterling Formation (Haeussler et al. 2008).

Central Alaska Range

The Central Alaska Range is defined by the Mt McKinley region (Fig. 1) and is the site of one
of the landmark vertical-transect AFT studies (Fitzgerald et al. 1993). The results clearly indicate a change in exhumation rate at approximately 6 Ma, which is interpreted as the beginning of the uplift of the Central Alaska Range. The exhumation event is correlated with the inferred depositional age of the 1000 m-thick Nenana Gravel of the Tanana Basin, located about 150 km to the east (Wahrhaftig et al. 1994). The question remains whether the limited spatial scope of the Fitzgerald et al. (1993) study (restricted to Mt McKinley, with no samples dated from the vicinity of the Denali Fault) was sufficient to capture the full exhumation history of the region considering the large variation in exhumation patterns found in other major orogens (e.g. Little et al. 2005; Yin 2006; Tricart et al. 2007).

**Eastern Alaska Range**

The Eastern Alaska Range as defined here spans the area between the Nenana River in the west and the Tok River valley in the east (Figs 1 & 2). Uranium–lead zircon emplacement ages of approximately 70 Ma were obtained from plutons in the Black Rapids Glacier, which is part of the Eastern Alaska Range (Aleinikoff et al. 2000). Plutons in the Mount Nenana region of the western part of the Eastern Alaska Range are thought to have approximately 38 Ma emplacement ages based on K–Ar and 40Ar/39Ar dating of biotite and hornblende (Csejtey et al. 1992; Benowitz et al. 2011a). The plutons around Mount Kimball along the easternmost edge of the Eastern Alaska Range have inferred emplacement ages of about 100 Ma based on K–Ar dating of hornblende (Nokleberg et al. 1992). Knowing the age of pluton emplacement in the Eastern Alaska Range allows distinction between post-emplacement cooling and cooling related to exhumation.

Less than about 3 Ma AFT and (U–Th/He) apatite (AHe) ages in the Eastern Alaska Range (Armstrong et al. 2007; Benowitz et al. 2011a), as well as active seismicity including the 2002 M7.9 Denali Fault earthquake (Eberhart-Phillips et al. 2003), imply that the region is tectonically active. Deformation and uplift of the Eastern Alaska Range has recently been correlated with the Neogene Usibelli Group of the Tanana Basin, which is interpreted to contain a long-term record of a transpressional foreland basin system related to regional shortening in the Alaska Range along the Denali fault system (Ridgway et al. 2007). This Neogene basin association makes the region a prime location to investigate long-term exhumation patterns and, thus, the far-field drivers of exhumation in southern Alaska.

**Methods and stacked thermochronology approach**

**Analytical and sampling methods**

We undertook 40Ar/39Ar dating of 30 bedrock samples of granitoid rocks from granitic plutons along and across the strike of the Eastern Alaska Range, proximal to the north side of the Denali fault system, in order to better constrain the initiation of rapid Neogene exhumation, the long-term exhumation history in the Eastern Alaska Range and the spatial pattern of exhumation (Fig. 2). These samples combined with 20 previously 40Ar/39Ar K-spar geochronologically dated samples (Benowitz et al. 2011a, b) are predominately from the Mount Kimball (KIM) College Glacier (COL) the Black Rapids Glacier (RAP), the Mount Balchen (BAL) and Mount Deborah (DEB) and Nenana Glacier (NEN) regions (Fig. 2). A compilation of K-spar minimum age 40Ar/39Ar results are given in Figure 2. A summary of the three biotite (integrated ages) and two white mica 40Ar/39Ar results (integrated and plateau ages) are given in Figures 3 and 4, with all ages quoted to the ±1σ level. All 40Ar/39Ar age determinations were calculated using the constants of Steiger & Jäger (1977).

For 40Ar/39Ar analysis, samples were processed at the geochronology laboratory at the University of Alaska Fairbanks (UAF), where samples were crushed, sieved for the 250–1000 μm fraction, washed, paper-shook and hand-picked for mica mineral phases. A Franz magnetic separator and a variable density liquid (sodium-polytungstate and deionized water) were used to separate out K-spar grains. Aliquots of K-spar separates derived from the heavy liquid separation were analysed at UAF using a Panalytical wavelength dispersive Axios

![Fig. 3. Biotite 40Ar/39Ar age spectrum for sample 01KIM.](image-url)
X-ray fluorometer (XRF) to confirm mineral identification and purity.

The mineral standard MMhb-1 (Samson & Alexander 1987), with an age of 513.9 Ma (Lanphere & Dalrymple 2000), was used to monitor neutron fluence and calculate the irradiation parameter ($J$).

The samples and standards were wrapped in aluminium foil and loaded into aluminium 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 MWh. 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 were step-heated using a Coherent Innova 300 W laser.

Fig. 4. Muscovite/biotite $^{40}$Ar/$^{39}$Ar age spectra pairs for samples 26 and 28 RAP. The ‘age gap’ represents the time between Ar closure of the two mineral phases. Steps filled in grey (top line) were used for muscovite plateau determination.
argon-ion laser, following the technique described in Layer et al. (1987) and Layer (2000). Argon purification was achieved using a liquid nitrogen cold trap and two SAES Zr–Al getters at 400 °C and room temperature. The samples were analysed with a fully automated VG-3600 mass spectrometer at the UAF Geophysical Institute, controlled by an in-house Visual Basic control program. The UAF instrument has a Neir-type source operating with a trap current of 200 μA, and a 4.5 kV accelerating voltage producing an effective sensitivity of $1.5 \times 10^{-14}$ mol/V. The instrument has both an off-axis Faraday (with a $10^{-11}$ ohm resistor) and a Daly detector, and operates in single-collector mode. Data for the five argon isotopes were collected primarily using the Daly in peak-hopping mode (5 s integration time on each peak), with baseline values collected at ‘masses’ 36.5 and 39.5. Nine scans were performed over a period of approximately 20 min, and then linearly regressed to determine the isotopic value and error at the time of sample introduction. The $^{40}$Ar was measured on each detector for each step to determine the relative gain between them (c. 70). For fractions that exceeded the range of the Daly Multiplier, the gain determined from other analyses from the run was used to calibrate the $^{40}$Ar measured on the Faraday detector. Error in this gain calculation was included in the determination of the isotopic values for isotopes measured on the Faraday.

The argon isotopes measured were corrected for system blank and mass discrimination, as well as calcium and potassium interference reactions following procedures outlined in McDougall & Harrison (1999). Typical full-system 8 min laser blank values (in moles) were generally $2 \times 10^{-16}$ mol $^{40}$Ar, $3 \times 10^{-16}$ mol $^{39}$Ar, $9 \times 10^{-16}$ mol $^{38}$Ar and $2 \times 10^{-18}$ 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$_2$SO$_4$ as follows: $(^{39}$Ar/$^{37}$Ar)$_{Ca} = 7.06 \times 10^{-4}$, $(^{36}$Ar/$^{37}$Ar)$_{Ca} = 2.79 \times 10^{-4}$ and $(^{40}$Ar/$^{39}$Ar)$_K = 0.0297$.

Mass discrimination was monitored by running calibrated air shots. The mass discrimination during the 5 year period of this research varied due to filament replacement, ranging from 0.2 to 1.3% per mass unit. While doing our experiments, calibration measurements were made on a weekly–monthly basis to check for changes in mass discrimination with no significant variation seen during these intervals, other than during filament replacement.

Plateau and integrated ages were determined from the isotopic ratios for each step determined from these corrected measurements weighted by the amount of $^{39}$Ar released per step. The integrated age is the age given by the total gas measured and is analogous to a K–Ar age. The spectrum provides a 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, with a mean-square weighted deviation (MSWD) equivalent to a probability of greater than 5%.

Bulk furnace-run samples consisting of about five K-spar crystals were reloaded in aluminium packets and into the fingers of a glass storage tree and which was then attached to the top of the Modifications Ltd low-blank furnace connected on-line to the mass spectrometer. Samples were step-heated after being dropped into the furnace tantalum crucible. The furnace is controlled using a Eurotherm thyristor and controller. Temperature was monitored by means of a thermocouple positioned in a pit at the base of the crucible and a maximum temperature in excess of 1600 °C is achievable. A molybdenum liner was not used in order to: (a) increase accuracy of the diffusion experiment recorded temperature by lessening the distance from the thermocouple to the degassing sample; (b) lessen thermal mass of the unit to decrease heating time and decrease cooling off time; and (c) reduce the cost.

The furnace was calibrated by both the colour temperature correlation assuming a black body (Davis 1931), by the temperature aluminium foil melts at (660 °C) and collaborated by the breakdown of volume diffusion behaviour in K-spar above 1150 °C (Lovera et al. 1991) demonstrated by irregular higher temperature age spectra (Fig. 5). Temperature was recorded every 30 s, and averaged to mitigate and take into account heat up time, cool off time and any slight overshot of set temperature. Recorded temperature is estimated to have an error of ±5 °C with a limited affect on thermal models based on numerous diffusion experiments on the same sample (Lovera et al. 2002).

Approximately 31 duplicated isothermal step-heating schedules were conducted on the K-spar separates in order to retrieve $^{39}$Ar diffusion characteristics, to apply diffusion models and to calculate model thermal histories (Fig. 5) (Lovera et al. 1993; Harrison et al. 1994). About three high-temperature step-heats (c. >1150) were run to fully degas the furnace before the next analysis and were not input for MDD thermochronology, with 12 min blanks run at room temperature (cold blank), and at approximately 588 and 980 °C. Typical full-system cold 12 min furnace blank values were generally $3 \times 10^{-13}$ mol $^{40}$Ar, $1 \times 10^{-15}$ mol $^{39}$Ar, $1 \times 10^{-17}$ mol $^{38}$Ar and $1 \times 10^{-15}$ mol $^{36}$Ar. Blanks at about 588 and 980 °C were generally the same, at $5 \times 10^{-15}$ mol $^{40}$Ar,
MDD thermochronology has proven to be a useful tool in examining orogenic development because of the wide Ar closure-temperature window (c. 150–350 °C) of the system (McDougall & Harrison 1999 and references therein). K-spar MDD thermochronology is also useful because the depth for closure of the Ar system minimizes the effect of topography and advection on the temperature distribution in 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, associated with Cl, resulting in 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).

However, corrections using the equations from Harrison et al. (1994) did not yield usable results, as also found by Sanders et al. (2006). We used the isothermal correction technique outlined by Sanders et al. (2006), in which 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.

We base our calculation of the initiation of rapid cooling and rapid cooling rate determination on the slope of the bottom line of the MDD best-fit thermal history (90% confidence interval of the media) for each sample from the core of the Range (Fig. 6). We used the 10 °C/Ma knick-points of the lower slope, based on constraints on regional background exhumation rates, to quantify when rapid cooling began and ended (Fig. 6). This provides an estimate of the rapid cooling rate for each sample, allowing us to discuss overall variations in cooling rates for one or multiple samples.

The minimum K-spar age method is based on the work of Copeland & Harrison (1990) using minimum age steps and Valli et al. (2007) using minimum age isochron populations. The minimum age determination of an 40Ar/39Ar K-spar analysis is associated with lower Ar closure temperature for K-spar (c. 150 °C). In this paper we use minimum age steps to determine the minimum K-spar age for each sample because in 40Ar/39Ar dating there is often a component of trapped initial 40Ar in the low temperature release steps. These steps may provide information for regressing back to the initial 40Ar/36Ar ratio but these steps often have limited use in determining a plateau age based on their small radiogenic 40Ar component (e.g. Kuiper 2002). Hence, we often used more steps to calculate an isochron age for an individual sample than to calculate a corresponding plateau age.

We use the same general geothermal gradient, approximately 30 °C/km, used in many of the exhumation studies performed in southern Alaska to calculate exhumation rate (O’Sullivan & Currie 1996; Haeussler et al. 2008; McAleer et al. 2009; Benowitz et al. 2011a). This allows direct comparison of exhumation rates between southern Alaska regional exhumation studies. In addition, based on

\[ 3 \times 10^{-18} \text{ mol } ^{39}\text{Ar}, \ 1 \times 10^{-17} \text{ mol } ^{38}\text{Ar} \text{ and } 2 \times 10^{-17} \text{ mol } ^{36}\text{Ar}. \]

MDD thermochronology has proven to be a useful tool in examining orogenic development because of the wide Ar closure-temperature window (c. 150–350 °C) of the system (McDougall & Harrison 1999 and references therein). K-spar MDD thermochronology has proven to be a useful tool in examining orogenic development because of the wide Ar closure-temperature window (c. 150–350 °C) of the system (McDougall & Harrison 1999 and references therein). K-spar MDD thermochronology has proven to be a useful tool in examining orogenic development because of the wide Ar closure-temperature window (c. 150–350 °C) of the system (McDougall & Harrison 1999 and references therein). K-spar MDD thermochronology has proven to be a useful tool in examining orogenic development because of the wide Ar closure-temperature window (c. 150–350 °C) of the system (McDougall & Harrison 1999 and references therein). K-spar

![Fig. 5. Complex K-spar 40Ar/39Ar age spectra from samples 01KIM, 26RAP and 19BAL. Steps filled in red (grey in print version) were used for MDD modelling.](image-url)
the maximum depth of aftershocks (c. 11 km), the
geothermal gradient for the Denali Fault region is
inferred to presently be approximately 30°C/km
(Fisher et al. 2004). We acknowledge that we have
no actual constraints on the Denali Fault
zone palaeo-geothermal gradient, nor temporal and
spatial variations in palaeo-geothermal gradient.
However, K-spar has an Ar closure tempera-
ture window of approximately 150–350°C. This
crustal temperature zone is less affected by both
heat advection and variations in isotherm depth
linked to variations in surface topography (e.g.
Braun et al. 2006). In addition, there is no known
history of extensional events, magmatic events or
hot spring activity along the Denali Fault during
the Neogene that would dramatically alter the
regional geothermal gradients (Plafker et al. 1994).

Background rock cooling rate and indicators
of deeper crustal exhumation

K-spar MDD modelling of sample 01KIM was used
to examine the background exhumation rate adja-
cent to the Denali Fault at the SE edge of the
region of high topography in the Eastern Alaska
Range (Figs 1, 2 & 7). Unaltered biotite from sam-
ple 01KIM was also dated using 40Ar/39Ar laser
step heating to confirm the previous K–Ar emplace-
ment age of 103.6 ± 3.1 Ma (Hornblende K–Ar)
determined in the region (Fig. 3) (Nokleberg et al.
1992). 40Ar/39Ar laser step heating of muscovite–
biotite pairs from samples 26RAP and 28RAP
(Figs 2 & 4) were used to constrain the exhumation
rates above the K-spar closure temperature in the
high peak region of the Eastern Alaska Range.

Age spectra from biotite have been shown to be
a potentially unreliable means to evaluate Ar con-
centration gradients because of instability during
heating in vacuo (Gaber et al. 1988). However, bio-
tite 40Ar/39Ar analysis can provide useful cooling-
rate information if ages are reported as integrated
ages and the range of published possible closure
temperatures (Tc; c. 350–400°C) (e.g. Reiners
et al. 2005) is taken into consideration and it can
be compared to muscovite, which has a better-
constrained closure temperature and is stable dur-
ing heating in vacuo (Harrison et al. 2009). We
assume an Ar closure temperature of approxi-
mately 450°C for muscovite (500 μm grain size)
(Harrison et al. 2009), which is a reasonable
approximation for our samples because muscovite is
known to yield flat 40Ar/39Ar age spectra when
rapidly cooled (e.g. Batt et al. 2004).

We step-heated the biotite separates of samples
26RAP, 28RAP and 01KIM to check for evidence of
gross alteration. We used the integrated (total gas
age) of the biotite 40Ar/39Ar analysis as our age deter-
mination because of the aforementioned potential
for instability during biotite heating in vacuo.

Stacked multi-domain diffusion modelling

We offer a simple approach to reconstructing the
exhumation history of an orogen, building on the
previous work of Batt et al. (2004) by vertically
stacking the best-fit MDD thermal histories of
eight K-spar-bearing bedrock samples collected
along and across the strike of an orogen (Figs 2 &
6), including two new samples (26RAP and 19BAL)
in addition to previous work of Batt et al. (2011a).
The amount of cooling (inferred in terms of exhumation)
recorded in each sample is complicated by differ-
ces in palaeo-depth, present-day elevation and the
location of each individual sample in relation to
structures (e.g. the Denali Fault). Stacking each
MDD best-fit thermal history using a y-axis with no
physical meaning allows construction of a com-
posite mosaic that shows slopes and trends in the
thermal history that reflect the long-term spatial
variations in the rate of bedrock cooling along and
across the strike of an orogen (Fig. 8). We stack
the cooling histories in descending order of age of
initiation of rapid cooling (i.e. using the ages of the
10°C/Ma knick-points in Fig. 6). Thus, by stacking
the cooling histories of numerous samples (Fig. 8),
breaks in slope between samples reveal informa-
tion about whether rapid exhumation within an
entire orogen is episodic or relatively constant.

Results

Mica 40Ar/39Ar ages

Biotite is a hydrous mineral that is unstable during
heating in vacuo laser heating (Gaber et al. 1988), and thus
may not produce geologically meaningful release
patterns that reflect spatial Ar isotopic gradients
(e.g. Brownlee & Renne 2010). Although a flat
age spectrum does not definitively indicate limited
40Ar loss, conversely there are numerous examples
in the literature where concave biotite age spec-
tra are interpreted as indicative of loss or slow

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Fig. 6. MDD thermal models generated from K-spar samples 26RAP and 19BAL (new data), and 26BAL, 03RAP,
03BAL, 18BAL, 22DEB and 32NEN data are from Benowitz et al. (2011a). The MDD magenta band is the 90%
certainty interval of the mean and the purple band is the 90% confidence of the distribution. The black lines mark the
exhumation rate knick-points. The error bars for the micas for sample 26RAP are smaller than the symbols used.
cooling (Hacker et al. 2009). Based on the general sequential closure of mineral phases from high to low nominal closure temperatures, we infer that a flat biotite age spectrum is evidence of minimal $^{40}\text{Ar}$ loss, although we are aware that this interpretation is not unequivocal. In addition, based on the general sequential closure of mineral phases from high to low nominal closure temperatures, we infer that the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations are not affected by excess $^{40}\text{Ar}$.

Fig. 7. MDD thermal models generated from K-spar and the biotite age from sample 01KIM. The MDD magenta band is the 90% confidence interval of the mean and the purple band is the 90% confidence of the distribution. The blue line is a projection of the long-term cooling rate past the closure temperature of K-spar to the 0 °C intercept.

Fig. 8. (a) Examples of stacked MDD plots, using the 90% confidence interval of the mean from samples 03RAP, 03BAL, 18BAL and 22DEB from the high peak region of the Eastern Alaska Range with the temperature window shown for each sample. (b) Stacked MDD 90% confidence interval of the mean of all the samples from the high peak region of the Eastern Alaska Range (26RAP, 19BAL, 26BAL, 03RAP, 03BAL, 18BAL, 22DEB and 32NEN). The average rapid cooling rate is labelled. Temperature windows have been removed for clarity.
Biotite from sample 01KIM yields an integrated (total fusion) age of 94.8 ± 0.5 Ma (Fig. 3). Muskovite from samples 26RAP and 28RAP show simple spectra with little evidence of argon loss (Fig. 4). The individual integrated and plateau ages are within error for both muscovite samples and yielded flat age spectra. Muskovite from sample 26RAP has a plateau age of 24.3 ± 0.2 Ma (Fig. 4). Biotite from sample 26RAP has an integrated age of 19.5 ± 0.2 Ma (Fig. 4). The time between Ar closure of the two distinct mineral phases is approximately 4.8 Ma. Muskovite from sample 28RAP has a plateau age of 23.4 ± 0.1 Ma (Fig. 4), while biotite from 28RAP has an integrated age of 19.7 ± 0.2 Ma (Fig. 4). The time between Ar closure of the two distinct mineral phases is about 3.7 Ma.

**K-spar** $^{40}$Ar/$^{39}$Ar minimum age constraints

The majority of the new $^{40}$Ar/$^{39}$Ar analysis of the K-spar samples (20 out of 29) did not provide isochron age determinations because of the generally homogenous radiogenic content of the minimum age step release (Kuiper 2002). The nine samples that did provide isochron age determinations were within error of the minimum age step(s) determination and did not demonstrate the presence of excess $^{40}$Ar. For this study, we use the minimum age steps(s) determination for the new data.

**Samples proximal to the north side of the Denali Fault south of the Hines Creek Fault.** The youngest (Miocene) K-spar minimum ages are located in a tight wedge within about 15 km of the north side of the Denali Fault and south of the Hines Creek Fault (shaded area Figs 2 & 9). There is a general trend of younging of K-spar minimum ages towards the Denali Fault, as was identified in Benowitz et al. (2011a). The youngest K-spar minimum ages are approximately 8–6 Ma at the apex of the Denali Fault.

**Samples south of the Denali Fault.** K-spar minimum ages are significantly older south of the Denali Fault, with the youngest recorded ages at about 26 Ma. There is a general trend of younger ages at lower elevations and closer to the Denali Fault (Figs 2 & 9).

**Samples on the eastern and western edge of the Range front.** K-spar minimum ages are older than ages at the centre of the range in the high peak region, with the youngest recorded ages at approximately 28 Ma (Fig. 2).

**Samples near or north of the Hines Creek Fault.** K-spar minimum ages near and across the Hines Creek Fault at the core of the range are significantly older (c. 64 Ma) than the K-spar minimum ages proximal to the Denali Fault. In addition, one sample distal to the north side of the Denali Fault east of the Hines Creek intersect has an old age of about 58 Ma (Fig. 2).

**K-spar** $^{40}$Ar/$^{39}$Ar MDD thermal models

All three new bulk K-spar furnace step-heating experiments yielded K-spar age spectra that display complex thermal histories that reflect prolonged post-emplacement cooling (Fig. 5). In addition, all three new bulk K-spar furnace step-heating experiments yielded diffusion patterns compatible with MDD modelling. The step-heating results yielded an activation energy (E) of 48.52 kcal/mol (203.14 kJ mol$^{-1}$) and a frequency factor ($D_o$) $= 7.97 \text{ cm}^2 \text{s}^{-1}$ for 01KIM, $E = 47.55$ kcal/mol (199.08 kJ mol$^{-1}$) and $D_o = 7.97 \text{ cm}^2 \text{s}^{-1}$ for 26RAP, and $E = 47.45$ kcal/mol (198.66 kJ mol$^{-1}$) and $D_o = 6.68 \text{ cm}^2 \text{s}^{-1}$ for 19BAL. Results are all within the ranges expected for K-spars (Lovera et al. 1997). The thermal model from sample 01KIM demonstrates slow prolonged cooling starting at about 68 Ma at a long-term rate of approximately 6 °C/Ma until around 52 Ma when cooling is slightly slower at 3.4 °C/Ma until Ar closure (Fig. 7). MDD models (Fig. 6) from samples 26RAP and 19BAL show initiation of rapid cooling at about 12 Ma. This falls in the middle of the range of rapid cooling initiation documented in previous MDD models from the high relief region of the Eastern Alaska Range Rapid (samples 03RAP, 03BAL, 18BAL, 22DEB and 32NEN in Fig. 6) (Benowitz et al. 2011a).

**Stacked K-spar** $^{40}$Ar/$^{39}$Ar MDD thermal models

Most of the models (Fig. 6) show non-systematic short-term maximum cooling rates (c. 1 Ma) between approximately 30 and 45 °C/Ma. Analysis of such short timescales is not relevant to our goal of understanding long-term cooling patterns and may be overinterpreting the $T$–$t$ constraints provided by the MDD modelling technique. It has also been shown that long-term histories of cooling rate better reflect the effects of far-field driving forces than short-term, spatially limited thermal variations (Bernet et al. 2009). The 90% confidence level of the median (best-fit) of K-spar thermal models from samples 26RAP and 19BAL were stacked with six previously published K-spar best-fit thermal models (Benowitz et al. 2011a) from the Eastern Alaska Range (Fig. 8b). The eight K-spar samples all record periods of rapid cooling, with an average rate of approximately 26 °C/Ma.
No single K-spar sample records rapid cooling for more than about 4 Ma but, if the results are viewed collectively, rapid cooling occurred somewhere within the region throughout the entire time between approximately 21 and 6 Ma (Fig. 8b).

Discussion

We will: (1) constrain the background rock-cooling rate (inferred due to exhumation) for the Eastern Alaska Range; (2) demonstrate the minimum age for the start of Neogene rapid exhumation in the region; (3) examine the spatial pattern of Miocene exhumation in the Eastern Alaska Range based on the collective K-spar minimum age data set; (4) apply (and thus evaluate) the stacked thermochronology approach to eight best-fit MDD thermal models from the high peak region to discern whether exhumation has been episodic or persistent in the core of the orogen since the initiation of rapid exhumation; and, finally, (5) discuss the large-scale regional tectonic implications of applying our stacked approach to thermochronology.

Background cooling rate

The biotite age of 01KIM ($^{40}$Ar/$^{39}$Ar age = 94.8 ± 0.5 Ma, Fig. 3) is roughly concordant with the 103.6 ± 3.1 Ma hornblende age of plutons in the Kimball region (Nokleberg et al. 1992). We infer that the emplacement age of the Kimball pluton is slightly older than about 104 Ma based on the concordance of these two thermochronometers and extrapolation to a pluton emplacement temperature of approximately 700 °C. The average rate of cooling between about 90 and 68 Ma, based on K-spar from sample 01KIM, is approximately 0.5 °C/Ma (Fig. 7). From around 68 to 36 Ma, the long-term average rate of cooling for sample 01KIM increases to about 4 °C/Ma. There is a slightly higher (c. 6 °C/Ma) long-term cooling rate between about 68 and 52 Ma. With that in mind, we interpret the K-spar MDD model for sample 01KIM (Fig. 7) to reflect slow 0.5 °C/Ma post-emplacement cooling until a change in tectonic environment, at around 68 Ma, led to an increase in the cooling rate to 6 °C/Ma. Intrusion of alkaline dykes occurred in the Kimball region at about 68 Ma (Foley 1985) and may have been related to a short-lived extensional event. The time of the change in cooling rate is also coincident with an interpreted period of movement along the western Denali Fault at around 66 Ma (Miller et al. 2002). Thus, we interpret that the approximately 6 °C/Ma cooling rate at about 68 Ma derived from sample 01KIM may be related to the onset of movement of the Denali Fault in the region.
If the average cooling rate of sample 01KIM is projected past the closure age of K-spar to the 0 °C/Ma intercept, the derived cooling rate of approximately 4 °C/Ma is the same average cooling rate (c. 3.4 °C/Ma) demonstrated between about 52 and 36 Ma in the MDD modelling from sample 01KIM. Fitzgerald et al. (1995) inferred a similar background cooling rate of approximately 3 °C/Ma between about 20 and 6 Ma for the Central Alaska Range (i.e. Mount McKinley). We therefore assume any documented well-constrained best-fit MDD thermal model cooling rate change from slow (c. 5 °C/Ma) to rapid (c. >10 °C/Ma) represents a definitive increase in exhumation-related cooling (e.g. Fig. 6). We choose a rate of about 10 °C/Ma to avoid rate changes that are simply a reflection of minor thermal perturbations along the Denali fault zone and to take into account the constrained Tertiary background exhumation rate along the long-lived (c. 85 Ma: Miller et al. 2002) Denali Fault strike-slip fault system. The use of a standard rapid-rate-change limit (c. >10 °C/Ma) significantly greater than the demonstrated background cooling rate allows us to compare cooling rate trends between samples and the sample set as a whole from the high peak region of the Eastern Alaska Range. After each sample (Fig. 6) starts cooling at a rate greater than about 10 °C/Ma most of the individual samples continue to cool at this rate or higher through the low-temperature K-spar Ar closure temperature (c. 150 °C). Samples 18BAL and 26RAP are exceptions where after a period of rapid cooling the samples records period of slow cooling (c. <10 °C/Ma) (Fig. 6).

Initiation of rapid exhumation-related cooling

Based on the emplacement age (c. 70 Ma) of plutons in the Black Rapids Glacier region (Nokleberg et al. 1992), the Ar closure ages of about 20–24 Ma for muscovite and biotite from samples 26RAP and 28RAP (Figs 4 & 6) reflect cooling related to exhumation and not cooling related to initial pluton emplacement. Assuming an Ar closure temperature of around 450 °C for muscovite (Harrison et al. 2009) and about 350–400 °C for biotite (Reiners et al. 2005), the difference in muscovite and biotite closure ages for sample 26RAP (c. 4.8 Ma) indicates a cooling rate of between approximately 10 and 21 °C/Ma. The difference in muscovite and biotite closure ages for sample 28RAP (c. 3.7 Ma) reflects a cooling rate of between about 14 and 27 °C/Ma. Regardless of which biotite closure temperature is used for samples 26RAP and 28RAP, the short age span between the mica pairs from these samples demonstrate rapid cooling. We infer that the cooling is related to rock uplift and rapid exhumation in the Eastern Alaska Range, which began by about 24 Ma.

Miocene K-spar minimum ages

Miocene K-spar minimum cooling ages are only located between the Denali Fault and the Hines Creek Fault at the apex of the Denali Fault (Figs 2 & 9). The youngest ages are also proximal (within c. 10 km) of the Denali Fault itself. The pattern of the youngest K-spar minimum cooling ages being located along the Denali Fault is a common pattern along transpressive strike-slip faults (e.g. Little et al. 2005). This distinct pattern is most probably related to differential unroofing adjacent to the master strand of the Denali Fault caused by a combination of a non-vertical fault dip, as discussed in detail in Benowitz et al. (2011a), and the fault zone being a region of erosional weakness (Fig. 2).

K-spar minimum cooling ages south of the Denali Fault (Fig. 9) and to the east of the Hines Creek–Denali fault intersection are significantly older (Fig. 2), as are the K-spar minimum cooling ages near or north of the Hines Creek Fault and to the west of the Denali Fault apex (Fig. 2). We discuss a geodynamical model for this large-scale pattern of focused Miocene deformation in the Eastern Alaska Range in the subsection ‘Alaska Range deformation in response to the Yakutat collision’ later in this paper.

Vertically stacked approach

The stacked approach presented here (Fig. 8) reveals that, although the location of rapid exhumation varies over time, orogenesis has been occurring within the region quite persistently since about 24 Ma (K-spar and mica analysis combined). From these findings, we now believe that our previous work (Layer & Benowitz 2008) misinterpreted the lack of evidence for exhumation to conclude that no exhumation had occurred. We believe that the stacked approach reveals a more complete and coherent story, which indicates that the focus of rapid exhumation in the Eastern Alaska Range varied spatially through time and reflects a long history of persistent deformation. We also believe that the stacked approach better constrains the initial timing of rapid exhumation in the Eastern Alaska Range and makes the case that there is no single all-encompassing uplift age for the entire region.

A new view of Eastern Alaska Range exhumation rates

Assuming a geothermal gradient of about 30 °C/km (Fisher et al. 2004), as discussed in the Methods
section of this paper, when the sample set is viewed in its entirety a rapid exhumation has occurred within the Eastern Alaska Range at a persistent rate of approximately 0.9 km/Ma between about 24 and 6 Ma (Fig. 10). This is roughly the same approximate average of 1.0 km/Ma exhumation rate from about 6 Ma to present as determined by apatite fission track work in the Nenana Glacier region (Perry et al. 2010) if calculated using the same 30 °C/km geothermal gradient applied in this study. Thus, there is no evidence of a region-wide increase in tectonically driven exhumation since about 24 Ma–present in the Eastern Alaska Range.

Alaska Range deformation in response to the Yakutat collision

The long-term occurrence of rapid exhumation in the Eastern Alaska Range demands a long-term, continuous tectonic driving mechanism. The progressive ‘collision’ of the Yakutat microplate with south-central Alaska is an obvious candidate (Plafker 1987; Spotila & Berger 2010). We define ‘collision’ in this case as highly coupled flat-slab subduction at the subduction margin. The Yakutat microplate is composed of crystalline crust that is 15–30 km thick and is inferred to have an oceanic plateau origin (Christenson et al. 2010; Worthington et al. 2012). Based on tomographical studies, the Yakutat microplate is currently undergoing flat-slab subduction beneath the Chugach–Saint Elias Mountains, with a northern edge 500 km inboard of the subduction zone at a depth of about 100 km (Eberhart-Phillips et al. 2006). The arrival time of the Yakutat microplate into the southern Alaska subduction zone is thought to have been around 25 Ma (Plafker et al. 1994), yet it remains unclear when collision began (e.g. Spotila & Berger 2010). The 40Ar/39Ar thermochronology data presented here demonstrate an increase in the exhumation rate at about 24 Ma in the Eastern Alaska Range, potentially in response to Yakutat flat-slab subduction.

Fig. 10. Summary figure of K-spar MDD thermal models and mica closure ages for the Eastern Alaska Range. The base map is a detailed digital elevation model of the Eastern Alaska Range flooded to 1000 m to emphasize topography. The thermal history of 01KIM on the SE edge of the high peak region indicates slow post-pluton emplacement cooling followed by slower background exhumation related to inferred movement along the Denali Fault. The initiation of rapid cooling of samples from the high peak region is based on the 40Ar/39Ar K-spar MDD modelling of each sample (Fig. 6) at the initial point where cooling is >10 °C/Ma. The average rapid cooling rate (°C/Ma) is a minimum time-averaged long-term rapid cooling rate of >10 °C/Ma. The bold sample labels indicate close proximity to the Denali Fault and the grey filled triangles are biotite cooling ages from Benowitz et al. (2011a). The error bars for the micas are smaller than the symbols used. The figure was inspired by Batt et al. (2004).
Other regions of Alaska also show evidence of a late Oligocene–early Miocene exhumation rate change in regional tectonic forcing. Ridgway et al. (2007, 2012) suggested that the strata of the Tanana Basin encompass the entire Neogene and showed that the basin is genetically related to the formation of the Alaska Range (Fig. 2). Trop et al. (2012) correlated Miocene basin development in the Wrangell volcanic field with flat-slab subduction of the Yakutat microplate. Thermochronological work in the Tordrillo Mountains (Haussler et al. 2008), approximately 50 km WNW of Anchorage, Alaska (Fig. 1), indicates that rapid exhumation began there at around 23 Ma. Detrital zircon fission track work in the Chugach–Saint Elias Range at Alaska’s southern margin (Fig. 1) (Enkelmann et al. 2008) shows a pulse of exhumation beginning at about 25 Ma. Recent AFT work in SW Alaska indicates rapid cooling in both plutonic and meta-sedimentary samples between approximately 24 and 20 Ma, implying regional cooling due to exhumation during this time period (O’Sullivan et al. 2010; Benowitz et al. 2012a). Deformation and metamorphism was occurring on part of the eastern Denali Fault by about 25 Ma at the Cottonwood complex (Fig. 1) (Richter 1976; Benowitz et al. 2011c, 2012b). Fold-and-thrust-style deformation began in the St Elias Range by the early Miocene (Chapman et al. 2012). In addition, the Wrangell volcano field became active at around 26 Ma and is associated with convergence of the Yakutat microplate (Richter et al. 1990). Furthermore, AFT data from a core in Cook Inlet were used to document about 4 km of exhumation at approximately 25 Ma associated with a regional unconformity (Murphy & Clough 1999). With the compiled regional evidence and this study, it is clear that significant deformation across southern Alaska was initiated by about 25 Ma and continues presently.

In terms of kinematics, Koons et al. (2010) used a three-dimensional thermal–mechanical numerical model to show that both near-field (i.e. Chugach–Saint Elias) and far-field (i.e. the Alaska Range) mountain ranges could have been created by the Yakutat microplate collision. An alternative model (Soofi & Wu 2008) used a thin-viscous-sheet model to investigate the effect of the Yakutat microplate colliding with the North American plate. The model predicted topographical development where the Alaska Range is located and demonstrated that lateral strength heterogeneities in the crust play a role in the location of deformation. The timing of deformation predicted by the models differs from our new geological constraints but the general concepts of the models are still applicable.

An analogue for the Yakutat–Southern Alaska collision is the India–Asia collision, where modeling predicts that the intraplate deformation in the Tibet region, which began soon after collision, was caused by an indenting boundary concentrating strain along the southern edge of the strong Tarim Basin region (Dayem et al. 2009). Similarly, the deepest Neogene exhumation recorded in the Alaska Range is located at the apex of the curve in the Denali Fault. The Hines Creek Fault zone (Figs 1, 2 & 10), which is a major tectonostratigraphical boundary and offsets the Moho, is possibly acting as a strong backstop that concentrates strain from the Yakutat microplate collision (Figs 1, 2 & 10) (Veenstra et al. 2006), with deformation being focused along the weak zone of the north-dipping Denali Fault (Freed et al. 2006; Benowitz et al. 2011a).

Geophysically plausible kinematic mechanisms have been proposed to drive coeval orogenesis in the Chugach–Saint Elias and Alaska ranges. During the Neogene, basin formation and regional magmatism also occurred concurrently in southern Alaska. Although we cannot definitively constrain the timing of the initial collision of the Yakutat microplate, we add the results of this paper to the growing evidence that flat-slab subduction was underway by about 25 Ma (Fig. 10).

Conclusions

In this paper we investigated the spatially variable exhumation history of the Eastern Alaska Range and the far-field driving mechanism for regional Neogene deformation in southern Alaska using a simple graphical approach for thermochronological analysis combined with extensive 40Ar/39Ar muscovite and biotite cooling ages. Based on stacked K-spar MDD thermal models and mica 40Ar/39Ar thermochronology of samples collected over an approximately 100 km transect from the Eastern Alaska Range, we show that sub-orogen-scale regions have cooled rapidly, at an average rate of approximately 26 °C/Ma, between about 24 Ma and the present. Although the focus of exhumation varied over time, continual exhumation at a rate of approximately 0.9 km/Ma has occurred somewhere within the Eastern Alaska Range since about 24 Ma. Neogene exhumation north of the Denali Fault in the Eastern Alaska Range has been constant, not episodic.

The preponderance of evidence from thermochronology and basin analysis data shows initiation of rapid exhumation by about 25 Ma in southern Alaska that continues to the present. Collision (highly coupled flat-slab subduction) of the Yakutat microplate is the most plausible far-field driving mechanism and we suggest that it began by about 25 Ma, as Plafker et al. (1994) first broadly proposed.
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