Eocene activity on the Western Sierra Fault System and its role incising Kings
Canyon, California

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ABSTRACT

Combining new and published apatite (U-Th)/He and apatite ⁴He/³He data from along the Kings
River canyon, California we rediscover a west-down normal fault on the western slope of the
southern Sierra Nevada, one of a series of scarps initially described by Hake (1928) which we
call the Western Sierra Fault System. Integrating field observations with apatite (U-Th)/He data,
we infer a single fault trace 30 kilometers long, and constrain the vertical offset across this fault

to be roughly a kilometer. Thermal modeling of apatite $^4\text{He}/^3\text{He}$ data documents a pulse of footwall cooling near the fault and upstream in the footwall at circa 45-40 Ma, which we infer to be the timing of a kilometer-scale incision pulse resulting from the fault activity. In the context of published data from the subsurface of the Sacramento and San Joaquin Valleys, our data from the Western Sierra Fault System suggests an Eocene tectonic regime dominated by low-to-moderate magnitude extension, surface uplift, and internal structural deformation of the southern Sierra Nevada and proximal Great Valley forearc.

1. INTRODUCTION

Distinguishing actively developing topographic features from landforms that evolved under earlier tectonic and climatic regimes is often a difficult, if not impossible task. It has long been known that this challenge is confounded by changes in the climate system that can force cycles of erosion and aggradation. The more recent geodynamic realization that vertical displacement transients may migrate rapidly through regions due to redistributions in lower crust and upper mantle loads (Loomis and Glazner, 1986; Saleeby et al., 2013a) now adds additional complexity to the problem. This raises a number of fundamental questions: What controls the initial formation of a landscape? To what extent can early landforms influence topographic patterns forced under subsequent regimes?

We pursue these questions, which through a long history of studies have been posed for the southern Sierra Nevada, California. We focus on the Kings River canyon (Kings Canyon), which has the greatest local relief of all Sierra canyons, with maximum vertical relief of about 2,500 meters (vertical relief is about 2,000 meters at our study location). Previous studies argue that at

least two or three distinct erosional cycles have carved the canyon (House et al., 1998, 2001; Stock et al., 2004; Clark et al., 2005; McPhillips and Brandon, 2012; Pelletier, 2007). However, important details of the earlier cycles, such as timing and relative magnitude, elude us.

A three-dimensional array of apatite $^4\text{He}/^3\text{He}$ (Ap- $^4\text{He}/^3\text{He}$) and bulk apatite (U-Th)/He (Ap-He) data clarifies an early Cenozoic phase of southern Sierra landscape evolution. New Ap-He data constrain a discrete, kilometer scale exhumation difference across a topographic step, which we interpret as a west-down normal fault. This fault is one of a set running along the western slope of the southern Sierra initially described by Hake (1928), and which was dismissed (Wahrhaftig, 1965) and neglected in the literature for most of the last century. We herein name this the Western Sierra Fault System (WSFS).

Bayesian Monte Carlo Markov Chain (MCMC) modeling of the thermal history of a sample from just upstream of the inferred fault scarp constrains fault activity to be circa 45-40 Ma. Additional thermal modeling of data from high relief topography of Kings Canyon east of the fault, but below the region of clearly recognizable glacial erosion indicates that this Eocene fault activity also corresponds to a kilometer scale pulse of incision in the Kings Canyon. Data and thermal modeling presented here elucidate an Eocene tectonic regime during which the WSFS played a critical role in generating much of the relief present along the modern Kings River. This analysis raises the question of the potential importance of similar early Cenozoic activity on other scarps of the WSFS, which are identified along the length spanning from the San Joaquin River to the Kern River (Hake, 1928), as well as the question of potentially important Eocene incision events along other major southern Sierran trunk channels.

70

71 **2. OVERVIEW OF THE PROBLEM**

72 In the southern Sierra Nevada, deep fluvial canyons separate high elevation, low relief
73 interfluvies. Together these geomorphic zones define regional longitudinal topographic profiles
74 marked by large amplitude (greater than 1 km), long wavelength (greater than 10 km) relief.

75 Debate over the timing of the generation of this regional relief lies at the core of an unsettled
76 question: How old are the southern Sierra river canyons?

77

78 Several diverse views summarize the current understanding of this issue. The first claims that
79 modern relief was generated primarily in late Cenozoic time. Several workers argue for this by
80 long distance extrapolation of limited geomorphic and stratigraphic data, which is only available
81 in the northern Sierra and its western foothills (Huber, 1981; Unruh, 1991; Wakabayashi and
82 Sawyer, 2001). Gabet (2014) discusses a number of weaknesses in the conclusions of this view.
83 The second concept utilizes horizontal transects of Ap-He data to contend that longitudinal relief
84 was greater in Late Cretaceous than at present (House et al., 1998, 2001). A third idea argues for
85 a rapid pulse of Plio-Pleistocene uplift and incision across the central Sierra, documented by
86 cosmogenic radionuclide burial dating of sediments deposited on abandoned fluvial cut and
87 terraces (Stock et al., 2004). Yet a fourth idea argues for a significant pulse of mid-Cenozoic
88 uplift and incision based on different datasets including Ap-He data coupled to geomorphic analysis
89 (Clark et al., 2005), a numerical landscape evolution model integrating multiple data types
90 (McPhillips and Brandon, 2012), and stream incision data extrapolated from the northern Sierra
91 combined with published thermochronology and geomorphic data from the southern Sierra
92 (Wakabayashi, 2013).

93

94 Despite the vast temporal and spatial differences amongst these concepts, they have been
95 generally treated as being in competition (e.g. is relief Late Cretaceous? or late Cenozoic?). This
96 approach confuses attempts to integrate the different models. However, none of the concepts
97 preclude the validity of the others. Thus we try to interpret these concepts as complementary
98 rather than competitive.

99

100 ***2.1 Previous work***

101 The assumption of Cenozoic rigid-block behavior for the Sierra Nevada mountain range
102 underpins the analysis presented in several previous studies. Many of these studies explicitly
103 state this assumption, and some use its implications to extrapolate geologic data over long
104 distances and argue for late Cenozoic origin of most of the present-day topography, particularly
105 north of the Kings River canyon (Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001).
106 This assumption of rigid behavior has also been extended westward into the Great Valley, where
107 sedimentation has been used to balance erosion of the southern Sierra uplands during rigid west
108 tilting (Wakabayashi and Sawyer, 2001).

109

110 On the other hand, vertical transects of Ap-He data from the southern Sierra show a consistent
111 age-elevation slope of 0.04 – 0.06 mm/year and lack clear inflections that would record canyon
112 incising events. This implies that the high elevation, low relief interfluvial plateaus mimic the
113 landscape that developed in the Late Cretaceous and was slowly exhumed at roughly this same
114 rate throughout the Cenozoic (Clark et al., 2005; Maheo et al., 2009, House et al., 1997, 2001).
115 Furthermore, analysis of Ap-He data from two horizontal transects along the axis of the central

Sierra supports a Late Cretaceous antiquity of the large amplitude, long wavelength longitudinal pattern (House et al., 1998, 2001; Braun 2002a, 2002b). Together these interpretations imply that low relief highlands and high relief canyons were both part of the Late Cretaceous landscape. In this view, it has been argued that much of the form of the modern landscape mimics regional Late Cretaceous geomorphology.

In contrast, Stock et al. (2004) identify a pulse of late Cenozoic river incision across the central Sierra using cosmogenic radionuclide burial dates from vertical transects of quartz bearing sediment deposited on abandoned fluvial-cut terraces in carbonate caves. These data resolve late Pliocene to Pleistocene incision of the lowest 20% of total relief of several central Sierra river canyons (approximately 400 m in Kings Canyon). As Stock et al. (2004) point out, the question of the antiquity of the upper 80% of relief (approximately 1600 m in Kings Canyon) is left unconstrained.

In another study, Clark et al. (2005) identify two knickpoints in stream long profiles of the main trunks and tributaries of the Kings and Kern rivers and argue that these knickpoints correspond to two pulses of incision responsible for most of the relief in these canyons. It is asserted that these events must post-date the youngest Ap-He age on the Kings River (circa 32 Ma). Pelletier (2007) uses a numerical model to test different bedrock erosion models in the southern Sierra, and the results of his preferred model (sediment-flux driven) indicate that the southern Sierra Nevada experienced range-wide surface uplift in the latest Cretaceous and late Miocene.

McPhillips and Brandon (2012) integrate published Ap-He and apatite fission track thermochronometry, and aluminum-in-hornblende igneous geobarometric data into a numerical landscape evolution model encompassing much of the modern Sierra. Their preferred model finds onset of range-wide uplift and incision at circa 30 – 10 Ma.

Studies in the western foothills and eastern San Joaquin Valley subsurface report direct measurements of minimum Paleogene paleo-relief. 500 meters of such minimum relief is identified in the Kaweah River drainage near the Sierra-Great Valley transition based upon interpretation of Ap-He data and bedrock pediment geomorphology (Saleeby et al., 2013b; Sousa et al., 2013, 2014). Reid (1988) measures the same scale (500 m) of relief on the Upper Cretaceous basement nonconformity in the San Joaquin Valley subsurface.

We next move on to presenting our new data and analysis from Kings Canyon. In the context of the studies discussed above, we constrain an Eocene tectonic regime that provides insights into the early Cenozoic evolution of the southern Sierra. In doing so, we hope to move toward a more complete story of southern Sierra Nevada landscape evolution.

3. MATERIAL AND METHODS

3.1 Analytical methods

Samples were taken from outcrops of felsic granitoids of the Sierra Nevada Batholith along the North Fork Kings River, the main trunk of the Kings River, and near the confluence of the Middle and South Forks of the Kings River (**FIGURE 1**). After crushing, sieving, and standard heavy mineral separation, a stereoscopic microscope was used to select apatite grains from each

sample for analysis. Euhedral grains were selected and checked to exclude any grains with birefringent inclusions (examined with cross-polarized light and immersed in ethanol). The dimensions of each grain were then measured and recorded. For each sample, four to ten individual grains were first analyzed for bulk Ap-He age determination. A Pfeiffer Prisma quadrupole mass spectrometer was used for measuring helium by isotope dilution with ^3He . U, Th, and Sm concentrations were measured via isotope dilution on an Agilent 7500 ICP-MS (e.g. Farley, 2002). An alpha-ejection corrected age for each grain was calculated using the Ft parameter based on the measured grain dimensions (after Farley et al., 1996).

For each sample chosen for $^4\text{He}/^3\text{He}$ analysis, additional grains were subjected to a fluence of 10^{15} protons/cm² with an energy of 220 MeV at the Francis H. Burr Proton Therapy Center of Massachusetts General Hospital to make a uniform distribution of ^3He (Shuster and Farley, 2004; 2005). Individual grains were picked using the same criteria as for bulk age determination, with particular attention paid to the lack of birefringent inclusions. Each individual grain was step-wise degassed using a halogen lamp as heat source (Farley et al, 1996). ^4He and ^3He were measured at each degassing step using either a MAP215-50 or GV-SFT sector field mass spectrometer. The Ap-He and Ap- $^4\text{He}/^3\text{He}$ data used in our analysis are presented in **TABLE 1** and **SUPPLEMENTAL DATA**.

Because isochrones (surfaces of equal cooling age) are not horizontal in the Sierra, but are tilted, previous studies utilizing Ap-He data from the Sierra have made a correction to allow samples taken at different distances from the range axis to be compared. This is done by applying a tilt-correction of a few degrees (House et al. 1997, 1998, 2001; Maheo et al. 2009). McPhillips and

Brandon (2010) explicitly model isochronal tilt based on published Ap-He data and conclude a larger tilt value of 3.4°. In general these studies have explained isochronal tilting as the result of late Cenozoic tectonics, assuming rigid body behavior of the Sierra (none of the tilting is due to local rotation) and original isochrone horizontality (none of the tilting is due to tilt at time of cooling). Because of the proximity of all our data, particularly within the individual vertical transects, this type of correction has only a minor effect on our study. However we do apply a correction by measuring the distance of each sample to a line parallel to the local axis of the southern Sierra, and then reversing a 2° down-to-the-west tilt according to this measured distance. Modern elevation and tilt corrected elevation are both reported for each sample in **TABLE 1.**

3.2 Ap-He and Ap-⁴He/³He data

Any single Ap-He age is generally compatible with a wide range of thermal histories. A considerably more restricted range is permitted when a bulk Ap-He age is combined with a ⁴He rim-to-core concentration profile. This is because different time-temperature (t-T) paths result in significantly different ⁴He concentration profiles based on the time-integrated balance between alpha-particle in-growth and loss by both ejection and diffusion. This balance can be conceptually grasped by considering the amount of time that the sample spent in the partial retention zone (PRZ). For example, a sample that was in the PRZ for a relatively long time will have a diffusively rounded ⁴He profile, whereas a sample that cooled rapidly would have a squarer ⁴He profile. The Ap-⁴He/³He method allows us to mine this ⁴He rim-to-core concentration profile (Shuster and Farley, 2004, 2005).

3.3 QTQt Modeling

To extract t-T information from both bulk ages and $^4\text{He}/^3\text{He}$ spectra, we utilize the thermochronologic modeling software, QTQt (Gallagher, 2012) to model thermal histories of samples with Ap-He and Ap- $^4\text{He}/^3\text{He}$ data. QTQt employs a trans-dimensional bayesian (MCMC) statistical approach to find the best t-T paths for a sample by employing a large number of iterative perturbations in t-T space (we use at least 10^6 iterations). After each perturbation, the proposed path is compared to the initial path and the better-fitting of the two is chosen according to a specific acceptance criterion (Gallagher, 2012). The model converges on the best fit t-T path through this process during what is referred to as the “burn in” period (Gallagher, 2012). For each of our model runs the “burn in” period consists of at least 5×10^5 iterations. After the model has converged on the best fit t-T path, we run a set of 5×10^5 “post-burn in” model iterations which are used to document the distribution of best fit t-T histories. The result of this “post-burn in” period is represented in the model outputs.

In addition to applying this iterative process to a single sample, QTQt is designed to simultaneously apply this iterative process to find a set of most likely t-T paths comprising a vertical transect. In doing so, QTQt employs a linear thermal gradient that can be prescribed to be a fixed value, or allowed to vary with time.

For each model run we impose the same set of manually controlled thermal history constraints. The age of youngest local plutonism at 86 Ma (Chen and Moore, 1982; Moore and Nokleberg, 1992) is used as a high temperature constraint ($650^\circ\text{C} \pm 100^\circ\text{C}$, 86 Ma ± 1 my). A reasonable bounding box of temperature and time is assigned for the model to explore ($85^\circ\text{C} \pm$

70° C, 90 Ma to present). A rough estimate of modern mean annual surface temperature (20° C +/- 5° C) is also utilized. All of the input data are listed in **TABLE 1** and **SUPPLEMENTAL DATA**.

4. AP-HE DATA

We present nine new Ap-He bulk ages ranging from 34.7 Ma to 64.6 Ma at modern day elevations of 402 meters to 1426 meters above sea level. Five of these new Ap-He ages are accompanied by $^4\text{He}/^3\text{He}$ spectra. In addition to these nine samples, we utilize three published bulk Ap-He ages from House et al., (1998) and one published bulk Ap-He age from House et al., (1997). The location of each of the samples is shown on **FIGURE 1** and the details are tabulated in **TABLE 1**. KR1, KR2, KR3, and KR4 comprise a vertical transect near the confluence of the Middle and South Forks Kings River spanning modern day elevations of 660 m to 1430 m above sea level (ASL). At this location the total vertical relief is about 2,000 meters (Stock et al., 2004). KR5, KR6, and KR7 comprise a second vertical transect on the North Fork Kings River spanning modern day elevations of 540 m to 1230 m ASL, and together with KR8 and 13SS6, are located farther west, and at lower elevation than previously published Ap-He data from the area. KR8 and 13SS6 are from within roughly 10 meters of the modern river level of the main trunk Kings River. Because of the distance of some of our samples from the fault (up to a few kilometers) we rule out the possibility that cooling due to fluid flow rather than exhumation may play a role in our Ap-He data.

Several published datasets of bulk Ap-He data from the southern Sierra include vertical transects that consistently form a linear trend in age-elevation space with a slope of 0.04-0.06 mm/yr

(House et al., 1997; 1998, 2001, Clark et al., 2005; Maheo et al., 2009). This age-elevation relationship is generally invariant in time and space, and generally extends down to an age of approximately 40 Ma; younger ages are very sparse. The slope of the age-elevation relationship is interpreted to represent the regional long-term Cenozoic erosion rate (House et al., 1997; 1998; Maheo et al., 2009; Clark et al., 2005). To compare our data with this regional relationship we plot Ap-He age versus corrected elevation for each of the two new vertical transects (**FIGURE 2A, B**). Because of its location close to KR 1-4, we include the high elevation sample KC4 (from House et al., 1997). On both of the new vertical transects, the higher elevation samples are in good agreement with the regional age-elevation relationship discussed above, as shown by the slopes of the linear regressions shown on **FIGURES 2A and B**. However, the lowest samples on both vertical transects (KR1, KR3, and KR7) clearly deviate from this trend. This deviation is greatest on the KR5-7 vertical transect (**FIGURE 2B**), where the bulk Ap-He age of KR7 is 20 m.y. older than expected, and is older than either of the Ap-He ages from higher elevations on the same transect (KR5 and KR6). On the KR1-4 vertical transect the deviation of the low elevation samples is of lesser magnitude but in the same direction, with the ages of KR1 and KR3 each about 5 m.y. older than expected (**FIGURE 2A**).

These deviations from the expected age-elevation trend comprise a local breakdown of the expected pattern of predominantly slow Cenozoic cooling. Furthermore, the large deviation within the KR5-7 vertical transect suggests the possibility that a fault offsets it (e.g. Maheo et al. 2009). In the next section we investigate the KR5-7 vertical transect for potential geologic structures.

5. FAULT IDENTIFICATION

Field reconnaissance along the KR5-7 vertical transect led to the discovery of several curvilinear, approximately northwest-striking, steeply west-dipping topographic steps. One of these steps crosses the vertical transect between KR5-6 and KR7 and preserves approximately 100 meters of modern relief (**FIGURE 3**). Immediately to the east of the vertical transect is a larger (500 m) topographic step, sub-parallel to the step crossing the vertical transect.

Considering the large offset in age-elevation space and the topographic step crossing the vertical transect between KR5-6 and KR7, we infer this west dipping topographic step to be a significant west-down normal fault at this location. In 1928, Hake studied the geomorphology of the southern Sierra Nevada and interpreted a series of topographic steps as west-down normal fault scarps stepping southward from the San Joaquin River to the Kern River. Despite the descriptive detail and mapping with which Hake documents the fault scarps, his study has been disregarded in the literature (e.g. Wahrhaftig, 1965).

In the vicinity of the Kings River canyon, Hake (1928) described a set of en echelon faults, including one along the North Fork Kings River in the immediate vicinity of KR5-7, but the map scale used by Hake (1928) does not allow for more precise location. We hypothesize that the modern topographic step is an erosional remnant of a west-down normal fault which intersects the KR5-7 vertical transect, and is responsible for the age-elevation offset between KR5-6 and KR7.

5.1 Confirmation of a fault scarp with Ap-He data

We hypothesize that the age-elevation offset along the KR5-7 vertical transect is due to offset on a discrete west-down normal fault. In this scenario, the cooling ages were already set at the time of the faulting, and the age-elevation slope on either side of the fault was the same, as controlled by slow pre-40 Ma cooling. Under this interpretation, timing of faulting is required to post-date the bulk Ap-He age of sample KR8 (42.5 Ma). The footwall of the fault (east-side) was uplifted and exhumed relative to the hanging wall (west-side) and Ap-He data from each side of the fault should fall on two vertically-offset, parallel age-elevation lines. The vertical offset between these parallel lines should represent the exhumation difference across the fault and therefore approximate the total vertical component of offset along the fault. To test this hypothesis we layer more Ap-He data onto the KR5-7 age-elevation plot (FIGURE 2C). As predicted, all of the other Ap-He data from nearby the fault, including our new data (KR8, 13SS6) as well as data from House et al. (1998) fall consistently on two subparallel, vertically-offset age-elevation arrays. Linear regression of the data show a vertical offset of roughly 1000 meters. Combining the eight Ap-He data points with geomorphic control from our field reconnaissance, we infer a fault trace over 30 km long (FIGURE 1). With recognition to the mapping and description in Hake (1928), this consistent offset in Ap-He age-elevation data is strong evidence for kilometer-scale, west-down normal faulting spanning at least from the North Fork Kings River across the main trunk of the Kings River (FIGURE 1).

A pulse of footwall incision must have initiated where this fault crossed any streams, and this pulse would have subsequently migrated upstream. In the next section we constrain the timing of faulting by modeling the t-T paths of samples from the locations most affected by this fault-related footwall incision.

322

323 **6. THERMOCHRONOLOGIC MODELLING**

324 A number of questions arise from the identification of kilometer-scale normal fault scarps on the
325 western slope of the southern Sierra Nevada. When was the fault active? How does the
326 magnitude of fault offset compare to the total relief of Kings Canyon? Did this fault play a role
327 in range wide uplift and incision? What is the relationship between the fault related pulse of
328 incision and the relief of the modern Kings River canyon?

329

330 ***6.1 Footwall low elevation sample: KR8***

331 A major pulse of footwall incision by the Kings River would have immediately followed the
332 fault activity discussed above. In our first set of QTQt model runs we constrain the timing of
333 this pulse of footwall incision, and thus the timing of fault activity, by modeling the thermal
334 history of the footwall sample that is closest to the fault and at the lowest elevation. This sample,
335 KR8, comes from the main trunk of the Kings River approximately 500 m east of the fault and a
336 modern day elevation of 402 m ASL (**FIGURE 1**). KR8 was the deepest and warmest sample
337 prior to faulting, and thus most likely to record cooling from the post-faulting incision pulse.
338 There is no break in slope in the age-elevation plot of KR8 (**FIGURE 2C**), indicating that
339 faulting must post date 42.5 Ma. However, modelling the more sensitive $\text{Ap-}^4\text{He}/^3\text{He}$ data
340 allows us to much more tightly constrain the cooling history of this sample.

341

342 QTQt model parameters are summarized in **SUPPLEMENTAL DATA** and model results are
343 shown in **FIGURE 4**. The upper panel shows the t-T probability distribution of accepted thermal
344 histories from the post-burn in phase of the model run. The model result requires that KR8

cooled from greater than 80° C to less than 30° C between 45 Ma and 40 Ma, suggesting that the fault was active during, or immediately prior to this time.

6.2 South-Middle Fork Kings River Vertical Transect: KR1-4

If the fault offset and rapid cooling identified above was accompanied by uplift across the southern Sierra, then the pulse of incision should also be recorded upstream from the fault scarp. One would expect this incision pulse to be recorded as rapid cooling of samples in the KR1-4 vertical transect, possibly at a later date. The incipient break in slope at roughly 40 Ma on this vertical transect qualitatively confirms this (FIGURE 2A). With our next QTQt model runs, we aim to quantitatively constrain the timing of this incision pulse at the location of the KR1-4 vertical transect.

As a start, we first model the thermal histories of each sample in this vertical transect individually. Results of this modeling show that each of KR1-4 require rapid cooling around 45-40 Ma to temperatures consistent with their location in the vertical transect, about 50° - 60° C for the lowest sample and below 30° C for the upper sample (FIGURE 5A-D). This rapid cooling is roughly contemporaneous with footwall incision closer to the fault, confirming that the major fault-related incision pulse was not spatially limited to the immediate vicinity of the fault scarp, but is also recorded about 10 km upstream. These results demonstrate the potential for using thermochronometric data to constrain knickpoints migration rates. However, due to the uncertainties and the distance between our samples, we do not calculate knickpoints migration rates here.

For the lowest sample in the vertical transect, KR1, the individual QTQt model predicts cooling to about 50-60° C circa 45-40 Ma, followed by slow cooling at roughly 0.8°/m.y. throughout much of the rest of the Cenozoic. Combined with a reasonable Sierran geothermal gradient of 25°C/km, this corresponds to about 1,200 -1,600 meters of total exhumation at a rate of 0.04 mm/year, which is 60-80% of total vertical relief at the location of the vertical transect, and about 50-60% of maximum relief in modern Kings Canyon. This suggests that after the pulse of fault-related cooling occurred, the southern Sierra returned to a state of slow exhumation and cooling similar to the pre-faulting scenario.

Next we model as a composite vertical transect all four of these samples and a fifth high elevation sample, KC4 from House et al (1997), all of which are on the same fault block. QTQt simultaneously seeks a t-T path for each of the input data points, which are linearly offset by a temperature value that is optimized by the model at each 1 m.y. time increment. For this model we input Ap-He ages and Ap-⁴He/³He spectra for each of KR1-4, and an Ap-He age for the high elevation sample (KC4; no ⁴He/³He data exist for this sample). The model result agrees with the individual models for each sample, showing a rapid cooling event circa 45-40 Ma, after which the upper samples remain below 30° C and the lower samples slowly cool (FIGURE 6).

Unsurprisingly, this model is not able to fit the data as well as the individual model runs do (see SUPPLEMENTAL DATA for results from the composite vertical transect QTQt model run).

This is at least partly because QTQt requires a linear thermal offset across the entire vertical transect at each 1 m.y. time increment, an imperfect simplification of the way a rapid cooling pulse would propagate downward through the upper crust. However, the internal consistency of this composite model result with the prediction of rapid cooling from the individual model runs

as well as the KR8 model further supports the hypothesis of a major pulse of footwall incision and cooling following fault activity circa 45-40 Ma.

7. DISCUSSION

7.1 Implications for incision of Kings River canyon

We posit that the major pulse of footwall incision that resulted from fault activity circa 45-40 Ma incised about 60-80% of Kings Canyon at the location of the KR1-4 vertical transect. Multiple model results support the specific prediction of rapid cooling of footwall samples at this time. These results include thermal models for KR8, the closest sample to the fault and at lowest elevation on the footwall, as well as individual and composite vertical transect thermal models from roughly 10 km east of the inferred fault trace, near the confluence of the Middle and South Forks Kings River (**FIGURE 1**). This result strongly supports the conclusion that kilometer scale west-down normal faulting created a large amount of relief across the paleo-Kings River, and that the pulse of incision triggered by this event is directly responsible for much of the relief that comprises modern day Kings Canyon.

In contrast to the rapid Eocene cooling required by our vertical transect data, samples from higher elevations of Kings Canyon, as well as from the hanging wall of the fault, contain little to no information regarding this event. This is consistent with the idea that these rocks were already cooled through the PRZ by Eocene time. Accordingly, our data constrains a major phase of relief generation in the Kings Canyon circa 45-40 Ma, but also are consistent with previous workers' conclusions that the low-relief high-elevation interfluvies mimic the Late Cretaceous landscape, eroded slowly until circa 45 Ma.

414

415 7.2 *Integrating the different stories*

416 As we point out in SECTION 2, considering previous published data as complementary rather
417 than competitive shows that our data, and the Eocene incision pulse that it requires, is also in
418 agreement with the analyses of House et al (1998, 2001). With two horizontal transects of Ap-
419 He data, both of which are located upstream of the sampling from our study, House et al. (1998,
420 2001) argue that long wavelength relief of San Joaquin and Kings River canyons was greater in
421 Late Cretaceous time than in the modern. In accord with this result, we propose that Late
422 Cretaceous relief slowly decreased through the Paleogene until it was rejuvenated circa 45-40
423 Ma by the tectonic regime resolved in this paper.

424

425 Thermochronologic data and thermal modeling with QTQt presented in this study constrain the
426 timing and magnitude of this phase of southern Sierra relief generation. In total the incisional
427 response to west-down normal faulting on the WSFS circa 45-40 Ma has accounted for over 50%
428 of maximum vertical relief of Kings Canyon, and 60 - 80% of vertical relief at the location of our
429 samples. We suggest that this event accounts for the pulse of Cenozoic relief generation in the
430 southern Sierra argued for by previous studies (Clark et al., 2005; McPhillips and Brandon,
431 2012; Wakabayashi, 2013), none of which were able to precisely constrain the timing or
432 mechanism in the way we have done here. After faulting occurred, the southern Sierra returned
433 to a background erosion rate of roughly 0.04-0.06 mm/year until late Cenozoic time when
434 another pulse of uplift and incision occurred, resulting in incision of inner slot canyons that are
435 present in many southern Sierra river canyons on the order of hundreds of meters (Stock et al,

2004). By treating these different stories as complementary rather than competitive, we are able to integrate them together and form a mutually consistent timeline.

7.3 *Eocene faulting and Great Valley Sedimentation Patterns*

While evidence for similar events has not been found elsewhere along the western slope of the southern Sierra, several studies have documented a parallel style and similar magnitude of Eocene tectonic activity in the Great Valley subsurface (FIGURE 7).

In the northern San Joaquin Valley, flanking the Stockton Arch and Diablo uplift, the deep-marine Kreyenhagen shale is conformably overlain by the late-Middle Eocene Poverty Flat Sandstone, a conglomerate-bearing, shallowing upwards unit comprised of marine-shelf to fluvial deposits (Bartow, 1992). In this area the Kreyenhagen and Poverty Flat are unconformably overlain by the Oligocene to Miocene Valley Springs formation, suggesting an extended period of erosion and/or non-deposition following deposition of the Poverty Flat Sandstone. To the north in the Sacramento Valley (FIGURE 7), the steeply dipping, north-northwest striking Midland and Kirby Hills Fault systems created a kilometer-scale Early to Middle Eocene deep-marine structurally-controlled graben depocenter (Imperato, 1995 and references therein; Sullivan and Sullivan 2012, 2013). Tectonic activity on the Midland Fault is further associated with Middle Eocene submarine canyons (Sullivan and Sullivan, 2012; 2013). The location of these vertically stacked, southwestwardly trending submarine canyons is interpreted to be structurally controlled by the Midland and Kirby Hills fault systems, while the timing of erosion and filling of the canyons is interpreted to be due to sea level variations. These submarine canyons include the Sidney Flat Canyon and Markley Canyon, which reach maximum

depths of 500 meters to 750 meters in the Sacramento Valley subsurface (Sullivan and Sullivan, 2012; 2013). To the south this graben system continues into the Mount Diablo area, where the Kirby Hills fault joins the Kirker fault on the west side of the graben, and the Midland fault terminates into the Brushy Creek fault on the east side (Unruh et al., 2007). Deposition of growth strata within this structurally controlled graben occurred during Eocene deposition (unit EP2 of Unruh et al., 2007).

These data from the Great Valley subsurface suggest control of deep marine depocenters along high angle extensional faults contemporaneous with proximal marine shallowing (Kreyenhagen-Poverty Flats deposition). Combined with our findings of erosional and implicit tectonic activity circa 45-40 Ma in the southern Sierra, data from the Great Valley subsurface suggest an Eocene east-west extensional tectonic regime marked by contemporaneous uplift and erosion of the southern Sierra, shallowing of the proximal Great Valley forearc, and complex structural control of deeper marine depocenters.

The Eocene was a transitional time period in the evolution of western North America, between Late Cretaceous-early Cenozoic Sevier-Laramide crustal shortening and mid to late Cenozoic initiation and growth of the San Andreas transform plate boundary. At this time Sierra Nevada was the western flank of an erosional highland spanning much of the western United States, commonly referred to as the Nevadaplano (DeCelles, 2004; Henry et al., 2012). To the south was the Late Cretaceous gravitationally collapsed southernmost Sierra Nevada and Mojave-Salinia batholiths (Saleeby, 2003; Chapman, 2012). However, the lack of early Cenozoic deposits from the southern Sierra kept previous workers from constraining the tectonic activity

of this time period. By utilizing the $\text{Ap-}^4\text{He}/^3\text{He}$ method, we are able to discern evidence for Eocene tectonics in the southern Sierra, and find it to be consistent with evidence from the Great Valley subsurface.

8. CONCLUSIONS

Ap-He data from high elevation samples on vertical transects along the North Fork and main trunk of the Kings River are consistent with regionally interpreted slow erosion at a rate of 0.04-0.06 mm/year during Late Cretaceous to early Cenozoic time. However, low elevation samples from these same vertical transects are too old to be explained by this trend. Along the North Fork Kings River, this large deviation led us to identify a northwest striking, west-down normal fault, corroborating the presence of a system of faults, the WSFS, which has been neglected or dismissed (Wahrhaftig, 1965) in the literature since discovery by Hake (1928). Combining Hake's (1928) early description with new Ap-He data and field reconnaissance, we infer a fault trace and constrain the vertical offset on this fault to be on the order of a kilometer. Thermal modeling of individual samples and a composite vertical transect of Ap-He and $\text{Ap-}^4\text{He}/^3\text{He}$ data constrain the timing of fault activity to circa 45-40 Ma. Furthermore, this fault activity was contemporaneous with, or immediately followed by, a major incision pulse on the main trunk of the Kings River, which corresponds to 60 – 80% of vertical relief of modern Kings Canyon at the location of the samples. By integrating this fault activity and subsequent incision with other published work, we present a coherent framework for the Cenozoic evolution of the southern Sierra Nevada.

This new Eocene erosional regime is broadly consistent with previous studies of Sierra Nevada topographic evolution, including arguments for Late Cretaceous large-magnitude long-wavelength relief on the Kings River canyon (House et al., 1998) as well as Plio-Pleistocene rapid incision (Stock et al., 2004). Considered in conjunction with other studies from the Great Valley subsurface, our data suggest a previously unconstrained Eocene tectonic regime for the southern Sierra Nevada-Great Valley forearc system. This regime is marked by uplift, erosion, and internal structural deformation of both the southern Sierra Nevada mountain range and proximal Great Valley forearc, and deep marine depocenters structurally controlled by east-west extensional tectonics.

Thermal modelling of $\text{Ap-}^4\text{He}/^3\text{He}$ data from the Kings River canyon has allowed us to constrain the timing and magnitude of incision of much of the relief present in the modern canyon. However, this was not the first version of this landscape, rather this Eocene incision was superimposed on older relief (e.g. House et al. 1998). We have shown that this incision was directly controlled by a kilometer-scale west-down normal fault located along the western slope of the southern Sierra.

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Figure 1. Overview map of study area along the Kings River Canyon, Sierra Nevada, California. Inferred trace of normal fault scarp constrained by Ap-He data is shown as dashed black line with ticks. Approximate location of scarp mapped by Hake (1928) is shown as gray dashed line. Locations of Ap-He data constraining the fault location are plotted as squares (hanging wall) and circles (foot wall). Locations of Ap-He data comprising the KR1-4, KC4 vertical transect are plotted as triangles. Base imagery is a hillshade derived from USGS national elevation dataset 10 m digital elevation model. Inset at upper right shows location of San Joaquin (SJ), Kings, and Kern Rivers, as well as outline of the Figure 1 extent on California state boundary.

Figure 2. Ap-He age versus corrected elevation for each vertical transect and across inferred normal fault trace. **A.** KR1-4, KC4 vertical transect. Linear regression is plotted through the three samples above the break in slope (slope = 0.04 mm/yr). **B.** KR5-7 vertical transect. Line is drawn through KR5 and KR6 (slope = 0.05 mm/yr). **C.** Plot of all Ap-He data near the inferred fault trace (this study and House et al. 1998). Lines shown for each fault block (hanging wall vs. foot wall) are linear regressions through the data. Slopes are 0.05 mm/yr (hanging wall) and 0.06 mm/yr (footwall). As described in the text, a minor correction is applied to the elevation of samples based on their perpendicular distance to the axis of the range (referred to as tilt corrected, or TC elevations in [TABLE 1](#)).

Figure 3. Field photo of KR5-7 vertical transect, view to the NW from Blackrock Road pull out at 36.904° N, 119.070°W. Arrows point to topographic steps discussed in the text. A is approximately 100 m step and is the location of the inferred normal fault trace (red line with tick marks). B is approximately 500 m high step east of vertical transect. Balch penstock is shown as faint gray line for reference.

Figure 4. Results from thermal modelling of sample KR8 done using QTQt (Gallagher, 2012). Upper panel shows the probability at each 1 Ma time step of the thermal history of the sample passing through each pixel in temperature space. Thin line shows the best fit t-T path (Max Posterior), which resulted in the model fit $^4\text{He}/^3\text{He}$ spectrum plotted in middle panel. Middle panel shows measured $^4\text{He}/^3\text{He}$ spectrum (black boxes) and model fit spectrum (maximum posterior, gray line). Lower panel shows measured age and uncertainty plotted over histogram of accepted model ages. Total number of model iterations during post burn-in phase is 5×10^5 .

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Figure 5. Individual results from KR1, KR2, KR3, and KR4 thermal modeling with QTQt (Gallagher, 2012). Upper panel of each shows the probability at each 1 Ma time step of the thermal history of the sample passing through each pixel in temperature space. The thin black line on each upper panel shows the best fit t-T path (Max Posterior) which resulted in the model fit $^4\text{He}/^3\text{He}$ spectrum plotted in middle panel. Middle panel of each shows measured $^4\text{He}/^3\text{He}$ spectrum (black boxes) and model fit spectrum (maximum posterior, thick gray lines). Lower panel of each shows measured ages and uncertainties plotted over histogram of accepted model ages. Total number of model iterations during post burn-in phase of each model run is 5×10^5 .

Figure 6. Time-temperature results of composite QTQt thermal modeling of the KR1-4, KC4 vertical transect. The model optimizes a time-variable linear thermal gradient (different at each 1 Ma time step) across the entire vertical transect.

Figure 7. Regional map showing geographic context of study area and the location of data from the Great Valley subsurface discussed in text. BCF = Brushy Creek Fault. KF = Kirker Fault. KHF = Kirby Hills Fault. MF = Midland Fault. SF = Stockton Fault. PFS = Poverty Flat Sandstone. WSFS = Western Sierra Fault System. Base image is a hillshade derived from USGS 10 m national elevation dataset digital elevation model.

Sample	N ^b	r (μ m) ^c	eU (ppm) ^e	Raw Age (Ma)	$\pm$ 1 st err ^g	Corr Age (Ma) ^f	$\pm$ 1 st err	Data Source ^h	⁴ He/ ³ He Data ^h	pluton ^h	UTM Zone 11		Elevation	TC Elevation ^k
											E	N		
KR1	4	64	43	27.2	1.76	34.7	2	(1)	(1)	QD of Yucca Point (5). 110 Ma (4).	330649	4079476	658	281
KR2	4	62	39	28.9	1.1	37.2	1.3	(1)	(1)	QD of Yucca Point (5). 110 Ma (4).	330946	4079974	987	596
KR3	3 ^a	66	48	29.3	1.9	37.1	2.2	(1)	(1)	QD of Yucca Point (5). 110 Ma (4).	332120	4078503	745	343
KR4	4	68	42	39.1	0.9	49	1.1	(1)	(1)	QD of Yucca Point (5). 110 Ma (4).	330586	4077995	1426	1080
KR5	3 ^a	62	42	45.7	3.8	60.1	4.7	(1)	no	Unmapped	314403	4088026	1231	1217
KR6	4	66	64	41.9	1.9	54.1	2.3	(1)	no	Unmapped	314564	4087333	930	925
KR7	3 ^a	68	64	50.4	2.7	64.6	3.3	(1)	no	Unmapped	313825	4086827	536	560
KR8	4	62	38	32.5	0.7	42.5	0.7	(1)	(1)	Unmapped	318786	4081525	402	378
13SS6	9 ^a	49	8	44.1	1.5	62.8	1.6	(1)	no	Unmapped	313781	4081334	345	472
96-1	NR ^d	97 ^d	47	68.2	NR ^d	80.3	4.6 ^g	(2)	no	Giant Forest GD (5). 97-102 Ma (4).	332656	4073310	1829	1506
95-15	NR ^d	77 ^d	37	68.5	NR ^d	84.6	8.5 ^g	(2)	no	Granite of Grant Grove (5). 106 Ma (4).	325237	4073927	1768	1655
95-14	NR ^d	81 ^d	21	54.4	NR ^d	66.3	4.7 ^g	(2)	no	Giant Forest GD (5). 97-102 Ma (4).	333459	4073818	1829	1468
KC4	NR ^d	48 ^d	10	49.4	NR ^d	70.6	3.5 ^g	(3)	no	GD of Brush Canyon (5). 86 Ma (4).	330899	4085954	2490	2001

Table 1. Ap-He and Ap-⁴He/³He data used in this study. KR1-KR8 and 13SS6 are newly reported here. The four remaining samples are taken from previously published studies. ^aSingle outlier apatite is excluded from mean. ^bN is number of single grain He analyses used for each sample. ^cr is average equivalent spherical radius. ^dNR is "not reported." Where radius not reported, sphere equivalent radius is estimated from average Ft (Farley, 1996). ^eeU is effective uranium concentration, weights U and Th for their a productivity, computed as (U + (0.235 * Th)). ^fUncorrected date is corrected for a-ejection using Farley et al., (1996). ^gUncertainty on the mean He dates reported here as the 1 sigma standard error of the mean, except for samples taken from (2), where standard deviation is reported. ^hData sources: (1) this study; (2) House et al. 1998; (3) House et al., 1997; (4) Chen and Moore, 1982; (5) Moore and Nokleberg, 1992. ^kTC Elevation is tilt corrected elevation, based on the perpendicular distance of each sample to a line parallel to the range axis, as described in the text.