Synorogenic extension localized by upper-crustal thickening: An example from the Late Cretaceous Nevadaplano

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ABSTRACT

Synconvergent extension within orogenic systems is often interpreted as gravitational spreading of thickened crust or as a response to thrust belt dynamics. However, the processes that spatially localize extension during orogenesis are not fully understood. Here, a case study from the United States Cordillera demonstrates that localized upper-crustal thickening can exert a first-order control on the spatial location of synorogenic extension. The Eureka culmination, a 20-km-wide, north-trending anticline with 4.5 km of structural relief in the hinterland plateau of the Sevier orogenic belt (or "Nevadaplano") in eastern Nevada was deformed by two sets of north-striking normal faults that pre-date late Eocene volcanism. (U-Th)/He and fission-track thermochronology data collected from Paleozoic quartzite in the footwalls of two normal faults demonstrate rapid (10 °C/m.y.), Late Cretaceous to Paleocene (75–60 Ma) cooling, which we interpret as tectonic exhumation during extension, and which was concurrent with late-stage shortening in the frontal Sevier thrust belt. This example illustrates that structural and topographic relief generated within zones of localized upper-crustal thickening can spatially focus extension during orogenesis, and adds to a growing body of evidence that Late Cretaceous–Paleocene extension in the Nevadaplano occurred at both mid- and upper-crustal levels.

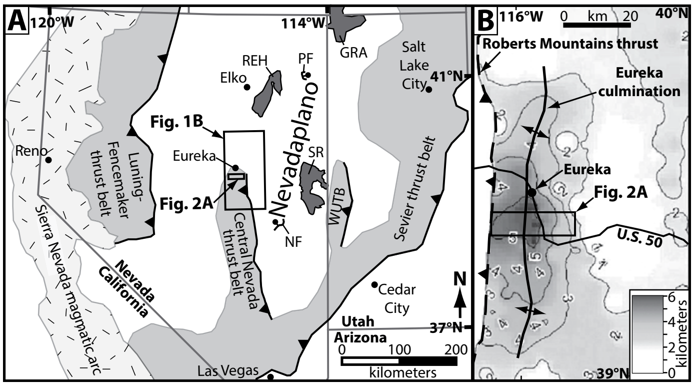

Figure 1. A: Map of Cordilleran retroarc region in Nevada and Utah (United States), modified from Long et al. (2014). Approximate extents of Cordilleran thrust systems are shaded light gray, and metamorphic core complexes are shaded dark gray. WUTB—Western Utah thrust belt; NF—Late Cretaceous Ninemile fault of Druschke et al. (2009); PF—Late Cretaceous Pequop fault of Camilleri and Chamberlain (1997); REH—Ruby–East Humboldt core complex; SR—Snake Range core complex; GRA—Grouse Creek–Raft River–Albion core complex. B: Exhumation map of Eureka region, with contours of vertical kilometers of Paleozoic–Mesozoic rock eroded prior to Paleogene volcanism (modified from Long, 2012). Eureka culmination is defined by north-trending exhumation high. U.S. 50—U.S. Highway 50.

INTRODUCTION

Synorogenic extension within thickened continental crust has been widely recognized, indicating that it is a fundamental process that contributes to the structural and erosional history of orogenic systems (e.g., Burchfiel and Royden, 1985; England and Houseman, 1989; Wells and Hoisch, 2008). Such extension is often attributed to gravitational spreading of overthickened, isostatically compensated crust, commonly proximal to regional elevation gradients (Burchfiel and Royden, 1985; Dewey, 1988), or is interpreted to be induced by the dynamic responses of fold-thrust belts to external factors such as the balance between accretion and erosion rates, isostatic uplift and thermal weakening initiated by lithospheric delamination, or changes in décollement strength (Dahlen, 1990; Houseman et al., 1981). The purpose of this study is to examine additional factors that may control the location of synorogenic extension by presenting a case study from the United States Cordillera.

In the western United States, significant crustal thickening was accommodated during Cretaceous–Paleogene shortening in the Sevier retroarc thrust belt in Nevada and Utah (Fig. 1A), which represents part of the greater North American Cordilleran orogenic system. The Late Cretaceous–Paleogene hinterland of the Sevier thrust belt in Nevada and western Utah is the hypothesized site of a relict orogenic plateau, termed the "Nevadaplano" after comparison to the Andean Altiplano-Puna (DeCelles, 2004), which supported surface elevations of ~3 km (DeCelles and Coogan, 2006; Snell et al., 2014). Thermobarometric data from the Ruby–East Humboldt core complex in northeastern Nevada and the Raft River–Grouse Creek–Albion core complex in northern Utah (Fig. 1A) provide evidence for synorogenic decompression of mid-crustal rocks as early as ca. 85–75 Ma (e.g., Hodges and Walker, 1992; McGrew et al., 2000; Wells et al., 2012). However, upper-crustal normal faulting of demonstrable Late Cretaceous age in the Nevadaplano has been documented only in two spatially isolated localities in eastern and northeastern Nevada (Fig. 1A) (Camilleri and Chamberlain, 1997; Druschke et al., 2009).

In this study, we examine the case of the Eureka culmination, an anticline in eastern Nevada constructed during the Early Cretaceous (Figs. 1B and 2). Published mapping and construction of retro-deformed cross-sections show that the culmination was extended by two sets of normal faults that pre-date late Eocene volcanism (Long et al., 2014). We present time-temperature paths determined for rocks sampled from the footwalls of these normal faults, which quantify the timing of tectonic exhumation, and demonstrate upper-crustal extension in the Nevadaplano concurrent with shortening in the Sevier thrust belt. The spatial confinement of normal faults within the map area of the culmination reveals that localized upper-crustal thickening can exert a first-order control on the location of later extension. This spatially limited deformation system provides a unique opportunity to examine controls on synorogenic extension at the scale of an individual structure.

EUREKA CULMINATION AND PRE-VOLCANIC NORMAL FAULTS

In the region surrounding Eureka, Nevada, erosion levels below a late Eocene (ca. 37 Ma), sub-volcanic unconformity define an 80-km-long, north-trending exhumation high that records erosion of as much as 6 km of Paleozoic and Mesozoic rocks (Fig. 1B) (Long, 2012). Geologic mapping and retro-deformed cross-sections constructed across this exhumation high (Fig. 2) define the Eureka culmination, an anticline with a 20 km wavelength, a 4.5 km amplitude, and limb dips of 25°–40° (Long et al., 2014). The anticline is interpreted as a fault-bend fold that formed from

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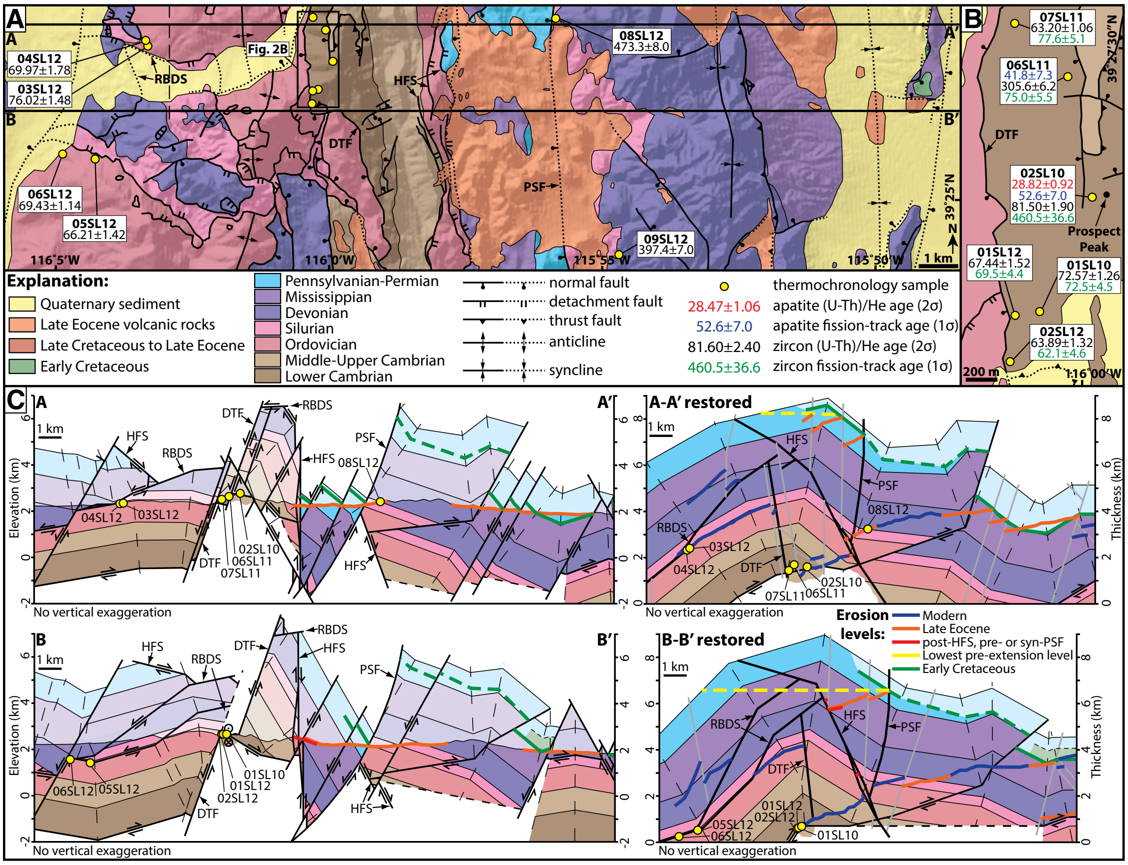

Figure 2. A: Geologic map of northern Fish Creek Range and southern Diamond Mountains (Nevada, USA), simplified from Long et al. (2014), showing thermochronology samples and ages. B: Geologic map showing locations and ages of Cambrian thermochronology samples. C: Cross-sections A-A′ and B-B′, modified from Long et al. (2014). Quaternary and Tertiary rocks are omitted for simplicity. Cross-sections on left show modern geometry, and on right show retrodeformed, pre-extensional geometry; modern and restored positions of thermochronology samples are shown. Explanation of erosion levels on lower right; translucent areas represent eroded rock. HFS—Hoosac fault system; RBDS—Reese and Berry detachment system; PSF—Pinto Summit fault; DTF—Dugout Tunnel fault.

eastward motion of a thrust sheet over a buried footwall ramp, synchronous with deposition of the Aptian (ca. 116–122 Ma) Newark Canyon Formation in a piggyback basin on the eastern limb (Long et al., 2014).

After its construction, the Eureka culmination underwent 7–8 km (40%–45%) of extension, accommodated by two sets of normal faults that are overlapped by the late Eocene unconformity (Long et al., 2014). Therefore, the erosion pattern on Figure 1B is the cumulative result of erosion of the culmination crest during and after its construction and tectonic exhumation of the footwalls of pre-volcanic normal faults. The earliest extension, bracketed between ca. 116 and 37 Ma, was accommodated by oppositely verging normal fault systems developed in each limb, oriented approximately symmetrically about the axial plane (Fig. 2C) (Long et al., 2014), defined here as set 1 faults. Set 1 faults include the Hoosac fault system in the eastern limb, an anastomosing series of 70°–90° east-dipping normal faults with a cumulative offset of 5 km, which place Mississippian and Permian rocks over Ordovician rocks; and the Reese and Berry detachment system in the western limb, which consists of one or more 10°–30° west-dipping faults developed at 0°–20° cutoff angles to Ordovician to Devonian rock units, with a cumulative offset of 2–4 km.

The second episode of extension was accommodated by steeply dipping (60°–70°), multiple-kilometer-throw (2–4 km), down-to-the-west normal faults, defined here as set 2 faults, including the Pinto Summit fault and Dugout Tunnel fault (Fig. 2). Motion on set 2 faults was accompanied by 20°–30° of eastward tilting, which steepened the dip of the eastern limb, shallowed the dip of the western limb, and rotated the Hoosac fault system and the Reese and Berry detachment system to their present steep and shallow dip angles, respectively. Set 2 faults cut a ca. 86 Ma metamorphic contact aureole, tilt conglomerate that has a ca. 72 Ma maximum deposition age, and are overlapped by ca. 37 Ma volcanic rocks, and are therefore bracketed between Late Cretaceous and late Eocene (Long et al., 2014).

EXHUMATION TIMING AND THERMAL MODELING

To assess the timing of cooling that accompanied tectonic exhumation within the Eureka culmination, we collected low-temperature thermochronology data from quartzite sampled from the footwalls of set 1 and set 2 normal faults. In this study, (U-Th)/He ages from zircon (ZHe) and apatite (AHe) are combined with fission-track ages from zircon (ZFT) and apatite (AFT) to provide details on the timing and rates of cooling over the range of ~220–60 °C (Reiners et al., 2005) (see the GSA Data Repository[1] for methods and data tables).

We collected 12 samples of Paleozoic quartzite (Fig. 2): six from the Cambrian Prospect Mountain Quartzite in the footwall of the Hoosac fault system and Dugout Tunnel fault in the culmination crest zone, four from the Ordovician Eureka Quartzite in the footwall of the Reese and Berry detachment system in the western limb, and two from the basal quartzite of the Devonian Beacon Peak Dolomite in the footwall of the Pinto Summit fault in the eastern limb. Five of the six Cambrian samples yielded ZFT ages between ca. 77 Ma and 62 Ma, and one (sample 02SL10) yielded a Paleozoic age, indicating a maximum post-depositional burial temperature of ~185–225 °C (Bernet, 2009) for this sample. Four of the six Cambrian samples yielded ZHe ages between ca. 72 and 63 Ma, with one outlier (sample 02SL10) at ca. 81 Ma, and one sample (06SL11) that yielded a Paleozoic age. Apatite was obtained only from two Cambrian samples (02SL10, 06SL11), which yielded AFT ages between ca. 52 and 42 Ma, and a single AHe age of ca. 29 Ma. The four Ordovician samples

[1]GSA Data Repository item 2015127, thermochronology sample information (Section DR1, Table DR1), methods and supporting data for fission-track analyses (Section DR2, Table DR2), methods and supporting data for (U-Th)/He analyses (Section DR3, Tables DR3 and DR4), and supporting information for time-temperature path modeling (Section DR4, Tables DR5 and DR6, and Figures DR1–DR3), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

yielded ZHe ages between ca. 66 and 76 Ma. The Devonian samples (08SL12, 09SL12) yielded ZHe ages between ca. 400 and 475 Ma, indicating that post-depositional burial temperatures for these samples did not exceed ~160–200 °C (Reiners et al., 2005), consistent with their ~4 km maximum burial depths.

The cooling ages were inverse-modeled using HeFTy software (Ketcham, 2005) in order to derive time-temperature (*t-T*) paths (Fig. 3) (see the Data Repository for methods). Well-defined fault geometries and stratigraphic thicknesses, cross-section retro-deformation, and constraints on the stratigraphic levels of erosion surfaces before and after normal faulting (Fig. 2C) (Long et al., 2014) allowed estimation of the individual contributions of tectonic exhumation in the footwalls of set 1 and set 2 normal faults versus pre- and post-extensional erosional exhumation for each sample (Table DR5 in the Data Repository). Structural depths measured on the cross sections were converted to burial temperature ranges, using an estimated 30 ± 3 °C/km geothermal gradient obtained from integration of reset and un-reset ages with peak burial depths (Table DR6). This allowed relating cooling ages from specific thermochronologic systems directly to tectonic exhumation during normal faulting (Fig. 3). Thermal models were constrained to start at pre-extensional burial temperature ranges unique to each sample (Table DR5) at ca. 122–116 Ma, the time of construction of the Eureka culmination (Long et al., 2014), and all samples were modeled to have reached 10 ± 10 °C at 0 Ma. Composite *t-T* paths for median ages and for all ages obtained from Cambrian samples are shown in Figure 3 (see the Data Repository for *t-T* paths of all samples).

Cambrian samples in the footwall of the Hoosac fault system and Dugout Tunnel fault yielded weighted mean *t-T* paths that record rapid cooling from ~210 to 100 °C between ca. 75 and 60 Ma, at rates varying between 3 and 45 °C/m.y. (Fig. DR2), with a rate of 11 °C/m.y. supported by median cooling ages (Fig. 3A). Motion on the Hoosac fault system (set 1) exhumed the samples from depths of 6–8 km (~190–260 °C) to 4–5 km (~110–160 °C), and motion on the Dugout Tunnel fault (set 2) exhumed the samples to depths of 2–2.5 km (~50–80 °C) (Table DR5). Therefore, we interpret the ca. 75–60 Ma period of rapid cooling as the timing of tectonic exhumation during motion on normal faults of both set 1 and set 2. Prior to this rapid exhumation, cooling rates between ca. 120 and 75 Ma varied between ~0.2 and 2.0 °C/m.y., with a median value of 0.4 °C/m.y., which we interpret as the long-term, minimum rate accommodated by erosional exhumation of the crest zone of the culmination during and after its construction, prior to the onset of extension. Cooling rates between ca. 60 and 0 Ma slowed to 0.7–4.4 °C/m.y., with median rates of 0.9–2.8 °C/m.y., which we interpret as long-term rates associated with younger normal faulting and erosional exhumation that brought samples to the modern surface.

Ordovician samples in the footwall of the Reese and Berry detachment system, which exhumed samples from depths of 5–6 km (~140–200 °C) to 2–4 km (~60–130 °C) (Table DR5), record cooling through ZHe closure (~160–200 °C) between ca. 76 and 66 Ma. Therefore, we interpret these ages to be related to tectonic exhumation during motion on the Reese and Berry detachment system. Cooling rates prior to passage through ZHe closure range from 0.4 to 0.6 °C/m.y. (Fig. DR3), and are interpreted as long-term, pre-extensional rates accommodated by erosional exhumation of the western limb of the culmination. However, because cooling ages from lower-temperature systems were not obtained, the long-term cooling rates that post-date passage through ZHe closure, which range from 1.8 to 2.3 °C/m.y. (Fig. DR3), are interpreted as a minimum during motion on the Reese and Berry detachment system.

DISCUSSION

The data presented here provide evidence for Late Cretaceous to Paleocene (ca. 75–60 Ma), spatially isolated, surface-breaching extension within the Nevadaplano, concurrent with the final stages of shortening in the Sevier thrust belt at this latitude (DeCelles and Coogan, 2006). These results add to an existing body of evidence for synorogenic extension within the plateau, which includes upper-crustal normal faulting as old as ca. 85–65 Ma documented on the Ninemile fault in eastern Nevada (Druschke et al., 2009) and the Pequop fault in northeast Nevada (Camilleri and Chamberlain, 1997). In addition, multiple studies have documented initial exhumation of mid-crustal rocks in the Ruby–East Humboldt and Raft River–Grouse Creek–Albion core complexes as early as ca. 85–75 Ma, and have identified shear zones that accommodated this early exhumation (e.g., Hodges and Walker, 1992; Wells et al., 1998, 2012; McGrew et al., 2000; Hallett and Spear, 2014).

Late Cretaceous extension in the Nevadaplano has been interpreted as a consequence of isostatic adjustment and thermal weakening following a regional mantle lithosphere delamination event, proposed on the basis of initial exhumation in core complexes synchronous with regional intrusion of peraluminous granites (Wells and Hoisch, 2008; Wells et al., 2012). The two sites of documented mid-crustal exhumation, the Ruby–East Humboldt and Raft River–Grouse Creek–Albion core complexes and surrounding areas, have been demonstrated to be regions of localized, high-magnitude crustal thickening (e.g., Coney and Harms, 1984; Camilleri and Chamberlain, 1997; McGrew et al., 2000; Wells et al., 2012). This highlights that regional gradients in crustal thickness, and therefore gravi-

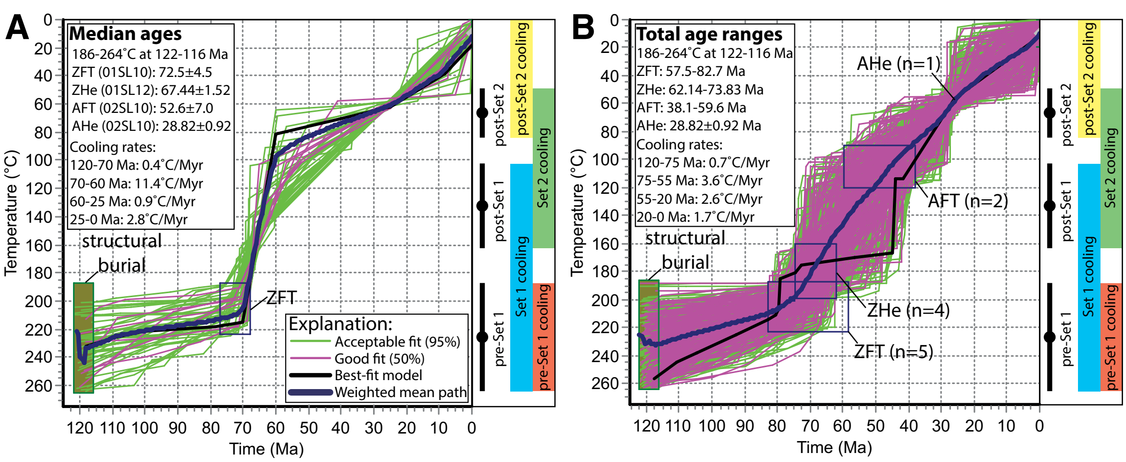

Figure 3. Modeled time-temperature (*t-T*) paths for Cambrian quartzite samples in footwall of Hoosac fault system (HFS) and Dugout Tunnel fault (DTF). Total burial temperature (black dots with bars) and cooling ranges (colored bars) for all samples before and after motion on set 1 and set 2 normal faults (Table DR5 [see footnote 1]) are plotted on right. A: *t-T* path constrained by median zircon fission-track (ZFT), (U-Th)/He zircon (ZHe), and apatite fission-track (AFT) ages of the Cambrian samples, and single (U-Th)/He apatite (AHe) age (ZFT closure temperature range from Bernet [2009]). B: Total range of permissible *t-T* paths constrained by total age and error ranges of all ZFT, ZHe, AFT, and AHe ages from Cambrian samples (closure temperature ranges from Reiners et al. [2005] and Bernet [2009]).

tational potential energy, influenced the location of synorogenic extension during the dynamic response of the orogenic belt to delamination.

Similarly, the Eureka culmination provides an example of synorogenic extension superimposed over a site of localized upper-crustal thickening. A regional compilation of Paleogene erosion levels indicates that pre-Paleogene, surface-breaching normal faults are confined to the map area of the culmination (Long, 2012; Long et al., 2014). Construction of the culmination generated ~4.5 km of structural relief relative to the surrounding region. In addition, Mississippian and Permian rocks that are preserved in the hanging wall of the Hoosac fault system restore high in the culmination crest zone (Fig. 2C), which shows that the culmination crest could have undergone only ~1–2 km of erosion prior to extension (Table DR5). Therefore, we interpret that remnant topographic relief between the culmination and the surrounding region was integral for spatially focusing an extensional stress regime within this area of upper-crustal thickening (e.g., Dalmayrac and Molnar, 1981; Burchfiel and Royden, 1985). The example of the Eureka culmination, combined with the results from the core complexes discussed above, illustrates that gradients in gravitational potential energy, at different scales and crustal levels, played a primary role in controlling the location of late-stage, synorogenic extension within the Nevadaplano.

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