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NEW CONSTRAINTS ON THE TIMING, RATE, AND STYLE OF EXHUMATION OF THE WOOD HILLS AND PEQUOP MOUNTAINS, ELKO COUNTRY, NEVADA

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INTRODUCTION

The Ruby Mountain Detachment Fault is a regionally significant structure and is responsible for exhumation of the Ruby Mountains-East Humboldt Range metamorphic core complex. Despite numerous thermochronometric studies, many uncertainties remain concerning the rate, style, and timing of the on set of extension along the Ruby Mountain Detachment Fault. Some believe that the bulk of regional extension occurred during the Miocene (Colgan et al., 2010; Snee et al., 2016), whereas others argue that extension began much earlier during the Eocene (McGrew and Snee, 1994; (Kistler et al., 1981; Dallmeyer et al., 1986; Wright and Snoke, 1993; McGrew and Snee, 1994; McGrew and Casey, 1998). McGrew and Snee (1994) used $^{40}Ar/^{39}Ar$ biotite cooling ages and a suite of WNW-deformed 29 Ma biotite monzogranitic orthogneisses in the East Humboldt Range to argue for progressive unroofing of the footwall of a WNW-rooting crustal scale normal fault system between ~30 Ma and 21 Ma. The goal of this study is to use zircon (U-Th)/He thermochronometry to provide new constraints on the timing, rate, and style of exhumation of the Wood Hills and Pequop Mountains (located east of the Wood Hills), which are part of the Ruby Mountains-East Humboldt Range metamorphic core complex.

Study Area

The Ruby Mountains-East Humboldt Range metamorphic core complex, which is located within the hinterland region of the Sevier Orogen (Howard, 2003), exposes Precambrian basement, Neoproterozoic-Paleozoic metamorphosed shelf margin sediments, and Mesozoic-Cenozoic plutonic rocks (Snee et al., 2016). Strata were duplicated across the study area during Mesozoic crustal shortening in the sewer oroga, and the same stratigraphic units are exposed in the East Humboldt Range, Wood Hills, and Pequop Mountains. Metamorphic grade increases northwestward across the study area (Camilleri, 1998). The Pequop Mountains are located farthest east and preserve the lowest grade of metamorphism (unmetamorphosed to lower amphibolite) (Camilleri, 2010). The gently eastward dipping top-west normal fault, the Pequop Fault, separates the Pequop Mountains into two domains of Proterozoic-Paleozoic rocks. The two domains have different structural and metamorphic characteristics, which increase in metamorphic grade with burial depth (Camilleri, 2010). Camilleri and Chamberlain (1997) bracket the age of the Pequop Mountain metamorphism (age of crustal shortening) between 154 and 86 Ma from dating a premetamorphic dike that is deformed by the metamorphic fabric (older bracket) and a U-Pb metamorphic sphene from the Toano Limestone, which is inferred to represent the time of peak metamorphism (younger bracket). Paleozoic strata within the hanging wall of the fault to the east are unmetamorphosed. Calcite-dolomite exchange thermometry shows that carbonates in the Pequops preserve peak metamorphic temperatures that increase from ~300-500 °C towards the south and with increased structural depth within the footwall (Howland, this volume).

The Wood Hills are located centrally within the study area and contain the same stratigraphic units as the Pequop Mountains, although at higher metamorphic grades and attenuated by as much as 50 percent

(Camilleri, 1994). Metamorphic grade increases from lower amphibolite facies in the southeast to upper amphibolite facies in the northwest. Quartz c-axis fabric opening-angle thermometry shows that the Wood Hills reached metamorphic temperatures of 380-515 °C (Jordan, this volume). Further, progressive changes in quartz grain size and the style of quartz recrystallization are consistent with increasing temperatures to the NW (Jordon, this volume).

(U-Th)/He Thermochronometry

Thermochronometry has emerged as a prominent tool for gaining insight into the tectonic history of metamorphic core complex rocks (Stockli, 2005). It provides an estimate for the time elapsed since a sample passed through the respective closure temperature of the thermochronometric system being analyzed. The closure temperature is the isotherm at which the mineral has cooled sufficiently to prevent diffusion of isotopes through radioactive decay (Reiners, 2005).

Zircon is highly suitable for thermochronology because it contains high U and Th concentrations, has high abundance in a wide range of lithologies, is refractory under metamorphic and some magmatic conditions, and resists physical and chemical weathering (Reiners, 2005). The (U-Th)/He thermochronometer measures the accumulation of ^{4}He in a sample over time, due to the radioactive decay of uranium, thorium, and/or samarium. When a zircon is above the system's closure temperature (~180-200 °C), He diffuses out of the system and is not retained in the sample; however, once the zircon cools past this closure temperature, He is retained. Effectively, the (U-Th)/He thermochronometer measures the time elapsed since the zircon cooled (or in the case of metamorphic core complexes: exhumed) past the closure temperature isotherm. This cooling could be associated with exhumation during normal faulting; in this case, rocks will cool (and therefore young) in the direction of slip. The potential is there to get both the timing and rate of cooling (Stockli, 2005).

METHODS

Field Work

Most samples (6) were collected from the Eureka Quartzite, an ideal target because it outcrops extensively across the entire study area and contains abundant zircon. Eureka Quartzite is Ordovician aged, fine-grained, white sandstone with sparse grey, graphite streaks (Camilleri, 2010). One sample was collected from the Prospect Mountain Quartzite (PMQ) in the footwall of the Independence Thrust, is a Mesozoic top-southeast thrust fault. PMQ is Precambrian-Cambrian aged, dark-grey quartzite with minor garnet-bearing micaceous layers (Camilleri, 2010). In the Pequop Mountains, one sample was collected from the footwall and one from the hanging wall of the Independence Thrust. (Fig. 2) In the Wood Hills, samples were collected along a SE-NW transect in the direction of the supposed extension. (Fig. 1)

Mineral Separation

Standard mineral separation procedures were used to isolate zircon for dating. First, a half-gallon of each sample was crushed and pulverized at the University of Dayton using a jaw crusher and Bico Rock Pulverizer. Next, at Washington and Lee University, samples were sieved in a rho-tap machine for 10 minutes to collect grains within the size range of 63-125 μm. A RP-4 Shaker Concentration Table was then used for density separation. The table's angle was altered at the start of each run to achieve aggressive separation (90-95% light and 5% heavy). Samples were sonicated in deionized water for 15 minutes to dissolve salt from the grains and subjected to multiple passovers by a bar magnet to prevent the machine jamming. Samples were passed through the Frantz Magnetic Separator three times at different magnetic amperage intensities (0.5, 1.0, and 1.5 amp) with the separator at a horizontal tilt of 5° and a vertical tilt of 20°. Lastly, non-magnetically separated samples were subjected to heavy liquids separation using sodium polytungstate.

Zircon Grain Selection and (U-Th)/He Analysis

At Dr. Rebecca Flowers' Tectonics and Thermochronometry Lab, University of Colorado-Boulder, zircon grains were screened for quality (crystal size, shape, and presence of inclusions) and hand-selected using a binocular microscope in preparation for (U-Th)/He analysis. Emphasis was placed on finding the largest grains with the most symmetric crystal shape; however, spherical or very well rounded grains were the best available specimens in some samples. Generally, three grains were collected and analyzed for each sample. Grains were placed into niobium tubes, loaded into an ASI Alphachron helium (He) extraction and measurement line, heated to ~800-1100 °C with a diode laser for 5 to 10 minutes to extract the radiogenic ^{4}He, and then analyzed using a mass spectrometer. Degassed grains were dissolved using Parr large-capacity dissolution vessels in a multi-step, acid-vapor dissolution process. First, samples were mixed with 200 µl of Optima grade HF and baked at 220 °C for 72 hours. Next, samples were mixed with 200 µl of Optima grade HCl and baked at 200 °C for 24 hours. Lastly, 200 µl of a 7:1 HNO_3:HF mixture was added to each sample and samples were cooked on a hot plate at 90 °C for 4 hours. Sample solutions, along with standards and blanks, were analyzed for U and Th. He dates were calculated using a custom spreadsheet provided by the Tectonics and Thermochronometry Lab.

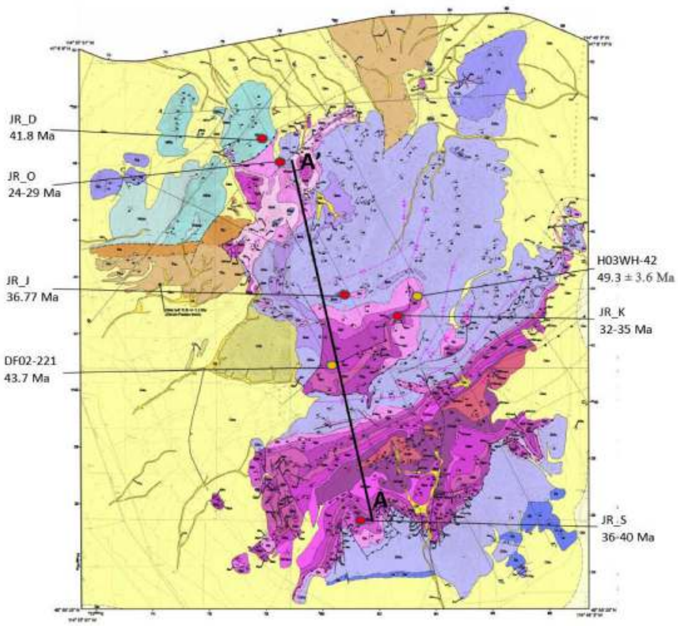


Figure 1. Sample localities and average calculated ages from multiple grains for each sample in this study are indicated by red circles. Gifford et al. (2008) muscovite $^{40}Ar/^{39}Ar$ ages are indicated by yellow circles. Wood Hills, Elko County, Nevada map by Camilleri (2010).

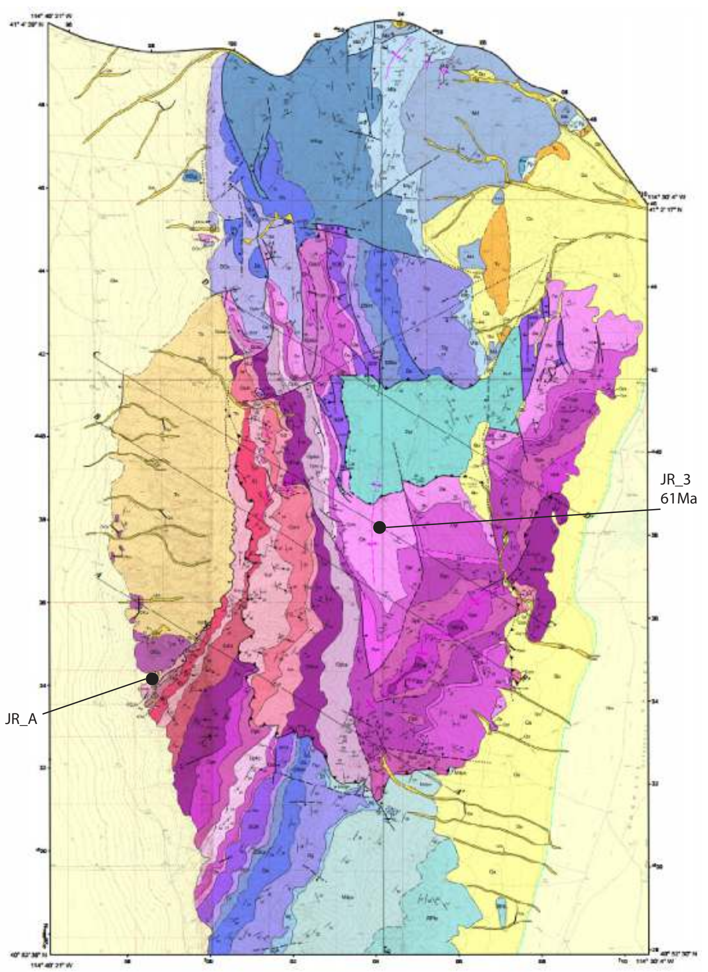


Figure 2. Sample localities and average calculated ages from multiple grains for each sample in this study are indicated by red circles. Northern Pequop Mountains, Elko County, Nevada map by Camilleri (2010).

RESULTS

Cooling ages are Cenozoic and range from 60 Ma (in the Pequops) to as young as 24 Ma (in the Wood Hills) (Fig. 1 & 2). Overall, all grains for a sample produced similar ages; exceptions are samples JR_D and JR_J. For these samples, there is a relationship between age and eU – this is because radiation damage effects closure temperature (Guenthner et al., 2013). For JR_J, I will also use the average as of three grains (36.77 Ma), which produced a spread of ages: 31.21 ± 2.26 Ma, 35.36 ± 2.57 Ma, and 43.76 ± 3.17 Ma.

For JR_D, two grains produced nearly identical ages (~41.8 Ma) and one grain produced an age of 21.18 ± 1.53 Ma. Interestingly, the grain with the dissimilar age has uranium content and eU values that are 7 times the value for the other two grains and likely a much lower closure temperature. The other two grains have eU values similar to others in the dataset. Therefore, I will use an average of the other two grains for subsequent data analysis and interpretation for JR_D. This sample appears older than would be expected for the trend (younging towards northwest), as though it came from higher structural levels. Notably, this sample was taken from within the hanging wall of a fault (Camilleri, 2010).

The two oldest samples are located within the Pequop Mountains (JR_A and JR_3) (Fig. 2). Grains for JR_3 indicate an age of ~60 Ma. JR_3 is located east of JR_A, whose grains produced ages ~43 Ma. The oldest ages in the Wood Hills are from the southernmost (JR_S) and northernmost (JR_D) samples. Excepting sample JR_D, the Wood Hills cooling ages young from the SE to the NW.

DISCUSSION

Timing of the on set of extension on the Ruby Mountain Detachment Fault

The Wood Hills transect provides opportunity to document the time of cooling of footwall rocks exhumed along the Ruby Mountain Detachment Fault. Samples within the transect young towards the northwest, which indicate that they were exhumed along this fault (Fig. 3). The mylonitic shear zone in the NW is well described with kinematic indicators consistent with top-NW shear (MacCready et al., 1997; Plummer, this volume; Jordan, this volume).

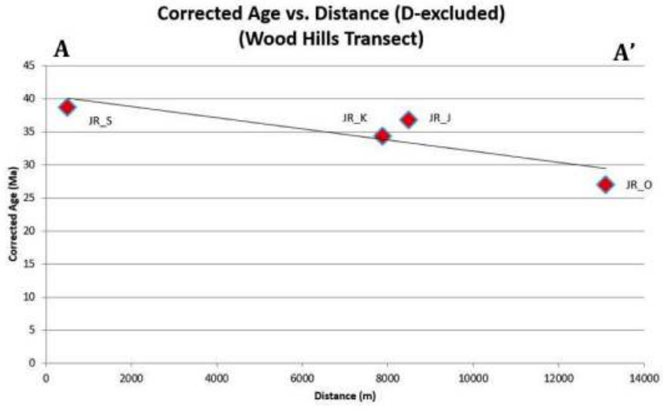


Figure 3. Demonstration of the trend in younging of ages from the southeast to the northwest across the Wood Hills along Transect A-A’ (Fig. 1). Northwest is towards the right side of the figure. With sample JR_D excluded, which may be reasonable (see Results), the trend line would be even steeper.

In the northwestern Wood Hills, where samples O and D were collected, rocks generally show mylonitic overprinting (Jordan, this volume). Quartz fabrics in some samples show top-NW shearing and top-NW CPO – therefore, samples were deformed at temps well-above those of zircon He closure and cooling ages must post-date deformation. Sample 1315-3 from Jordan’s study shows a strong mylonitic fabric and is from the same location as sample JR_O from this study, which records a zircon (U-Th)/He age of 24-29 Ma, consistent with the Ruby Mountain Detachment Fault active during Oligocene times. In addition, Eocene aged, samples throughout the rest of the Wood Hills suggest that the on set of extension could be Eocene or older. This finding is in contrast the findings by Colgan et al. (2010), who document a later on set of extension in the Ruby Mountains to the south.

The Rate of Exhumation on the Ruby Mountain Detachment Fault

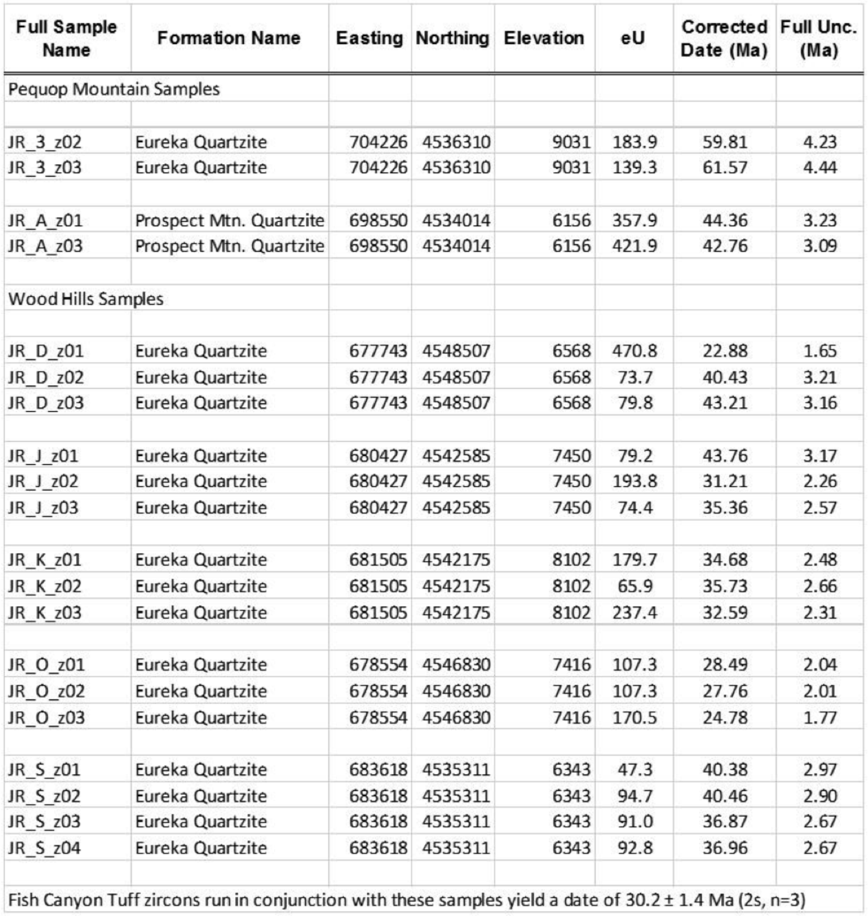
My zircon helium ages can be compared with two muscovite ^{40}Ar/^{39}Ar ages from the Wood Hills (Fig. 1) (Gifford et al., 2008). Muscovite ^{40}Ar/^{39}Ar records the time since a sample has passed through the 400 °C isotherm. Sample DF02-221 is from a quartz vein and the muscovite gave an age of 43.7 ± 5.3 Ma (89% ^{39}Ar, MSWD = 4.50). H03WH-42 is a marble and produced an age of 49.3 ± 3.6 Ma (75% ^{39}Ar, MSWD = 5.40). Samples JR_J (31-44 Ma) and JR_K (32-35 Ma) are located closest to the Wood Hills samples, DF02-221 (43.7 ± 5.3 Ma) and H03WH-42 (49.3 ± 3.6 Ma), reported by Gifford et al. (2008). Taking the average of the two zircon (U-Th)/He samples (~35 Ma) and of the two muscovite ^{40}Ar/^{39}Ar samples (~46 Ma), these results indicate that rocks within this portion of the Wood Hills rapidly cooled ~200 °C over 10 Ma (20 °C/Ma). This is slower than the consistently rapid cooling rates (>40-100 °C) reported for the complexes further south in Colorado River extensional corridor (Foster and John, 1999). However, during the lifetime of a detachment fault, cooling rates are expected to be variable (Ruppel et al., 1988). In the Wood Hills, it appears that there was at least ~13 km of extension (distance from JR_S to JR_O) over ~13 Ma, which indicates a slip rate of ~1 km/Ma. This is a slower slip rate than observed for other metamorphic core complexes; for example, Brichau et al. (2006) estimated a slip rate of of ~6-8 km/Ma for the core complex in Naxos, Greece. Both temperature and distance over time analyses indicate that exhumation of the Wood Hills was relatively slow.

Pequop Mountains

The two reconnaissance samples from the Pequops provide new context on the cooling history in the upper levels of the core complex (Fig. 2). New metamorphic temperature estimates (Howland, this volume) indicate that the grains reached temperatures at which they should have been reset following burial. He found that the rocks closest to sample JR_A in the footwall of the Independence Thrust in the Pequop Mountains recorded peak temperatures of 400-520 °C. His study does not include peak temperatures less than 2 km away from sample JR_3; however, he reported temperatures decreasing away from the hanging wall towards the east. The two temperatures closest to the hanging wall were 291 ± 23 °C and 407 ± 21 °C. Therefore, it is reasonable to assume sample JR_3 reached peak temperatures lower than JR_A, perhaps, in the range of 200-400 °C. Due to the zircon (U-Th)/He age of ~60 Ma calculated in this study (Ordovician depositional age), it is clear this rock reached temperatures deeper than the closure temperature for zircons (180-220 °C) following deposition and that samples were reset. The subsequent exhumation could be due to several possibilities, including (1) slow cooling due to progressive erosional exhumation, and (2) cooling due to extension, which suggests that slip along the Ruby Mountain Detachment Fault began as early as 60 Ma. Further investigation is needed to draw further conclusions. (3) conductive cooling due to relaxation of pluton induced heat (Holland, this volume), (4) movement of the Pequop Fault.

CONCLUSION

Key study results are: (1) the Ruby Mountain Detachment Fault was active by atleast Oligocene,



Full Sample Name	Formation Name	Easting	Northing	Elevation	eU	Corrected Date (Ma)	Full Unc. (Ma)
Pequop Mountain Samples							
JR_3_z02	Eureka Quartzite	704226	4536310	9031	183.9	59.81	4.23
JR_3_z03	Eureka Quartzite	704226	4536310	9031	139.3	61.57	4.44
JR_A_z01	Prospect Mtn. Quartzite	698550	4534014	6156	357.9	44.36	3.23
JR_A_z03	Prospect Mtn. Quartzite	698550	4534014	6156	421.9	42.76	3.09
Wood Hills Samples							
JR_D_z01	Eureka Quartzite	677743	4548507	6568	470.8	22.88	1.65
JR_D_z02	Eureka Quartzite	677743	4548507	6568	73.7	40.43	3.21
JR_D_z03	Eureka Quartzite	677743	4548507	6568	79.8	43.21	3.16
JR_J_z01	Eureka Quartzite	680427	4542585	7450	79.2	43.76	3.17
JR_J_z02	Eureka Quartzite	680427	4542585	7450	193.8	31.21	2.26
JR_J_z03	Eureka Quartzite	680427	4542585	7450	74.4	35.36	2.57
JR_K_z01	Eureka Quartzite	681505	4542175	8102	179.7	34.68	2.48
JR_K_z02	Eureka Quartzite	681505	4542175	8102	65.9	35.73	2.66
JR_K_z03	Eureka Quartzite	681505	4542175	8102	237.4	32.59	2.31
JR_O_z01	Eureka Quartzite	678554	4546830	7416	107.3	28.49	2.04
JR_O_z02	Eureka Quartzite	678554	4546830	7416	107.3	27.76	2.01
JR_O_z03	Eureka Quartzite	678554	4546830	7416	170.5	24.78	1.77
JR_S_z01	Eureka Quartzite	683618	4535311	6343	47.3	40.38	2.97
JR_S_z02	Eureka Quartzite	683618	4535311	6343	94.7	40.46	2.90
JR_S_z03	Eureka Quartzite	683618	4535311	6343	91.0	36.87	2.67
JR_S_z04	Eureka Quartzite	683618	4535311	6343	92.8	36.96	2.67
Fish Canyon Tuff zircons run in conjunction with these samples yield a date of 30.2 ± 1.4 Ma (2s, n=3)							

Table 1. Data from all samples analyzed in the study 'eU' is the effective Uranium, a measurement of the total amount of radiation experienced by the crystal, equivalent to U + .235Th. Corrected Date (Ma) is the alpha-ejection corrected age. 'Unc.' Is uncertainty. 'Ma' is million years since present.

probably Eocene times and exhumed the Wood Hills through the zircon (U-Th)/He closure temperature isotherm (~180-220 °C), (2) the SE-NW trend in exhumation of the Wood Hills matches the trend suggested for the Ruby Mountain Detachment Fault in the broader study area, (3) the Wood Hills were exhumed relatively slowly (cooling ~20 °C/Ma & slipping ~1 km/Ma), and (4) the footwall and portions of the hanging wall of the Independence Thrust within the Pequop Mountains reached temperatures great enough to reset zircon (U-Th)/He ages; however, more sampling is needed to confirm that the Pequop Mountains were exhumed along the Ruby Mountain Detachment Fault.

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