Proterozoic to Phanerozoic Tectonism in Southwestern Montana Basement Ranges Constrained by Low Temperature Thermochronometric Data

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Abstract Crystalline basement rocks of southwestern Montana have been subjected to multiple tectonothermal events since ~3.3 Ga: the Paleoproterozoic Big Sky/Great Falls orogeny, Mesoproterozoic extension associated with Belt-Purcell basin formation, Neoproterozoic extension related to Rodinia rifting, and the late Phanerozoic Sevier-Laramide orogeny. We investigated the long-term (>1 Ga), low-temperature (erosion/burial within 10 km of the surface) thermal histories of these tectonic events with zircon and apatite (U-Th)/He thermochronology. Data were collected across nine sample localities (n = 55 zircon and n = 26 apatite aliquots) in the northern and southern Madison ranges, the Blacktail-Snowcrest arch, and the Tobacco Root uplift. Our zircon (U-Th)/He data show negative trends between single aliquot date and effective uranium (a radiation damage proxy), which we interpreted with a thermal history model that considers the damage-He diffusivity relationship in zircon. Our model results for these basement ranges show substantial cooling from temperatures above 400°C to near surface conditions between 800 and 510 Ma. Subsequent Phanerozoic exhumation culminated by ∼75 Ma. Late Phanerozoic cooling is coincident with along-strike Sevier belt thin-skinned thrusting in southeastern Idaho, and older than exhumation in basement-involved uplifts of the Wyoming Laramide province. Our long-term, low-temperature thermal record for these southwestern Montana basement ranges shows that: (a) these basement blocks have experienced multiple episodes of upper crustal exhumation and burial since Archean time, possibly influencing Phanerozoic thrust architecture and (b) the late Phanerozoic thick-skinned thrusting recorded by these rocks is among the earliest thermochronologic records of Laramide basement-involved shortening and was concomitant with Sevier belt thin-skinned thrusting.

1. Introduction

In contrast to much of the western North American Cordillera, where crystalline basement rocks remain buried beneath a veneer of Phanerozoic sediment, southwestern Montana preserves widespread exposures of Archean and Proterozoic basement rocks that record an extensive Proterozoic through Phanerozoic tectonic history. Though these crystalline basement rocks, termed the Montana metasedimentary province (e.g., Mogk et al., 1992) in our study area (Figure 1), were uplifted and exhumed during the late Phanerozoic Laramide orogeny (Carrapa et al., 2019; Perry et al., 1983), they experienced prolonged histories of burial, metamorphism, and exhumation in Archean and Paleoproterozoic time that extend well beyond the most recent Cretaceous-Paleogene phase of deformation (Condit et al., 2015; Ersliev & Sutter, 1990; Frost et al., 2000; Holm & Schneider, 2002; James & Hedge, 1980). Prior work investigating these deep-time records of burial and exhumation of this province has primarily targeted high temperature (>400°C) thermochromometers, leading to a significant gap in our understanding of the intermediate temperature (between ~400°C and 110°C) and time histories (between ~1,800 and 88 Ma) of basement rocks in the region. Thus, more work is needed to evaluate the Montana metasedimentary province’s relationship to the broad tectonothermal influence of Mesoproterozoic Belt Basin development, which occurred in regional proximity (Lageson, 1989; Schmidt & Garihan, 1983; Schmidt & Hendrix, 1981), and Neoproterozoic Rodinia rifting (Brennan et al., 2020; Harlan et al., 2003; Link et al., 2017; Lund et al., 2010). Furthermore, a lower temperature (<300°C) deep time record could illuminate the extent to which inheritance tectonics from upper crustal, Proterozoic faulting may have played a role in the activation of later Laramide structures (e.g., Audet & Bürgmann, 2011; Marshak et al., 2000; Orme et al., 2016; Schmidt & Garihan, 1983).
The timing and driver of Cretaceous and Paleogene Laramide deformation in southwestern Montana is also of interest as the traditional delineation of Laramide-style and Sevier-style faulting into discrete episodes is challenged in this region by several lines of evidence. Previous studies suggested that basement-involved deformation in southwestern Montana overlapped spatially and temporally with Sevier-style deformation (≥ 84 Ma, DeCelles, 1986; McDowell, 1997; Nichols et al., 1985; Perry et al., 1983; Schmidt & Hendrix, 1981; Tysdal et al., 1986) and predated shortening accommodated in the type-section Laramide-style structures in Wyoming (<ca. 70 Ma, Harlan et al., 1988; Kellogg & Harlan, 2007; Peyton & Carrapa, 2013). Basement-involved structures in southwestern Montana were also active at a similar time as plutonism in the nearby Idaho batholith (Gaschnig et al., 2010); this contrasts with magmatism in the Sierra Nevada batholith, which shut off during an interpreted Late Cretaceous interval of flat-slab subduction, the putative cause of Laramide-style deformation (Coney & Reynolds, 1977; Dickinson et al., 1978; Jordan et al., 1983; Lowell, 1974). Newer data sets from Carrapa et al. (2019) and Garber et al. (2020) corroborate earlier results (e.g., Nichols et al., 1985) suggesting that basement uplift along Laramide-style reverse faults in southwestern Montana may have occurred before ~88 Ma, which predates initiation of flat-slab subduction beneath the southwestern U.S. at ~80 Ma. Taken together, these various authors demonstrated that thick-skinned deformation did not necessarily occur in a cause-and-effect relationship with flat-slab subduction, and that other factors, such as pre-deformation crustal architecture (e.g., Allmendinger et al., 1983; Kley et al., 1999; Marshall et al., 2000; Pearson et al., 2013; Schmidt & Garihan, 1986; Schmidt et al., 1988), may have played an important role in the transition from thin skinned to thick-skinned thrusting.

In order to address the long-term influences on deformation in this area, and to bridge the time-temperature gap in thermochronologic data sets, we utilize zircon and apatite (U-Th)/He thermochronology. This technique can provide insights into both the Neoproterozoic and late Phanerozoic thermal histories of Laramide-style uplifts through a data interpretation process that relies upon relationships between zircon He dates and effective uranium (eU; eU = U + 0.235*Th) concentrations (e.g., Guenthner et al., 2014; Johnson
et al., 2017; Orme et al., 2016). For grains with a shared thermal history, the eU concentration of each grain is proportional to that grain’s degree of radiation damage, and the ability to exploit date-eU relationships for thermal history information therefore relies upon an understanding of the relationship between a zircon grain’s degree of radiation damage and He diffusivity (Guenthner et al., 2013). With progressive accumulation of structural damage from the decay of U, Th, and their large daughter nuclides, He diffusivity initially decreases (closure temperature increases) and then subsequently increases (closure temperature decreases). Given a range of zircon grains that have experienced the same thermal history, each will have its own amount of radiation damage (proportional to eU concentration), and therefore its own closure temperature. This behavior manifests in measured data sets most clearly as positive and negative correlations between He date and eU.

In our study area, we primarily use zircon He date-eU relationships to probe the deep-time thermal histories of crystalline basement rocks in the region, with two main objectives: (a) to constrain the Proterozoic t-T paths of the Montana metasedimentary province and investigate hypotheses that relate the province’s emergence (or lack thereof) relative to development of the Mesoproterozoic Belt Basin and Neoproterozoic to Cambrian break-up of Rodinia; and (b) to investigate whether zircon He date-eU trends from these ranges are consistent with other results that suggest a Late Cretaceous phase of Laramide-style uplift. To accomplish this task, we utilize both forward and inverse modeling of new zircon and apatite He data. Our modeling results: (a) demonstrate the utility of using low-temperature thermochronometric data for constraining elusive intervals of Earth history; (b) yield important constraints on the >1 Ga, low-temperature thermal history of the Montana metasedimentary province; (c) provide compelling evidence for pronounced cooling (exhumation) in southwestern Montana during Neoproterozoic rifting of Rodinia; and (d) support earlier results that indicate early Late Cretaceous (100–80 Ma) basement-involved thrusting.

2. Geologic Background

2.1. Archean to Mesoproterozoic Tectonism

Crystalline basement rocks of southwestern Montana, which have both sedimentary and igneous protoliths, define the Montana metasedimentary province and constitute the northwestern margin of the Archean Wyoming Province (Figure 1, Mogk et al., 1992, 2020; Mueller & Frost, 2006; Mueller et al., 1993). The oldest rocks in this region yield U/Pb zircon dates of ∼3.2–3.5 Ga (Jones, 2008; Mogk et al., 1992; Mueller et al., 2004, 2011). Later magmatism and high-temperature metamorphism at ∼2.7 Ga and ∼2.45 Ga is variably preserved by crystalline basement rocks exposed in the Ruby Range (Alcock & Muller, 2012; Cramer, 2015; James, 1990; Jones, 2008; Mueller et al., 1993), Tobacco Root Mountains (Cheney et al., 2004; Krogh et al., 2011; Roberts et al., 2002), Tendoy Range (Kellogg et al., 2003), and Beaverhead Mountains (Anderson, 2017b; Mueller et al., 2016; Pearson et al., 2017). Between ∼1.86 and 1.72 Ga, basement rocks within the Montana metasedimentary province were subjected to a northeast-trending zone of high-grade metamorphism (>700°C) during the Great Falls and Big Sky orogenies, which are thought to record subduction of an ocean basin and subsequent collision of the Medicine Hat-Hearne block against the Wyoming block (Condit et al., 2015; Gifford et al., 2020; Harms et al., 2004; Mueller et al., 2002, 2016; O’Neill & Lopez, 1985). Prior work has shown that late Paleoproterozoic metamorphism decreases in metamorphic grade southeast of “Gilletti’s line” (Gilletti, 1966, 1971) where peak temperatures did not exceed ∼400°C, according to biotite, muscovite, and hornblende 40Ar/39Ar dates of 1.8–2.5 Ga (Condit et al., 2015; Ersliev & Sutter, 1990). Gilletti’s line (Figure 1) loosely divides the northern Madison Range and Ruby Range from the southern Madison and Beartooth ranges (Gilletti, 1966, 1971), and the possible thermal history significance of this line to our samples will be a key focus in subsequent thermal history modeling sections.

After Paleoproterozoic Big Sky-Great Falls tectonism, western Montana became the locus of ∼1.4 Ga Mesoproterozoic sedimentation associated with the Belt Basin. Given that many of our sample locations are just beyond the boundaries of where Belt Supergroup-equivalent rocks are exposed (see Figure 1), an important consideration for thermal history modeling is whether our sampled basement blocks were actively exhuming (cooling) and supplying sediments to this depozone, or subsiding (reheating) at this time. The detrital zircon provenance record and paleocurrent indicators from the Belt Supergroup, as well as pre-Belt sedimentary rocks, provide some context as to which regions adjacent to Belt Basin may have been topographic highs and actively eroding. The overwhelming distal provenance for upper Belt Basin rocks of the Missoula
and Lemhi group rocks suggests that there was minimal exhumation of rocks adjacent to the Belt Basin at this time (Anderson, 2017a; Fox, 2017; Link et al., 2007, 2016; Parker & Winston, 2019; Stewart et al., 2010). In contrast, the pre-Belt-Purcell Neihart Quartzite, deposited over metasedimentary basement rocks of the Montana metasedimentary province no earlier than 1.7 Ga (Mueller et al., 2016; Ross & Villeneuve, 2003), shows a small percentage of detrital zircon grains characteristic of Wyoming Craton basement provenance. Although these grains may represent recycled sediment derived from the Montana metasedimentary province (Mueller et al., 2016), detrital zircon populations in the overlying LaHood Formation were likely derived from the Paleoarchean metasediments of the western Wyoming craton (Anderson, 2017a; Fox, 2017; Mueller et al., 2016), which provides some evidence that our study area was eroding at this time.

2.2. Neoproterozoic Rodinia Rifting

During Neoproterozoic and early Cambrian time, southwestern Montana was on the incipient western margin of Laurentia as Rodinia rifting progressed (e.g., Lund, 2008). The geologic record of this interval in southwestern Montana is sparse, given that middle Cambrian Flathead Sandstone unconformably overlies crystalline basement rocks or Belt-Purcell Supergroup rocks in the area, so we instead consider possible tectonic influences on thermal histories at this time in a broad, regional context. The Rodinia supercontinent accretion cycle culminated in the Grenville orogeny on the E and SE boundaries of Laurentia, between 1.3 and 0.9 Ga (Dalziel, 1991; Moores, 1991; Whitmeyer & Karlstrom, 2007). Though contractional structures from this orogeny are not observed in the Wyoming craton, extensional fault networks associated with far-field effects of the Grenville orogeny have been proposed as early as 1.3 Ga (Marshak et al., 2000). In proximity to our sample sites, early rifting may be signaled by the Gunbarrel dike intrusions at 782 and 775 Ma that were dated in the southern Tobacco Root Mountains (Harlan et al., 2003), and very limited preservation in the Montana Pioneer Mountains of possible Neoproterozoic sedimentary rocks previously mapped as Mesoproterozoic Missoula Group (Kovalchuk, 2017; Trippe, 2019). A synthesis of data collected from synrift deposits in Utah and Idaho by Yonkee et al. (2014) shows that rifting was a multiphase process with an early stage of initial rifting from ~770 to 660 Ma, cessation of rifting, and then resumption of rifting at ~570 Ma that led to development of the Paleozoic passive margin. In this context, the earliest stage of rifting (770–660 Ma) was likely restricted to Utah and environs to the south, and the Gunbarrel intrusions were not necessarily accompanied by development of a rift margin in Idaho. Indeed, synrift deposits that are present in central Idaho correlate best with the Windermere Supergroup to the north, and Cryogenian-Ediacaran units to the south (Pocatello Formation and Brigham Group, Brennan et al., 2020). Deposition of these units began at >667 Ma (Brennan et al., 2020), spanned the timing of Yonkee et al.’s (2014) rift failure and subsidence phase (660–580 Ma) and later stage of rifting phase (570–520 Ma), and was accompanied by extension-related, alkalic plutonism that ranges in age from 651 to 488 Ma (Link et al., 2017; Lund et al., 2010). Kilometer-scale exhumation of southwestern Montana basement blocks at these time periods could have been accomplished by footwall uplift and erosion, or our sample locations may have composed a regional scale horst block that experienced erosion due to its relative relief to adjacent subsiding rift basins (i.e., Stockli, 2005).

2.3. Phanerozoic Geology

The Phanerozoic sedimentary record in southwestern Montana and eastern Idaho is substantially more complete than the Proterozoic. In the vicinity of our sample locations, the Paleozoic Era is represented by Cambrian through Permian sedimentary units of variable thickness with a prominent unconformity that places Devonian on Cambrian rocks (i.e., Ordovician and Silurian units are absent in southwestern Montana, Lonn et al., 2000; Skipp & Janecke, 2004; Sloss, 1950). Previously measured conodont alteration indices (Perry et al., 1983) and isopachs (Perry, 1986) show that maximum Phanerozoic burial depths were significantly greater in the Snowcrest trough, which encompasses our Gravelly and Ruby ranges samples, as compared to locations southeast of the Snowcrest-Greenhorn thrust system (Figure 1). These observations are considered in subsequent sections that focus on the interpretations for our thermal history models.

Following this prolonged interval of burial and deposition, our sample locations were uplifted and exhumed along Laramide-style reverse thrusts. Although the purpose of this work is in part to use our data to constrain the timing of this exhumation, we also seek to place these data within the broader context of previous
t-T and geologic constraints on Laramide thrusting. These constraints come primarily from estimates on the timing of deposition for synorogenic sedimentary units, and low temperature thermochronometers. Basal conglomerates of the Kootenai Formation suggest that the foreland basin may have been disrupted by low-magnitude uplift of the basement blocks in southwestern Montana as early as 100 Ma (DeCelles, 1986; Rosenblume et al., 2021; Schwartz & DeCelles, 1988), although the resulting exhumation from this uplift may have been on the order of less than a kilometer (Carrapa et al., 2019). Provenance data from the Black-tail-Snowcrest uplift suggest basement-involved thrusting prior to ∼81 Ma (Garber et al., 2020; Nichols et al., 1985). In the southern Madison Range, the synorogenic Sphinx Conglomerate was shed from and deposited adjacent to the Madison-Gravelly arch between 79 and 69 Ma (DeCelles et al., 1987; Kellogg & Harlan, 2007). Apatite fission track, apatite He, and limited zircon He data from several ranges in southwestern Montana, including the Tobacco Root Mountains and the northern Madison Range, constrain a regional cooling episode between 80 and 70 Ma, with possible evidence for cooling as early as 100 Ma (Carrapa et al., 2019). The AFT oldest track ages (i.e., oldest fission track that has not been fully annealed) from the Carrapa et al. (2019) thermal history models suggest that our study region experienced temperatures in excess of ∼120°C by 86 Ma. Collectively, these studies detail a pronounced phase of cooling (as the result of uplift and erosion of basement blocks) within our study region most likely between 80 and 70 Ma, but possibly as old as 100 Ma.

3. Methods

3.1. Sampling Strategy

Sampling in the southwestern Montana basement ranges focused on spatial distribution within Archean and Paleoproterozoic basement exposures, in the context of previously mapped Laramide-style faults and folds (Figure 1). Multiple hand samples were collected from each basement uplift in order to accommodate total exposed basement area of each range, with the exception of the Tobacco Root Mountains where appropriate sampling areas were sparse. Samples were collected a minimum of 1 km from any major intrusive body (the Tobacco Root batholith), and a minimum of 100 m from any mapped dikes to avoid thermal resetting not associated with burial and exhumation processes. Because intrusions could still potentially influence the thermal history of our samples, even at these distances (e.g., Karlstrom et al., 2019; Murray et al., 2018), we will examine the possibility of thermal resetting from igneous bodies in our thermal history modeling.

3.2. Apatite and Zircon (U-Th)/He Thermochronology

Apatite and zircon crystals were separated from whole rock samples at Idaho State University using standard mineral separation procedures. These steps included crushing to a fine powder with a jaw crusher and disc mill, gravity separation with a Wilflrey water table, magnetic separation with a Frantz barrier separator, and density separation with heavy liquids. Apatite and zircon (U-Th)/He dating methods were conducted at the University of Illinois at Urbana-Champaign and the University of Arizona, and followed procedures described in Guenthner et al. (2016). Diode or CO₂ laser heating, cryogenic purification, and quadrupole mass-spectrometry were conducted for ⁴He analysis on noble gas measurement and extraction lines at both institutions. Apatite and zircon dissolution was followed by U and Th analysis via isotope-dilution inductively coupled plasma-mass spectrometry on an Element2 at the University of Arizona and iCAP Q at the University of Illinois. A minimum of five aliquots (i.e., crystals) were selected from each sample, so that each mountain range had a sample suite of >10 aliquots. Zircon aliquots were picked for a large selection of visual apparent radiation damage in order to utilize their spread in eU concentrations (Ault et al., 2018). Increasing eU concentrations results in radiation damage accumulation and discoloration, changing the diffusion parameters and therefore the closure temperature of the grain. Alpha ejection corrections were applied using equations described by in Hourigan et al. (2005) for zircon and Farley (2002) for apatite.
4. Results

We report a total of \( n = 55 \) new zircon He dates and \( n = 28 \) new apatite He dates from some of the main mountain ranges in southwestern Montana where basement rocks are exposed in the hanging walls of Laramide-style thrust faults (Tables S1 and S2; Figure 1): the Tobacco Root Mountains and northern Madison Range, which are in the Tobacco Root uplift in the hanging wall of the Bismark-Spanish Peaks-Gardiner fault system; the Gravelly and Ruby ranges, which are within the Blacktail-Snowcrest arch in the hanging wall of the Snowcrest-Greenhorn fault; and the southern Madison Range, which is in the Madison-Gravelly arch in the hanging wall of the Scarface-Beaver Creek-Hilgard fault system. Collectively, but also for certain individual ranges and samples, our zircon He data show dispersion that greatly exceeds analytical precision, with a dominant negative correlation between date and eU (Figure 2a). The samples from each individual range show distinct deviation from this trend though, and in some cases a correlation with eU concentration is insufficient to solely explain the observed dispersion. We therefore organize our samples into groups with clear negative date-eU correlations and those for which the trends are either relatively flat or not clear.

Zircon grains from the Madison Range possess clear negative date-eU correlations. Here, we divide our description into sample suites from the southern and northern parts of the range because of the metamorphic boundary (and therefore different Proterozoic thermal histories) dividing the two, as described by Giletti’s line (Figure 1, Giletti, 1966, 1971). All of the data reported and plotted as individual points in figures represent single grain aliquots. From three localities in the southern Madison Range (i.e., Madison-Gravelly arch; hanging wall of the Scarface-Beaver Creek-Hilgard fault system), we analyzed \( n = 11 \) aliquots, with corrected dates that range from 10.7 to 765 Ma and eU concentrations that range from 180 to 3,508 ppm. A prominent negative date-eU correlation is observed from \( \sim 180 \) to 500 ppm eU. Grains with an eU concentration >500 ppm have young dates with a narrower age range from \( \sim 11 \) to 59 Ma, forming a high-eU “pediment.” A total of \( n = 16 \) aliquots from three localities in the northern Madison Range (i.e., Tobacco Root uplift; hanging wall of the Bismark-Spanish Peaks-Gardiner fault system) were dated with ZHe thermochronology. Corrected single grain dates from the northern Madison Range span from 29.9 to 815 Ma, with eU concentrations from 43 to 6,347 ppm. Grains with an eU concentration less than \( \sim 800 \) ppm show a negative date-eU correlation with some dispersion. Samples above this \( \sim 800 \) ppm eU threshold have young, consistent dates across a wide spectrum of eU concentrations, forming a pediment similar to those samples from the southern Madison Range, with an age range from 30 to 67 Ma (a single grain at 91 Ma and 1098 ppm eU).

In contrast to the Madison Ranges, our results from the Tobacco Root Mountains (i.e., Tobacco Root uplift) and Gravelly and Ruby ranges (i.e., Blacktail-Snowcrest arch; hanging wall of the Snowcrest-Greenhorn fault) do not show clear date-eU correlations. We analyzed \( n = 12 \) aliquots from one sample in the Tobacco Root Mountains, and these data have an age range from 12.3 to 164 Ma. These samples have an eU concentration range from 159 to 1232 ppm. Data from \( n = 16 \) aliquots from two samples in the Gravelly and Ruby ranges also do not have a clear negative date-eU trend despite selecting aliquots for a range of visible radiation damage. Corrected single grain dates range from 17.1 to 483 Ma, with eU concentrations from 451 to 7,140 ppm, and an anomalously high eU concentration grain at 25,726 ppm. Although the oldest dates are observed at low eU, the apparent negative date-eU trend is dominated by a single date of \( \sim 483 \) Ma at \( \sim 900 \) ppm eU. If this grain is excluded, then the trend is more subdued and flatter as compared to data from the northern and southern Madison Range. This data set also has several grains with extremely high eU concentrations, all greater than 2,000 ppm, which yield relatively consistent dates that range from 17 to 64 Ma and resemble the date-eU pediments seen in other southwestern Montana samples.

A total of \( n = 28 \) apatite grains from these four sample suites show dates ranging from 11.2 to 90.4 Ma (Figure 2b). All samples have eU concentrations below 80 ppm, with the exception of one aliquot with an eU concentration of 199 ppm. There is no apparent correlation between aliquot grain size and date or eU concentration.
5. Thermal History Modeling

In order to interpret the date-eU trends in our (U-Th)/He data sets, we rely upon thermal history modeling. Our focus throughout the remaining sections will be on the zircon He results, as these data provide the most detailed information about a sample's deep-time thermal history. Our apatite He data are included in this analysis as well, but the apatite results are used primarily to guide interpretation of the late Phanerozoic
record given their relatively young dates. Thermal history modeling requires both independent constraints for thermal episodes that impacted our samples (i.e., sedimentary records, other thermochronometers), as well as testable t-T hypotheses that have been previously proposed by other authors but not fully investigated or constrained. Before describing our modeling methods and results, we therefore first summarize the major tectonic events that will be considered in our modeling setup (graphically summarized in Figure 3). Certain events act as fixed points in the thermal history of basement rocks of southwestern Montana, whereas we consider others as thermal history hypotheses that need to be tested with forward and inverse modeling.

Given the geologic and chronometric observations described in Section 2, ages for the Great Falls/Big Sky orogeny northwest of Giletti’s Line (1.77 Ga) serve as robust high temperature starting points for samples from the Madison Range, Tobacco Root Mountains, and Ruby-Gravelly Ranges (Figure 1, Condit et al., 2015; Harms et al., 2004; Mueller et al., 2011, 2016; O’Neill & Lopez, 1985). As an additional Mesoproterozoic constraint, we consider the previously proposed tectonic model that the Montana sedimentary province was an up-thrown horst relative to the down-thrown Belt Basin (Lageson, 1989; Schmidt & Garihan, 1983; Schmidt & Hendrix, 1981). We hypothesize that if southwestern Montana was exhuming (cooling) prior to and coincidentally with Belt-Purcell Supergroup deposition, modeling results should show t-T segments that cool from high to low temperatures between 1700 and 1450 Ma, the approximate depositional ages of the Neihart Quartzite and overlying lower Belt Supergroup (Lageson, 1989; Mueller et al., 2016; Schmidt & Garihan, 1983; Schmidt & Hendrix, 1981; Sears, 2007).

For the Neoproterozoic, we examined the possible cooling (exhumation) response of our sample locations to Rodinia rift-related tectonism during early (770–660 Ma) and later phases of rifting (570–520 Ma). If Neoproterozoic cooling occurred during exhumation associated with Rodinia rifting, model results should show t-T segments that bracket cooling to low temperatures between 770 and 660 Ma for an early phase of rifting.
or 570–520 Ma for a later phase of rifting, in agreement with various regional indicators of rifting described in Section 2 (Brennan et al., 2020; Harlan et al., 2003; Link et al., 2017; Lund et al., 2003, 2010; Yonkee et al., 2014). All model t-T paths have samples at surface temperatures at 515 Ma (estimated depositional age of Cambrian Flathead Sandstone, which is generally considered to represent initial Sauk transgression sedimentation in southwestern Montana in the Albertella trilobite zone; e.g., Thomas, 2007). We incorporate the deposition of <1 km of Cambrian through Silurian strata, and subsequent removal of Ordovician and Silurian units before the Devonian (Sloss, 1950), with slight reheating to 50°C and then cooling to 30°C. The post-Devonian stratigraphy contains various disconformities through the early Cretaceous, but for the purposes of thermal history modeling, we infer that these ranges were progressively buried (i.e., heated) with no major episodes of exhumation (i.e., cooling) until post-Kootenai Formation deposition (∼100 Ma) at the earliest. Exhumation due to Laramide uplifts is tested with cooling episodes that begin at 100 and 80 Ma.

5.1. Model Design

The goal of forward and inverse thermal history modeling is two-fold: (a) to examine the extent to which the radiation damage effect can explain the observed date variations, and (b) to test the plausibility of certain thermal history hypotheses using the damage-diffusivity relationship. For the first objective, we focus on the first-order trends between zircon He date and eU concentration, but acknowledge that not all dispersion can be explained by the damage-diffusivity relationship. That is, our data sets show date dispersion beyond the first-order trend date-eU trend, which could result from the influence of U and Th zonation. The influence of zonation can be large, but currently lacks a routine approach for quantification (Guenthner et al., 2013). Because the zonation effect cannot be currently constrained, we show the date-eU model output in all cases plotted with the observed data to demonstrate whether the damage-diffusivity relationship explains all of the observed date dispersion, or if other sources of dispersion (i.e., zonation) could contribute. Given the billion-year timescales we must consider, and the relatively under-constrained nature of much our t-T space, we first use ZRDAAM forward modeling to explore the range of plausible t-T paths and determine which portions of the observed date-eU correlations are most sensitive to modifications in specific thermal history scenarios. In this sense, we are not searching for the best fit t-T path. Rather, subsequent inverse modeling is used to test many more paths and find best-fit solutions, and this inverse modeling is informed by our initial forward approach.

To implement ZRDAAM, we use a Matlab code (Guenthner, 2020) for forward models that combines the damage-diffusivity function of Guenthner et al. (2013) with a ZFT annealing model (also presented in Guenthner et al., 2013 with data from Yamada et al., 2007). For inverse modeling, we use the HeFTy modeling software package (Ketcham, 2005), which implements the same algorithms for ZRDAAM in a Monte Carlo simulation and determines best fit paths with goodness-of-fit (GOF) statistics. Forward models take t-T paths as input and return model date-eU curves that can be compared to observations, whereas inverse models use aliquot eU, dates, and size parameters, combined with user specified t-T constraints, to produce a suite of best-fit t-T paths based upon GOF.

5.2. Forward Models

Given the broad agreement in regional chronometers, and the paucity of available chronometric information for specific sample locations, we grouped samples based on their relation to Giletti’s Line and tested the same Proterozoic cooling histories for all basement ranges in southwestern Montana. This setup investigates the sensitivity (or lack thereof) of sample date-eU correlations to different Proterozoic thermal scenarios. Specific tests included various key t-T constraints described in Section 5.2: cooling from high (400°C) to low (20°C) temperatures at 1.77 Ga, 1.4 Ga, 770 Ma, and 570 Ma, tested in isolation and combination. For single-step cooling (Figure 4), the maintenance of surface temperatures for 1000+ Ma is admittedly an over-simplification, but this approach allows us to best discriminate among the various cooling options (i.e., is there one dominant timing of Proterozoic cooling that best explains the data?). Our modeling also suggests that there is almost no difference between model date-eU output for t-T paths that feature residence at or slight reheating to temperatures equivalent to a couple of kilometers of overburden (∼50°C) and residence at surficial temperatures. For testing combinations of Proterozoic cooling, we investigated two-step monotonic cooling (Figure 5), as well as reheating and subsequent cooling at younger time periods (e.g.,
cooling at 1.77 Ga, reheating, and cooling again at 1.4 Ga, Figure 6). These scenarios required intermediate residence temperatures, and we tested a range of such temperatures between 120°C and 200°C in increments of 20°C. Reheating and two-step cooling are hypothetical for the Proterozoic thermal history of the region, but we note that they are not ruled out by any other thermochronometric or geologic observations and our purpose here in part is to determine whether our data are sensitive to such scenarios. In the Phanerozoic portions of our t-T paths, we modeled maximum reheating followed by cooling at 80 Ma (Figure 7), to account for possible late-Cretaceous cooling associated with basement-involved thrusting constrained by other workers (e.g., Carrapa et al., 2019; Garber et al., 2020). A range of maximum Phanerozoic reheating temperatures were tested in 20°C increments from 120°C to 200°C (subsequent sections discuss how

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**Figure 4.** Plots of zircon He results from crystalline basement rocks in southwestern Montana in the (a) northern Madison Range, (b) southern Madison Range, (c) Ruby-Gravelly Ranges, and (d) Tobacco Root Mountains. Larger plots show date (Ma) versus eU (ppm) of individual zircon grains analyzed, with superimposed colored curves showing predicted date-eU trends corresponding to forward-modeled thermal histories. Upper right inset plots for each mountain range show temperature (°C) versus time (Ma) forward models for monotonic cooling at three different times: 1.7 Ga (black) during Neihart Quartzite deposition, 770 Ma (orange) during the first phase of Rodinia rifting, and 570 Ma (cyan) during the second phase of Rodinia rifting.
well these increments align with previous estimates of maximum Phanerozoic reheating). The duration of cooling starting at 100 or 80 Ma was also modified in increments such that we examined the influence of both slow, cooling to 20°C by the present, and fast, cooling to 20°C within 10 million years (e.g., 80-70 Ma), cooling on date-eU correlations. The most salient aspects of these tests are shown in Figures 4–7, and we highlight the results for each sampled range in the next few sections.

5.2.1. Monotonic Cooling in Proterozoic Time

Cooling trends from high (400°C) to low (20°C) temperatures at 1.77 Ga before residing 150°C till end of Belt-Purcell deposition at 1.4 Ga (black), first phase of Rodinia rifting at 770 Ma (yellow), and second phase of Rodinia rifting at 570 Ma (orange). Black, yellow, and orange paths undergo rapid Phanerozoic cooling from 150°C at 100 Ma to 20°C at 80 Ma. Purple, blue, and cyan time temperature paths, Proterozoic cooling at 1.4 Ga, 770 Ma, and 570 Ma respectively, have a Phanerozoic cooling path of 150°C at 100 Ma to surface temperatures at present.

Figure 5. Forward model tests of two-stage Proterozoic cooling in the (a) northern Madison Range, (b) southern Madison Range, (c) Ruby-Gravelly Ranges, and (d) Tobacco Root Mountains. Cooling from 400°C begins at 1.77 Ga before residing 150°C till end of Belt-Purcell deposition at 1.4 Ga (black), first phase of Rodinia rifting at 770 Ma (yellow), and second phase of Rodinia rifting at 570 Ma (orange). Black, yellow, and orange paths undergo rapid Phanerozoic cooling from 150°C at 100 Ma to 20°C at 80 Ma. Purple, blue, and cyan time temperature paths, Proterozoic cooling at 1.4 Ga, 770 Ma, and 570 Ma respectively, have a Phanerozoic cooling path of 150°C at 100 Ma to surface temperatures at present.
Each subplot in Figure 4 shows the model output compared to the measured data. Although best-fit curves are not always apparent, model results bracket observed data in most samples and we can draw some general conclusions about the likely timing of Proterozoic cooling for each data set. The northern Madison Range data (Figure 4a) are dispersed, and no single curve captures all of the data, but a large number of dates, both at low and high eU concentrations, are reproduced by date-eU curves that show a dominant Neoproterozoic episode of cooling. Model output for cooling episodes between 1.77 Ga and 570 Ma bracket nearly all of the observed date-eU spread of the southern Madison Range (Figure 4b), which suggests that these data record a major phase of Proterozoic cooling that we further investigate below with inverse modeling.

Ruby-Gravelly ranges data are also dispersed (Figure 4c), but are better captured by Neoproterozoic cooling curves that encompass dates of ~200 Ma at ~500 ppm eU, as well as the young dates at ~3000 ppm eU. The relatively flat date-eU correlation observed in the Tobacco Root Mountains data is not reproduced by any of these Proterozoic curves (Figure 4d).

Figure 6. Forward models testing reheating during Belt-Basin deposition following cooling to surface temperatures at 1.7 Ga in the (a) northern Madison Range, (b) southern Madison Range, (c) Ruby-Gravelly ranges, and (d) Tobacco Root Mountains. Reheating temperatures tested are 200°C (cyan), 180°C (blue), 160°C (purple), 140°C (orange), and 120°C (black) before re-exhuming to surface temperatures at 1.4 Ga.
5.2.2. Reheating and Two-Step Cooling in Proterozoic Time

Tests of simplified two-phase cooling during the Proterozoic use initial cooling from 400°C to 150°C at 1.77 Ga, and secondary cooling at 1.4 Ga, 770 Ma and 570 Ma (Figure 5). Resultant modeled date-eU curves are similar to those produced by simple monotonic cooling at 1.77 Ga in Figure 4. The age of the second cooling phase affects the dates for the oldest portions of the date-eU curve, but the position and slope of the curve, as well as the position and extent of the high eU, young date pediment are unchanged. Prolonged Proterozoic residence in the zircon He partial retention zone thermally resets grains at the lowest eU concentrations (and therefore lowest damage levels), but this residence is insufficient to anneal radiation damage and high radiation damaged grains, which determine the date-eU curve's slope and pediment position.

In contrast to prolonged residence in the mid-crust, our tests of Proterozoic reheating (Figure 6) produced little variation in resulting date-eU curves. There is slight variation in the oldest dates in each modeled date-eU curve, but the shape, slope, and pediment of each curve are identical. This result implies that the...
dominant Proterozoic control on our date-eU curves is the timing of cooling events, not reheating temperatures after these events.

### 5.2.3. Phanerozoic Reheating and Exhumation

Forward models investigating a range of maximum temperatures during Phanerozoic reheating, from 200°C to 120°C at 80 Ma, provide the most date-eU spread of any hypotheses tested, regardless of range-specific inputs (Figure 7). Modeled date-eU curves for each 20°C temperature step display markedly different maximum dates, position in eU space of negative trends, and eU concentration range of date-eU pediments; decreasing reburial temperature moves the produced date-eU curve to higher eU values and increases the maximum age of the curve. Reheating to ∼160°C produces an eU curve that closely approximates data from the southern Madison Range (Figure 7b), whereas few dates are captured by the model curves in the northern Madison Range (Figure 7a) and the Ruby-Gravelly ranges (Figure 7c). Temperatures of reheating above 180°C yield flat date-eU curves that capture none of the observed dates in these three locations, but data from the Tobacco Root Mountains are best described by a t-T path with reheating between 180°C and 200°C (Figure 7d).

### 5.2.4. Summary of Forward Model Results

Forward modeling of different t-T scenarios suggests the following: (a) a single phase of monotonic cooling in Proterozoic time, rather than two episodes or Proterozoic cooling, better reproduces our data. Additional model results are consistent with the interpretation that sampled basement rocks were not subjected to Mesoproterozoic burial and subsequent erosion during deposition of nearby Belt Supergroup strata; (b) data from samples collected from south of Giletti’s Line in the southern Madison Range are best modeled with a phase of monotonic cooling that initiated after ∼1.77 Ga (i.e., after the Great Falls/Big Sky orogeny) but before the Neoproterozoic; (c) data from samples north of Giletti’s Line in the northern Madison Range, Ruby Range, and Gravelly Range are best modeled with a phase of monotonic cooling during Neoproterozoic time; (d) model results suggest the highest reheating temperatures in Tobacco Root Mountains samples (180°C–200°C; probably related to the ∼75 Ma Tobacco Root batholith; Vitaliano et al., 1980), which explains why the date-eU trend for this model is “decoupled” and flat (e.g., Ault et al., 2018, all grains are fully reset regardless of damage level), and why models are unable to evaluate the deep-time thermal evolution of that area; and (e) model results suggest maximum Phanerozoic reheating temperatures of 160°C–180°C for the Madison, Ruby, and Gravelly ranges.

### 5.3. Inverse Models

Each range was individually modeled using the inverse modeling program HeFTy (Ketcham, 2005). HeFTy allows up to seven data inputs to run a randomized simulation through t-T space that must travel through constraint boxes dictated by the user. In order to encapsulate all dates within a data set, while also accounting for second-order date dispersion beyond radiation damage effects, ZHe data were binned by eU concentration and the dates and grain sizes within each bin were averaged to create “synthetic” grains (standard deviation of the dates within each bin was used for 1 sigma error; Table S3). The “synthetic” grain approach has been used effectively in previous apatite and zircon (U-Th)/He studies with data sets that show first-order date-eU trends and second-order dispersion (DeLucia et al., 2018; Flowers & Kelley, 2011; Flowers et al., 2020; Murray et al., 2016). Where available, AHe data were included in our HeFTy models by averaging all aliquots; our apatite (U-Th)/He data do not display any radiation damage effects making this simplistic treatment possible.

We define the model’s exploration of t-T space by using constraint boxes. The constraint boxes are used to accomplish two separate, but related tasks: (a) to outline independent geologic constraints that the random-walk model scenario must pass through, and (b) to test or explore certain regions of t-T space for best fit scenarios. For the first objective, model solutions demonstrate whether our data conforms to the available, independent geologic and thermochronologic constraints, whereas the second objective shows whether specific t-T hypotheses are viable. Due to the limited number of available independent constraints, the same constraint boxes were used for each of the basement ranges. The constraint box encapsulating high temperature metamorphism is 2.5–2.4 Ga, at temperatures from 400°C–600°C, as indicated by available U/Pb zircon and monazite data (Anderson, 2017b; Jones, 2008; Mueller et al., 2011; Pearson et al., 2017).
A constraint box from 600 to 500 Ma at 80°C–20°C, contains the minimum possible duration of the Great Unconformity in this region, including the 570–520 Ma phase of Rodinia rifting and the ~515 Ma deposition of the Flathead Sandstone (Chaudhuri & Brookins, 1969; Thomas, 2007; Yonkee et al., 2014). Cooling to present day is captured in a box from 35-0 Ma at 50–20 ˚C; this age bracket slightly exceeds the mean AHe date from each of our ranges and forces cooling to occur sometime post-Eocene to best simulate the timing of extension-related faulting in the region. In addition to independent constraints, two additional “exploration” boxes are included to test the model’s behavior within certain ranges. The first of these covers much of Proterozoic time, spanning from 2,400 to 600 Ma between 400°C and 20°C. The purpose of this exploration box is to see when the model cools to near surface temperatures before it is forced through the Flathead Sandstone nonconformity constraint box. The second exploration box covers the extent of possible maximum Phanerozoic reburial times and temperatures, from 160-35 Ma and 250°C–50°C, and is designed to test the age and temperature of Phanerozoic reheating.

The various inputs, constraint boxes, and model parameters for each tested range are listed in Table S1. In addition to our zircon He data, we also considered our apatite He results, where available, which are described further below. Apatite thermochronologic data are insensitive to the Proterozoic portions of the modeled thermal histories, but can inform the timing of late-stage cooling associated with Laramide tectonism. Model output is characterized by HeFTy as either “good” (goodness of fit >0.5) or “acceptable” (goodness of fit >0.05) tT path fits to the input data. We focus our discussion of individual range results on those models that yield good fits.

5.3.1. Tobacco Root Mountains

ZHe data from the Tobacco Root Mountains were binned and averaged into two “synthetic” grains, available in Table S1. Of the 100,000 paths tested, the inversion produced 38 good paths (goodness of fit >0.5) and 176 acceptable paths (goodness of fit >0.05). These good paths fill much of the dictated t-T exploration space, which limits our ability to draw any conclusions about the Proterozoic history of these samples. The Phanerozoic reheating box is also spanned by good path results, including at the highest temperatures within the box, which suggests that these samples were thermally reset at high temperatures between 60 and 80 Ma (i.e., majority of dates in this sample, Figure 8). The most likely cause of this reheating is the emplacement of the Tobacco Root batholith at ~75 Ma (Giletti, 1966; Scarberry et al., 2020; Vitaliano et al., 1980). Subsequent cooling from high temperatures initiates at 130 Ma according to the weighted mean path in our inverse models, although we again stress that there is a wide array of good paths for this timing of cooling, which is not well defined.

5.3.2. Southern Madison Range

The HeFTy inverse model of the southern Madison Range used four “synthetic” ZHe inputs, and one averaged AHe input. The date and eU values of these grains (see Table S1) follow the negative trend of the observed data. Of 100,000 paths tested, the inverse model produced 200 acceptable fit paths (goodness of fit <0.05) and six good fit paths (goodness of fit >0.5). Unlike the Tobacco Root Mountains results, a clearer Proterozoic cooling signal is apparent as all paths remain above 250°C until ~850 Ma, at which point they cool to surface temperatures by the end of Neoproterozoic and through early Cambrian time (Figure 9). For the Phanerozoic portion of the thermal history, model paths do not predict Phanerozoic reheating above 200 ºC, and the weighted mean path shows cooling initiating at ~80 Ma.

5.3.3. Northern Madison Range

Data from the northern Madison Range were binned into three “synthetic” grains, excluding three grains with anomalously low date-eU values that fell outside of the negative date-eU trend (Table S1). Inverse modeling of 100,000 tested paths, using three “synthetic” ZHe inputs and one averaged AHe input, resulted in 12 good fit paths (goodness of fit >0.5) and 320 acceptable fit paths (goodness of fit >0.05). Paths show cooling below 250°C occurred after ~750 Ma, with the majority of paths showing a more rapid phase of cooling between 700 and 580 Ma. The weighted mean path shows an inflection at ~680 Ma and that segment of the weighted mean continues cooling until ~550 Ma. Phanerozoic reheating did not exceed 200°C, and the model did not predict a narrow time window for maximum Phanerozoic reheating (Figure 10). The weighted mean path cooled from ~150°C starting at ~80 Ma for this Phanerozoic portion.
5.3.4. Ruby and Gravelly Ranges

A total of four “synthetic” ZHe grains and one averaged AHe grain were used in the HeFTy inversion of the Ruby and Gravelly ranges data. These synthetic grains were calculated using eU bins of data with eU values less than 7,000 ppm, as HeFTy only considers eU values up to 3000 ppm (Table S1). The inversion results of this model yielded four good fit paths (goodness of fit >0.5) and 63 acceptable fit paths (goodness of fit >0.05). The good paths show cooling below 250°C by ∼650 Ma, and a majority of paths show relatively more rapid cooling than the northern or southern Madison Ranges. The weighted mean path has an inflection at ∼600 Ma, and achieves near surface temperatures at ∼520 Ma. Model results indicate Phanerozoic reheat- ing between 200 C and 250°C (Figure 11).

5.3.5. Summary of Inverse Models

With the exception of the Tobacco Root Mountains, inverse models of each range follow similar t-T histories. In most scenarios, Neoproterozoic cooling to surface temperatures initiated after 800 Ma, and a majori- ty of paths in the southern and northern Madison ranges and the Ruby and Gravelly ranges show a phase of Neoproterozoic cooling sometime between 710 and 510 Ma. This broad time frame overlaps with estimates of early stage (770–660 Ma) and late stage (570–520 Ma) Rodinia rifting discussed above, but given the range of possible cooling paths, our data provide support for either phase of rifting as the main driver of exhuma- tion. In the discussion below, we return to which phase could be more plausible in light of other evidence.

During Phanerozoic time, modeled thermal histories diverge, as the Ruby and Gravelly ranges are modeled to have reached higher reburial temperatures than the ranges to its east. Maximum reheating temperatures are in the 130°C–150°C in the northern and southern Madison Ranges, but in excess of 200°C in the Ruby and Gravelly ranges. Higher temperatures agree with estimates of greater sedimentary burial for these two ranges in the upper Paleozoic Snowcrest trough, where the upper Paleozoic section was ∼1 km thicker compared to sites south of the Snowcrest-Greenhorn fault system (Perry, 1986) and the structural relief along

Figure 8. Inverse modeling results from the Tobacco Root Mountains, overlaid on regional thermal events, alongside forward modeled date-eU correlations of good fit paths. Good fit inverse paths are in blue, acceptable fit paths are in green, and the weighted mean path is in red. Forward modeled date-eU correlations of good fit paths are shown in the lower panel. Observed data in date-eU space are shown in yellow, and synthetic grains in red. The inset panel shows modeled paths from the Jurassic to the present. Paths fill nearly all available inverse space, indicating samples are thermally reset. Synthetic grain information in Table S3.
6. Discussion

6.1. Implications of Thermal Histories for Neoproterozoic Tectonism in Western Laurentia

In this section, we use the forward and inverse modeling results to interpret the long-term thermal history of these basement uplifts. To facilitate this discussion, we first place these models in the broader context of previously published results for the region. Our interpretations of inverse model results are focused on the “good” path (GOF > 0.5) outcomes. The set-up for the forward and inverse models tested two previously proposed hypotheses for the Proterozoic history of the region: (a) basement rocks of southwestern Montana represented an eroding structural high (and potential provenance source) during Belt-Purcell deposition (Lageson, 1989; Schmidt & Garihan, 1983; Schmidt & Hendrix, 1981), and (b) Rodinia rifting, which occurred in an early and late phase that initiated at 770 Ma and 570 Ma, respectively (Brennan et al., 2020; Yonkee et al., 2014), caused extension-related exhumation of basement rocks in southwestern Montana (Harlan et al., 2003; Lund et al., 2003, 2010). Our forward model results show that the nature of the date-eU correlations at low eU concentrations is most responsive to cooling from high (400°C) to low (<50°C) temperatures and that the majority of our sample locations (with the exception of the Tobacco Root Mountains data) are best captured by one phase of cooling in the Mesoproterozoic to Neoproterozoic. Phanerozoic thermal history scenarios are equally as important for influencing the shape of the forward modeled date-eU curve as the timing of Proterozoic cooling (i.e., Figures 5 and 7). In this sense, forward modeling of our Proterozoic cooling $T_t$ paths should be considered as a demonstration of plausible thermal history hypotheses, whereas our inverse modeling better defines the likelihood of these hypotheses.
These forward model results are further supported by our inverse model output. Here, we see a signal of relatively more rapid cooling that begins after 800 Ma and concentrated between 710 and 510 Ma for the northern Madison Range, southern Madison Range, and Ruby-Gravelly ranges data sets (Figures 12a–12c). Some variability in the timing of this cooling is evident, both for a given data set and comparing among data sets, but the earliest t-T path in model output that shows cooling below \( \sim 300°C \) (i.e., the approximate upper bound of the ZFT partial annealing zone used in ZRDAAM) in any of these three model outputs post-dates 900 Ma. We further note that the Proterozoic constraint box is designed to be purposefully large such that the model can search a wide range of cooling scenarios between 2,400 and 600 Ma, bridging the time temperature space between the known high temperature metamorphic constraint box in the Paleoproterozoic and the box outlining the Precambrian-Cambrian nonconformity surface. That is, the data yield best fits for a Neoproterozoic episode of cooling and do not support a Mesoproterozoic episode of cooling. If we consider this cooling pulse as a consequence of exhumation, then our models suggest that southwestern Montana was a locus of exhumation at a time that broadly overlapped with both the early and late phases of Rodinia rifting (Brennan et al., 2020; Yonkee et al., 2014).

Given this overlap in timing, we suggest that our study region was an eroding, topographic high throughout late Neoproterozoic-Early Cambrian time in response to Rodinia rifting (Figure 12f). Continental rifting could promote exhumation in two distinct ways (Stockli, 2005). At the local scale, normal faulting can result in focused uplift and erosion of footwall blocks, with thermochronometers collected from these footwalls recording cooling at a horizontal distance equivalent to the throw of the fault. From a regional perspective, large horsts may erode as a consequence of their relief relative to adjacent downthrown grabens, which will in turn cause exhumation over a more regional scale (10s-\( \sim \)100 km). In either scenario, we interpret that the Montana metasedimentary province experienced extensional faulting during Neoproterozoic and middle Cambrian time. Additional lines of evidence for regional extension during this time include Rodinia rifting-related dike intrusions dated at 782 and 775 Ma (Harlan et al., 2003), followed by a significant time

Figure 10. Northern Madison Range inverse modeling overlaid on key tectonothermal events. Good fit paths are in blue, acceptable fit paths are in green, and the weighted mean path is red. Forward modeled date-eU correlations of good fit paths are shown in the lower panel. Observed data in date-eU space are shown in blue crosses and asterisks, and synthetic grains in red circles. The inset panel shows modeled paths from the Jurassic to the present. Inverse paths show Proterozoic cooling from 250°C to surface temperatures occurs between \( \sim 770 \) and \( \sim 550 \) Ma. Phanerozoic maximum reburial temperatures do not exceed 170°C, and exhumation begins as early as \( \sim 110 \) Ma. Synthetic grain information in Table S3.
Figure 11. Ruby-Gravelly ranges inverse modeling overlaid on key tectonothermal events. Good fit paths are in blue, acceptable fit paths are in green, and the weighted mean path is red. Forward modeled date-eU correlations of good fit paths are shown in the lower panel. Observed data in date-eU space are shown in green squares and diamonds, and synthetic grains in red circles. The inset panel shows modeled paths from the Permian to the present. The weighted mean path cools from 250°C to surface temperatures between 700 Ma and ~520 Ma. Phanerozoic reburial reaches temperatures of 250°C indicating these samples are partly thermally reset. The weighted mean path begins its Phanerozoic exhumation at ~190 Ma. Synthetic grain information in Table S3.

Figure 12. Summary of salient inverse modeling results. Insets A-D show good fit (GOF > 0.5) envelopes and weighted mean inverse tT paths over key tectonothermal events for reference. The northern Madison Range (a) displays an increased rate of exhumation after ~650 Ma. The southern Madison Range (b) shows more gradual exhumation from ~850 to ~550 Ma. The Ruby-Gravelly Ranges (c) have an increased exhumation rate after ~650. The Tobacco Root Mountains (d) have such a broad envelope of good fit paths that any interpretation beyond thermal resetting is impossible. A direct comparison of each range’s weighted mean path (e) shows the relative rapidity of Neoproterozoic exhumation. In particular, the northern Madison Range and the Ruby-Gravelly Ranges exhumation rates increase during and immediately following Snowball Earth. All four ranges cool below 200°C before the second phase of Rodinia rifting. Inset F shows a cartoon interpretation of exhumation during rifting, which could apply to the first and second phases of Rodinia rifting.
lag before deposition of synrift rocks in central Idaho that are dated at <685 Ma (Lund et al., 2003), and syenite-diorite plutons related to extension that were emplaced from 651 to 488 Ma (Link et al., 2017; Lund et al., 2010).

Recent mapping and detrital zircon analysis by Brennan et al. (2020) ~160 km southwest of our study sites in central Idaho described a previously unrecognized Neoproterozoic to Cambrian succession of rift-related rocks, the deepest encountered portion of which stratigraphically overlies a ~668 Ma tuff (Isakson, 2017; Lund et al., 2010). This work confirms a substantial westward deflection of the western Laurentian rift margin from its predominantly north-south trend (e.g., Yonkee et al., 2014) and suggests that older, Mesoproterozoic Belt basin-related tectonics precluded development of a major Neoproterozoic and Cambrian extension in east-central Idaho and southwestern Montana (Brennan et al., 2020; Link et al., 2017). Prior work west of the current study area in east-central Idaho and western Montana has documented the presence of a northwest-trending, relatively unextended block that formed a paleotopographic high (Lemhi arch) and algal shoal (Montana arch) between southwestern Montana and central Idaho from late Neoproterozoic to late Cambrian time (Brennan et al., 2020; Bush & Novack-Gotshall, 2012; Link et al., 2017; Lund et al., 2010). Directly within the current study area in the Ruby Range and Tobacco Root Mountains, prior detailed structural analysis (Schmidt & Garihan, 1986; Schmidt et al., 1993) documented that mafic dikes (some of which constitute the Gunbarrel dikes of Harlan et al., 2003) crosscut Archean and Paleoproterozoic foliations but are, in turn, crosscut by the Great Unconformity. The dikes were also shown to intrude older normal faults and were reactivated during basement-involved reverse faulting that was presumed to be Cretaceous in age (Schmidt & Garihan, 1986; Schmidt et al., 1993). Because some of these mafic dikes yielded ~780 Ma ages, these observations suggest that Neoproterozoic dike intrusion was followed by an important episode of erosion prior to middle Cambrian deposition of the Flathead Sandstone (Schmidt & Garihan, 1986), a result that independently supports the episode of Neoproterozoic to early Cambrian cooling constrained with our modeling results.

In addition to the above, U/Pb detrital zircon (DZ) data from synrift and early passive margin Neoproterozoic and Cambrian sedimentary rocks in Idaho may contain evidence for erosion of southwestern Montana sources. DZ age spectra from this succession, which are similar to much of the western Laurentian margin, generally exhibit: (a) a substantial 1.3–1.0 Ga age-peak of zircon grains interpreted to have a provenance in the eastern Laurentian Grenville province; (b) a strong age peak at ~660 Ma, which is thought to have a local source; (c) a variable but locally dominant ~1.78 Ga peak, generally interpreted to have a source in the Yavapai-Mazatzal province in southwestern Laurentia; as well as (d) subsidiary age peaks at ~1.4 Ga and 2.45–2.7 Ga (Brennan et al., 2020; Link et al., 2017; Matthews et al., 2018; Milton, 2020; Yonkee et al., 2014). A combination of 1.3–1.0 Ga and ~660 Ma zircon grains seems to require a mix of eastern Laurentian Grenville and local volcanic sources, which is an interpretation that most prior authors prefer (e.g., Yonkee et al., 2014). However, major additional age peaks at ~1.78, ~1.4, and 2.4–2.7 Ga are a reasonable provenance match for sparsely dated, but apparently widespread magmatic and high-grade metamorphic rocks in southwestern Montana (Anderson, 2017b; Condit et al., 2015; Jones, 2008; Mueller et al., 2016; Pearson et al., 2017). As such, our results suggest that southwestern Montana may represent an alternative, more proximal source of zircon grains in sedimentary rocks for the northern Rockies.

Though inverse modeling results of data from the southern Madison Range, northern Madison Range, Gravelly Range, and Ruby Range all generally indicate Neoproterozoic cooling, the southern Madison Range appears to have undergone cooling prior to the other localities (Figure 12e). To explain both Neoproterozoic cooling inboard of the rift margin, as well as the contrast in cooling histories on either side of Giletti’s line, we focus on an apparent transition in the style of rifting northwest of the modern location of the eastern Snake River Plain (Brennan et al., 2020; Lund, 2008; Lund et al., 2010; Yonkee et al., 2014). In northern Utah and southeastern Idaho, rift-related sedimentation and eventual <540 Ma passive margin subsidence resulted in accumulation of a >6.5-km thick stratigraphic succession (Link, 1982; Yonkee et al., 2014); in contrast, along-strike to the northwest in central Idaho, a much thinner, ~2.5 km thick age-correlative section records disruption of this segment of the rift margin (Brennan et al., 2020; Link et al., 2017; Yonkee et al., 2014). To explain the dramatic contrast in subsidence and rift style, prior workers have proposed the presence of a major Neoproterozoic to Cambrian, northeast-striking transverse structure in the modern location of the eastern Snake River Plain called the Snake River transfer fault (Brennan et al., 2020; Link et al., 2020).
A similar northeast-trending region was proposed by other workers to project beyond the Yellowstone-eastern Snake River Plain volcanic track into western Montana (Eaton et al., 1975; Mabey et al., 1978). Field-based evidence corroborates the presence of similar and possibly correlative northeast trending, likely Proterozoic crustal-scale structures along-strike to the northeast; these include the Snowy shear zone (Erslev, 1988) and Madison mylonite zone (Erslev & Sutter, 1990). We suggest that these basement features may have been exploited by the Neoproterozoic to Cambrian Snake River transfer fault (e.g., Lund, 2008). In the context of this prior work, we hypothesize the following timeline of Rodinia tectonism in the northern Rockies: (a) the earliest phase of rift-related tectonism is recorded by the ∼780 Ma Gunbarrel dikes (e.g., Harlan et al., 2008), which locally intruded low-displacement, northwest-striking normal faults (e.g., Schmidt et al., 1993). Some erosion may have begun in response to early rifting, but was relatively slow as southwestern Montana was distal with respect to the active rift zone (e.g., inverse model paths for northern and southern Madison Range between ∼800 and 700 Ma, Figures 12a and 12b). (b) Following a lull in rift activity, a resumption in the latest Cryogenian to Ediacaran would have created an increase in erosion rates at ∼600 Ma (e.g., inverse model paths for southern Madison Range and Ruby Range between ∼600 and 510 Ma, Figures 12b and 12c). Subsequent along-strike structural segmentation of the rift margin by the Snake River transfer fault exploited an older, northeast-trending basement weakness and facilitated development of the dramatic differences in the character and geometry of the rift margin between southeastern and central Idaho. Differential exhumation across the northeastward projection of this transverse fault system into southwestern Montana may explain contrasting Neoproterozoic cooling histories of rocks in our study area. We note that some of these more rapid time-temperature paths also overlap with Snowball Earth glaciations, which have been proposed as a driver of erosion that contributed to the creation of the Great Unconformity surface (Keller et al., 2019). The closest correlative diamicite units that could relate to this erosion are located some distance from our sample sites in central (Brennan et al., 2020; Lund et al., 2003, 2010) and southeastern Idaho (Keeley et al., 2013; Link, 1982; Yonkee et al., 2014). (c) Following this episode of erosion, limited sedimentation may have commenced during Ediacaran time (Kovalchuk, 2017; Trippe, 2019) prior to widespread sedimentation during the middle Cambrian Sauk transgression, which records flooding of much of the western margin of Laurentia.

### 6.2. Congruence of Thermal Histories With Previous Results for Late Phanerozoic Tectonism

Our model results for the Phanerozoic portions of sample thermal histories yield a range of plausible $t$-$T$ paths that are congruent with previous results. All results require reheating through Paleozoic and Mesozoic time, in agreement with regional evidence of basement reburial under passive margin and then foreland basin sediments (Perry, 1986). If we associate this reheating with sedimentary burial, then our northern and southern Madison Range results support maximum burial temperatures of ∼150°C (∼5 km burial depth with a geothermal gradient of 25°C/km), achieved as early as 100 Ma in the northern Madison data, and 80 Ma for the southern Madison data. Subsequent cooling of these paths, which we interpret in the context of exhumation and uplift of basement-involved, thick-skinned structures, occurred as early as 100 Ma for the northern Madison Range data and 80 Ma for the southern Madison Range data, but weighted mean $t$-$T$ paths for both data sets show initiation of cooling at ∼80 Ma. The inverse results from the Ruby-Gravelly Ranges and Tobacco Root Mountains datasets show a wider range of Phanerozoic reheating and cooling scenarios. Despite our efforts to sample at locations far from the Tobacco Root batholith, the high maximum reheating temperatures and lack of precision in model outputs for our Tobacco Roots data likely result from contact heating due to emplacement of the Tobacco Root batholith. The Ruby and Gravelly ranges model output supports high maximum reheating temperatures (between 200°C and 250°C, or ∼6–8 km burial depth with a geothermal gradient of 25°C/km) and subsequent cooling that initiates any time between 200 and 100 Ma, although the youngest time here is most plausible with previous results (see below). As mentioned previously, higher temperatures in these data sets agree with greater sedimentary burial in the Snowcrest trough north of the Snowcrest-Greenhorn fault system (Perry, 1986), and high structural relief as well along this fault system (Perry et al., 1983). Of further note, many of the good $t$-$T$ paths in Figure 11 show a two-phased cooling trend whereby model paths cool to ∼150°C by 150 Ma, and then cool again to temperatures below 50°C after 50 Ma. This outcome is a direct result of our zircon data, which include a set of relatively consistent dates between ∼20 and ∼40 Ma at high eU concentrations (>2,000 ppm). These highest
eU concentration grains close at temperatures below \(\sim 50^\circ C\) (Guenthner et al., 2014; Johnson et al., 2017) and overlap in timing and temperature sensitivity with our apatite He results from this range.

Previous authors have shown a significant phase of pre-80 Ma basement-involved uplift in southwestern Montana, and these model results are consistent with those findings. As discussed previously, sedimentary evidence from conglomerate clast counts and detrital zircon provenance shows emergent basement blocks as early as 100 Ma (DeCelles, 1986; Schwartz & DeCelles, 1988), but prior to 82 Ma (Garber et al., 2020; Nichols et al., 1985; Ryder & Scholten, 1973; Schmitt et al., 1995). A younger timeframe of 79 to 69 Ma in the Madison Range (DeCelles et al., 1987; Kellogg & Harlan, 2007), and 80 to 70 Ma in the Tobacco Root and northernmost Madison Range (Carrapa et al., 2019) has also been discussed for the basement uplifts in this region, with the thermochronologic results of Carrapa et al. (2019) showing the possibility of cooling initiation at 100 Ma. Our inverse and forward modeled \(t-T\) paths show cooling (exhumation) within this 100 Ma to 70 Ma window, and the weighted mean \(t-T\) paths further argue for cooling toward the older bound on this period. Collectively, our data fit within the context of a phase of basement uplift and erosion that pre-dates uplift of Laramide-style structures in the type-section of Wyoming (<70 Ma; Harlan et al., 1988; Kellogg & Harlan, 2007; Peyton & Carrapa, 2013).

7. Conclusions

Our zircon and apatite He results have geologic implications for both the Proterozoic and late Phanerozoic portions of the thermal history of basement rocks of southwestern Montana. We argue that the dominant Neoproterozoic cooling trend seen in the northern Madison Range, southern Madison Range, and Blacktail-Snowcrest uplifts’ inverse and forward model results provides insight into the development of Rodinia rifting-related exhumation and the Great Unconformity surface in this region. Inverse modeling results from the Ruby-Gravelly range samples indicate exhumation below 250°C after \(\sim 700\) Ma, and increasingly rapid exhumation after \(\sim 650\) Ma until surface temperatures are achieved at \(\sim 520\) Ma; these intervals of exhumation are coincident with the first and second phases of Rodinia rifting (Yonkee et al., 2014). Similarly, the northern Madison Range inverse modeling results show cooling below 250°C after 800 Ma, and an increased rapidity in exhumation at \(\sim 650\) Ma. Inverse modeling results in the southern Madison Range differ slightly, indicating a slower exhumation from \(\sim 850\) Ma to \(\sim 550\) Ma. The inverse modeling of the Tobacco Root Mountains data yielded little information beyond that the samples were thermally reset, likely during emplacement of the Tobacco Root batholith. As a whole, Neoproterozoic exhumation in southwestern Montana was likely the result of erosion of upthrown blocks during local and regional extensional faulting.

Our results suggest recurrent tectonism in this area from Paleoproterozoic to late Phanerozoic time, as indicated by episodes of cooling and burial in basement rocks. We therefore agree with prior workers (Garhan et al., 1983; McBride et al., 1989; Perry, 1986; Perry et al., 1983; Schmidt & Garhan, 1983, 1986; Schmidt et al., 1993) that this repeated history of reactivation imparted a pre-existing architecture that influenced subsequent thick-skinned tectonism in the latest Mesozoic. Because our exhumation timing constraints and those of previous authors pre-date exhumation constraints from the flat-slab influenced Laramide province of Wyoming, we suggest that structural inheritance serves as an alternative to the flat-slab paradigm for explaining basement-involved uplifts in southwestern Montana.

Given the results of this study, it is apparent that further thermochronologic investigation of southwestern Montana’s thermal history is necessary to (a) determine the role of Snowball Earth glaciation in developing the Great Unconformity surface and, (b) compare the timing of exhumation for the Sevier hinterland and Laramide foreland of eastern Idaho and southwestern Montana. By showing the deep-time (>1 Ga), low-temperature thermal history of southwestern Montana, our data provide a direct link between rifting and contraction over several Wilson cycles.

Data Availability Statement

All data supporting the conclusions herein are available in the accompanying tables. The data can be found in Kaempfer et al. (2021) (DOI: 10.17632/rbrywry2my.1).
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