Helium and argon thermochronometry of the Gold Butte block, south Virgin Mountains, Nevada

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Abstract

One of the largest exposures of Precambrian crystalline rock in the Basin and Range province of the southwestern USA is the Gold Butte block of the south Virgin Mountains, about 15 km west of the Colorado Plateau. It has been interpreted as a largely continuous crustal cross-section about 15–20 km thick that was exhumed by a deeply penetrating normal fault during Miocene extension. To test this interpretation as well as the use of the newly developed titanite (U-Th)/He thermochronometer, we examined the low temperature thermal history of the Gold Butte block with the apatite and titanite (U-Th)/He and muscovite 40Ar/39Ar thermochronometers. Apatite He ages average 15.2 ± 1.0 (2σ) Ma throughout the block, indicating that the entire section was warmer than 70°C prior to Miocene exhumation. Titanite He ages increase from 18.6 ± 1.5 Ma near the paleobottom (west) end of the block, to 195 ± 15 Ma near the paleotop (east) end. A rapid change from mid-Tertiary to increasingly older titanite He ages to the east is observed at about 9.3 km paleodepth, and is interpreted as a fossil He partial retention zone for titanite. Assuming a pre-exhumation geotherm of 20°C/km (consistent with earlier apatite fission track work), this depth would have corresponded to 196°C prior to exhumation, indicating that laboratory-derived He diffusion characteristics for titanite that yield a closure temperature of about 200°C are applicable and correct. Muscovite 40Ar/39Ar ages are 1.0–1.4 Ga near the paleotop of the block, and 90 Ma near the paleobottom. Together with 207Pb/206Pb ages on apatite and titanite, and an earlier apatite fission track transect across the Gold Butte block, our data indicate that the continental crust at the western edge of the Colorado Plateau resided at moderate geothermal gradients (and slowly declined in temperature) from 1.4 Ga to about 100–200 Ma. A 90 Ma cooling event clearly affected the mid-crust (deepest portions of Gold Butte), which may reflect accelerated cooling or a brief heating and cooling cycle at this time, after which gradients returned to about 20°C/km prior to rapid exhumation in the Miocene. This work thus supports previous structural and thermochronologic studies that suggest that the Gold Butte block is the thickest largely continuous cross-section of crust exposed in the southwestern USA. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: thermochronology; Basin and Range Province; exhumation; helium; Ar/Ar; extension

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1. Introduction

The Gold Butte block is a large exposure of Precambrian crystalline rock in the south Virgin Mountains of southeastern Nevada, about 15 km west of the largely undeformed and flat lying sedimentary rocks of the Colorado Plateau (Fig. 1). The block is bounded on the east by steeply dipping (50°–65°) Phanerozoic sedimentary rocks similar to those of the Grand Canyon, on the north by a large-displacement tear fault, and on the west and south by unconformably overlying Tertiary sediments [1]. Structural, petrologic, and thermobarometric lines of evidence have been used to argue that the block represents a 15–20 km thick section of Proterozoic crust that was uplifted, tilted to the east, and exhumed, by deeply penetrating west-dipping normal faulting, exposing a thick continuous section through the mid-crust [1–3]. Evidence for the largely continuous nature of the pre-exhumation crustal section includes systematic east-to-west changes in: (1) pressure estimates from a variety of thermobarometers, (2) abundance and size of cumulate phenocrysts in the large Gold Butte granite pluton, and (3) deformation style, from brittle faulting through brecciation and mylonitization [3]. Some workers, however, have used sedimentologic and erosional evidence to argue that most of the Precambrian rock in the Gold Butte block is flat-lying upper crust that was not strongly tilted or exhumed from deep levels during Miocene extension [4]. Resolving between these two contrasting interpretations is of critical importance for at least two reasons. First, the former interpretation implies that the Gold Butte block is one of the largest intact crustal sections in the Cordillera, and thus provides valuable insights into the petrologic, thermal, and structural evolution of the crust in the region of the Colorado Plateau. The latter suggests that large regions of crystalline mid-crustal rocks were at shallow levels in the Gold Butte area prior to Miocene extension. Second, the first model implies deep exhumation and high angles

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![Fig. 1. Location and generalized geologic map, after [3], of the Gold Butte block. Numbers beside (U-Th)/He and ⁴⁰Ar/³⁹Ar sample locations refer to sample numbers in Tables 1–3. Samples dated by apatite FT by Fitzgerald et al. [4] were collected along the northern and western margin of the block. The locations of these and the Ar-dated samples have been projected onto the line of the (U-Th)/He samples in Fig. 2. Because of the potential for north-south tilting of the block, the projected paleodepths of the FT samples may not be exactly the same as the He samples. ‘MHWF’ is the Million Hills Wash fault that may disrupt the pre-exhumation structural sequence between samples 18 and 20 (see text for details).](image)
of tilting of exhumed crustal blocks, suggesting large amounts of extension in this portion of the Basin and Range, while the second model implies only limited or localized exhumation and extension in this region.

Crystalline rocks in the interior of the Gold Butte block include metamorphic rocks (primarily orthogneiss and garnet gneiss), and the intrusive Gold Butte granite, a large pluton of rapakivi granite [3,5]. Previous Rb/Sr and U/Pb dating indicates that the gneissic lithologies have ages of about 1.7–1.8 Ga [6], while the 1.45 Ga Gold Butte granite is representative of the widespread 1.4–1.5 Ga anorogenic magmatism at this time [7]. More recent magmatism in the lower part of the block has also been documented by 64–66 Ma monazite U/Pb ages from a two-mica granite in the western portion of the block [1,8].

Previous fission track (FT) studies indicate late Cretaceous through Miocene cooling in the Gold Butte block. A single biotite FT analysis by Volborth [5] yielded an age of 84.7±0.2, and zircon and apatite samples from the central portion analyzed by Parolini et al. [9] yielded FT ages of 84.9 and 27.2 Ma (no errors given) respectively. In the most detailed thermochronologic study of the block to date, Fitzgerald et al. [10] showed that apatite FT ages from samples below about 5 km paleodepth (assuming an overlying sedimentary thickness of 2.5 km prior to exhumation) were essentially invariant at about 14–17±1–3 Ma, whereas ages of samples towards the east (decreasing paleodepth) increased to about 50±3 Ma near the unconformity. Fitzgerald et al.’s work supports previous structural and thermobarometric evidence that, at least at paleodepths less than 5 km (which show a fossil apatite partial annealing zone), Gold Butte is a relatively intact crustal section that was rapidly exhumed at about 15–16 Ma.

A number of recent studies have shown that apatite (U–Th)/He thermochronometry provides reliable cooling ages through temperatures of about 70°C [11–20]. Most applications of this technique have focused on age-elevation relationships in vertical transects of mountain ranges to constrain the timing and rate of exhumation. This study instead uses (U–Th)/He thermochronometry to characterize the timing, rate, and structural style of exhumation of extremely tilted, now sub-horizontal, crustal sections. This study also represents the first application of the newly developed titanite (U–Th)/He thermochronometer [21,22], which, according to laboratory diffusion measurements, provides cooling ages corresponding to closure temperatures (Tc) of about 200°C (for a cooling rate of 10°C/Myr). Together with apatite He ages and muscovite 40Ar/39Ar dates that provide cooling ages corresponding to about 350–425°C [23], titanite He ages in Gold Butte provide an important test of the closure temperature of this newly developed chronometer.

We collected and analyzed apatite, titanite, and muscovite samples from a transect running through a roughly paleo-vertical section of the Gold Butte block (as suggested by the continuous crustal section model) for (U–Th)/He, 40Ar/39Ar, and 207Pb/206Pb dating. Age-paleodepth relationships for each of these systems provide long-term thermal histories throughout different regions of the block that are consistent with the model of Gold Butte as a largely continuous section of Pre-

<table>
<thead>
<tr>
<th>Sample</th>
<th>Paleodepth (km)</th>
<th>Total gas age</th>
<th>Plateau age</th>
<th>Intercept age</th>
</tr>
</thead>
<tbody>
<tr>
<td>52-1-89</td>
<td>4.0</td>
<td>1368.5±11.7</td>
<td>1374.4±13.0</td>
<td>1362.7±12.9</td>
</tr>
<tr>
<td>47-5-89</td>
<td>12.2</td>
<td>999.8±8.8</td>
<td>994.8±11.4</td>
<td>999.3±9.4</td>
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<td>5-10-88</td>
<td>16.0</td>
<td>88.5±1.2</td>
<td>none</td>
<td>89.9±2.0</td>
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<tr>
<td>16-1-88</td>
<td>16.5</td>
<td>92.6±1.0</td>
<td>89.8±1.1</td>
<td>92.0±2.6</td>
</tr>
<tr>
<td>1-10-88</td>
<td>17.4</td>
<td>92.7±1.2</td>
<td>none</td>
<td>92.8±3.7</td>
</tr>
</tbody>
</table>

Samples were run in nine step-heating extractions, from 730°C to fusion (above 1280°C).
cambrian basement. These data also support the experimentally derived 200°C (U-Th)/He $T_c$ for titanite.

2. Samples and methods

To characterize (U–Th)/He age–depth relationships in a steeply dipping pre-exhumation profile, we collected samples of the Gold Butte granite from a roughly east–west transect, perpendicular to the strike of the overlying sedimentary rocks on the east side of the block (Fig. 1). Many samples from the western and central portions of the block did not contain apatite or titanite. Samples collected for muscovite 40Ar/39Ar dating were collected from pegmatite dikes and gneissic lithologies in the eastern and western portions of the block. We show these results along with locations of samples analyzed for muscovite K/Ar dating (Fig. 1) by Wasserburg and Lanphere [6].

Muscovite 40Ar/39Ar dates were obtained by step-heating experiments at the University of Maine (Table 1). Apatite and titanite (U–Th)/He dates (Table 2) were obtained by standard procedures at Caltech (e.g., [18] for apatite; [21,22] for titanite), involving heating of inclusion-free grains in a resistance furnace and measurement of released $^4$He by isotope dilution on a Balzers quadrupole mass spectrometer. $^4$He contents of some titanite grains were also measured by peak height comparison to standards on a sector mass spectrometer (MAP 215-50). Grains were then recovered, spiked with $^{230}$Th and $^{235}$U, dissolved in HNO$_3$, HCl, and/or HF. Th and U isotope ratios were then measured on a single-collector double-focussing ICP–MS (Finnigan Element).

Raw apatite ages were corrected for the effects of alpha-ejection ([24]; $F_T$ parameters were 0.68–0.79), and estimated uncertainties on apatite He ages are 6% (2$\sigma$). Titanite ages were not corrected for alpha-ejection because of uncertainties in orig-
inal grain sizes and shapes. We do not expect these corrections to exceed about 8% however, based on typical titanite crystal sizes and replicate analyses of other samples with known ages (primarily Fish Canyon Tuff and Mt. Dromedary specimens [22]). An additional complication with titanite He ages is the possibility of diffusive rounding of He profiles within individual crystals [22]. Crystals with histories involving slow cooling or prolonged residence at temperatures near the closure temperature will result in strongly zoned He concentrations from core to rim. Because our sample preparation procedure produced irregular fragments (about 200 × 500 µm) of larger titanite crystals (about 300 × 800 µm), it is possible that fragments with a large fraction of material from either the original core or rim of a whole crystal record ages that are different from those of bulk grains [22]. This is especially true for samples from the eastern part of the block, where low pre-exhumation temperatures and partial He retention would be expected. Nonetheless, based on the relative sizes of observed whole crystals and the fragments we selected for analyses, as well as the reproducibility of ages from individual samples, we do not expect these effects to exceed about 8%. Our estimated analytical uncertainty on titanite He ages of 8% is based on the reproducibility of these and other samples, and is greater than the propagated uncertainty on U, Th, and He content determinations (≈2–3%).

Apatite and titanite U/Pb and Pb/Pb dates (Table 3) were obtained by dissolving and spiking approximately 0.1 mg of inclusion-free apatite and titanite grains with 235U and 205Pb, and measuring peak intensities on a single-collector, double-focussing ICP–MS. Initial Pb isotopic compositions were assumed to be those of potassium.

Table 3
Pb/Pb and U/Pb ages of apatite and titanite from Gold Butte

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Apatite 207Pb/206Pb age</th>
<th>Titanite 207Pb/206Pb age</th>
<th>Titanite 206Pb/235U age</th>
<th>Titanite 207Pb/238U age</th>
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</thead>
<tbody>
<tr>
<td>98PRGB4</td>
<td>1130</td>
<td>1384</td>
<td>1457</td>
<td>1450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1417</td>
<td>1439</td>
<td>1452</td>
</tr>
<tr>
<td>98PRGB18</td>
<td>1389</td>
<td>1391</td>
<td>1435</td>
<td>1439</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1392</td>
<td>1467</td>
<td>1459</td>
</tr>
</tbody>
</table>

Estimated analytical errors, based on reproducibility of ages on these and other samples on the element, are 2% and 4% for titanite and apatite Pb/Pb ages, respectively, and about 4% for titanite U/Pb ages.
feldspar we measured from a sample of the Gold Butte granite (98PRGB4; $^{206}\text{Pb}/^{204}\text{Pb} = 16.25$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.45$) While not as precise as conventional TIMS Pb dates, based on our experience with these and other Precambrian age samples, after correction for mass fractionation, isobaric interferences, and blanks, we estimate that the method provides suitably precise $^{207}\text{Pb}/^{206}\text{Pb}$ ages ($\sim 2\%$ for titanite and $\sim 4\%$ for apatite), for samples greater than several hundred million years old. Titanite U/Pb ages were slightly more variable ($\sim 4\%$) than titanite Pb/Pb dates (above). Apatite U/Pb ages were considerably more variable (in some cases greater than 20%); this method was not fully evaluated and developed, and these results are not discussed here.

3. Results

Fig. 2 shows all ages as a function of location in the block, expressed as pre-exhumation paleodepth, with sample locations projected onto our transect parallel to the strike of the overlying sedimentary rocks. We have assumed a pre-exhumation sedimentary cover of 2.5 km thickness, based on thicknesses of the stratigraphic section on the east side of the block (Cambrian through Permain units [3]), which is similar to sections in adjacent areas, including the Grand Canyon. Also shown in Fig. 2 are the apatite FT ages of Fitzgerald et al. [10] and K/Ar ages of Wasserburg and Lanphere ([6]; ages recalculated using constants from [25]). The (77 Ma) southwesternmost sample of Fitzgerald et al. [10] is not shown in Fig. 2 because it was inferred to have been excised from a higher structural position and transported by motion along the overlying fault that exhumed the block.

Apatite (U–Th)/He ages from the Gold Butte block show no consistent relationship with location, averaging 15.2 $\pm$ 1.0 Ma (Table 1, Fig. 2). In detail, the youngest ages (as young as 12.0 $\pm$ 0.7 Ma) are found in the central part of the block, and older ages are found on the western and eastern edges (17.0 $\pm$ 1.0 and 17.4 $\pm$ 1.0, respectively). Titanite was not found in samples to the west of 98PRGB4, nor between 98PRGB4 and 98PRGB12. Replicate analyses of the westernmost titanite bearing sample yielded an average age of 18.6 $\pm$ 1.5 Ma, slightly older than the apatite He ages at the same depth. Titanite in 98PRGB12, in the central portion, yielded an average age of 25.7 $\pm$ 2.1 Ma. Titanites east of this point become progressively older to the east, from 73.2 $\pm$ 5.9 to 192 $\pm$ 16 Ma. An exception to this eastward-increasing age rule is the easternmost sample, 98PRGB18, with an age of 150 $\pm$ 12 Ma, which is younger than the adjacent sample to the west (Fig. 2). As a whole these apatite and titanite (U–Th)/He ages are consistent with apatite FT ages (with the exception of the 77 Ma westernmost sample of Fitzgerald et al.; not shown here) which average 16.1 $\pm$ 1.5 Ma from estimated paleodepths of 16.5–5 km, then increase to 50 $\pm$ 3.0 Ma from about 5 to 3.5 km (Fig. 2).

Muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ and K/Ar ages (total gas) from samples at paleodepths of 18–16 km are tightly constrained to 91.3 $\pm$ 1.3 Ma (Table 2, Fig. 2). Samples at shallower paleodepths are consistently older, increasing from 1000 $\pm$ 8.8, through 1196 $\pm$ 35, and 1385 $\pm$ 39 Ma to the east; the easternmost sample is 1368 Ma (the 1196 and 1385 Ma ages are recalculations of Wasserburg and Lanphere’s [6] dates).

Apatite and titanite $^{207}\text{Pb}/^{206}\text{Pb}$ ages from the easternmost sample (98PRGB18) are 1389 $\pm$ 56 Ma, and 1392 $\pm$ 28 Ma, respectively (Table 3), and are concordant with $^{40}\text{Ar}/^{39}\text{Ar}$ ages from samples at comparable paleodepths (Table 2). Titanite U/Pb ages are slightly older, between 1435 $\pm$ 57 and 1467 $\pm$ 57 Ma. The westernmost sample (98PRGB4) also yielded titanite Pb/Pb and U/Pb ages between 1384 $\pm$ 55 and 1457 $\pm$ 58 Ma, similar to the ages of the easternmost sample. The apatite Pb/Pb age of the westernmost sample, however, is 1130 $\pm$ 45 Ma, distinctly younger than any of the other Pb ages.

4. Discussion

Age-distance relationships among the different chronometers in this study provide a range of constraints on the structure of Gold Butte, the timing and rate of exhumation, and the pre-exhu-
The first important result is that with the possible exception of unexpectedly young titanite He ages in the easternmost portion of the block, which may represent duplication of section by faulting (as discussed below), all of these data are consistent with the interpretation of Gold Butte as a single, intact, steeply dipping section of crust that was rapidly exhumed and cooled at 15–16 Ma. The pre-exhumation vertical thickness of the block is constrained by the correlation between paleodepth and titanite He age through paleodepths shallower than about 14 km. These age–paleodepth relationships suggest a continuous depth–temperature increase, which we interpret as a continuous crustal section, to at least 14 km. Thus the internally consistent age results of each chronometer in this study and those of Fitzgerald et al. [10] strongly support the interpretation made by previous workers that the Gold Butte block is a largely intact, continuous crustal section with paleodepth increasing towards the west [1–3]. This recognition also provides an important basis for more detailed thermochronologic interpretations of the ages.

Generally uniform \sim 15–16 Ma apatite (U–Th)/He ages throughout the block indicate that at this time, within less than about 2 Myr (the standard deviation of apatite He ages in the block) all the samples in this transect were rapidly cooled below 70°C. This is consistent with Fitzgerald et al.’s [10] evidence for rapid exhumation at 16 Ma from the age of the base of the apatite FT partial annealing zone (PAZ) [10]. Assuming 2.5 km of overlying sediments, a 10°C ambient surface temperature, and a 20°C/km geothermal gradient (consistent with the 5 km paleodepth of Fitzgerald et al.’s apatite FT PAZ), the depth of the 85°C isotherm that is typically assumed to be the base of the apatite He partial retention zone (PRZ [14,18]) would be 3.8 km, slightly deeper than the inferred paleodepth of the easternmost sample (3.4 km; Fig. 2). Thus the average 17.4 ± 1.0 Ma age determined for this sample indicates that this pre-exhumation geotherm was at least 20°C/km. The approximately 2 Myr spread in apatite ages also provides a crude constraint on the maximum duration for the cooling that accompanied exhumation at this time. Assuming that the approximately 13 km section of paleovertical relief represented by the eastern- and westernmost apatite samples was exhumed in 2 Myr yields an exhumation rate of 7 mm/yr. This is only a minimum estimate of the exhumation rate however, because it relies on the estimated range of apatite He ages as the temporal constraint (i.e., cooling of the block was too rapid to produce a non-infinite age–paleodepth trend that could be used to constrain exhumation rate). Thermochronologic constraints on other large-offset extensional faults in the southwestern USA have determined slip rates that are similar or slightly higher than this (3–9 mm/yr; generally 7–8 mm/yr) [26–31]. Due to the inferred steep dip of the exhuming normal fault [1–3], in the case of Gold Butte the exhumation rate was probably only slightly less than the slip rate.

In detail, apatite He ages do show a variation between 12.0 ± 0.7 Ma and 17.4 ± 1.0 Ma, with the youngest ages in the central part of the block. This may reflect the topography and surficial drainage patterns of the block following exhumation and tilting to an approximately 50–65° eastward dip.

In contrast to apatite, titanite shows a wide range of (U–Th)/He ages throughout the section. The average age of 18.6 ± 1.5 Ma for the westernmost sample is slightly older than that of apatite throughout the block, but if the single sample with the 22.5 Ma age is removed, the average age is 17.3 ± 1.0 Ma, which is indistinguishable from the apatite He ages. Assuming that the 22.5 Ma age is spurious (possibly because of inclusions of undissolved U- and Th-bearing minerals within the grains), these data indicate that the temperature at this pre-exhumation depth was higher than 200°C, the closure temperature of titanite [21,22], consistent with crustal depths greater than 10 km for a geothermal gradient of 20°C/km.

The 25–27 Ma titanite He ages at 9.3 km paleodepth are consistent with cooling below 200°C at this depth significantly before 15–16 Ma. However, rocks at this depth were probably not significantly cooler than 190°C just prior to exhumation, because: (1) apatite He ages show that at...
least up to 3.4 km paleodepth, rocks were still hotter than about 85°C, and (2) apatite FT ages show that at least up to 5 km paleodepth, rocks were still hotter than about 110°C. Both of these results are consistent with a 20°C/km geotherm, which predicts a temperature of 196°C at 9.3 km. Isothermal holding of titanite at this temperature prior to 15−16 Ma exhumation would result in sufficient He retention to produce an age greater than 15−16 Ma. For example, Wolf et al. [14] have shown that all crystals, including those open to He diffusion due to residence at temperatures near Tc, will achieve steady state He ages, \( t_{eq} = (1/15)(D/a^2)^{-1} \). Assuming an activation energy and frequency factor for titanite of 44.6 kcal/mol and 59 cm²/s [22], an average grain radius of 200 μm, and an isothermal holding temperature of 196°C, the titanite \( t_{eq} \) is 8.7 Ma. Additional isothermal holding for 16 Ma at ambient surface temperatures following exhumation yields an age of 25 Ma, in good agreement with the observed titanite ages of 25−27 Ma at 9.3 km paleodepth.

The rapidly increasing titanite He ages above 9 km are consistent with a fossil titanite He PRZ established some time prior to about 192 Ma. The upper 9 km of the Gold Butte block has been cooler than 200°C since about this time, although it is possible that it was significantly cooler than 200°C well before then, and was subsequently heated and cooled again before 192 Ma. The unexpectedly young 150 Ma age of the easternmost sample is problematic in the interpretation of a continuous fossil He PRZ. One possibility is that this sample represents a slightly greater structural depth than the one immediately to the west, due to motion along an extension of the Million Hills Wash fault, a fairly large offset (> 1 km), shallowly dipping, top-to-the-west normal fault with a southern projection between these two samples [1,3]. This would mean that sample 98PRGB20 is the structurally shallowest sample in the He transect. This interpretation is supported by a 15.6 ± 2.3 Ma apatite FT age for 98PRGB18 [32]. Projection of the apatite FT ages of Fitzgerald et al. to our transect indicate that samples in a continuous vertical sequence at the paleodepth of sample 98PRGB18 should have ages of about 50 Ma. Thus the 15.6 Ma apatite FT age on our sample also suggests that this easternmost sample in the transect may be out of structural sequence.

With closure temperatures in the 350−425°C range [23] muscovite \(^{40}\)Ar/\(^{39}\)Ar and K/Ar ages provide higher temperature thermochronologic constraints than (U−Th)/He or apatite FT ages. The 1.37−1.39 Ga ages at the top of the section are consistent with slow regional cooling of the crust following intrusion of the 1.45 Gold Butte granite, while the decreasing 1.0 and 1.2 Ga ages in the next two samples to the west probably reflect partial Ar retention over long time periods. Together with the tight cluster of 89−93 Ma ages towards the western end of the block, this age−paleodepth relation resembles a fossil PRZ [33] with a break-in-slope somewhere between 12 and 16 km paleodepth. A 20°C/km geotherm predicts a 350°C isotherm at about 17 km depth, so 15−16 Ma Ar ages reflecting zero Ar retention prior to exhumation would only be expected at greater crustal depths than observed here. Most importantly, the cluster of 90 Ma ages at the 18−16 km paleodepths clearly represents a cooling event at this time not recorded by the (U−Th)/He chronometers. It is unlikely that heating from a young (64−66 Ma) two-mica granite [8] in the west-central part of the block significantly affected the muscovite Ar ages, because all three samples are concordant at 90 Ma, and Parolini et al. [9] also reported a single zircon FT age from the Gold Butte townsite (north-central portion of the block) with a similar age of 85 Ma. Dumitru et al. [34] also observed late Cretaceous apatite FT ages from ~65−90 Ma in samples from the Grand Canyon region. Possible causes of this late Cretaceous cooling include cessation of Sevier thrusting [35], the end of intense plutonism in the Sierra Nevada and a regional decrease in geothermal gradients at this time [16,35,36], or erosion caused by Laramide deformation [34]. In any case, Ar age−depth relationships also suggest a structurally continuous block, and indicate a mid-crustal depth for the western end of the block from the late Cretaceous through Miocene.

Similar 1389−1392 Ma \(^{207}\)Pb/\(^{206}\)Pb ages of both titanite and apatite for the easternmost sample are also consistent with regional cooling of the crust.
following 1.45 Ga plutonism. The approximately 20 Myr age difference between the Pb and Ar ages from the easternmost samples probably reflect the higher closure temperature of the U/Pb system (approximately 700°C for titanite [37] and 450°C for apatite [38]). The markedly younger 1130 Ma apatite $^{207}\text{Pb}/^{206}\text{Pb}$ age for the westernmost sample probably reflects significantly slower regional cooling at 15 km crustal depths.

Combining U/Pb, Pb/Pb, Ar/Ar, FT, and (U–Th)/He dates on samples from the eastern and western ends of the Gold Butte block provides a detailed time–temperature history for the different crustal levels of the block (Fig. 3). Zircon U/Pb [7] and titanite Pb/Pb dates indicate rapid cooling of the pluton from magmatic temperatures at 1.45 Ga to temperatures less than that of the titanite Pb $T_c$ ($\sim 700°C$ [37]) by about 1.4 Ga. Apatite Pb/Pb ages indicate that rapid cooling of the eastern portion through about 450°C [38] continued quickly (1.39 Ga), while the western portion did not cool below the apatite Pb $T_c$ until about 1.13 Ga. The largest difference in eastern and western ages for the same system is muscovite $^{40}\text{Ar}/^{39}\text{Ar}$; the eastern part of the block cooled through this blocking temperature (assumed to be the median, 388°C, of the 350–425°C range suggested by Hodges [23]) by 1.37 Ga, while the western portion did not close with respect to Ar diffusion until about 90 Ma. Assuming a pre-Miocene paleodepth of 17 km for the muscovite samples at the west end of the block, geotherms of 20–25°C/km predict temperatures from 350 to 435°C at this depth. The 90 Ma muscovite ages in this portion of the block could therefore represent either a decrease in the geotherm below 25°C/km at this time, or a transient heating and cooling cycle from a 20°C/km geotherm (Fig. 3). Subsequent to this late Cretaceous cooling event, the only other cooling event recorded in rocks of the western portion of the block is the 15–16 Ma Miocene exhumation reflected in all of the titanite (U–Th)/He, apatite FT, and apatite (U–Th)/He systems.

The timing of cooling through 200°C is more difficult to ascertain for the eastern portion of the block, as the location of the top of the titanite He PRZ is not clear, possibly due to structural complications in the easternmost portion of the block.

Assuming the simplest possible cooling path, judging by the rapid Proterozoic cooling indicated by Pb and Ar ages and assuming the pre-Miocene paleodepth of about 5.1 km and inferred geother-
mal gradient of 20°C/km, the east end of the block near sample 98PRGB20 should have been about 112°C by the late Proterozoic, well below the titanite He \( T_C \). However, sample 98PRGB20 yields a 192 Ma titanite He age. A modestly increased geotherm (30–33°C/km) or slightly greater paleodepth (~6 km, rather than 5.1 km) any time between the late Proterozoic and about 90 Ma could have caused considerable He loss and decreased the titanite He ages in the eastern portion of the block. For example, assuming the same titanite He diffusion parameters as above, an isothermal holding temperature of 163°C (achievable by either 5.1 km paleodepth at 30°C/km, or 6.1 km paleodepth at 25°C/km) would generate a \( t_{eq} \) of 184 Ma. With an additional 16 Ma of post-Miocene holding at 10°C, this would produce a titanite He age of 200 Ma, not far from the observed age of 98PRGB20. Thus the mid-Jurassic titanite He ages for the eastern portion of the Gold Butte block probably reflect low but partial He retention at ~150–170°C temperatures over long time periods (any time between ~500 Myr and 1 Gyr) prior to Miocene exhumation, rather than any specific geologic event.

The 50 Ma apatite FT age for the eastern portion of the block [10] may also be related to isothermal holding at temperatures at which FTs anneal at slow rates, rather than any particular cooling event. Alternatively, it could represent the latest cooling associated with Laramide-age tectonism, as suggested by other studies of the region [34]. Laramide uplift near Gold Butte has been inferred from evidence for a basement high to the south (e.g., the Kingman uplift of [4,39], Paleozoic and Mesozoic strata erosionally bevelled southward towards Gold Butte, Eocene gravel deposits filling northeastward-draining palaeocanyons near the edge of the Hualapai plateau [40], and drainage patterns to the northeast in southeastern Nevada and northwestern Arizona [4]). Because of the 15–16 Ma apatite He ages in the eastern portion of the block however, one firm constraint we can place on the eastern (shallow paleodepth) end of the block is that the temperature was above 70°C until the Miocene exhumation event.

Taken as a whole these data suggest that rocks at middle crustal depths at the western edge of the Colorado Plateau resided at moderate geothermal gradients (and slowly declined in temperature) from 1.4 Ga to about 90 Ma. The 90 Ma event may reflect accelerated cooling, a brief heating and cooling cycle (after which gradients returned to a 20°C/km prior to rapid exhumation in the Miocene), or a regional exhumation event as suggested by Dumitru et al. [34]. Similar pre-extensional geothermal gradients of 20–25°C/km have also been interpreted from thermochronologic data in other areas of the Basin and Range [41,42]. The shallower crustal history is more difficult to interpret between 1.4 Ga and 192 Ma, but these data are consistent with rapid cooling through the muscovite Ar \( T_C \) (350–425°C) following intrusion of the Gold Butte granite by ~1380 Ma, followed by residence at temperatures typical of the upper 5–6 km of crust (~110–160°C) probably until the Tertiary. A Laramide-age cooling event may have affected this shallow part of the crust, but the most clearly expressed cooling event is the Miocene exhumation that rapidly decreased the temperature of this part of the crust to below 70°C at 15–16 Ma.

5. Conclusions

Systematic spatial variations in U/Pb, Ar/Ar, FT, and (U–Th)/He ages of samples from Gold Butte are consistent with the interpretation of the block as a single, largely intact, steeply dipping cross-section of crust >15 km thick. Apatite and titanite He ages throughout the block indicate that prior to rapid (at least 7 mm/yr) exhumation at about 15–16 Ma, crust just west of the present-day Colorado Plateau resided at geothermal gradients of about 20–25°C. A cooling event at 90 Ma affected the mid-crust in this area, represented by samples from >15 km depth, bringing rock to a temperature between the \( T_C \) of Ar in muscovite and He in titanite (200 to ~388°C). Prior to this event the time-temperature path of the block is difficult to interpret, but taken as a whole, the He, Ar, and Pb ages from the upper and lower portions of the block suggest different cooling patterns from near magmatic tempera-
tures at 1.45 Ga that reflect different pre-exhumation depths. The lower portion of the block did not cool through 450°C until about 1.13 Ga, and probably remained at temperatures near 350°C until about 90 Ma, consistent with a geotherm of about 20-25°C/km for this pre-exhumation depth. In contrast, the upper portion of the block cooled rapidly from near magmatic temperatures through 350-425°C by 1.37 Ga, consistent with a much shallower depth. Finally, the agreement between the apparent depth of the fossil He PRZ for titanite and the inferred depth of the pre-exhumation 200°C isotherm supports the laboratory-derived diffusion measurements indicating a 200°C $T_c$ for this chronometer.[RV]

References


[40] R.A. Young, Laramide deformation, erosion and plutonism along the southwestern margin of the Colorado plateau, Tectonophysics 61 (1979) 25–47.
