Constraining timing of extension in the southern Rio Grande Rift and basin and range using apatite and zircon (U-Th)/He thermochronology

J. Biddle and Ricketts, J. W., Amato, J.M.

2018, pp. 127-135. https://doi.org/10.56577/FFC-69.127
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2018002

in:

Las Cruces Country III, Mack, Greg H.; Hampton, Brian A.; Ramos, Frank C.; Witcher, James C.; Ulmer-Scholle, Dana S., New Mexico Geological Society 69th Annual Fall Field Conference Guidebook, 218 p.
https://doi.org/10.56577/FFC-69

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 69th Field Conference, Las Cruces Country III, 2018, p. 127-135.

CONSTRAINING TIMING OF EXTENSION IN THE SOUTHERN RIO GRANDE RIFT AND BASIN AND RANGE USING APATITE AND ZIRCON (U-TH)/HE THERMOCHRONOLOGY

Julian Biddle[1], Jason W. Ricketts[1], and Jeffrey M. Amato[2]

[1]Department of Geological Sciences, The University of Texas at El Paso, 500 West University Ave. El Paso, TX 79968
[2]Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003

Abstract—We sampled rocks for zircon (ZHe) and apatite (AHe) (U-Th)/He thermochronology from seven mountain ranges across the Rio Grande rift-Basin and Range transition zone in southeastern Arizona, southern New Mexico, and western Texas. Individual AHe ages (n=23) range from 8–26 Ma, and ZHe ages (n=42) range from 19–649 Ma. Samples from the Basin and Range province, west of the Cookes Range and the Florida Mountains (southwestern New Mexico), have a small spread in ZHe ages, whereas samples from the southern Rio Grande rift yield a wide range of ZHe ages that is related to a corresponding spread in effective uranium (eU). Forward and inverse modeling suggests that cooling from temperatures >200°C in the southeastern Basin and Range may have been due to a combination of tectonic exhumation and mid-Cenozoic igneous activity, whereas extension in the southern Rio Grande rift exhumed rocks from depths corresponding to temperatures <200°C. However, basins in the southern Rio Grande rift are up to 3 km deep, whereas the southeastern Basin and Range is characterized by basins with less than 700 m of basin fill. While further work is needed to fully understand the effects of normal faulting vs. igneous activity on thermochronologic data in southwestern New Mexico, these observations may be a reflection of different styles of extension in each region, separated by a N–S trending boundary in southern New Mexico. Core complex style extension involving low-angle normal faults and mid-crustal detachments are common within the Basin and Range. In contrast, extension in the southern Rio Grande rift may have been accomplished through high-angle faults, which would favor the formation of deep basins, but which did not exhume rocks from depths corresponding to temperatures >200°C.

INTRODUCTION

The Rio Grande rift is one of the world's major intracratonic rifts, extending more than 1,000 km from Colorado to Mexico (e.g., Keller et al., 1990). Although the rift has been extensively studied, there remain fundamental questions regarding its origin. Understanding the timing of extension in different parts of the rift can provide important constraints on possible causes of rifting. Although the timing of earliest extension is somewhat unconstrained, changing patterns in sedimentation, magmatism, and style of deformation all suggest that the region was subjected to early extension by 35–30 Ma (Smith, 2004), and rifting is ongoing (Berglund et al., 2012). Several competing geodynamic models for the initiation of the rift have been proposed to account for this period of extension. Some models suggest that Rio Grande rift extension is driven by mantle forces, either through large-scale mantle upwelling based on mantle tomography (Moucha et al., 2008) or small-scale mantle convection at the edge of the stable Great Plains province (van Wijk et al., 2008). Other models rely on crustal forces to drive extension, and include clockwise rotation of the Colorado Plateau (Hamilton, 1981; Chapin and Cather, 1994; Landman and Flowers, 2013), collapse of over-thickened continental crust (Cordell, 1978; Eaton, 1986), and initiation of a transform setting along the western margin of the North American plate (Dickinson and Snyder, 1979; Baldridge et al., 2006). One model suggests that detachment of a piece of the Farallon plate beneath the Rio Grande region in New Mexico enhanced asthenospheric upwelling in the slab window, creating a N–S trending zone of extension along the weakened crust that developed into the Rio Grande rift (Ricketts et al., 2016).

In addition, the relationship between the Rio Grande rift and the adjacent Basin and Range province remains poorly understood. Some argue that the Rio Grande rift is a not a distinct structural feature and is simply part of the larger Basin and Range province (e.g., Baldridge et al., 1984). Physiographically, the southern Rio Grande rift resembles the immediately proximal Basin and Range because extension is more diffuse and affects a wider region (Fig. 1). However, the southern Rio Grande rift in southern New Mexico can still be distinguished from the Basin and Range because it has higher heat flow, deeper basins with Neogene sedimentary fill, and an abundance of Quaternary faults (Seager and Morgan, 1979; Keller et al., 1990; Nakai et al., 2017). Constraining the timing of extension across the southern Rio Grande rift – Basin and Range transition is therefore important for addressing a variety of structural questions related to the underlying driving forces that have caused extension, and for investigating the nature of the boundary separating the two structural domains.

TECTONIC SETTING

Rio Grande Rift

The Rio Grande rift is a region of lithospheric extension situated between the Basin and Range Province and Colorado Plateau to the west and the Great Plains to the east. The rift trends approximately north-south from northern Colorado to northern Mexico, and has a distinctive structural style of

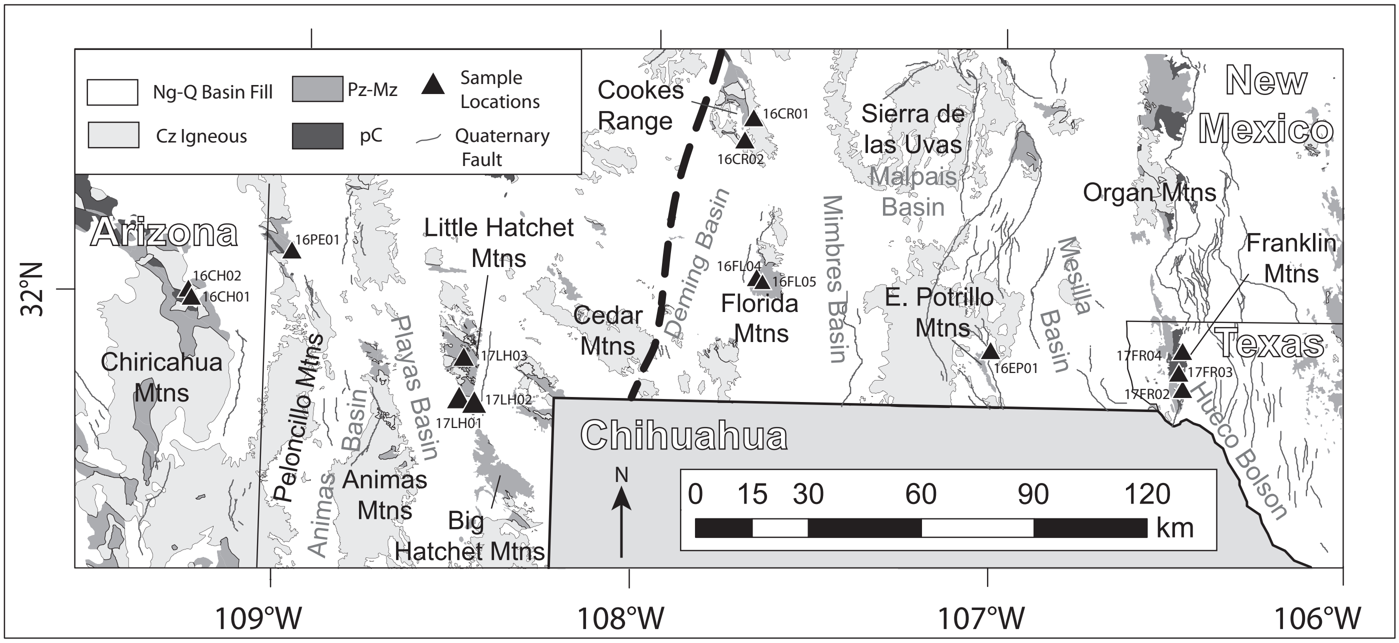

FIGURE 1. Simplified geologic map of southeastern Arizona, southern New Mexico, and western Texas highlighting sample locations. The thick dashed line is the proposed boundary between the Basin and Range and Rio Grande rift from Woodward et al. (1978). Uplifted ranges are in black text, and basins are named in gray text.

asymmetrical half-graben basins bounded by normal faults (e.g., Chapin and Cather, 1994; Lewis and Baldridge, 1994). Half-grabens are typically bordered by master normal faults that accumulate a majority of fault displacement and result in uplift of the footwall block, typically exposing Precambrian crystalline rocks. From northern Colorado to central New Mexico, the rift is a discrete, narrow feature that consists of interconnected basins that have widths less than ~80 km. South of the Socorro "constriction" (Kelley, 1952), the rift abruptly widens, and its physical expression becomes more diffuse. Here, the rift consists of multiple adjacent basins that have a combined width of ~180 km (Seager and Morgan, 1979).

Low-temperature thermochronologic data have been obtained for many of the uplifts associated with the central and northern portions of the Rio Grande rift in New Mexico and Colorado, including apatite fission-track (AFT) and apatite (U-Th)/He (AHe) datasets (Kelley et al., 1992; Kelley and Chapin, 1997; House et al., 2003; Landman and Flowers, 2013; Ricketts et al., 2015; 2016). Combined AFT and AHe studies constrain the low-temperature cooling history of rocks that were exhumed during rifting (e.g., House et al., 2003; Ricketts et al., 2016). In particular, Ricketts et al. (2016) use AFT and AHe constraints from the same samples to document a period of cooling from 25–10 Ma along the length of the Rio Grande rift from northern Colorado to southern New Mexico. These data do not support earlier models of rift extension which suggest two discrete periods of faulting from 32–18 Ma and from 10–5 Ma (Cordell, 1978; Morgan et al., 1986). AHe ages from the Franklin Mountains, where the southern Rio Grande rift begins to physiographically blend with the Basin and Range province, suggest extension in the south occurred simultaneously with the central and northern segments of the Rio Grande rift (Delfin and Ricketts, 2016).

Basin and Range Province

The Basin and Range is a significant extensional province along western North America. The region's characteristic physiographic appearance is controlled by systems of alternating horsts and grabens (Stewart, 1971). Large-magnitude Eocene-late Miocene extension in the Basin and Range resulted in a belt of metamorphic core complexes that extends from British Columbia, Canada, to northern Mexico (Coney, 1980; Axen et al., 1993; Constenius, 1996; Dickinson, 2002, 2009). Dickinson (2002) viewed the Basin and Range province as a taphrogen, a composite extensional terrane where different regions (subtaphrogens) preserve different times or styles of extension. In particular, the southeastern Basin and Range, the Piman subtaphrogen, includes southern Arizona as well as the Rio Grande rift in New Mexico (Dickinson, 2002). In this region, core complex formation in southeastern Arizona occurred from ~30 to 12 Ma (Dickinson, 2002). Based on geochronologic analysis of mylonite zones, the easternmost core complex in the Pinaleño Mountains in southeastern Arizona was active until 19 Ma (Long et al., 1995). Widespread renewed crustal extension in the Piman subtaphrogen started at ~12.5 Ma, when the Rivera triple junction began migrating southward along the Pacific-North American plate boundary (Dickinson, 2002). Piman deformation largely ended at 6 Ma as extension was concentrated in the Gulf of California (Stock and Hodges, 1989; Staude and Barton, 2001). This timing of extension in the southeastern Basin and Range is similar to the discrete periods of extension in the Rio Grande rift envisioned by early workers (Cordell, 1978; Morgan et al., 1986), but are inconsistent with thermochronologic data which now suggest a main phase of extension from 25–10 Ma along the length of the rift (Kelley et al., 1992; Kelley and Chapin, 1997; Ricketts et al., 2016).

METHODS

Samples for thermochronology were collected from the footwalls of major basin-bounding normal faults in southeastern Arizona, southern New Mexico, and western Texas for the purpose of (1) comparing the timing of extension in this region to the wealth of thermochronologic data in the northern and central segments of the rift; and (2) to compare the timing of extension across the Basin and Range – Rio Grande rift transition zone in southern New Mexico (Fig. 1). Samples were collected immediately adjacent to faults because these rocks are most likely to record exhumation during faulting, and, therefore, can be used to interpret when faulting occurred (Stockli, 2005). For most samples, we obtained AHe and zircon (U-Th)/He (ZHe) data to tightly constrain the low-temperature cooling history from approximately 240°C to near-surface temperatures (~25ºC). Individual apatite and zircon grains were selected based on grain morphology (euhedral), size, and minimal inclusions.

In (U-Th)/He thermochronology, the closure temperature is not a specific value because minerals can partially retain He at different rates across a temperature range known as the partial retention zone (PRZ) (Harrison and Zeitler, 2005). In the AHe method, the PRZ exists between ~30–90°C (Flowers et al., 2009). ZHe has a PRZ between ~140–220°C (Guenthner et al., 2013), although other studies suggest that high-damage zircons can record temperatures <50°C (Johnson et al., 2017).

The effective uranium (eU) concentration (eU = U + 0.235Th) expresses the productivity during the decay of both U and Th within a grain. An apatite grain with higher eU will experience more damage from decay, resulting in a higher closure temperature and higher apparent age for the mineral. Thus, a positive correlation between AHe age and eU indicates relatively slow cooling through the AHe PRZ, while uniform AHe ages across a range of eU values indicates relatively rapid cooling through this temperature window (Flowers et al., 2009). Like apatite, closure temperatures in zircon are affected by eU, but have a more complex relationship. At lower radiation damage (less than 1.5 x $10^{18}\alpha$/g), ^{4}He diffusivity rapidly decreases (Guenthner et al., 2013). This results in a positive relationship between ZHe ages and eU, similar to what is observed in the AHe system. However, damage accumulation at α-doses >1.5 x $10^{18}\alpha$/g becomes so great that He diffusivity begins to increase, creating an inverse relationship between ZHe ages and eU (Guenthner et al., 2013). These relationships can be used to differentiate between rapid and slow cooling through the AHe and ZHe PRZs.

Because of the complexities involved with AHe/ZHe age and eU values, individual ages typically do not date a specific event. Therefore, forward and inverse modeling of ZHe and AHe data was completed using HeFTy software (Ketchum, 2005) in order to constrain the cooling history of samples through time. These thermal history models are the primary means of constraining when faults in different regions of the southern Rio Grande rift–Basin and Range transition were active. In addition, these models were used to compare thermal history models produced for the central and northern segments of the Rio Grande rift (Ricketts et al., 2016). Radiation damage accumulation and annealing models (RDAAM) from Guenthner et al. (2013) and Flowers et al. (2009) were used in HeFTy for zircon and apatite data, respectively. Both AHe and ZHe ages were given an uncertainty of 20% of their age to be consistent with the methods of Ricketts et al. (2016).

THERMOCHRONOLOGY RESULTS AND INTERPRETATION

A total of 42 ZHe and 23 AHe ages were obtained from 14 samples (Fig. 1; Table 1, see Data Repository). Samples from the Chiricahua, Little Hatchet, and Peloncillo Mountains show rather uniform AHe and ZHe ages ranging from 30–10 Ma, regardless of a large spread in eU (Fig. 2). Ages from the Florida Mountains are also less than 30 Ma, and ZHe ages from 16FL05 have a slight negative correlation with eU. ZHe ages from the Cookes Range have a high spread in ages from 40 to 280 Ma, though correlation with eU was not significant. The two AHe samples from the Cookes Range (sample 16CR02) have ages between 25 and 5 Ma. Only ZHe ages were obtained from the East Potrillo and Franklin Mountains because of the lack of suitable apatite grains. The East Potrillo Mountains yielded ZHe ages between 65 and 20 Ma, while ZHe samples from the Franklin Mountains have a large spread in ages between 19 and 649 Ma. Samples from both ranges have negative correlations with eU (Fig. 2).

Forward Modeling

Forward models were constructed in HeFTy using hypothesized time-temperature paths in order to compare calculated ZHe age-eU relationships to observed data (Fig. 3). Five hypothetical cooling paths were investigated. These paths do not use the specific geologic constraints put on the inverse models discussed below, but are general paths representing regional cooling patterns. Each model begins at 1400–1300 Ma at temperatures of 300°C to reflect approximate crystallization timing of basement plutonic rocks, and is forced to surface temperatures (25ºC) at 550 Ma to represent the Great Unconformity (Fig. 3A). Path 1 simulates burial to temperatures of 100°C by 200 Ma, followed by cooling to surface temperatures at 25–10 Ma. Path 2 is very similar to path 1, but simulates burial to higher temperatures of 290°C by 200 Ma, followed by cooling from 25–10 Ma. Both of these paths are used to test whether the 25–20 Ma cooling observed in the central and northern rift segments (Ricketts et al., 2016) is also observed to the south. Path 3 simulates 28.5–17.5 Ma cooling from high temperatures (290°C), followed by a renewed pulse of cooling from 12.5–6 Ma (Dickinson, 2002). Path 4 is the best-fit path from the 17LH01 and 17LH02 inverse model (see below). Path 5 simulates prolonged time within the ZHe PRZ, followed by slight cooling during the 80–40 Ma Laramide Orogeny, and concluding with cooling to surface temperatures from 25–10 Ma (Fig. 3B). For each of these forward models, calculated ZHe age-eU paths were constructed using grain radius values that range from 50–150 μm.

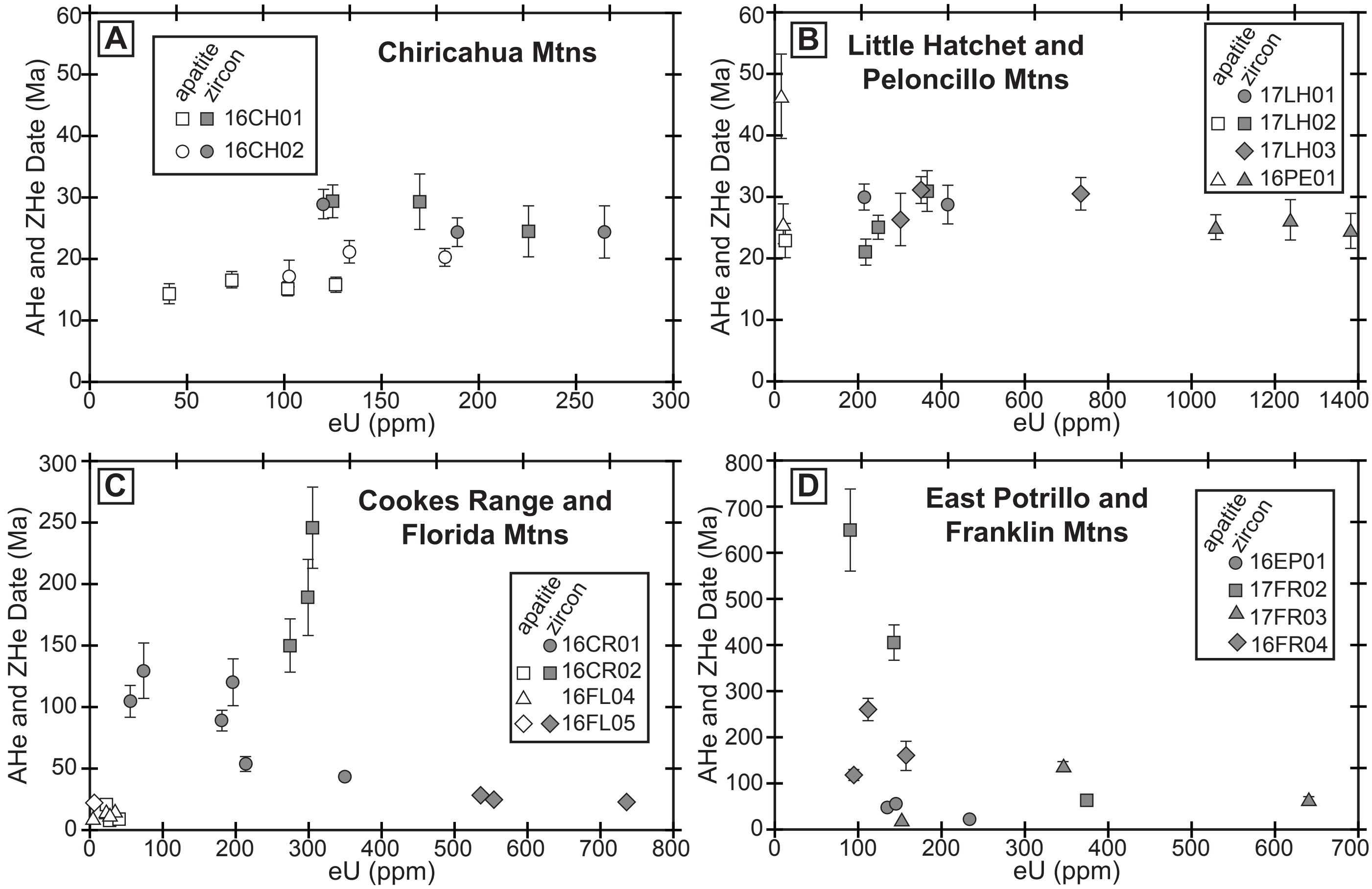

FIGURE 2. Apatite and zircon age-eU plots for samples in the **A**) Chiricahua, **B**) Little Hatchet and Peloncillo, **C**) Cookes Range and Florida Mountains, and **D**) East Potrillo and Franklin Mountains (ZHe only). All error bars are 2σ.

Resulting forward models for the Basin and Range (using the boundary in Figure 1) suggest that path 1 does a poor job of fitting the observed data (Fig. 3C). Paths 2 and 3, which simulate 25–10 Ma cooling (Ricketts et al., 2016) and a multi-phase cooling history involving plate boundary interactions (Dickinson, 2002), respectively, predict ZHe ages that show a similar trend, but are younger than observed (Fig. 3D). However, path 4, which predicts rapid cooling from 26–23 Ma from temperatures of >200°C, predicts a ZHe age-eU relationship that is best represents the observed spread in ZHe age and eU (Fig. 3D). These results indicate that most of the samples within the Basin and Range province of southeastern Arizona and southwestern New Mexico were at temperatures higher than the ZHe PRZ at the onset of extension.

ZHe data from uplifts in the Rio Grande rift, including the Cookes Range, Florida Mountains, East Potrillo Mountains, and Franklin Mountains, show a much larger spread in apparent age ranging from 19–649 Ma (Fig. 3E). For this dataset, paths 1, 2, and 3 are ineffective models for the observed relationships. Path 5, which involves cooling from 25–10 Ma from temperatures of 120°C, provides the best fit to the observed data. The large spread in ZHe age suggests that, in general, these samples likely spent significant time within the ZHe PRZ prior to being exhumed towards the surface during extension.

Inverse Modeling

To refine the results of these forward models, inverse models that incorporate available ZHe and AHe data were constructed for each of these uplifts (Fig. 4). In southeastern Arizona, two models from the Chiricahua Mountains (16CH01 and 16CH02, not pictured) suggest a period of cooling from ~30–15 Ma from relatively high temperatures. Model 16CH01 was rerun to investigate the possibility of reheating from the 29 Ma Turkey Creek caldera (du Bray et al., 1997). The similarity of the two 16CH01 models suggest that the ZHe and AHe ages from the Chiricahua Mountains were likely reset during the volcanism associated with the caldera. One sample from the Peloncillo Mountains (16PE01) yielded ZHe and AHe ages that are only slightly younger than the 33.2 Ma crystallization age of the granite (McLemore et al. 1995). Although this model does not yield any information on times of extension, the data suggest that this intrusion likely cooled at relatively shallow depths in the crust. Two samples from the Little Hatchet Mountains (17LH01 and 17LH02) were combined into a single thermal history model (Fig. 4) because each model separately was relatively unconstrained due to insufficient ZHe and AHe data, and the samples were collected within close proximity to one another in an area of no major faulting. The combined model suggests that this region experienced a pulse of cooling from

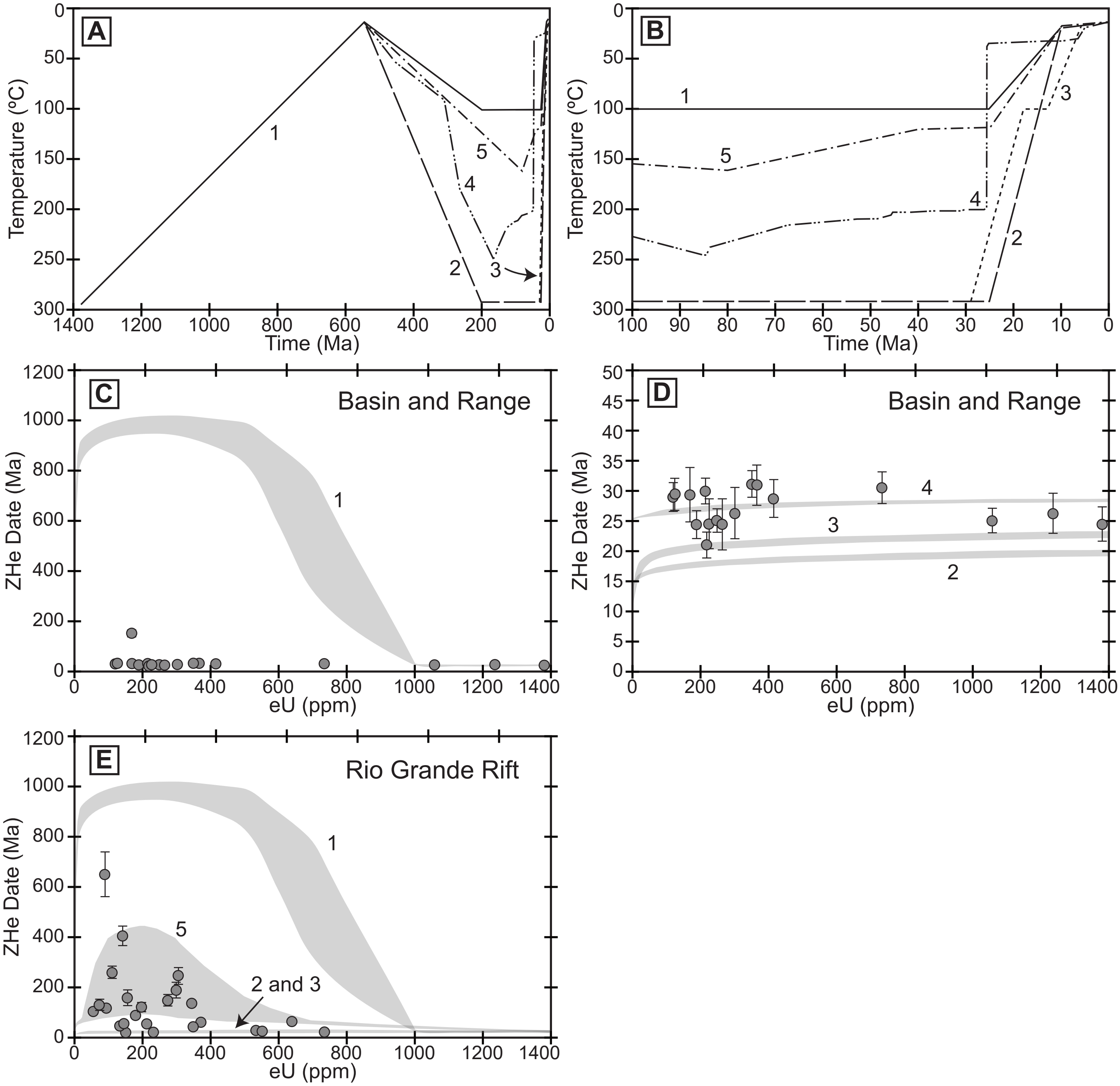

FIGURE 3. **A**) Five hypothetical forward models for samples in the Basin and Range–Rio Grande rift transition. All models begin at elevated temperatures at 1400-1300 Ma and are forced to surface temperatures at 550 Ma. **B**) Enlarged view of each hypothetical path over the last 100 Ma. **C**) All ZHe data from Basin and Range samples plotted against eU. The gray envelope is the predicted age-eU pattern from path 1, using a range of grain radius values from 50-150 µm. Samples are differentiated from Rio Grande rift samples using the boundary shown in Figure 1. **D**) Enlarged view of the last 50 Ma, as well as forward model results for paths 2, 3, and 4. **E**) ZHe data from the southern Rio Grande rift compared to forward model results from paths 1, 2, 3, and 5.

~28–19 Ma. A third sample collected from the Little Hatchet Mountains (17LH03) yields a model suggesting a period of cooling beginning at 30 Ma, but is constrained by only three ZHe ages. Cooling recorded in the Little Hatchet samples is close to the age of the 32.3 Ma granite intrusion present in the mountain range (Channell et al., 2000), and it is possible that this intrusion affected the observed cooling ages. Additional data are needed to more carefully explore the possible effects of magmatism vs. extension in this region.

Within the southeastern Rio Grande rift, two samples were collected from the Cookes Range (16CR01 and 16CR02). However, no thermal history model is presented from these samples because of the difficulty in modeling all available ZHe and AHe data. The spread in ZHe ages for these samples cannot be explained by a corresponding spread in eU. This may be an indication that sedimentary rocks in the Cookes Range

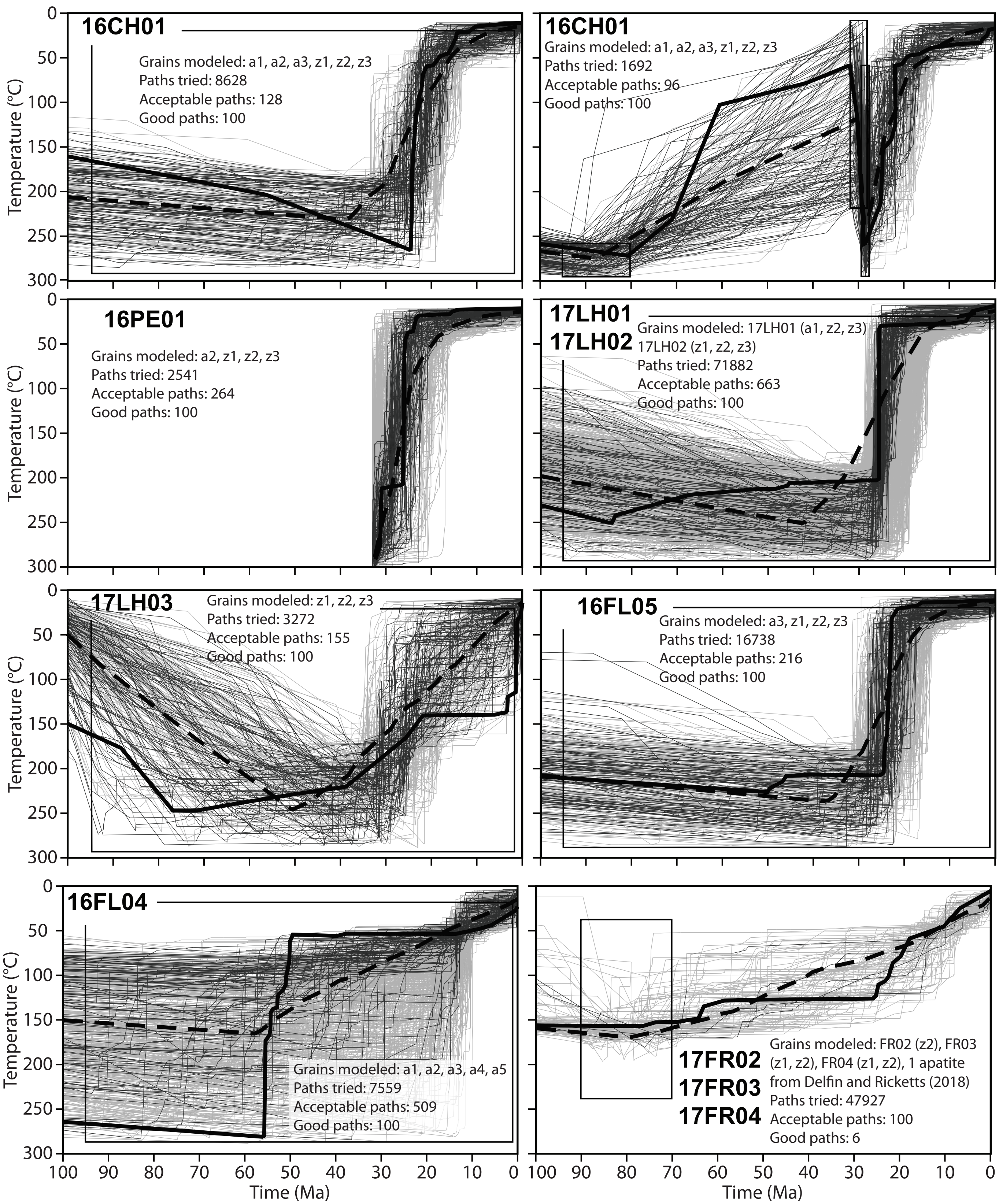

FIGURE 4. Inverse model results from individual fault block uplifts in southeastern Arizona, southern New Mexico, and western Texas. Model 16CH01 was run twice, once including a reheating event at 29 Ma (right) and once without (left). Resulting "good" paths are shown in dark gray, and have a goodness-of-fit parameter >0.05. Resulting "acceptable" paths are shown in lighter gray, and have a goodness-of-fit parameter >0.5. Thin black lines are constraint boxes incorporated into each model.

were never buried sufficiently to completely anneal zircon crystals, and each crystal may therefore record a separate thermal history. Although there are Eocene-Oligocene age intrusions in the Cookes Range (Clemons, 1982), the high spread in ages suggests that igneous activity did not reset the ages of the samples. In the Florida Mountains, sample 16FL05 indicates rapid cooling from ~26–17 Ma (Fig. 4). The resulting inverse model from sample 16FL04 is unconstrained at higher temperatures because this sample lacks any ZHe data. However, the majority of "good" paths for this model are at relatively low temperatures, indicating that this sample likely remained at temperatures of <150°C and cooled to near-surface temperatures by 10 Ma. Rhyolite flows and dikes occurred in the Florida Mountains from ~29–23 Ma (Clemons, 1998), and it is possible that the cooling in the Florida samples was affected by this igneous activity. A single thermal history model is presented for the Franklin Mountains which includes ZHe data from three samples (17FR02, 17FR03, and 17FR04), as well as a single AHe age from Delfin and Ricketts (2016). This model strongly suggests that the rocks exposed in the Franklin Mountains were at temperatures <200°C prior to the formation of the Rio Grande rift, and they reached near-surface temperatures by ~10 Ma. The high spread in ZHe ages from the Franklin Mountains samples indicate that the 49–45 Ma andesite plutons near the mountain range (Lovejoy, 1975) did not reset the samples' ages. No thermal history model for the East Potrillo Mountains is presented because of the difficulty in modeling all available ZHe data. The age of andesitic intrusions on Mt. Riley near the East Potrillo Mountains is not precisely known, but likely occurred between 35–26 Ma (Seager and Mack, 1994). The majority of ZHe ages from the East Potrillo samples are older than 35 Ma, so igneous activity probably did not affect the samples' ages.

DISCUSSION

Boundary Between the Basin and Range Province and Rio Grande Rift

Differences in heat flow, gravity, and crustal thickness in the Basin and Range and Rio Grande rift in southern New Mexico (e.g., Keller et al., 1990) suggest that the two structural features are separate and discrete tectonic provinces. However, the boundary between these provinces has not been conclusively identified, in part because the two provinces generally display diffuse extension and are physiographically similar. Differing interpretations of geologic and geophysical features identify a discrete boundary located either to the west of the Cookes Range and the Florida Mountains (e.g., Woodward et al., 1978; Keller et al., 1990), or east of these ranges (e.g., Seager and Morgan, 1979; Mack, 2004).

Using the boundary from Woodward et al. (1978) highlighted in Figure 1, there is a distinct difference in ZHe thermochronologic dates from the Rio Grande rift and the Basin and Range. Samples from the Rio Grande rift show a large spread in ZHe ages (19–649 Ma), with most of the ages being much older than the rift itself. Basin and Range samples yield ZHe ages between 20 and 32 Ma, except for a single 150 Ma age from the Little Hatchet Mountains, which may be due to an unrecognized inclusion in the sample grain. These age relationships suggest that the Rio Grande rift either exhumed samples slowly through the ZHe PRZ or that extension was not sufficient to exhume samples from beneath this temperature window. However, basins in the southern Rio Grande rift are typically deeper and this region is characterized by higher heat flow, suggesting that samples should have been exhumed from temperatures higher than the ZHe PRZ.

Southern Rio Grande rift basins are generally 1–3 km deep, in contrast to basins within the Basin and Range which only reach depths <700 m (Averill and Miller, 2013). Up to 3 km of uplift across the rift is recorded by AFT data for uplifted ranges to the north (Kelly and Chapin, 1997). The similarity in AHe ages from the southern Rio Grande rift (8–40 Ma) and Basin and Range (14–46 Ma) suggests that extension in both provinces was sufficient to exhume the ~1–3 km deep AHe PRZ, assuming a geothermal gradient of 25ºC/km. However, the maximum of 3 km of uplift in the rift is not enough to exhume the >5 km deep ZHe PRZ. This implies that samples from the rift were not exhumed through the ZHe PRZ, resulting in a wide range in ZHe ages. The relatively shallow extensional basins in the Basin and Range suggest that a similar pattern should be observed in these ZHe ages, but the young, restricted range of ages suggests that the rocks now exposed in Basin and Range mountains were either exhumed rapidly through the ZHe PRZ during normal faulting or were strongly affected by mid-Cenozoic volcanism, which heated them to temperatures >200ºC. The effect of igneous activity on the ZHe ages in the Basin and Range makes it difficult to compare the timing of extension to the Rio Grande rift, but the presence of shallow basins may reflect a difference in the styles of extension in the two regions.

Comparing Styles of Extension in the Basin and Range and Rio Grande Rift

As noted previously, a distinct difference between extension in the Basin and Range province and Rio Grande rift is the presence of metamorphic core complexes in the former, which evolve from low-angle detachments that largely control extension in the upper to middle crust (e.g., Coney, 1980; Wernicke, 1981; Coney and Harms, 1984; Wernicke and Axen, 1988). Hence, Basin and Range extension is facilitated by listric normal faulting along master detachment faults that exhume deeply buried rocks, and, therefore, this style of deformation is conducive to the formation of shallow basins. Conversely, higher-angle extensional faults are likely to produce deeper basins even with less total accumulated fault slip. The Rio Grande rift preserves isolated fragments of low-angle normal faults, which may represent the early stages of core complex formation, although the degree of extension has not been sufficient to expose ductilely-deformed rocks at the surface (Ricketts et al., 2015). Therefore, it is likely that structural basins of the rift are controlled to a large degree by high-angle faults that form deep basins.

This difference in structural style between the two provinces is supported by seismic imaging across the Basin and Range – Rio Grande rift transition zone in southern New Mexico (Averill, 2007; Averill and Miller, 2013). Sedimentary basins in southern New Mexico are less than 1 km deep but progressively deepen eastward from the Florida Mountains. In addition, the seismic reflectivity and velocity patterns in the New Mexico Basin and Range are comparable to that of metamorphic core complex belts in western Arizona and eastern California (Averill, 2007; Averill and Miller, 2013). The shallow basins in the Basin and Range suggest an extension process similar to core complexes, which can exhume deep material with low vertical slip. If the core complex style of extension observed in southeastern Arizona continued eastward into southern New Mexico, it could account for the observed shallow basins and possibly for the uniform ZHe ages preserved in southwestern New Mexico.

CONCLUSIONS

A total of 42 new ZHe and 23 new AHe ages were collected from seven mountain ranges across the Rio Grande rift-Basin and Range transition zone in southern New Mexico and Arizona. AHe ages from each uplift are relatively restricted and show minimal variation in eU. However, ZHe ages range from 19–649 Ma and have a wide range in eU.

Several important conclusions can be made when these data are sorted into Basin and Range samples vs. southern Rio Grande rift samples. First, ZHe ages from the Basin and Range fall within a narrow range of 20–32 Ma, whereas ZHe ages from the southern Rio Grande rift have a much wider range of 19–649 Ma. Second, forward model results from the Basin and Range samples suggest that these samples remained at elevated temperatures >200°C until they were cooled to near-surface temperatures from ~30–15 Ma. In contrast, samples from the southern Rio Grande rift likely resided within the ZHe PRZ for prolonged periods of time, and extension in this region exhumed rocks from temperatures <200°C, resulting in a large spread in ZHe ages. Lastly, inverse models for each uplift refine the forward modeling results, and place important constraints on the times of cooling in each individual range. Overall, Basin and Range samples experienced a slightly earlier pulse of cooling than samples from the Rio Grande rift, likely due to a combination of extension and relaxation of isotherms following volcanism in the Basin and Range.

Together with differences in heat flow, basin depth, and Quaternary faulting across this region, our data suggest the presence of a tectonic boundary separating the Basin and Range province and the southern Rio Grande rift. In particular, the Rio Grande rift samples yield a wide range in ZHe ages, and have deeper basins than the Basin and Range.

ACKNOWLEDGMENTS

Funding for (U-Th)/He analyses came from the National Science Foundation grant EAR 1624538, awarded to Ricketts and Amato. Jose Garcia, Nathan Reade, and Jose Adrian Rubio were instrumental in the sample collection and mineral separation process. We thank Michelle Gavel, Shari Kelley, and Jacob Thacker for their comments, which greatly improved the paper.

REFERENCES

Averill, M.G., 2007, A lithospheric investigation of the southern Rio Grande rift [Ph.D. dissertation]: El Paso, University of Texas at El Paso, 231 p.

Averill, M.G., and Miller, K.C., 2013, Upper crustal structure of the southern Rio Grande rift: a composite record of rift and pre-rift tectonics, *in* Hudson, M.R. and Grauch, V.J.S., eds., New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater: Geological Society of America, Special Paper 494, p. 463-474.

Baldridge, W.S., Olsen, K.H., and Callender, J.F., 1984, Rio Grande rift—Problems and perspectives: New Mexico Geological Society, Guidebook 35, p. 1-12.

Baldridge, W.S., Keller, G.R., Haak, V., Wendlandt, E., Jiracek, G.R., and Olsen, K.H., 2006, The Rio Grande rift, *in* Olsen, K.H., ed., Continental Rifts: Evolution, Structure, Tectonics: Developments in Geotectonics, v. 25, p. 233-275.

Berglund, H.T., Sheehan, A.F., Murray, M.H., Roy, M., Lowry, A.R., Nerem, R.S., and Blume, F., 2012, Distributed deformation across the Rio Grande rift, Great Plains, and Colorado Plateau: Geology, v. 40, p. 23-26.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America Special Paper 291, p. 5–25.

Clemons, R.E., 1982, Geology of Massacre Peak quadrangle, Luna county, New Mexico: New Mexico Bureau of Mines & Mineral Resources Geologic Map 51, scale 1:24,000.

Clemons, R.E., 1998, Geology of the Florida Mountains, southwestern New Mexico: New Mexico Bureau of Mines & Mineral Resources Memoir 43, 112 p.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073-1090.

Constenius, K., 1996, Late Paleogene collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20–39.

Delfin, R.A. and Ricketts, J., 2016, Constraints on the timing of extension in the Franklin Mountains from apatite (U-Th)/He thermochronology, El Paso, Texas, (abs.): New Mexico Geological Society Annual Spring Meeting, Socorro, NM, Proceedings volume, p. 18.

Dickinson, W.R., 2002, The Basin and Range province as a composite extensional domain: International Geology Review, v. 44, p. 1-38.

Dickinson, W.R. and Snyder, W.S., 1979, Geometry of subducted slabs related to San Andreas transform: Journal of Geology, v. 87, p. 609-627.

du Bray, E.A., Pallister, J.S., and Yager, D.B., 1997, Geologic map of the Turkey Creek caldera, Chiricahua Mountains, Cochise County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2544, scale 1:50,000, sheet 1.

Eaton, G.P., 1986, A tectonic redefinition of the southern Rocky Mountains: Tectonophysics, v. 132, p. 163-193.

Flowers, R.M., Ketcham, R.A., Shuster, D.L., and Farley, K.A., 2009, Apatite (U-Th)/He thermochronometry using a radiation damage accumulation and annealing model: Geochimica et Cosmochimica Acta, v. 73, p. 2347-2365.

Guenthner, W.R., Reiners, P.W., Ketcham, R.A., Nasdala, L., and Giester, G., 2013, Helium diffusion in natural zircon: radiation damage, anisotropy, and the interpretation of zircon (U-Th)/He thermochronology: American Journal of Science, v. 313, p. 145-198.

Hamilton, W., 1981, Plate-tectonic mechanism of Laramide deformation, *in* Boyd, D.W., and Lillegraven, J.A. eds., Rocky Mountain Foreland Basement Tectonics: University of Wyoming Contributions to Geology, v. 19, p. 87-92.

Harrison, T.M. and Zeitler, P.K., 2005, Fundamentals of noble gas thermochronometry, *in* Reiners, P.W. and Ehlers T.A., eds., Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Chantilly, Mineralogical Society of America, Reviews in Mineralogy and Geochemistry, v. 58, p. 123-149.

House, M.A., Kelley, S.A., and Roy, M., 2003, Refining the footwall cooling history of a rift flank uplift, Rio Grande rift, New Mexico: Tectonics, v. 22., no. 5, p. 1-18.

Johnson, J.E., Flowers, R.M., Baird, G.B., and Mahan, K.H., 2017, "Inverted" zircon and apatite (U-Th)/He dates from the Front Range, Colorado: High-damage zircon as a low-temperature (<50°C) thermochronometer: Earth and Planetary Science Letters, v. 466, p. 80-90.

Keller, G.R., Morgan, P., and Seager, W.R., 1990, Crustal structure, gravity anomalies and heat flow in the southern Rio Grande rift and their relationship to extensional tectonics: Tectonophysics, v. 174, p. 21–37.

Kelley, S. and Chamberlin, R., 2012, Our growing understanding of the Rio Grande rift: New Mexico Earth Matters, v. 12, no. 2, 5 p.

Kelley, S.A., and Chapin, C.E., 1997, Cooling histories of mountain ranges in the southern Rio Grande rift based on apatite fission-track analysis – a reconnaissance survey: New Mexico Geology, v. 19, no. 1, p. 1-14.

Kelley, S.A., Chapin, C.E., and Corrigan, J., 1992, Late Mesozoic to Cenozoic cooling histories of the flanks of the northern and central Rio Grande rift, Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 145, 39 p.

Kelley, V.C., 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mexico Geological Society, Guidebook 3, p. 92-105.

Landman, R.L., and Flowers, R.M., 2013, (U-Th)/He thermochronologic constraints on the evolution of the northern Rio Grande Rift, Gore Range, Colorado, and implications for rift propagation models: Geosphere, v. 9, p. 170-187.

Long, K.B., Baldwin, S.L., and Gehrels, G.E., 1995, Tectonothermal evolution of the Pinaleño-Jackson Mountain core complex, southeast Arizona: Geological Society of America Bulletin, v. 107, p. 1231-1240.

Lovejoy, E.M.P., 1975, An interpretation of the structural geology of the Franklin Mountains, Texas: New Mexico Geological Society, Guidebook, 26, p 261-268.

Morgan, P., Seager, W.R., and Golombek, M.P., 1986, Cenozoic thermal, mechanical and tectonic evolution of the Rio Grande rift: Journal of Geophysical Research, v. 91, p. 6263-6276.

Moucha, R., Forte, A.M., Rowley, D.B., Mitrovica, J.X., Simmons, N.A., and Grand, S.P., 2008, Mantle convection and the recent evolution of the Colorado Plateau and the Rio Grande rift valley: Geology, v. 36, p. 439-442.

Nakai, J.S., Sheehan, A.F., and Bilek, S.L., 2017, Seismicity of the Rocky Mountains and Rio Grande rift from the EarthScope Transportable Array and CREST temporary seismic networks, 2008-2010: Journal of Geophysical Research: Solid Earth, v. 122, p. 2173-2192.

Reiners, P.W., 2005, Zircon (U-Th)/He thermochronometry, *in* Reiners, P.W. and Ehlers T.A., eds., Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Chantilly, Mineralogical Society of America, Reviews in Mineralogy and Geochemistry, v. 58, p. 151-179.

Ricketts, J.W., Karlstrom, K.E., and Kelley, S.A., 2015, Embryonic core complexes in narrow continental rifts: the importance of low-angle normal faults in the Rio Grande rift of central New Mexico: Geosphere, v. 11, p. 425-444.

Ricketts, J.W., Kelley, S.A., Karlstrom, K.E., Schmandt, B., Donahue, M.S., and van Wijk, J., 2016, Synchronous opening of the Rio Grande rift along its entire length at 25-10 Ma supported by apatite (U-Th)/He and fission-track thermochronology, and evaluation of possible driving mechanisms: Geological Society of America Bulletin, v. 128, p. 397–424.

Seager, W.R., and Mack, G.H., 1994, Geology of East Potrillo Mountains and vicinity, Doña Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 113, 27 p.

Seager, W.R., and Morgan, P., 1979, Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua, *in* Riecker, R.E., ed., Rio Grande Rift: Tectonics and Magmatism: Washington, D.C., American Geophysical Union, p. 87–106.

Smith, G.A., 2004, Middle to late Cenozoic development of the Rio Grande rift and adjacent regions in northern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11, p. 331–358.

Staude, J.G., and Barton, M.D., 2001, Jurassic to Holocene tectonics, magmatism, and metallogeny of northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1357-1374.

Stewart, J.H., 1971, Basin and Range structure: A system of horsts and grabens produced by deep-seated extension: Geological Society of America Bulletin, v. 82, p. 1019-1044.

Stock, J.M., and Hodges, K.V., 1989, Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific plate: Tectonics, v. 8, p. 99-115.

Stockli, D.F., 2005, Application of low-temperature thermochronometry to extensional tectonic settings, *in* Reiners, P.W. and Ehlers T.A., eds., Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Chantilly, Mineralogical Society of America, Reviews in Mineralogy and Geochemistry, v. 58, p. 411-448.

van Wijk, J., van Hunen, J., and Goes, S., 2008, Small-scale convection during continental rifting: Evidence from the Rio Grande rift: Geology, v. 36, p. 575–578.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen: Nature, v. 291, p. 645-648.

West, M., Ni, J., Baldridge, W.S., Wilson, D., Aster, R., Gao, W., and Grand, S., 2004, Crust and upper mantle shear wave structure of the southwest United States: implications for rifting and support for high elevation: Journal of Geophysical Research, v. 109, B03309.

Woodward, L.A., Callender, J.F., Seager, W.R., Chapin, C.E., Gries, J.C., Shaffer, W. L., and Zilinski, R.E., 1978, Tectonic map of Rio Grande rift region in New Mexico, Chihuahua, and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 163, scale 1:1,000,000, sheet 2.

Zeller, R.A., Jr., 1970, Geology of the Little Hatchet Mountains, Hidalgo and Grant Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 96, 33 p.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2018002

Jim Witcher at a geothermal well head. Photograph by Greg H. Mack.