

GSA TODAY

 THE GEOLOGICAL SOCIETY
OF AMERICA®

VOL. 31, NO. 10 | OCTOBER 2021

The Origin and Tectonic Significance of the Basin and Range–Rio Grande Rift Boundary in Southern New Mexico, USA



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ABSTRACT

Cenozoic extension in the western United States occurred within two iconic domains: the Basin and Range and Rio Grande rift. These provinces merge in southern New Mexico to form an interconnected zone of extension, although the existence, location, and nature of the boundary between the two provinces are uncertain. In southern New Mexico, existing thermochronologic, geologic, and geophysical data sets, combined with thermal modeling of zircon (U-Th)/He (ZHe) data, define a subvertical, 30–40-km-wide boundary that extends through the lithosphere to depths of at least 100 km. Thermal modeling indicates Proterozoic basement in the upper crust of the southeastern Basin and Range exceeded 225 °C during Oligocene magmatism, resetting ZHe dates and creating a thermal boundary that coincides with independent geologic and geophysical data sets. Although many aspects of this boundary are transient, others may become permanent features to define a lithospheric-scale boundary prone to reactivation during future tectonism. This assessment of the boundary supports models in which the southern Rio Grande rift is a separate structural entity from the adjacent Basin and Range, and this region provides an exceptional case study for understanding how extensional lithospheric-scale boundaries evolve to become stable features of continents.

INTRODUCTION

The Rio Grande rift and Basin and Range Province are two of the most iconic extensional domains on Earth; the Basin and Range Province is the archetypal example of a wide rift, and the neighboring Rio Grande rift is one of the classic modern examples of a narrow continental rift (e.g., Buck, 1991). For most of its length, the Rio Grande rift is

separated from the Basin and Range Province by the Colorado Plateau, and they exist as distinct structural entities, but in southern New Mexico, they merge to form an interconnected zone of extension that continues south into Mexico (Fig. 1). The existence of a discrete boundary between the two domains and the nature of this transition in southern New Mexico remain unclear, although understanding the transition is crucial for assessing how these two extensional provinces evolved through time. The physiographic expression of extension in southern New Mexico suggests an indistinct or nonexistent boundary, favoring models where the Rio Grande rift is the easternmost segment of the Basin and Range Province (Eaton, 1982). This view is contentious, however, because thermochronologic (Gavel, 2019) and geophysical (e.g., Keller et al., 1990; Averill and Miller, 2013; Feucht et al., 2019) data sets highlight important differences between the two provinces, supporting models where they exist as two separate, albeit contiguous entities. This nontrivial distinction has implications for the relative role of plate-boundary versus mantle processes driving extension in western North America (Dickinson, 2002).

A more complete understanding of the boundary requires diverse data sets at different scales to constrain its current characteristics and evolutionary history. Here we use thermochronologic data, including apatite fission-track (AFT), apatite (U-Th)/He (AHe), and zircon (U-Th)/He (ZHe), together with a synthesis of geologic and geophysical data from southwestern New Mexico to investigate the nature of the transition at a lithospheric scale. We then document a pronounced thermal boundary across the transition preserved in ZHe data sets. When viewed collectively, these independent data sets reveal a complex and dynamic tectono-

thermal boundary and reinforce the idea that the southern Rio Grande rift is a separate structural entity from the adjacent Basin and Range Province.

THE RIO GRANDE RIFT–BASIN AND RANGE BOUNDARY IN SOUTHERN NEW MEXICO

There are three models for how to assess the Rio Grande rift–Basin and Range Province boundary (Fig. 1): (1) The northern Rio Grande rift is a separate entity from the Basin and Range Province, and is distinguished by its narrow width (dark orange in Fig. 1); (2) the entire Rio Grande rift exists as a separate entity along its entire length (light and dark orange in Fig. 1); and (3) the two provinces are contiguous and coeval and thus the Rio Grande rift is just a localized term for the Basin and Range Province on its eastern margin adjacent to the Colorado Plateau (thick dark green line in Fig. 1). We investigate the nature of a possible boundary in southern New Mexico, and use “transition zone” to refer to a 40-km-wide zone that includes major differences in the crust and lithosphere. Physiographic maps, which are based on modern topography and drainage basins, lump the southern Rio Grande rift with the Basin and Range Province (Hammond, 1970). Most workers place the boundary at the eastern edge of the transition zone (e.g., Mack, 2004; van Wijk et al., 2018), which coincides with the western edge of the rift farther north, but it has not yet been clearly documented as to why this is a meaningful or geologically relevant location in southern New Mexico.

GEOLOGIC AND GEOPHYSICAL MANIFESTATIONS OF A BOUNDARY

In southern New Mexico, independent data sets highlight a subvertical boundary 30–40 km wide that extends to depths of at

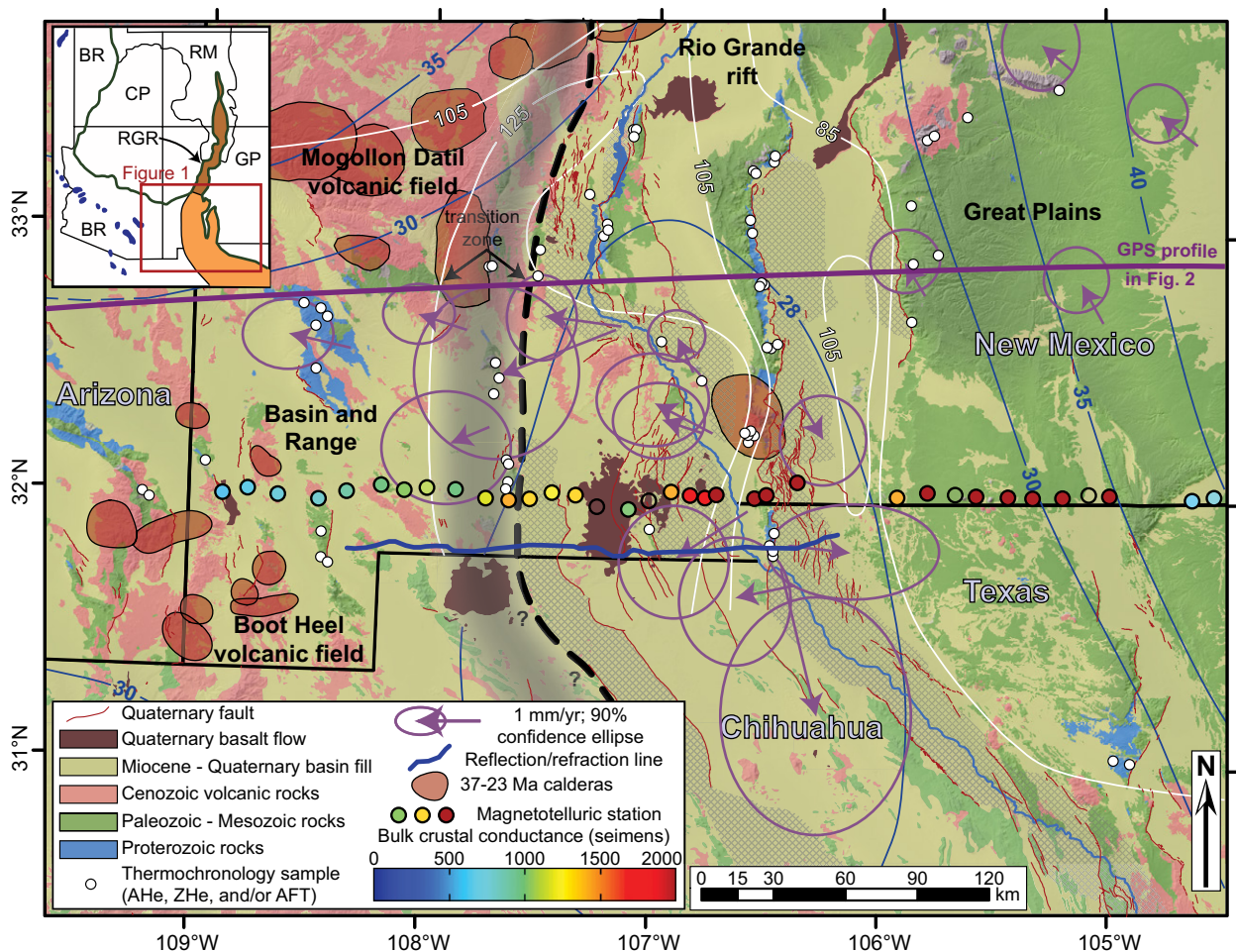


Figure 1. Geologic map of the southern Rio Grande rift (RGR)–Basin and Range Province transition. Map includes thermochronology data (Kelley and Chapin, 1997; Ricketts et al., 2016; Biddle et al., 2018; Gavel, 2019; Reade et al., 2020), global positioning system (GPS) data (Murray et al., 2019), reflection/refraction line (Averill, 2007; Averill and Miller, 2013), and magnetotelluric data recording bulk crustal conductance (Feucht et al., 2019). Thick dashed black line is the boundary of Mack (2004). Cross-hatched areas show deep basins of the RGR (Seager and Morgan, 1979). Blue lines show crustal thickness (km), and white lines show heat flow (mWm^{-2}) (Keller et al., 1990). AFT—apatite fission-track; AHe—apatite (U-Th)/He; ZHe—zircon (U-Th)/He. Inset shows metamorphic core complexes in blue and different models for the RGR–Basin and Range Province boundary, as discussed in the text. BR—Basin and Range; CP—Colorado Plateau; GP—Great Plains; RM—Rocky Mountains.

least 100 km (Figs. 1 and 2). Global positioning system (GPS) data show variable strain rates between the Great Plains and the Basin and Range Province (Fig. 2A; Murray et al., 2019). The Great Plains has low strain rates of 0.68 ± 0.17 nanostrains/year (nstr/yr), but strain rates are an order of magnitude higher in the Basin and Range Province and southern Rio Grande rift. Notably, there is a sharp transition from the highest strain rates of 8.54 ± 2.10 nstr/yr in the Rio Grande rift to lower rates of 1.45 ± 0.31 nstr/yr in the adjacent eastern Basin and Range Province. GPS results are consistent with a greater number of Quaternary faults in the southern Rio Grande rift, but these data also indicate that the rift is deforming at interseismic time scales.

AHe, AFT, and ZHe thermochronology, sensitive to temperatures of 30–90 °C,

60–120 °C, and 50–240 °C, respectively (Ketcham, 2005; Flowers et al., 2009; Guenther et al., 2013), are compiled across the transition zone (Fig. 1; Kelley and Chapin, 1997; Ricketts et al., 2016; Biddle et al., 2018; Gavel, 2019; Reade et al., 2020). AFT and AHe dates show little variation across this region, and ages overlap with the time of Cenozoic extension. However, ZHe dates change drastically over short distances (Fig. 2B). West of the transition ZHe dates are similar to AFT and AHe dates, but east of the transition ZHe dates range from 2 to 731 Ma.

Across this region, overall crustal thickness gradually increases from ~28–30 km beneath the axis of the Rio Grande rift to 35 km in southwestern New Mexico (Fig. 2C; Keller et al., 1990; Averill, 2007). Basins are typically deeper in the southern rift (2–4 km)

and abruptly shallow toward the Basin and Range Province, which have typical depths of less than 1 km (Averill, 2007). Additional shallow expressions of this boundary include more voluminous Quaternary volcanism, active faulting (Seager and Morgan, 1979; Keller et al., 1990), and higher heat flow (Keller et al., 1990) in the southern Rio Grande rift (Fig. 1).

Gravity models are consistent with a welt of high-density material beneath the axis of the southern Rio Grande rift at depths of ~12–21 km (Fig. 2C; Averill, 2007). This welt thins to the west and becomes absent in the transition zone. Velocity and gravity models highlight decreased densities and upper mantle velocities within the southern Rio Grande rift (Averill, 2007), which is associated with higher Moho temperatures of 900–1000 °C (Hamblock et al., 2007).

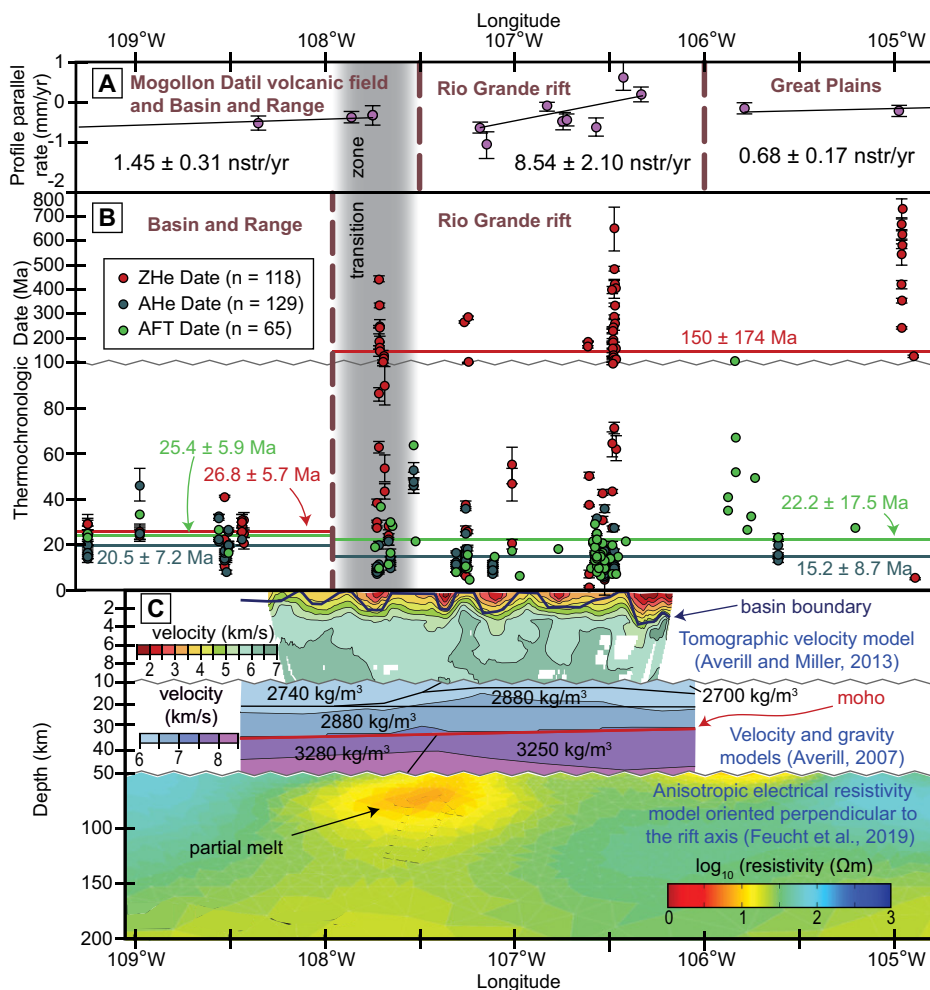


Figure 2. E-W cross section across the transition. (A) Global positioning system velocities across the profile line shown in Figure 1 (Murray et al., 2019). (B) Thermochronologic dates for all samples shown in Figure 1. Average dates are calculated for each data set in the Basin and Range Province and Rio Grande rift (± 1 standard deviation). (C) Stacked geophysical models for the crust and upper mantle. Note changes in scale with depth. AFT—apatite fission-track; AHe—apatite (U-Th)/He; ZHe—zircon (U-Th)/He; nstr/yr—nanostream/year.

Magnetotelluric data collected along an E-W transect through southern New Mexico show that the upper mantle is moderately resistive (30–100 Ωm ; Feucht et al., 2019). The one exception is a zone of age conductive material centered on 107.5°W at the eastern margin of the transition zone that is exceptionally pronounced at depths of 50–100 km and that may also extend to depths >200 km (Fig. 2C). This feature is interpreted to be a zone of lithospheric decompression melting (Feucht et al., 2019). Interestingly, this region of decompression melting is slightly asymmetric beneath the southern Rio Grande rift and skewed to the west, as opposed to more symmetric lithospheric thinning and mantle upwelling in central New Mexico (Wilson et al., 2005).

THE THERMAL IMPRINT OF A BOUNDARY

ZHe dates from the Basin and Range Province (Fig. 2B) largely overlap with ages of volcanic rocks in southwestern New Mexico, suggesting they were likely reset by magmatism (Gavel, 2019), and we use these data to model the heating effects of Oligocene magmatism in this region. Individual zircon grains from a single sample have variable closure temperatures due to accumulation of varying amounts of radiation damage that is proportional to eU ($eU = U + 0.235Th$), where low eU, high He retentivity grains typically correspond to oldest ZHe dates and high eU, low retentivity grains yield youngest ZHe dates (Guenther et al., 2013). These properties allow for thermal modeling of ZHe data

from 240 to 50 °C (Guenther et al., 2013). Compiled ZHe dates (Biddle et al., 2018; Gavel, 2019; Reade et al., 2020) show dramatic differences across the transition zone with relation to eU (Fig. 3). In the Basin and Range Province, ZHe dates are consistent for all eU values. In contrast, east of and including the transition zone, ZHe dates have a wide range, where oldest ZHe dates are correlated with lowest eU and youngest ZHe dates have highest eU values. This observation suggests that radiation damage in zircon is a primary control on ZHe dates in this region.

Forward modeling allows for the calculation of ZHe date-eU curves from an input thermal history, and here it provides a means of testing the potential effects of reheating during magmatism (see supplemental material for complete modeling details¹). We use a general thermal history of southern New Mexico that includes crystallization at 1.6 Ga and cooling to 350 °C at 1.45 Ga, based on $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite data (Amato et al., 2011), 15 °C at 500 Ma based on the age of the overlying Bliss Formation, and maximum reheating to 150 °C at 80 Ma from accumulation of Paleozoic and Mesozoic sediment (Fig. 3A). We include two endmember Proterozoic cooling histories: multiple cooling pulses during assembly of Rodinia (path 1; Ricketts et al., 2021), and multiple pulses of cooling that coincide with assembly and then breakup of Rodinia (path 2; DeLucia et al., 2017). Resulting ZHe date-eU curves are roughly similar to observed ZHe dates for the southern Rio Grande rift regardless of the Proterozoic cooling history. Boot Heel volcanic field magmatism in southwestern New Mexico occurred from 37 to 26 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine geochronology (McIntosh and Bryan, 2000), and we test the effects of this event on ZHe dates (Fig. 3B). Calculated ZHe date-eU curves only match the observed data for reheating temperatures of >225 °C and indicate that this thermal event did not affect ZHe dates in the southern Rio Grande rift. These results suggest that late Oligocene magmatism imprinted a major thermal boundary that coincides with independent geologic and geophysical data sets.

DISCUSSION

Age and Evolution of the Boundary

The collective data sets suggest that the southern Rio Grande rift is best explained

¹Supplemental Material. Full description of zircon (U-Th)/He modeling, inputs, and assumptions. Go to <https://doi.org/10.1130/GSAT.S.14794197> to access the supplemental material; contact editing@geosociety.org with any questions.

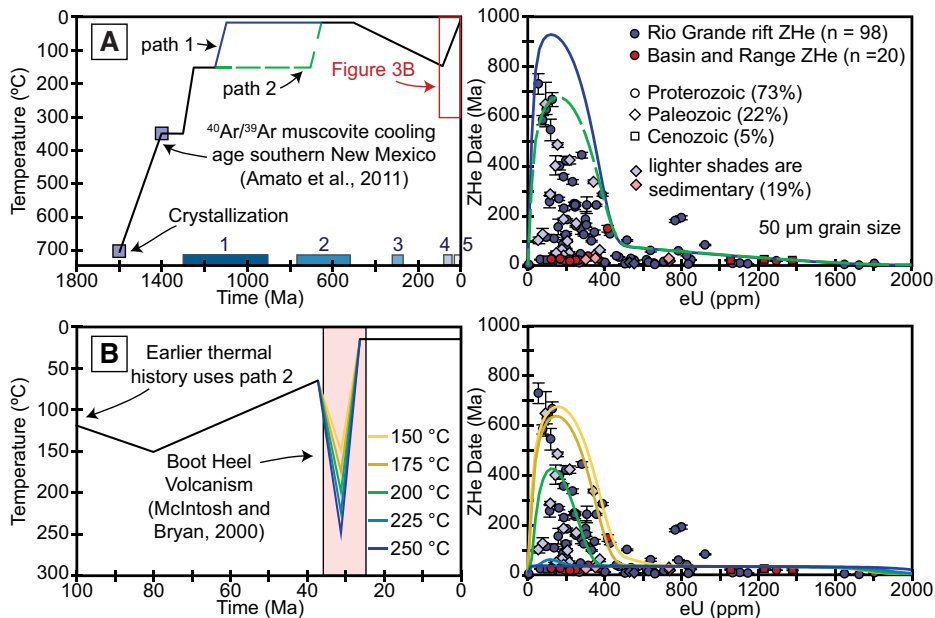


Figure 3. (A) Forward modeling and calculated zircon (U-Th)/He (ZHe) date-eU curves compared to a compilation of ZHe dates from the southern Rio Grande rift and Basin and Range Province (Biddle et al., 2018; Gavel, 2019; Reade et al., 2020), where Basin and Range Province data are west of 108°W longitude and Rio Grande rift data are east. ZHe date-eU curves are calculated from a thermal history using the helium diffusion model of Guenther et al. (2013). 1—assembly of Rodinia; 2—breakup of Rodinia; 3—Ancestral Rocky Mountains; 4—Laramide orogeny; 5—Neogene exhumation. (B) Testing the effects of magmatic reheating in the Boot Heel volcanic field. Grain size used on modeling is the average of all zircon grains.

as an active extensional province that developed adjacent to the generally inactive southeastern Basin and Range Province (Fig. 1). The data do not support models where the northern Rio Grande rift is separate from the Basin and Range of southern New Mexico (dark orange in Fig. 1) or that the entire Rio Grande rift is the easternmost arm of the larger Basin and Range Province (dark green line in Fig. 1). Many of the observed manifestations of a boundary in southern New Mexico can be understood in the context of active extension in the southern Rio Grande rift and a relative lack thereof in the Basin and Range Province. Active lithospheric extension produces higher mantle conductance through partial melting, higher strain rates, active faulting, young volcanism, thinner crust, decreased upper mantle velocities and densities, and possibly deeper basins within the southern Rio Grande rift, where the westernmost expression of each of these features defines a 30–40-km-wide subvertical boundary that extends through the lithosphere (Fig. 2). At the surface, we place the boundary at the eastern edge of the transition zone, because this coincides with changes in basin depth, Quaternary faulting, volcanism, active strain rates, and bulk crustal conductance (Fig. 1). As active extension continues in the southern Rio Grande rift, the boundary will

become more pronounced in independent data sets, suggesting that many of the differences across this boundary are controlled by differences in the timing of extension from the Basin and Range Province to the Rio Grande rift.

Constraining the timing of extension across the transition zone provides context for how and when the boundary evolved. Regionally, the easternmost metamorphic core complexes in southern Arizona are the Pinaleno, active from 29 to 19 Ma (Long et al., 1995), and the Catalina-Rincon, active from 27 to 20 Ma (e.g., Davy et al., 1989). Post-detachment extension in the region persisted until the onset of seafloor spreading in the Gulf of California at 6 Ma (e.g., Lizarralde et al., 2007). The sedimentary record of extension in southwestern New Mexico is relatively unexplored compared to the central and northern segments of the Rio Grande rift because there are few outcrops of Miocene and older basin strata. Available data suggest that initial Basin and Range Province extension in this region was under way during the Oligocene based on thickness of sedimentary basin fill and sparse age control from interbedded volcanic rocks (Mack, 2004). Although main extension is thought to have ceased by 6 Ma, minor Quaternary extension is evident by short fault segments that offset

young alluvium (Mack, 2004). In the southern Rio Grande rift, the timing of initial extension was inferred by Amato et al. (2019) to have begun by ca. 27 Ma when the voluminous Uvas basalts were erupted (Clemons, 1979), which was coeval with deposition of the Thurman Formation (Boryta, 1994). Extension was active through the late Quaternary as evidenced by long fault scarps that bound major rift flank uplifts.

Thermochronologic data from the study area offer an opportunity to further constrain the times of extension and compare to the sedimentary record and regional tectonic history. Inverse thermal history modeling of AHe, AFT, and ZHe data in southern New Mexico suggests that main cooling in the southeastern Basin and Range Province was from 35 to 14 Ma (Gavel, 2019). In contrast, thermal modeling documents distinctly younger cooling from 25 to 5 Ma in the southern Rio Grande rift east of the transition (Fig. 1) to create a complex and highly dynamic lithospheric boundary that formed during diachronous pulses of extension. Initial Cenozoic development of the boundary occurred from 35 to 25 Ma when the southeastern Basin and Range Province experienced voluminous magmatism in the Boot Heel volcanic field and coeval extension (Fig. 4; McIntosh and Bryan, 2000; Gavel, 2019), and extension had not yet initiated in the Rio Grande rift. Evolution of the boundary dramatically slowed from 25 to 14 Ma when extension in both provinces occurred. Thermochronologic data indicate that the main phase of rapid extension ended at 14 Ma in the Basin and Range Province, although slower extension likely continued until 6 Ma. During this time, formation of the boundary may have continued again as Rio Grande rift extension outpaced Basin and Range Province extension. However, a crucial difference at this stage is that continued formation of the boundary was due to active extension to the east of the boundary (Rio Grande rift) rather than extension to the west (Basin and Range Province). Formation of the boundary accelerated again at 6 Ma when Basin and Range Province extension dramatically decreased and continued to the present. Thermochronology is thus consistent with the available sedimentary record and, when viewed within the context of the regional tectonic framework, reveals important differences in the timing of extension across the transition zone, where boundary evolution occurred in two discrete pulses and continues today.

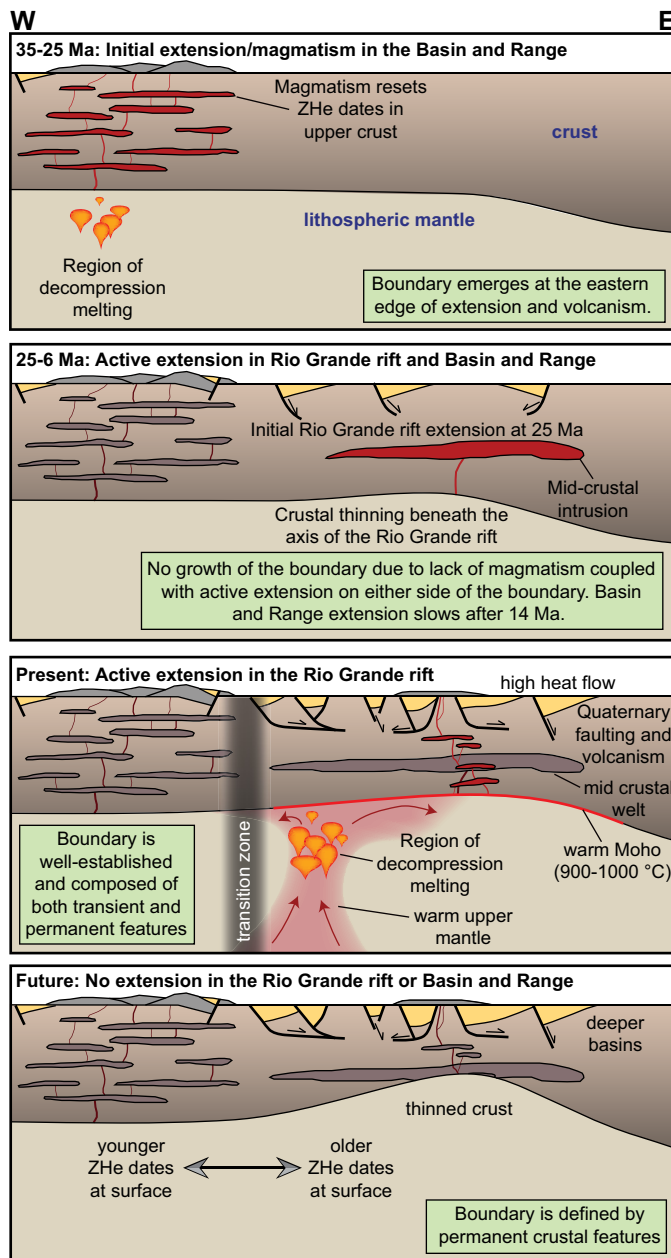


Figure 4. Schematic W-E cross sections showing the evolution of the Basin and Range Province–Rio Grande rift boundary. ZHe—zircon (U-Th)/He.

These independent data sets document the timing of formation of a near-vertical, lithospheric-scale boundary in southern New Mexico, but do not address the origins of this feature. It may have emerged during Oligocene magmatism in the Boot Heel volcanic field, which modified the chemical structure of the lithosphere and created a sharp thermal gradient that influenced extensional tectonism on either side. This model may indicate separate driving mechanisms, where mantle processes are responsible for Rio Grande rift extension and magmatism (Ricketts et al., 2016) and the Basin

and Range Province was more influenced by plate boundary effects (Bird, 2002). Cenozoic development of the boundary may also have been superimposed upon N-S-trending or NW-trending extensional Neoproterozoic structures that likely formed within an overall convergent tectonic setting during Grenville orogenesis (e.g., Karlstrom and Humphreys, 1998; Timmons et al., 2001). However, evidence for their existence or history is cryptic in southwestern New Mexico, and such structures have been more thoroughly documented in central and northern New Mexico (Karlstrom et al., 2004).

Our analysis in southern New Mexico is essentially a 2D cross-sectional view of the boundary, and further data sets to the south are needed to test whether the transition zone has an overall NS or NW trend and coincides with major Proterozoic boundaries. Based on available data, we therefore suggest that initial development of the boundary occurred during the late Eocene with Basin and Range Province extension and resulted from separate driving mechanisms from the Basin and Range Province to the Rio Grande rift.

Preservation Potential in the Geologic Record

If active extension is the underlying cause for most of the observed differences across the transition, then some boundary features are transient, such as differences in heat flow, conductance, and upper mantle velocities and densities on either side of the boundary. These features will likely vanish when extension ceases. In contrast, permanent boundary features include changes in basin depth, changes in the style of extension (presence or absence of metamorphic core complexes), differences in the timing of faulting, and the thermal imprint on thermochronologic data sets (Fig. 4). These permanent features will become more pronounced as Rio Grande rift extension continues. Permanent and transient boundary features are similar to the Rio Grande rift boundary in central New Mexico. In this well-defined segment of the rift, the boundary is demarcated by differences in mantle velocities (West et al., 2004), crustal thickness (Wilson et al., 2005), surface heat flow (Reiter et al., 2010), and extensional basins bounded by normal faults. The transition from thinned lithosphere with these characteristics to adjacent unaffected lithosphere over short distances is a classic and definitive description of a continental rift boundary, and this has been documented in other rifts worldwide (e.g., Achauer and Masson, 2002; Corti, 2009).

Lithospheric-scale boundaries are long-lived features of continents that can form through a multitude of major tectonomagmatic events. Once established, these features are prone to reactivation (e.g., New Madrid fault zone; Hurd and Zoback, 2012) and are therefore influential in guiding the style and geometry of future deformation (Karlstrom and Humphreys, 1998). Across the Colorado Plateau, Rocky Mountains, and Midcontinent regions, there are numerous examples of Ancestral Rocky Mountain and

Laramide basement uplifts that reactivated inherited structures (Soreghan et al., 2012; Bader, 2019), including Proterozoic extensional fault systems (Marshak et al., 2000; Timmons et al., 2001). These events attest to the longevity of extensional structures in continental lithosphere and their susceptibility for reactivation. We propose that after extension in the Basin and Range Province and Rio Grande rift ceases, this boundary will persist as a stable feature of North American lithosphere, possibly guiding future tectonic structures through reactivation of normal faults.

ACKNOWLEDGMENTS

We thank John Singleton, an anonymous reviewer, and science editor Mihai Ducea for comments that helped strengthen the arguments made in this paper. Becky Flowers and Jim Metcalf at the University of Colorado TRaIL lab in Boulder, Colorado, USA, helped acquire (U-Th)/He data. This work is supported by NSF grants EAR-1624538 to Ricketts and EAR-1624575 to Amato.

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MANUSCRIPT RECEIVED 20 MAR. 2021

REVISED MANUSCRIPT RECEIVED 1 JUNE 2021

MANUSCRIPT ACCEPTED 11 JUNE 2021