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PROCESSES CONTROLLING THE DEVELOPMENT OF THE RIO GRANDE RIFT AT LONG TIMESCALES

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ABSTRACT—This manuscript highlights several processes that may have been influential in the development of the Rio Grande rift by reviewing important results from recent studies. In the Albuquerque Basin, low-angle normal faults exist in several locations, but are discontinuously preserved and generally offset and rotated by high-angle normal faults. The Sandia and Sierra Ladrones rift flank uplifts, which are the highest elevation rift flanks on opposite sides of the Albuquerque Basin, both have low-angle normal faults, have maximum extension in the Albuquerque Basin, show fault dips that increase from the rift margin towards the axis of the basin, and show fault ages that young towards the center of the basin. Thermochronologic data suggest that both of these rift flanks were exhumed at nearly the same time, 10-25 Ma. These observations suggest a rolling-hinge mechanism for the formation of low-angle normal faults in the Rio Grande rift, where isostatic uplift appears to be a dominant process in regions of maximum extension. This process can therefore dramatically affect basin and rift-flank geometry as rifting progresses and suggests that the Sandia and Ladron uplifts are moderate-extension analogs to core complexes. To further understand extensional processes and timing of extension within the Rio Grande rift, apatite fission-track (AFT) and apatite (U-Th)/He thermochronologic methods were used to produce thermal history models from Rio Grande rift flank uplifts in Colorado and New Mexico. These models indicate that extension along the majority of the length of the rift was synchronous from 10-25 Ma. Existing geodynamic models for rift formation such as collapse of high topography or reduction of far field stresses due to growth of the San Andreas transform, or reactivation of older weaknesses, may not adequately explain the simultaneous 10-25 Ma opening of the Rio Grande rift from Colorado to Texas, nor explicitly link rifting to prior events such as the ignimbrite flare-up and Laramide orogeny. A model is therefore favored that involves Laramide flexure of the downgoing Farallon plate at the eastern Rocky Mountain front, delamination of sections of the Farallon Plate beneath the San Juan and Mogollon Datil volcanic fields to initiate and explain migrations of volcanism in the ignimbrite flare up, then a “big break” and foundering of the Farallon plate beneath the Rio Grande rift at ca. 25-30 Ma. This event focused asthenospheric upwelling along a north-south trend, weakening the overlying North American lithosphere and facilitating E-W extension from Colorado to southern New Mexico.

INTRODUCTION

Processes controlling continental extension operate at a variety of scales in time and space, ranging from seconds (earthquakes) to tens or hundreds of millions of years (break-up of continents). The Rio Grande rift is a narrow (10s of km) zone of east-west extension that extends, at least, from central Colorado to Texas. Initial extension may have been as early as 36-37 Ma (Kelley and Chamberlain, 2012), but most extension took place in the Miocene and resulted in the formation of discrete north-south-trending rift basins that are separated by accommodation zones (Chapin and Cather, 1994). This paper focuses on two main processes at timescales of tens of millions of years that have played a significant role in determining the geometry of the rift and explaining the timing and geodynamic causes of its formation. The two main ideas presented are: (1) isostatic rebound of rift flanks led to formation of low-angle normal faults (LANF) and (2) tearing and foundering of a section of the Farallon plate ca. 25-30 Ma focused extension along the north-south Rio Grande rift. This paper represents a summary of the main conclusions presented by Ricketts et al. (2015a, b).

ROTATION OF FAULTS THROUGH ISOSTATIC REBOUND

LANFs are exposed along the entire length of the Rio Grande rift and have been recognized for decades (e.g., Black,

1964). However, they are set within a predominantly high-angle normal fault environment and make up a relatively small percentage of the total fault population (Baldrige et al., 1984). In the Albuquerque Basin of central New Mexico, LANFs crop out within the Sandia uplift along the northeastern margin of the basin (Van Hart, 1999), within the Joyita Hills to the southeastern (Beck and Chapin, 1994; DeMoor et al., 2005), in the Sierra Ladrones along the southwestern edge of the basin (e.g., Black, 1964; Lewis and Baldrige, 1994; Read et al., 2007), and within the Lucero uplift near Carrizo Arroyo (Candler and Zilinski, 1976; Ricketts and Karlstrom, 2014; Fig. 1, see also Color Plate 3). Of these locations, exposed LANFs in the Sandia Mountains and Sierra Ladrones provide an excellent opportunity to investigate interactions between high- and low-angle normal faults and the processes responsible for fault geometry, because they are located in regions of the Albuquerque Basin that have undergone the most extension.

Physiographically, the Albuquerque Basin is a coherent feature of the Rio Grande rift, but structurally the basin can be subdivided into multiple subbasins. The northern Albuquerque subbasin is an east-tilted half-graben that is bounded at the base of the Sandia Mountains by west-dipping normal faults (Fig. 1). These faults include the high-angle Rincon fault and the low-angle Knife Edge fault. These faults primarily separate Proterozoic granitic rocks capped by Paleozoic sedimentary rocks in the footwall against Santa Fe Group sediment in the hanging wall. In contrast, the southern Belen subbasin appears

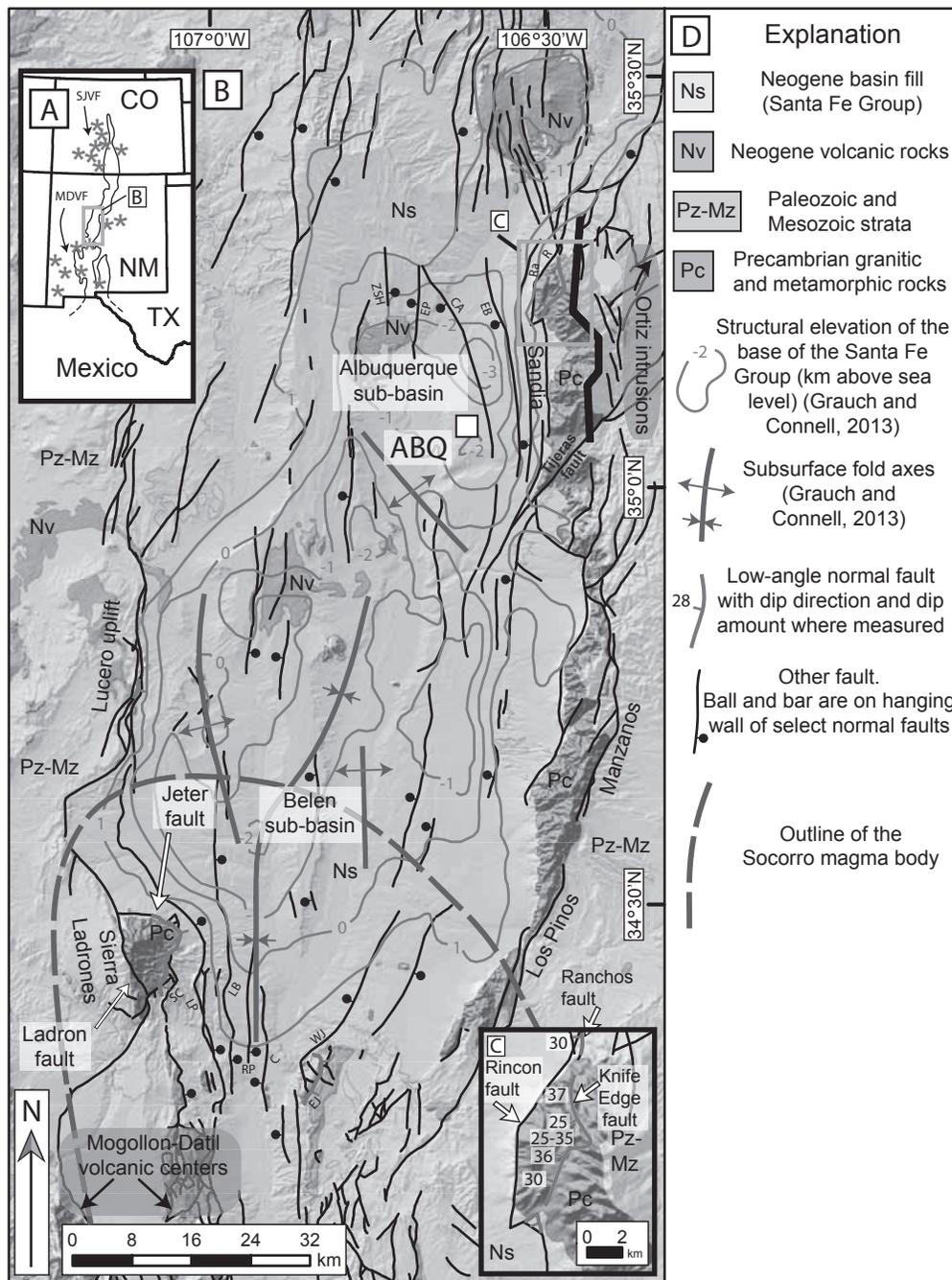


FIGURE 1. A) Regional outline of the Rio Grande rift in Colorado and New Mexico. Stars indicate Oligocene-early Miocene calderas. SJVF – San Juan volcanic field; MDVF – Mogollon Datil volcanic field. B) General geologic map of the Albuquerque Basin. ABQ – Albuquerque; C – Cliff fault; CA – Coronado-Alameda strand, East Heights fault zone; EB – Eubank strand, East Heights fault zone; EJ – East Joyita fault; EP – East Paradise fault; LB – Loma Blanca fault; LP – Loma Pelada fault; R – Rincón fault; Ra – Ranchito fault; RP – Río Puerco fault; SC – Silver Creek fault; WJ – West Joyita fault; ZSH – Zia and Star Heights fault zones. C) The low-angle Knife Edge fault of the Sandia Mountains with measured fault dip measurements. Figure modified from Ricketts et al. (2015a). A color version of this figure can be found in Color Plate 3.

to encompass multiple structural basins, filled with gently-dipping Santa Fe Group strata. In the southwestern edge of the Belen subbasin, Santa Fe Group beds dip more steeply to the southwest (Grauch and Connell, 2013) and are truncated by the east-dipping, low-angle Jeter fault (e.g., Black, 1964; Lewis and Baldrige, 1994; Ricketts et al., 2015a). This fault consistently dips $\sim 15^{\circ}$ – 30° east, with Proterozoic granitic rocks

in the footwall faulted against Paleozoic, Mesozoic and Cenozoic sedimentary rocks in the hanging wall (e.g., Read et al., 2007).

Observations on fault geometries in different parts of the basin and timing constraints on fault activity provide a method of investigating processes resulting in the development of LANFs in the Albuquerque Basin. The Sandia and Sierra Ladrones are the highest flanks surrounding the Albuquerque Basin, at elevations of 3.2 km and 2.7 km above mean sea level, respectively. Based on a synthesis of geophysical data, these locations are adjacent to the deepest depocenters in the basin. The northern Albuquerque subbasin reaches minimum elevations of less than -3 km, while at the base of the Sierra Ladrones, the southern Belen subbasin reaches maximum depths of less than -2 km (Grauch and Connell, 2013). These relationships suggest that the Sandia uplift and Sierra Ladrones are regions of maximum fault throw, and it is also in these regions that LANFs are best developed.

Faults in both parts of the basin also have similar geometries extending from the rift flank uplift towards the axis of the basin. In the Sandia uplift and Sierra Ladron Mountains, LANFs are restricted to the mountain front, and the dip of exposed faults increases towards the central parts of the basin, where faults generally dip $60 \pm 10^{\circ}$. For example, in the Belen subbasin, the Jeter fault dips 15° – 30° . In the hanging wall of the Jeter fault, multiple branches of the Silver Creek fault are exposed that dip 24° and 48° in the direction towards the basin center (Read et al., 2007). All other intrabasinal faults dip greater than 50° . Seismic images show an overall listric shape to rift faults (Russell and Snelson, 1994) such that overall extension geometry includes both low-angle and high-angle normal faults, often with high-angle faults offsetting older, low-angle normal faults.

Apatite fission-track (AFT) and apatite (U-Th)/He (AHe) thermochronologic data for both the Sandia uplift and Sierra Ladrones place important constraints on the timing of main fault activity in each part of the basin. In the Sandia uplift, thermal history models in the footwall of the high-angle Rincon fault that incorporate both AFT and AHe data suggest that this range was exhumed to near-surface temperatures from 12 to 20 Ma (House et al., 2003). In the Sierra Ladrones, AFT and AHe data has been collected from the footwall of the Jeter fault (Kelley et al., 1992; Ricketts et al., 2015a) and from the fault sliver between the Jeter and Silver Creek faults (Ricketts et al., 2015a). Thermal history models derived from these data indicate that the footwall of the Jeter fault was rapidly exhumed towards the surface during a major pulse from 10-20 Ma (Fig. 2, see also Color Plate 13). In contrast, the fault sliver that represents the immediate hanging wall of the Jeter fault and the footwall of the Silver Creek fault records two separate times of cooling. Initial cooling occurred from ca. 80–60 Ma, where it then resided at temperatures of approximately 80°C, followed by a final period of cooling from 5 to 10 Ma (Ricketts et al., 2015a). In both the northern and southern parts of the basin, intrabasinal high-angle faults typically record Quaternary displacement (U.S. Geological Survey and New Mexico Bureau of Geology and Mineral Resources, 2006). Although it is difficult to determine when these faults became active, combining all available timing information suggests that early-formed LANFs are restricted to the Sandia uplift and the Sierra Ladrones. These faults were at some point abandoned, and faulting then migrated basinward.

These observations from the Albuquerque Basin lead to application of the rolling-hinge model where isostatic uplift in regions of maximum extension is a primary driving force to rotate faults to a shallow angle (Spencer, 1984; Buck, 1988; Wernicke and Axen, 1988; Axen and Bartley, 1997). Isostatic uplift has previously been proposed for the Sandia uplift (May et al., 1994; Roy et al., 1999) as well as the Sierra Ladrones (Wernicke and Axen, 1988; Lewis and Baldrige, 1994). Ricketts et al. (2015a) expanded upon these models by integrating fault geometries, constraints on the timing of faulting, and detailed subsurface models of the Albuquerque Basin from multiple geophysical methods (Grauch and Connell, 2013); they suggested that a rolling-hinge mechanism explains all of these datasets (Fig. 2). In this conceptual model, initial extension in the Albuquerque Basin was localized within the Sandia Mountains and Sierra Ladrones and was accommodated by slip along high-angle faults. As faulting continued, early-formed faults (Jeter and Knife Edge fault) began to rotate to shallower angles because of isostatic uplift as faulting migrated basinward. The rolling-hinge model has been widely applied to explain the formation of metamorphic core complexes in the Basin and Range Province (e.g., Spencer, 1984; Buck, 1988; Wernicke and Axen, 1988), and this process also operated in the Rio Grande rift (Ricketts et al., 2015a). The main difference between the two regions, however, is that fully-developed metamorphic core complexes of the Basin and Range province accumulated enough slip to expose ductilely deformed rocks in their footwall at the Earth's surface, whereas fault rocks exposed in the Rio Grande rift appear

entirely brittle at exposed crustal levels. Therefore, although the process by which the lithosphere is extending appears to be similar in both regions, the magnitude of extension is different. If extension had continued in the rift, ductile rocks would have been eventually brought to the surface to form a mature metamorphic core complex.

FARALLON SLAB BREAK TO TRIGGER EXTENSION IN THE RIFT

Initial extension likely began 36-37 Ma (Kelley and Chamberlain, 2012), but early extension was relatively minor. The main phase of extension began approximately 25 Ma (Ricketts et al., 2015b) and continues with slow strain rates today (Berglund et al., 2012). Rio Grande rifting followed lithospheric shortening during the Laramide orogeny and large-volume eruption of volcanic rocks during the Oligocene ignimbrite flare-up. Although the Rio Grande rift remains one of the best-studied continental rifts of the world, there is still no consensus on why it formed where and when it did.

Several models have been proposed to explain extension in the Rio Grande rift; these include geometric and kinematic models that explain extensional movements and geodynamic models that attempt to explain stresses from within the North American lithosphere and/or the underlying asthenospheric mantle. Geometric models sometimes posit pre-existing zones of weakness that may have been prone to reactivation (e.g., Karlstrom and Humphreys, 1998). Kinematic models include translation and/or clockwise rotation of the Colorado Plateau (Hamilton, 1981; Karlstrom and Daniels, 1993; Chapin and Cather, 1994; Landman and Flowers, 2012), but these do not attempt to explain the forces that resulted in deformation.

Models invoking stresses sourced from the North American lithosphere include collapse of overthickened crust following the Laramide orogeny (Cordell, 1978; Eaton, 1986) and removal of far field plate margin compressive stress due to development of the San Andreas transform (e.g., Dickinson, 2002, 2009). Alternatively, some models call upon deeper-seated forces that originate within the mantle beneath North America and include whole-mantle convection beneath western North America (Moucha et al., 2008) and small-scale mantle convection adjacent to the thick lithospheric keel beneath the Great Plains (van Wijk et al., 2008).

These various models are not all mutually exclusive, but neither can they all be first order controls. Our interpretation is that the Rio Grande rift, although it is a northern expression of Basin and Range extension, is a unique feature of the Cordilleran orogeny. Thus, models of the evolution of the Rio Grande rift should be rooted within the overall Cenozoic tectonic and magmatic history of western North America, including Laramide shortening and the widespread Oligocene “ignimbrite flare-up” (Coney and Reynolds, 1977; Lawton and McMillan, 1999; Chapin et al., 2004).

In order to evaluate the various models proposed to explain extension in the Rio Grande rift, Ricketts et al. (2015b) collected 147 new apatite (U-Th)/He (AHe) ages from Rio Grande rift flank uplifts in Colorado and New Mexico. They combined

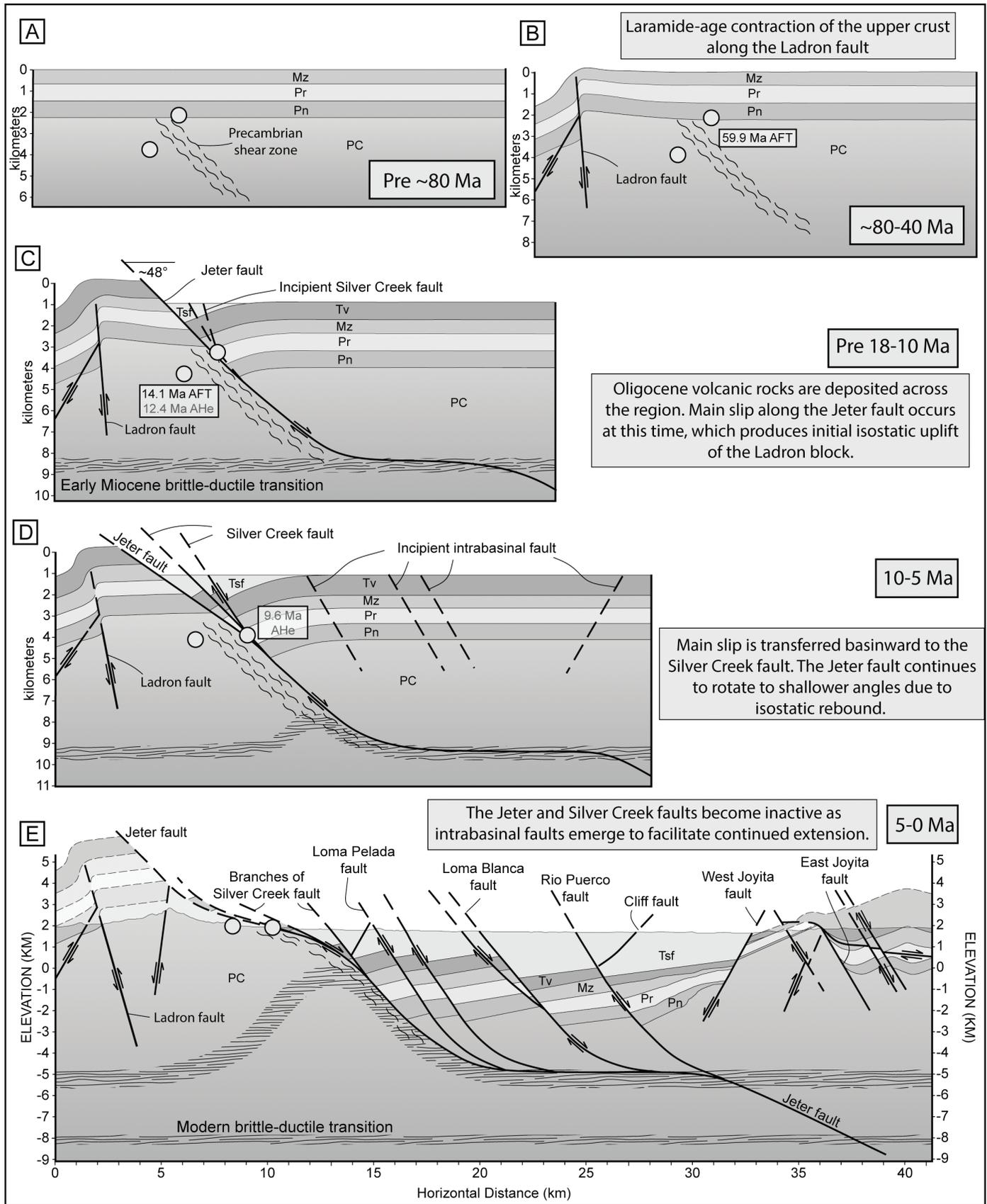


FIGURE 2. Evolution of the Jeter fault system of the southern Albuquerque Basin from ca. 80-0 Ma. Circles are apatite fission-track (AFT) and (U-Th)/He (AHe) sample locations. Mz – Mesozoic; PC – Precambrian; Pr – Permian; Pn – Pennsylvanian; TsF – Tertiary Santa Fe Group; Tv – Tertiary volcanic and volcaniclastic rocks. Modified from Ricketts et al. (2015a). Color Plate 13 is a color version of this diagram.

these data with existing AFT data (Kelley et al., 1992; Kelley and Chapin, 1997) and modeled them together to produce joint AFT-AHe inverse thermal history models of many of the rift flank uplifts. Ricketts et al. (2015b) combined these thermal history models with existing AHe data in the Gore Range of northern Colorado (Landman and Flowers, 2012) and the Sierra Ladrones of central New Mexico (Ricketts et al., 2015a), as well as with previous efforts to combine both systems in the Sandia Mountains (House et al., 2003) to provide first-order constraints on possible mechanisms that may have driven continental extension in the narrow north-south-trending region of the Rio Grande rift.

Thermochronologic results indicate that, although each of the various rift flank uplifts preserves its own geologic history, a main phase of synchronous rapid extension along the length of the rift from northern Colorado to southern New Mexico is recorded from 10 to 25 Ma (Ricketts et al., 2015b). Ricketts et al. (2015b) used these results to evaluate previously proposed mechanisms to explain rifting. Important observations that need to be explained by any model include the >1000 km length of the rift, its narrow north-south-trending location, how rifting was related to previous tectonomagmatic events, mantle tomography (West et al., 2004; Schmandt and Humphreys, 2010; Hansen et al., 2013; MacCarthy et al., 2014; Schmandt and Lin, 2014), and data on simultaneous north-south opening (Landman and Flowers, 2012; Ricketts et al., 2015a, b) rather than north-propagating extension (e.g., McMillan et al., 2002; Leonard, 2002; Heller et al., 2003).

Ricketts et al. (2015b) proposed a geodynamic model involving upper mantle forces that originate from multistage foundering and rollback of a segment of the Farallon Plate following the Laramide orogeny. In this model, the shallowly-subducting Farallon plate conformed to variations in thickness of the mantle lithosphere of the North American plate that had thicker keels now represented by the Wyoming high velocity anomaly and the southeast New Mexico “Artesia” high velocity anomaly. Lateral ramps or tears in Farallon slab dip eventually may have become unstable after Laramide contraction ceased, and may have formed the first windows for upwelling asthenosphere to interact with the overlying North American lithosphere. This concentration of upwelling asthenospheric material focused initial magmatism and volcanism, and it resulted in the development of the large-volume San Juan and Mogollon-Datil volcanic fields from ca. 20-40 Ma (Fig. 3; e.g., Colucci et al., 1991; McIntosh et al., 1992; Lipman, 2007). Then, by ca. 25-30 Ma, the remaining parts of the Farallon slab detached from beneath central New Mexico, as documented in deep tomographic images of the sinking Farallon slab (van der Lee and Nolet, 1997; Sigloch et al., 2008; Schmandt and Humphreys, 2010; Sigloch, 2011; Porritt et al., 2013). This event may have focused asthenospheric upwelling along a north-south trend from central Colorado to southern New Mexico. Upwelling asthenosphere then critically weakened the overlying North American lithosphere over the next several million years so that by ca. 25 Ma the entire length of the rift was extending synchronously over > 850 km of its length (Ricketts et al., 2015b).

This model, therefore, takes advantage of previous work

that suggests patchy and incomplete removal of the Farallon plate (e.g., Atwater, 1989; Chapin et al., 2004; Schmandt and Humphreys, 2010) coupled with a major late Oligocene slab break that produced the necessary forces to drive synchronous extension in the rift from 10 to 25 Ma (Ricketts et al., 2015b). It is compatible with, and could have interacted with, pre-existing zones of lithospheric weakness, extensional stresses from topographic gravitational potential energy, rotation of a Colorado Plateau microplate, and change in far field stresses at the plate margin.

CONCLUSIONS

Two case studies are presented to highlight various processes that operated during continental extension. First, it appears that the Rio Grande rift is similar to the adjacent Basin and Range Province in that isostatic footwall rebound is a major process controlling the geometry of fault networks. In the Albuquerque Basin, this process can help explain various fault dips, timing of faulting, and the existence of low-angle normal faults in regions of maximum extension (Ricketts et al., 2015a). This region, therefore, represents a snapshot into the early stages in the development of extended terranes that could evolve into mature metamorphic core complexes. Second, Ricketts et al. (2015b) used timing constraints on extension in rift flank uplifts in Colorado and New Mexico to evaluate existing models for formation of the rift. None of the models seem to satisfactorily explain near synchronous extension along the >1000 km length of the rift at 10-25 Ma, while also relating rift extension to previous tectonic and magmatic events associated with the Laramide orogeny and the Oligocene ignimbrite flare-up. The model presented here and by Ricketts et al. (2015b) calls upon forces originating within the upper mantle following the Laramide orogeny. In this model, a north-south-trending break in part of the Farallon plate at ca. 25-30 Ma focused asthenospheric upwelling along a narrow zone, which critically weakened the North American lithosphere and resulted in rapid exhumation of rift flanks through extension from 10 to 25 Ma. These two processes may have been significantly important in the evolution of the Rio Grande rift, and they may shed light onto general mechanisms that control the style of continental extension in other rifts of the world as well.

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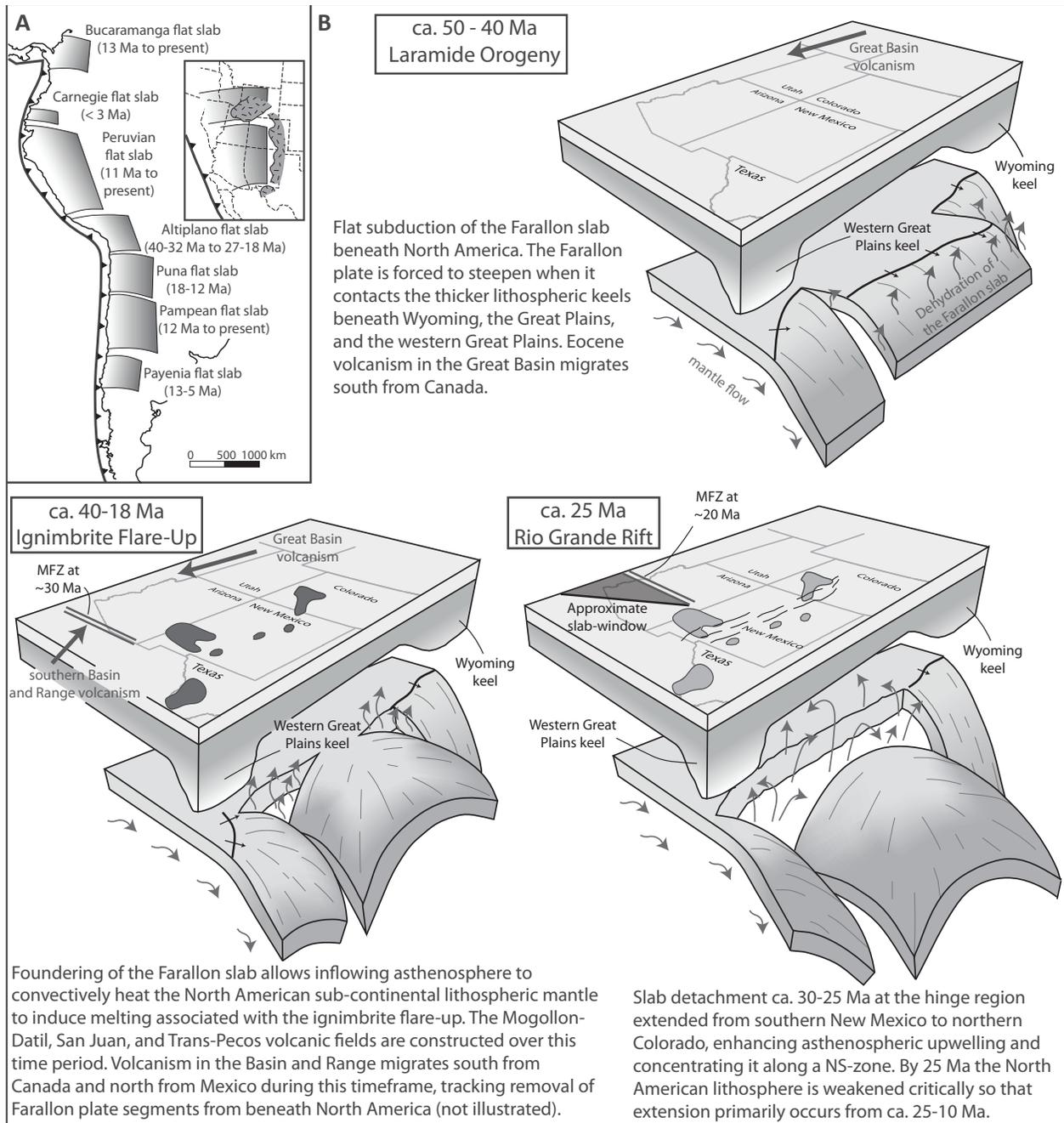


FIGURE 3. **A**) Flat slabs of the South American subduction zone compared to flat subduction of the Farallon slab. **B**) Proposed tearing and foundering of a section of the Farallon slab beneath Colorado and New Mexico and subsequent development of large-volume volcanic fields and the Rio Grande rift. MFZ – Mendocino fracture zone. Modified from Ricketts et al. (2015b).

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