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U-PB MONAZITE AND ^{40}AR/^{39}AR DATA SUPPORTING POLYPHASE TECTONISM IN THE MANZANO MOUNTAINS: A RECORD OF BOTH THE MAZATZAL (1.66-1.60 GA) AND PICURIS (1.45 GA) OROGENIES

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Abstract—Proterozoic basement rocks of the Sandia-Manzano-Los Pinos Mountains record two phases of plutonism, at 1.66-1.65 Ga and 1.46-1.45 Ga. These episodes correspond to two episodes of pluton-enhanced regional metamorphism and deformation that collectively resulted in the development of top-to-the-north thrust sense shear zones referred to as the Manzano thrust belt. U-Pb monazite ages indicates that prograde aureole metamorphism took place at ~1.68-1.66 Ga and again at 1.45 Ga, and both are tied to regional fabric-forming episodes. ^{40}Ar/^{39}Ar dating of muscovite reveals a variable 1.45 Ga thermal overprint. "Cold blocks" (at 1.45 Ga) were not heated above 375°C at 1.45 Ga; they have muscovite ages of ~1.66 Ga and record cooling of 1.65 Ga pluton aureoles through 350-400°C shortly after pluton emplacement. "Hot" blocks are in thrust sheets containing 1.45 Ga plutons and these record more extensive 1.45 Ga monazite rim growth and muscovite cooling ages of 1.44-1.42 Ga. The presence of sillimanite and andalusite in contact aureoles of 1.65 Ga and 1.45 Ga plutons suggests both were emplaced at 2-4 kbar middle crustal depths. This area does not contain 1.5 Ga rocks correlative with the Trampas Group. The 1.60-1.50 Ga "tectonic gap" in magmatism and metamorphism in New Mexico is best explained by a 100-million-year period of erosion following the 1.65-1.60 Ga Mazatzal orogeny. Plate tectonic models to explain these and other regional data require two orogenic pulses: the 1.65-1.60 Ga Mazatzal orogeny and 1.45-1.35 Ga Picuris orogeny. Total observed strain reflects shortening that occurred during both events. The Picuris orogeny resulted in formation of the Monte Largo and other thrust-sense shear zones in New Mexico. Additional studies are needed to parse the metamorphic and deformational products of each event across New Mexico.

INTRODUCTION

The Proterozoic orogenic system of southern Laurentia has emerged as a type example of accretionary orogenesis and continental growth. The wide Proterozoic orogenic belts evolved through numerous stages by addition of juvenile as well as continental material that ultimately adding more than 1000 km of new continental lithosphere to southern Laurentia (Karlstrom and Bowring 1988; Karlstrom et al., 2001; Whitmeyer and Karlstrom, 2007). This paper focuses on the 1.7-1.6 Ga Mazatzal province of central New Mexico, including calc-alkaline granitic plutons as well as thick quartzite-rhyolite sequences (Jones et al., 2011; Doe et al., 2012; 2013) and their subsequent deformation and metamorphism.

Several characteristics of the Proterozoic orogenic history of New Mexico remain as uncertainties in (or challenges to) the regional accretionary orogen model. First, the proposed age boundary between the 1.8-1.7 Ga Yavapai province and the 1.7-1.6 Ga Mazatzal province has recently been re-examined by U-Pb and hafnium isotopic analyses of plutonic zircons that show it is a transitional boundary and that some areas of the 1.7-1.6 Ga Mazatzal province are underlain by older, Yavapai-age, crust (Grambling et al., 2015). Second, the recent recognition of deformed and metamorphosed sedimentary rocks of the early Mesoproterozoic Trampas Group (1.50-1.45 Ga) within the Picuris Mountains of New Mexico and the Mazatzal Province of Arizona has led to controversy and uncertainty about the tectonic history of this region. The Trampas Group (Pilar and Piedra Lumbre formations) of New Mexico (Jones et al., 2009, 2011; 2015; Jones and Thrane, 2012, Daniel et al., 2013), and correlatives quartzites of the Defiance uplift (Doe et al., 2013), and Arizona (Doe et al., 2012, Mako et al., 2015) that were previously thought to be >1.65 Ga are now known to have been deposited after 1.50 Ga. This indicates unroofing of earlier basement to the surface by 1.5 Ga. Penetrative deformational fabrics in these younger successions record post-1.45 Ga middle crustal deformation and metamorphism (e.g., Williams et al., 1999; Shaw et al., 2005; Daniels et al., 2013). Thus, at least some of the total strain observed in New Mexico basement rocks formed during the ca. 1.45 Ga Picuris orogeny (Daniel et al., 2013). At one extreme, this has led to questions about the very existence of the Mazatzal orogeny, and a favored model (model 4 of Daniel et al., 2013) proposed that the Mazatzal province was accreted to Laurentia as an exotic terrane after 1.46 Ga. A contrasting model is that 1.45 Ga Picuris orogenesis involved intracratonic reactivation of the Mazatzal province that had been previously accreted to North America during the Mazatzal orogeny (Karlstrom et al., 2004; Whitmeyer and Karlstrom 2007; Bickford et al., 2015).

The Sandia-Manzano-Los Pinos (SML) uplift forms the east rift flank of the Albuquerque basin and provides excellent Proterozoic basement exposures of the 1.67-1.60 Ga Manzano Group and the Manzano thrust belt of the Mazatzal province (Karlstrom et al., 2004). This transect has been postulated to contain both 1.45 Ga and also older fabrics (Thompson et al., 1996). The goal of this paper is to summarize aspects of the age and character of the metavolcanic and metasedimentary succession, present new monazite and $^{40}Ar/^{39}Ar$ data that support a polyphase deformational and metamorphic history, and examine conflicting plate tectonic models for the Proterozoic orogenic history of New Mexico.

METHODS

In-situ monazite dating of deformation and metamorphism offers a powerful method for characterizing multistage tectonic histories (Williams and Jercinovic, 2002; Williams et al., 2006; Dumond et al., 2008; 2015). The major steps in the monazite analytical method involve: (1) full thin-section mapping to locate all accessory phases; (2) high-resolution compositional mapping of monazite (and xenotime); (3) integration of high-resolution maps with full-section maps to allow relative timing of monazite-forming reactions to be interpreted with respect to structural and petrologic context; and (4) U-Pb "total-Pb" dating using the Ultrachron microprobe at the University of Massachusetts. This method does not measure the different U, Th, and Pb isotopes, but instead assumes all Pb is radiogenic, i.e. derived from decay of U and Th during the time since growth of the parent monazite grain (or domain) with assumed $^{235}U/^{238}U$ ratios based on measured elemental concentrations.

Background is characterized first using the "Multipoint" measurement method (Allaz et al., 2011, 2016). This involves measuring background at four or more spectrometer positions (wavelengths) on the high and low side of the peak, and then using Savitsky-Golay regression to determine the background value at the peak position. Peak measurements are made near the background measurement location, all within the domain of interest, until the uncertainty stabilizes (typically 5-10 measurements). The current monazite analysis involves analysis of 25 elements (major, trace, REE) and correction for ~50 spectral interferences. All of these analyses are combined to produce one "date" for the domain of interest.

$^{40}Ar/^{39}Ar$ thermochronology studies focus on the cooling history of basement terranes. Samples are step heated to incrementally release (and date) Ar gas to establish age plateaus or cooling spectra. Such studies in New Mexico have used $^{40}Ar/^{39}Ar$ analyses to date multiple potassium-bearing minerals (hornblende, muscovite, biotite and K-spar) to develop cooling histories from ~550 to 200°C (e.g., Karlstrom et al., 1997; Heizler et al. 1997; Shaw et al., 2005; Amato et al., 2008; 2011; Gaston, 2014). These studies have documented regionally pervasive, but spatially variable, metamorphism in the interval 1.46-1.35 Ga with peak temperatures that ranged from <300°C to >600°C, and they have revealed some regions where the 1.45 Ga thermal regime was cool enough that 1.65 Ga cooling histories are preserved. Understanding this variable metamorphic history offers clues to understanding the timing of cooling episodes; for example, as driven by punctuated post-orogenic erosion or extensional denudation, versus slow cooling during long-term middle crustal residence or progressive erosional unroofing (Heizler et al., 1997).

REGIONAL CROSS SECTION

Figure 1 (Color Plate 12) is a schematic N-S cross section of the Sandia–Manzano-Los Pino uplift from the southern Sandia Mountains to the Priest pluton near Abo Pass (Plate 4). The cross section shows the Manzano Group (metamorphosed sedimentary and volcanic rocks) and plutons, as well as the major shear zones that make up the Manzano thrust belt. The lower volcanic section has yielded U-Pb ages as old as 1700±20 Ma in the Monte Largo Hills (Karlstrom et al., 2004) and in monazite cores in the northern Manzano Mountains (Fig. 1). It includes the Sevilleta Rhyolite which was dated at 1662±1 Ma (Shastri, 1993). This "greenstone" succession is more mafic near its base, has interbedded rhyolites, and includes interbedded metasedimentary rocks that transition from immature arenites to increasingly mature quartzite up-section. The clean quartzite is overlain by the Blue Springs schist and an upper rhyolite dated as 1601±4 Ma in the uppermost exposed part of the section. No rocks of ~1.5 Ga age that would correlate with the Trampas Group (Daniel et al., 2013) are exposed in the Manzano Mountains and it is not known if they were deposited in this region.

Granodiorites (1.66-1.65 Ga; Grambling et al., this volume) intrude as high in the section as the Blue Springs schist. The plutons are tens of millions of years younger than the Manzano Group volcanic rocks that they intrude and are the same age as each other, within error. They are variably foliated and have incompletely preserved metamorphic aureoles that locally contain andalusite and sillimanite (Grambling et al., this volume; Holland et al., this volume). The calc-alkaline and mafic character of these plutons suggests a subduction-related magmatic arc, and the contemporaneous bimodal volcanic rocks suggest a magmatic arc setting.

The 1.6-1.5 Ga "tectonic gap" (Karlstrom et al., 2004) was a time with no known magmatism, deformation or metamorphism in New Mexico. Regionally, this gap exists across much of southern Laurentia such that the 1.6-1.5 Ga zircons found in the Trampas Group and correlatives are hypothesized to have been derived from an outboard continent (possibly Australia) and transported onto Laurentia by continental-scale rivers (Doe et al. 2012; 2013). This was a time of tectonic quiescence within what was otherwise a nearly 800 Ma continuum of progressive tectonism from 1.8 to 1.0 Ga in southern Laurentia that has been interpreted as a record of a long-lived Cordilleran style convergent margin (Karlstrom et al., 2001). Thus, for plate tectonic models, this suggests that the New Mexico region may have been distant from any convergent plate margin and possibly undergoing erosional unroofing between between 1.6 and 1.5 Ga to explain the tectonic gap.

Two 1.46-1.45 Ga plutons are present in the cross section, the 1.45 Ga Sandia pluton and the 1.45 Ga Priest pluton. Both

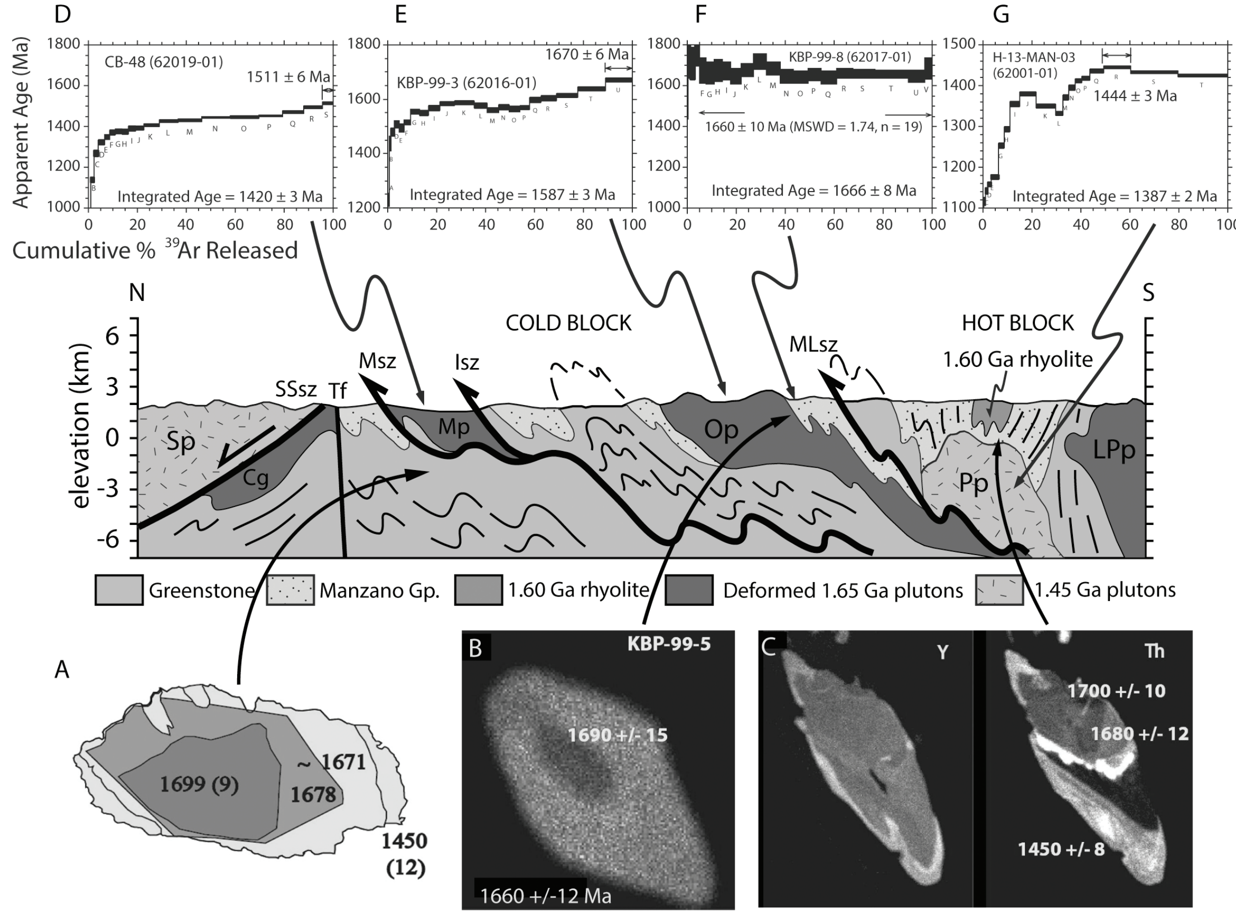

FIGURE 1. Generalized N-S cross section of the Manzano Mountains (Manzano thrust belt), NM (1B). Sp = Sandia pluton, SSsz = Seven Springs shear zone, Tf = Tijeras fault, Msz = Manzanita shear zone, Isz = Isleta shear zone, Op = Ojito pluton, MLsz = Monte Largo shear zone, Pp = Priest pluton, LPp = Los Pinos pluton. **A – C**) are selected U-Pb microprobe ages and compositional images of monazites. **D – G**) show Ar-Ar spectra of muscovite; hot blocks were 400-600°C at 1.45 Ga; cold blocks were < 400°C at 1.45 Ga and record cooling through 400°C at 1.65 Ga. See also Color Pate 12.

have well-developed metamorphic aureoles containing two or three alumino silicates and syn-plutonic ductile deformation. However, the plutons are internally undeformed except for local magmatic fabrics consisting of aligned feldspar megacrysts and aligned enclaves. The enclaves consist of mafic igneous rocks (diorites) that have textures suggestive of co-mingled magmas. Xenoliths of foliated country rocks are also present in both plutons, documenting pre-pluton regional deformation.

All of the shear zones shown in Figure 1 are ductile shear zones that record top-to-the-north displacement. The Seven Springs shear zone exposed near Tijeras Canyon dips north under the Sandia pluton and also deforms the 1.65 Ga Cibola granite. It may be an extensional shear zone that facilitated emplacement of the Sandia pluton (Kirby et al., 1995) and/or a folded top-north earlier thrust continuation of the Manzanita shear zone. The Manzanita and Isleta shear zones are high-strain domains adjacent to NW and SE margins of the syntectonic 1.65 Ga Manzanita pluton which shows top-north thrust sense shearing throughout (Brown et al., 1999). The Monte Largo shear zone separates rocks with amphibolite grade 1.4 Ga metamorphism and deformation to the south from rocks with 1.65 Ga greenschist-grade fabrics to the north (Thompson et al., 1996).

RESULTS OF U-PB MONAZITE DATING

In-situ monazite dating was applied to rocks in several of the thrust sheets to constrain the time of peak metamorphism(s) and to relate mineral growth to deformational fabrics. Figure 1A shows monazite from the 1.65 Ga Manzanita pluton. The 1699 Ma core is interpreted to be an inherited monazite. The 1670 Ma rim is a bit older than, but within error of the 1.65 Ga crystallization age, and is interpreted to record pluton crystallization. The asymmetry of rim growth is interpreted to reflect strain shadows during fabric formation. The 1450 Ma rim is interpreted to reflect dissolution and re-growth of monazite during 1.45 Ga regional metamorphism and renewed fabric intensification in the Manzanita pluton.

Figure 1B is a monazite from the southern aureole of the 1.66 Ga Ojito pluton. Monazite cores yield an age of 1690±15 which may be the age of volcanic rocks of the aureole. The 1,660±12 Ma rim is interpreted to record peak aureole metamorphism during pluton emplacement. The foliation-parallel rim growth is interpreted to record folding and foliation development during prograde metamorphism in this sample.

Figure 1C is from the aureole of the 1.45 Ga Priest pluton south of the Monte Largo shear zone. This monazite grain shows 1.70-1.68 Ga detrital cores overgrown by a 1450±18 Ma monazite overgrowth. The rim age of this grain is the same as the zircon age of the pluton and is interpreted to record the time of pluton emplacement and aureole deformation around the Priest pluton.

RESULTS OF ^{40}AR-^{39}AR DATING

^{40}Ar/^{39}Ar step-heating analyses were applied to muscovite in the same thrust sheets as the monazite dating to investigate the time of cooling of these regions to below 350-400°C after the metamorphic events recorded by the monazite growth. Figure 1D (CB-48) is a muscovite spectrum from the Manzanita pluton and is characterized by a strong age gradient with a terminal age near 1511±6 Ma, then progressively lower step ages that yield an integrated age of 1420 Ma. This spectrum indicates that these rocks were above 400°C at 1.5 Ga during the time that deposition of the Trampas Group was taking place in the Picuris Mountains to the north, or that reheating at 1.45 Ga partially reset older muscovite.

Figure 1E shows spectra from muscovite from the southern Ojito pluton and its aureole. It yields a preferred age of 1670±6 Ma that analytically overlaps the intrusive age within uncertainty. Sample 1F is a coarse muscovite (KBP-99-8) collected within the metamorphic contact aureole of the Ojito granite; it has a flat age spectrum and a preferred age of 1660±10 Ma. These preserved Paleoproterozoic ages suggest that this part of the Manzano Mountains could not have been significantly heated above about 375°C during 1.45 Ga magmatism and metamorphism associated with the Picuris orogeny.

Figure 1G shows an Ar-Ar spectrum from coarse muscovite from the Priest pluton. The spectrum is saddle shaped suggesting individual grains likely have variable argon closure temperatures. However, the 1444±3 Ma preferred age of the highest temperature step is concordant with the 1456±13 Ma preferred ICPMS U-Pb zircon age and similar to the older 1427±10 Ma U/Pb TIMS zircon age (see Holland et al., this volume). Heizler et al. (1997) found flat age spectra for muscovite from undeformed pegmatites in the Manzano Mountains with plateau ages of ca. 1400 Ma. They were interpreted as recording the time of cooling through ~350°C nearly 30 Ma after emplacement of the Priest pluton. However, recalculation of the Heizler et al. (1997) results to the age of Fish Canyon tuff sanidine (28.201 Ma) and the decay constants of Min et al. (2000) change the 1400 Ma age to 1419 Ma (Gaston, 2014). Thus, sample 1G, as well as the pegmatite samples of Heizler et al. (1997), indicate that rocks cooled through ~ 350°C closely following magma emplacement. This suggests a country rock temperature that compatible with an emplacement depth of approximately 10-12 km for the Priest pluton. Heizler et al. (1997) and Marcoline et al. (1999) both found substantial age gradients in deformed muscovite of the Manzano Mountains and it is possible that some of the disturbed age spectra shown here are also the result of mica deformation that can reduce the effective diffusion radius compared to large undeformed pegmatite crystals. Overall, thermochronology data from the Manzano Mountains and Sandia Mountains are very similar indicating that these two locations share similar plutonic and pegmatite emplacement histories.

PLATE TECTONIC MODELS

The data presented above do not support the hypothesis that there was no Mazatzal orogeny and demonstrate the need to better distinguish two events, the 1.7-1.6 Ga Mazatzal orogeny and the 1.45-1.35 Ga Picuris orogeny. Both events need to be incorporated into refined plate tectonic models for accretion of southern Laurentia.

Figure 2 shows the favored plate tectonic model proposed by Daniel et al. (2013) to explain the newly discovered 1.5-1.45 Ga basins in New Mexico. Figure 2A postulates a miogeocline on a rifted Yavapai margin that then transitioned to a foreland basin during the 1.45 Ga Picuris orogeny, which was driven by docking of an offshore Mazatzal microcontinent. Figure 2B depicts the post-Picuris orogeny deformational geometry, with the dashed line added by us as the modern 10-15 km isobaric crustal level exposed in New Mexico (Williams and Karlstrom, 1997) and also showing the Manzano thrust belt and deep crustal seismic interpretation of a bivergent root zone of the Mazatzal orogeny located beneath the Jemez lineament (Magnani et al., 2004).

Problems with this model are as follows. (1) The Trampas Group is very thin in Figure 2A (hundreds of meters) compared to passive margin successions (up to ten km), and the Hondo Group may be much older (1.68 Ga according to Kopera, 2003) suggesting the possibility of two times of sediment accumulation in this basin. (2) The model would predict subduction-related (calc-alkaline) granodiorites of 1.5-1.46 Ga only in the upper plate of the subduction zone in Figure 2A but, instead, both sides of the proposed subduction system have similar ~1.45 Ga plutons that are A-type (non-subduction related) granites and that perforate both Yavapai and Mazatzal province rocks. (3) The model for subduction- related closing of an ocean basin prior to 1.5 Ga in Figure 2A does not seem compatible with the observed lack of 1.6-1.5 Ga tectonism during the 1.6-1.5 Ga tectonic gap in New Mexico which would have been recorded in the over-riding plate. (4) There is no paired metamorphic belt and no contrast in P-T evolution between the proposed over-riding plate and down-going slab, but rather similar isobaric 3.5 kbar 1.45 Ga peak metamorphism (Figure 2B; Williams and Karlstrom, 1997), similar post-1.45 Ga cooling histories across the proposed suture (Shaw et al., 2005), and similar NE-trending subvertical fabrics. (5) The top-to-the-north Manzano thrust belt is shown as disconnected from the suture zone with no apparent explanation for this shortening whereas scales are relatively short between the Manzano and Picuris Mountains (<150 km) and hence we view the Spring Creek (Davis et al., 2011), Plomo (Daniel et al., 2013), Silver Creek (Davis et al., 2011), and Monte Largo shear zones (Thompson et al., 1996) as all part of the same ~1.45 Ga contractional deformation system. Orogenic wedging and bivergent thrusting (Magnani et al. 2004) may have taken place at

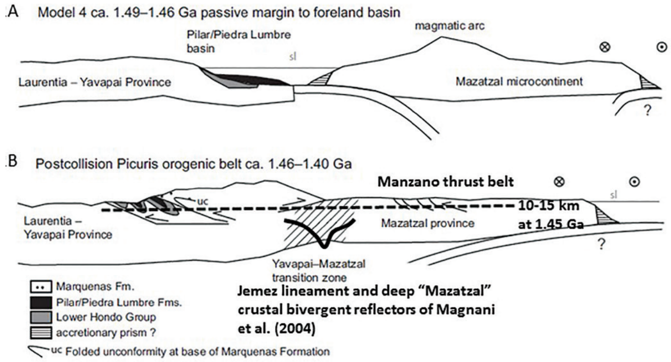

FIGURE 2. **A**) Plate tectonic model (model 4 of Daniel et al., 2013) that postulates that the 1.5-1.45 Ga Trampas Group was deposited in a miogeocline on a rifted Yavapai margin that then transitioned to a foreland basin during the 1.45 Ga Picuris orogeny. In this model, the Picuris orogeny was driven by docking of an offshore Mazatzal microcontinent. **B**) Postcollision development of Mesoproterozoic fold and thrust belt across northern New Mexico, resulting in basin closure, deformation, and regional metamorphism of the Trampas Group (Pilar, Piedra Lumbre, and Marqueñas Formations) as well as older Paleoproterozoic rocks. sl = sea level, dashed black line = 10-15 km depth of isobaric 1.45 Ga metamorphism (Williams et al., 1999). Deep crustal lines show postulated bivergent root zone of the Mazatzal orogen from Magnani et al. (2004). Final crustal cross section shows strain from the combined 1.65 and 1.45 Ga orogenies.

deep crustal levels but with the exception of the Cimarron area (Pedrick et al., 1998; Read et al., 1999) middle crustal levels seem to record top-north vergence.

An alternative plate tectonic model is shown in Figure 3 (Color Plate 5). This adds an older 1.65 Ga timeslice that is needed to depict the entire 300 Ma orogenic history under debate. This model explains 1.66 Ga volcanic rocks and granodiorite plutons in the Manzano Mountains as parts of a single continental arc built across Yavapai as well as juvenile 1.65 Ga Mazatzal crust. It explains the 1.6-1.5 Ga tectonic gap as a time of progressive erosion of the Mazatzal orogenic system that accompanied a change from a subduction to a transform margin far to the south, and/or as a flip in subduction polarity from 1.6-1.5 Ga. The 1.5-1.45 Ga Trampas basin, like the previous 1.70-1.60 Ga Hondo basins (Jones et al., 2009), are interpreted to reflect renewed extension in upper plates due to northward subduction and subduction roll back of the subducting plate that can put upper plates of arcs into extension. The Picuris orogeny is attributed to closing of these basins synchronous with accretion of a Granite-Rhyolite province juvenile block to the south (Bickford et al., 2015). Inboard lithosphere delamination at 1.45-1.35 Ga might best explain the extensive A-type granitoids and rhyolites via a basalt underplating (non-subduc-

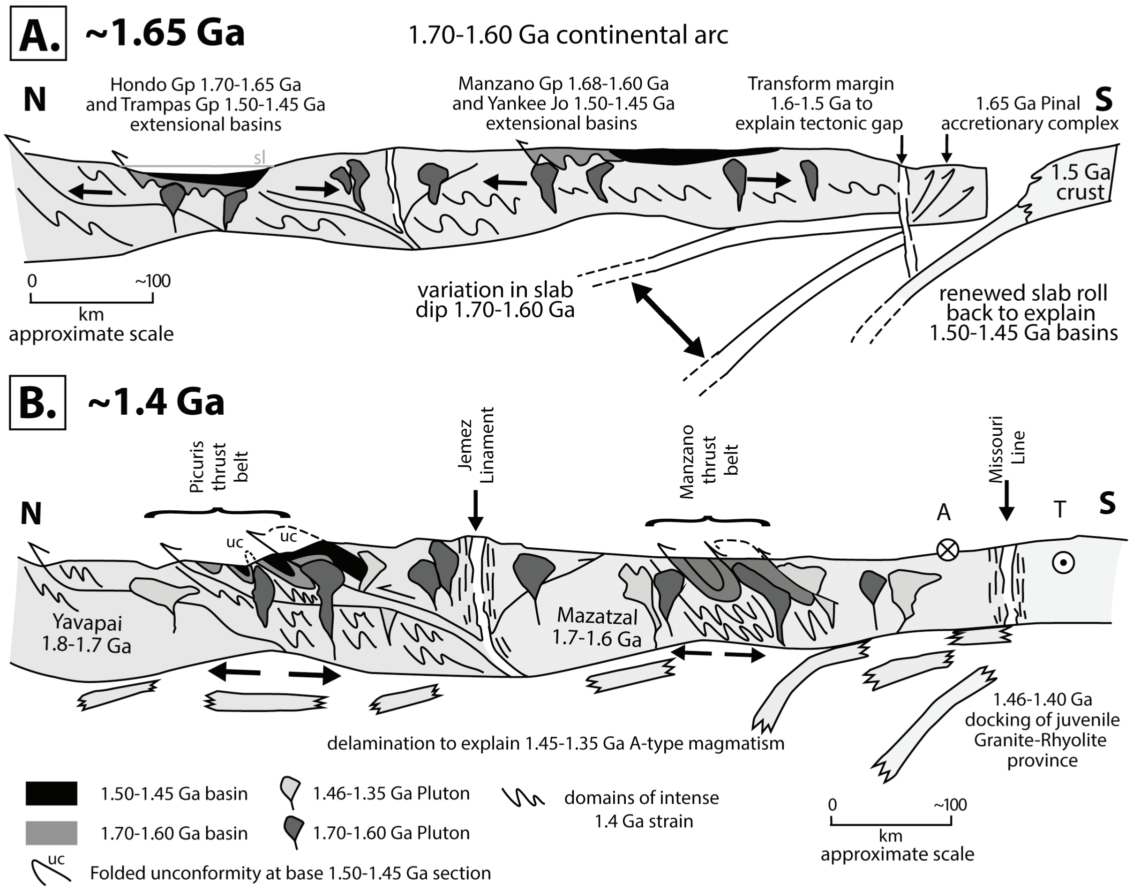

FIGURE 3. Two-stage plate tectonic model. **A**) 1.70-1.60 Ga Mazatzal continental margin arc built atop both pre-1.7 Ga Yavapai and ~1.65 Ga juvenile crust. Variation in subduction slab dip may explain diachronous Hondo and Manzano Group extensional basins (Jones et al., 2009). Transition to transform margin at 1.6 Ga may explain the 1.6-1.5 Ga tectonic gap. Renewed northward subduction 1.5-1.46 Ga may explain intracratonic 1.50-1.45 Ga extensional basins. **B**) Intracratonic orogenic plateau model for Picuris orogeny with renewed shortening caused by convergence of 1.50 Ga crust far to the south (across the Missouri line of Bickford et al., 2015) and 1.46-1.35 Ga A-type magmatism driven by intracratonic lithospheric delamination. See also Color Plate 5.

tion driven) petrogenetic model (Frost and Frost, 1997, 2011; Kay and Kay, 1991).

DISCUSSION AND FUTURE WORK

Additional U-Pb monazite analyses tied to structural/metamorphic studies combined with $^{40}Ar/^{39}Ar$ studies of differential post-1.6 Ga and 1.4 Ga cooling are needed to provide new tests to resolve current controversies and to develop a new template for understanding the Proterozoic assembly of North America. Data presented here for 1.65 Ga and 1.45 Ga pluton aureoles are similar to models published for synchronous ductile deformation and pluton-enhanced metamorphism in Proterozoic rocks of Arizona where amphibolite grade metamorphism took place adjacent to 1.7- 1.67 Ga plutons at ~10 km but overall ambient metamorphism far from plutons was greenschist grade (Williams, 1991; Burr, 1991; Karlstrom and Williams, 1995; Williams and Jercinovik, 2002). This model suggests that structural/ metamorphic (P-T-t) analysis and monazite/zircon dating of plutons and pluton aureoles will be especially useful. Already, such studies have shown that there was an earlier period of metamorphism, perhaps punctuated around plutons at 1.65 Ga. There was also a second pervasive, but spatially variable, metamorphism in the interval 1.46-1.35 Ga with peak temperatures ranging from <300°C to >600°C. Regionally, amphibolite facies "hot blocks" (at 1.45 Ga) tend to alternate with greenschist to lower amphibolite facies "cold blocks" (at 1.45 Ga) both in the Manzano Mountains and across the Southwest (Karlstrom and Bowring, 1988; Ilg et al., 1996; Williams, 1991; Williams et al., 1999; Dumond et al., 2007). In New Mexico, hot blocks are extensive and heavily overprinted by ca 1.45 Ga metamorphism and deformation (Shaw et al., 2005), but blocks that were lower-grade at 1.45 Ga preserve evidence for older (1.65 Ga) plutonism, deformation, and metamorphism. Field work should focus on areas where exposed hot and cold blocks are juxtaposed (e.g., Davis et al., 2011). Our model would predict slow cooling of the 1.65 Ga rocks by erosional denudation over 100 Ma of a continental margin arc or Colorado Plateau-like orogenic plateau, and it can be tested with additional monazite and muscovite multiple diffusion domain (MDD) dating and modeling. The cooling data will be especially powerful when combined with P-T-t studies from aureoles of plutons emplaced before and after the tectonic gap.

The tectonic gap, characterized by a lack of 1.6-1.5 Ga tectonism throughout New Mexico, is best explained by a 100-million-year period of erosion following the Mazatzal orogeny that accompanied a change from a convergent to transform plate boundary to the south, and/or flip of subduction polarity at the south edge of the magmatic arc to the south of New Mexico.

Constraints on the depths of 1.65 Ga and 1.45 Ga plutonism and metamorphism need improvement, but preliminary data from the Manzano Mountains from both monazite and $^{40}Ar/^{39}Ar$ data suggest that the aureoles of the 1.65 Ga Ojito and Manzanita plutons underwent 1.65 Ga penetrative deformation at depths of 2-4 kbars during the Mazatzal orogeny. $^{40}Ar/^{39}Ar$ muscovite data from the northern Manzano Mountains suggest this block was never heated above 350°C during the Picuris orogeny. In contrast, an adjacent hot block shows extensive 1.45 Ga monazite rims on 1.65 monazite cores and resetting of all $^{40}Ar/^{39}Ar$ muscovite ages during the Picuris orogeny. Microstructures link both events with top-north shearing, and we posit a thrust belt that underwent shortening both at 1.65 and 1.45-1.35 Ga. Thus, the unroofing of the ~10-km-deep 1.65 Ga plutons of the region that occurred before deposition of the 1.60 rhyolites was relatively rapid (50 Ma) but overall unroofing of the Mazatzal orogen prior to the deposition of the ~1.5 Ga Yankee Joe Formation (in northern New Mexico and Arizona) was slower (150 Ma). Both were part of the erosional demise of the Mazatzal orogenic belt. Burial of 1.5 Ga Yankee Joe Formation to 10-15 km between 1.5 and 1.45 Ga, by thrust sheets and emplacement of intracratonic plutons at 10-15 km, was relatively fast (tens to 50 Ma) but can readily be explained using rates seen in modern convergent orogenic processes. Unroofing of the Picuris orogeny also seems to have taken tens of millions of years based on $^{40}Ar/^{39}Ar$ cooling data. Thus, all of the proposed stages of the polyphase orogenic system of the Manzano thrust belt took place over 10s-100 Ma durations that are compatible with more modern orogenic systems.

SUMMARY

The relative importance of the Mazatzal (1.7-1.6 Ga) and Picuris (1.45-1.35 Ga) orogenies for assembling southwestern Laurentia is currently undergoing debate and re-evaluation. The details of the 350 Ma (1.75-1.35 Ga) evolution of this orogen are complex (like all orogens), but the debates are resolvable. <u>Was there a Mazatzal orogeny?</u> Our data suggest yes; in areas of low grade 1.45 Ga tectonism we can document the extent of 1.7-1.6 Ga shortening events using monazite and ^{40}Ar-^{39}Ar dating. <u>Did the Mazatzal province dock</u> at 1.65 Ga (Whitmeyer and Karlstrom, 2007) or 1.45 Ga (model 4 of Daniel et al., 2013)? Probably neither, and instead, we propose a continental margin arc model for the Mazatzal province and a long-lived convergent boundary south of present day New Mexico. <u>What drove the Picuris orogeny</u>? We postulate that accretion of 1.5 Ga crust south of New Mexico (i.e. across the Missouri line of Bickford et al., 2015) caused back arc reactivation within older provinces, and that delamination magmatism drove mafic underplating and formation of 1.45 Ga A-type granite plutons.

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