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A three-sided orogen: A new tectonic model for Ancestral Rocky Mountain uplift and basin development

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ABSTRACT

The tectonic origin of the Pennsylvanian–Permian Ancestral Rocky Mountain system is debated. Most models invoke stress from collision along the Ouachita-Marathon belt as the primary driver for Ancestral Rocky Mountain (ARM) (western USA) tectonism, but no existing model has convincingly explained the timing, northeast-southwest contractional kinematics, and amagmatic nature of this system. We propose that stress generated by transpressional deformation along the southwestern (Sonora) margin of Laurentia combined with that from collision along the Ouachita-Marathon and Nevada margins drove uplift and basin development of the ARM. This model explains ARM timing, uplift kinematics, and lack of magmatism, and is supported by a new generation of late Paleozoic global plate reconstructions.

INTRODUCTION

The Ancestral Rocky Mountain (ARM) system developed in an intraplate setting and consists of northwest-southeast–oriented basement-cored uplifts and hydrocarbon-rich basins from Utah and Colorado to Texas (USA; Fig. 1). Uplift of ARM structures began in Early Pennsylvanian time and continued into the early Permian. Deformation was dominated by northeast-southwest–directed reverse slip along steep faults (e.g., Hoy and Ridgway, 2002; Barbeau, 2003), although some strike-slip movement has also been documented (e.g., Budnik, 1986; McConnell, 1989; Marshak et al., 2003). Structural relief of as much as 12 km has been documented on some ARM structures (McConnell, 1989). No evidence exists of ARM-related magmatism.

The tectonic origin of the ARM system remains poorly understood. Various tectonic processes have been invoked to explain the ARM, including foreland stress from closure of the Ouachita-Marathon belt (Kluth and Coney, 1981), left-lateral slip along the Wichita megashear (Budnik, 1986), flat-slab subduction along the southwest (Sonora) Laurentian margin (Ye et al., 1996), reactivation of preexisting basement faults (Marshak et al., 2000), wrenching associated with Ouachita-Marathon closure (Dickinson and Lawton, 2003), and dynamic response of mafic roots beneath ARM uplifts (Soreghan et al., 2012). None of these proposed mechanisms, however, has fully accounted for the orientation, deformation style, and lack of magmatism associated with the ARM system.

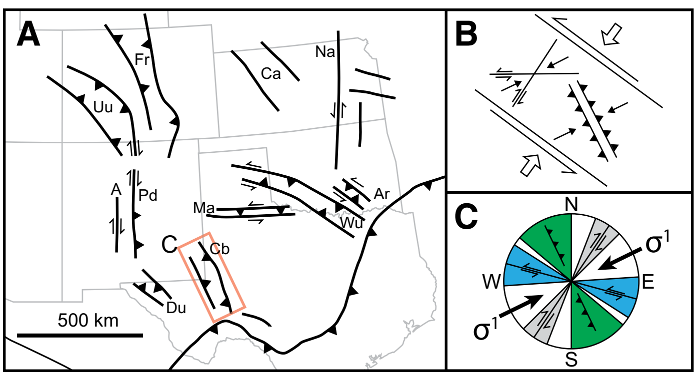

Figure 1. A: Traces of Pennsylvanian–Permian fault systems after Ye et al. (1996) and Marshak et al. (2003). Uu—Uncompahgre uplift; Fr—Front Range uplift; A—Albuquerque fault; Pd—Pedernal uplift; Du—Diablo uplift; Cb—Central Basin Platform; Ma—Matador uplift; Wu—Wichita uplift; Ar—Arbuckle uplift; Ca—Cambridge arch; Na—Nemaha uplift. B: Predicted fault geometries from transpressional deformation (Sanderson and Marchini, 1984). C: Compiled fault kinematics and geometry from the Central Basin Platform (red box in A) from Shumaker (1992).

Approximately simultaneous with ARM deformation, the North American mid-continent underwent deformation along north- to northeast–oriented basement-cored uplifts. This deformation is generally attributed to Appalachian and/or Ouachita-Marathon collision (e.g., Marshak et al., 2003). Displacements along these structures were mostly an order of magnitude less than along ARM structures, with average throw on steep reverse faults generally <150 m (McBride and Nelson, 1999; Marshak et al., 2003).

Here we propose that northeast-directed stress from transpression along the southwestern continental margin between ca. 320 and 280 Ma was the principal driver of ARM deformation (Fig. 2), possibly supplemented by stress generated along the Nevada paleomargin. We interpret this stress to have driven the larger magnitude deformation in the ARM, relative to the more modest mid-continent deformation driven by stress from the Appalachian-Ouachita-Marathon collision. We review the Pennsylvanian–Permian deformational histories of the three nearest active Laurentian continental margins, present an updated chronology of ARM subsidence based on improvements in the geologic time scale (Heckel, 2008; Schmitz and Davydov, 2012; Cohen et al., 2013), and integrate these histories into a new global plate reconstruction (Domeier and Torsvik, 2014).

OUACHITA-MARATHON MARGIN

Following Alleghenian (late Paleozoic) collision along the Appalachian orogen (Hatcher et al., 1989), closure of the Ouachita-Marathon belt began near the Black Warrior Basin during the Late Mississippian and migrated southwestward (Graham et al., 1975; Kluth and Coney, 1981; Dickinson and Lawton, 2003). Closure was accommodated by southward subduction of Rheic oceanic lithosphere beneath Africa and was complete by middle Wolfcampian time (Ross, 1986). Lower plate flexural foredeep basins (Black Warrior, Arkoma, Fort Worth, Valverde, and Marfa Basins) formed as the result of loading by north- and northwest-vergent thrust sheets (Fig. 2) (e.g., Whiting and Thomas, 1994; Yang and Dorobek, 1995).

Most researchers have interpreted stress generated by the closure of the Ouachita-Marathon belt to have been the sole driver of ARM uplift and basin formation. Most ARM deformation, however, was from northeast-southwest–directed convergence (Ye et al., 1996; Hoy and Ridgway, 2002; Barbeau, 2003), 90° offset from that expected if the Ouachita-Marathon belt was the principal source of stress. In addition, if the Ouachita-Marathon margin was the principal source of stress, ARM structures would be expected to show major structural interaction with Ouachita-Marathon structures. However, Middle Pennsylvanian deformation of the Central Basin Platform (Hills, 1970) and the Wichita uplift (Brewer et al., 1983) show little structural interaction. Also, if Ouachita-Marathon stress was

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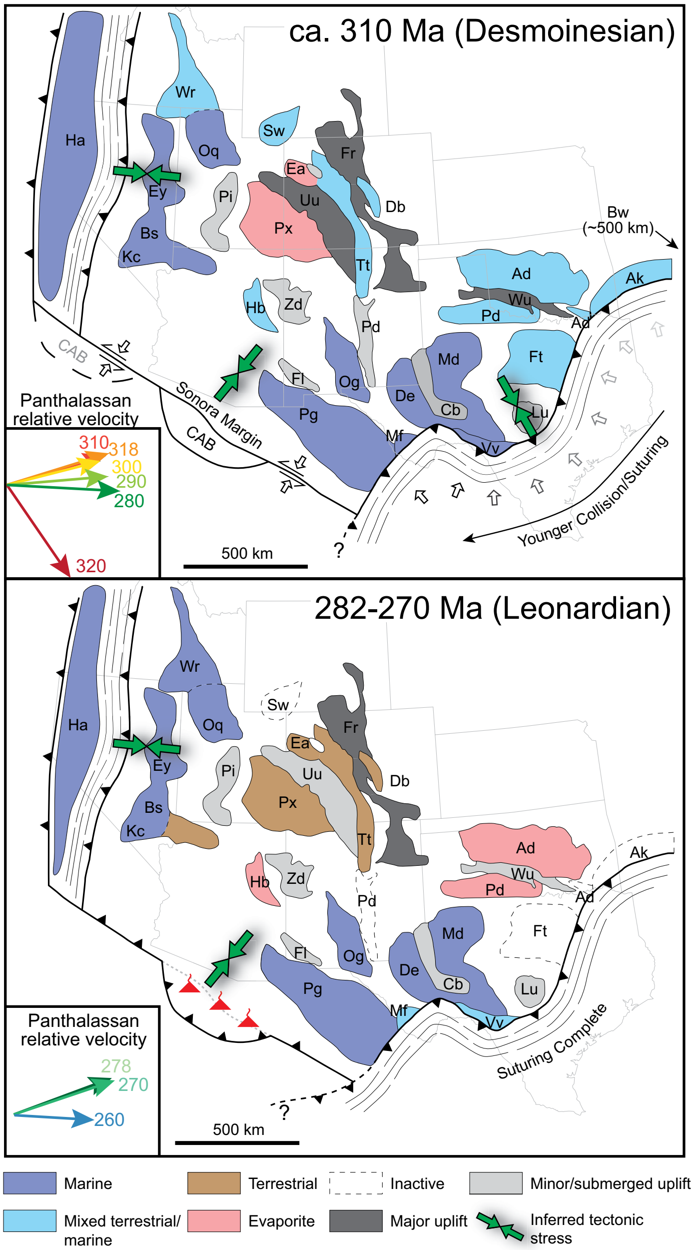

Figure 2. Paleogeography of the Ancestral Rocky Mountains (ARM) system in Middle Pennsylvanian (ca. 310 Ma) and middle Permian (ca. 282–270 Ma) time. Reconstructed Panthalassan plate velocities relative to North America and the associated ages (in Ma) are from Domeier and Torsvik (2014). Green arrows show tectonic stresses inferred from plate margin orientation and kinematics. Basins: Ha—Havallah; Wr—Wood River; Ey—Ely; Bs—Bird Springs; Kc—Keeler Canyon; Oq—Oquirrh; Sw—Sweetwater Trough; Ea—Eagle; Px—Paradox; Hb—Holbrook; Tt—Taos Trough; Og—Orogrande; Db—Denver; Pg—Pedregosa; Mf—Marfa; De—Delaware; Vv—Val Verde; Md—Midland; Pd—Palo Duro; Ad—Anadarko; Ft—Fort Worth; Ad—Ardmore; Ak—Arkoma; Bw—Black Warrior. Uplifts: Fr—Front Range; Uu—Uncompahgre; Pi—Piute; Zd—Zuni-Defiance; Pd—Pedernal; Fl—Florida; Cb—Central Basin Platform; Lu—Llano; Wu—Wichita. CAB—Caborca block. See the GSA Data Repository[1] for references.

the only driver of ARM deformation, displacement along ARM structures would likely have been <150 m, comparable to that on similar mid-continent structures (Marshak et al., 2003). Thus, we suggest that closure of the Ouachita-Marathon belt was not the primary source of stress that drove ARM deformation and that stress generated along the Ouachita-Marathon margin likely contributed only minor offset to intracontinental faults or else served as a tectonic backstop (as opposed to a free boundary) against stress generated at the Sonora and Nevada margins.

NEVADA MARGIN

A growing body of work has documented ongoing Mississippian–Permian convergent deformation in Nevada (Erickson and Marsh, 1974; Trexler et al., 2004; Cashman et al., 2011) that drove sedimentation in the Wood River, Bird Springs, Dry Mountain Trough, and possibly Oquirrh basins (Gallegos et al., 1991; Mahoney et al., 1991; Geslin, 1998). Recent palinspastic reconstructions suggest a generally north-south orientation (modern coordinates) for this margin (Dickinson, 2013), and we suggest that convergence along it could have contributed an oblique component to ARM deformation (Fig. 2). We view this contribution as minor, given that convergent deformation along the Nevada margin occurred between Early Mississippian and late Permian time, whereas ARM deformation was limited to the Pennsylvanian and early Permian.

SONORA MARGIN

Numerous studies have proposed truncation of the Sonora margin by a late Paleozoic left-lateral strike-slip boundary (e.g., Stone and Stevens, 1988; Dickinson and Lawton, 2001). Although the timing of movement along, and existence of, this structure is still debated, this fault is thought to have translated the Caborca block, a crustal fragment interpreted as the southern continuation of the Cordilleran miogeocline (Anderson and Silver, 1979), as much as 950 km to the southeast beginning in Early or Middle Pennsylvanian time (Stone and Stevens, 1988; Dickinson and Lawton, 2001). Geochronologic and geochemical data from plutons intruding the Caborca block indicate that subduction-related magmatism occurred beginning ca. 275 Ma (Riggs et al., 2010; Arvizu and Iriondo, 2015) and suggest that northeast-dipping subduction initiated along the Sonora margin by at least this time, likely facilitated by the presence of the major lithospheric-scale transcurrent fault (Fig. 2).

Ye et al. (1996) invoked Pennsylvanian northeast-directed flat-slab subduction along the Sonora margin to explain the orientation of ARM uplifts and northeast-southwest displacement along ARM faults. However, the expected magmatic remnants of this process (e.g., Humphreys, 1995; Constenius, 1996) have not been discovered, and this model does not conform to reconstructed relative plate motions (Figs. 2 and 3) (Domeier and Torsvik, 2014).

TIMING

Few ARM kinematic records are well preserved at the surface, and basin subsidence has been the principal record used to reconstruct the timing of ARM deformation. The timing of ARM subsidence has been

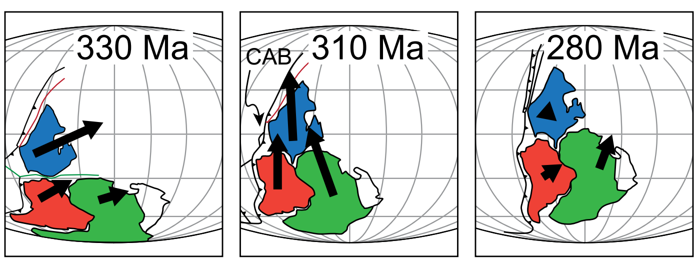

Figure 3. Paleogeographic reconstruction after Domeier and Torsvik (2014). Black arrows indicate plate velocity in a mantle reference frame. CAB—Caborca block.

[1]GSA Data Repository item 2017243, complete references for Figures 1, 2, and 4, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

central to several contrasting interpretations of ARM tectonics (e.g., Ye et al., 1996; Dickinson and Lawton, 2003). Here we present an updated chronology of regional basin subsidence based on recent improvements in the Pennsylvanian–Permian time scale (Fig. 4) (Heckel, 2008; Schmitz and Davydov, 2012; Cohen et al., 2013). Important differences between our interpretation and those of previous workers are (1) we exclude Nevada (Bird Springs, Keeler Canyon, Wood River, and Dry Mountain Trough) and Ouachita-Marathon (Black Warrior, Arkoma, Ardmore, Fort Worth, Val Verde, and Marfa) basins from consideration in the ARM system because they formed as peripheral basins distinct in tectonic setting from the intracontinental ARM basins, and (2) we interpret the onset of sedimentation rather than the timing of maximum subsidence (e.g., Dickinson and Lawton, 2003) to reflect the initiation of local ARM tectonism.

When projected into one-dimensional (1-D) transects, ARM maximum basin subsidence is younger to the southwest (Dickinson and Lawton, 2003). However, when our updated chronology of the onset of basin subsidence is plotted in map view (2-D) (Fig. 4), the initiation of ARM subsidence appears generally synchronous during early Morrowan time (ca. 323–318 Ma), given the uncertainties inherent in biostratigraphic and lithostratigraphic correlations within ARM basins. The only exceptions to this are the Anadarko and Holbrook Basins. Roughly synchronous basin development suggests that the tectonic driver(s) of the ARM system also began synchronously and argues against stress from the progressive closure of the Ouachita-Marathon belt as the principal driver of ARM tectonism (Dickinson and Lawton, 2003).

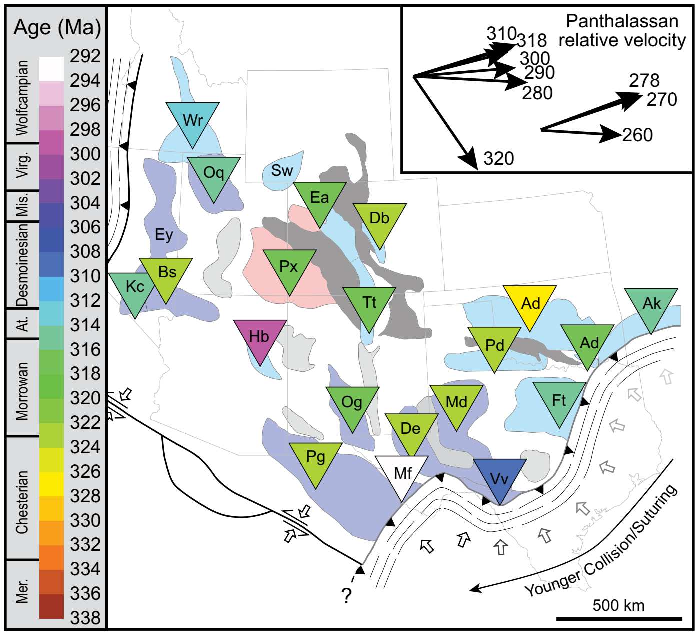

Figure 4. Estimates of the initiation of Ouachita-Marathon, Ancestral Rocky Mountains (ARM), and Nevada margin basin subsidence by color (abbreviations as in Fig. 2). North American stages based on Heckel (2008) and Schmitz and Davydov (2012). Mer.—Meramecian; At.—Atokan; Mis.—Missourian; Virg.—Virgilian. See the Data Repository (see footnote 1) for references.

GLOBAL PLATE RECONSTRUCTION

A new global plate reconstruction for late Paleozoic time (Domeier and Torsvik, 2014) provides insight into the processes driving the evolution of the ARM system by enabling calculation of relative plate vectors in the program GPlates (http://www.gplates.org). Relative to a fixed North American reference frame, Domeier and Torsvik (2014) reconstructed southeast motion (modern coordinates) of the Panthalassan oceanic plate from ca. 330–320 Ma (Fig. 2A). At 319 Ma, this changed to northeast oblique convergence, after which plate motion shifted progressively southward until 280 Ma. During this time interval, convergence along the Sonora margin was left-laterally oblique. At 279 Ma, Panthalassan plate motion abruptly shifted ~25° north (Fig. 2B); movement continued along a similar vector until 270 Ma, after which it shifted southward again. Domeier and Torsvik (2014) did not explicitly quantify uncertainty within their reconstruction, but given the nature of the data and the lack of preserved oceanic crust for this time period, we infer that both timing and plate velocities must have large uncertainties. Despite these uncertainties, however, the plate reconstructions of Domeier and Torsvik (2014) independently support a transpressional regime along the Sonora margin during late Paleozoic time.

THREE-SIDED OROGEN

We propose that combined Panthalassan-Laurentian transpressional plate interactions along the Sonora margin and collision along the Ouachita-Marathon and possibly Nevada margins produced an overall northeast-southwest–directed stress field (modern coordinates) that drove ARM uplift and basin development during the Pennsylvanian and early Permian. We suggest that these combined stresses distinguished the large thrust displacements (up to 12 km) observed in the ARM region from the generally <150 m thrust displacements that resulted only from Appalachian-Ouachita-Marathon–generated stress (McBride and Nelson, 1999; Marshak et al., 2003).

Beginning ca. 320 Ma, the Sonora margin underwent oblique left-lateral convergence that likely produced northeast-directed stress and initiated ARM deformation (Fig. 2A). A northward shift in relative plate motion after ca. 280 Ma likely caused the initiation of northeast-dipping subduction that produced ca. 275 Ma volcanism in northern Sonora (Riggs et al., 2010; Arvizu and Iriondo, 2015). The shift from transpression to subduction likely ended ARM deformation as convergence could have been accommodated by subduction-zone slip rather than by deformation of Laurentian basement.

We suggest that the Caborca block may have augmented transpressional stress as a rigid indentor along the Sonora margin between ca. 320 and 280 Ma. However, because of uncertainty surrounding the Caborca block size, original position, timing of movement, and even existence as an allochthonous block (Anderson and Silver, 1979; Dickinson and Lawton, 2001; Poole et al., 2005), it is important to note that transpressional stress could have also been generated along this margin without a rigid indentor (e.g., Lebrun et al., 2003). Evidence of emplacement of allochthonous rocks northward onto the Sonora margin by late Permian time (Poole et al., 2005) provides a minimum age for the end of Caborca translation if it occurred.

The model proposed here builds on, and fills several gaps in, existing ARM models (Marshak et al., 2000; Soreghan et al., 2012). Marshak et al. (2000) proposed that ARM uplifts resulted from reactivation of faults formed during Proterozoic rifting events; in this model, movement along those faults could have occurred even under relatively weak (20–40 MPa) stresses. Transpressional deformation of the Sonora margin in combination with convergence along the Nevada margin could have produced stresses of at least this magnitude, and the resulting northeast-southwest–oriented stress field better explains the overall kinematics of ARM structures (Fig. 1) than does stress generated along the Ouachita-Marathon belt. The model of Soreghan et al. (2012), in which anomalous density structures of mafic-underplated Proterozoic and Cambrian rift systems produced uplift in response to a regional stress field, would similarly be more effective with an orthogonal stress field relative to uplifts; northeast-southwest–oriented stress from transpression along the Sonora margin could have produced effects similar to those modeled by Soreghan et al. (2012).

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