The geologic history and lithospheric character of Texas

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1 Geology of Texas

Here I present the assembly and later modification of the basement underlying Texas, focusing also upon sedimentary loading and the development of major structural features. I also show salient aspects of the lithospheric structure of the area. This discussion was originally written to support my Ph.D. research proposal to study the state of stress in Texas. The initial results of the Stress Map of Texas are shown in Figure 1 and described by Lund Snee and Zoback (2016).

1.1 Precambrian basement assembly

Parts of four northeast-trending basement domains make up Texas, each of which represents crust that has a distinct tectonic heritage and age range for its formation (Lund et al., 2015; Figure 2). The development, accretion, and subsequent deformation of these domains define a varied geologic history spanning nearly 2 Ga. Assembly and emplacement of these domains produced weak suture zones that were reactivated during later tectonic events (Van Schmus et al., 1996; Thomas, 2006; Carlson, 2007). The southern margin of the oldest basement domain, the Great Plains (or Yavapai) domain, trends northeast near the northwestern corner of the Texas Panhandle (Holm et al., 2007; Van Schmus et al., 2007; Whitmeyer and Karlstrom, 2007; Lund et al., 2015; Figure 2). This domain was assembled partly outboard of the developing Laurentian (North American) continent by collisions of primitive-composition intra-oceanic arcs between 1800–1720 Ma, followed by protracted accretion of these assemblages and additional intra-island arcs onto the continent between 1710–1680 Ma above a subduction zone that dipped northwest (present coordinates) under Laurentia (Sims et al., 1987; Aleinikoff et al., 1993; Whitmeyer and Karlstrom, 2007; Van Schmus et al.,

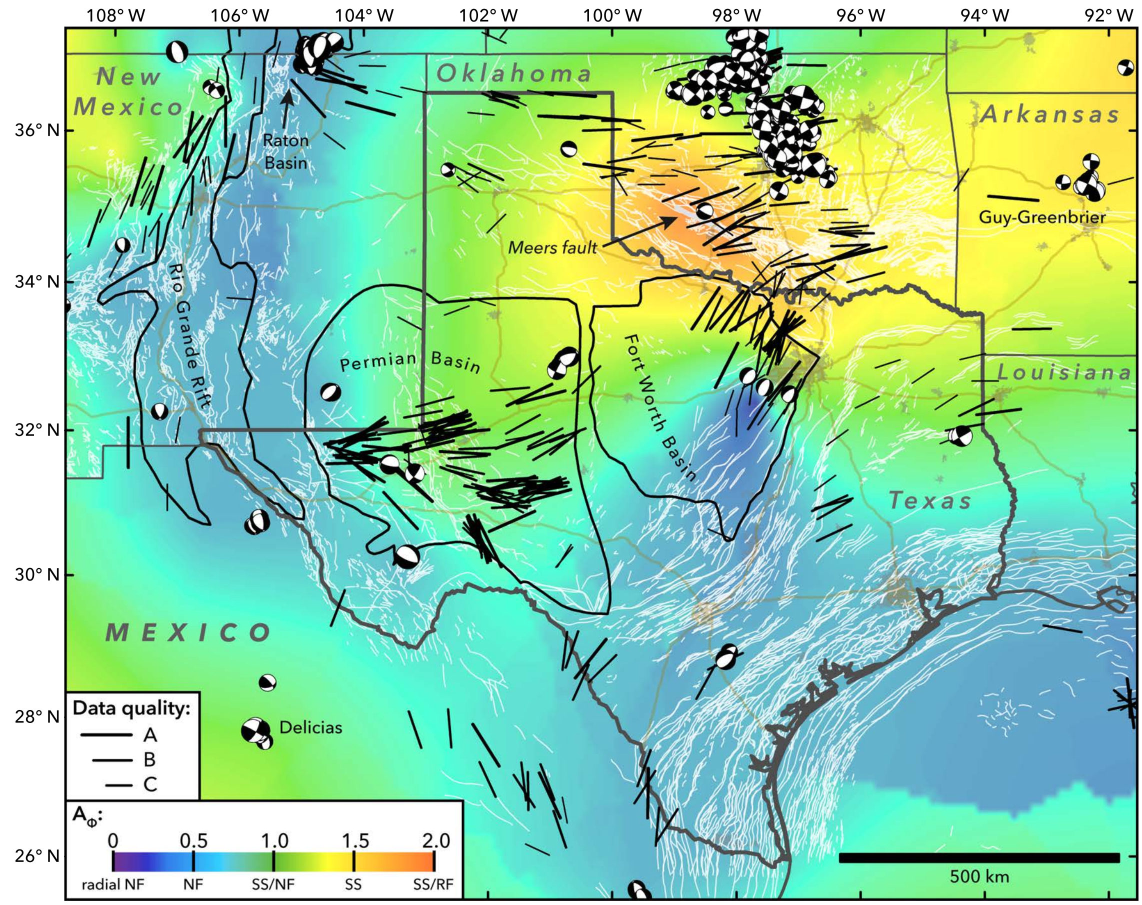


Figure 1: Map of the state of stress in Texas from Lund Snee and Zoback (2016). $S_{\mathrm{H}_{\max}}$ orientations are from this project, Stanford Stress Group projects (Sone, 2012; Heller, 2013; Xu and Zoback, 2015; Alt and Zoback, 2017, in press), and the 2016 World Stress Map (Heidbach et al., 2016). Faulting regime is mapped according to the A_ϕ system (Simpson, 1997). Faults are from Ewing et al. (1990), Ewing and Lopez (1991), Green and Jones (1997), and Darold and Holland (2015). Basins are from the U.S. Energy Information Administration (EIA).

2007; Duebendorfer, 2015; Lund et al., 2015).

The younger (1720–1650 Ma) Mazatzal domain is situated immediately to the south and underlies a small portion of northwestern Texas (Holm et al., 2007; Whitmeyer and Karlstrom, 2007; Wirth and Long, 2014; Lund et al., 2015; Figure 2). This domain consists of continental arc rocks and back-arc basin deposits (Whitmeyer and Karlstrom, 2007). After a pause of plate convergence that followed emplacement of the Great Plains domain, the Mazatzal domain was accreted northwestward (present coordinates) onto the continent between 1650–1620 Ma above a northwest-dipping subduction zone (Van Schmus et al., 2007; Whitmeyer and Karlstrom, 2007; Jones et al., 2013; Lund et al., 2015). Seismic reflection imaging suggests that the location of the suture between the Great Plains and Mazatzal domains may be along or near the Jemez lineament in New Mexico, a northeast-trending structural zone in northern New Mexico that obliquely crosses the Rio Grande rift near Santa Fe, where it is offset southward and then continues toward slightly north of the northwestern tip of the Texas panhandle (Aldrich, 1986; Marshak et al., 2003; Magnani et al., 2004; Figure 2).

Adjacent to the Mazatzal domain to the southeast lies the northeast-trending Shawnee domain, which includes the Granite-rhyolite and Llano provinces. The "Granite-rhyolite province," which is the northern and much more aerially extensive of the two provinces, has been defined by the observation of granitoids and felsic volcanic rocks derived from underlying juvenile, mantle-derived crust (Van Schmus et al., 1996; Lund et al., 2015; Figure 2). Together, the formation of the underlying basement and the younger felsic rocks within this province spans 1550–1350 Ma; the age of the igneous rocks youngs from northeast to southwest within the range of 1450–1350 Ma (Van Schmus et al., 1996; Whitmeyer and Karlstrom, 2007). Following apparent tectonic quiescence in this part of North America beginning at 1600 Ma, the juvenile basement predating these felsic igneous rocks was accreted to the southeast margin of Laurentia between 1450–1350 Ma (Sims et al., 1987; Carlson, 2007; Van Schmus et al., 2007; Whitmeyer and Karlstrom, 2007; Wirth and Long, 2014). The suture zone associated with the accretion parallels, but is northwest of, the later Reelfoot Rift in southeastern Missouri, as well as major basement faults in southern and central Oklahoma (Van Schmus et al., 1996; Lund et al., 2015; Figure 2). This Mesoproterozoic collision, or an associated terrane accretion within the Shawnee domain, is a suspected cause of the original crustal flaw later exploited by the Neoproterozoic Reelfoot Rift in and near southeast Missouri, which hosts the active New Madrid seismic zone (Van Schmus et al., 1996).

The "Llano province," which is situated south of the Granite-rhyolite province, is a smaller, east-trending terrane that is restricted to south-central Texas and is grouped within the Shawnee domain as a consequence of its similar (Mesoproterozoic) age to the Granite-rhyolite province (Whitmeyer and Karlstrom, 2007; Lund et al., 2015). This province contains several tectonically unrelated continental and oceanic arc-related terranes of ca. 1330–1260 Ma age that were imbricated with one another and with Granite-rhyolite province crust during an inferred collision with a continent (either Amazonia or the Kalahari craton) on the southern margin of Laurentia (Mosher, 1998; Reese et al., 2000; Tohver et al., 2002; Loewy et al., 2003; Whitmeyer and Karlstrom, 2007; Li et al., 2008; McLelland et al., 2010). This collision produced the east- and northeast-trending, ca. 1230–1120 Ma Llano deformation front, which probably links with the Grenvillian deformation front in the eastern and southeastern United States that resulted from the ca. 1300–1000 Ma Grenvillian orogenies (Walker, 1992; Adams and Miller, 1995; Adams and Keller, 1996; Bickford et al., 2000; Tohver et al., 2002; Thomas, 2006; Whitmeyer and Karlstrom, 2007; McLelland et al., 2010).

1.2 Basement modification, rifting, and final assembly

Between ca. 1200–1000 Ma, during the protracted Grenvillian orogenies, approximately NE–SW extension occurred across Laurentia, creating a fabric of W–NW- and NE-striking basement fault systems in the midcontinent and Cordillera that probably accommodated extensional or transform displacement during their initiation, before being multiply reactivated following Mesoproterozoic–Neoproterozoic time (Thomas, 1991; Marshak and Paulsen, 1996; Timmons et al., 2001; Marshak et al., 2003; Whitmeyer and Karlstrom, 2007). The NW-striking Texas-Mogollon-Walker lineament ("Texas transform"), extends from the southern tip of Nevada into western Texas, where it linked with or paralleled a NW-trending part of the margin of the Shawnee domain at what was the southern edge of Laurentia during this time (Pindell and Dewey, 1982; Thomas, 1991; Marshak and Paulsen, 1996; Marshak et al., 2003; Poole et al., 2005; Thomas, 2006; Figure 2). The WNW-trending Oklahoma aulacogen in southern Oklahoma and the Texas Panhandle accommodated failed NNE–SSW Neoproterozoic rifting that coincides spatially with the later (Pennsylvanian–Permian) Wichita-Amarillo uplift and Wichita Mountains, and its compressional reactivation also created the mostly Late Cambrian–Pennsylvanian age Anadarko Basin to its north (Brewer et al., 1983; Gilbert, 1983; Perry, 1989; Thomas, 1991; Marshak et al., 2003; Poole et al., 2005; Figure 2). Northwest-striking dikes of ca. 1350 Ma age within the Oklahoma aulacogen suggest that it initiated as an extensional structure in early Grenvillian time (Thomas, 2006, and sources therein).

Both the Texas-Mogollon-Walker lineament and the Oklahoma aulacogen are prominently expressed on maps of topography and subsurface faults, but the most prominent late Mesoproterozoic–early Neoproterozoic extensional structure on gravity and aeromagnetic anomaly maps, as well as in the sedimentary and igneous geologic record, is the failed ca. 1109–1094 Ma Midcontinent Rift system (Keller et al., 1983; Van Schmus and Hinze, 1985; Hinze et al., 1992; Paces and Miller, 1993; Cannon, 1994; Timmons et al., 2001; Vervoort et al., 2007; Swanson-Hysell et al., 2014; Figure 2). The rift initiated in the Great Lakes region and one strand propagated SW, likely passing SSW through central Oklahoma and then possibly jumping west into southeast New Mexico and western Texas (Adams and Keller, 1994; Adams and Miller, 1995). Shortly following propagation of the Midcontinent Rift, the stress state became compressive in the NW–SE direction, resulting in thrust faulting and partial inversion of the rift and other similarly oriented extensional structures between ca. 1080–1060 Ma (Cannon, 1994). The presently north-striking Nemaha fault zone and uplift in Oklahoma approximately parallel the failed rift (Marshak et al., 2003).

These accretion events were part of the protracted development of Rodinia, which finished by 900 Ma (Li et al., 2008). Multistage extension and breakup subsequently occurred, beginning on the western margin (present coordinates) of Laurentia after about 825 Ma, with additional rifting occurring there until 485 Ma (Lund et al., 2003; Li et al., 2008; Lund et al., 2010). Amazonia and/or the Kalahari craton, which were attached to the southeastern margin of Laurentia (including along southern and central Texas), began to rift away after ca. 800 Ma, with the first oceanic crust developing after ca. 570 Ma (Tohver et al., 2002; Loewy et al., 2003; Poole et al., 2005; Li et al., 2008). The extension direction was NW–SE and took place along NE-striking normal fault systems and NW-striking transforms, probably reactivating older structures including the Texas–Mogollon–Walker lineament and the Alabama-Oklahoma transform, and causing strike slip faulting to encroach into the continent (Thomas, 1991; Poole et al., 2005; Thomas, 2006; Figure 2). This rifting geometry left a series of promontories and embayments along the new Laurentian margin —bound by NW-striking transform faults and NE-striking rifted margins—including the Alabama promontory (with its southernmost point near the central part of the southern border of Alabama) and the Texas promontory (with its southern point near San Antonio) (Perry, 1989; Thomas, 1991; Poole et al., 2005). During extension, unsuccessful rifting occurred along the NE-striking Reelfoot Rift, which extends from the rifted margin in southern Arkansas into southwestern Indiana, and the Oklahoma aulacogen, which can be traced onto the subparallel Alabama-Oklahoma transform to the southeast (Ervin and McGinnis, 1975; Lowe, 1985; Thomas, 1991, 2006; Figure 2).

Late Neoproterozoic–Early Mississippian age rift basin and then shelf and off-shelf deposition occurred along the southeast margin of Laurentia (including Texas) as a result of rifting and breakup (Poole et al., 2005). This deposition was especially pronounced in the broad Tobosa Basin that persisted along the Laurentian margin for most of this time, occupying a similar aerial extent as the later Permian Basin but opening southward toward the Iapetus Ocean (Galley, 1958; Adams, 1965; Poole et al., 2005). This "precursor" to the Permian Basin was deepest in the center, near the present-day Central Basin Platform, and it was the site of Ordovician–Mississippian strata including the lower Ordovician Ellenburger Formation.

Several terranes that rifted from Laurentia during the breakup of Rodinia began to reassemble into the Gondwana supercontinent, away from Laurentia, between ca. 600–530 Ma (Li et al., 2008).

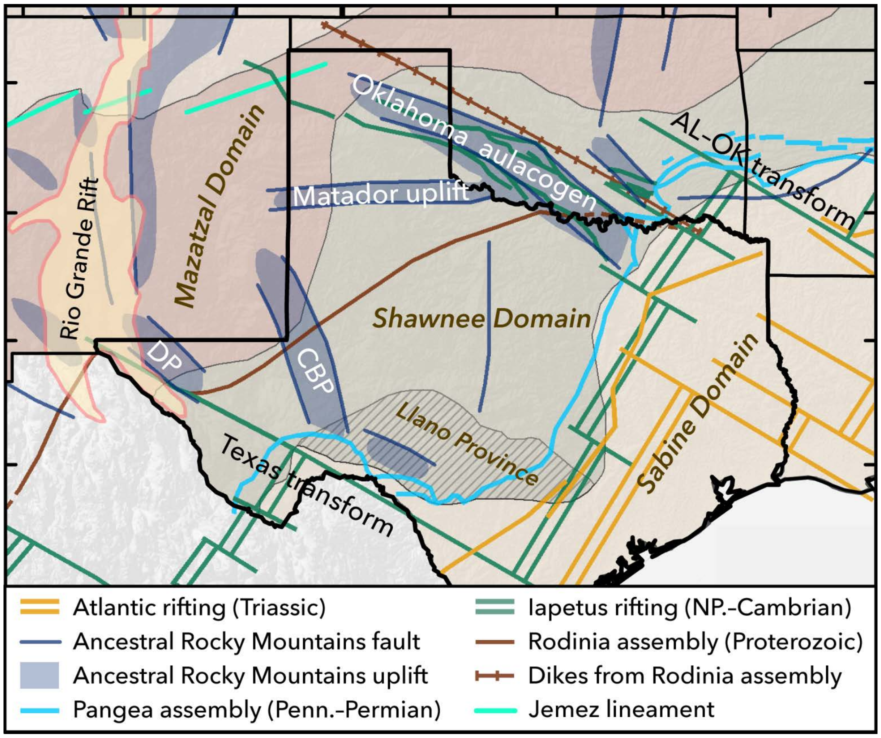


Figure 2: Map of Texas showing major structural elements. Limits of the Gulf of Mexico basin from Salvador (1987). Proterozoic and Paleozoic rift and transform structures compiled from Poole et al. (2005) and Thomas (2006). Basement domain boundaries from Lund et al. (2015). Approximate Ancestral Rocky Mountains uplift locations after Marshak et al. (2000), and sources therein. Jemez lineament location after Magnani et al. (2004) and Rio Grande rift location compiled from Seager and Morgan (1979) and Perry et al. (1987). Llano province location after Whitmeyer and Karlstrom (2007), and Midcontinent Rift locations compiled from Adams and Miller (1995) and Whitmeyer and Karlstrom (2007).

Beginning at 325 Ma and continuing until at least 280 Ma in Texas, the South American part of Gondwanaland (near Colombia) collided with the southeastern margin (present coordinates) of Laurentia (Pindell and Dewey, 1982; Shurbet and Cebull, 1987; Poole et al., 2005). In Texas, this collision placed the ca. 360–300 Ma age Sabine domain, consisting of heterogenous remnant crust from development of Gondwanaland, as well as syncollisional sediments and a volcanic arc system, in contact with the Shawnee domain (Shurbet and Cebull, 1987; Poole et al., 2005; Lund et al., 2015, and sources therein). This accretion completed the assembly of Texas basement.

The NW-directed (present coordinates) collision (NW $S_{\mathrm{H_{max}}}$ axis) produced the sinuous and narrow (typically < 100 km wide), doubly vergent and thin-skinned Oachita-Marathon orogenic belt along the former southeastern margin of Laurentia, which passes through central Texas along the Oachita Mountains and the Marathon area, and appears to have taken advantage of the preexisting NW- and NE-trending geometry of margin promontories and structural weaknesses including the Texas–Mogollon–Walker lineament and the Alabama-Oklahoma transform (Shurbet and Cebull, 1987; Thomas, 1991; Harry and Londono, 2004; Poole et al., 2005, Figure 2). This orogenic belt

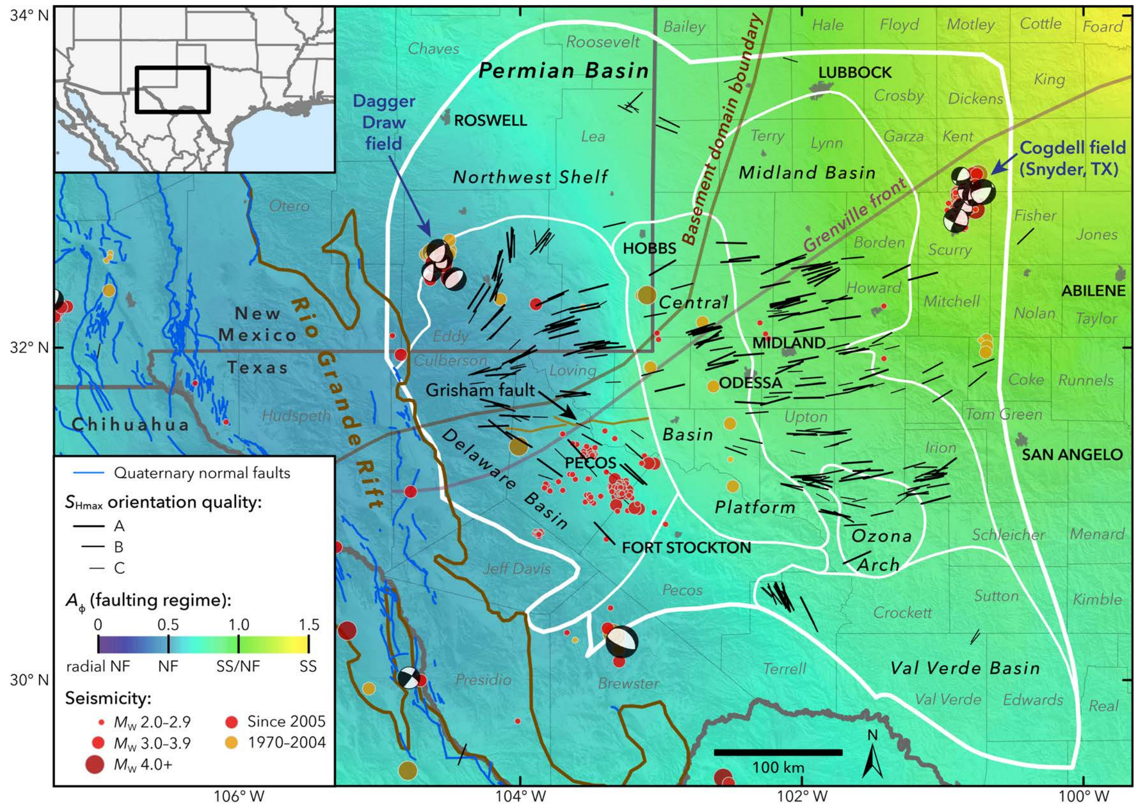


Figure 3: Map of the state of stress in the Permian Basin, Texas and New Mexico, from Lund Snee and Zoback (2018). Black lines are the measured orientations of $S_{\mathrm{H_{max}}}$, with line length scaled by data quality. The colored background is an interpolation of measured relative principal stress magnitudes (faulting regime) expressed using the A_ϕ parameter of Simpson (1997). Blue lines are fault traces known to have experienced normal-sense offset within the past 1.6 Ma, from the USGS Quaternary Faults and Folds Database (Crone and Wheeler, 2000). The boundary between the Shawnee and Mazatzal basement domains is from Lund et al. (2015), and the Precambrian Grenville Front is from (Thomas, 2006). The Permian Basin boundary is from the U.S. Energy Information Administration, and the sub-basin boundaries are from the Texas Bureau of Economic Geology Permian Basin Geological Synthesis Project. Earthquakes are from the USGS National Earthquake Information Center, the TexNet Seismic Monitoring Program, and Gan and Frohlich (2013). Focal mechanisms are from Saint Louis University (Herrmann et al., 2011).

approximately forms the southeastern boundary of the present-day Permian Basin in west Texas and southeast New Mexico (Figure 3). During the collision, existing structures were reactivated inboard of the collision zone, including the Oklahoma aulacogen, which accommodated compression, creating the Arbuckle–Wichita–Amarillo basement uplift system and the Anadarko Basin (Perry, 1989; Thomas, 1991, 2006, and references therein; Figure 2).

It has been hypothesized that this collision was responsible for the Late Mississippian to Permian Ancestral Rocky Mountains orogenic event, in which numerous NW–W-trending basement zones were uplifted and exposed between central Wyoming and central Texas (Marshak et al., 2000; Dickinson and Gehrels, 2003; Dickinson, 2006). During this event, existing W- and NW-striking faults, originally formed during Proterozoic extension, were probably re-activated in compression and transpression, although the tectonic cause has been a source of controversy (e.g. Kluth and Coney, 1981; McBride and Nelson, 1999; Marshak et al., 2000). More recent work (Leary et al., 2017) proposes that the kinematics of the Ancestral Rocky Mountains uplifts and other observations are best satisfied by a "three-sided orogen" model involving partially synchronous collisions on three margins of Laurentia: On the west (present-day Nevada), southwest (present-day Sonora), and southeast (Oachita-Marathon margin). In addition to uplift and reactivation of the Oklahoma aulacogen, uplifts in Texas included the Matador arch (W-trending) along the southern part of the Texas Panhandle, the Central Basin uplift (NW-trending) that extended from west-central Texas to the southeastern corner of New Mexico (and separating the Delaware and Midland basins within the greater Permian Basin), and the Diablo platform (NW-trending) to the west of the Delaware Basin in westernmost Texas (Kluth and Coney, 1981; Goldhammer and Lehmann, 1993; McBride and Nelson, 1999; Marshak et al., 2000; Figures 2 and 3).

Basins developed or deepened between these uplifts, notably resulting in thick Late Mississippian–Permian age sediment deposition in the Midland and Delaware sub-basins of the Permian Basin (Figure 3) in north-central and western Texas (Keller et al., 1980; Handford and Dutton, 1980; Keller et al., 1989; McBride and Nelson, 1999; Dickinson and Gehrels, 2003). Many of the conventional and unconventional reservoirs in the Delaware and Midland sub-basins that contain the largest historical petroleum reserves were deposited in Permian and upper Pennsylvanian time, including the Wolfcamp shale and Bone Spring and San Andres formations (e.g., Cartwright Jr., 1930; Handford and Dutton, 1980; Yang and Dorobek, 1995; Engle et al., 2016). Thick carbonate successions also developed along shallower parts of the Permian Basin during Pennsylvanian–Permian time, including along the shelves and on the Central Basin Platform (e.g., Galley, 1958; Adams, 1965; Yang and Dorobek, 1995). Some of these carbonate systems were the primary conventional reservoirs that were targeted during previous decades of oil and gas production in the Permian Basin, including the San Andres and Grayburg formations.

1.3 Gulf of Mexico rifting and deposition

Accretion of Laurentia (North America) to northwestern Gondwanaland (South America) helped complete the development of Pangea, which persisted from Carboniferous time until breakup initiated in late Permian time (Ziegler, 1992; Keppie and Ramos, 1999). The southeastern continental margin of Texas developed during rifting, which began in Late Triassic time mostly within the Sabine domain, and generally outboard (SE) of the Paleozoic Oachita-Marathon orogenic belt and suture zone (Pindell and Dewey, 1982; Salvador, 1987; Ziegler, 1992; Harry and Londono, 2004; Thomas, 2006; Lund et al., 2015; Figure 2). The rift may have propagated southwest from the developing

Atlantic Rift, resulting in southward drift of South America away from Laurentia, and counterclockwise rotation of Yucatán crust away from Florida that continued into Early Cretaceous time (Buffler, 1991; Ziegler, 1992; Harry and Londono, 2004; Pindell and Kennan, 2013). Although rifting occurred mostly outboard of crustal weaknesses formed during previous rifting and accretionary events, it developed a similar geometry that included NE-striking rifts and NW-striking transforms such as the Bahamas fracture zone, which apparently occupied the same location and geometry as the Alabama-Oklahoma transform, suggesting that lithosphere-scale tectonic inheritance occurred along weak zones (Harry et al., 2003; Harry and Londono, 2004; Thomas, 2006; Figure 2).

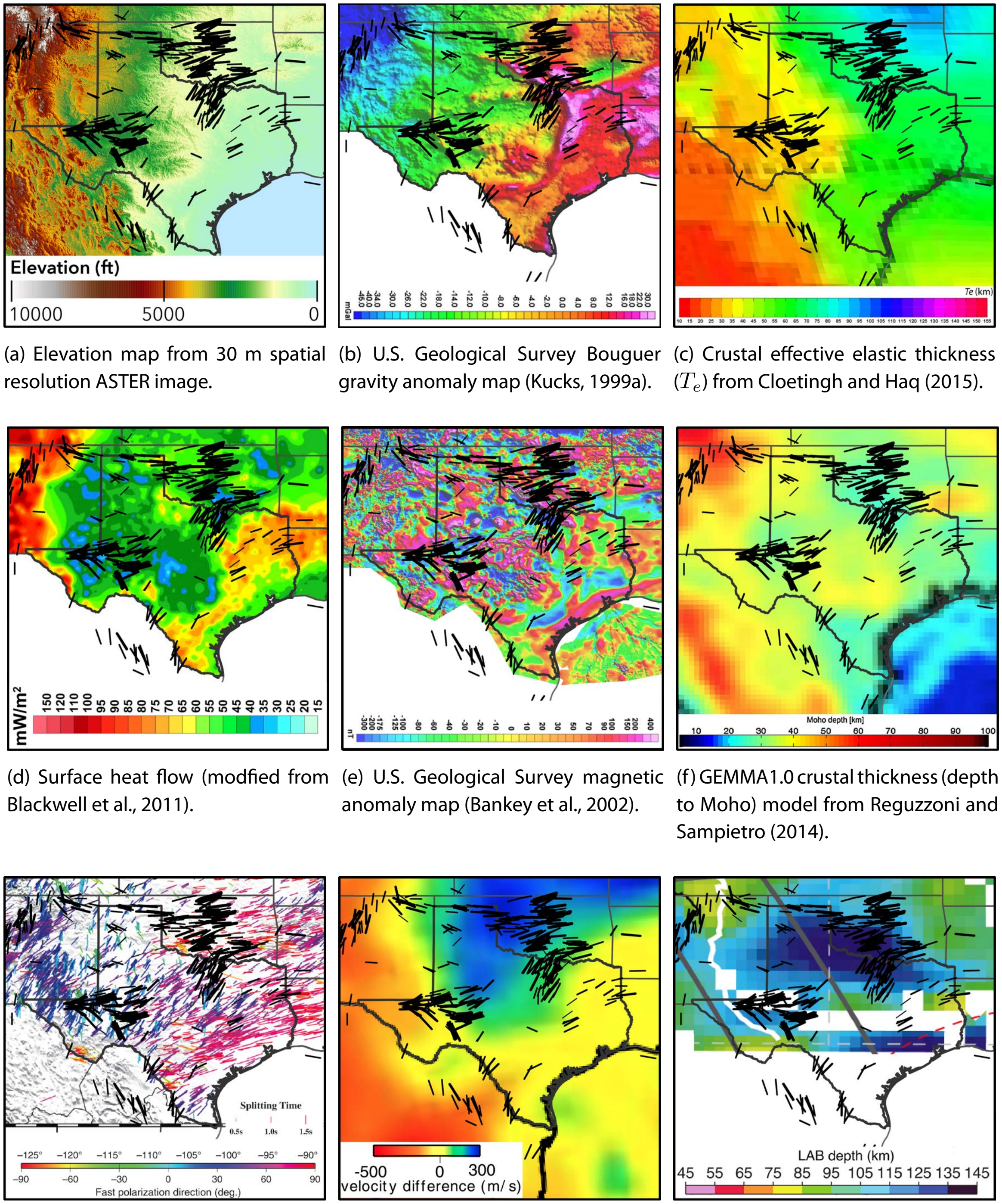
Opening of the Gulf of Mexico thinned continental crust on the margins during Middle–Late Jurassic time, then generated Late Jurassic–Early Cretaceous oceanic crust near the center of the basin, and eventually led to deposition of a thick succession of syn- and post-rifting sedimentary rocks (e.g. Pindell and Dewey, 1982; Salvador, 1987; Buffler, 1991; Harry et al., 2003; Harry and Londono, 2004; Galloway, 2008; Pindell and Kennan, 2013). Synextensional volcanic and fluviolacustrine sedimentary rocks were deposited in localized rift basins during Late Triassic time (Salvador, 1987). Between Middle and Late Jurassic time, the developing Gulf of Mexico was repeatedly flooded by water that reached increasingly large aerial extents as the basin widened and subsided, resulting in locally thick (0–4000 m) evaporite deposits of the Jurassic Luann Salt (halite) and Werner Anhydrite (Salvador, 1987; Pindell and Kennan, 2013). The Gulf basin was briefly connected to the Pacific Ocean in the Late Jurassic (Oxfordian–Tithonian), and then finally connected to the Atlantic Ocean beginning in Late Jurassic (Kimmeridgian) time (Salvador, 1987). Spreading until ca. 140 Ma resulted in separation of the evaporites into northern and southern deposits, and continued subsidence facilitated deposition of thick (up to 20,000 m) Late Jurassic–Holocene age marine sediments (Pindell and Dewey, 1982; Salvador, 1987; Buffler, 1991; Galloway, 2008). Between Cretaceous and Paleocene time, these sediments were deposited primarily by river systems that flowed from the west and northwest (Mexico and southern Texas), but by Miocene time the sediment predominantly entered the basin from southeastern Texas and southern Louisiana and Mississippi (Buffler, 1991; Galloway and Williams, 1991; Galloway, 2008; Galloway et al., 2011). Gulf of Mexico sedimentary strata from Late Cretaceous–Quaternary age are exposed in Texas along the Gulf Coastal Plain, where exposed rocks young basinward (Galloway, 2008). The weight of the sedimentary column mobilized the Jurassic salt, which flowed downhill toward the center of the basin or formed pillows, diapirs, and canopies within the overlying sediments (Salvador, 1987; Galloway, 2008). Supracrustal extension has mostly been accommodated by flow within the Jurassic Luann Salt and normal ("growth") faults in the overlying sedimentary rocks (Salvador, 1987; Galloway, 2008). This extension has resulted in a present-day normal faulting regime within the supracrustal rocks along the Gulf Coast, with the extension direction ($S_{h_{min}}$) oriented perpendicular to the margin, mechanically decoupled from the underlying pre-Jurassic basement (Zoback and Zoback, 1980, 1989).

1.4 Cretaceous and Cenozoic tectonic history

Beginning perhaps as early as Late Devonian time, and continuing until the Miocene, the western margin of North America experienced east-dipping subduction and arc magmatism, punctuated by collisions with island arc terranes, the last of which occurred in the Early Cretaceous (Burchfiel et al., 1992; DeCelles, 2004; Dickinson, 2006). As a result of convergence, the Trans-Pecos region of western Texas experienced approximately ENE compression in Cenzoic time, ending at ca. 31–28 Ma, and continental arc magmatism from 48–24 Ma (Price and Henry, 1984; Henry et al., 1991). Following the end of compression, this part of Texas experienced Basin and Range-related ENE *extension* and associated mafic volcanism that lasted until 17 Ma. Subsequently, magmatism ceased in the Trans-Pecos region (but continued until the present further north and west in the Rio Grande Rift), and the extension direction rotated to the present E to ESE azimuth (Seager et al., 1984; Zoback and Zoback, 1989; Keller et al., 1990; Price and Henry, 1984; Henry et al., 1991; Figure 1). Both phases of extension culminated in the approximately N–S-trending Rio Grande rift, which extends from south-central Colorado, through central and eastern New Mexico, into western Texas (Cordell, 1978; Averill and Miller, 2013; Figure 2).

2 Character of Texas lithosphere

Figure 4 presents maps of several lithospheric parameters across the study area. These maps demonstrate that structures that developed during the geologic history of Texas (Section 1) have had a strong effect upon its present crustal configuration, and processes active during the recent (Cretaceous and later) geologic past continue to exert a strong influence. Western Texas is situated near a transition between active extensional tectonics in the Cordillera to the west and stable craton in eastern Texas and to the north and east (Figures 2 and 4). Compared with further east and north, western Texas has thick (≥ 35 km; Reguzzoni and Sampietro, 2014; Figure 4f) and weak crust, with effective elastic thicknesses (T_e) of 30–40 km (Cloetingh and Haq, 2015; Figure 4c). Heat flow is relatively high in the far western Trans-Pecos region and, to a lesser degree, in a concave-north arc extending southeast from there toward the Gulf Coast and then northeast toward southern Arkansas, with values ranging between about 65–105 mW m^{-2} (Jaupart and Mareschal, 2007; Figure 4d). In contrast, crustal thicknesses are less than 30 km in much of the southern and southeastern United States (Reguzzoni and Sampietro, 2014; Figure 4f) and heat flow is low in central and northern Texas (Jaupart and Mareschal, 2007; Figure 4d).



(a) Elevation map from 30 m spatial resolution ASTER image.

(b) U.S. Geological Survey Bouguer gravity anomaly map (Kucks, 1999a).

(c) Crustal effective elastic thickness (T_e) from Cloetingh and Haq (2015).

(d) Surface heat flow (modfied from Blackwell et al., 2011).

(e) U.S. Geological Survey magnetic anomaly map (Bankey et al., 2002).

(f) GEMMA1.0 crustal thickness (depth to Moho) model from Reguzzoni and Sampietro (2014).

(g) Shear-wave splitting directions from Yang et al. (2016).

(h) S-wave velocity at 90 km depth from Bedle and Van Der Lee (2009).

(i) Approximate depth to the lithosphere-asthenosphere boundary (lab) modified from Kumar et al. (2012).

Figure 4: Maps illustrating the lithospheric structure of Texas with the Stress Map of Texas overlain (stress measurement sources and symbols as in Figure 1).

The poorly imaged lithosphere-asthenosphere boundary (LAB) is of moderate depth (75–105 km) across Texas, but is deepest northeastward toward the craton, is shallowest westward toward the Basin and Range Province, and is within the shallow end of this range near the Gulf Coast (Plomerová et al., 2002; Rychert and Shearer, 2009; Abt et al., 2010; Fischer et al., 2010; Ainsworth et al., 2014; Figure 4i). It is likely that a ca. 75 km thick, layered lithosphere-asthenosphere transition zone underlies the LAB in this area (Ainsworth et al., 2014), which complicates interpretations of lithospheric thickness. S-wave velocities at 90 km depth (near the upper LAB) are significantly slower in a concave-north arc in southern Texas (Bedle and Van Der Lee, 2009; Figure 4h) that coincides with an area of slightly elevated heat flow (Figure 4d); fast S-wave velocities are observed in north-central Texas and northeastward into the center of the craton.

Gravity (Kucks, 1999b) and magnetic (Bankey et al., 2002; Figure 4e) maps show strong linear anomalies that have assisted with mapping crustal structures in the U.S. midcontinent and southwest (e.g. Keller et al., 1983; Buffler, 1991; Hinze et al., 1992; Adams and Keller, 1994; Adams and Miller, 1995; Adams and Keller, 1996; Harry and Londono, 2004). Prominent gravity and magnetic highs help delineate the WNW-trending Oklahoma aulacogen, a possible southward continuation of the north-trending Mesoproterozoic Midcontinent Rift system into western Texas (Adams and Keller, 1994; Adams and Miller, 1995; Adams and Keller, 1996), and north-trending Ancestral Rocky Mountains uplifts in western Texas (see Marshak et al., 2000; Section 1). In addition, a fabric of gravity and magnetic anomalies partly outlines basement domains (Figure 2) mapped by Lund et al. (2015), and the Llano province mapped by Whitmeyer and Karlstrom (2007). This imagery thus assists with building models of density and mechanical structure.

References

Abt, D.L., Fischer, K.M., French, S.W., Ford, H.A., Yuan, H., and Romanowicz, B., 2010, North American lithospheric discontinuity structure imaged by Ps and Sp receiver functions, v. 115: 1–24 p., doi:10.1029/2009JB006914.

Adams, D.C., and Keller, G.R., 1994, Possible extension of the Midcontinent Rift in west Texas and eastern New Mexico: Canadian Journal of Earth Sciences, v. 31, no. 4, p. 709–720, doi:10.1139/e94-063.

Adams, D.C., and Keller, G.R., 1996, Precambrian basement geology of the Permian basin region of west Texas and eastern New Mexico: A geophysical perspective: AAPG Bulletin, v. 80, no. 3, p. 410–431, doi:10.1306/64ED87FA-1724-11D7-8645000102C1865D.

Adams, D.C., and Miller, K.C., 1995, Evidence for late Middle Proterozoic extension in the Precambrian basement beneath the Permian basin: Tectonics, v. 14, no. 6, p. 1263–1272, doi:10.1029/95TC02317.

Adams, J.E., 1965, Stratigraphic-tectonic developement of Delaware Basin: AAPG Bulletin, v. 49, no. 11, p. 2140–2148.

Ainsworth, R., Pulliam, J., Gurrola, H., and Evanzia, D., 2014, Sp receiver function imaging of a passive margin: Transect across Texas's Gulf Coastal Plain: Earth and Planetary Science Letters, v. 402, p. 138–147, doi:10.1016/j.epsl.2014.05.056.

Aldrich, M.J.J., 1986, Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande Rift: Journal of Geophysical Research, v. 91, no. B2, p. 1753, doi:10.1029/JB091iB02p01753.

Aleinikoff, J.N., Reed, J.C., and Wooden, J.L.P., 1993, Lead isotopic evidence for the origin of Paleo- and Mesoproterozoic rocks of the Colorado Province, U.S.A.: Precambrian Research, v. 63, no. 1-2, p. 97–122, doi:10.1016/0301-9268(93)90007-O.

Alt, R.C., and Zoback, M.D., 2017, In situ stress and active faulting in Oklahoma: Bulletin of the Seismological Society of America, v. 107, no. 1, p. 216–228, doi:10.1785/0120160156.

Averill, M.G., and Miller, K.C., 2013, Upper crustal structure of the southern Rio Grande rift: A composite record of rift and pre-rift tectonics, *in* Geological society of america special papers, v. 494: p. 463–474, doi:10.1130/2013.2494(17).

Bankey, V., Cuevas, A., Daniels, D., Finn, C.A., Hernandez, I., Hill, P., Kucks, R.P., Miles, W., Pilkington, M., Roberts, C., Roest, W., Rystrom, V., Shearer, S., Snyder, S., Sweeney, R., Velez, J., Phillips, J., and Ravat, D., 2002, Digital data grids for the magnetic anomaly map of North America: U.S. Geological Survey Open-File Report 02-414.

Bedle, H., and Van Der Lee, S., 2009, S velocity variations beneath North America: Journal of Geophysical Research: Solid Earth, v. 114, no. 7, doi:10.1029/2008JB005949.

Bickford, M., Soegaard, K., Nielsen, K.C., and McLelland, J.M., 2000, Geology and geochronology of Grenville-age rocks in the Van Horn and Franklin Mountains area, west Texas: Implications for the tectonic evolution of Laurentia during the Grenville: Geological Society of America Bulletin, v. 112, no. 7, p. 1134–1148, doi:10.1130/0016-7606(2000)112<1134:GAGOGR>2.0.CO;2.

Blackwell, D.D., Richards, M.C., Frone, Z.S., Batir, J.F., Williams, M.A., Ruzo, A.A., and Dingwall, R.K., 2011, SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States,

Brewer, J.A., Good, R., Oliver, J.E., Brown, L.D., and Kaufman, S., 1983, COCORP profiling across the Southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko Basin: Geology, v. 11, no. 2, p. 109, doi:10.1130/0091-7613(1983)11<109:CPATSO>2.0.CO;2.

Buffler, R., 1991, Early evolution of the Gulf of Mexico basin, *in* Goldwaite, D., ed., An introduction to central gulf coast geology: American Association of Petroleum Geologists, p. 1–15.

Burchfiel, C., Cowan, D.S., and Davis, G.A.H., 1992, Introduction, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The geology of north america: The cordilleran orogen: Conterminous us, v. 3: Geological Society of America, p. 407–479.

Cannon, W.F., 1994, Closing of the Midcontinent rift-A far—field effect of Grenvillian compression: Geology, v. 22, no. 2, p. 155, doi:10.1130/0091-7613(1994)022<0155:COTMRA>2.3.CO;2.

Carlson, M.P., 2007, Precambrian accretionary history and Phanerozoic structures—A unified explanation for the tectonic architecture of the Nebraska region, USA, *in* Geological society of america memoirs, v. 200: Geological Society of America, p. 321–326, doi:10.1130/2007.1200(15).

Cartwright Jr., L.D., 1930, Transverse section of Permian basin, west Texas and southeast New Mexico: American Association of Petroleum Geologists Bulletin, v. 14, no. 8, p. 969–981.

Cloetingh, S.A., and Haq, B.U., 2015, Inherited landscapes and sea level change: Science, v. 347, no. 6220, p. 1258,375–1258,375, doi:10.1126/science.1258375.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, no. 7, p. 1073, doi:10.1130/0016-7606(1978)89<1073:RGSOTR>2.0.CO;2.

Crone, A.J., and Wheeler, R.L., 2000, Data for Quaternary faults, liquefaction features, and possible tectonic features in the Central and Eastern United States, east of the Rocky Mountain front: U.S. Geological Survey Open-File Report 00-260, p. 332.

Darold, A.P., and Holland, A.A., 2015, Preliminary Oklahoma Optimal Fault Orientations: Oklahoma Geological Survey Open File Report, v. OF4-2015, p. 2015.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: American Journal of Science, v. 304, no. 2, p. 105–168, doi:10.2475/ajs.304.2.105.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, no. 7, p. 353–368, doi:10.1130/GES00054.1.

Dickinson, W.R., and Gehrels, G.E., 2003, U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA: Paleogeographic implications: Sedimentary Geology, v. 163, no. 1, p. 29–66, doi:10.1016/S0037-0738(03)00158-1.

Duebendorfer, E.M., 2015, Refining the Early History of the Mojave-Yavapai Boundary Zone: Rifting versus Arc Accretion as Mechanisms for Paleoproterozoic Crustal Growth in Southwestern Laurentia: The Journal of Geology, v. 123, no. 1, p. 21–37, doi:10.1086/678950.

Engle, M.A., Reyes, F.R., Varonka, M.S., Orem, W.H., Ma, L., Ianno, A.J., Schell, T.M., Xu, P., and Carroll, K.C., 2016, Geochemistry of formation waters from the Wolfcamp and "Cline" shales: Insights into brine origin, reservoir connectivity, and fluid flow in the Permian Basin, USA: Chemical Geology, v. 425, p. 76–92, doi: 10.1016/j.chemgeo.2016.01.025.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot Rift: Reactivated precursor to the Mississippi embayment: Geological Society of America Bulletin, v. 86, no. 9, p. 1287, doi:10.1130/0016-7606(1975)86<1287:RRRPTT>2.0.CO;2.

Ewing, T.E., Budnik, R.T., Ames, J.T., and Ridner, D.M., 1990, Tectonic map of Texas: Austin, TX, Bureau of Economic Geology, University of Texas at Austin.

Ewing, T.E., and Lopez, R., 1991, Principal structural features, Gulf of Mexico Basin, *in* Salvador, A., ed., The gulf of mexico basin: The geology of north america: Geological Society of America.

Fischer, K.M., Ford, H.A., Abt, D.L., and Rychert, C.A., 2010, The Lithosphere-Asthenosphere Boundary: Annual Review of Earth and Planetary Sciences, v. 38, no. 1, p. 551–575, doi:10.1146/annurev-earth-040809-152438.

Galley, J.E., 1958, Oil and Geology in the Permian Basin of Texas and New Mexico: North America, *in* Aapg special volume sp 18: Habitat of oil: p. 395–446.

Galloway, W.E., 2008, Chapter 15: Depositional Evolution of the Gulf of Mexico Sedimentary Basin, *in* Sedimentary basins of the world, v. 5: Elsevier, p. 505–549, doi:10.1016/S1874-5997(08)00015-4.

Galloway, W.E., Whiteaker, T.L., and Ganey-Curry, P., 2011, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin: Geosphere, v. 7, no. 4, p. 938–973, doi: 10.1130/GES00647.1.

Galloway, W.E., and Williams, T.a., 1991, Sediment accumulation rates in time and space: Paleogene genetic stratigraphic sequences of the northwestern Gulf of Mexico basin: Geology, v. 19, no. 10, p. 986, doi:10.1130/0091-7613(1991)019<0986:SARITA>2.3.CO;2.

Gan, W., and Frohlich, C., 2013, Gas injection may have triggered earthquakes in the Cogdell oil field, Texas: Proceedings of the National Academy of Sciences of the United States of America, v. 110, no. 47, p. 18,786–18,791, doi:10.1073/pnas.1311316110.

Gilbert, M.C., 1983, Timing and chemistry of igneous events associated with the Southern Oklahoma Aulacogen: Tectonophysics, v. 94, no. 1-4, p. 439–455, doi:10.1016/0040-1951(83)90028-8.

Goldhammer, R.K., and Lehmann, P.J., 1993, The Origin of High-Frequency Platform Carbonate Cycles and Third-Order Sequences (Lower Ordovician El Paso Gp, West Texas): Constraints from Outcrop Data and Stratigraphic Modeling: SEPM Journal of Sedimentary Research, v. Vol. 63, no. 3, p. 318–359, doi:10.1306/D4267AFA-2B26-11D7-8648000102C1865D.

Green, G.N., and Jones, G., 1997, The Digital Geologic Map of New Mexico in ARC/INFO Format: U.S. Geological Survey Open File Report, v. 97-52, p. 9.

Handford, C.R., and Dutton, S.P., 1980, Pennsylvanian-Early Permian Depositional Systems and Shelf-Margin Evolution, Palo Duro Basin, Texas: AAPG Bulletin, v. 64, no. 1, p. 88–106, doi:10.1306/2F918932-16CE-11D7-8645000102C1865D.

Harry, D.L., and Londono, J., 2004, Structure and evolution of the central Gulf of Mexico continental margin and coastal plain, southeast United States: Geological Society of America Bulletin, v. 116, no. 1, p. 188, doi:10.1130/B25237.1.

Harry, D.L., Londono, J., and Huerta, a., 2003, Early Paleozoic transform-margin structure beneath the Mississippi coastal plain, southeast United States: Geology, v. 31, no. 11, p. 969–972, doi:10.1130/G19787.1.

Heidbach, O., Rajabi, M., Reiter, K., and Ziegler, M., 2016, The 2016 release of the World Stress Map: doi: 10.5880/WSM.2016.002.

Heller, R.J., 2013, Multiscale investigation of fluid transport in gas shales [Ph.D. thesis]: Stanford University, 166 p.

Henry, C.D., Price, J.G., and James, E.W., 1991, Mid-Cenozoic stress evolution and magmatism in the Southern Cordillera, Texas and Mexico: Transition from continental arc to intraplate extension: Journal of Geophysical Research, v. 96, no. B8, p. 13,545, doi:10.1029/91JB00202.

Herrmann, R.B., Benz, H.M., and Ammon, C.J., 2011, Monitoring the earthquake source process in North America: Bulletin of the Seismological Society of America, v. 101, no. 6, p. 2609–2625, doi:10.1785/0120110095.

Hinze, W.J., Allen, D.J., Fox, A.J., Sunwood, D., Woelk, T., and Green, A.G., 1992, Geophysical investigations and crustal structure of the North American Midcontinent Rift system: Tectonophysics, v. 213, no. 1-2, p. 17–32, doi: 10.1016/0040-1951(92)90248-5.

Holm, D.K., Schneider, D., Rose, S., Mancuso, C., McKenzie, M., Foland, K.a., and Hodges, K.V., 2007, Proterozoic metamorphism and cooling in the southern Lake Superior region, North America and its bearing on crustal evolution: Precambrian Research, v. 157, no. 1-4, p. 106–126, doi:10.1016/j.precamres.2007.02.012.

Jaupart, C., and Mareschal, J., 2007, Heat flow and thermal structure of the lithosphere: Treatise on Geophysics, v. 6, p. 1–55.

Jones, D.S., Barnes, C.G., Premo, W.R., and Snoke, A.W., 2013, Reactivation of the Archean-Proterozoic suture along the southern margin of Laurentia during the Mazatzal orogeny: Petrogenesis and tectonic implications of ca. 1.63 Ga granite in southeastern Wyoming: Geological Society of America Bulletin, v. 125, no. 1-2, p. 164–183, doi: 10.1130/B30577.1.

Keller, G.R., Hills, J.M., Baker, M.R., and Wallin, E.T., 1989, Geophysical and geochronological constraints on the extent and age of mafic intrusions in the basement of west Texas and eastern New Mexico: Geology, v. 17, no. 11, p. 1049, doi:10.1130/0091-7613(1989)017<1049:GAGCOT>2.3.CO;2.

Keller, G.R., Hills, J.M., and Djeddi, R., 1980, A regional geological and geophysical study of the Delaware basin, New Mexico and west Texas: Trans-Pecos Region (31st Field Conference Guidebook), , no. July, p. 105–111.

Keller, G.R., Lidiak, E., Hinze, W.J., and Braile, L., 1983, The role of rifting in the tectonic development of the midcontinent, U.S.A.: Tectonophysics, v. 94, no. 1-4, p. 391–412, doi:10.1016/0040-1951(83)90026-4.

Keller, G.R., Morgan, P., and Seager, W.R., 1990, Crustal structure, gravity anomalies and heat flow in the southern Rio Grande rift and their relationship to extensional tectonics: Tectonophysics, v. 174, no. 1-2, p. 21–37, doi:10.1016/0040-1951(90)90382-I.

Keppie, J.D., and Ramos, V.a., 1999, Odyssey of terranes in the Iapetus and Rheic oceans during the Paleozoic, *in* Special paper 336: Laurentia-gondwana connections before pangea, v. 336: Geological Society of America, p. 267–276, doi:10.1130/0-8137-2336-1.267.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, no. 1, p. 10, doi:10.1130/0091-7613(1981)9<10:PTOTAR>2.0.CO;2.

Kucks, R.P., 1999a, Bouguer gravity anomaly data grid for the conterminous US: .

Kucks, R.P., 1999b, Isostatic residual gravity anomaly data grid for the conterminous US,

Kumar, P., Kind, R., Yuan, X., and Mechie, J., 2012, USArray Receiver Function Images of the Lithosphere-Asthenosphere Boundary: Seismological Research Letters, v. 83, no. 3, p. 486–491, doi:10.1785/gssrl.83.3.486.

Leary, R.J., Umhoefer, P., Smith, M.E., and Riggs, N., 2017, A three-sided orogen: A new tectonic model for Ancestral Rocky Mountain uplift and basin development: Geology, v. 45, no. 7, p. G39,041.1, doi:10.1130/G39041.1.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu S., Natapov, L.M., Pease, V., Pisarevsky, S.a., Thrane, K., and Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: a synthesis: Precambrian Research, v. 160, no. 1, p. 179–210.

Loewy, S.L., Connelly, J.N., Dalziel, I.W., and Gower, C.F., 2003, Eastern Laurentia in Rodinia: constraints from whole-rock Pb and U/Pb geochronology: Tectonophysics, v. 375, no. 1-4, p. 169–197, doi:10.1016/S0040-1951(03)00338-X.

Lowe, D.R., 1985, Ouachita trough: Part of a Cambrian failed rift system: Geology, v. 13, no. 11, p. 790, doi:10.1130/0091-7613(1985)13<790:OTPOAC>2.0.CO;2.

Lund, K., Aleinikoff, J.N., Evans, K.V., DuBray, E.A., Dewitt, E.H., and Unruh, D.M., 2010, SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian-Early Ordovician alkalic magmatism in central Idaho: Implications for Rodinian rift tectonics: Bulletin of the Geological Society of America, v. 122, no. 3-4, p. 430–453, doi:10.1130/B26565.1.

Lund, K., Aleinikoff, J.N., Evans, K.V., and Fanning, C.M., 2003, SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits: Bulletin of the Geological Society of America, v. 115, no. 3, p. 349–372, doi:10.1130/0016-7606(2003)115<0349:SUPGON>2.0.CO;2.

Lund, K., Box, S.E., Holm-Denoma, C., San Juan, C., Blakely, R.J., Saltus, R., Anderson, E., and Dewitt, E.H., 2015, Basement Domain Map of the Conterminous United States and Alaska: U.S. Geological Survey Data Series 898, p. 41, doi:10.3133/ds898.

Lund Snee, J.E., and Zoback, M.D., 2016, State of stress in Texas: Implications for induced seismicity: Geophysical Research Letters, v. 43, no. 19, p. 10,208–10,214, doi:10.1002/2016GL070974.

Lund Snee, J.E., and Zoback, M.D., 2018, State of stress in the Permian Basin, Texas and New Mexico: Implications for induced seismicity: The Leading Edge, v. in press, no. January 2017, p. 810–819.

Magnani, M.B., Miller, K.C., Levander, A., and Karlstrom, K.E., 2004, The Yavapai-Mazatzal boundary: A long-lived tectonic element in the lithosphere of southwestern North America: Geological Society of America Bulletin, v. 116, no. 9, p. 1137, doi:10.1130/B25414.1.

Marshak, S., Karlstrom, K.E., and Timmons, J.M., 2000, Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States: Geology, v. 28, no. 8, p. 735, doi:10.1130/0091-7613(2000)28<735:IOPEFA>2.0.CO;2.

Marshak, S., Nelson, W.J., and McBride, J.H., 2003, Phanerozoic strike-slip faulting in the continental interior platform of the United States: examples from the Laramide Orogen, Midcontinent, and Ancestral Rocky Mountains: Geological Society, London, Special Publications, v. 210, no. 1, p. 159–184, doi:10.1144/GSL.SP.2003.210.01.10.

Marshak, S., and Paulsen, T., 1996, Midcontinent U.S. fault and fold zones: A legacy of Proterozoic intracratonic extensional tectonism?: Geology, v. 24, no. 2, p. 151, doi:10.1130/0091-7613(1996)024<0151:MUSFAF>2.3.CO;2.

McBride, J.H., and Nelson, W.J., 1999, Style and origin of mid-Carboniferous deformation in the Illinois Basin, USA—Ancestral Rockies deformation?: Tectonophysics, v. 305, no. 1-3, p. 249–273, doi:10.1016/S0040-1951(99)00015-3.

McLelland, J.M., Selleck, B.W., and Bickford, M., 2010, Review of the Proterozoic evolution of the Grenville Province, its Adirondack outlier, and the Mesoproterozoic inliers of the Appalachians, *in* The geological society of america memoir, v. 206: p. 21–49, doi:10.1130/2010.1206(02).

Mosher, S., 1998, Tectonic evolution of the southern Laurentian Grenville orogenic belt: Geological Society of America Bulletin, v. 110, no. 11, p. 1357–1375, doi:10.1130/0016-7606(1998)110<1357:TEOTSL>2.3.CO;2.

Paces, J.B., and Miller, J.D., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent Rift System: Journal of Geophysical Research, v. 98, no. B8, p. 13,997, doi:10.1029/93JB01159.

Perry, F.V., Baldridge, W.S., and DePaolo, D.J., 1987, Role of asthenosphere and lithosphere in the genesis of Late Cenozoic basaltic rocks from the Rio Grande Rift and adjacent regions of the southwestern United States: Journal of Geophysical Research, v. 92, no. B9, p. 9193–9213, doi:10.1029/JB092iB09p09193.

Perry, W.J., 1989, Tectonic Evolution of the Anadarko Basin Region, Oklahoma: US Geological Survey Bulletin 1866-A, p. 28.

Pindell, J.L., and Dewey, J.F., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, no. 2, p. 179–211, doi:10.1029/TC001i002p00179.

Pindell, J.L., and Kennan, L., 2013, Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update: Geological Society, London, Special Publications, v. 328, no. 1, p. 1–55, doi:10.1144/SP328.1.

Plomerová, J., Kouba, D., and Babuška, V., 2002, Mapping the lithosphere–asthenosphere boundary through changes in surface-wave anisotropy: Tectonophysics, v. 358, no. 1-4, p. 175–185, doi:10.1016/S0040-1951(02)00423-7.

Poole, F.G., Perry, W.J., Madrid, R.J., and Amaya-Martínez, R., 2005, Tectonic synthesis of the Ouachita-Marathon-Sonora orogenic margin of southern Laurentia: Stratigraphic and structural implications for timing of deformational events and plate-tectonic model, *in* Special paper 393: The mojave-sonora megashear hypothesis: Development, assessment, and alternatives, v. 393: Geological Society of America, p. 543–596, doi:10.1130/0-8137-2393-0.543.

Price, J.G., and Henry, C.D., 1984, Stress orientations during Oligocene volcanism in Trans-Pecos Texas: timing the transition from Laramide compression to Basin and Range tension (USA).: Geology, v. 12, no. April, p. 238–241, doi:10.1130/0091-7613(1984)12<238:SODOVI>2.0.CO;2.

Reese, J.F., Mosher, S., Connelly, J., and Roback, R., 2000, Mesoproterozoic chronostratigraphy of the southeastern Llano uplift, central Texas: Geological Society of America Bulletin, v. 112, no. 2, p. 278–291, doi:10.1130/0016-7606(2000)112<278:MCOTSL>2.0.CO;2.

Reguzzoni, M., and Sampietro, D., 2014, GEMMA: An Earth crustal model based on GOCE satellite data: International Journal of Applied Earth Observation and Geoinformation, v. 35, p. 31–43, doi:10.1016/j.jag.2014.04.002.

Rychert, C.A., and Shearer, P.M., 2009, A Global View of the Lithosphere-Asthenosphere Boundary: Science, v. 324, no. 5926, p. 495–498, doi:10.1126/science.1169754.

Salvador, A., 1987, Late Triassic-Jurassic Paleogeography and Origin of Gulf of Mexico Basin: AAPG Bulletin, v. 71, no. 4, p. 419–451, doi:10.1306/94886EC5-1704-11D7-8645000102C1865D.

Seager, W.R., and Morgan, P., 1979, Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua: Rio Grande Rift: Tectonics and magmatism, v. 14, p. 87–106, doi:10.1029/SP014p0087.

Seager, W.R., Shafiqullah, M., Hawley, J.W., and Marvin, R.F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, no. 1, p. 87, doi:10.1130/0016-7606(1984)95<87:NKDFBA>2.0.CO;2.

Shurbet, D.H., and Cebull, S.E., 1987, Tectonic interpretation of the westernmost part of the Ouachita-Marathon (Hercynian) orogenic belt, west Texas–Mexico: Geology, v. 15, no. 5, p. 458.

Simpson, R.W., 1997, Quantifying Anderson's fault types: Journal of Geophysical Research, v. 102, no. B8, p. 17,909–17,919, doi:10.1029/97JB01274.

Sims, P.K., Kisvarsanyi, E.B., and Morey, G.B., 1987, Geology and metallogeny of Archean and Proterozoic basement terranes in the northern midcontinent, U.S.A.—An overview: U.S. Geological Survey Bulletin 1815, p. 51.

Sone, H., 2012, Mechanical properties of shale gas reservoir rocks and its relation to the in-situ stress variation observed in shale gas reservoirs [Ph.D. thesis]: Stanford University, 225 p.

Swanson-Hysell, N.L., Burgess, S.D., Maloof, A.C., and Bowring, S.a., 2014, Magmatic activity and plate motion during the latent stage of Midcontinent Rift development: Geology, v. 42, no. 6, p. 475–478, doi:10.1130/G35271.1.

Thomas, W.A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, no. 3, p. 415–431, doi:10.1130/0016-7606(1991)103<0415:TAORMO>2.3.CO;2.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, no. 2, p. 4—-11, doi:10.1130/1052-5173(2006)016[4:TIAACM]2.0.CO;2.

Timmons, J.M., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., and Heizler, M.T., 2001, Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest- and north-trending tectonic grains in the southwestern United States: Bulletin of the Geological Society of America, v. 113, no. 2, p. 163–180, doi:10.1130/0016-7606(2001)113<0163:PMCAGE>2.0.CO;2.

Tohver, E., van der Pluijm, B.a., Van der Voo, R., Rizzotto, G., and Scandolara, J., 2002, Paleogeography of the Amazon craton at 1.2 Ga: early Grenvillian collision with the Llano segment of Laurentia: Earth and Planetary Science Letters, v. 199, no. 1-2, p. 185–200, doi:10.1016/S0012-821X(02)00561-7.

Van Schmus, W., Bickford, M., and Turek, A., 1996, Proterozoic geology of the east-central Midcontinent basement, *in* van der Pluijm, B.A., and Catacosinos, P.A., eds., Special paper 308: Basement and basins of eastern north america: Geological Society of America, p. 7–32, doi:10.1130/0-8137-2308-6.7.

Van Schmus, W., and Hinze, W.J., 1985, The Midcontinent Rift System: Annual Review of Earth and Planetary Sciences, v. 13, no. 1, p. 345–383, doi:10.1146/annurev.earth.13.1.345.

Van Schmus, W., Schneider, D., Holm, D.K., Dodson, S., and Nelson, B., 2007, New insights into the southern margin of the Archean–Proterozoic boundary in the north-central United States based on U–Pb, Sm–Nd, and Ar–Ar geochronology: Precambrian Research, v. 157, no. 1-4, p. 80–105, doi:10.1016/j.precamres.2007.02.011.

Vervoort, J.D., Wirth, K.R., Kennedy, B., Sandland, T., and Harpp, K.S., 2007, The magmatic evolution of the Midcontinent rift: New geochronologic and geochemical evidence from felsic magmatism: Precambrian Research, v. 157, no. 1, p. 235–268, doi:10.1016/j.precamres.2007.02.019.

Walker, N., 1992, Middle Proterozoic geologic evolution of Llano uplift, Texas: Evidence from U-Pb zircon geochronometry: Geological Society of America Bulletin, v. 104, no. 4, p. 494–504.

Whitmeyer, S., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, no. 4, p. 220, doi:10.1130/GES00055.1.

Wirth, E.A., and Long, M.D., 2014, A contrast in anisotropy across mid-lithospheric discontinuities beneath the central United States–A relic of craton formation: Geology, v. 42, no. 10, p. 851–854, doi:10.1130/G35804.1.

Xu, S., and Zoback, M.D., 2015, Analysis of stress variations with depth in the Permian Basin Spraberry / Dean / Wolfcamp Shale: American Rock Mechanics Association, v. 15-189.

Yang, B.B., Liu, K.H., Dahm, H.H., and Gao, S.S., 2016, A Uniform Database of Teleseismic Shear-Wave Splitting Measurements for the Western and Central United States: December 2014 Update: Seismological Research Letters, v. 87, no. 2A, p. 295–300, doi:10.1785/0220150213.

Yang, K.M., and Dorobek, S., 1995, The permian basin of West Texas and New Mexico: Tectonic history of a "composite" foreland basin and its effects on stratigraphic development, *in* Stratigraphic evolution of foreland basins, sepm publication no. 52: p. 149–170, doi:10.2110/pec.95.52.0149.

Ziegler, P.A., 1992, Plate tectonics, plate moving mechanisms and rifting: Tectonophysics, v. 215, no. 1-2, p. 9–34, doi:10.1016/0040-1951(92)90072-E.

Zoback, M.L., and Zoback, M.D., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, no. B11, p. 6113–6156, doi:10.1029/JB085iB11p06113.

Zoback, M.L., and Zoback, M.D., 1989, Tectonic Stress Field of the Continental United States, *in* Geological society of america memoirs, v. 172: p. 523–540, doi:10.1130/MEM172-p523.