

Initial Laramide tectonism recorded by Upper Cretaceous paleoseismites in the northern Bighorn Basin, USA: Field indicators of an applied end load stress

W.T. Jackson Jr.¹, M.P. McKay², M.J. Bartholomew³, D.T. Allison¹, D.L. Spurgeon², B. Shaulis⁴, J.A. VanTongeren⁵ and J.B. Setera⁵

¹Department of Earth Sciences, University of South Alabama, Mobile, Alabama 36688, USA

²Department of Geography, Geology and Planning, Missouri State University, Springfield, Missouri 65897, USA

³Department of Earth Sciences, The University of Memphis, Memphis, Tennessee 38152, USA

⁴Department of Geosciences, Trace Element and Radiogenic Isotope Laboratory (TRaIL), University of Arkansas, Fayetteville, Arkansas 72701, USA

⁵Department of Earth and Planetary Sciences, Rutgers University, New Brunswick, New Jersey 08901, USA

ABSTRACT

Soft-sediment deformational structures associated with paleoseismicity (e.g., planar clastic dikes) exist within Upper Cretaceous Mesaverde Group strata in the Laramide Elk Basin anticline, northern Bighorn Basin (Wyoming, USA). Retrodeformation of the Elk Basin anticline to a horizontal Mesaverde Group position indicates that all basement offset is removed and that clastic dikes exhibit a dominant northeast trend. The trend of clastic dikes corresponds to the interpreted northeast-southwest direction of early Laramide layer-parallel shortening, suggesting that the development of clastic dikes recorded initiation of basement deformation and Laramide tectonism. To determine the timing of clastic dike development, we present zircon U-Pb geochronology from the stratigraphically lowest sand-source bed generating upwardly injected clastic dikes and a volcanic bentonite bed (Ardmore bentonite) above the stratigraphic interval containing clastic dikes. Weighted mean ages bracket clastic dike development between 82.4 and 78.0 Ma. Our results imply initiation of basement deformation ~8–15 m.y. prior than other estimates in the Bighorn Basin. Therefore, we interpret the development of clastic dikes in the Elk Basin anticline to represent an initial phase of Laramide tectonism associated with an applied end load stress transmitted from the southwestern North American plate margin in response to the collision of the conjugate Shatsky Rise oceanic plateau ca. 90–85 Ma. Results demonstrate how sedimentary responses in the foreland can be used to understand tectonic processes at plate boundaries and provide spatial-temporal parameters for models of Laramide deformation.

INTRODUCTION

Late Cretaceous through Eocene Laramide-style (basement-involved) deformation occurred east of the Sevier thrust front in the western United States Cordillera (Fig. 1A; Dickinson and Snyder, 1978; DeCelles, 2004; English and Johnston, 2004; Yonkee and Weil, 2015). Spatial and temporal observations of Laramide deformation continue to motivate geodynamic models aimed at understanding the driving forces and mechanisms for intraplate tectonism. The onset and duration of Laramide deformation are temporally bracketed by the transition from marine to nonmarine sedimentation (Dickinson et al., 1988; Raynolds, 2003; Cather, 2004), crosscutting structural and stratigraphic relationships (Wiltschko and Dorr,

1983; Stone, 1993; Hoy and Ridgway, 1997; Cather, 2004; Tindall et al., 2010), basin subsidence (Mitrovica et al., 1989; Lawton, 1994; Heller et al., 2003; Leary et al., 2015), lulls in magmatic activity (Dickinson and Snyder, 1978; Humphreys, 2009), deposition of synorogenic strata (DeCelles et al., 1991), exhumation of basement arches (Omar et al., 1994; Crowley et al., 2002; Peyton et al., 2012), and paleoelevation estimates (Fan and Carrapa, 2014; Fan et al., 2014).

To describe these spatial and temporal relationships, models propose basal friction (e.g., Bird, 1998; Yonkee and Weil, 2015; Behr and Smith, 2016; Copeland et al., 2017), hydrodynamic stresses and flow in the asthenosphere (e.g., Liu et al., 2008; Jones et al., 2011; Heller

and Liu, 2016), and plate-margin end load stresses (e.g., Livaccari and Perry, 1993; Erslev, 1993; Tikoff and Maxson, 2001; Axen et al., 2018) as driving forces of Laramide tectonism. While models vary in methods and interpretations, flat-slab subduction of the Farallon plate is commonly required as a principal mechanism. Flattening of the Farallon plate beneath the North American lithosphere commenced at ca. 90–85 Ma, presumably in response to the arrival and subduction of a buoyant oceanic plateau, which was a conjugate feature to the Shatsky Rise in the modern western Pacific Ocean (Saleeby, 2003; Liu et al., 2010). Numerical models by Axen et al. (2018) show that an applied end load along the plate margin associated with the collision of the conjugate Shatsky Rise would have resulted in a compressional stress state in the overriding North American lithosphere, thereby promoting the development of Laramide tectonism. However, it remains unclear how the application of an end load stress would be recorded in the rock record and, if so, how the end load stress would be distributed throughout the Laramide belt.

Soft-sediment deformational structures form in response to natural processes such as rapid sedimentation and paleoseismicity (Obermeier, 1996; Audemard and Michetti, 2011; Owen and Moretti, 2011). Paleoseismites, defined as pre-Neogene soft-sediment deformational structures associated with paleoseismicity, record syndepositional tectonism prior to lithification and the onset of major orogenic events (Winslow, 1983; Bartholomew et al., 2002; Stewart et al., 2002; Bartholomew and Whitaker, 2010). Upper Cretaceous through Eocene strata in the northern

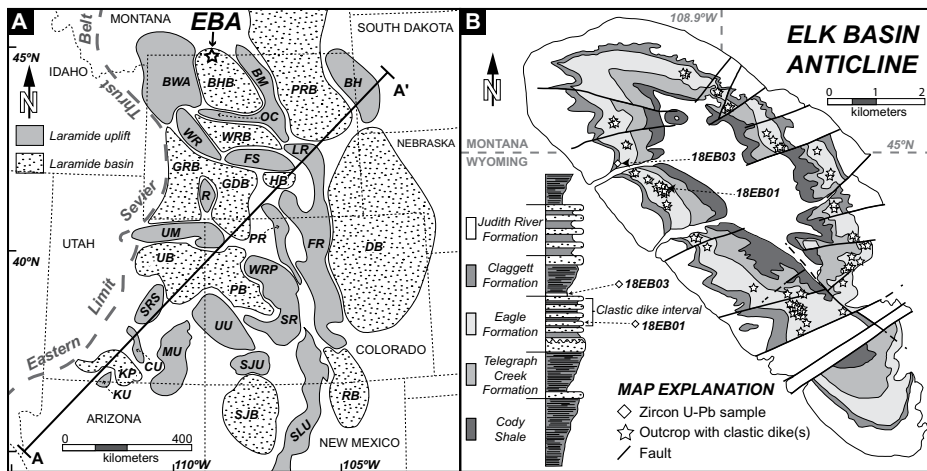


Figure 1. (A) Spatial distribution of Laramide arches and basins throughout western United States Cordillera, adapted from Heller and Liu (2016). Location of Elk Basin anticline (EBA) is denoted in northern Bighorn Basin (Wyoming, USA). A-A' line corresponds to section A-A' in Figure 4. BH—Black Hills; BHB—Bighorn Basin; BM—Bighorn Mountains; BWA—Beartooth, Washakie, Absaroka Ranges; CA—Casper Arch; CU—Circle uplift; DB—Denver Basin; FR—Front Range; FS—Ferris, Green, Seminoe, Shirley Mountains; GDB—Great Divide Basin; GRB—Green River Basin; HB—Hanna Basin; HM—Hogback monocline; KP—Kaiparowits Plateau; KU—Kaibab uplift; LR—Laramie Range; MU—Monument upwarp; OC—Owl Creek Mountains; PB—Piceance Creek Basin; PR—Park Range; PRB—Powder River Basin; R—Rock Springs uplift; RB—Raton Basin; SJB—San Juan Basin; SJU—San Juan uplift; SLU—San Luis uplift; SR—Sawatch Range; SRS—San Rafael Swell; UB—Uinta Basin; UM—Uinta uplift; UU—Uncompahgre uplift; WR—Wind River Range; WRB—Wind River Basin; WRP—White River Plateau. **(B)** Geologic map and generalized stratigraphic column of Elk Basin anticline with distribution of clastic dikes (stars) and locations of zircon U-Pb samples (diamonds). Geologic map and stratigraphic column adapted from Jackson et al. (2016) and Engelder et al. (1997), respectively.

Bighorn Basin (Wyoming, USA) contain paleoseismites that are interpreted to record Laramide deformation in the region (Bartholomew et al., 2008; Stewart et al., 2008; Jackson et al., 2016). Thus, the objective of this study was to bracket the timing of paleoseismite development in the northern Bighorn Basin in order to evaluate the spatial-temporal evolution of Laramide deformation as it relates to an applied end load stress. We present field observations and structural analysis of paleoseismites coupled with zircon U-Pb geochronology from Mesaverde Group strata in the Elk Basin anticline, northern Bighorn Basin.

ELK BASIN ANTICLINE

The Elk Basin anticline (Fig. 1B) is a north-west-southeast-trending fault-propagation fold structure (McCabe, 1948; Engelder et al., 1997). Beneath the anticline, the Elk Basin thrust fault displaces Wyoming Province basement rock ~1900 m to the northeast, with net slip dissipating toward the surface (Stone, 1993). The Elk Basin anticline is erosionally breached, exposing an ~250-m-thick sequence of Mesaverde Group strata (Fig. 1B). Mesaverde Group strata represent a progradational sequence of marine, shallow-marine, and nonmarine deposits along the western margin of the Cretaceous Interior Seaway (Swift and Rice, 1984; Fitzsimmons and Johnson, 2000; Swift et al., 2008). At the Elk Basin anticline, the Mesaverde Group is subdivided from oldest to youngest into the Telegraph Creek, Eagle, Claggett, and Judith River Formations (Fig. 1B).

Mesaverde Group strata are assigned Campanian ages based on ammonite biostratigraphy (Gill et al., 1972), paleomagnetic analysis (Hicks et al., 1995), and the age of the Ardmore bentonite bed (Hicks et al., 1999), a regionally correlatable unit located stratigraphically in the middle part of the Mesaverde Group (Bertog et al., 2007).

PALEOSEISMITES

Soft-sediment deformational structures in the form of clastic dikes, convolute bedding, and overturned subvertical vents (i.e., modern pipe features) are present within Mesaverde Group strata in the Elk Basin anticline (Bartholomew et al., 2008). We focused on clastic dike development for tectonic interpretations and to define the term paleoseismite because they provide the most direct evidence of soft-sediment deformational structures associated with seismic shaking (e.g., Tuttle and Seeber, 1991; Obermeier, 1996; Bourgeois and Johnson, 2001; Stewart et al., 2002). In the Elk Basin anticline, the Eagle Formation contains 71 outcrops with 145 clastic dike segments. Clastic dikes exhibit planar shapes (Figs. 2A–2C), tend to taper upward and/or terminate at the base of the overlying sandstone (Fig. 2D), and contain en echelon segments (Fig. 2E), indicating that they were injected along preexisting, mixed-mode (opening and shear) fracture avenues (Jackson et al., 2016). When the Elk Basin thrust fault is retro-deformed to a horizontal Mesaverde Group, a requirement for the generation of soft-sediment

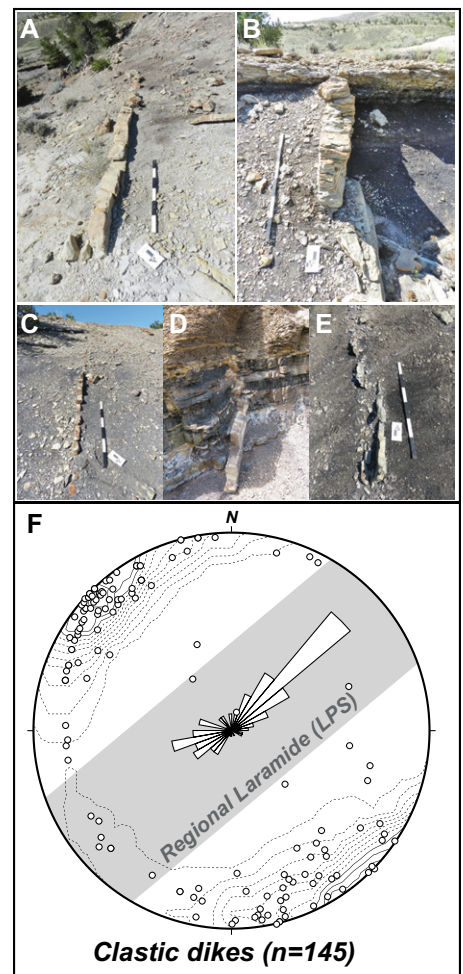


Figure 2. (A–E) Examples of clastic dikes in Elk Basin anticline (Wyoming, USA). Scale bar = 0.92 m. **(F)** Stereographic plot illustrating clastic dike measurements. Dots represent poles to bedding with corresponding 2σ contouring. Rose diagram demonstrates strike of unfolded clastic dikes corresponding to early Laramide layer-parallel shortening (LPS; gray shading) for Bighorn Basin and southern Wyoming (e.g., Weil and Yonkee, 2012).

deformational structures (e.g., Obermeier et al., 2002), all basement displacement is removed (Jackson et al., 2016). The unfolded strike of clastic dikes indicates a prominent northeast trend (Fig. 2F), which is compatible with interpreted early Laramide layer-parallel shortening directions in the Bighorn Basin and central Wyoming (e.g., Weil and Yonkee, 2012). Together, these observations suggest that the clastic dikes (paleoseismites) recorded seismic shaking associated with initial displacement of basement rock beneath the Elk Basin anticline.

GEOCHRONOLOGY

We dated the stratigraphically lowest sandstone bed in the Mesaverde Group (Eagle Formation) that produced upwardly injected clastic dikes (sample 18EB01) and a volcanic bentonite deposit (sample 18EB03) in the Claggett Formation (Fig. 1B). Zircon grains were separated and

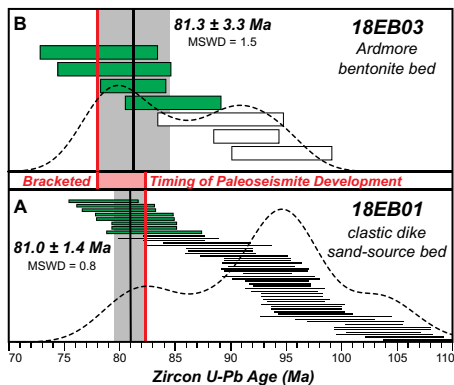


Figure 3. (A,B) Weighted mean averages of youngest zircon U-Pb age population for sample 18EB01 (A) and sample 18EB03 (B) in Elk Basin anticline, northern Bighorn Basin (Wyoming, USA). Samples are ordered relative to stratigraphic position. Horizontal bars represent 2σ error for individual analyses. Green bars indicate grains that were included in weighted mean age calculation. Dashed lines represent kernel density estimations for each sample at a bandwidth of 15. Bracketed timing of paleoseismite development from 82.4 to 78.0 Ma was established by using minimum 2σ age for 18EB03 and maximum 2σ age for sample 18EB01. MSWD—mean square of weighted deviates.

mounted using standard mineral extraction methods at Missouri State University (Springfield, Missouri, USA), and U-Pb analyses were conducted by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the University of Arkansas (Fayetteville, Arkansas) and Rutgers University (New Brunswick, New Jersey) (Table DR2 in the GSA Data Repository¹). Analyses that yielded discordant results (>30% discordant or 10% reverse discordant) or high U (>2000 ppm) were excluded. Reported ages for each sample are based on a weighted mean average of the youngest age population, which we defined as all grains within 2σ uncertainty of the youngest grain. Eight grains from sample 18EB01 were used to determine the weighted mean average of 81.0 ± 1.4 Ma (Fig. 3). Four grains from sample 18EB03 were used to determine the weighted mean average of 81.3 ± 3.3 Ma (Fig. 3).

Because the bentonite bed represents a volcanic deposit, we interpreted the weighted mean average for sample 18EB03 as an approximation of the true depositional age of that bed. The stratigraphic position of the bentonite bed above the clastic dike interval in the Mesaverde Group establishes the upper age bound for paleoseismite development in the Elk Basin anticline. This bentonite bed, regionally referred to as the Ardmore bentonite, is 80.04 ± 0.40 Ma based on Ar/Ar dating of biotite grains (Hicks et al., 1999).

¹GSA Data Repository item 2019369, Table DR1 (clastic dike field data) and Table DR2 (U-Pb geochronology), is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from editing@geosociety.org.

Obrovich (1993) and Hicks et al. (1995) dated the Ardmore bentonite bed in the Elk Basin anticline using Ar/Ar to 80.54 ± 0.55 Ma and 80.71 ± 0.55 Ma, respectively. Our weighted mean average is within error of all three age determinations for the Ardmore bentonite. Because the clastic dikes originated from the sand-source bed, we interpret the weighted mean average for sample 18EB01 as the lower age bound for paleoseismite development. Both of our detrital U-Pb age determinations correspond to regional ammonite zones (*Baculites obtusus*) and paleomagnetic results for the Mesaverde Group in the northern Bighorn Basin (Hicks et al., 1995). The overlap in our ages and previously reported age determinations suggests that Mesaverde Group strata were rapidly deposited in the northern Bighorn Basin region. This interpretation fits well with Late Cretaceous subsidence patterns for the Bighorn Basin (e.g., May et al., 2013). Our results indicate that the clastic dikes developed ca. 81 Ma; however, to provide an encompassing interpretation of the data, we use the minimum 2σ age uncertainty for sample 18EB03 (Ardmore bentonite) and the maximum 2σ age uncertainty for sample 18EB01 (sand-source bed) to bracket the development of clastic dikes from 82.4 to 78.0 Ma (Fig. 3).

DISCUSSION

Our interpretation of 82.4–78.0 Ma for initial Laramide tectonism in the Elk Basin anticline is ~8–15 m.y. older than other estimates for the Bighorn Basin (Peyton et al., 2012; Fan and Carrapa, 2014; Stevens et al., 2016; Beaudoin et al., 2018). However, our results do correlate to thermochronology results from the Beartooth Range, which bounds the Bighorn Basin to the west (Carrapa et al., 2019). Carrapa et al. (2019) suggested that early regional Laramide deforma-

tion and exhumation were products of propagating stress associated with enhanced intraplate coupling over the flat-slab region. We suggest a connection exists between the development of paleoseismites in the Elk Basin anticline and the collision of the conjugate Shatsky Rise along the southwestern North American plate margin ca. 90–85 Ma (e.g., Saleeby, 2003; Liu et al., 2010).

Collision of the conjugate Shatsky Rise with the North American plate margin established a compressional stress through the upper-mantle lithosphere (Axen et al., 2018). Weil et al. (2014) suggested that stress propagation through the North American plate was enhanced because of a relatively cold and thick lithosphere, while also noting that heterogeneities in the upper lithosphere often collect propagating stresses, resulting in preferred zones of deformation. Bader (2018) summarized how tectonically inherited basement anisotropies in the Wyoming Province controlled the spatial distribution of Laramide deformation in the Bighorn Basin region. Thus, we envision an applied end load stress, established at the plate margin, propagating through the overriding North American plate and coalescing at preexisting basement weaknesses, culminating in basement-involved thrusting. Displacement along basement rock then generated earthquake waves that applied a localized shear stress to unconsolidated, saturated sedimentary layers at or near the surface. The applied shear stress caused an increase in the pore-fluid pressure for the saturated sand-source layer, which overcame overburden pressures and produced soft-sediment deformational structures (e.g., clastic dikes). As the conjugate Shatsky Rise subducted into and past the trench, the Farallon plate transitioned to flat-slab subduction, resulting in subsequent, more traditionally interpreted Laramide deformation (Fig. 4).

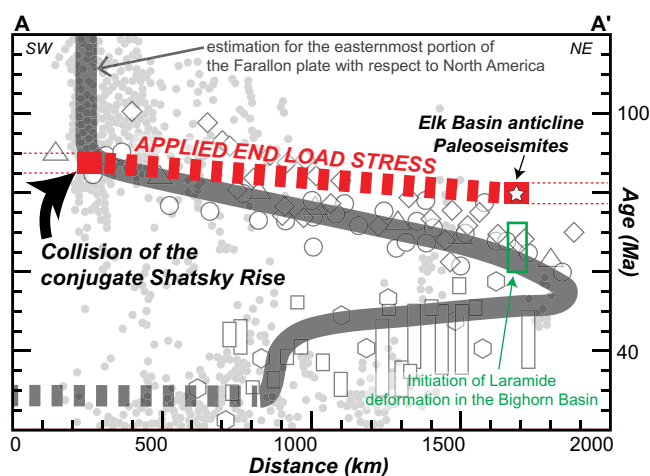


Figure 4. Plot illustrating spatial and temporal relationship between easternmost edge of Farallon plate (gray line) and southwestern North American plate margin (adapted from Copeland et al., 2017). This relationship incorporates magmatism (solid gray dots), modeled location of conjugate Shatsky Rise (triangles), youngest marine deposits (diamonds), timing of initiation of Laramide deformation (circles), timing of cessation of Laramide deformation (vertical bars), and attainment of maximum surface elevation (hexagons). We

correlated arrival and collision of conjugate Shatsky Rise to generation of paleoseismites (clastic dikes) in Elk Basin anticline, northern Bighorn Basin. Multi-million-year lag time from collision of conjugate Shatsky Rise to development paleoseismites in Elk Basin anticline (red dashed line) represents an opportunity to quantify relationships between sedimentary responses in foreland and tectonic processes at plate margin during Laramide tectonism. Because paleoseismites indicate Laramide tectonism 8–15 m.y. prior to estimations for Bighorn Basin (green box), we propose that paleoseismites are surficial features that record initial phase of basement deformation.

The predictive nature of our results provides motivation for future paleoseismic investigations. If paleoseismites in the Elk Basin anticline were products of an applied end load stress from the plate margin, similar soft-sediment deformational structures should be present in age-equivalent strata throughout the Laramide belt. In contrast, if the Elk Basin anticline paleoseismites were a result of localized Laramide deformation, and if similar paleoseismites are present throughout the Laramide belt, we would expect a spatial-temporal progression of paleoseismites with regard to their stratigraphic position, in either a southwest-northeast or, possibly, a northeast-southwest direction. Therefore, to evaluate models of Laramide deformation, we advocate for continued examination of Upper Cretaceous through Eocene soft-sediment deformational structures adjacent to Laramide structures in the western United States Cordillera.

CONCLUSIONS

The development of paleoseismites in the Elk Basin anticline recorded an initial phase of Laramide tectonism in the northern Bighorn Basin. By coupling the stratigraphic position of planar clastic dikes and zircon U-Pb geochronology, we can bracket the timing of paleoseismic development from 82.4 to 78.0 Ma. We propose that the development of paleoseismites represents a surficial expression of basement deformation, associated with an applied end load stress from the southwestern North American plate margin that resulted from the arrival and collision of the conjugate Shatsky Rise ca. 90–85 Ma. The applied end load stress propagated through the overriding North America lithosphere, spatially concentrating along preexisting basement heterogeneities. Earthquakes associated with the displacement of basement rock produced shear waves that traveled through and increased the pore-fluid pressure in unconsolidated, saturated sand layers, producing soft-sediment deformational structures (clastic dikes) at or near the surface. This study highlights the opportunity provided by Upper Cretaceous–Eocene paleoseismites for understanding the spatial-temporal development of Laramide deformation as well as the temporal relationships between tectonic processes at the plate margin and sedimentary responses in the foreland.

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REFERENCES CITED

Audemard, M.F.A., and Michetti, A.M., 2011, Geological criteria for evaluating seismicity revisited: Forty years of paleoseismic investigations and the natural record of past earthquakes, *in* Audemard, M., et al., eds., *Geological Criteria for Evaluating Seismicity Revisited: Forty Years of Paleoseismic Investigations and the Natural Record of Past Earthquakes*: Geological Society of America Special Papers, v. 479, p. 1–21, [https://doi.org/10.1130/2011.2479\(00\)](https://doi.org/10.1130/2011.2479(00)).

Axen, G.J., van Wijk, J.W., and Currie, C.A., 2018, Basal continental mantle lithosphere displaced by flat-slab subduction: *Nature Geoscience*, v. 11, p. 961–964, <https://doi.org/10.1038/s41561-018-0263-9>.

Bader, J.W., 2018, Structural inheritance and the role of basement anisotropies in the Laramide structural and tectonic evolution of the North American Cordilleran foreland, Wyoming: *Lithosphere*, v. 11, p. 129–148, <https://doi.org/10.1130/L1022.1>.

Bartholomew, M.J., and Whittaker, A.E., 2010, The Alleghanian deformational sequence at the foreland junction of the Central and Southern Appalachians, *in* Tollo, R.P., et al., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*: Geological Society of America Memoir 206, p. 431–454, [https://doi.org/10.1130/2010.1206\(19\)](https://doi.org/10.1130/2010.1206(19)).

Bartholomew, M.J., Brodie, B.M., Willoughby, R.H., Lewis, S.E., and Syms, F.H., 2002, Mid-Tertiary paleoseismites: Syndepositional features and section restoration used to indicate paleoseismicity, Atlantic Coastal Plain, South Carolina and Georgia, *in* Etensohn, F.R., Rast, N., and Brett, C.E., eds., *Ancient Seismites*: Geological Society of America Special Papers, v. 359, p. 63–74, <https://doi.org/10.1130/0-8137-2359-0.63>.

Bartholomew, M.J., Stewart, K.G., Wise, D.U., and Ballantyne, H.A., 2008, Field Guide: Paleoseismites of Laramide tectonism and other events near the Bighorn Basin, Montana and Wyoming: *Northwest Geology*, v. 37, p. 135–158.

Beaudoin, N., Lacombe, O., Roberts, N.M.W., and Koehn, D., 2018, U-Pb dating of calcite veins reveals complex stress evolution and thrust sequence in the Bighorn Basin, Wyoming, USA: *Geology*, v. 46, p. 1015–1018, <https://doi.org/10.1130/G45379.1>.

Behr, W.M., and Smith, D., 2016, Deformation in the mantle wedge associated with Laramide flat-slab subduction: *Geochemistry Geophysics Geosystems*, v. 17, p. 2643–2660, <https://doi.org/10.1002/2016GC006361>.

Bertog, J., Huff, W., and Martin, J.E., 2007, Geochemical and mineralogical recognition of the bentonites in the lower Pierre Shale Group and their use in regional stratigraphic correlation, *in* Martin, J.E., and Parris, D.C., eds., *The Geology and Paleontology of the Late Cretaceous Marine Deposits of the Dakotas*: Geological Society of America Special Papers, v. 427, p. 23–50, [https://doi.org/10.1130/2007.2427\(03\)](https://doi.org/10.1130/2007.2427(03)).

Bird, P., 1998, Kinematic history of the Laramide orogeny in latitudes 35–49N, western United States: *Tectonics*, v. 17, p. 780–801, <https://doi.org/10.1029/98TC02698>.

Bourgeois, J., and Johnson, S.Y., 2001, Geologic evidence of earthquakes at the Snohornish Delta, Washington, in the past 1200 yr: *Geological Society of America Bulletin*, v. 113, p. 482–494, [https://doi.org/10.1130/0016-7606\(2001\)113<0482:GEOEAT>2.0.CO;2](https://doi.org/10.1130/0016-7606(2001)113<0482:GEOEAT>2.0.CO;2).

Carrapa, B., DeCelles, P.G., and Romero, M., 2019, Early inception of the Laramide orogeny in southwestern Montana and northern Wyoming: Implications for models of flat-slab subduction: *Journal of Geophysical Research—Solid Earth*, v. 124, p. 2102–2123, <https://doi.org/10.1029/2018JB016888>.

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.A., eds., *The Geology of New Mexico: A Geologic History*: New

Mexico Geological Society Special Publication 11, p. 203–248.

Copeland, P., Currie, C.A., Lawton, T.F., and Murphy, M.A., 2017, Location, location, location: The variable lifespan of the Laramide orogeny: *Geology*, v. 45, p. 223–226, <https://doi.org/10.1130/G38810.1>.

Crowley, R.D., Reiners, P.W., Reuter, J.M., and Kaye, G.D., 2002, Laramide exhumation of the Bighorn Mountains, Wyoming: An apatite (U-Th)/He thermochronology study: *Geology*, v. 30, p. 27–30, [https://doi.org/10.1130/0091-7613\(2002\)030<0027:LEOTBM>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0027:LEOTBM>2.0.CO;2).

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: *American Journal of Science*, v. 304, p. 105–168, <https://doi.org/10.2475/ajs.304.2.105>.

DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pedraza, N., and Pivnik, D.A., 1991, Kinematic history of foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana: *Geological Society of America Bulletin*, v. 103, p. 1458–1475, [https://doi.org/10.1130/0016-7606\(1991\)103<1458:KHOAFU>2.3.CO;2](https://doi.org/10.1130/0016-7606(1991)103<1458:KHOAFU>2.3.CO;2).

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny, *in* Matthews, W., III, ed., *Laramide Folding Associated with Basement Block Faulting in the Western United States*: Geological Society of America Memoir 151, p. 355–366, <https://doi.org/10.1130/MEM151-p355>.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Jannecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: *Geological Society of America Bulletin*, v. 100, p. 1023–1039, [https://doi.org/10.1130/0016-7606\(1988\)100<1023:PAPSOL>2.3.CO;2](https://doi.org/10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2).

Engelder, T., Gross, M.R., and Pinkerton, P., 1997, An analysis of joint development in thick sandstone beds of the Elk Basin anticline, Montana-Wyoming, *in* Hoak, T.E., Klawitter, A.L., and Blomquist, P.K., eds., *Fractured Reservoirs: Characterization and Modeling*: Denver, Colorado, Rocky Mountain Association of Geologists, p. 1–18.

English, J.M., and Johnston, S.T., 2004, The Laramide orogeny: What were the driving forces?: *International Geology Review*, v. 46, p. 833–838, <https://doi.org/10.2747/0020-6814.46.9.833>.

Erslev, E.A., 1993, Thrusts, backthrusts and detachment of Laramide foreland arches, *in* Schmidt, C.J., Chase, R., and Erslev, E.A., eds., *Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States*: Geological Society of America Special Papers, v. 280, p. 125–146, <https://doi.org/10.1130/SPE280-p125>.

Fan, M., and Carrapa, B., 2014, Late Cretaceous–early Eocene Laramide uplift, exhumation, and basin subsidence in Wyoming: Crustal responses to flat slab subduction: *Tectonics*, v. 33, p. 509–529, <https://doi.org/10.1002/2012TC003221>.

Fan, M., Heller, P.L., Allen, S.D., and Hought, B.G., 2014, Middle Cenozoic uplift and concomitant drying in the central Rocky Mountains and adjacent Great Plains: *Geology*, v. 42, p. 547–550, <https://doi.org/10.1130/G35444.1>.

Fitzsimmons, R.J., and Johnson, S.D., 2000, Forced regressions: Recognition, architecture and genesis in the Campanian of the Bighorn Basin, Wyoming, *in* Hunt, D., and Gawthorpe, R.L., eds., *Sedimentary Responses to Forced Regressions*: Geological Society, London, Special Publications, v. 172, p. 113–139, <https://doi.org/10.1144/GSL.SP2000.172.01.06>.

Gill, J.R., Cobban, W.A., and Schultz, L.G., 1972, Correlation, ammonite zonation, and a reference

- section for the Montana Group, central Montana: *Montana Geological Society Guidebook*, 21st Annual Field Conference, p. 91–97.
- Heller, P.L., and Liu, L., 2016, Dynamic topography and vertical motion of the U.S. Rocky Mountain region prior to and during the Laramide orogeny: *Geological Society of America Bulletin*, v. 128, p. 973–988, <https://doi.org/10.1130/B31431.1>.
- Heller, P.L., Dueker, K., and McMillan, M.E., 2003, Post-Paleozoic alluvial gravel transport as evidence of continental tilting in the U.S. Cordillera: *Geological Society of America Bulletin*, v. 115, p. 1122–1132, <https://doi.org/10.1130/B25219.1>.
- Hicks, J.F., Obradovich, J.D., and Tauxe, L., 1995, A new calibration point for the Late Cretaceous time scale: The ⁴⁰Ar/³⁹Ar isotope age of the C^{33r}/C³³ⁿ geomagnetic reversal from the Judith River Formation (Upper Cretaceous), Elk Basin, Wyoming, USA: *The Journal of Geology*, v. 103, p. 243–256, <https://doi.org/10.1086/629744>.
- Hicks, J.F., Obradovich, J.D., and Tauxe, L., 1999, Magnetostratigraphy, isotope age calibration and intercontinental correlation of the Red Bird section of the Pierre Shale, Niobrara County, Wyoming, USA: *Cretaceous Research*, v. 20, p. 1–27, <https://doi.org/10.1006/cres.1998.0133>.
- Hoy, R.G., and Ridgway, K.D., 1997, Structural and sedimentological development of footwall growth synclines along an intraforeland uplift, east-central Bighorn Mountains, Wyoming: *Geological Society of America Bulletin*, v. 109, p. 915–935, [https://doi.org/10.1130/0016-7606\(1997\)109<0915:SASDOF>2.3.CO;2](https://doi.org/10.1130/0016-7606(1997)109<0915:SASDOF>2.3.CO;2).
- Humphreys, E., 2009, Relation of flat subduction to magmatism and deformation in the western United States, in Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., *Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrace Collision*: Geological Society of America Memoir 204, p. 85–98, [https://doi.org/10.1130/2009.1204\(04\)](https://doi.org/10.1130/2009.1204(04)).
- Jackson, W.T., Jr., Bartholomew, M.J., Dupre, W.R., Armstrong, T.F., and Stewart, K.G., 2016, Campanian paleoseismites of the Elk Basin anticline, northern Bighorn Basin, U.S.A.: A record of initial Laramide deformation: *Journal of Sedimentary Research*, v. 86, p. 394–407, <https://doi.org/10.2110/jsr.2016.28>.
- Jones, C.H., Farmer, G.L., Sageman, B., and Zhong, S., 2011, Hydrodynamic mechanism for the Laramide orogeny: *Geosphere*, v. 7, p. 183–201, <https://doi.org/10.1130/GES00575.1>.
- Lawton, T.F., 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States, in Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., *Mesozoic Systems of the Rocky Mountain Region*, USA: Denver, Colorado, Society of Sedimentary Geology (SEPM), p. 1–26.
- Leary, R., DeCelles, P., Gehrels, G., and Morriss, M., 2015, Fluvial deposition during transition from flexural to dynamic subsidence in the Cordilleran foreland basin: Ericson Formation, western Wyoming, USA: *Basin Research*, v. 27, p. 495–516, <https://doi.org/10.1111/bre.12085>.
- Liu, L., Spasojević, S., and Gurnis, M., 2008, Reconstructing Farallon plate subduction beneath North America back to the Late Cretaceous: *Science*, v. 322, p. 934–938, <https://doi.org/10.1126/science.1162921>.
- Liu, L., Gurnis, M., Seton, M., Saleeby, J., Muller, R.D., and Jackson, J.M., 2010, The role of oceanic plateau subduction in the Laramide orogeny: *Nature Geoscience*, v. 3, p. 353–357, <https://doi.org/10.1038/ngeo829>.
- Livaccari, R.F., and Perry, F.V., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: *Geology*, v. 21, p. 719–722, [https://doi.org/10.1130/0091-7613\(1993\)021<0719:IEFPOC>2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021<0719:IEFPOC>2.3.CO;2).
- May, S.R., Gray, G.G., Summa, L.L., Stewart, N.R., Gehrels, G.E., and Pecha, M.E., 2013, Detrital zircon geochronology from the Bighorn Basin, Wyoming, USA: Implications for tectonostratigraphic evolution and paleogeography: *Geological Society of America Bulletin*, v. 125, p. 1403–1422, <https://doi.org/10.1130/B30824.1>.
- McCabe, W.S., 1948, Elk Basin anticline, Park County, Wyoming, and Carbon County, Montana: *American Association of Petroleum Geologists Bulletin*, v. 32, p. 52–67.
- Mitrovica, J.X., Beaumont, C., and Jarvis, G.T., 1989, Tilting of continental interiors by dynamical effects of subduction: *Tectonics*, v. 8, p. 1079–1094, <https://doi.org/10.1029/TC008i005p1079>.
- Obermeier, S.F., 1996, Use of liquefaction-induced features for paleoseismic analysis: An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes: *Engineering Geology*, v. 44, p. 1–76, [https://doi.org/10.1016/S0013-7952\(96\)00040-3](https://doi.org/10.1016/S0013-7952(96)00040-3).
- Obermeier, S.F., Pond, E.C., Olson, S.M., and Green, R.A., 2002, Paleoliquefaction studies in continental settings, in Etensohn, F.R., Rast, N., and Brett, C.E., eds., *Ancient Seismites: Geological Society of America Special Papers*, v. 359, p. 13–27, <https://doi.org/10.1130/0-8137-2359-0.13>.
- Obradovich, J.D., 1993, A Cretaceous time scale, in Caldwell, W.G.E., and Kaufman, E.G., eds., *Evolution of the Western Interior Basin*: Geological Association of Canada Special Paper 39, p. 379–396.
- Omar, G.I., Lutz, T.M., and Giegengack, R., 1994, Apatite fission-track evidence for Laramide and post-Laramide uplift and anomalous thermal regime at the Beartooth overthrust, Montana-Wyoming: *Geological Society of America Bulletin*, v. 106, p. 74–85, [https://doi.org/10.1130/0016-7606\(1994\)106<0074:AFTEFL>2.3.CO;2](https://doi.org/10.1130/0016-7606(1994)106<0074:AFTEFL>2.3.CO;2).
- Owen, G., and Moretti, M., 2011, Identifying triggers for liquefaction-induced soft-sediment deformation in sands: *Sedimentary Geology*, v. 235, p. 141–147, <https://doi.org/10.1016/j.sedgeo.2010.10.003>.
- Peyton, S.L., Reiners, P.W., Carrapa, B., and DeCelles, P.G., 2012, Low-temperature thermochronology of the northern Rocky Mountains, western USA: *American Journal of Science*, v. 312, p. 145–212, <https://doi.org/10.2475/02.2012.04>.
- Raynolds, R.G., 2003, Upper Cretaceous and Tertiary stratigraphy of the Denver Basin, Colorado: *Rocky Mountain Geology*, v. 37, p. 111–134, <https://doi.org/10.2113/37>.
- Saleeby, J., 2003, Segmentation of the Laramide slab—Evidence from the southern Sierra Nevada region: *Geological Society of America Bulletin*, v. 115, p. 655–668, [https://doi.org/10.1130/0016-7606\(2003\)115<0655:SOTLSF>2.0.CO;2](https://doi.org/10.1130/0016-7606(2003)115<0655:SOTLSF>2.0.CO;2).
- Stevens, A.L., Balgord, E.A., and Carrapa, B., 2016, Revised exhumation history of the Wind River Range, WY, and implications for Laramide tectonics: *Tectonics*, v. 35, p. 1121–1136, <https://doi.org/10.1002/2016TC004126>.
- Stewart, K.G., Bartholomew, M.J., and Ballantyne, H.A., 2008, Laramide paleoseismites of the Bighorn Basin, in Raynolds, R.G., ed., *Roaming the Rocky Mountains and Environs: Geologic Field Trips*: Geological Society of America Field Guide 10, p. 249–263, [https://doi.org/10.1130/2008.fld010\(13\)](https://doi.org/10.1130/2008.fld010(13)).
- Stewart, K.G., Dennison, J.M., and Bartholomew, M.J., 2002, Late Mississippian paleoseismites from southeastern West Virginia and southwestern Virginia, in Etensohn, F.R., Rast, N., and Brett, C.E., eds., *Ancient Seismites: Geological Society of America Special Papers*, v. 359, p. 127–144, <https://doi.org/10.1130/0-8137-2359-0.127>.
- Stone, D.S., 1993, Basement-involved thrust-generated folds as seismically imaged in the subsurface of the central Rocky Mountain foreland, in Schmidt, C.J., Chase, R.B., and Erslev, E.A., eds., *Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States*: Geological Society of America Special Papers, v. 280, p. 271–318, <https://doi.org/10.1130/SPE280-p271>.
- Swift, D.J.P., and Rice, D.D., 1984, Sand bodies on muddy shelves: A model for sedimentation in the Western Interior Cretaceous Seaway, North America, in Tillman, R.W., and Siemers, C.T., eds., *Siliciclastic Shelf Sediments: Society of Sedimentary Geology (SEPM) Special Publication 34*, p. 43–62, <https://doi.org/10.2110/pec.84.34.0043>.
- Swift, D.J.P., Parson, S.B., and Howell, K.A., 2008, Campanian continental and shallow marine architecture in a eustatically modified clastic wedge: Mesa Verde Group, Wyoming, U.S.A., in Hampson, G.J., ed., *Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy: Society for Sedimentary Geology (SEPM) Special Publication 90*, p. 473–490.
- Tikoff, B., and Maxson, J., 2001, Lithospheric buckling of the Laramide foreland during Late Cretaceous to Paleogene, western United States: *Rocky Mountain Geology*, v. 36, p. 13–35, <https://doi.org/10.2113/gsrocky.36.1.13>.
- Tindall, S.E., Storm, L.P., Jenesky, T.A., and Simpson, E.L., 2010, Growth faults in the Kaiparowits Basin, Utah, pinpoint initial Laramide deformation in the western Colorado Plateau: *Lithosphere*, v. 2, p. 221–231, <https://doi.org/10.1130/L79.1>.
- Tuttle, M., and Seeber, L., 1991, Historic and prehistoric earthquake-induced liquefaction in Newbury, Massachusetts: *Geology*, v. 19, p. 594–597, [https://doi.org/10.1130/0091-7613\(1991\)019<0594:HAPAIL>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<0594:HAPAIL>2.3.CO;2).
- Weil, A.B., and Yonkee, A., 2012, Layer parallel shortening across the Sevier fold-thrust belt and Laramide foreland of Wyoming: Spatial and temporal evolution of a complex geodynamic system: *Earth and Planetary Science Letters*, v. 357–358, p. 405–420, <https://doi.org/10.1016/j.epsl.2012.09.021>.
- Weil, A.B., Yonkee, W.A., and Kendall, J., 2014, Towards a better understanding of the influence of basement heterogeneities and lithospheric coupling on foreland deformation: A structural and paleomagnetic study of Laramide deformation in the southern Bighorn Arch: *Geological Society of America Bulletin*, v. 126, p. 415–437, <https://doi.org/10.1130/B30872.1>.
- Wiltshcko, D.V., and Dorr, J.A., Jr., 1983, Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah: *American Association of Petroleum Geologists Bulletin*, v. 67, p. 1304–1322.
- Winslow, M.A., 1983, Clastic dike swarms and the structural evolution of the foreland fold and thrust belt of the southern Andes: *Geological Society of America Bulletin*, v. 94, p. 1073–1080, [https://doi.org/10.1130/0016-7606\(1983\)94<1073:CDSATS>2.0.CO;2](https://doi.org/10.1130/0016-7606(1983)94<1073:CDSATS>2.0.CO;2).
- Yonkee, W.A., and Weil, A.B., 2015, Tectonic evolution of the Sevier and Laramide belts within the North American Cordillera orogenic system: *Earth-Science Reviews*, v. 150, p. 531–593, <https://doi.org/10.1016/j.earscirev.2015.08.001>.