11-1-2019

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Recommended Citation

Jackson Jr, William T., Matthew P. McKay, M. J. Bartholomew, D. T. Allison, D. L. Spurgeon, B. Shaulis, J. A. VanTongeren, and J. B. Setera. "Initial Laramide tectonism recorded by Upper Cretaceous paleoseismites in the northern Bighorn Basin, USA: Field indicators of an applied end load stress." Geology 47, no. 11 (2019): 1059-1063.

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GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G46738.1

Manuscript received 18 February 2019
Revised manuscript received 9 August 2019
Manuscript accepted 17 August 2019

Published online 23 September 2019

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

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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

CITATION: Jackson, W.T., et al., 2019, Initial Laramide tectonism recorded by Upper Cretaceous paleoseismites in the northern Bighorn Basin, USA: Field indicators of an applied end load stress: Geology, v. 47, p. 1059–1063, https://doi.org/10.1130/G46738.1

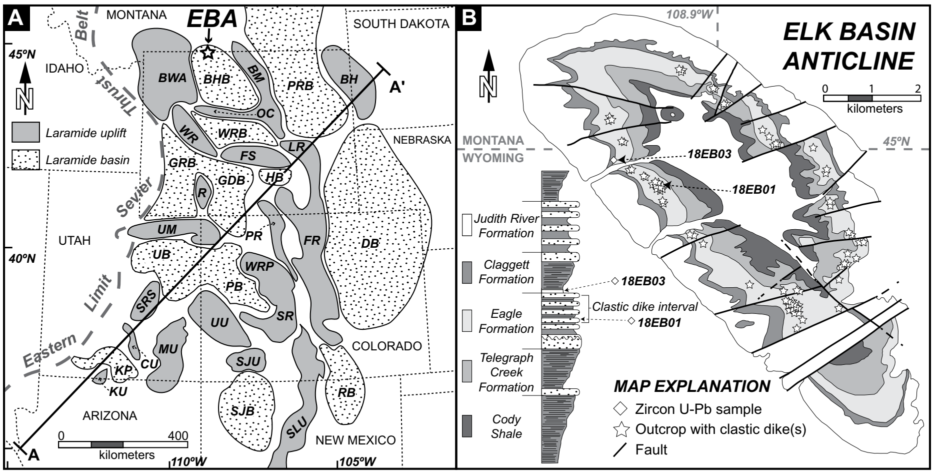

Figure 1. (A) Spatial distribution of Laramide arches and basins throughout western United States Cordillera, adapted from Heller and Liu (2016). Location of Elk Basin anticline (EBA) is denoted in northern Bighorn Basin (Wyoming, USA). A-A′ line corresponds to section A-A′ in Figure 4. BH—Black Hills; 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.

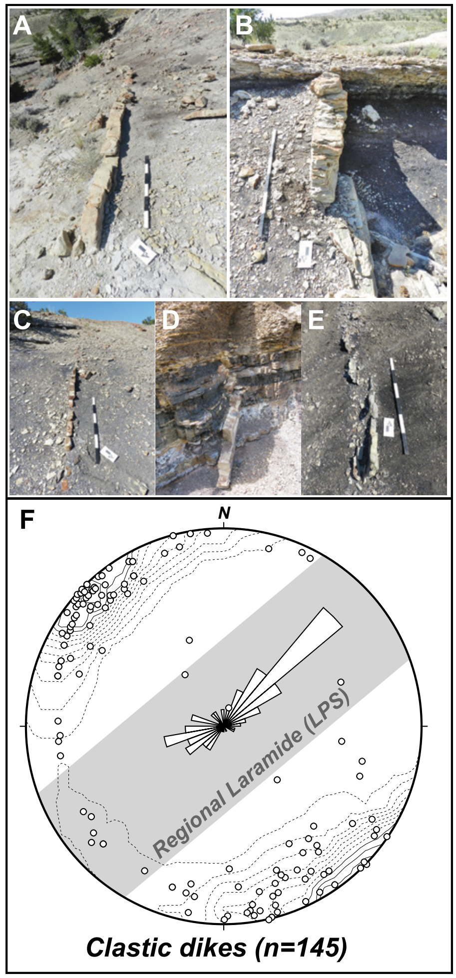

Figure 2. (A–E) Examples of clastic dikes in Elk Basin anticline (Wyoming, USA). Scale bar = 0.92 m. (F) Stereographic plot illustrating clastic dike measurements. Dots represent poles to bedding with corresponding 2σ contouring. Rose diagram demonstrates strike of unfolded clastic dikes corresponding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

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 northwest-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 retrodeformed to a horizontal Mesaverde Group, a requirement for the generation of soft-sediment 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 sand-source 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

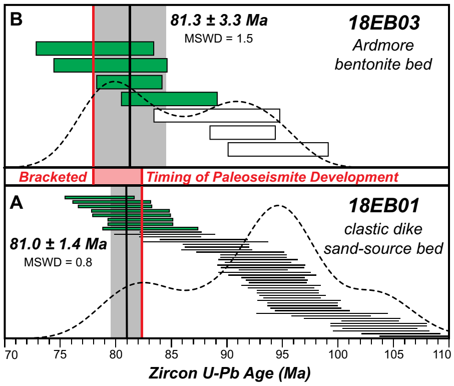

Figure 3. (A,B) Weighted mean averages of youngest zircon U-Pb age population for sample 18EB01 (A) and sample 18EB03 (B) in Elk Basin anticline, northern Bighorn Basin (Wyoming, USA). Samples are ordered relative to stratigraphic position. Horizontal bars represent 2σ error for individual analyses. 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 Repository[1]). 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). Obradovich (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 deformation 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).

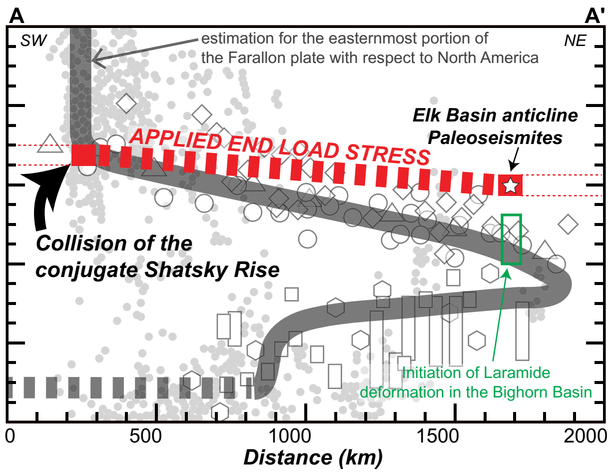

Figure 4. Plot illustrating spatial and temporal relationship between easternmost edge of Farallon plate (gray line) and southwestern North America plate margin (adapted from Copeland et al., 2017). This relationship incorporates magmatism (solid gray dots), modeled location of conjugate Shatsky Rise (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.

[1]GSA 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.

The predictive nature of our results provides motivation for future paleoseismite 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 paleoseismite 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.

ACKNOWLEDGMENTS

The Geological Society of America's Stephen E. Laubach Award and internal faculty awards from the University of South Alabama and Missouri State University supported this study. Previous discussions with William R. Dupré and Kevin G. Stewart aided in our paleoseismite interpretations. This work benefited from comments by Theresa M. Schwartz, Gary J. Axen, and two anonymous reviewers.

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