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
M. P. McKay
Missouri State University
M. J. Bartholomew
D. T. Allison
D. L. Spurgeon
MSU Graduate Student

See next page for additional authors

Follow this and additional works at: https://bearworks.missouristate.edu/articles-cnas

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.

This article or document was made available through BearWorks, the institutional repository of Missouri State University. The work contained in it may be protected by copyright and require permission of the copyright holder for reuse or redistribution. For more information, please contact BearWorks@library.missouristate.edu.
Authors
W. T. Jackson, M. P. McKay, M. J. Bartholomew, D. T. Allison, D. L. Spurgeon, B. Shaulis, J. VanTongeren, and J. B. Setera

This article is available at BearWorks: https://bearworks.missouristate.edu/articles-cnas/1149
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., M.P. McKay, M.J. Bartholomew, D.T. Allison, D.L. Spurgeon, B. Shaulis, J.A. VanTongeren and J.B. Setera

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 (TRaLL), University of Arkansas, Fayetteville, Arkansas 72701, USA
5Department of Earth and Planetary Sciences, Rutgers University, New Brunswick, New Jersey 08901, USA

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; Royd 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), hydromorphic 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., Livacci and Perry, 1993; Erselev, 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-Pliocene 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 Whittaker, 2010). Upper Cretaceous through Eocene strata in the northern...
Bighorn Basin (Wyoming, USA) contain paleo-seismites 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 paleo-seismitic 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 paleo-seismites 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 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 paleo-seismitism 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 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 Young, 2012). Together, these observations suggest that the clastic dikes (paleo-seismites) recorded seismic shaking associated with initial displacement of basement rock beneath the Elk Basin anticline.

**GEOCRONOLOGY**

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 paleoseismic 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.

Figure 4. Plot illustrating spatial and temporal relationship between eastwardly propagating 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, tectonic, 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.
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 paleoseismitic 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 paleoseismic interpretations. This work benefited from comments by Theresa M. Schwartz, Gary J. Axen, and two anonymous reviewers.

REFERENCES CITED

Audebard, M.F.A., and Michetti, A.M., 2011, Geologic criteria for evaluating seismicity revisited: Forty years of paleoseismic investigations and the natural record of past earthquakes, in Audebard, 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).

Axen, G.J., van Wijk, J.W., and Currie, C.A., 2018, Basal continental material replaced 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, Montana, and Idaho, Ph.D. thesis, v. 11, p. 129–148, https://doi.org/10.1130/1022.1.

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

Bartholomew, M.J., Brodie, B.M., Willoughby, R.H., Lewis, S.E., and Symhs, E.F., 2002, Mid-Tertiary paleoseismites: Synedpositional features and seismotectonic environments north of the Cretaceous–Eocene paleoseismites for understanding the 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/10.1130/8173-2359.063.

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/10.1002/2015GC006289.

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 Petrology of Bentonites in the Wyoming Basin System, western USA, v. 1, p. 81–103, https://doi.org/10.2475/ajs.304.2.105.

Bird, P., 1998, Kinematic history of the Laramide orogeny of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 203–248.

Copeland, C., Currie, C.A., Lawson, 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.

Crawley, 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.

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.s304.2.105.

DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N., and Pinvik, 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:KFHOUF>2.3.CO;2.

Dickinson, W.R., and Sykes, R.C., 1991, Plate tectonics of the Laramide orogeny, in Matthews, W., III, ed., Laramide Folding Associated with Basement Block Faulting in the Western United States: Geologic Society of America Memoir 151, p. 355–366, https://doi.org/10.1130/MEM151-p355.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Ja-
necke, 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:PBLSOL>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 antcline, 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. 275–288.

English, J.M., and Hoak, T.E., 2004, The Laramide orogeny: What were the driving forces?: International Geology Review, v. 46, p. 833–838, https://doi.org/10.1080/002068146.9.833.

Erslev, E.A., 1993, Thrusts, backthrusts and detach- ment of Laramide foreland arches, in Schmidt, C.J., Hoatson, R., and Swanson, M.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/10.1130/0163-SEP280-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 ad- jacent Great Plains: Geology, v. 42, p. 547–550, https://doi.org/10.1130/0091-7613(2014)042<0547:MCUICA>2.0.CO;2.

Fitzsimmons, R.J., and Johnson, S.D., 2000, Forced regressions: Recognition, architecture and gen- esis in the Campanian of the Bighorn Basin, Wy-oming, in Hunt, D., and Gawthrop, R.L., eds., Sedimentary Responses to Forced Regressions: Geological Society, London, Special Publications, v. 172, p. 113–139, https://doi.org/10.1144/GSL.SP.2000.172.01.06.

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