Subsurface Characterization of the Quaternary Active Cheraw Fault in Southeastern Colorado Based on Seismic Imaging

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Abstract
The subsurface structure of the late Quaternary active Cheraw fault is relatively unstudied. Vertical displacement estimates of faulted bedrock horizons, characteristics of bedrock structure (e.g., dip), potential association with dissolution of underlying Permian evaporite strata, and whether or not a postulated northeast extension of the topographic scarp is associated with Quaternary faulting have remained open questions. In this study, we assess six 2D seismic reflection profiles that cross the Cheraw fault scarp, demonstrate how Quaternary normal faulting has reactivated pre-existing structures along the northwest flank of the Las Animas arch, and provide new constraints for seismic hazard characterization. We map the fault to depths of at least 1.5–1.8 km into lower Paleozoic strata in which the continuity of the fault through Permian evaporite indicates that dissolution of those stratigraphic intervals has no role in Quaternary surface faulting. Interpretation of the seismic data reveals an \(\sim 75^\circ \pm 5^\circ\) northwest-dipping fault with \(\sim 24–30\) m vertical displacement of upper Cretaceous strata, which coincides with Quaternary scarps at the surface.

Introduction
The Cheraw fault (Fig. 1) is a crustal fault source in the U.S. Geological Survey (USGS) National Seismic Hazard Map (NSHM; Petersen et al., 2020) and the Electric Power and Research Institute (EPRI) central and eastern United States (CEUS) seismic source characterization (CEUS-SSCn, 2012). It is one of the few faults within the CEUS known to have experienced a surface-rupturing earthquake in the Holocene (CEUS-SSCn, 2012), and it contributes more ground-motion hazard to the Colorado Front Range communities than any other fault source (Petersen et al., 2020). Prior studies investigated paleoseismic earthquakes and mapped the Quaternary scarp. However, there remains limited information about the characteristics of bedrock structures of the subsurface Cheraw fault, and vertical displacement estimates are poorly constrained. This gap has created uncertainty for seismic source characterizations regarding the extent of possible Quaternary faulting and the potential for nontectonic origins.

Our analysis of six 2D seismic reflection profiles crossing the Cheraw fault shows how Quaternary scarps relate to bedrock structures along the central and northeast portions of the fault. This provides a basis for characterizing the subsurface structure of the fault in terms of its prior displacement history and rules-out evaporite dissolution as a causative factor for surface faulting. These results provide critical inputs for seismic source characterizations and the evaluation of regional earthquake hazards.

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### Geologic Setting

The Cheraw fault is an 80 km long normal fault on the western limb of the northeast-plunging Las Animas arch (LAA) in southeastern Colorado (Fig. 1). The LAA overlies a Proterozoic suture zone that experienced at least three periods of tectonic reactivation. In the Proterozoic eon, Mazatzal terrain accreted against Yavapai terrain along a convergent boundary, as recorded by northeast-trending structures within crystalline basement (Karlstrom and Bowring, 1988) that are coincident with the LAA. The LAA experienced uplift and stratigraphic thinning during the Ancestral Rocky Mountain (ARM) orogeny in the late Paleozoic from north-northwest regional compression driven by the Ouachita–Marathon orogeny (Kluth and Coney, 1981) or from other alternative explanations summarized in Leary et al. (2020). The structure was rejuvenated by Laramide shortening, which warped Cretaceous rocks into a broad anticline (Tweto, 1980; Curtis, 1988; Tickoff and Maxson, 2001). Post-Laramide activity is characterized by late-Quaternary extensional faulting along the Cheraw fault (Crone et al., 1997; Levandowski et al., 2017; Ostenaa and Zellman, 2018), and a transition to regional extension shown by stress models (Levandowski et al., 2018; Lund Snee and Zoback, 2020) and Global Navigation Satellite System data (Berglund et al., 2012).

The Cheraw fault was first described as a Quaternary feature by Scott (1970) and Kirkham and Rodgers (1981). Although Scott (1970) noted ~8 m of displacement in Quaternary alluvium, Sharps (1976) depicted a ~45 km long fault trending N45°E cutting upper Cretaceous Smoky Hill Shale Member of the Niobrara Formation (Fm.) but concealed beneath the same Quaternary deposits. A possible northeast extension of the fault was first published by Kirkham and Rodgers (1981), who recognized that the topographic scarp extends farther to the northeast. More recently, evaluations using USGS National Elevation Dataset 10 m digital elevation model data extended the scarp even farther to the northeast (See discussion in CEUS-SSCN, 2012). Geomorphic mapping with ~1 m lidar (Ostenaa and Zellman, 2018) now shows that Quaternary scarps extend about 35 km farther to northeast than the fault mapped by Sharps (1976), for a minimum length of 80 km (Fig. 1).

Prior investigators (Sharps, 1976; Crone et al., 1997) recognized the relatively limited total vertical displacement across the Cheraw fault based on the stratigraphic thickness of faulted and juxtaposed Cretaceous units (Fig. 2). Total vertical displacement is constrained by the 150–215 m estimated thickness of the Smoky Hills member of the Niobrara Fm. because neither the underlying Fort Hays member of the Niobrara Fm. nor overlying Pierre Shale are in contact with the Smoky Hills member along the fault. Structure contours for the top of the Dakota Fm. from Sharps (1976) depict a maximum of 6–8 m of vertical displacement across the Cheraw fault (Crone et al., 1997). On the southern part of the fault, Kirkham and Rodgers (1981) reported that Quaternary alluvium is displaced ~12 m. Crone et al. (1997) studied the same site and documented 3.2–4.1 m of late Quaternary vertical displacement from trenching, but they limited total Quaternary vertical displacement based on the structure contours from Sharps (1976). Investigations by Ostenaa and Zellman (2018) on the northeastern part of the fault showed the base of middle Quaternary deposits that have vertical displacement of ≤9 m.

Kirkham and Rodgers (1981) noted many closed depressions along the northwest side of the Cheraw fault. Closed depressions are also mapped on pediment surfaces capped with Quaternary alluvium displaced by the fault and are broadly distributed throughout southeastern Colorado (Sharps, 1976; Walker, 1985). The depressions range from tens to thousands of meters in width. Their origin is poorly understood, but possible explanations include topographic enclosure from faulting, aeolian deposition and deflation, local subsidence due to shallow dissolution of Niobrara Fm., and subsidence due to dissolution of deeper Permian evaporites (Walker, 1985; White, 2012). A prominent northwest–southeast alignment of three large (>1000 m wide) depressions intersects the northeastern end of the Cheraw fault. These large depressions are thought to be caused by the dissolution of Permian evaporite units (Walker, 1985; White, 2012) that are brought closer to the ground surface in the core of the LAA in which fractures and faults can bring water into contact with the soluble strata (Walker, 1985).

### Subsurface Analysis of the Cheraw Fault

We used six 2D seismic reflection profiles for the structural characterization of the Cheraw fault (Fig. 1). Two profiles (A and B) are parts of longer seismic lines that crossed the northeast extension of the Cheraw fault scarp at near-orthogonal angles. We reprocessed and depth-migrated profiles A and B for interpretation and analysis in this study. Four other profiles (C–F) are extracted from seismic lines that crossed the fault obliquely along a north–south alignment. Profiles C–F are shown as static images of time-domain profiles and were not reprocessed or depth migrated.
Figure 1. (a) Location map showing the Cheraw fault as mapped by Ostenaa and Zellman (2018) with prior paleoseismic study sites (black boxes) from (1) Ostenaa and Zellman and (2) Crone et al. (1997). Locations of seismic profiles used in this study are labeled A–F (darker lines, e.g., A\textsuperscript{d} are depth migrated; lighter lines, e.g., D\textsuperscript{t} are time domain). Base map with the Las Animas arch, borehole profile, and counties is modified from Merewether (1987). Inset map shows U.S. Geological Survey (USGS) National Seismic Hazard Map (NSHM) source faults (Shumway, 2019); the Cheraw fault is labeled (CF). Cities Denver (D), Colorado Spring (Cs), and Pueblo (P) are labeled along with physiographic regions and states. (b) Borehole profile modified from Merewether (1987) with top of select stratigraphic intervals and a schematic representation of the Cheraw fault. Hillshade basemap is from 30 m National Elevation Dataset (NED) digital elevation model (DEM) data.
Seismic profiles A and B were reprocessed by Eskaton Seismic, Inc., using the following sequence: geometry quality control, reflection statics, residual statics, noise attenuation, deconvolution, and poststack time migration. An interval velocity model was built by iteratively flattening prestack depth-migration gathers. Finally, the reprocessed time-domain data were depth migrated using reverse-time depth migration.

We assessed the 2D prestack depth-migration files for profiles A and B using IHS Kingdom software. Approximate geologic formation tops ranging in age from Cretaceous to Mississippian (Figs. 2 and 3) were attributed to seven seismic reflectors. The stratigraphic assignment was informed by the Sharps (1976) geologic map and the Colorado Oil and Gas Information System (COGIS) (2015) oil and gas well data within 5 km of each profile. Formation top depth picks from 17 wells near profile A and two wells near profile B were projected onto the seismic profiles and used to approximate formation top picks. Stratigraphic intervals older than the Mississippian St. Genevieve Fm., including Precambrian basement (Fig. 2), were not assigned because of sparse well control. We estimate the top of basement to be no less than ~260 m below the St. Genevieve Fm. in the vicinity of the Cheraw fault based on Merewether (1987) and top-of-basement contours by Hemborg (1996).

On the seismic profiles (Figs. 3 and 4), faults are mapped as solid lines where displaced, truncated, or warped reflectors support their presence, and dashed lines where inferred. The surface projection of the Cheraw fault identified in each profile aligns with the mapped location of the Quaternary scarp. The Cheraw fault’s apparent vertical displacement was measured by projecting prominent reflectors in depth-migrated profiles at scales of 1:1 in IHS Kingdom software. The extent of continuous reflectors on either side of the fault defines limits for the dip of planar faults cutting the sequence on each profile.

**Interpretation of seismic reflection profiles**

In all profiles (Figs. 3 and 4), the location of the subsurface Cheraw fault is defined by a zone (~250 m wide) of truncated, folded, and tilted reflectors. Fold amplitudes and apparent vertical displacements generally increase with depth. Scattering and incoherency around the Cheraw fault zone increases with depth in both depth-migrated profiles, but relatively more in profile A. Deformation of deep reflectors in profiles A and B shows that the Cheraw fault penetrates below Mississippian strata (unit Msg on Fig. 3). The time-domain images (Fig. 4) do not provide specific estimates of vertical fault displacement or dip, but they do show characteristics of faulting that are consistent with those seen in the depth-migrated data (Fig. 3). In all seismic profiles, we map a steep and planar fault that is superimposed on a broader, more complex deformation zone (~2000 m wide) with overall larger vertical displacement that extends through lower Paleozoic units before becoming obscured by poor data resolution.

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**Figure 2.** Stratigraphy of the Las Animas arch area modified from Merewether (1987). Key horizons mapped on Figure 3 are noted with unit abbreviations in circles. Approximate periods of major orogenic events are shaded and labeled. Cr., creek; Dol., dolomite; Fm., formation; Ls., limestone; Ss., sandstone.
In each seismic profile, the up-dip projection of the interpreted fault is spatially correlative with the map trace of the topographic scarp that characterizes the Quaternary Cheraw fault (Fig. 1). Seismic profiles A and B are oriented slightly oblique to the Cheraw fault (Fig. 1), so the fault dip in each image is apparent due to vertical exaggeration and the seismic line orientation relative to the fault strike. We estimate the average dip along this steeply dipping fault to be $\sim 75^\circ \pm 5^\circ$ to the northwest to depths of at least 1.8 km, based primarily on profile B. The estimated true dip in profile B ($\sim 73^\circ$) is favored over the dip estimated from profile A, because profile B is nearly orthogonal to the Cheraw fault ($\sim 83^\circ$ incidence), and the fault zone is visible deeper into the profile. Profile B is also closer to the central portion of the fault. The true dip in profile A is somewhat steeper ($\sim 78^\circ$), but data incoherence around the fault increases with depth.

**Evidence of recurrent deformation**

The strata imaged in the seismic profiles record at least three distinct periods of deformation (Fig. 2)—the shortening and uplift associated with the Paleozoic ARM orogeny and the late Cretaceous to early Cenozoic Laramide orogeny, and Neogene to modern northwest–southeast extension (Tweto, 1980; Curtis, 1988; Levandowski et al., 2017).

Analysis of the apparent vertical displacement of prominent reflectors across the Cheraw fault identifies at least two clear styles of faulting. In profiles A and B (Fig. 3), the depth-migrated 2D seismic reflection data indicate a steep, planar, apparently dip-slip fault, dipping $\sim 75^\circ \pm 5^\circ$ to depths of at least 1.8 km as seen in profile A or 1.5 km as seen in profile B. Along this discrete fault break, we observe $\sim 24–30$ m of...
apparent vertical displacement in upper Cretaceous units within a narrow zone around the fault (near-fault column in Table 1). In profile B, which lies closer to the center of the Quaternary scarp, vertical displacement is larger, with more complex structure and increased vertical displacement with depth in pre-Cretaceous units. Across a broader zone of tilting, folding, and faulting, vertical displacements are $\sim 50–100$ m in upper Cretaceous units and $\sim 60–160$ m in Mid-Cretaceous to older Mesozoic and Paleozoic units (far-field column in Table 1).

The LAA experienced uplift during the ARM orogeny in the Paleozoic era (Kluth and Coney, 1981; Leary et al., 2020). This period of deformation is recognized in the seismic data from reflectors that are faulted and tilted to a greater degree than is observed in the overlying younger strata. Hemborg (1996) infers major fault along the east side of the LAA, and the sense of displacement or dip angle is not indicated. This fault is not interpreted in the seismic profiles (Figs. 3 and 4). However, Paleozoic faults are shown in profile A (Fig. 3) to the northwest of the Cheraw fault. These faults are steeply dipping and exhibit apparent vertical displacement, probably due to a lateral or oblique slip. The strike of these faults is unknown, because they are not recognized in any other seismic profile included in this study. The most prominent Paleozoic-related fold is observed in both profiles A and B on the footwall of the Cheraw fault (Fig. 3). In both the profiles, the forelimb is intersected by the Cheraw fault, and the backlimb extends to the southeast toward the axis of the LAA. The upsection limit of

Figure 4. Uninterpreted (left) and interpreted (right) time domain seismic profiles. (a) Profile C, (b) profile D, (c) profile E, and (d) profile F. Arbitrary horizons and location of the Cheraw fault are shown (solid where certain, dashed where inferred, and arrows show relative motion). See Figure 1 for profile locations. Seismic data images are published with authorization from Seismic Exchange, Inc. (SEI). All interpretations are by the authors.
this fold is interpreted to be no younger than the Permian Blaine Fm., which suggests the largest growth must have occurred sometime in the mid-to-late Pennsylvanian period at the time of the ARM orogeny.

Post-Paleozoic deformation that includes northeast-directed Laramide shortening (Erslev et al., 2004) and modern north–southeast extension (Levandowski et al., 2017) is reflected in the seismic profiles (Figs. 3 and 4) as broadly warped Mesozoic strata and the vertical displacements that coincide with the surface trace of the Cheraw fault. Subtle warps and apparent truncations of Mesozoic strata through at least the Greenhorn Fm. over the near-vertical Paleozoic faults (Fig. 3 —profile A) suggest some reactivation of these faults since the late Cretaceous, but to a lesser extent than the nearby Cheraw fault. In profile B (Fig. 3), a similarly inferred Paleozoic fault is generally coincident with the secondary scarp (Fig. 1) mapped by Ostenaa and Zellman (2018) from lidar and inferred by Kirkham and Rodgers (1981). However, it cannot be mapped with confidence through the lower Cenozoic strata.

**Impact of Permian evaporites**

In the stratigraphic section underlying the Cheraw fault scarp, Permian evaporites are located between Pennsylvanian Virgilian Series carbonate rocks and the Triassic Dockum Group (Fig. 2). Some dissolution features mapped at the surface in southeastern Colorado are thought to be related to these evaporites, and Walker (1985) and White (2012) hypothesize that recent vertical displacement on the Cheraw fault may be related to dissolution of these units. In that case, seismic reflection images should show significant differences in stratigraphic thickness across the Cheraw fault, termination of the fault, or changes in vertical displacement at these horizons.
To evaluate this hypothesis, the approximate location of Permian evaporite deposits (unit Pb) was identified in the depth-migrated profiles (Fig. 3) based on the formation of top depth picks in local oil and gas wells (COGIS, 2015). The approximate depth to the top of the Permian evaporites, as shown in Figure 3, is 750 ± 30 m. The Permian units are characterized by a set of parallel, discontinuous, and wavy reflectors, which may have deformed as a result of dissolution and which are observed to directly overlie a continuous horizontal to subhorizontal reflectors. In both the depth-migrated and time-domain profiles (Figs. 3 and 4), the Cheraw fault can be seen to cut cleanly through Permian evaporite horizons into lower Paleozoic units. As discussed earlier, our interpretations of the profile data strongly indicate that the present surface trace of the Cheraw fault corresponds to a relatively planar structure that extends from the surface through lower Mississippian strata before becoming obscured in the data (Fig. 3). Thus, the hypothesis that recent vertical displacement on the Cheraw fault might be related to dissolution within the Permian evaporite section is not supported.

Implications for seismic source models

Evaluation of the 2D seismic reflection data shows that the Cheraw fault overprints a zone of older tectonic deformation and highlights the role of tectonic rejuvenation of pre-existing structural weakness. Each period of reactivation is recognized from changes in the style and magnitude of deformation through geologic time. These findings show the importance of fault-specific data in fault source characterizations for seismic hazard models.

We consider the minimum structural and rupture length of the Quaternary Cheraw fault to be 80 km, as defined by the surface scarps mapped by Ostenaa and Zellman (2018; Fig. 1). The strong similarity of bedrock structure and vertical displacements seen in all six seismic profiles (Figs. 3 and 4) suggests a similar displacement history consistent with the similar expression of the Quaternary surface fault scarps over that length.

The Cheraw fault interpretation in all seismic profiles is that of a planar and steeply dipping structure (Figs. 3 and 4). In depth-migrated seismic profiles A and B (Fig. 3), the Cheraw fault extends to a depth of at least 1.8 km into lower Paleozoic strata and probably into basement rocks with an average dip of ~75° ± 5°. This is a significantly steeper dip than previously modeled by the USGS NSHM (Petersen et al., 2020) or EPRI (CEUS SSCn, 2012), which give more weight to a dip of 50°. The USGS NSHM assigns lesser weight to 65° and 35° dips (Moschetti et al., 2015), and EPRI only considers the 35° dip alternative. The 2020 Magna earthquake near the Wasatch fault (Pang et al., 2020; Wesnousky, 2021, and references therein) is a recent example that is consistent with the lower (30°–35°) dip ranges of the prior seismic hazard models. Data compiled by Collettini (2011) show a dip distribution of 30°–75° for well-studied normal-faulting earthquakes with $M > 5.5$. The Cheraw fault dip lies at the upper end of that range, likely because Cheraw fault ruptures follow inherited steeply dipping structure derived from earlier tectonic stress regimes and faulting styles. Our data indicate that the characterization parameters for the Cheraw fault in seismic hazard models warrant significant weighting for steeper dips than “typical” normal faults.

Our interpretation of the seismic profiles shows total Cenozoic (i.e., post-Dakota Fm. [Kd]) vertical displacement on the Cheraw fault is 24–61 m (Table 1), much more than the 6–8 m implied from the Sharps (1976) structural contours. Increased vertical displacement and structural complexity with depth shows that the Cheraw fault is reactivating structures from early Cenozoic and older deformation events similar to other seismically active structures in the Intermountain West (e.g., Smith et al., 2021; Wesnousky, 2021, and references therein). Near the Cheraw fault and within the extent of profiles A and B (Fig. 3), these older deformational events were primarily compressional and likely produced folds and structures with lateral or oblique displacements and steep dips. However, it is not clear what proportion of the total Cenozoic vertical displacement estimated from the near-fault and far-field projections (Table 1) should be ascribed to late Cenozoic extension versus early Cenozoic compression.

We favor restricting late Cenozoic extensional vertical displacement primarily to the narrow, discrete zone of faulting seen on the profile A and B interpretations in Figure 3. In this interpretation, the broader zone of warping and tilting that extends 1000–2000 m horizontally from the main fault is seen as primarily related to the early Cenozoic (Laramide) compressional deformation, which may have also included oblique–reverse motion on the steeply dipping faults northwest of the Cheraw fault. Maximum late Cenozoic vertical displacement on the Cheraw fault defined by near-fault offset of the upper Cretaceous Greenhorn Fm. is about 30 m in profile B and 24 m in profile A (Table 1). Reduced vertical displacement seen in profile A may reflect decreasing overall displacement toward the northeast end of the fault. We do not identify any
Neogene or Quaternary reflectors in either profile, and the measured post mid-Quaternary vertical displacement near profile B is <9 m (Ostenaa and Zellman, 2018). The actual displacement associated with late Cenozoic extension could still be significantly less than the values estimated from profiles A and B. Conversely, if late Cenozoic extensional faulting includes a broader zone of tilting and warping, then late Cenozoic vertical displacement may be better represented by the far-field values in Table 1. That would imply that vertical displacements derived from surface profiles or trenching might have been missing additional slip and should also be measured from far-field values.

Conclusions
The results of this study support four broad conclusions: (1) the 80 km long Quaternary scarp of the Cheraw fault is associated with fault structure that dips about ~75° ± 5° to the northwest from the surface to at least 1.8 km depth and through Paleozoic Mississippian strata; (2) the Quaternary Cheraw fault reactivates pre-existing structures and has experienced multiple prior periods of activity; (3) total Cenozoic vertical displacement is <100 m, with late Cenozoic vertical displacement likely <30 m, but it is unclear how to partition vertical displacement between early Cenozoic reverse-oblique slip and late Cenozoic normal faulting; and (4) vertical surface displacements and shallow structure of the Cheraw fault are not impacted by Permian evaporite deposits, because the Cheraw fault structures extend to depths below the Permian units.

Data and Resources
Seismic data are shown herein with authorization from ConocoPhillips and Seismic Exchange, Inc. (SEI). All other data and resources used in this study are listed and cited in throughout the text and captions.

Declaration of Competing Interests
The authors declare no competing interests.

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References
Berglund, H. T., A. F. Sheehan, M. H. Murray, R. Mousumi, A. R. Lowry, R. S. Nerem, and F. Blume (2012). Distributed deformation across the Rio Grande rift, Great Plains, and Colorado plateau, Geology 40, no. 1, 23–26.

CEUS-SSCn (2012). Central and Eastern United States Seismic Source Characterization for Nuclear Facilities, EPRI, US DOE, and US NRC, Palo Alto, California.

Collettini, C. (2011). The mechanical paradox of low-angle normal faults: Current understanding and open questions, Tectonophysics 510, 253–268.

Colorado Oil and Gas Information System (COGIS) (2015). Oil and gas well database, available at http://cogcc.state.co.us/ (last accessed June 2021).

Crone, A. J., M. N. Machette, L. A. Bradley, and S. A. Mahan (1997). Late Quaternary surface faulting on the Cheraw fault, southeastern Colorado, U. S. Geol. Surv. Misc. Invest. I-2591, 7 pp., 1 pamphlet, 1 oversize pl.

Curtis, B. F. (1988). Sedimentary rocks in the Denver basin, in Basins of the Rocky Mountain region—Decade of North American Geology, D. L. Baars, B. L. Bartleson, and C. E. Chapin, et al. (Editors), Vol. D-2, Geological Society of America, The Geology of North America, Boulder, Colorado, 109–221.

Erslev, E. A., S. M. Holdaway, S. A. O’Meara, B. Jurista, and B. Selvig (2004). Laramide minor faulting in the Colorado Front Range, New Mex. Bur. Geol. Miner. Res. Bull. 160, 181–204.

Hemborg, T. (1996). Basement structure map of Colorado with major oil and gas fields, Colorado Geol. Surv. Map Series 30, plate 1.

Karlstrom, K. E., and S. A. Bowring (1988). Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America, J. Geol. 96, 561–576.

Kirkham, R. M., and W. P. Rodgers (1981). Earthquake potential in Colorado—A preliminary evaluation, Colorado Geol. Surv. Bull. 43, 171 pp., 3 pls.

Kluth, C. F., and P. J. Coney (1981). Plate tectonics of the Ancestral Rocky Mountains, Geology 9, no. 1, 10–15.

Leary, R. J., P. Umhoefer, M. E. Smith, T. M. Smith, J. E. Saylor, N. Riggs, G. Burr, E. Lodes, D. Foley, A. Licht, et al. (2020). Provenance of Pennsylvanian–Permian sedimentary rocks associated with the Ancestral Rocky Mountains orogeny in southwestern Laurentia: Implications for continental-scale Laurentian sediment transport systems, Lithosphere 12, no. 1, 88–122, doi: 10.1130/L1115.1.

Levandowski, W., R. B. Herrmann, R. W. Briggs, O. S. Boyd, and R. D. Gold (2018). An updated stress map of the continental United
States reveals heterogeneous intraplate stress, Nature Geosci. 11, 433–437.
Levandowski, W., M. S. Zellman, and R. W. Briggs (2017). Gravitational body forces focus North American intraplate earthquakes, Nat. Commun. 8, 14,314, doi: 10.1038/ncomms14314.
Lund Snee, J. E., and M. D. Zoback (2020). Multiscale variations of the crustal stress field throughout North America, Nat. Commun. 11, 1951, doi: 10.1038/s41467-020-15841-5.
Merewether, E. A. (1987). Oil and gas plays of the Las Animas arch, southeastern Colorado, U. S. Geol. Surv. Open-File Rept. 87-450D.
Moschetti, P. M., P. M. Powers, M. D. Petersen, O. S. Boyd, R. Chen, E. H. Field, A. D. Frankel, K. M. Haller, S. C. Harmsen, C. S. Mueller, et al. (2015). Seismic source characterization for the 2014 update of the U.S. National Seismic Hazard Model, Earthq. Spectra 31, no. 1, s31–s57, doi: 10.1193/110514EQS183M.
Ostena, D. A., and M. S. Zellman (2018). Paleoseismic investigation of the Cheraw fault at Haswell, Colorado, Colorado Geol. Surv. Paleoseismic Misc. Invest. MI-97.
Pang, G. N., K. D. Koper, M. Mesimeri, K. L. Pankow, B. Ben, J. Farrell, J. Holt, J. M. Hale, P. Roberson, R. Burlacu, et al. (2020). Seismic analysis of the 2020 Magna, Utah, earthquake sequence: Evidence for a Listric Wasatch fault, Geophys. Res. Lett. 47, no. 18, 10.
Petersen, M. D., A. M. Shumway, P. M. Powers, C. S. Mueller, M. P. Moschetti, A. D. Frankel, S. Rezaeian, D. E. McNamara, N. Luco, O. S. Boyd, et al. (2020). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications, Earthq. Spectra 36, no. 1, 5–41, doi: 10.1177/0278364917728138.
Scott, G. R. (1970). Quaternary faulting and potential earthquakes in east-central Colorado, U. S. Geol. Surv. Profess. Pap.700-C, C11–C18.
Sharps, J. A. (1976). Geologic map of the Lamar quadrangle, Colorado and Kansas, U. S. Geol. Surv. Misc. Invest. Map I-944, scale 1:250,000.
Shumway, A. M. (2019). Data release for the 2014 National Seismic Hazard Model for the Conterminous U.S., U. S. Geol. Surv. Data Release, doi: 10.5066/P9P77LGZ.
Smith, E. M., H. R. Martens, and M. C. Stickney (2021). Microseismic evidence for bookshelf faulting in western Montana, Seismol. Res. Lett. 92, 802–809, doi: 10.1785/0220200321.
Tickoff, B., and J. Maxson (2001). Lithospheric buckling of the Laramide foreland during late Cretaceous and Paleogene, western United States, Rocky Mt. Geol. 36, no. 1, 13–35.
Tweto, O. (1980). Tectonic history of Colorado, in Rocky Mountain Association of Geologists, H. C. Kent and K. W. Porter (Editors), Colorado Geology, Denver, Colorado, 5–9.
Walker, G. T. (1985). High plains depressions in eastern Colorado: Distribution, classification, and genesis, Unpublished Ph.D. Dissertation, University of Denver. Denver, Colorado.
Wesnousky, S. G. (2021). Seismotectonic snapshots: The 18 March 2020 Mw 5.7 Magna, 31 March 2020 Mw 6.5 Stanley, and 15 May 2020 Mw 6.5 Monte Cristo Intermountain West earthquakes, Seismol. Res. Lett. 92, 755–772, doi: 10.1785/0220200314.
White, J. L. (2012). Colorado map of potential evaporite dissolution and evaporite karst subsidence hazards: Map discussion, Colorado Geol. Surv. Open-File Rept. OF-12-02.

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