Learning Science Through Research
Published by the Keck Geology Consortium

Short Contributions
Keck Geology Consortium
Volume 35
May 2023
doi: 10.18277/AKRSG.2023.35.01

STRUCTURAL EVOLUTION OF THE SEGMENTED SEVIER NORMAL FAULT, SOUTHERN UTAH

BENJAMIN SURPLESS, Trinity University

INTRODUCTION

While it has long been recognized that major normal fault systems are commonly segmented in map view, as opposed to continuous, planar surfaces (e.g., Goguel, 1952; Tchalenko, 1970; Wallace, 1970; Schwartz and Coppersmith, 1984), only recently have researchers made significant advances in the role that segmentation plays in the evolution of these fault systems (e.g., Biddle and Christie-Blick, 1985; Crone and Haller, 1991; Peacock and Sanderson, 1996; Peacock, 2002). The geometry and relative strength of links between fault segments can strongly influence the propagation of slip during an earthquake (e.g., King and Nabalek, 1985; Crone and Haller, 1991; Zhang et al., 1991), and the perturbations of the local stress field caused by interaction of fault segments can influence the formation of relay ramps, minor faults, and associated fracture networks in transfer zones between synthetic normal fault segments (e.g., Peacock and Sanderson, 1996; Crider and Pollard, 1998; Faulds and Varga, 1998; Peacock, 2002).

In addition, the high fracture densities developed at these segment boundaries (e.g., Stock and Hodges, 1990; Hudson, 1992; Faulds, 1996) may enhance fluid flow, thus increasing rates of groundwater flow (e.g., Rowley, 1998), permitting hydrocarbon migration (e.g., Morley et al., 1990), or promoting ore mineralization (e.g., DeWitt et al., 1986). Because normal faults that typically develop in sedimentary basins, where natural resources commonly occur, are relatively planar and steeply-dipping in cross-section, with displacements of up to hundreds of meters (e.g., Peacock, 2002), well-exposed fault systems with these characteristics permit researchers to shed light on the evolution of similar faults in the subsurface. In this Keck Utah Advanced Project, students used the Sevier fault zone in southern Utah (Fig. 1), a segmented normal fault system with ~600 – 700 m dip-slip displacement, to investigate the structural evolution of a normal fault transfer zone across a range of spatial scales.

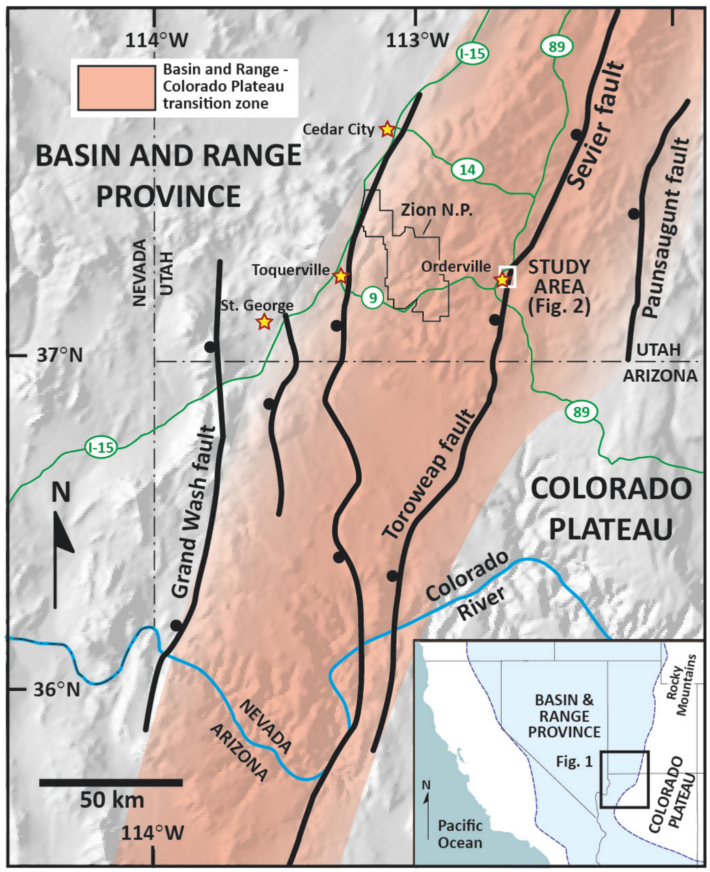

Figure 1. Physiographic context for the Sevier fault zone study area within the Basin and Range-Colorado Plateau transition zone (see inset). In combination with the Grand Wash, Hurricane, and Paunaugunt faults, the Sevier-Toroweap fault helps accommodate extension across the transition zone. Ball is on the hanging wall of the west-dipping faults. Detailed structure of the study area (boxed) is displayed in Figure 2. Digital shaded relief modified from Thelin and Pike (1991). Figure modified from Reber et al. (2001) and Surpless and McKeighan (2022).

STUDY AREA

The Sevier normal fault, considered one of the most important structures in the Basin and Range province (e.g., Davis, 1999; Lund et al., 2008), is part of the Toroweap-Sevier fault system, which extends for more than 300 km from northern Arizona to southern Utah (Fig. 1). The fault has accommodated extension across the transition zone from the Basin and Range province to the relatively stable Colorado Plateau since the Miocene (e.g., Reber et al., 2001; Lund et al., 2008), and previous workers have noted the potential of the fault to produce significant earthquakes (Anderson and Rowley, 1987; Doelling and Davis, 1989; Anderson and Christenson, 1989; Lund et al., 2008). It is likely that many segments of the Sevier fault reactivate older high-angle, Laramide-age contractional structures (e.g., Stewart and Taylor, 1996; Schiefelbein and Taylor, 2000), which may explain why the steeply-west-dipping fault zone is segmented in map view, with variations in the geometry of the linkages between normal fault segments (e.g., Davis, 1999; Reber et al., 2001; Schiefelbein, 2002; Doelling, 2008).

In this project, students focused their investigations on a particularly complex portion of the Sevier fault zone, termed the Orderville geometric bend (e.g., Reber et al., 2001) (Fig. 2). The Orderville bend displays a range of geometries associated with the interactions of three fault segments, which include the Mt. Carmel segment, the Orderville segment, and the Spencer Bench segment. The interaction of these 3 fault segments is likely responsible for the formation of the minor faults (displayed in white) and relay ramps shown adjacent to Red Hollow Canyon and Stewart Canyon (Fig. 2); these features likely evolved within the perturbed stress field associated with the transfer zones between dominant fault segments (Fig. 3).

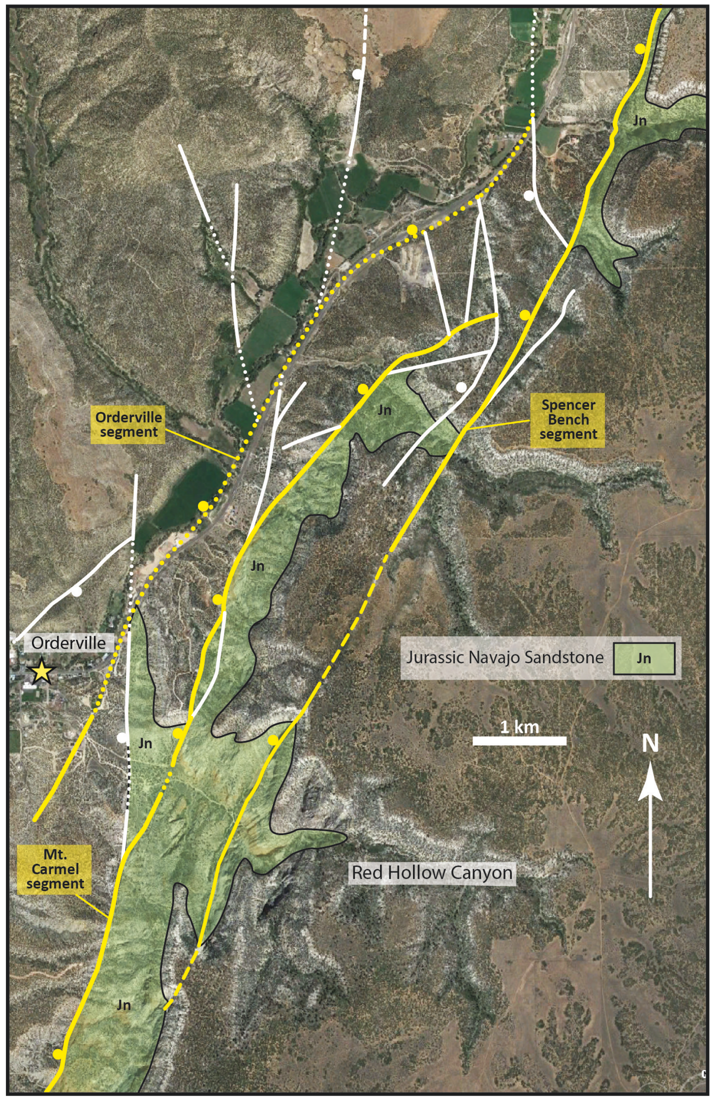

Figure 2. Structure map of the fault network within the Orderville geometric bend of the Sevier fault zone. Thick yellow lines are primary segments of the Sevier fault zone. Green shading indicates outcrop extent of the Jurassic Navajo Sandstone (Jn). Ball symbols on hanging wall of normal faults. Faults shown here are based primarily on mapping performed by Schiefelbein (2002) and our mapping, at 1:12,000 scale or larger. See Figure 1 for location. Figure modified from Surpless and McKeighan (2022).

STUDENT PROJECTS

The excellent vertical and lateral exposure of the Jurassic Navajo sandstone at the two primary study areas, at Red Hollow Canyon and Elkheart Cliffs (Fig. 2), provided students opportunity to directly observe faults, fractures, and deformation bands within these well-studied lithologies (e.g., Rogers et al., 2004; Schultz et al., 2010; Solom et al., 2010). The Elkheart Cliffs exposure (Fig. 2) displays the simplest fault geometry because the Mt. Carmel segment accommodates all E-W extension. In contrast, at Red Hollow Canyon, extensional strain is accommodated by a more complex system that includes the Orderville relay ramp and several other faults (Fig. 2). This spatial variation in fault complexity allows student researchers to treat these two locations as end members, permitting them to evaluate how the evolution of different fault geometries damages adjacent rock volumes (Fig. 3).

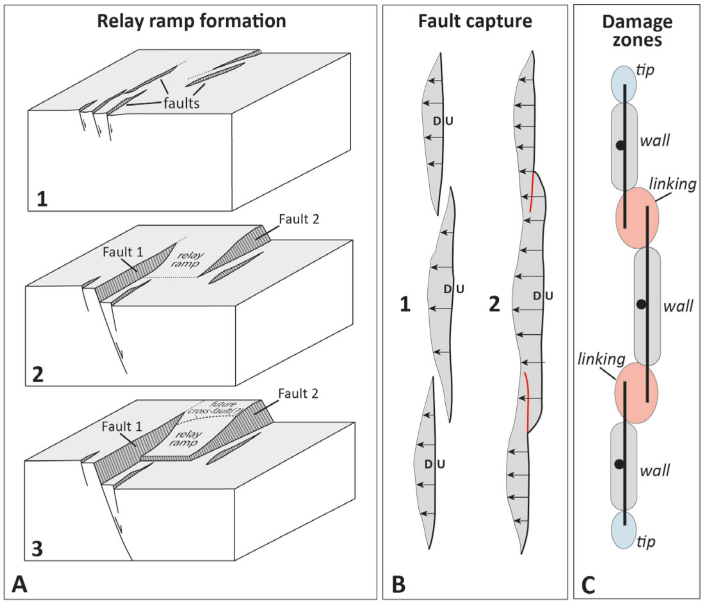

Figure 3. Diagrams displaying relay ramp development, fault capture, and damage zone classification. A) In all diagrams, the dark gray shaded area represents the magnitude of displacement, and the lines represent the slip direction as the hanging wall drops relative to the footwall. 1. A system of small-displacement faults develops to accommodate upper crustal stresses. The dotted lines represent the future propagation of the faults. 2. As displacement increases across the system, two faults (1 and 2) become dominant, both lengthening in map view and displaying increasing total displacement. A relay ramp forms in the zone of overlap between the faults. 3. Faults 1 and 2 link as a new cross-fault connects them. A future cross-fault may form where indicated, fully breaching the relay ramp. B) Map-view of a segmented fault system (bold lines are faults), with 1 and 2 representing progressive stages of fault segment linkage and capture. In 1, the three fault segments overlap but are only soft linked, and in 2, one of the segments has "captured" displacement from the other segments, isolating the overlapped portions of segments (red lines) that are no longer active. The segments are now hard linked and act as a single, corrugated fault. Arrows show the direction and relative magnitude of fault slip projected onto plan view. C) Schematic map view diagram of damage zone types associated with a segmented normal fault system (bold lines) with ball symbols on the hanging wall. Figure A. adapted from Peacock (2002) and Long and Imber (2011), Figure B. adapted from Reber et al. (2001), and Figure C. adapted from Kim et al. (2004).

To address fundamental questions about how rock volumes respond to the evolution of complex, segmented, normal fault systems, students applied a variety of approaches, including analysis of field data, 3D digital modeling and analysis of photographic data, development of a 3D retrodeformable model of the fault network based on previously published cross-sections and map data, and 3D stress-strain modeling of fault and fracture formation and propagation. Their work improves our understanding of the 3D evolution of fracture networks in complex normal fault zones, which has important implications for natural resource exploration.

Audrey Jennings (Trinity University) analyzed stress, strain, and fracture evolution using the Fault Response Modeling module of the Move 2020 software suite (by Petex). She created 3D models of a 2-fault-segment system, consistent with the approximate geometries of the Mt. Carmel and Spencer Bench segments of the steeply-dipping Sevier system (Fig. 2), at increasing levels of overlap. Models included a single layer defined by the mechanical properties of Navajo Sandstone, which is better exposed than any other lithology in the study area. Audrey modeled throw, stress, strain, and fracture orientation and intensity at varying fault slip displacements, ranging from 25 to 400 m.

All models showed the highest strain at fault tips, with strain also transferred between tips. Of her models, the less overlapped systems had the most intense strain fields between tips. Throw gradually changed from highly negative to slightly positive in this zone, indicating the initial development of a highly-fractured relay ramp, which thus would have high geothermal potential. In all models, fracturing is most intense in zones of elevated stress and strain fields, with fractures curving to connect tips, a feature best revealed in models where the fault segments display lesser overlap. Fracture intensity is higher in the hanging wall of segments, with vertical fractures roughly parallel to the fault. Due to predicted high strain and fracture density, Audrey confirmed that fault tips in segmented normal faults are promising for geothermal energy. Furthermore, she learned that slightly underlapped or overlapped faults represent the most likely setting for fracturing that might promote geothermal production.

Jasper Neath (Trinity University) used the Move2020 modeling suite (by Petex) to develop a viable 3D model of the complexly-segmented Sevier fault zone based on previously published geologic maps and cross-sections. He focused primarily on the fault network displayed in Fig. 2. With previously published geologic maps and cross-sections (Schiefelbein, 2002) as a base, he digitized geologic layers and fault horizons to build a 3D model of the fault network. He used his model to test the validity of initial cross-sectional interpretations, because earlier subsurface interpretations in cross-sections were based on surface mapping rather than direct documentation of subsurface fault and layer geometries.

Because the cross-sectional lengths of individual layers should remain constant from their initial length to their deformed length, Jasper was able to test the viability of cross-section interpretations of subsurface structure with the restorable 3D models he developed. Where lengths were not consistent, we noted that subsurface model characteristics such as fault dip, magnitude of fault displacement, fault shape, spatial relationships between fault segments, or undocumented blind faults might be required. Jasper's work set the stage for future researchers, with the hope that eventually, several research questions can be addressed. These include: 1) How do the displacement and propagation of separate fault segments interact to form the present-day complexity exposed along the Orderville fault network? 2) How is strain accommodated along these fault zones at different stages of fault zone evolution? and 3) How do permeability and fluid flow pathways change as a segmented fault zone evolves?

Michelle Nishimoto (Wellesley College) used field data and Strucure-from-Motion (SfM) model analysis to investigate how fault-tip damage zones develop (Fig. 3) in response to fault propagation and displacement due to amplification of stresses at the fault tip. Because fractures initiate as a result of stresses exceeding rock strength and propagate based on the stress field at the fault tip, Michelle investigated the damage zone of the Spencer Bench segment near Orderville, Utah (Fig. 2), focusing on fractures that developed within the Jurassic Navajo Sandstone, the Temple Cap Formation, and the oldest beds of the Carmel Formation. Because normal faults grow laterally as slip and displacement increase, she focused on the tip zone of the Spencer Bench fault segment where fracturing is well-exposed.

Utilizing unmanned-aerial-vehicle (UAV) flights to capture high-resolution imagery of inaccessible rock exposures, Michelle constructed structure-from-motion (SfM) virtual outcrop models (VOMs) that she georeferenced and analyzed using Agisoft Metashape Professional, 3D modeling software. Based on those models, Michelle collected and analyzed fracture orientation and intensity data in the field and with VOMs.

Both types of data revealed an asymmetrical fracture intensity distribution proximal to the fault, with higher fracture intensity in the hanging wall relative to the footwall. The damage zone asymmetry she documented is consistent with some previous normal fault damage zones studies. Michelle also documented similar footwall damage zone widths in the same lithology, the Jurassic Navajo Sandstone, proximal to both the Mt. Carmel and Spencer Bench segments. Because the Mt. Carmel segment accommodates approximately 800 m dip-slip displacement while the Spencer Bench segment accommodates less than 10-m displacement, Michelle's work revealed that damage zone width must be established very early in the evolution of a fault, so damage zone width will not increase with increasing displacement.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Keck Geology Consortium and the National Science Foundation under Grant No. 2050697. It was also supported by NSF Award 2042114 to PI Surpless. Finally, funding was provided by the Geosciences Department at Trinity University, including funding from the Roy and Tinker Funds to support undergraduate student research.

REFERENCES

Anderson, R.E., and Christenson, G.E., 1989, Quaternary faults, folds, and selected volcanic features in the Cedar City 1°x2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89-6, 29 p.

Anderson, J.J., and Rowley, P.D., 1987, Geologic map of the Panguitch NW quadrangle, Iron and Garfield Counties, Utah: Utah Geological and Mineral Survey Map 103, 8 p. pamphlet, scale 1:24,000.

Biddle, K.T., and Christie-Blick, N., 1985, Strike – slip deformation, basin formation, and sedimentation, In: Biddle, K.T., Christie-Blick, N., Eds.: Strike– Slip Deformation, Basin

Formation, and Sedimentation. Society of Economic Mineralogists Special Publication, v. 37, p. 375– 386.

Crider, J., and Pollard, D., 1998, Fault linkage: Three-dimensional mechanical interaction between echelon normal faults: Journal of Geophysical Research, v. 103, p. 24,373 – 24,391.

Crone, A.J., and Haller, K.M., 1991, Segmentation and the coseismic behavior of Basin and Range normal faults: examples from east-central Idaho and southwest Montana, U.S.A.: Journal of Structural Geology, v. 13, p. 151– 164.

Davis, G., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342.

DeWitt, E., Thompson, J., and Smith, R., 1986, Geology and gold deposits of the Oatman district, northwestern Arizona: U.S. Geologic Survey Open-File Report 86-0638, 34 p.

Doelling, H.H., 2008, Geologic map of the Kanab 30’x60’ quadrangle, Kane and Washington Counties, Utah, and Coconino and Mohave Counties, Arizona, 1:100,000-scale: Utah Geological Survey, MP-08-2DM.

Doelling, H.H., and Davis, F.D., 1989, The geology of Kane County, Utah, with sections on petroleum and carbon dioxide by Cynthia J. Brandt: Utah Geological and Mineral Survey Bulletin 124, 192 p., scale 1:100,000, 10 plates.

Faulds, J., 1996, Geologic map of the Fire Mountain 7.5’ quadrangle, Clark County, Nevada, and Mohave County, Arizona: Nevada Bureau of Mines and Geology Map 106, scale 1:24,000 (with accompanying text).

Faulds, J., and Varga, R., 1998, The role of accommodation zones and transfer zones in the regional segmentation of extended terranes, In Faulds, J.E., and Stewart, J.H., Eds., Accommodation zones and transfer zones: the regional segmentation of the Basin and Range province: Geological Society of America Special Paper No. 343, p. 1 – 45.

Goguel, J., 1952, Traite de Tectonique: Masson, Paris (Translated by Thalmann, H.E., 1962). Tectonics: Freeman Publishing Company, San Francisco, 384 p.

Hudson, M., 1992, Paleomagnetic data bearing on the origin of arcuate structures in the French Peak – Massachusetts Mountain area of southern Nevada: Geological Society of America Bulletin, v. 104, p. 581 – 594.

Kim, K.-S., Peacock, D., and Sanderson, D., 2004, Fault damage zones: Journal of Structural Geology, v. 26, p. 503–517.

King, G.C.P., and Nabalek, J.L., 1985, The role of bends in faults in the initiation and termination of earthquake rupture: Science, v. 228, p. 984 – 987.

Long, J., and Imber, J., 2011, Geological controls on fault relay zone scaling: Journal of Structural Geology, v. 33, p. 1790 – 1800.

Lund, W.R., Knudsen, T.R., and Vice, G.S., 2008, Paleoseismic reconnaissance of the Sevier fault, Kane and Garfield Counties, Utah: Utah Geologic Survey Special Study 122, Paleoseismology of Utah, v. 16, 31 p.Lowe, D., 2004, Distinctive image features from scale invariant keypoints: International Journal of Computer Vision, v. 60, p. 91–110, doi: 10 .1023 /B: VISI .0000029664 .99615.94.

Morley, C., Nelson, R., Patton, T., and Munn, S., 1990, Transfer zones in the East African Rift system and their relevance to hydrocarbon exploration in rifts: American Association of Petroleum Geologists Bulletin, v. 74, p. 1234 – 1253.

Peacock, D.C.P., 2002, Propagation, interaction and linkage in normal fault systems: Earth-Science Reviews, v. 58, p. 121 – 142.

Peacock, D.C.P., and Sanderson, D.J., 1996, Effects of propagation rate on displacement variations along faults: Journal of Structural Geology, v. 18, p. 311 –320.

Reber, S., Taylor, W., Stewart, M., and Schiefelbein, I., 2001, Linkage and Reactivation along the northern Hurricane and Sevier faults, southwestern Utah, In XXX, Eds., The Geologic Transition, High Plateaus to Great Basin – A Symposium and Field Guide, The Mackin Volume: Utah Geological Association Publication 30, Pacific Section American Association of Petroleum Geologists Publication GB78, p. 379 – 400.

Rogers, C., Myers, D., and Engelder, T., 2004, Kinematic implications of joint zones and isolated joints in the Navajo Sandstone at

Zion National Park, Utah: Evidence for Cordilleran relaxation: Tectonics, v. 23, TC1007, doi:10.1029/2001TC001329.

Rowley, P., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, Western United States: Their tectonic and economic implications In Faulds, J.E., and Stewart, J.H., Eds., Accommodation zones and transfer zones: the regional segmentation of the Basin and Range province: Geological Society of America Special Paper No. 343, p. 195-228.

Schiefelbein, I., 2002, Fault segmentation, fault linkage, and hazards along the Sevier fault, southwestern Utah [M.S. thesis]: Las Vegas, University of Nevada at Las Vegas, 132 p.

Schiefelbein, I., and Taylor, W., 2000, Fault development in the Utah transition zone and High Plateaus subprovince: Abstracts with Programs, v. 32, No. 7, p. 431.

Schultz, R., Okubo, C., and Fossen, H., 2010, Porosity and grain size controls on compaction band formation in Jurassic Navajo Sandstone: Geophysical Research Letters, v. 37, L22306, , doi:10.1029/2010GL044909.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes – Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, p. 5681 – 5698.

Solum, J., Brandenburg, J., Kostenko, O., Wilkins, S. and Schultz, R., 2010, Characterization of deformation bands associated with normal and reverse stress states in the Navajo Sandstone, Utah: AAPG Bull., v. 94, p. 1453–1475, doi:10.1306/01051009137.

Stewart, M., and Taylor, W., 1996, Structural analysis and fault segment boundary identification along the Hurricane fault in southwestern Utah: Journal of Structural Geology, v. 18, p. 1017 – 1029.

Stock, J., and Hodges, K., 1990, Miocene to recent structural development of an extensional accommodation zone, northeastern Baja California, Mexico: Journal of Structural Geology, v. 12, p. 312 – 328.

Surpless, B.E., and McKeighan, C., 2022, The role of dynamic fracture branching in the evolution of fracture networks: an outcrop study of the Jurassic Navajo Sandstone, southern Utah: Journal of Structural Geology, v. 161. DOI: 10.1016/j.jsg.2022.104664.

Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes: Bulletin of the Geological Society of America, v. 81, p. 1625–1640.

Thelin, G.P., and Pike, R.J., 1991, Landforms of the Conterminous United States - A Digital Shaded-Relief Portrayal: U.S.G.S. Geologic Investigations Series I – 2720.

Wallace, R.E., 1970, Earthquake recurrence intervals on the San Andreas fault: Bulletin of the Seismological Society of America, v. 81, p. 2875 – 2890.

Zhang, P., Slemmons, D.B., and Mao, F., 1991, Geometric pattern, rupture termination and fault segmentation of the Dixie Valley– Pleasant Valley active normal fault system, Nevada, U.S.A.: Journal of Structural Geology, v. 13, p. 165–176.