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TESTING MODELS OF NORMAL FAULT PROPAGATION AND DAMAGE ZONE DEVELOPMENT

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INTRODUCTION

Because seismic hazard assessment and natural resource development rely on prediction of fault behavior, structural geologists commonly model the evolution of fault systems to better understand their long-term evolution. Researchers have established that faults perturb local stress fields as they propagate, influencing the formation of minor faults and intense fracturing in an envelope, or "damage zone", around them (Fig. 1) (e.g., Peacock and Sanderson, 1996; Shipton and Cowie, 2003; Kim et al., 2004; Choi et al., 2016). These damage zones increase rock permeability, which enhances groundwater flow rates (e.g., Rowley, 1998), hydrocarbon migration (e.g., Morley et al., 1990), ore mineralization (e.g., DeWitt et al., 1986), and geothermal energy production potential (e.g., Siler et al., 2018; Shervais et al., 2024).

In addition, although researchers have long recognized that fault zones are segmented, as opposed to continuous, planar surfaces (e.g., Tchalenko, 1970; Schwartz and Coppersmith, 1984), researchers have made significant advances in the role that segmentation plays in overall fault system evolution (e.g., Long and Imber, 2011; Siler et al., 2018; Surpless and Thorne, 2021) as well as how interacting faults affect damage zone development (e.g., Kim et al., 2004; Choi et al., 2016). Where two adjacent normal fault segments interact, fracturing is commonly amplified, increasing the volume of rock damaged relative to two separate, isolated faults (e.g., Stock and Hodges, 1990; Hudson, 1992; Faulds, 1996).

In this Keck Utah Advanced Project, students investigated the evolution of normal fault networks, using their results to learn how faults and their damage zones evolve through time. Four students investigated different aspects of the central Sevier fault zone in southern Utah (Fig. 2), a well-studied, steeply west-dipping normal fault system with ~400 – 800 m dip-

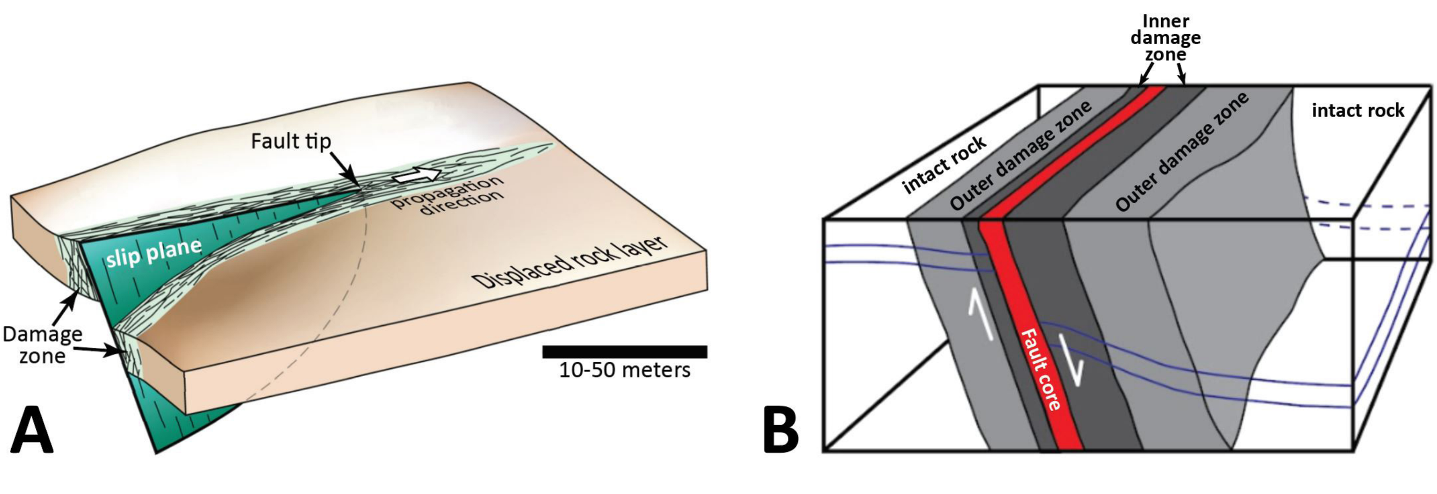

Figure 1. Development of a fault damage zone during normal fault propagation and displacement. A. damage zone development ahead of a propagating, elliptical fault tip and parallel to the fault plane (adapted from Fossen, 2016). B. Damage zone architecture and terminology (adapted from Laio et al., 2020).

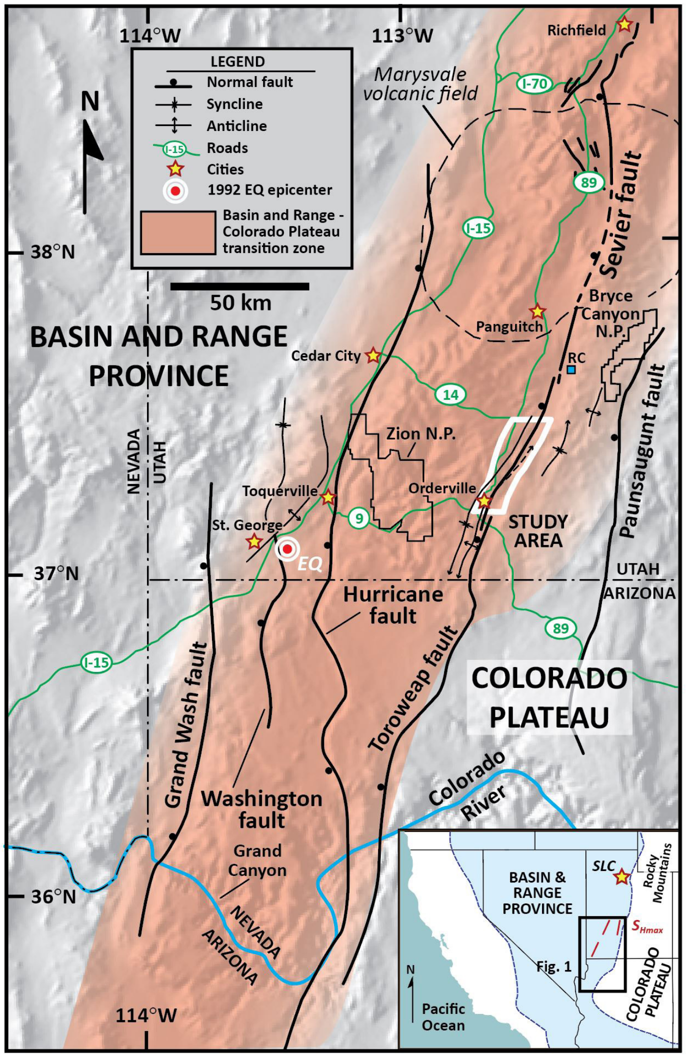

Figure 2. The Sevier fault zone study area within the Basin and Range-Colorado Plateau transition zone [see inset, with the location of Salt Lake City (SLC) indicated with a star]. The red lines on the inset figure are orientations of the maximum horizontal stress field (SHmax) as constrained by Lundstern and Zoback (2020). The Sevier-Toroweap fault, the Grand Wash fault, the Washington fault, the Hurricane fault, and the Paunsaugunt fault accommodate extension across the transition zone. Ball is on the hanging wall of faults. The epicenter of the 1992 M5.8 St. George earthquake is indicated by the red and white symbol, labeled "EQ" (Christenson et al., 1995). Approximate areal distribution of the Marysvale volcanic field is outlined by dashed lines. Blue box indicates the location of Red Canyon (RC), where Hecker (1993) constrained slip rate along the Sevier fault. Study area boxed in white. Fold data are from Doelling et al. (1989), Bowers (1991), and Stewart and Taylor (1996). Digital shaded relief modified from Thelin and Pike (1991). Figure modified from Hecker (1993), Reber et al. (2001), Surpless and McKeighan (2022), and Taylor et al. (in press).

slip displacement (e.g., Scheifelbein, 2002; Taylor et al., in press), and one student studied spectacularly well-exposed normal fault systems in the Tharsis region of Mars to investigate the structural evolution of a normal fault systems across a range of scales.

STUDY AREAS

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. 2). 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; Christenson, 1995; 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 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 (Taylor et al., in press). 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).

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 and fractures within this well-studied lithology (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 and Stewart Canyon (Fig. 3), extensional strain is accommodated by a more complex system.

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, 3D stress-strain software modeling of fault and fracture formation and propagation, and remote-sensing analysis of a complex, segmented fault system in the Tharsis region of Mars. Their work improves our understanding of the 3D evolution of faults and fracture networks in complex normal fault zones, which has important implications for natural resource exploration.

Demi Durham (Trinity University) used the Move2022 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. She focused primarily on the fault network displayed in Fig. 3, focusing especially on the fault network north of the south tip of the Spencer Bench segment. With previously published geologic maps and cross-sections (Schiefelbein, 2002) as a base, she digitized geologic unit contacts and fault planes to build a 3D model of the fault network. She used this 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.

Demi identified inconsistencies in cross-section interpretations based on misaligned unit horizons and fault surfaces. She revised these cross sections to integrate more accurate fault dips, include new fault planes, where they projected across lines of section, and changed the thicknesses of units, where those thicknesses were inconsistent across fault blocks. Demi also added new cross-sections where the density of published and revised sections was not sufficient to constrain the interaction of faults at depth. Her resulting model was a more accurate depiction of the Sevier system, which included complex but viable

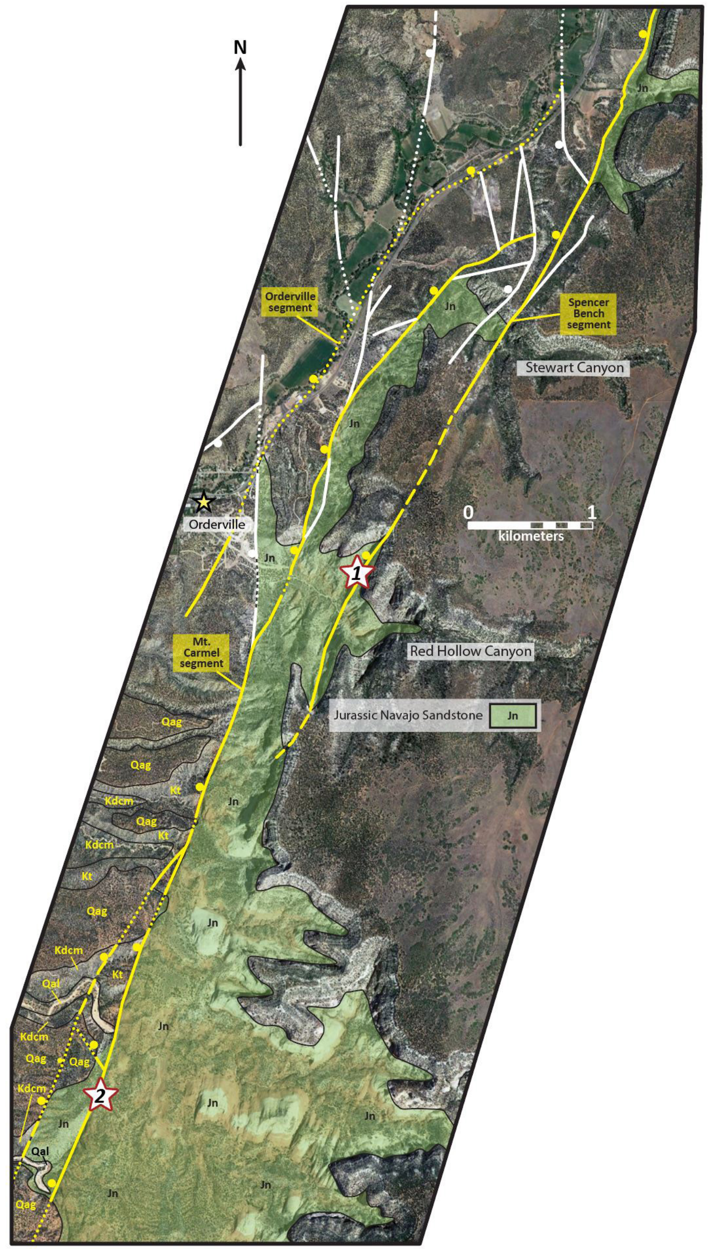

Figure 3. Simplified structural map of the steeply WNW-dipping central Sevier fault zone. Yellow faults represent the primary segments of the fault zone, and the white faults are subsidiary faults that help accommodate extension across the fault network. The green shaded areas represent exposures of the Jurassic Navajo Sandstone, and outlined areas labeled with yellow abbreviations are lithologies in the hanging wall of the Mt. Carmel segment, including: Kt (Cretaceous Tropic Shale), Kdcm (Cretaceous Dakota and Cedar Mountain Formations), Qag (older alluvial gravels), and Qal (modern alluvium). The white stars represent the locations of field and modeling studies performed by Pierce Hayton (1) and Morgan Sharp (2). Demi Durham focused her modeling investigation on the region north of the tip of the Spencer Bench segment.

structural geometries. This final model constrains both the subsurface orientations of faults and the geometric relationships between them. Although it was beyond the scope of her research, future researchers should be able to use her model investigate what retrodeformation of extension tells us about the evolution of the overall network.

Importantly, this three-dimensional model of the complexly segmented normal fault network can be applied to other fault zones with similar subsurface geometries across the Basin and Range Province, where heat flows are high. Because fault damage zones adjacent to faults usually create zones of higher permeability, the geometric relationships between these faults can be used to target zones with high geothermal energy potential in similar segmented systems.

Pierce Hayton (Colorado College) used field data and Structure-from-Motion (SfM) model analysis to investigate how a propagating fault affects the rock around it. As a propagating fault fractures the rock around it, subsequent weathering and erosion will strongly affect how the local landscape evolves. Pierce focused on the Spencer Bench segment, which displaces the Jurassic Navajo Sandstone (Fig. 3). Because the Navajo Sandstone is located on both sides of the fault, he was able to hold lithology constant to evaluate differences in damage zone distribution and resulting impacts on erosional processes. In addition, the headward erosion process permitted him to use cross-drainage profiles from the northernmost exposure of the segment in Red Hollow Canyon to the main drainage as temporal snapshots of profile evolution to evaluate how damage zone fracturing affects valley evolution.

Pierce found that the hanging wall of the steeply dipping fault was far wider than the footwall of the fault, consistent with previous studies of normal fault damage zones (e.g., Berg and Skar, 2005; Liao et al., 2020). In addition, he found a weak correlation between the intensity of damage zone fracturing and topographic evolution. Pierce also found that erosion rates were higher in the hanging wall compared to the footwall of the system, consistent with the idea that deformation can impact landscape evolution.

Audrey Jennings (Trinity University) analyzed stress, strain, and fracture evolution using the Fault Response Modeling module of the Move 2022 software suite (by Petex). She created 3D models of a single-fault system and investigated how the hanging wall and footwall of the normal fault accommodated strain using different models of fault evolution (the constant length model vs. the propagating model). Audrey found that the spatial distribution of strain was most strongly controlled by accumulated displacement, stage of lateral propagation, pore fluid pressure, and depth relative to the centroid of the fault, assuming a relatively elliptical slip model. Her findings can be applied to poorly exposed fault systems in high heat flow regions, where an understanding of fault damage zone distribution is important.

Jack Mrachek (Purdue University) investigated the evolution of an unusual circumferential fault network within and adjacent to the Alba Mons volcano-tectonic complex of the Tharsis region of Mars. He analyzed high-resolution orbital imagery to investigate the cross-cutting relationships between fluvial systems, normal faults, and volcanic lava flows. He also documented fault segment lengths and associated heave and throw values to compare displacement-length relationships on Mars relative to similar fault networks on Earth.

Jack confirmed the results of previous researchers, learning that lava flows pre-dated both fluvial systems and faulting, while faults across the region cut fluvial systems, establishing those features as the youngest across the Alba Mons region. Jack also documented the total extension accommodated by the circumferential system along an approximately East-West line of section, with 21 faults accommodating 5.5% extension. He also measured 200 faults' displacements and lengths and derived a power-law relationship between the variables that suggested a different relationship relative to similar displacement - length data on Earth. Jack hypothesized that this discrepancy might be the result of differing crustal thicknesses for the two planets.

Morgan Sharp (Whitman College) used field data and Structure-from-Motion (SfM) model analysis to investigate how fault- damage zones develop (Fig. 1) in response to fault propagation and accumulated displacement. He focused on multiple exposures of the damage zone associated with the Mt. Carmel segment of the Sevier fault zone; because displacements along that fault vary along strike, Morgan was able to compare damage zone development at different stages of fault slip. He also compared how hanging wall fracture data compared with footwall fracture data, revealing asymmetry in damage zone development.

Morgan's results are consistent with those of Savage and Brodsky's (2011) hypothesis that normal fault damage zones evolve in two phases, including a first phase, when damage zone width increases proportionally with displacement, and a second phase, when above a critical displacement value, the rate of damage zone width increase slows and is not linked as strongly to displacement. Morgan's data show that footwall damage zone width varies on the meter scale for displacements that vary by hundreds of meters, which is consistent with the second phase of normal fault displacement suggested by Savage and Brodsky (2011).

His work also reveals asymmetry in both fracture orientations and damage zone widths in the hanging wall and footwall. The damage zone width in the hanging wall is significantly wider than the footwall, and fractures in the hanging wall are dominated by fault-perpendicular fractures in contrast with fault-parallel fractures in the footwall.

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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.

Berg, S., and T. Skar, 2005, Controls on damage zone asymmetry of a normal fault zone: Outcrop analyses of a segment of the Moab fault, SE Utah: Journal of Structural Geology, 27, 1803–1822, doi: 10.1016/j.jsg.2005.04.012.

Bowers, W.E., 1991, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah: United States Geological Survey Miscellaneous Investigations Series Map 2180, 1:24,000.

Choi, J-H., Edwards, P., Ko, K., and Kim, Y-S., 2016, Definition and classification of fault damage zones: a review and a new methodological approach: Earth Science Reviews, v. 152, p. 70-87.

Christenson, G.E., ed., 1995, The September 2, 1992 ML 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular 88, 41 pp.

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).

Fossen, H., 2016, Structural Geology: Cambridge

University Press, Cambridge, UK, 510 p.

Hecker, S., 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, p. 1-31.

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.

Liao, Z., Hu, L., Huang, X., Carpenter, B.M., Marfurt, K.J., Vasileva, S., and Zhou, Y., 2020, Characterizing damage zones of normal faults using seismic variance in the Wangxuzhuang oilfield, China: Interpretations v. 8, p. 1- 24.

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.

Lundstern, J-E., and Zoback, M.D., 2020, Multiscale variations of the crustal stress field throughout North America: Nature Communications, v. 11:1951, https://doi.org/10.1038/s41467-020-15841-5.

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., 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.

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.

Savage, H.M., and Brodsky, E.E., 2011, Collateral damage: Evolution with displacement of fracture distribution and secondary fault strands in fault damage zones: Journal of geophysical research, v. 116, doi:10.1029/2010jb007665.

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.

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.

Shipton, Z.K., and Cowie, P.A., 2003, A conceptual model for the origin of fault damage zone structures in high-porosity sandstone: Journal of structural geology, v. 25, p. 333–344, doi:10.1016/s0191-8141(02)00037-8.

Siler, D., Hinz, N., and Faulds, J., 2018, Stress concentrations at structural discontinuities in active fault zones in the western United States: Implications or permeability and fluid flow in geothermal fields: Geological Society of America Bulletin, v. 130, No 7, p. 1273 – 1288.

Shervais, J. et al., 2024, Geothermal play fairway analysis, part 1: Example from the Snake River Plain, Idaho, v. 117, p. 1 – 18.

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.

Surpless, B., and Thorne, S., 2021, Segmentation of the Wassuk Range normal fault system, Nevada (USA): implications for earthquake rupture and Walker Lane dynamics: Geological Society of America Bulletin, v. 134, p. 39-59, DOI: 10.1130/B35756.1

Taylor, W., Surpless, B., and Schiefelbein, I., in press, Complex segment linkage along the Sevier normal fault, southwestern Utah: Lithosphere.

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.