Structural controls on stratigraphic architecture of the southern Bouse Formation near Cibola, Arizona

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Introduction

The latest Miocene to early Pliocene Bouse Formation is a regionally extensive deposit of carbonate and siliciclastic sedimentary rocks exposed discontinuously along the lower Colorado River corridor (Buising, 1990; Metzger, 1968). These deposits record arrival and integration of the early Colorado River (House et al., 2008; Pearthree and House, 2014), though the conditions and paleo-environments of deposition are controversial and uncertain (Spencer et al., 2013). Recent work reveals systematic stratal wedging, basinward thickening, and pinch-out of units toward the eastern basin margin in the Cibola area (Homan, 2014), indicating a need to better understand the style, timing, and origin of syn- to post-Bouse deformation in the southern Blythe basin region.

The goal of the research presented here is to determine if there is a structural control on the stratigraphic architecture of the Bouse Formation southeast of Cibola, Arizona. To address this question, we combine field data and structural interpretations from measured sections, lithofacies descriptions, stratigraphic panels, geologic mapping, and fault measurements. While structural controls on Bouse Formation depocenters are suggested by the regional map pattern (Howard and Miller, 1992; Jachens and Howard, 1992), and several faults cut the Bouse Formation (e.g. Homan, 2014), little work has been done to understand the age and kinematics of syn- to post-Bouse Formation faults and folds in this region. Below we suggest that excellent exposures of the Bouse Formation display stratigraphic architecture that likely was produced by two stages of normal fault propagation and tilting during deposition of the Bouse Formation.

Stratigraphic architecture

Tracing of key stratal surfaces from east to west in the study area reveals: (1) a lower stratigraphic wedge consisting of Bouse basal carbonate and overlying Colorado River sediment (including green claystone, red mudstone, and thick cross bedded channel sandstone), which thickens to the west toward the basin center and thins to the east toward the basin-bounding normal fault; and (2) an upper wedge comprised of the upper bioclastic limestone unit that thickens to the east toward the normal fault (Figs. 2, 3). The lower wedge thins from ca. 100 m in the southern Blythe basin

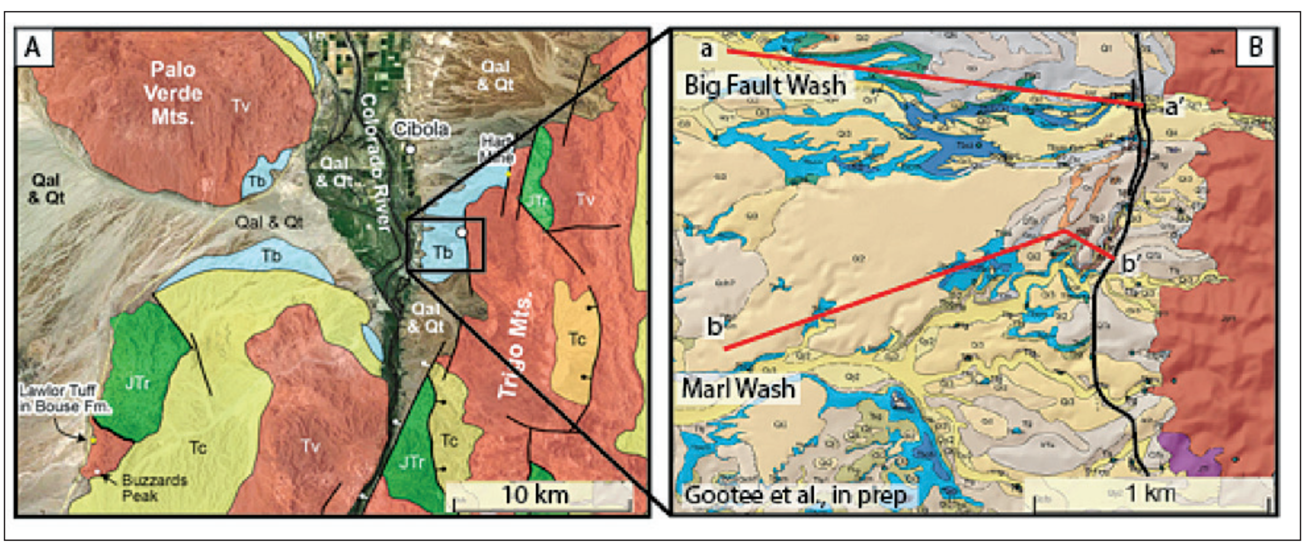

Figure 1. A: Simplified geologic map of the of the study area (compiled from (Richard, 1993; Ricketts et al., 2011; Sherrod and Tosdal, 1991) B: Geologic Map of study area (Gootee et al., 2016). Panels a-a' and b-b' located in Big Fault Wash and Marl Wash, respectively.

subsurface (Metzger et al., 1973) to <10 m in the immediate hanging wall of the normal fault in Big Fault Wash. Westward stratal thickening and expansion of the section is also seen in stratigraphic panels in Big Fault Wash and Marl Wash, which show that the lower marl unit (marl 1) and the green claystone increase from zero thickness to 6 m and 1.5 m thick, respectively, in the west, and both pinch out completely to the east (Figs. 2, 3).

In contrast, the upper bioclastic limestone unit wedge expands eastward from thin or absent in western locations to the thickest (~10 m) section of upper bioclastic limestone unit located in the immediate hanging wall adjacent to the normal fault. This geometry is seen consistently in Marl Wash and Big Fault Wash, along the strike of the normal fault (Figs. 2, 3)

Lithofacies descriptions

Lithofacies of the upper bioclastic limestone unit (map unit Tbz (termed "upper bioclastic unit") from Gootee et al., 2016) conformably and unconformably overlie Colorado River sand and mud, and grade up-section from (i) UL1: fine-grained wave-rippled sandy calcarenite, locally interbedded with Colorado River red mudstone; to (ii) UL2: poorly sorted coarse tributary sourced pebbly calcarenite with gravelly, flat-based long-wave-length, convex and concave cross bedding; to (iii) UL3: channelized pebbly calcarenite in Colorado River mud–very fine-grained Colorado River and locally derived sand; to (iv) UL4: poorly sorted calcareous-matrix conglomerate with >90% siliciclastic material. In the Marl Wash locality, a subaerial conglomerate 'fanglomerate' unit, Tfg2, both conformably and unconformably overlies upper bioclastic limestone (Tbz) deposits (Gootee et al., 2016) (Fig. 4). Another lithofacies of the upper bioclastic limestone unit, UL5, is widespread in western Milpitas, though not found in the Cibola area, and consists of lime mudstone (micrite) with common mud cracks and <5% siliciclastic material.

We suggest that sediment was derived from a combination of local carbonate production, reworking of lower Bouse carbonate, and input of sediment from local tributaries and the

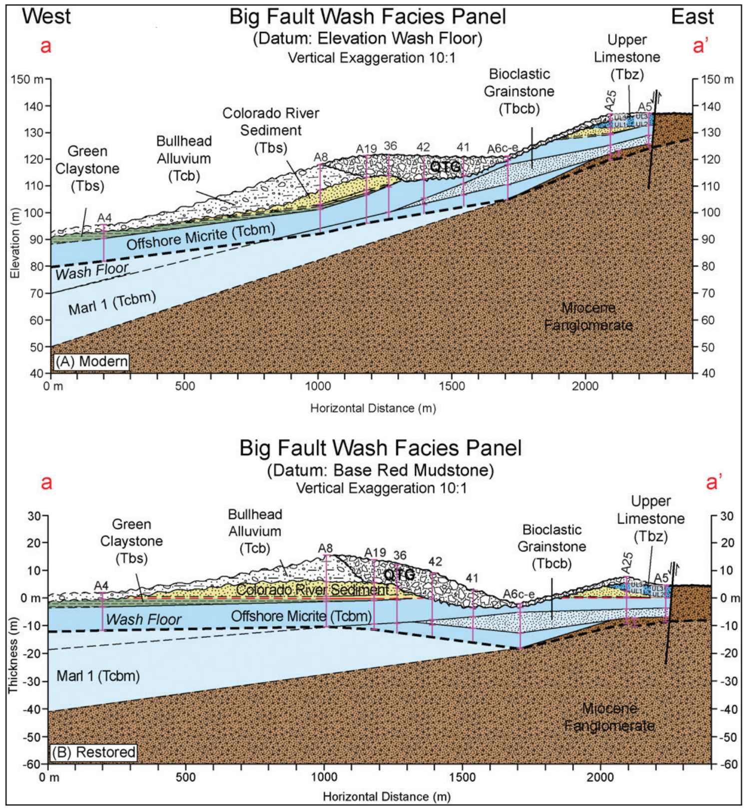

Figure 2. Facies panels of Big Fault Wash, a–a'. Map unit indicators in parentheses, from Gootee et al., 2016). See location of panel in Figure 1. Modified from Homan (2014).

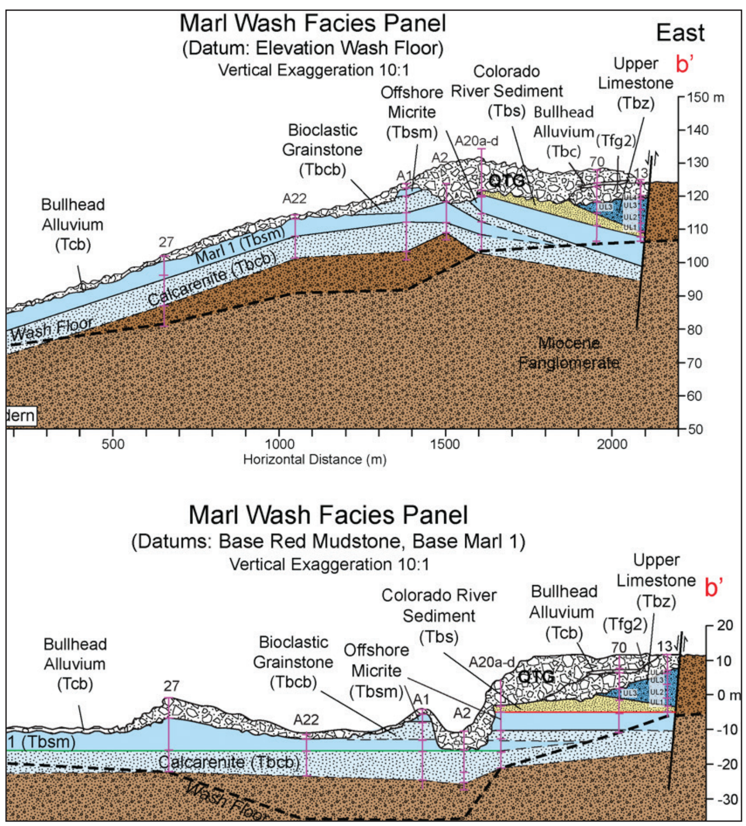

Figure 3. Facies panels of Marl Wash, b–b'. Map unit indicators in parentheses, from Gootee et al., 2016). See location of panel in Figure 1. Modified from Homan (2014).

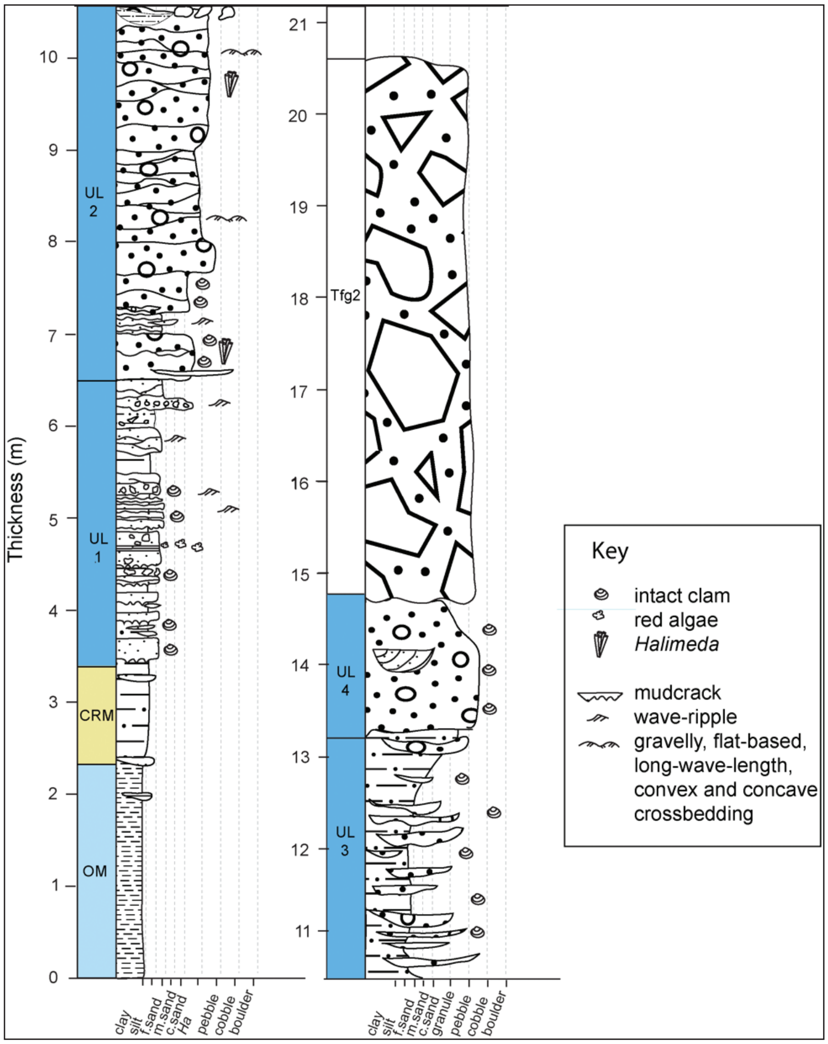

Figure 4. Measured Section 13, near the east end of panel b–b'. Section shows upper bioclastic limestone unit (Map unit Tbz) overlying older Bouse carbonate and siliciclastic units. Lithofacies UL 1–4 are defined in the text. CRM, Colorado River mud; OM, offshore micrite (marl).

Colorado River. Evidence for carbonate production in a shallow standing body of water, not solely by reworking and redeposition of older carbonate material includes: (1) the first appearance and common occurrence of the distinctive branching green algae *Halimeda*, which is either not present or is very rare in older Bouse carbonate deposits; (2) presence of mud-cracked lime mudstone (micrite) in western Milpitas wash area with distinctive *Halimeda* fossils (UL5); (3) water-lain sedimentary structures, including wave-ripples in UL1 and gravelly, flat-based long-wave-length, convex and concave cross bedding in UL2 that are known to form by strong storm currents in high-energy shallow shelf settings (Clifton, 1986; DeCelles, 1987) ; and (4) presence of fully articulated bivalve and mollusk shells (UL1–4), that likely could not survive significant erosional reworking and abrasion in an alluvial fan without disarticulation (Dorsey et al., this volume).

Upper bioclastic limestone unit lithofacies 1–4 are interpreted to record progradation of fan deltas into a shallow-water, carbonate-producing standing body of water. We interpret lithofacies 1–3 as shallow subaqueous deposits based primarily on the high carbonate content and presence of distinctive water-lain sedimentary structures such as wave-ripple cross lamination and gravelly, flat-based long-wave-length, convex and concave cross bedding that resemble hummocky cross stratification. We interpret lithofacies UL4 as the interface between the subaqueous fan delta, and a laterally adjacent subaerial alluvial fan, because UL4 is poorly sorted with >90% siliciclastic material, records no water-lain sedimentary structures, and has a carbonate matrix with sparse intact clam shells. Poor sorting and horizontal stratification in facies UL4 suggest deposition by sheetfloods in a distal alluvial fan setting at and near the margin of the shallow standing body of water. We interpret lithofacies UL5 in the Milpitas area as recording alternating wet and dry conditions on a shallow-water carbonate mud flat.

Discussion

Stratigraphic data presented above provide evidence for the progressive structural evolution of the eastern margin of the Blythe Basin southeast of Cibola, AZ. Integration of structural and stratigraphic data lead to our interpretation of two distinct stages of fault development: (1) In the first stage the fault was a blind fault at depth, and propagation of the fault tip toward the land surface resulted in growth of a broad monocline that produced gentle westward tilting and related thickening of strata toward the basin center, leading to pinch-out of units toward the eastern basin margin; and (2) When the migrating fault tip breached the surface, it initiated growth of a rollover fold that produced eastward tilting and related thickening of the upper limestone toward the normal fault, resulting in maximum preserved thickness of upper bioclastic limestone unit (map unit Tbz) in the immediate hanging wall of the normal fault. This two-stage model for normal fault growth and surface breaching is based on comparison to similar relationships and interpretations of (Gawthorpe et al., 1997). Similarly, we infer that during the first stage when the normal fault was a blind structure at depth, growth of a broad monocline above the propagating fault tip resulted in basinward tilting to the west that produced a westward-thickening, eastward-thinning stratigraphic wedge. In contrast, deposits that formed during the second stage thicken toward the fault in the immediate hanging wall of the normal fault. The stratal geometries in Figures 2 and 3 indicate that fault-controlled growth of the upper wedge (stage 2) took place during deposition of the upper limestone, after deposition of Colorado River sediment and before deposition of the upper fanglomerate (Tfg2). The fault appears to have undergone additional slip after deposition of Bullhead Alluvium.

We therefore suggest that basin subsidence (sagging) near Cibola is likely in part the downward component of basin-scale warping related to a propagating blind normal fault. We acknowledge that Bouse deposits thin toward the basin margins in other localities without map evidence for the presence of a normal fault. This suggests that basinward thickening observed in the Bouse basal carbonate and overlying Colorado River sediment are likely controlled by broader subsidence, and not exclusively a result of propagating blind normal faults. However, it is also possible that regional basin sagging may have been related to growth of other buried faults that never propagated to the surface. This idea might be evaluated with future geologic mapping, though it may be difficult to fully test without complementary subsurface data.

To summarize, stratal geometries observed in the Bouse Formation southeast of Cibola record a history of tilting away from—and then toward—the basin-margin normal fault. We interpret this history of reversing tilt directions to record monocline growth above a blind normal fault (Stage 1) that later breached the surface and caused titling back toward the fault (Stage 2). Similar stratal geometries are observed in other extensional settings and are similarly interpreted to result from syn-depositional growth and surface breaching of normal faults (Gawthorpe et al., 1997).

An idealized normal fault segment is predicted to have maximum displacement and accommodation space at its center where the fault first breaches the surface, and total displacement decreases along strike toward the fault tips where surface offset is zero (Barnett et al., 1987; Chapman et al., 1978; Dawers et al., 1993; Gawthorpe et al., 1997; Muraoka and Kamata, 1983; Schlische, 1995; Schlische and Anders, 1996; Walsh and Watterson, 1987; Young et al., 1995). Thickness variations in the upper limestone suggest that maximum subsidence and accommodation space are located immediately adjacent to the breached fault in two localities in Marl Wash and Big Fault Wash (Figs. 2, 3). We propose that in areas north and south of the fault, fold growth above buried fault tips resulted in westward tilting toward the basin center and did not create vertical accommodation space for the upper limestone, while localities in Big Fault Wash and Marl Wash did experience east tilting toward the normal fault where the fault tip breached the land surface.

Conclusions

Two distinct phases in the structural evolution of Blythe Basin southeast of Cibola, AZ, can be interpreted by analyzing the stratigraphic architecture of the Bouse Formation. During the first stage, upward propagation of the blind fault tip toward the Earth's surface resulted in gentle westward tilting and thickening of Bouse basal carbonate and Colorado River sediment toward the basin center. Stage 2 occurred when the normal fault breached the surface and initiated growth of a small rollover monocline, which caused eastward tilting and local subsidence for accumulation of the upper bioclastic limestone unit. Thus, the map distribution and preservation of the upper limestone appear to be directly controlled by the local faulting history in this area.

References

Barnett, J. A., Mortimer, J., Rippon, J. H., Walsh, J. J., and Watterson, J., 1987, Displacement geometry in the volume containing a single normal fault: AAPG Bulletin, v. 71, no. 8, p. 925-937.

Buising, A. V., 1990, The Bouse Formation and bracketing units, southeastern California and western Arizona: Implications for the evolution of the Proto- Gulf of California and the lower Colorado River: Journal of Geophysical Research: Solid Earth (1978–2012), v. 95, no. B12, p. 20111-20132.

Chapman, G. R., Lippard, S., and Martyn, J., 1978, The stratigraphy and structure of the Kamasia range, Kenya Rift Valley: Journal of the Geological Society, v. 135, no. 3, p. 265-281.

Clifton, H.E., 1986, Interpretation of paleoenergy levels from sediment deposited on ancient wave-dominated shelves, in Knight, J., ed., Shelf Sands and Sandstone: Canadian Society of Petroleum Geologists, Memoir 11, p. 181-190.

Dawers, N. H., Anders, M. H., and Scholz, C. H., 1993, Growth of normal faults: Displacement-length scaling: Geology, v. 21, no. 12, p. 1107-1110.

DeCelles, P.G., 1987, Variable preservation of middle Tertiary, coarse-grained, nearshore to outer-shelf storm deposits in southern California. Jour. of Sedimentary Petrology, v. 57, p. 250-264.

Gawthorpe, R. L., Sharp, I., Underhill, J. R., and Gupta, S., 1997, Linked sequence stratigraphic and structural evolution of propagating normal faults: Geology, v. 25, no. 9, p. 795-798.

Gootee, B.F., Pearthree, P.A., House, P.K., Youberg, A., Spencer, J.E., and O'Connell, B., 2016 in prep, Geologic map of the Cibola 7 ½' Quadrangle and the northwestern part of Cibola SE 7 ½' Quadrangle, La Paz County, Arizona, and Imperial County, California: Arizona Geological Survey Digital Map DGM-117, scale 1:24,000, with text.

Homan, M. B., 2014, Sedimentology and Stratigraphy of the Miocene-Pliocene Bouse Formation near Cibola, Arizona and Milpitas Wash, California: Implications for the Early Evolution of the Colorado River: University of Oregon.

House, P. K., Pearthree, P. A., and Perkins, M. E., 2008, Stratigraphic evidence for the role of lake spillover in the inception of the lower Colorado River in southern Nevada and western Arizona: Geological Society of America Special Papers, v. 439, p. 335-353.

Howard, K. A., and Miller, D. M., 1992, Late Cenozoic faulting at the boundary between the Mojave and Sonoran blocks: Bristol Lake area, California: Deformation associated with the Neogene, eastern California shear zone, southeastern California and southwestern Arizona, p. 92-91.

Jachens, R., and Howard, K., 1992, Bristol Lake basin—A deep sedimentary basin along the Bristol–Danby trough, Mojave Desert: Old Routes to the Colorado, p. 92-92.

Metzger, D., 1968, The Bouse Formation (Pliocene) of the Parker-Blythe-Cibola area, Arizona and California: Geological Survey Research, p. D126-D136.

Metzger, D. G., Loeltz, O. J., and Irelan, B., 1973, Geohydrology of the Parker-Blythe-Cibola area, Arizona and California, 2330-7102.

Muraoka, H., and Kamata, H., 1983, Displacement distribution along minor fault traces: Journal of Structural Geology, v. 5, no. 5, p. 483-495.

Pearthree, P. A., and House, P. K., 2014, Paleogeomorphology and evolution of the early Colorado River inferred from relationships in Mohave and Cottonwood valleys, Arizona, California, and Nevada: Geosphere, v. 10, no. 6, p. 1139-1160.

Richard, S. M., 1993, Palinspastic reconstruction of southeastern California and southwestern Arizona for the middle Miocene: Tectonics, v. 12, no. 4, p. 830-854.

Ricketts, J. W., Girty, G. H., Sainsbury, J. S., Muela, K. K., Sutton, L. A., Biggs, M. A., and Voyles, E. M., 2011, Episodic Growth of the Chocolate Mountains Anticlinorium Recorded By the Neogene Bear Canyon Conglomerate, Southeastern California, USA: Journal of Sedimentary Research, v. 81, no. 12, p. 859-873.

Schlische, R. W., 1995, Geometry and origin of fault-related folds in extensional settings: AAPG bulletin, v. 79, no. 11, p. 1661-1678.

Schlische, R. W., and Anders, M. H., 1996, Stratigraphic effects and tectonic implications of the growth of normal faults and extensional basins: SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA, p. 183-203.

Sherrod, D. R., and Tosdal, R. M., 1991, Geologic setting and Tertiary structural evolution of southwestern Arizona and southeastern California: Journal of Geophysical Research: Solid Earth (1978–2012), v. 96, no. B7, p. 12407-12423.

Spencer, J. E., Patchett, P. J., Pearthree, P. A., House, P. K., Sarna-Wojcicki, A. M., Wan, E., Roskowski, J. A., and Faulds, J. E., 2013, Review and analysis of the age and origin of the Pliocene Bouse Formation, lower Colorado River Valley, southwestern USA: Geosphere, v. 9, no. 3, p. 444-459.

Walsh, J., and Watterson, J., 1987, Distributions of cumulative displacement and seismic slip on a single normal fault surface: Journal of Structural Geology, v. 9, no. 8, p. 1039-1046.

Young, S., Schlische, R., and Ackermann, R., Micronormal fault populations in Mesozoic rift basins: lengthdisplacement scaling relations (abs.), *in* Proceedings Geological Society of America Abstracts with Programs1995, Volume 27, p. 94.