Hypothesis for post-Bouse distributed deformation of the Lower Colorado River corridor

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Introduction and background

Deposits of the >6-4.8 Ma Bouse Formation and ~4.5-3.8 Ma post-Bouse Bullhead Alluvium are present both in the subsurface and as erosional remnants within successive basins along much of the Lower Colorado River (LoCR). These deposits record the first arrival and integration of the Colorado River to the proto-Gulf of California (Bouse Formation) and aggradation of the Colorado River as a continent-scale river system (Bullhead Alluvium). Within basins, Bouse deposits occur at a range of elevations, and have been interpreted to represent the filling of lakes, leaving behind Bouse carbonates as a bathtub-like coating draped on paleotopography as lakes filled (Pearthree and House, 2014). Draping across topography at vertical scales of tens of meters is clearly evident by outcrops within the Yuma Proving Grounds. First-order observations show that the highest Bouse deposits are hundreds of meters higher on the flanks of basins than at their center (Pearthree et al., 2016). Additionally, a longitudinal (N to S) ~200 m change in elevation of Bouse deposits is evident across the Topock Divide (Fig. 1). Here, deposits north of the divide are at a maximum elevation of ~560 m elevation, while deposits to the south are at ~360 m elevations (Pearthree and House, 2014). Similarly, the highest Bouse deposits across the Chocolate Mountains divide are 300-400 m higher to the north (Metzger, 1968) and in wells to the south, near Yuma, Arizona (Olmstead et al., 1973). These elevation differences have been suggested to record the eventual spilling of the lake water southward to successively lower basins whereby topographic divides (Fig.1) blocked first-arriving river water into large inland lakes before eventually integrating and continuing their course downstream to the proto-Gulf of California (Spencer et al., 2012; Pearthree and House, 2014). $^{87}Sr/^{86}Sr$ values have been cited as evidence for a generally non-marine origin for the Bouse Formation (Spencer and Patchett, 1997). In this model, lakes are envisioned as 300-500 m deep, with present outcrop elevations reflecting original depositional elevation.

An alternative hypothesis is that tectonic activity associated with the evolving San Andreas plate boundary and Eastern California shear zone (ECSZ) may have influenced the observed elevations of Bouse and Bullhead strata after they were deposited. The rarity of mapped scarps and discrete structures within the study area suggests that deformation may be diffuse. In particular, deformation within the LoCR corridor at and between the Topock and Chocolate Mountain divides (e.g. Beard et al., 2016) may be manifested through diffuse transtensional strain whereby dominant structures consist of NW-SE –oriented distributed dextral systems, N-S-oriented normal faults, and E-W-oriented contractional structures (antiformal structures and reverse faults) (Fig. 1). In order to test these competing hypotheses, we have begun a compilation of faults and have targeted key locations for structural analysis and mapping.

Our preliminary assessment through the integration of diverse datasets suggests the viability of this second hypothesis of diffuse Pliocene-Recent tectonism throughout the LoCR corridor. Datasets include geologic data from past and active mapping (e.g. Faulds et al., 2004; Gootee et al., 2016; House et al., 2004; Howard et al., 2013), detailed observations of fault and stratigraphic relationships in the southern Blythe basin (Homan, 2014), depth-to-bedrock data (Richard et al., 2007), structural analysis (this study), high-precision GPS surveying of Bouse and post-Bouse deposits (in progress USGS effort), geospatial analysis of Colorado River deposits (Crow et al., 2016; in progress USGS effort), subsurface data (Metzger et al., 1973) fault and subsurface compilations (in progress USGS effort; this study), geodetic estimates (Kreemer et al., 2010), and historical seismicity in the study area (Yang et al., 2012). This paper is a progress report of this current evidence for Pliocene-Recent deformation in the LoCR corridor.

Evidence in the Chocolate Mountains and Blythe Basin

Evidence for elevation change of Bouse outcrops across the Chocolate Mountain divide (Fig. 1) includes paleontological (McDougall and Martinez, 2014) and stratigraphic (O'Connell et al., 2017) observations that suggest the Bouse Formation in the southern Blythe basin is marine. "Non-marine" Sr isotopic values (Spencer and Patchett, 1997) may be attributable to mixing in an estuary setting, somewhat analogous to modern San

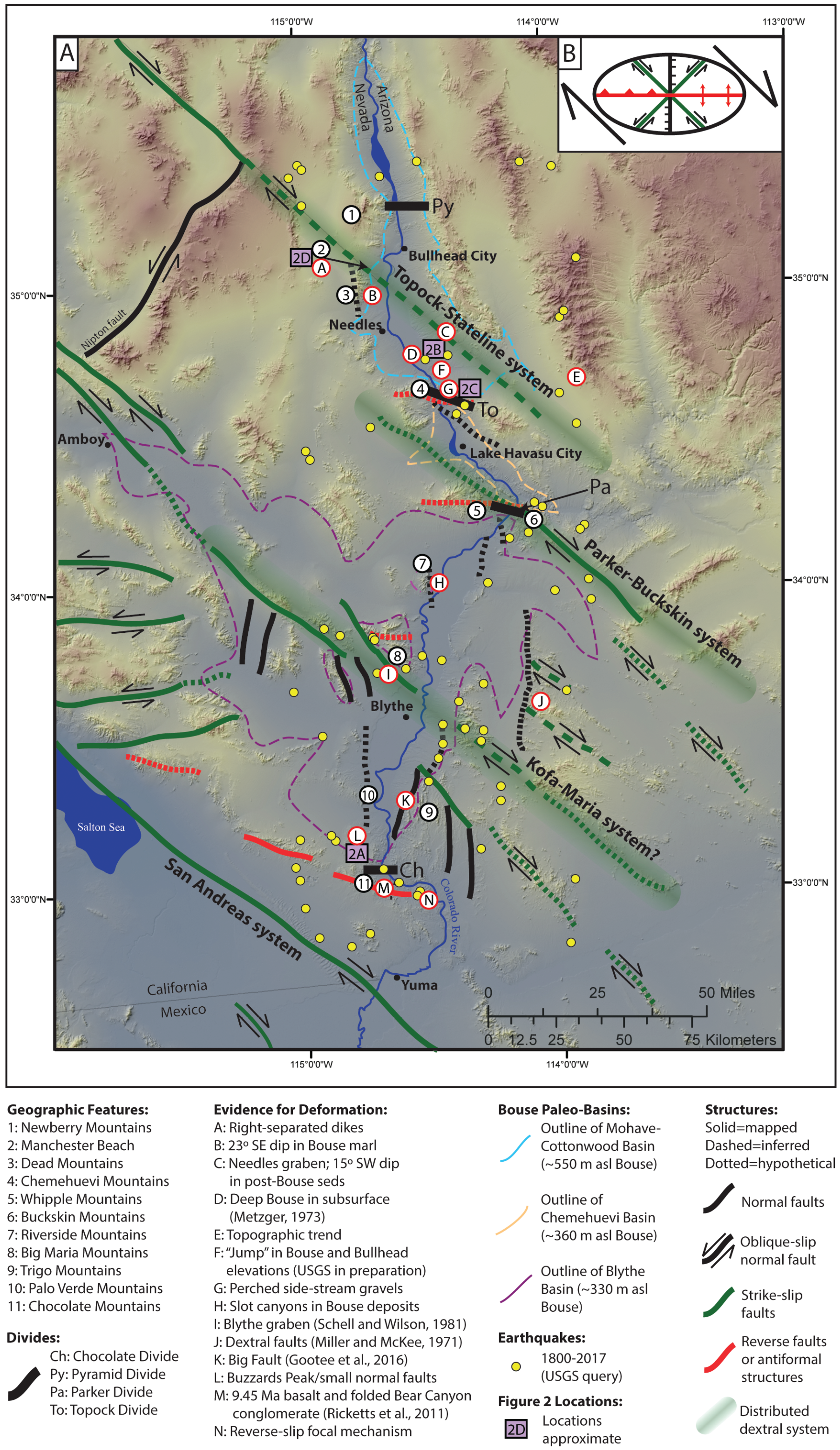

Figure 1: A) Digital elevation model of the Lower Colorado River corridor and surrounding region showing present evidence and our hypothetical tectonic framework (structures). References for present evidence listed unless from this study. Note that solid lines represent mapped structures or structural systems, while dashed represent inferred and dotted represent hypothetical. Basin outlines are approximate. Earthquakes shown were queried only along the LoCR corridor (e.g., Salton Sea seismicity omitted). Earthquake magnitudes not distinguished by size; all are less than magnitude 4. B) Schematic right-lateral shear couple with expected structures shown. Color-coded to structures in A.

Francisco Bay (Crossey et al., 2015). Interpreted marine facies of the Bouse Formation reach elevations of 120 m in the Blythe basin (McDougal and Martinez, 2014), and Beard et al. (2016) suggested that about ~300 m of <5 Ma tectonic uplift across the Chocolate Mountains divide would be needed to create a barrier between the Yuma basin and the Blythe basin to cut off the proposed Bouse marine inlet. Support for syn- and post-Bouse deformation in the southern Blythe basin include: (1) deformation of the Bouse in the southern Trigo Peaks of Arizona (Buising, 1990; Gootee et al., 2016); (2) a recently discovered syn-Bouse normal fault in lower Hart Mine Wash that has demonstrably 80-100 m of throw (Dorsey et al., this volume); (3) possible tilting of Bouse outcrops due to growth of the Chocolate Mountain anticlinorium (Beard et al., 2016); (4) stratal wedging and pinch-out patterns in the Bouse Formation that indicate syn-depositional fault-controlled tilting (O'Connell et al., 2017; Dorsey, et al., this volume); and (5) localities where faults that cut the Bouse Formation are unconformably overlapped by un-faulted younger Bouse deposits or Bullhead Alluvium (Homan, 2014).

Work on the Chocolate Mountains anticlinorium (Ricketts et al., 2011; Beard et al., 2016; Ricketts et al., this volume) suggests the region just south of the Chocolate Mountains divide records mid- to late-Miocene deformation related to the evolution of the San Andreas plate boundary system. Within this region, deformation is expressed through NW-oriented dextral faults and the EW-trending Copper Basin reverse fault. These structures cut the Bear Canyon conglomerate to the east of the Chocolate Mountains in and around Bear Canyon (Point L, Fig. 1; Ricketts et al., 2011; Girty et al., 2012; Ricketts et al., this volume). A 9.45 Ma basalt that is interbedded with the youngest Bear Canyon conglomerate deposits suggests post-9.45 Ma deformation (Ricketts et al., 2011; Girty et al., 2012; Ricketts et al., this volume). Quaternary deposits here, however, have not been shown to be deformed, suggesting no active tectonism.

Within the Blythe basin, we suggest N-S faults sub-parallel to the river, as displayed on figures in Sherrod and Tosdal (1991), have normal slip. The Blythe basin shows subsidence of the Bouse Formation and Bullhead gravels in the subsurface (Metzger et al., 1973; Pearthree et al., 2016) that is possibly explained by river-parallel grabens. Evidence for small-displacement N-S normal faults includes syn-Bouse structures within the Blythe basin (Buising, 1990; Dorsey et al., this volume). At the Big Fault (Point K, Fig. 1), Bouse Formation strata are displaced with a throw of ~20 m (Gootee et al., 2016) along a N-S-striking, west-dipping normal fault. Across the basin (near Buzzard Peak; Point L, Fig. 1), two small N-S-striking east-dipping normal faults cut Bouse marl with a collective throw of ~ 1 m (Fig. 2A). Though small, the east-directed down-dropping of these structures is compatible with tectonic subsidence in the southern Blythe basin. Dextral slip on NW-striking faults that obliquely cross the Colorado River are also hypothesized in this area.

Dispersed NW-SE dextral strike slip faults have also been inferred in the Plomosa Mountains near Quartzite, AZ (Miller and McKee, 1971) (Fig. 1). To the south, interesting NW-SE topographic trends in the Kofa and Dome Rock mountains are along-strike with dextral faults in the Big Maria Mountains. Other work in the area (Richard and Dokka, 1992; Miller et al., 2014) shows fault systems (the Packard Well fault) to the southwest of the Big Marias in line with this topographic trend. A post-Bouse structure known as the Blythe graben (Schell and Wilson, 1981) is also found along this system, and displaces Quaternary alluvial fan deposits. Subsurface data show the deepest Bouse deposits in this vicinity (Metzger et al., 1973), but work on the distribution of subsurface Bouse deposits (in progress) is required to more clearly define the role of faulting.

Evidence within the vicinity of Topock Divide

The Needles area also shows evidence for syn- and post-Bouse deformation (Points B-G, Fig. 1). The Needles graben (Point C, Fig. 1) is a NW-SE trending structure along-strike with the Stateline fault system. Here, early- to mid-Pleistocene surfaces are offset by ~ 4-5 m (Pearthree et al., 1983). Approximately 10 km to the SW, a considerably smaller graben is observed within post-Bouse river sediments (Fig. 2B). These sediments, mapped as the deposits of the Santa Fe Railroad (Howard et al., 2013), dip 15º SW. Interestingly, these structures also correspond roughly with a ~1000 m geophysically estimated depth-to-bedrock (substantially deeper than the surrounding area) (Richard et al., 2007), thicker and deeper subsurface Bouse deposits (Point D, Fig. 1; Metzger et al., 1973), the continuation of geophysically defined faults (Beard et al., 2011), and a change in topographic trend from ~N-S to NW-SE (Point E, Fig. 1). Three-dimensional geospatial analysis of Colorado River deposits (Crow et al., 2016; in progress USGS effort) show variations in the highest Bullhead outcrops in this vicinity (Fig. 3) that could partly be explained by cumulative displacement on such faults. A 100 m "jump" in the highest definitive Bullhead Alluvium outcrops is coincidental with the Needles Graben. Although this is suggestive of tectonic control, it can also be explained by incomplete preservation. The highest Bouse outcrops are at similar elevations north and south of the inferred Stateline-Topock fault system (515-530 m and 500-540 m, respectively). Therefore, the ~200 m elevation difference across Topock Divide would require another structure. Within Topock Divide itself (Topock Gorge), perched side-stream gravels suggest young incision (Point G, Fig. 1; Fig. 2C), and the age and sharpness of the bedrock gorge are in need of explanation.

South of the Topock Divide, the Buckskin-Rawhide metamorphic core complex is cut by post-detachment E-W extensional and NW-striking strike-slip faults that have an estimated 7-9 km of total post-12 Ma dextral offset (Singleton, 2015; Singleton et al., 2016). A youthful, Plio-Quaternary age for dextral faulting in this area is inferred from: (1) a small pull-apart basin that controls modern topography at a releasing step-over on the Mineral Wash fault; (2) constriction of the Bill Williams River where it is crossed by the Swansea fault; (3) right-lateral deflection of modern drainages; (4) a large beheaded Quaternary alluvial fan; and (5) other evidence of recent stream captures that suggest an unstable disequilibrium landscape adjusting to fault-controlled base-level change. New work is needed to assess the age and structural significance of these critical relationships. Along-strike projection of this system may be en echelon with the Stateline fault system, and, therefore, be an influential structural system in our hypothetical tectonic framework.

Additional new observations are compatible with the distributed deformation hypothesis. At Point B in Fig. 1, 23° southeast dip in basal marl of the Bouse Formation has been interpreted as a primary "drape" with no post-depositional tilting (Pearthree and House, 2014). However, detailed inspection shows that interbedded marly claystone and clayey marl overlying the basal marl also dip ~20-23° SE, much steeper than primary dip expected for these facies, suggesting significant post-depositional tilting. At Manchester Beach, N-S mafic dikes (42-62ºW dip) crosscut ~15 Ma Newberry Granite. Two locations show right-separations of ~3 and ~5 m where washes cut through the dikes at the point of separation and trend ~140º in the down-wash direction (Point A, Fig. 1; Fig. 2D). This trend is similar to the strike of the Stateline

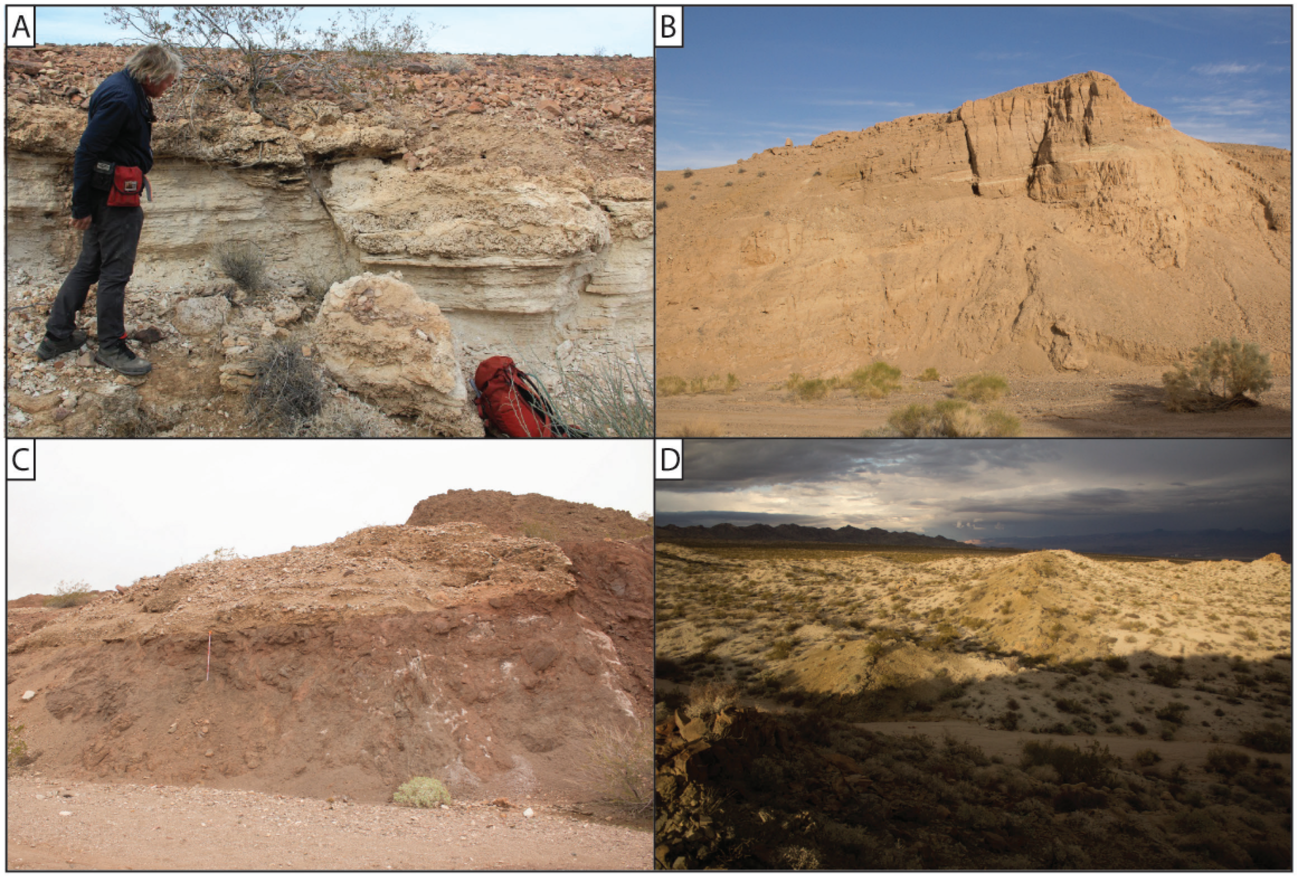

Figure 2: Evidence for Pliocene-Recent deformation in the LoCR, locations shown on Figure 1. A) Small faults near Buzzard Peak showing ~ 1 m total throw. Faults strike ~N-S and dip ~60E. View is to north. Photo: Laura Crossey. B) Small graben in ~15º SW tilted beds of post-Bouse river sediments, suggesting Pliocene or younger deformation. Bush ~1 m tall; view to north. C) Down-cutting of presently active wash (foreground) ~3 m through older wash material (at top) and basement rock in Topock Divide. Tape extended to one meter. D) Right-separated dike at Manchester Beach; separation ~5 m. Wash trends ~310, similar to and along-strike with the Stateline fault system. Dikes intrude ~15 Ma Newberry Granite, suggesting middle Miocene or younger deformation and continuation of the Stateline fault system to the LoCR. View to north.

fault system (Fig. 1; Guest et al., 2007; Mahan et al., 2009). However, slickenlines and discrete structures have not been found, precluding determination of these features as truly strike-slip. Interestingly, further south, a large (~10 m) left separation was also identified. This orientation is permissible within a dextral system (Fig. 1B). Because of a lack of structures offsetting the Bouse Formation in this area (due to limited preservation), the timing of these right-separated dikes can only be constrained to younger than <15 Ma.

Evidence from geodesy and historical seismicity

Geodetic measurements (Kreemer et al, 2010), Earthquake focal mechanisms (Yang et al., 2012), and a preliminary summary of historic seismic activity (Fig. 1) within the LoCR region show diffuse low magnitude seismicity. Evidence may suggest active deformation of the Chocolate Mountain anticlinorium. Focal mechanisms within this area are dominantly NW-striking dextral strike-slip faults, though a single focal mechanism east of the Chocolate Mountains (Point N, Fig. 1) is suggestive of E-W striking reverse faulting, and may be related to movement along the Copper Basin reverse fault (Ricketts et al., 2011; this volume).

A query of historic seismicity (earthquake.usgs.gov) within the study area was conducted for the period of 1800 to present. These results are shown on Figure 1, and exclude quarry blasts and earthquakes reported with negative depths. North of the Trigo Mountains, a N-S linear trend is observed, as well as possible NW-SE linear trends near the Buckskin-Rawhide metamorphic core complex that are compatible with distributed dextral motion as suggested by Singleton (2015) and Singleton et al. (2016). To the southwest of the Big Maria Mountains, a string of seismicity is observed that correlates with the Blythe graben (Point I, Fig. 1) and Packard Well fault. The remainder of seismic activity is sparse, but appears distributed throughout the region. This is consistent with Kreemer et al.'s (2010) estimates of 1.4 mm/yr diffuse extension in the northern LoCR.

Evidence from river profile constructions

Distributed tectonic activity associated with the ECSZ may also have influenced the elevations of Bouse and Bullhead strata across the Topock divide near Needles,

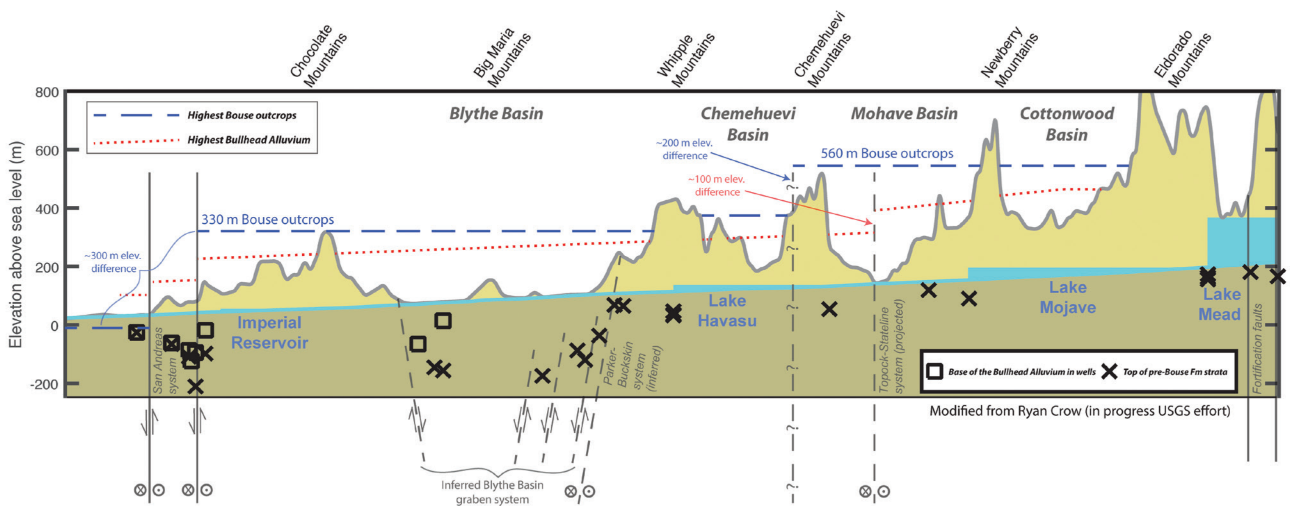

Figure 3: Lower Colorado River profile showing highest Bouse outcrops (blue dashed lines) and the Bullhead alluvium (red dotted lines). Inferred (dashed) and known (solid) faults and fault systems are shown. Elevations are from continued mapping and high-precision GPS measurements. Modified from Ryan Crow (in progress USGS effort).

as best evidenced by river profile constructions (Fig. 3). Subtle deformation may be related to southeastern continuations of the Stateline fault system (Guest et al., 2007; Mahan et al., 2009). Geospatial analysis of Colorado River outcrops along the LoCR show marked differences in elevations of Bouse deposits in the Mohave-Cottonwood (~550-560 m), Chemehuevi (~360 m), and the Blythe (~330 m) basins (Pearthree and House, 2014). Bouse deposits are also interpreted in the subsurface of all basins, while Bullhead deposits are interpreted in the subsurface of the southern Blythe Basin (Fig. 3). Some component of this elevation change could be related to distributed N-side-up throw and localized tectonic subsidence.

A hypothetical tectonic framework for the LoCR

Figure 1 shows a testable hypothesis for distributed syn- and post-Bouse deformation associated with the ECSZ whereby the LoCR's tectonic history has been influenced by Pacific/North American plate boundary motion. Deformation has taken place since the mid- to late Miocene (e.g. Atwater, 1989; Ricketts et al., 2011; Bennett et al., 2016), and may be ongoing. Regionally, structures that are observed and inferred in the study area fit into a right-lateral shear couple, bounded by the San Andreas fault to the south and the Stateline fault system to the north (Fig. 1B). In particular, distributed deformation may be through transtension, in that reactivated N-S normal faults and NW-SE dextral shear systems are likely prevalent. This transtensional hypothesis builds on the work of Bennett et al. (2016). In this regard, tectonic basin subsidence could have occurred through a mixture of distributed deformation within a far-field dextral stress regime (shear couple), as well as soft-linkages between en echelon dextral systems (such as in the Needles area). From north to south, potential systems in need of investigation include the Stateline-Topock system, the Parker-Buckskin system, the possible Kofa-Maria system, and the San Andreas system (Fig. 1). Basin-bounding E-W ranges would likely experience N-S directed compression within a right-lateral shear couple, and the N-S LoCR corridor itself may be the result of N-S grabens formed during extensional reactivation of older Miocene faults.

Conclusions

We have presented a hypothetical tectonic framework model that could account for some of the differences in elevations of Bouse and post-Bouse strata along the LoCR corridor. This hypothesis invites integration of diverse datasets, and acquisition of new structural data to test whether Pliocene to Recent deformation in the study area could be the result of distributed transtension. Further work is required, such as a comprehensive compilation of faults and new subsurface data on the distribution and depths of the Bouse Formation in the subsurface. But, even the subtle Pliocene-Recent tectonism presently identified within the LoCR corridor suggests modification of the fill-and-spill model, and seems to argue that some component of the observed elevation differences of Bouse outcrops could be the result of tectonic activity.

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