Influence of the Eastern California Shear Zone on deposition of the Mio-Pliocene Bouse Formation: insights from the Cibola area, Arizona

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Introduction

The Eastern California Shear Zone (ECSZ) is a wide zone of late Cenozoic strike-slip faults and related diffuse deformation that currently accommodates ~20–25% of relative Pacific–North America plate motion in the lower Colorado River region (Fig. 1A; Dokka and Travis, 1990; Miller et al., 2001; Guest et al., 2007; Mahan et al., 2009). The ECSZ is kinematically linked southward to dextral faults in the northern Gulf of California (Bennett et al., 2016a), and it may have initiated ca. 8 Ma when major strike-slip faults developed in the northern Gulf and Salton Trough region (Bennett et al., 2016b; Darin et al., 2016; Woodburne, 2017). Thus deformation related to the ECSZ occurred in the lower Colorado River region during deposition of the Bouse Formation, which is commonly bracketed between 6.0 and 4.8 Ma (House et al., 2008; Sarna-Wojcicki et al., 2011; Spencer et al., 2013) and may be as old as 6–7 Ma in the south (McDougall and Miranda Martínez, 2014, 2016). Post-4.5 Ma broad

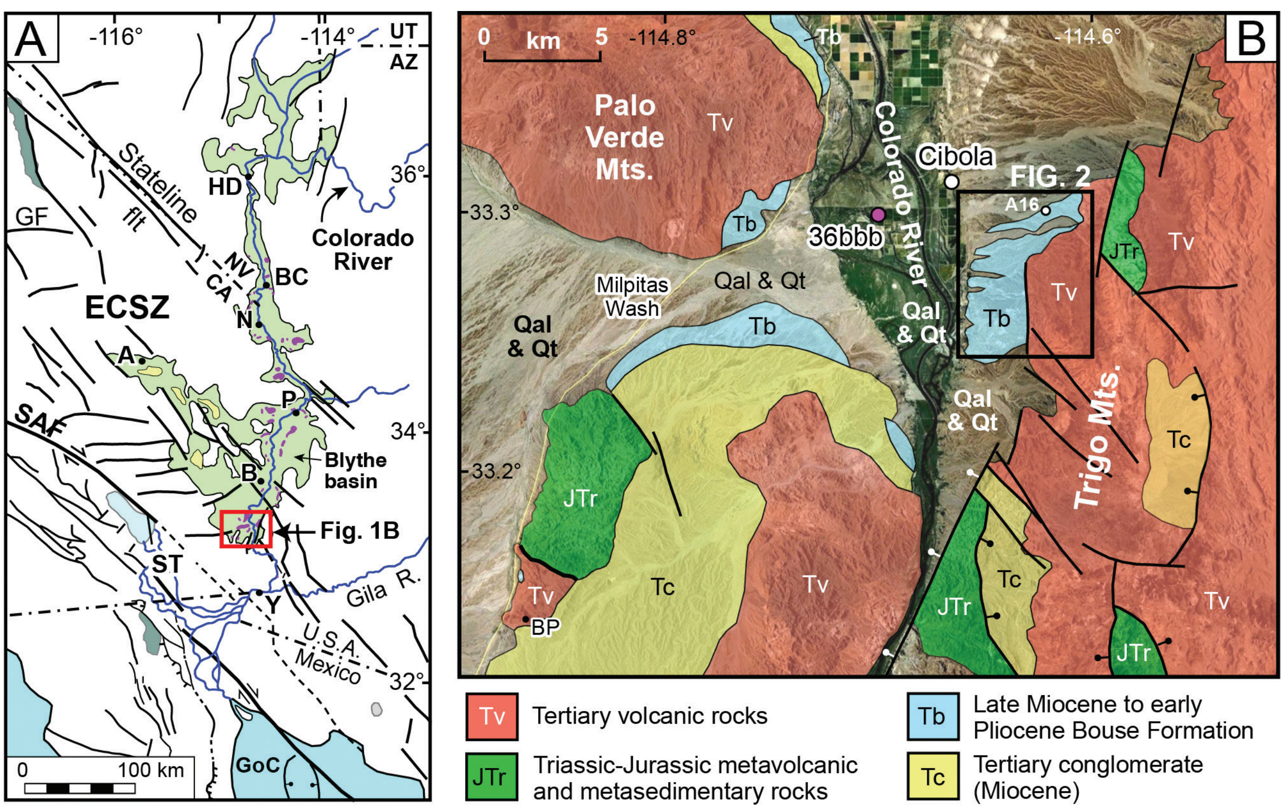

Figure 1. (A) Map of the lower Colorado River region highlighting faults, surface exposures of the Bouse Formation (purple), modern dry lakes (yellow), and inferred distribution of Bouse paleo- lakes (pale green; Spencer et al., 2008). Abbreviations: A, Amboy; B, Blythe; BC, Bullhead City; ECSZ, eastern California shear zone; GF, Garlock fault; GoC, Gulf of California; HD, Hoover Dam; N, Needles; P, Parker; SAF, San Andreas fault; ST, Salton Trough; Y, Yuma. (B) Simplified geologic map of the southern Blythe basin and surrounding ranges (compiled from Sherrod and Tosdal, 1991). BP = Buzzards Peak; 36bbb is a water well with Bouse Formation recorded to 92 m depth (Metzger et al., 1973). "Qal and Qt" is Quaternary alluvium and terrace deposits (undifferentiated).

Figure 2. Satellite image of the Cibola area showing location of measured sections and stratigraphic panels. Trace of normal fault from Homan (2014), Gootee et al. (2016), and this study. Location labels starting with "A" are sections from Homan (2014), labels starting with "B" are sections measured by B. O'Connell (unpubl. data). Location shown in Fig. 1B.

sagging is recognized along the lower Colorado River (Howard et al., 2015), but the possibility that faults of the ECSZ influenced local to regional subsidence patterns during deposition of the Bouse Formation has received little attention to date (e.g., Homan, 2014; O'Connell et al., 2016).

The Bouse Formation is a widespread sequence of late Miocene to early Pliocene deposits exposed discontinuously along the lower Colorado River corridor (Fig. 1A). In the southern Blythe basin it consists of three regionally correlative members: (1) Basal Carbonate, consisting of supratidal and intertidal mud-flat marls,

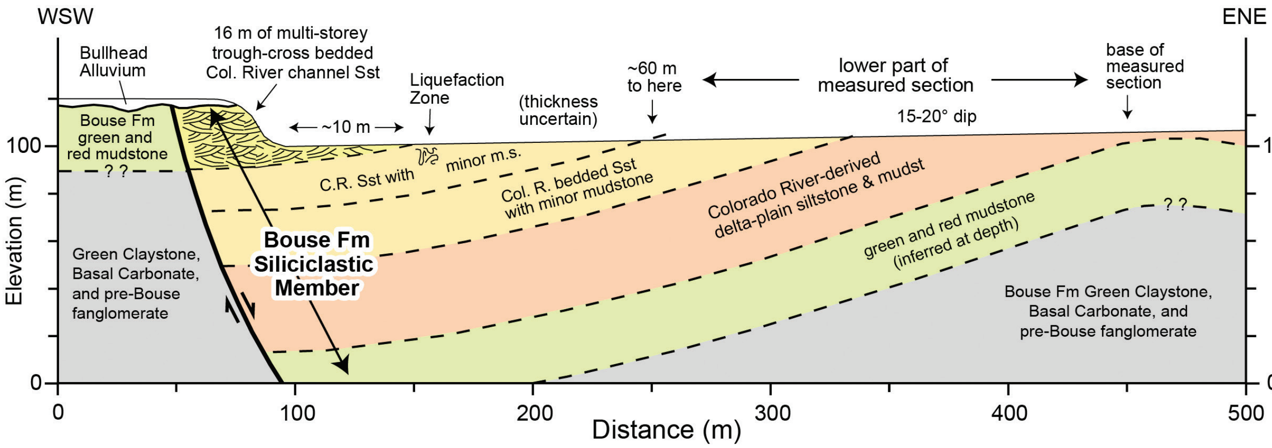

Figure 3. Geologic cross section across NE-dipping normal fault and thick hanging-wall section of Bouse Formation Colorado-River delta and channel deposits (Siliciclastic Member) in lower Hart Mine Wash. Line of section shown in Fig. 2.

intertidal and shallow subtidal bioclastic grainstone and conglomerate, and subtidal marl; (2) Siliciclastic member, consisting of Colorado River-derived green claystone, red mudstone and siltstone, and cross-bedded river channel sandstone; and (3) Upper Bioclastic member fossiliferous sandy calcarenite, coarse pebbly grainstone, and calcareous-matrix conglomerate (Homan, 2014; Dorsey et al., 2016; O'Connell et al., 2016, 2017). The southern Bouse Formation has been interpreted as recording deposition in either a lake (Spencer and Patchett, 1997; Spencer et al., 2008, 2013; Bright et al., 2016) or shallow marine setting (Buising, 1990; McDougall, 2008; McDougall and Miranda Martínez, 2014; O'Connell et al., 2017).

In this paper we summarize key results from five field seasons of detailed stratigraphic analysis south of Cibola, Ariz. (. 1). The data reveal systematic stratal thinning and thickening, pinch-outs, and wedging patterns in the Bouse Formation that we conclude were produced by syn-depositional tilting in response to growth of normal faults near the eastern margin of the basin. Similar stratal patterns in other nearby areas suggest widespread structural controls on deposition of the Bouse Formation. A palinspastic reconstruction of the lower Colorado River region at 5 Ma, modified from Bennett et al. (2016), provides insight to regional fault geometries in the ECSZ that may have controlled syn-depositional tilting and subsidence in Bouse depocenters shortly prior to and during initiation of the Colorado River.

Results

The Bouse Formation is well exposed in modern washes southeast of Cibola, Ariz. (Fig. 1B). Figure 2 shows the map distribution of Bouse Formation carbonate units, location of measured sections, and transects used to construct two stratigraphic panels. In the southern and central part of the map area, the Bouse Formation is truncated on the east by a steeply (60–70°) west-dipping normal fault (Homan, 2014; Gootee et al., 2016; this study). In western Hart Mine Wash a well exposed *northeast*-dipping normal fault cuts ~80–100 m of SW-dipping Colorado River siltstone, mudstone and sandstone in the hanging wall (Figs. 2, 3). This fault is located along-strike northwest of the west-dipping normal fault (Fig. 2), but it is not known if the two fault exposures are the same fault or two separate faults. In either case, the along-strike change in fault strike, dip, and sense of offset suggests a component of strike-slip motion on the fault in this area. This fault and hanging-wall deposits are unconformably capped by Bullhead Alluvium, and the section contains an interval of convolute bedding and large-scale liquefaction features that are typical of earthquake-induced seismites (Fig. 3).

Figure 4 shows two detailed stratigraphic panels that were constructed by correlating measured sections using laterally continuous stratigraphic contacts. Stratal architecture in the panels is restored to its original geometry by hanging units from reliable stratigraphic datums that we infer to represent paleo-horizontal surfaces based on the overall fine grain size and low energy of the deposits (e.g., Homan, 2014; O'Connell et al., 2017). In the Marl Wash panel, the base of the upper fanglomerate (Tfg2 in Fig. 4B) likely was deposited with a gentle west dip at the margin of a fan delta that prograded into the standing body of water recorded by the Bouse Upper Bioclastic member. Since we do not know *a-priori* the primary dip on the base of Tfg2, we also assign this datum a horizontal original dip, a choice that does not noticeably affect the resulting stratal architecture or structural interpretations.

The Hart Mine Wash panel (Fig. 4A) reveals a thin carbonate platform in the east represented by Bouse basal bioclastic limestone, and a gently west-tilted monocline defined by systematic westward thickening and wedging of the Basal Carbonate and green claystone of the Siliciclastic member. Units are inferred to thicken westward into the subsurface using the same angle of thickening that we document with surface exposures of lower bioclastic limestone and green claystone. The queried fault at depth is suggested as a possible control on the observed stratal thickening and wedging patterns.

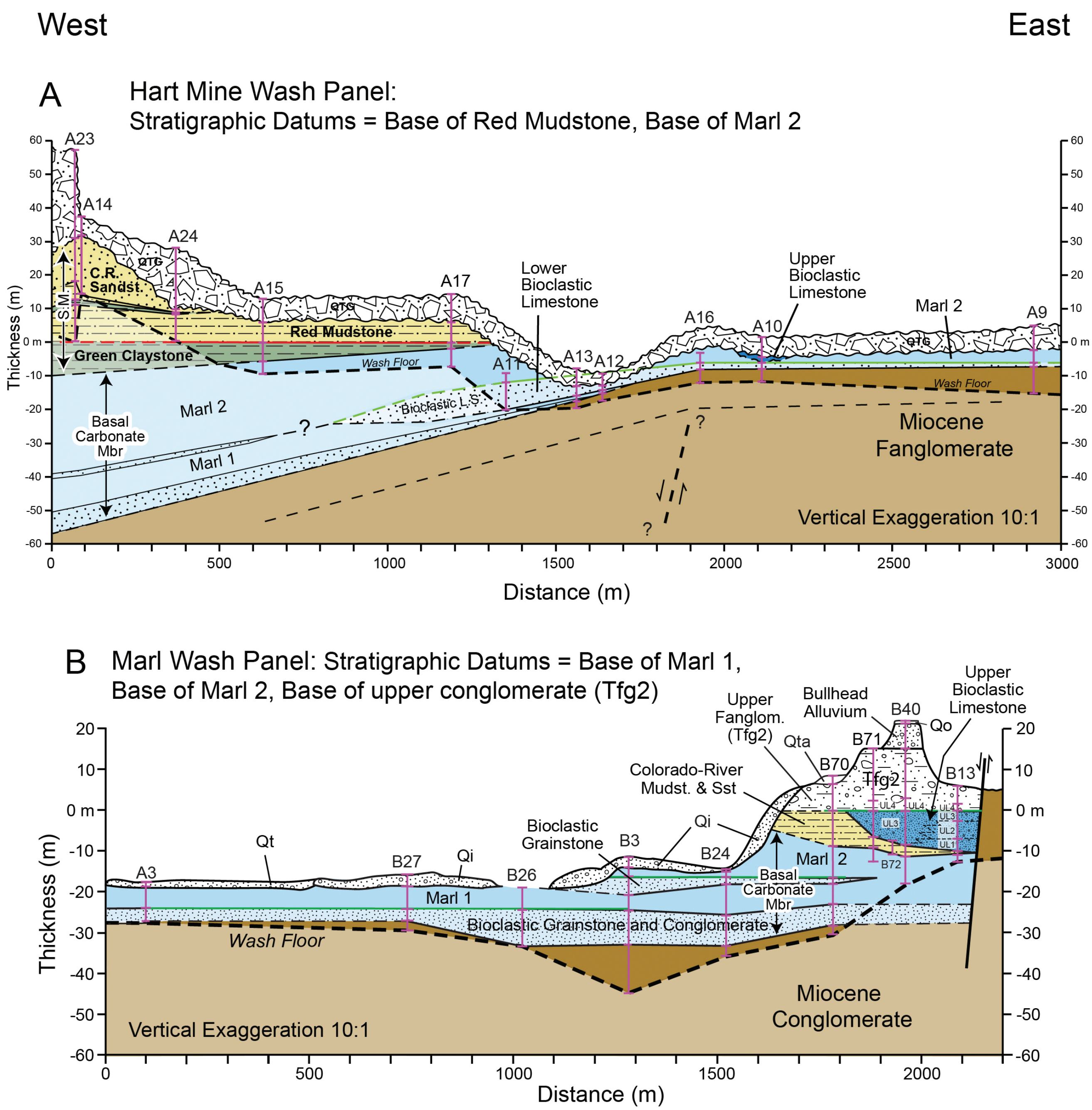

Figure 4. Restored stratigraphic panels for the Bouse Formation south of Cibola, AZ. (A) Hart Mine Wash displays a thin platform of carbonate in the east and westward thickening of Basal Carbonate and green claystone west of section A16, defining an overall monocline geometry. S.M. is siliciclastic member. (B) Marl Wash panel shows relatively uniform thickness of the Basal Carbonate member, westward thickening of the Siliciclastic member, and eastward thickening of the Bouse Upper Bioclastic member. Qta, Qi, Qt, and Qo are Quaternary gravel units of Gootee et al. (2016). UL1-UL4 are facies of the Upper Bioclastic member (O'Connell et al., 2016). Colored horizontal lines are stratigraphic datums. Darker colors represent units exposed above the wash floor, and lighter shades are units inferred below wash floor. Wash floor appears deformed because sections are restored to pre-deformation coordinates. Location of panels in Fig. 2.

Westward thickening in this panel may be a result of tilt on the northeast-dipping fault normal fault in lower Hart Mine Wash (Fig. 3), or growth folding above the propagating tip of a blind west-dipping normal fault, or both.

The Marl Wash panel displays relatively uniform thickness of Basal Carbonate in the western and central parts (Fig. 4B). The eastern part of this panel reveals westward thickening of the Bouse Siliciclastic member away from the normal fault, and eastward thickening of Upper Bioclastic member toward the fault. Importantly, the upper fanglomerate (Tfg2) conformably overlies the Upper Bioclastic member near the fault, and it rests unconformably on Colorado River mudstone and sandstone west of there in section B70. This indicates that accommodation space was produced close to the fault *during deposition of Upper Bioclastic Limestone and Tfg2,* while accommodation was being destroyed by uplift and erosion to the west at B70, yielding a structural relationship produced by tilting toward the fault. The eastern part of the panel thus defines a "double wedge" geometry consisting of a westward-thickening stratal wedge (Siliciclastic member) overlain by an eastward-thickening wedge (Upper Bioclastic member), which records syn-depositional tilting first away from and then toward the normal fault.

Based on data presented above, we propose a two-stage model (Fig. 5) for the evolution of normal faults that controlled deposition of the Bouse Formation in the Cibola area. This is a composite conceptual model that combines observations of: (1) westward thickening wedge geometries in Basal Carbonate and green claystone in Hart Mine Wash (Fig. 4A) and Siliciclastic member in Marl Wash (Fig. 4B); and (2) eastward thickening of Upper Bioclastic Limestone in a stratal wedge that dips toward the normal fault in Marl Wash (Fig. 4B). In Stage 1, syn-depositional westward tilting and stratal thickening occurs by growth of a monocline above the tip of a west-dipping, propagating blind normal fault at depth (Fig. 5A). In Stage 2, the normal fault propagates up to and breaches the surface, creating new accommodation space by eastward tilting toward the fault in a new fault-related monocline (Fig. 5B). This model was developed to explain similar double-wedge geometries in syn-rift deposits in the Gulf of Suez (Gawthorpe et al., 1997), and is widely applied to fault-related stratal architecture in other extensional rift-basin systems (e.g., Hardy and McClay, 1999; Jackson et al. 2006).

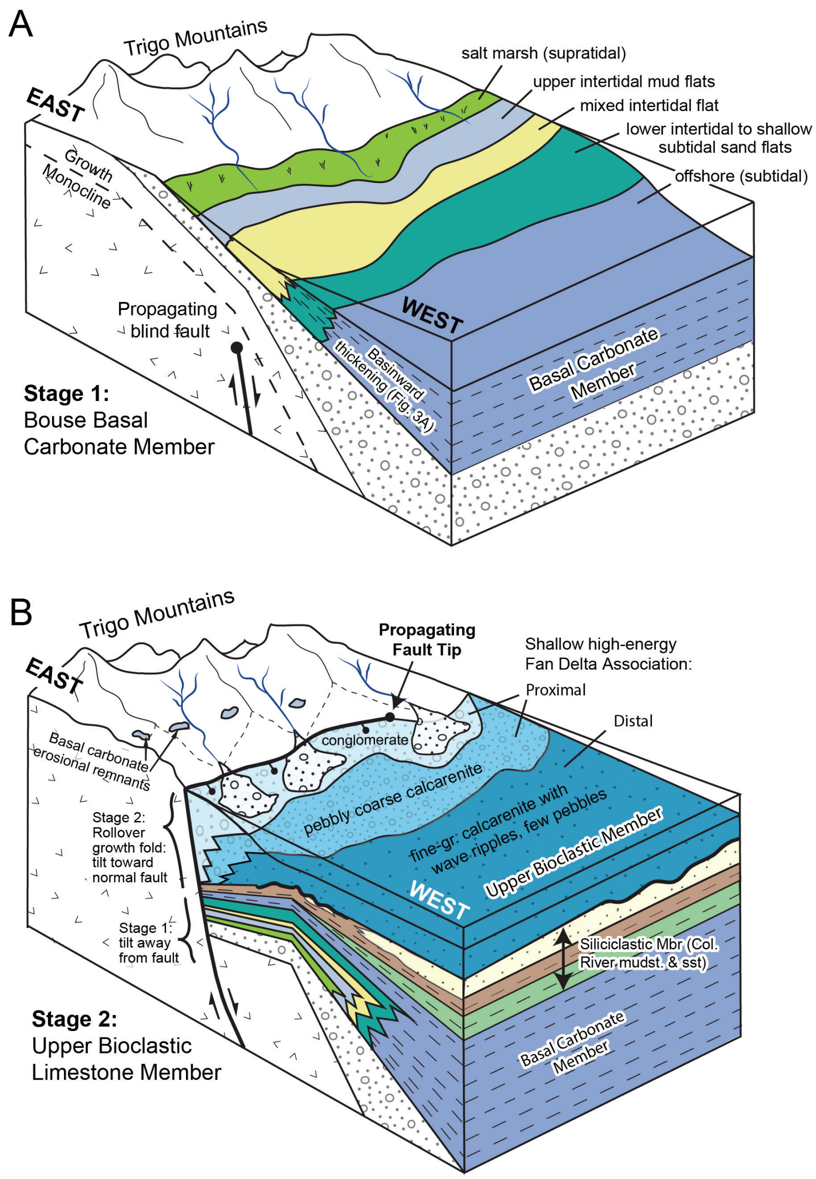

Figure 5. Proposed two-stage model for structural control on deposition of the Bouse Formation south of Cibola. (A) Stage 1: propagating blind normal fault causes westward tilting and stratal thickening toward basin depocenter. (B) Stage 2: fault breaches the surface and creates new accommodation space by eastward tilting toward the normal fault in a fault-related growth monocline (e.g., Gawthorpe et al., 1997)

Discussion and Conclusions

Data presented above show that syn-depositional fault-related tilting exerted an important control on production of accommodation space and resulting thickness variations in the Bouse Formation south of Cibola. This conclusion is highlighted by observations near the NE-dipping fault in lower Hart Mine Wash (Fig. 3): (1) the 80–100 m thick section of Colorado-River deltaic and channel sandstones in the hanging wall is by far the thickest exposed section of Siliciclastic member south of Blythe; (2) the fault and hanging-wall section are erosionally capped by ~4.5-Ma Bullhead Alluvium, and thus fault slip and tilting are pre-Bullhead (syn-Bouse); and (3) the hanging-wall section contains locally abundant convolute beds (seismites) and a large-scale liquefaction zone that likely record earthquakes on nearby faults, possibly the fault that cuts the section. Other patterns of stratal thickening and wedging south of Cibola (Figs. 4, 5) provide additional evidence for syn-depositional tilting due to slip on normal faults in this area.

The Hart Mine Wash panel reveals intra-formational westward thickening of about 50 m over a ~2 km distance, indicating an internal dip of ~1.4° (Fig. 4A). This angle predicts westward thickening of ~170 meters over 7 km from the hinge of the monocline at section A16 to well 36bbb in the Colorado River Valley (Fig. 1B). The maximum depth of Bouse Formation siliciclastic muds and sands in this well is 92 m (26 m below sea level) where it is a minimum of 52 meters thick (basal limestone was not encountered; Metzger et al., 1973), consistent with the prediction. This comparison suggests that syn-Bouse westward tilting can explain the increase in thickness from Hart Mine Wash to the subsurface beneath the Colorado River floodplain, though the NE-dipping normal fault in lower Hart Mine Wash complicates this pattern and may suggest additional structural controls on stratigraphic thickness variations in this area.

Similar stratal wedge geometries in other parts of the southern Blythe basin are consistent with syn-depositional basinward tilting and subsidence. In the southeast Palo Verde Mountains (Fig. 1B) Bouse Formation deposits dip 5-7° to the east and thicken to the east via stratal wedging, not onlap (Homan, 2014). Faults in several locations cut the Bouse Siliciclastic member and are unconformably overlain by un-faulted Upper Bioclastic member, and in western Milpitas wash (Fig. 1B) the Upper Bioclastic member unconformably caps the Basal Carbonate member (Homan, 2014). Structural controls on syn-Bouse subsidence are further indicated by the regional map pattern which shows modern dry lakes bounded by active faults of the ECSZ, with Bouse Formation present in the subsurface beneath the dry lakes (Fig. 1A; Howard and Miller, 1992; Jachens and Howard, 1992).

We therefore propose that the distribution of basinal depocenters that contain the Bouse Formation (Fig. 1A) is at least in part controlled by the distribution and kinematics of linked dextral and oblique normal faults that were active in this region during late Miocene to early Pliocene time. We present a palinspastic reconstruction of the ECSZ and lower Colorado River region at 5 Ma (Fig. 6; modified from Bennett et al., 2016a) illustrating the interaction of active faults that may have controlled formation of Bouse-age depocenters. NW-striking dextral faults are connected through a series of broad releasing stepovers to dextral faults that link southeast to a major late Miocene to early Pliocene dextral shear zone in coastal Sonora, Mexico (Bennett et al., 2016b; Darin et al., 2016). We infer that this fault network was active during deposition of the Bouse Formation and exerted a direct control on formation of basinal depocenters via fault-related tilting similar to processes documented in this study south of Cibola. Abundant NW-striking faults east and southeast of here in the Trigo Mountains (Fig. 1B) probably are kinematically linked and related to syn-Bouse faults documented in this study.

We further suggest that syn-Bouse diffuse transtension and subsidence throughout much of the lower Colorado River corridor may have formed deep basins in releasing stepovers (Fig. 6). For

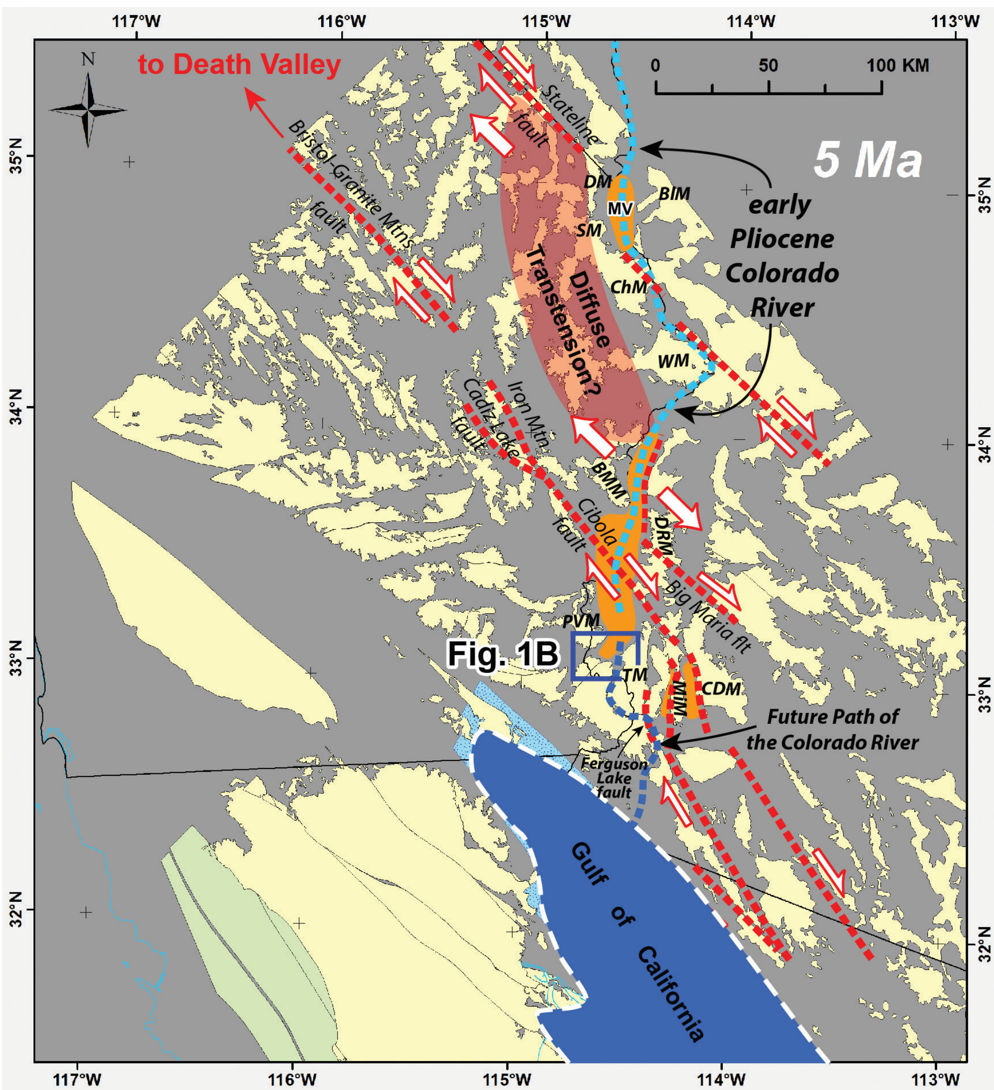

Figure 6. Palinspastic reconstruction of the ECSZ and lower Colorado River region at 5 Ma during deposition of the Bouse Formation, modified from Bennett et al. (2016a). Orange areas indicate basins that are predicted to open and subside due to extension or transtension (MV = Mohave Valley). Political boundaries are fixed in present-day coordinates for reference. Animation is available at: https://youtu.be/htzdDLW3-aQ. Mountain Ranges (yellow): BMM - Big Maria Mtns; BlM - Black Mtns; CDM - Castle Dome Mtns; ChM - Chemehuevi Mtns; DM - Dead Mtns; DRM - Dome Rock Mtns; MiM - Middle Mtns; PVM - Palo Verde Mtns; SM - Sacramento Mtns; TM - Trigo Mtns; WM - Whipple Mtns.

example, a ~3-km deep sedimentary basin is present beneath the Mohave Valley (Saltus and Jachens, 1995), though the age of subsurface sediments is not well known. Active fault-controlled subsidence in the ECSZ may have also contributed to setting and modifying the path of the early Colorado River during its initiation ca. 5 Ma. The predictions of this model need to be tested in future studies of stratal architecture, detailed geologic and structural mapping, and gravity surveys of subsurface basins.

Acknowledgments

This study was supported by funding from the Sedimentary Geology and Paleobiology Program of the National Science Foundation (EAR-1546006). Vicki Langenheim and Kris McDougall provided constructive reviews of this paper. Laurie Crossey, Karl Karlstrom, Keith Howard, and Brian Gootee are thanked for insightful discussions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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