Tectonostratigraphic record of late Miocene–early Pliocene transversal faulting in the Eastern California shear zone, southwestern USA

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ABSTRACT

The Eastern California shear zone (ECSZ; southwestern USA) accommodates ~20%–25% of Pacific–North America relative plate motion east of the San Andreas fault, yet little is known about its early tectonic evolution. This paper presents a detailed stratigraphic and structural analysis of the uppermost Miocene to lower Pliocene Bouse Formation in the southern Blythe Basin, lower Colorado River valley, where gently dipping and faulted strata provide a record of deformation in the paleo-ECSZ. In the western Trigo Mountains, stranding strata of the Lost Trigo fault zone include a west-dipping normal fault that cuts the Bouse Formation and a steeply NE-dipping oblique dextral-normal fault where an anomalously thick (~140 m) section of Bouse Formation siliciclastic deposits filled a local fault-controlled depocenter. Systematic basinward thickening and stratal wedge geometries in the western Trigo and southeastern Palo Verde Mountains, on opposite sides of the Colorado River valley, record basinward tilting during deposition of the Bouse Formation. We conclude that the southern Blythe Basin formed as a broad transversional sag basin in a diffuse releasing stepover between the dextral Laguna fault system in the south and the Cibola and Big Maria fault zones in the north. A palinspastic reconstruction at 5 Ma shows that the southern Blythe Basin was part of a diffuse regional network of linked right-stepping dextral, normal, and oblique-slip faults related to Pacific–North America plate boundary dextral shear. Diffuse transtensional strain linked northward to the Stateline fault system, eastern Garlock fault, and Walker Lane, and southward to the Gulf of California shear zone, which initiated ca. 7–9 Ma, implying a similar age of inception for the paleo-ECSZ.

INTRODUCTION

The eastern California shear zone (ECSZ; southwestern USA; Fig. 1) is a wide zone of diffuse strike-slip deformation that currently accommodates ~20%–25% of relative Pacific–North America plate motion in the Mojave Desert east of the San Andreas fault (Dokka and Travis, 1990; Miller et al., 2001; Meade and Hager, 2005; Oskin et al., 2007, 2008). Since late Miocene time, the ECSZ has been kinematically linked to the Gulf of California shear zone (Fig. 1; Bennett and Oskin, 2014; Bennett et al., 2017), where major strike-slip and normal faults related to oblique rifting across the Pacific–North America plate boundary developed ca. 7–9 Ma in the northern Gulf of California and Salton Trough region (Seiler et al., 2010, 2011; Dorsey et al., 2011; Bennett et al., 2013, 2015, 2016a, 2016b, 2017; Darin et al., 2016; Umhoefer et al., 2018). The ECSZ can be divided into a western belt of active deformation (modern ECSZ) defined by GPS motions, modern seismicity, and Quaternary-age faults (e.g., Oskin et al., 2008; Spinler et al., 2010; Parsons et al., 2013; Zeng and Shen, 2014, 2016; U.S. Geological Survey and California Geological Survey, 2020) and an eastern belt (paleo-ECSZ) that displays slow to negligible modern strain and is defined by structures that were active in Miocene time but are now mostly inactive (e.g., Guest et al., 2007; Mahan et al., 2009) (Fig. 1). The onset of faulting in the ECSZ is poorly known, with proposed ages of initiation ranging from ca. 10–12 Ma (Dokka and Travis, 1990; Schermer et al., 1996; Reheis and Sawyer, 1997; McQuarrie and Wernicke, 2005; Nuriel et al., 2019) to ca. 5–7 Ma (Fan et al., 2003; Langenheim and Powell, 2009) to ca. 2–4 Ma (Du and Aydin, 1996; Rubin and Sieh, 1997). While it is generally agreed that the width of the deformation zone has narrowed and become more localized through time into the western (active) ECSZ belt (Dokka and Travis, 1990; Dixon and Xie, 2018), few constraints exist on the timing, distribution, and structural style of strain in the paleo-ECSZ. Documenting the geologic evolution of the older, eastern belt of the ECSZ is needed to understand how late Miocene dextral strain in the Gulf of California shear zone was kinematically linked with paleo-ECSZ faults in the Mojave Desert east of the San Andreas fault and farther north in the Walker Lane.

Southern exposures of the uppermost Miocene to lower Pliocene Bouse Formation provide an
excellent opportunity to address these questions because of their location within a transtensional zone of right-stepping, NW-striking dextral faults and north-striking normal faults related to the Gulf of California shear zone and ECSZ (Fig. 1). Previous studies found that faults in this area were active during late Miocene time (Sherrod and Tosdal, 1991; Richard, 1993) and that fault-related deformation continued during deposition of the Bouse Formation (Buisong, 1990; Dorsey et al., 2017; Gardner and Dorsey, 2021; Thacker et al., 2020). The age of the Bouse Formation is bracketed between ca. 6.0 and 4.6 Ma (House et al., 2008; Sarna-Wojicki et al., 2011; McDougall, 2008; McDougall and Miranda Martinez, 2014; Dorsey et al., 2018; Crow et al., 2019a), which thus constrains the age of syn-depositional structures. Post–4.5 Ma broad sagging is recognized along the lower Colorado River (Howard et al., 2015; Crow et al., 2018; Cohen et al., 2019), including possible isostatic responses to sedimentation and erosion (Karlstrom et al., 2017), but the influence of ECSZ faults on regional subsidence patterns during deposition of the Bouse Formation remains poorly understood. Detailed studies are needed to test kinematic models for the ECSZ and its links to the northern Gulf of California, San Andreas fault system, and Walker Lane (e.g., Dolan et al., 2007; Oskin et al., 2008; Liu et al., 2010; Dixon and Xie, 2018).

Stratigraphic analysis offers a powerful method for documenting fault-related tilting and deformation of the Earth’s surface in areas of crustal extension, subsidence, and sedimentation (Gawthorpe and Leeder, 2000; Gawthorpe et al., 1997, 2018; Sharp et al., 2000; Withjack et al., 2002; Serck and Braathen, 2019). This approach is especially useful in areas of slow or diffuse deformation, where low strain rates produce gentle bedding dips that may be difficult to quantify with standard structural analysis or where structures are concealed or poorly exposed. Tilting related to syn-depositional normal and oblique-slip faults produces systematic thickness variations and distinctive stratal architectures that can be used to reconstruct the timing, geometries, and kinematics of the causal fault systems (e.g., Gawthorpe et al., 1997; Young et al., 2003; Lewis et al., 2017; Muravchik et al., 2018). We use this tectonostratigraphic approach to interpret structural controls on stratigraphic architecture and fault-related syn-depositional tilting dynamics that were not identified in previous published studies in the paleo-ECSZ (e.g., Miller and McKee, 1971; Sherrod and Tosdal, 1991; Richard, 1993; Thacker et al., 2020). In addition, these methods offer a powerful approach that could be used to reconstruct the late Cenozoic kinematic evolution of other important strike-slip fault zones such as the North Anatolian fault (northern Turkey; Şengör et al., 2005), Dead Sea transform (Garfunkel, 2014), and regional...
strike-slip systems in southeast Asia (Sumatra, Sagaing, and Red River fault zones; Morley, 2002).

This paper presents a detailed stratigraphic analysis of the Bouse Formation on opposing sides of the southern Blythe Basin, south of Blythe, California, integrated with geologic mapping and structural data, to document late Miocene to early Pliocene deformation in the paleo-ECSZ in the lower Colorado River corridor (Figs. 1, 2). We document diagnostic stratigraphic geometries that record a history of syn-depositional tilting and subsidence in response to growth of normal and oblique-slip faults around the margins of a transtensional basin. These results provide new constraints on the time-space evolution of the ECSZ and support prior suggestions that regional subsidence in a fault-bounded tectonic lowland controlled latest Miocene shallow-marine inundation and subsequent integration of the Colorado River into the northern Gulf of California at ca. 5 Ma (e.g., Buising, 1990; Bennett et al., 2016a; Dorsey et al., 2018).

**REGIONAL STRATIGRAPHIC FRAMEWORK**

The Bouse Formation is a thin sequence of upper Miocene to lower Pliocene sedimentary deposits that are discontinuously exposed along the lower Colorado River valley in western Arizona and southeastern California (Figs. 1–3). It unconformably overlies variably deformed Miocene volcanic and sedimentary rocks that accumulated during and after northeast-southwest extension in a belt of low-angle detachment faults known as the Colorado River extensional corridor (Howard and John, 1987; Spencer and Reynolds, 1991; Sherrod and Tosdal, 1991; Spencer et al., 2018). Previous studies have bracketed the age of the southern Bouse Formation between ca. 6.3 and 4.6 Ma using tephrachronology, biostratigraphy, and 40Ar/39Ar methods (Sarna-Wojcicki et al., 2011; Spencer et al., 2013; McDougall, 2008; McDougall and Miranda Martínez, 2014; Dorsey et al., 2018; Crow et al., 2019a), making these deposits an ideal target for studies of late Miocene to present deformation in the paleo-ECSZ.

In the southern Blythe Basin (Fig. 2), south of Blythe, California, the Bouse Formation consists of three regionally correlative members: (1) a basal carbonate member consisting of mixed carbonate-siliciclastic bioclastic grainstone, conglomerate, and marl; (2) a siliciclastic member comprising green claystone, red mudstone, siltstone, and cross-bedded channel sandstone of the earliest Pliocene Colorado River; and (3) an upper bioclastic member (UBM), which forms a coarsening-upward sequence of fossiliferous sandy grainstone, pebbly grainstone, and calcareous-matrix conglomerate that overlies older members of the Bouse Formation along a regional unconformity that likely represents ~100–200 k.y. (Fig. 3; Homan, 2014; O’Connell, 2016; Dorsey et al., 2018, 2019). Older members of the Bouse Formation below the UBM thicken toward the lower Colorado River valley in western Arizona (Figs. 1–3). It unconformably overlies variably deformed Miocene volcanic and sedimentary rocks that accumulated during and after northeast-southwest extension in a belt of low-angle detachment faults known as the Colorado River extensional corridor (Howard and John, 1987; Spencer and Reynolds, 1991; Sherrod and Tosdal, 1991; Spencer et al., 2018). Previous studies have bracketed the age of the southern Bouse Formation between ca. 6.3 and 4.6 Ma using tephrachronology, biostratigraphy, and 40Ar/39Ar methods (Sarna-Wojcicki et al., 2011; Spencer et al., 2013; McDougall, 2008; McDougall and Miranda Martínez, 2014; Dorsey et al., 2018; Crow et al., 2019a), making these deposits an ideal target for studies of late Miocene to present deformation in the paleo-ECSZ.

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The Bouse Formation in the southern Blythe Basin has been variably interpreted to record deposition in either a large saline lake (Spencer and Patchett, 1997; Spencer et al., 2008, 2013; Pearthree and House, 2014; Bright et al., 2016, 2018a, 2018b; Gootee et al., 2019) or a shallow-marine tidal strait or estuary (Buising, 1990; Turak, 2000; McDougall, 2008; McDougall and Miranda Martínez, 2014; Gootee et al., 2019). The UBM and unit Tfg2 gravel together define a laterally extensive conformable thick sequence known as “Trigo sediments” (Gootee et al., 2019) that we treat as a single map unit (Tbg2) in the western Trigo Mountains (Fig. 4). The Bullhead Alluvium is a widespread unit of lower Pliocene Colorado River gravel and sand that locally interfingers with unit Tfg2 gravel. In most places, Bullhead Alluvium is erosionally inset into older deposits and records incision followed by regional aggradation in the lower Colorado River region that took place ca. 4.5–3.5 Ma (Pearthree and House, 2014; Howard et al., 2015).

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Results for specific stratigraphic units are summarized below. Studies that support the saline lake model tend to emphasize evidence from carbonate major- and trace-element chemistry and isotopic data (Sr, O, and C isotopes), while papers supporting the marine and estuarine model base their conclusions primarily on evidence from process sedimentology, paleontology, and trace fossils.

**Methods**

Field work was conducted in the western Trigo Mountains, Arizona, and southeastern Palo Verde Mountains, California (Fig. 2). Geologic maps were compiled from previous work (Homan, 2014; Gootee et al., 2016; O’Connell et al., 2021; Dorsey et al., 2018; Gardner and Dorsey, 2021) and new mapping conducted for this study. Stratigraphic relations were characterized by detailed geologic mapping, measuring sections using a Jacob’s staff, correlation of key contacts and marker beds, and construction of geologic cross sections and stratigraphic panels to illustrate important stratal architectures and fault geometries. Detailed measured sections were compiled from Master’s theses (Homan, 2014; O’Connell, 2016; Gardner, 2019). Fault geometric analysis was conducted using Stereonet 10 software (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013). Kamb contours were calculated from poles to planes to decipher statistically significant geometric trends. Fault kinematic data were obtained by measuring faults and striations on fault planes; shear sense was interpreted in the field using criteria outlined in Pettit (1987) and geologic observations such as correlation of offset beds. Paleostress was analyzed from fault kinematic data using FaultKin 7 software (Marrett and Allmendinger, 1990; Allmendinger et al., 2012) to determine the incremental shortening (P) and extension (T) axes of measured faults. Stratigraphic and structural data were integrated with previously published age estimates (summarized above) to interpret regional paleogeography, faulting controls on basin evolution, and development of the paleo-EC SZ.

**Results**

Stratigraphic Summary

The basal carbonate member of the Bouse Formation ranges from ~1 to 25 m thick and overlies Miocene volcanic rocks and conglomerate along an unconformity that exhibits variable geometry and relief around the study area (Fig. 2). In the western Trigo Mountains, bioclastic facies overlie Miocene alluvial fan conglomerate along a sharp, quasi-planar, laterally continuous disconformity (O’Connell et al., 2021). In the southeastern Palo Verde Mountains, a thin basal travertine unit is encrusted on steep irregular paleotopography in Miocene volcanic rocks, and bioclastic facies onlap onto travertine-encrusted local relief. Basal carbonate in the western Trigo Mountains is subdivided into gravel-dominated and carbonate-dominated facies, map units Tbbg and Tbbc, respectively (Figs. 3, 4, 5A). The gravel-dominated facies (unit Tbbg) is primarily reworked from underlying conglomerate. It is clast supported and well sorted and displays tabular to trough cross bedding formed in beach ridges, gravelly barchan dunes, delta mouth bars, and small Gilbert deltas (Fig. 5B; Dorsey et al., 2018; O’Connell et al., 2021). Carbonate-dominated facies (unit Tbbc) overlies the gravel and are interbedded with unit Tbbg and contain a wide range of sedimentary structures, facies associations, and carbonate-siliciclastic mixtures that record deposition in low- to high-energy tidal
Figure 4. Geologic map of the western Trigo Mountains, compiled from Gootee et al. (2016), Homan (2014), O’Connell (2016), and this study (see location in Fig. 2). Dashed lines from measured section locations show projection into stratigraphic panels (Fig. 9). Background image is from Google Earth.
Figure 5. Examples of Bouse Formation and bounding units in the western Trigo Mountains. (A) Top of Miocene conglomerate (unit Tfg1) and contact with overlying Bouse Formation basal member conglomerate (Tbbg) and bioclastic carbonate (Tbbc) in Marl Wash. South of measured section B3 (Fig. 4). View looking WSW. Location of view point is 33.25628°N, 114.64008°W. (B) View looking southwest at interbedded bioclastic facies (Tbbc) and cross-beded conglomerate (Tbbg) of the Bouse basal carbonate member, overlying Miocene alluvial-fan conglomerate (Tfg1). Measured section B3 (Fig. 4). Location is 33.25763°N, 114.64189°W. (C) Upper marl unit of Bouse basal carbonate member (Tbbc) overlain by Colorado River–derived deposits of the siliciclastic member (Tbs), including thin lower green claystone, red mudstone, and pink sandstone in Big Fault Wash. Unit Tbs is sharply overlain by upper conglomerate (Tfg2). Measured section A19 in Big Fault Wash (Fig. 4); person (circled) for scale. View looking NE. Location of viewpoint is 33.27036°N, 114.64295°W. (D) Thick, multistory trough cross-bedded Colorado River channel sandstone in the Bouse siliciclastic member (Tbs), where it is cut by a NE-dipping fault on the north side of Hart Mine Wash (Fig. 4). Fault zone is interpreted to have oblique dextral-normal offset. “R” indicates inferred Riedel shears. Northeast dip in immediate hanging wall is due to local fault drag superimposed on large-scale trough cross bedding. The fault zone is capped by undeformed Bullhead Alluvium (Tcb) along an unconformity that correlates to the unconformity at the base of the upper bioclastic member (Fig. 6). Unit Qi is inset Quaternary terrace gravel (Fig. 4). Person (circled) for scale. View looking NW. Location is 33.29536°N, 114.64143°W.
channels, bars, and intertidal to shallow subtidal flats (O’Connell et al., 2017, 2021; Dorsey et al., 2018; Gardner and Dorsey, 2021). The youngest unit of the basal carbonate member consists of laterally extensive fine-grained carbonate micrite and shale (marl; Fig. 5C) interpreted to have accumulated in a pre–Colorado River subtidal marine embayment (McDougall, 2008; McDougall and Miranda Martinez, 2014; O’Connell et al., 2017; Dorsey et al., 2018) or low-energy saline lake fed by the early Colorado River (Bright et al., 2016, 2018a, 2018b).

The siliciclastic member of the Bouse Formation (unit Tbs), also known as the “interbedded unit” of Metzger (1968), overlies basal carbonate along a widespread abrupt but conformable contact (Fig. 5C) that records the sudden first arrival of Colorado River sediment in the study area. It is as much as ~200 m thick in subsurface wells and thins to zero thickness at the margins of the basin (Fig. 3; Metzger, 1968; Metzger et al., 1973; Dorsey et al., 2018). The siliciclastic member displays a conformable up-section change from extremely fine-grained green claystone, to red mudstone and siltstone with minor cross bedding and intermittent weak paleosols, to thick multistory trough cross-bedded quartz-rich sandstone that is interpreted to have formed in fluvial channels of the earliest through-flowing Colorado River (Figs. 3, 5D; Dorsey et al., 2018).

The upper bioclastic member of the Bouse Formation (UBM; 0–10 m thick) rests on the basal carbonate and siliciclastic members across a quasi-planar regional unconformity and makes up the lower subunit of map unit Tbug (Trigo sediments of Gooette et al., 2019) in the western Trigo Mountains (Figs. 3, 4). Where the UBM overlies basal carbonate facies, marl beneath the unconformity is altered by a distinctive 1–2-m-thick zone of karst- generated fissures and breccia that record pre-UBM subaerial exposure and weathering (Figs. 3, 6A, 6B; Dorsey et al., 2018). The UBM typically coarsens up-section from sandy grainstone with centimeter-scale wave ripple cross lamination, to pebbly grainstone with larger wave-formed gravelly ripples (wavelengths typically 1–3 m), to calcareous-matrix pebble conglomerate (Figs. 6C, 6D). Fossils in the UBM include upward-branching marine calcareous red algae, echinoderm spines, articulated barnacles, shallow-marine foraminifers, mollusks, and ostracodes that indicate deposition in a high-energy shallow-marine embayment that flooded the lower Colorado River valley after the river first ran through it (Dorsey et al., 2018, 2019). The conformable upward transition to alluvial-fan gravels of unit Tfg2 (Fig. 6D) records regional progradation of shoal-water fan deltas into the basin and termination of shallow-marine conditions.

Western Trigo Mountains

Stratal geometries of the Bouse Formation exposed at the western margin of the Trigo Mountains are revealed by the geologic map pattern (Fig. 4) and a series of geologic cross sections and stratigraphic panels (Figs. 7–9). Bedding dips in the Bouse Formation typically are very low (<3°–5°) but locally steepen to 15°–20° in Hart Mine Wash near a fault that cuts a thick interval of the siliciclastic member (Figs. 7, 8). Pre-Bouse conglomerate (unit Tfg2) is preferentially exposed in the south and east due to overall gentle Bouse Formation dips to the north and west (Fig. 4). Bedding dips in unit Tfg1 range from 32° to 4° west, with a general up-section decrease in dip angle that suggests westward tilting during deposition (Sherrod and Tosdal, 1991). In one area ~1 km south of Hart Mine Wash, Bouse basal carbonate (unit Tbbc) overlies unit Tfg1 and Miocene volcanic rocks along an angular unconformity, below which unit Tfg1 thickens markedly to the northwest (Fig. 7D). Bouse Formation upper bioclastic member (UBM) and unit Tfg2 gravel are grouped on the geologic map (Fig. 4), geologic cross sections (Fig. 7), and most stratigraphic panels (Figs. 9A, 9B) into one geologic unit, Tbug, due to their thin conformable nature that makes it impractical to separate at the scale of these diagrams. The unconformity at the base of unit Tbug (Figs. 6A, 6B, 6D), also the base of the UBM, is a regional sequence boundary that provides a useful stratigraphic datum for documenting stratal geometries in older units. Beneath this datum, older units of the Bouse Formation display systematic thickening to the west toward the center of the southern Blythe Basin, with concomitant thinning to the east toward the basin margin (Figs. 7, 9).

The Bouse Formation and older units in the western Trigo Mountains are cut by a prominent north- to NW-striking fault zone that displays a distinctive anastomosing surface exposure, traced for ~5 km across the map (Gooette et al., 2016; Fig. 4). This fault was first described by Metzger et al. (1973) but was not named. A geotechnical report by San Diego Gas and Electric Company (1976) mapped and named this the Lost Trigo fault (Schell and Wilson, 1982), and it was included on a fault compilation map for Arizona with the same fault name (Menges and Pearthree, 1983). The Lost Trigo fault also appears on maps by Sherrod and Tosdal (1991) and Richard (1993) and is likely the fault that Buising (1990) describes in Lopez Wash, Arizona, though none of these publications included a fault name. Recent published studies have referred to this fault as the “Big fault” (e.g., Gooette et al., 2016; Beard et al., 2016; Thacker et al., 2020). In this study, we use the original name “Lost Trigo fault” and propose that the name “Big fault” no longer be used. Dip direction on strands of the Lost Trigo fault zone varies along strike, with steep west and SW dips in the south changing to steep NE dip on the northern side of Hart Mine Wash (Fig. 4).

On the northern side of Hart Mine Wash, the Lost Trigo fault is a NW-striking, 4–5-m-wide fault zone that dips ~70° NE (Figs. 5D, 7A, 8). North-east of the fault, an anomalously thick (~100 m), SW-dipping interval of Colorado River siltstone, mudstone, and cross-beded channel sandstone is exposed in the hanging wall (Fig. 4). Deposits of this interval are observed nearby (measured section locations B33, A15; Figs. 4, 9) to overlie Bouse Formation green claystone, which in turn rests on the basal carbonate member, and therefore these older units are inferred to be present at depth in the hanging wall of the fault (Fig. 8). We estimate the SW-dipping interval of Colorado River siltstone, mudstone, and sandstone to be ~140 m thick using measured-section techniques and accounting for moderate bedding dips. Southwest of the fault, the older green claystone is exposed as high as 9 m above the floor of Hart Mine Wash (Fig. 5D). These relations indicate an apparent normal separation
Figure 6. (A) View looking south at Lost Trigo fault in Big Fault Wash and regional unconformity at base of the Bouse upper bioclastic member (UBM). KFW is a zone of karst fissures and weathering in upper marl of unit Tbbc directly beneath the unconformity. Tfg1 is Miocene alluvial fan conglomerate. Measured section A5 (Fig. 4). Location is 33.26984°N, 114.63174°W. (B) Close-up of sand-filled karst fissures and polygonal cracks (arrows) at base of UBM pebbly bioclastic carbonate, ~65 m northwest of the outcrop in A. Location is 3.27020°N, 114.63224°W. (C) Carbonate-rich bioclastic facies of UBM showing flat-based wave-formed ripple cross-bedding in shelly coquina interbedded with bioturbated sandy grainstone, southeast Palo Verde Mountains. Location is 33.30374°N, 114.75718°W. (D) UBM in the Palo Verde Mountains where it overlies Colorado River channel sandstone of the siliciclastic member (Tbs) along a sharp unconformable contact. This exposure reveals a typical coarsening-upward section of: (1) carbonate-rich sandy grainstone with small-scale wave-formed ripples, (2) pebbly grainstone with larger wave ripples, (3) calcareous matrix-rich pebble conglomerate, and (4) conformable transition to alluvial fan gravels of unit Tfg2. Measured section KG12 (Fig. 10). Location is 33.29239°N, 114.76478°W.
Figure 7. Geologic cross sections in the western Trigo Mountains. See Figure 4 for locations and lithologic unit descriptions. Red line is the modern-day ground surface. Unit contacts are dashed where extrapolated above and below the ground surface. VE—vertical exaggeration.
(throw) of roughly 140 m across the Lost Trigo fault at this locality (Fig. 8). The fault here is unconformably overlain and capped by unfaulted Bullhead Alluvium, showing that fault activity had ceased by ca. 4.5 Ma (lower bounding age of Bullhead Alluvium; Howard et al., 2015). South of this location, in Big Fault Wash, the Lost Trigo fault splays into an ~180-m-wide zone of mostly synthetic fault segments that strike north, dip steeply west, and cut all pre-Quaternary units including Bullhead Alluvium (Figs. 4, 6A, 7C), constraining fault activity here to ≤3.5 Ma (upper age of Bullhead Alluvium). The main west-dipping Lost Trigo fault segment at the eastern boundary of this zone exhibits ≥35 m of normal displacement (Fig. 6A; Gootee et al., 2016), while smaller synthetic and antithetic faults to the west display 1–3 m normal displacements.

Stratigraphic panels constructed across the eastern margin of the southern Blythe Basin (Fig. 9) highlight growth-strata relations that provide a record of fault-controlled tilting during deposition of the Bouse Formation. The panels were constructed from a series of detailed measured sections (Homan, 2014; O’Connell, 2016) that are hung from the basal contact of unit Tbug, thus revealing stratral architecture that existed at the time of unit Tbug deposition. An originally near-horizontal planar geometry for this datum (base of unit Tbug) is supported by the map pattern and field observations that reveal a widespread, continuous, very gently dipping contact that can be traced over large areas (5–6 km; Fig. 4) with no evidence for channelized or inset contact relations with underlying deposits. These panels (Fig. 9) provide a high-fidelity view of important stratigraphic relations that are not obvious at the scale of traditional geologic cross sections (Fig. 7) and thus provide a useful complement to the cross sections.

The Hart Mine Wash panel (Fig. 9A) reveals a monocline fold geometry in which southwestward-thickening subunits in unit Tbs on the SW-dipping fold limb are progressively truncated (eroded or not deposited) along a planar unconformity beneath unit Tbug. In this panel, a thin (2–3 m) interval of basal bioclastic grainstone defines the flat north-eastern upper limb of the monocline (Fig. 9A). We speculate that a blind, west-side-down normal fault may be present at depth to explain this monocline geometry. Farther south, at Big Fault Wash (Fig. 4), the siliciclastic member is ~20 m thick in the west and thins gradually to the east where it is similarly truncated beneath unit Tbug (Fig. 9B). Near the east end of this panel, the upper bioclastic member rests unconformably on marl of the basal carbonate, and all pre-Quaternary units are cut by the Lost Trigo fault just east of measured section A5 (Figs. 6A, 9B). Farther south, at Marl Wash, the Bouse Formation basal carbonate member is unconformably overlain by Quaternary terrace and inset gravels (unit QII) in the west (Fig. 9C). In the eastern part of the panel, in an area as far as 0.5 km west of the Lost Trigo fault, the basal carbonate member is overlain by an expanded ~26-m-thick Tbug unit (UBM and unit Tfg2 gravel) capped by Bullhead Alluvium. Stratal geometries in these three panels (Fig. 9) are interpreted further in the Discussion section below.

Southeastern Palo Verde Mountains

Geologic mapping and stratigraphic analysis in the southeastern Palo Verde Mountains (Gardner, 2019) provide additional evidence for fault-related tilting during deposition of the Bouse Formation in the southern Blythe Basin. In this area, the basal carbonate member is subdivided into travertine (unit Tbug-t) and bioclastic facies (unit Tbug-b), and the upper bioclastic member (UBM; unit Tbu) and locally derived alluvial-fan gravel (unit Tfg2) are mapped as separate units (Fig. 10). The hinge of a segmented monocline forms an irregular boundary between a narrow belt of subhorizontal bioclastic carbonate on the northwest and a wider belt of gently SE-dipping unit Tbs on the southeast, an
Figure 9. Stratigraphic panels. See Figure 4 for locations and lithologic unit descriptions (Bouse Formation upper bioclastic member [UBM] and unit Tfg2 conglomerate, undifferentiated). Vertical black lines represent measured sections; short horizontal ticks are contacts between the main stratigraphic units. (A) Hart Mine Wash. (B) Big Fault Wash. (C) Marl Wash. C.R. ms, sst—Colorado River mudstone and sandstone; congl—conglomerate.
indication that the monocline axis is an important facies boundary. The stratigraphic panel (Fig. 11) is hung from two datums: the base of the UBM and base of unit Tfg2. Both datums are present in measured section KG12, permitting reconstruction of stratal architecture at the time of unit Tbu deposition. The panel reveals a pronounced stratal wedge geometry in which the Bouse Formation siliciclastic member (unit Tbs) thickens to the southeast and thins to the northwest, pinching out at the base of unit Tbu at the monocline hinge. To the northwest, unit Tbu rests unconformably on Bouse basal carbonate on the upper flat limb of the monocline, and the intervening siliciclastic member is absent due to erosion and/or nondeposition. Unit Tbu thickens slightly to the southeast where it overlies thick unit Tbs and is capped by unit Tfg2 gravel, suggesting that unit Tbu is also involved in the stratal wedge geometry. Basal carbonate and underlying Miocene conglomerate dip SE by as much as ~8° on the limb of the monocline (Fig. 10), which restores to ~5° dip at the time of unit Tfg2 deposition (Fig. 11).

The observed relations show that monocline growth took place primarily during deposition of unit Tbs, with slower rates of fold growth likely occurring during deposition of the basal carbonate and upper bioclastic members (Fig. 11). We infer that the monocline formed above the propagating tip of a blind normal or oblique-normal fault, which we name the Palo Verde fault. Although fault exposures are mostly absent in this area, one small subvertical fault ~200 m south of measured section KG12 (Fig. 10) displays 1–3 m of apparent down-to-the-west normal displacement in Colorado River sandstone and siltstone of the siliciclastic member (Thacker et al., 2020, their fig. 3G). This example may represent a minor antithetic fault kinematically related to down-to-the-southeast slip inferred for the blind Palo Verde fault (Fig. 11).

**Cross-Valley Synthesis and Basin Architecture**

A geologic cross section across the southern Blythe Basin from the Palo Verde to the Trigo Mountains (Fig. 12) was constructed using the
Gentle basinward dips explain the observed thickening of the Bouse Formation basal carbonate member (unit Tbc) and siliciclastic (Tbs) members of the Bouse Formation prior to deposition of the upper bioclastic member and alluvial-fan conglomerate. Stratal wedging and pinch-out geometries provide evidence for tilting to the southeast during deposition of the Bouse siliciclastic member (unit Tbs) and UBM (Tbu). Tilting is inferred to have been controlled by slip on the Palo Verde fault, a propagating blind normal fault at depth. VE—vertical exaggeration. Vertical black lines represent measured sections.

The Bouse Formation basal carbonate member thickens toward the basin center from basin margins in the western Trigo Mountains and Palo Verde Mountains (Figs. 9, 11), but its thickness appears to decrease into deeper parts of the basin as indicated by observations that it is consistently <5 m thick where encountered in subsurface wells throughout the Blythe Basin (Metzger et al., 1973). Although the base of the Bouse Formation was not penetrated in well 36bbb, regional isopach analyses suggest that the basal carbonate member likely is <50 m below the bottom of the well (24 m below sea level) (Turak, 2000; Cassidy et al., 2018, 2019b; Cohen et al., 2019). Thus, the available constraints indicate a basin architecture characterized by gentle basinward bedding dips adjacent to high-angle faults at the basin margins, with bedding dips decreasing to subhorizontal in the basin center beneath the modern Colorado River (Figs. 2, 12).

Figure 12. Geologic cross section from the Palo Verde Mountains to the Trigo Mountains showing basin architecture of the southern Blythe Basin. See Figure 2 for location. Unit Qcrs is Quaternary to Holocene Colorado River sediment. Bullhead Alluvium (unit Tcb) is not present in well 36bbb (Metzger et al., 1973), probably due to removal by erosion at the base of unit Qcrs. Lithologic unit descriptions are the same as in Figure 4. Stratal relations exposed on both sides of the valley provide evidence for gentle tilting toward the basin center during deposition of the basal carbonate (Tbcc) and siliciclastic (Tbs) members of the Bouse Formation prior to deposition of the upper bioclastic member and alluvial-fan conglomerate (Tbug). Syn-depositional tilting was controlled by growth of normal and oblique-slip faults at depth. The Lost Trigo fault in the Trigo Mountains propagated to the surface during deposition of unit Tbug, which is cut by the fault. We infer that the Palo Verde fault, which controlled tilting in the Palo Verde Mountains, remains at depth today and has not yet propagated to the surface. VE—vertical exaggeration.
Fault Kinematic Analysis

Fault orientations and kinematic data were collected from several locations in the study area (Figs. 2, 4) and analyzed to estimate the orientations of the principal strain axes responsible for faulting (Fig. 13). In the western Trigo Mountains, geometric data for major and minor faults along the Lost Trigo fault zone are grouped according to their location in the northern, NW-striking segment of the fault zone (north of latitude 33.275°N) versus the southern, north-striking segment (south of latitude 33.275°N) (Fig. 4). The results reveal a conjugate fault pattern in both groups (Figs. 13A, 13B). Northern faults have an average strike of approximately N20°W (340°), and southern faults strike on average approximately due north (Figs. 13A, 13B). Although slickenlines were not observed in the NW-striking segment of the Lost Trigo fault zone exposed in Hart Mine Wash, subvertical Riedel shears, drag folds, and offset Bouse Formation strata indicate a large component of normal slip (Figs. 5D, 8). At three fault-slip data localities farther south (red circles on Fig. 4), fault striae within the Lost Trigo fault zone have steep to slightly dextral oblique rakes, and kinematic criteria indicate dominantly normal slip (Fig. 13C). Fault kinematic analysis yields a subhorizontal incremental extension axis oriented 262°/14° (trend/plunge) and a subvertical incremental shortening axis oriented 040°/72°, indicating east-west–directed extension with a very minor component of dextral shear (Fig. 13D). In the western part of the study area, several small normal faults that cut Bouse Formation carbonate near Buzzards Peak (Fig. 2) have a similar northerly strike with an average steep dip to the east (Figs. 13E, 13F), kinematically compatible with east-west extension. No fault kinematic indicators (slickenlines) were observed on faults at the Buzzards Peak locality.

We interpret the fault geometric and kinematic results and along-strike variations in fault strike and dip direction to suggest that the Lost Trigo fault zone accommodated roughly east-west extension with a small component of transtensional deformation on linked normal and dextral-normal fault segments. The southern segment of the Lost Trigo fault zone strikes approximately north-south and is dominantly a normal fault that formed due to approximately east-west extension (Figs. 13A–13D), similar to extension directions in the lower Colorado River region over the past ~10 m.y. (Thacker et al., 2020). The Lost Trigo fault zone changes northward to a NW-striking segment that displays complex anastomosing fault strands, a change in overall dip direction, and variable sense of dip-slip displacement along the trend of the fault zone (Figs. 4, 7), features that are commonly observed in strike-slip fault zones (e.g., Wilcox et al., 1973; Sylvester, 1988; McClay and Bonora, 2001; Bergh et al., 2019) and related sedimentary basins (Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995; McNabb et al., 2017). In the absence of fault kinematic data from the Lost Trigo fault in Hart Mine Wash, we speculate that it would have acted as a dextral oblique-normal fault under the same approximately east-west extensional strain regime recorded along the southern segment of the fault zone.

DISCUSSION

Data and results presented above provide a record of fault-controlled tilting, subsidence, and sedimentation during deposition of the Bouse Formation in the lower Colorado River valley (Fig. 1). In this section, we integrate stratigraphic data and prior studies in the region to decipher the basinal and surface response to late Miocene–early Pliocene transtensional faulting in the paleo-ECSZ.

Faulting and Folding during Bouse Formation Deposition

Syn-depositional growth of normal faults is commonly documented with detailed geologic mapping, structural cross sections, and stratigraphic analysis (Gawthorpe et al., 1997; Young et al., 2003; Garcia-Garcia et al., 2006; Lewis et al., 2017; Bennett et al., 2017; Muravchik et al., 2018; Serck and Braathen, 2019). Using this approach, we have identified two types of basinal response to fault growth in the southern Blythe Basin: (1) syn-depositional tilting toward a fault produces anomalously thick deposits in the immediate hanging wall of the fault; and (2) growth of a monocline above the upward-propagating tip of a normal or oblique-slip fault causes strata to be tilted and thicken away from the fault, followed by subsequent tilting and thickening toward the fault after it propagates up to Earth’s surface.

The first type of response is documented at Hart Mine Wash where the Bouse siliciclastic member (unit Tbs) dips 15°–20°SW toward the Lost Trigo fault, and a nearly continuous exposure of the section reveals ~100 m of dipping siltstone and mudstone overlain by cross-bedded Colorado River channel sandstone near the fault (Fig. 5D, 7A, 8). The close association of steeper bedding dips and excessive local thickness adjacent to the fault and the observation that the fault is unconformably capped by undeformed Bullhead Alluvium (Figs. 5D, 7A) indicate that the NW-striking northern segment of the Lost Trigo fault experienced ~100 m of dip-slip and an unknown magnitude of strike-slip offset during deposition of unit Tbs at this locality. While we interpret this NW-trending segment of the Lost Trigo fault to be a dextral oblique-normal fault, the dip-slip component of fault displacement is well constrained by stratigraphic data in Hart Mine Wash.

The second type of response is syn-depositional growth of fault-related monoclines that results in tilting away from a blind propagating fault tip. This pattern is observed around the margins of the southern Blythe Basin and is associated with gentle tilts toward a regional depocenter beneath the modern Colorado River (Figs. 9, 11, 12). Monocline growth related to the Lost Trigo fault in the western Trigo Mountains is documented at Hart Mine Wash where thin basal carbonate rests on a flat upper limb in the northeast and passes laterally into a wedge of southwestward-thickening marl and unit Tbs on the SW-dipping limb of the monocline (Fig. 9A). Farther south, a similar pattern of westward thickening and truncation of unit Tbs is observed at the base of unit Tbug (Fig. 9B), providing further evidence for tilting and monoclinal fold growth during deposition of the Bouse Formation. The Lost Trigo fault at this location cuts the eastern
Average map trend of northern fault segment

North of 33.275°N
South of 33.275°N

Lost Trigo fault zone

Figure 13. Geometric and kinematic fault data and paleostrain analysis for selected localities in the study area; all plots are lower-hemisphere, equal-area stereographic projections. Eigenvalue—statistical fit to data; C.I.—Kamb contour interval (in sigma); S.L.—significance level (in sigma); M.P.—mean plane determined from maximum eigenvector (diamonds). (A–B) Geometric data for major and minor faults from 16 locations along the Lost Trigo fault zone (blue and red circles in Fig. 4). Data are grouped according to location in either the northern, NW-striking segment of the fault zone (north of latitude 33.275°N), or the southern, N-striking segment of the fault zone (south of latitude 33.275°N) (Fig. 4). (A) Stereoplot of fault planes for northern (red) and southern (black) fault segments. The mean planes for each group define a conjugate geometry that strikes NNW-SSE (northern group) and north-south (southern group) and dips 61°–67° to the west and east. Dashed lines are mean planes for each population of poles to planes determined from a cylindrical best fit and shown with red (northern) and black (southern) diamonds. (C–D) Fault kinematic data and analysis for the Lost Trigo fault zone from three locations (red circles in Fig. 4) based on 12 faults that displayed kinematic criteria. (C) Stereoplot of fault planes and their respective slip lineations; arrows show hanging-wall slip direction. (D) Paleostrain analysis for data in C. Incremental shortening (P; blue) and extension (T; red) axes (linked Bingham axes; squares) and pseudo-fault plane solution indicate approximately east-west extension (T-axis trend = 262°; bold arrows) with a relatively minor component of dextral shear. (E–F) Geometric data for faults near Buzzards Peak (Fig. 2). (E) Stereoplot of fault planes. (F) Kamb-contoured stereoplot for poles to faults in E; mean fault plane = 357°, 63°E, similar to east-dipping fault surfaces in the southern segment of the Lost Trigo fault (panel B).
end of the west-dipping strata, indicating that fault activity continued after deposition of the Bouse Formation and the tip of the fault propagated up to the Earth’s surface near the end of Bouse deposition. In Marl Wash, the Bouse Formation upper bioclastic member (UBM) and overlying unit Tfg2 (collectively, unit Tbug) thicken and dip ~3° toward the fault (Figs. 4, 9C). Although the record is incomplete due to erosion in this area, the map pattern and stratigraphic data reveal some thickening and gentle dip of unit Tbug toward the fault, opposite the predominant direction of westward thickening and dip direction in older basal carbonate and siliciclastic members (Figs. 4, 9B, 9C). Taken together, these relations imply a double-wedge geometry that results when strata first tilt and thicken away from a normal fault in a growth monocline as the fault tip propagates upward at depth, followed by tilting and thickening back toward the fault after the fault ruptures Earth’s surface (Gawthorpe et al., 1997; Lewis et al., 2017). The stratigraphic relations thus indicate that the tip of the Lost Trigo fault breached the surface after deposition of unit Tbs, just prior to or during deposition of the lower part of the UBM. Blind strands of the Lost Trigo fault may also be present beneath the upper reaches of Hart Mine Wash (Fig. 9A). The Palo Verde fault represents another growth structure in the southeastern Palo Verde Mountains, similarly controlled by growth of a propagating normal fault that remains buried in the subsurface today (Fig. 11). Our analysis thus provides evidence for two stages of syn-depositional fault development on opposing sides of the southern Blythe Basin (Fig. 12).

Fault-related growth monoclines in the southern Blythe Basin provide a clear record of syn-depositional tilting away from mountain range fronts and toward a regional depocenter beneath the modern Colorado River valley (Fig. 12). Importantly, fine-grained lime mud and heterolithic facies of the Bouse basal carbonate record deposition in low-energy tidal flats on widespread horizontal surfaces (O’Connell et al., 2017, 2021; Gardner and Dorsey, 2021). We therefore conclude that 1°-5° basinward bedding dips in this area are tectonic in origin, not original primary bedding dips. Structurally controlled gentle bedding dips explain the observed thickening of the Bouse Formation from basin margins to basin center (Fig. 12) as well as the distribution of Bouse Formation exposures at higher elevations around the margins of the basin and at lower elevations near the basin center. This conclusion contrasts with those of previous studies that treated elevation as a proxy for stratigraphic position and age in the Bouse Formation and asserted that deposits at lower elevations are older than higher-elevation deposits (Spencer et al., 2008, 2013; Roskowski et al., 2010; McDougall and Miranda Martínez, 2014). An assumed correlation of age with elevation implies no syn- or post-Bouse tectonic deformation and a stratigraphic model in which horizontal beds of the Bouse siliciclastic member onlap onto preexisting steeper basin margins draped by the Bouse basal carbonate member (e.g., Peartree and House, 2014; Crow et al., 2019b; Cohen et al., 2019). In contrast, we document systematic gentle bedding dips that were produced by fault-related monocinal folding and basinward tilting, with the result that younger members of the Bouse Formation commonly are exposed at lower elevations over distances of 1–3 km (Figs. 4, 7, 10, 11). The observed basinward dips thus define a complex three-dimensional (3-D) basin architecture produced by fault-controlled, syn-depositional tilting on opposite sides of the southern Blythe Basin (Fig. 12).

### Structural Controls on Basin Evolution

Syn-depositional faulting, tilting, and basin subsidence documented in this study took place during a protracted history of late Miocene to Pliocene transtension in the Gulf of California shear zone in northwestern Sonora (Mexico) and the ECSZ of western Arizona and southeastern California (Fig. 1; Buising, 1990; Sherrod and Tosdal, 1991; Bennett et al., 2016a, 2017; Thacker et al., 2020; Mavor et al., 2020). Oblique extension in a diffuse network of strike-slip, oblique-slip, and normal faults led to tectonic subsidence in the lower Colorado River region (Jachens and Howard, 1992; Howard and Miller, 1992; Richard, 1993) and set the path for integration of the earliest Colorado River to the northern Gulf of California (Metzger et al., 1973; Buising, 1990; Howard et al., 2015; Bennett et al., 2016a). Fault-controlled tilting and subsidence were ongoing prior to deposition of the Bouse Formation, as indicated by widespread fault-bounded Miocene alluvial fan conglomerates that locally display distinctive fanning-dip geometries (e.g., Sherrod and Tosdal, 1991; Fig. 7D). Late Miocene faulting and subsidence produced topographic basins that later became the site of deposition for the Bouse Formation (e.g., House et al., 2008; Peartree and House, 2014; Howard et al., 2015). In addition, results presented above show that fault-controlled tectonic subsidence continued into Pliocene time, as recorded in syn-depositional growth structures of the Bouse Formation in the lower Colorado River region.

The 3-D pattern of syn- to post-Bouse fault-related tilting and subsidence documented in this study offers a unique perspective on interactions among crustal deformation, sedimentation, and landscape evolution in the paleo-ECSZ. Late Miocene transtensional fault activity continued into Pliocene time and influenced the evolution of the Blythe Basin as well as the geometry and extent of the Bouse Formation (Figs. 1, 14). Our results suggest that the present-day distribution and elevation of Bouse deposits (up to 330 m elevation in the Blythe region) reflect long-wavelength tectonic tilting and post-depositional uplift (e.g., Beard et al., 2016; Bennett et al., 2016b; Karlstrom et al., 2017; Thacker et al., 2020). This provides an alternative to suggestions that the Bouse Formation accumulated on a static landscape that has not experienced any significant post-depositional uplift and that deposits of the Bouse Formation in Blythe Basin formed in lakes at their present-day elevations (Spencer and Patchett, 1997; Spencer et al., 2013; Peartree and House, 2014). We find that diffuse transtensional strain in this region was active before, during, and after deposition of the Bouse Formation and was sufficient to modify the elevation of Bouse Formation deposits by subsidence in modern basins and broad uplift in flanking mountain ranges over the past ~5 m.y. This interpretation is consistent with evidence for deposition of the Bouse basal carbonate member in a tidal to subtidal marine...
basin (McDougall, 2008; McDougall and Miranda Martínez, 2014; O’Connell et al., 2017, 2021; Dorsey et al., 2018; Gardner and Dorsey, 2021).

Indirect evidence for syn- and post-Bouse deformation in the Blythe Basin comes from recognition of age-correlative deposits that occur at different elevations across the basin. Deposits of the Bouse Formation and Bullhead Alluvium have subsided or been faulted down in the central Blythe Basin (Fig. 12; Metzger et al., 1973; Howard et al., 2015; Cassidy et al., 2018; Cohen et al., 2019; Crow et al., 2019b), suggesting that structures in the Blythe Basin were active during late Miocene to Pliocene time. Direct evidence for syn- and post-Bouse faulting in the Blythe Basin includes basin-bounding faults such as the Lost Trigo fault mapped along the eastern margin of the basin (Metzger et al., 1973; San Diego Gas and Electric Company, 1976; Menges and Pearthree, 1983; Sherrod and Tosdal, 1991; Richard, 1993; this study). Detailed stratigraphic analysis (this study) indicates that the Lost Trigo fault played a fundamental role in syn-depositional basinward tilting and thickening of the lower members of the Bouse Formation (units Tbbc, Tbs), local tilting and thickening of upper Bouse Formation members toward the fault, and local control on the eastern extent of Blythe Basin deposits (Figs. 4, 7, 9). The Lost Trigo fault likely links south-southwestward to the Lighthouse Rock fault (Fig. 2; Sherrod and Tosdal, 1991; Beard et al., 2016), along which the southern Blythe Basin pinches out toward the south. This basin-bounding system of normal faults appears to link southward to the NW-striking dextral Laguna fault system in the southeastern Trigo Mountains and northward to the NW-striking dextral Cibola fault zone, a zone of NW-trending dextral faults in the lower Colorado River region (Fig. 14). The flat base, shallow depth, and moderate width (~5–20 km) of the southern Blythe Basin that formed as a result of transtensional deformation in a diffuse network of linked right-stepping dextral, normal, and oblique-slip faults in the lower Colorado River region (Fig. 14). The flat base, shallow depth, and moderate width (~5–20 km) of the southern Blythe Basin (Fig. 12), its association with low-strain bounding faults, and its stratigraphic position overlying older extensional fault systems all suggest a rift-sag style of basin formation. Rift-related sag basins are common in zones of orthogonal extension at now-submerged passive margins (Lambiase and Morley, 1999; Davison and Underhill, 2012; Pang et al., 2018; Zang et al., 2019). In this case, dilation and subsidence of the southern Blythe Basin and coeval basins of the paleo-ECSZ occurred as a result of diffuse transtensional fault kinematics and releasing-stepover geometries (Fig. 15). Because the ECSZ formed adjacent to an evolving transform plate boundary (Fig. 1), it did not undergo the protracted phase of post-rift thermal subsidence that is commonly documented at rifted continental margins. As a result, the deposits and bounding structures of these basins remain at shallow crustal levels providing access for direct observation around the basin margins (this study).

Implications for the Paleo-ECSZ

Based on results of this and previous studies (Bennett et al., 2016a; Beard et al., 2016; Thacker et al., 2020), we present a palinspastic reconstruction for the ECSZ and lower Colorado River region at ca. 5 Ma (Fig. 15). The southern Blythe Basin formed as a transtensional sag basin in a releasing stepover between the dextral Laguna fault system in the south and the Cibola and Big Maria dextral faults in the north. This interpretation builds on previous studies that document similar timing and kinematics of deformation in two NW-trending belts of dextral faults (Table 1): (1) Iron Mountain and Bristol-Granite Mountains fault zones that connect from the Blythe Basin northwestern to the eastern end of the Garlock fault (Dokka and Travis, 1990; Howard and Miller, 1992; Brady, 1992, 1993; Lease et al., 2009; Langenheim and Miller, 2017); and (2) Bill Williams River fault zone (Sherrerd, 1988) and a series of NW-striking dextral faults distributed across western and south-central Arizona (Singleton, 2015; Singleton et al., 2019) that may link northward to the Stateline fault system across a complex releasing stepover represented by extensional faults systems in Mohave Valley and Piute Valley (Figs. 1, 15; Sherrerd, 1988; Howard et al., 1999; Bennett et al., 2016a; Singleton et al., 2019; Thacker, 2019; Thacker et al., 2020). These two fault belts define a ~100-km-wide zone of diffuse extension and transtension (light red area in Fig. 15) that accommodated a portion of Pacific–North America plate motion during late Miocene to early Pliocene time (see also Bennett et al., 2016a; Thacker et al., 2020). Below we summarize published evidence for the slip history in these two fault belts (Table 1).
The Iron Mountain and Bristol-Granite Mountains fault zones form a NW-trending dextral fault system along strike of the Cibola and Big Maria fault zones along the northeastern margin of the modern ECSZ (Fig. 15; Sherrod and Tosdal, 1991; Richard, 1993; Beard et al., 2016, and references therein). Richard (1993) estimated dextral offset on the overlapping Laguna (2 km), Cibola (7 km), and Big Maria (4.5 km) faults. This NW-trending zone of linked transtensional faulting likely continues to the northwest across the northern Blythe Basin, where Umhoefer et al. (2020) suggested 30–35 km of dextral offset. Estimates of cumulative dextral slip on the Bristol-Granite Mountains fault zone range from 9–15 km to 24 ± 3 km (Dokka and Travis, 1990; Howard and Miller, 1992; Brady, 1992, 1993; Lease et al., 2009; Langenheim and Miller, 2017). Some or all of this dextral shear is transmitted northwestward along strike to the Soda-Avawatz fault zone (Fig. 1; Schermer et al., 1996; Langenheim and Miller, 2017), where cumulative dextral offset estimates range from 8–9 km (Langenheim and Miller, 2017) to as much as 20–28 km (Brady, 1984; Schermer et al., 1996). This transtensional strain likely continues north past the eastern tip of the Garlock fault onto the dextral-oblique Death Valley fault zone (Davis, 1977; Glazner et al., 2002). Although all of these fault zones are thought to have been active during late Miocene to Pliocene time, only the faults northwest of the Bristol-Granite Mountains fault zone remained unambiguously active into Quaternary time.

The Stateline fault system and Bill Williams River fault zone, and related faults, form another NW-trending belt of dextral faults along the northeastern margin of the paleo-ECSZ (Fig. 15).
Miocene–Pliocene dextral shear is documented on the Stateline fault system, which experienced as much as 30 ± 4 km of dextral displacement after ca. 13 Ma (Fig. 15; Guest et al., 2007). At least 30% of this slip appears to be transmitted south-eastward across Piute Valley and Mohave Valley to the Bill Williams River fault zone and Buckskin-Rawhide Mountains in western Arizona, where a minimum of 9–11 km of distributed dextral shear is documented in the Buckskin-Rawhide Mountains (~7–9 km; Singleton, 2015; Singleton et al., 2019) and in other ranges to the southeast (~2–4 km; Singleton et al., 2019). We speculate that two small transtensional stepovers north and northeast of the Whipple Mountains connect dextral strain from the Buckskin-Rawhide Mountains and Bill Williams River fault zone to the Needles deformation zone in Mohave Valley (Fig. 15; Thacker, 2019; Thacker et al., 2020). The remaining ~20 km of dextral shear on the Stateline fault system may step to the southwest via sinistral-oblique extension on the Nipton fault in Ivanpah Valley (Fig. 15; Miller and Wooden, 1993; Mahan et al., 2009; Miller et al., 2019) and in valleys flanking the Old Woman Mountains. Slip on these faults appears to be transferred south to NW-striking dextral fault zones such as the Big Maria fault zone (Miller and McKee, 1971), southern Plomosa Mountains (Strickland et al., 2018), and lower Colorado River region (Richard, 1993; Thacker et al., 2020) as a diffuse transtensional system of linked dextral, normal, and oblique faults and related basins, including faults around the margins of the southern Blythe Basin (Fig. 15).

These and other published constraints on the timing, magnitude, and style of strain across the southern San Andreas fault system, the greater ECSZ, and the Gulf of California shear zone inform our palinspastic tectonic reconstruction for this part of the Pacific–North America plate boundary at ca. 5 Ma (Fig. 15). We estimate 74 ± 7 km of post–12 Ma dextral shear across the modern ECSZ (Bennett et al., 2016a), a value that includes more recently documented and larger offset than the ~65 km estimate of Dokka and Travis (1990) and is indistinguishable from an estimate of 74 ± 17 km offset along strike to the northwest in the southern Walker Lane–Death Valley region (Renik and Christie-Blick, 1990).
2013). Northwest-striking faults with ~74 km of dextral shear project northwestward toward the eastern part of the Garlock fault, consistent with a suggestion that this broad zone of distributed shear has produced at least 60 km of oroclinal bending and right-lateral deflection of the eastern Garlock fault (Dokka and Travis, 1990). Oroclinal bending of the Garlock fault provides a mechanism to transmit dextral shear strain from the modern ECSZ in the Mojave Desert northward across the Garlock fault into the southern Walker Lane (Andrew and Walker, 2017), where active strike-slip structures occur in the Salton Trough region (Dorsey et al., 2011; Mason et al., 2017). Although this timing is slightly younger than the ca. 10 Ma initiation of the sinistral Cave Mountain fault in the modern ECSZ based on U-Pb dating of fault opal (Nuriel et al., 2019), it is consistent with estimates for the onset of dextral shear along the Camp Rock fault in the central Mojave Desert (ca. 7 Ma; Nuriel et al., 2019) and the southern San Andreas fault system based on stratigraphic analysis and thermochronology (ca. 8 Ma; Dorsey et al., 2011; Mason et al., 2017). The onset of rapid exhumation in the Little San Bernardino Mountains (Fig. 15; Spotila et al., 2020) at ca. 5 Ma records tectonic activity in the eastern Transverse Ranges that likely was related to transtensional faulting, further suggesting early development and antiquity of the western part of the modern ECSZ. The kinematic compatibility and along-strike linkage between faults of the paleo-ECSZ and the Gulf of California shear zone (Figs. 1, 15) and the absence of compelling evidence for major dextral shear in the Mojave Desert region prior to late Miocene time suggest that the paleo-ECSZ may have also initiated at ca. 7–9 Ma. While this timing is
diminishes southeastward along strike into central Arizona (Singleton et al., 2019); (2) a central extension-dominated, low-shear domain including the Fenner Valley, Old Woman Mountains, Riverside Mountains, and northern Blythe Basin; and (3) the >400-km-long transtensional belt of linked dextral and normal faults including the Bristol-Granite Mountains, Big Maria, Cibola, and Laguna fault zones (Fig. 15). Late Miocene faults in the paleo-ECSZ linked southeastward to dextral faults in northwestern Sonora that accommodated at least ~50 km of cumulative slip (Nourse et al., 2005) and other right-stepping transform faults in the northern Gulf of California (e.g., Pacheco et al., 2006; González-Escobar et al., 2013) that comprise the Gulf of California shear zone (Bennett and Oskin, 2014; Bennett et al., 2017).

The timing of earliest dextral shear and trans-rotation in the ECSZ is uncertain, although most studies suggest that major northwest-dextral shear began between ca. 10–12 Ma (Carter et al., 1987; Dokka and Travis, 1990; Schermer et al., 1996; Reheis and Sawyer, 1997; Nuriel et al., 2019) and ca. 6–7 Ma (Gan et al., 2003; Langenheim and Powell, 2009). In contrast, the onset of dextral shear is well constrained along strike in the Gulf of California shear zone of coastal Sonora and Baja California (Mexico) where structural studies show

### TABLE 1. PUBLISHED ESTIMATES OF DEXTRAL SLIP IN THE PALEO–EASTERN CALIFORNIA SHEAR ZONE

| Fault zone or region* | Cumulative dextral slip (km) | Timing of slip (Ma) | References |
|-----------------------|-----------------------------|---------------------|------------|
| Big Maria             | 4.5                         | Uncertain           | Miller and McKee (1971); Richard (1993) |
| Bill Williams River   | ~1                          | <10                 | Sherrod (1988); Thacker (2019); Thacker et al. (2020) |
| Bristol-Granite Mtns | 24 ± 3                      | ≤11                 | Lease et al. (2009) |
|                      | 12 ± 3                      | ≤16                 | Langenheim and Miller (2017) |
| Cibola                | 7                           | Uncertain           | Richard (1993) |
| Iron Mountain         | 5.5                         | Uncertain           | Howard and Miller (1992); Richard (1993) |
| Laguna                | 2                           | Uncertain           | Richard (1993) |
| Needles deformation zone* | <1 (? )                  | ≤2.58               | Pearthree et al. (2009); Thacker (2019); Thacker et al. (2020) |
| Soda-Avawatz          | 20–28                       | ≤10                 | Brady (1984); Schermer et al. (1996) |
|                      | 8–9                         | ≤16                 | Langenheim and Miller (2017) |
| Southern Plomosa Mtns | 6 to >24                    | <19 to <4.6         | Miller and McKee (1971); Strickland et al. (2018) |
| Slateline fault system | 30 ± 4                     | ≤13.1               | Guest et al. (2007) |
| Western to south-central Arizona | ≥9–11                | ≤12                 | Singleton (2015); Singleton et al. (2019) |

*Italicized text refers to regions.

*Pre-Quaternary dextral slip uncertain.
Conclusions

Our results from the southern Blythe Basin thus support an emerging picture of late Miocene deformation across the lower Colorado River region in which non-uniformly distributed dextral shear and transtension affected the entire ~200-km-wide ECSZ between the San Andreas fault and the California-Arizona border. Kinematically linked normal and strike-slip faults led to local tectonic subsidence in fault-controlled transtensional basins between zones of dextral shear, as we have documented in the southern Blythe Basin. Additional detailed studies are needed to better understand the distribution and pattern of strain in the paleo-ECSZ and evaluate their influence on the evolution and integration of the Colorado River and Gulf of California.

Stratal wedge geometries in the Bouse Formation south of Blythe, California, provide a record of latest Miocene to early Pliocene basinward tilting in response to growth of syn-depositional normal and oblique-slip faults of the paleo-ECSZ. Fault growth resulted in slow subsidence in a broad shallow basin that currently resides beneath the modern floodplain of the Colorado River. Some faults formed at depth and propagated up to the Earth’s surface during Bouse deposition, while others evolved as blind faults that remain buried in the subsurface today. Transtensional deformation across a diffuse system of normal, dextral, and oblique-slip faults played a protracted role in the structural development and evolution of the southern Blythe Basin. We interpret these faults to be the structural boundaries of a late Miocene to early Pliocene transtensional sag basin that subsided within the paleo-ECSZ. Diffuse transtensional strain in the paleo-ECSZ was connected southwest to the Gulf of California shear zone, now preserved in coastal Sonora and coastal Baja California, which initiated at ca. 7–9 Ma when relative plate motion became established in the northern Gulf of California and Salton Trough region. These results support prior suggestions that regional subsidence in a fault-bounded tectonic lowland controlled latest Miocene shallow-marine inundation followed by integration of the Colorado River into the northern Gulf of California at ca. 5 Ma.

Acknowledgments

Research for this study was supported by grants from the National Science Foundation (EAR-1546006), Society for Sedimentary Geology, Geological Society of America, and the U.S. Geological Survey National Cooperative Geologic Mapping Program. Support for Thacker was provided by the National Science Foundation (EAR-1548986 to Drs. Crossley and Karlstrom at the University of New Mexico). Glenn Sharman and Sue Beard are thanked for thoughtful reviews of an earlier draft of this paper. This study benefited from discussions with Sue Beard, Andy Cohen, Laura Crosssey, Ryan Crow, Brian Gooette, Kyle House, Keith Howard, Karl Karlstrom, Kris McDougall, and Phil Peartree. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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