Late Neogene deformation of the Chocolate Mountains Anticlinorium: implications for deposition of the Bouse Formation and early evolution of the Lower Colorado River

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Introduction

Deformation related to late Neogene dextral shear can explain a shift from an estuarine to lacustrine depositional environment in the southern Bouse Formation north of Yuma, Arizona. We infer that late Neogene deformation in the Chocolate Mountain Anticlinorium (CMA) created a barrier that blocked an estuary inlet, and that pre-existing and possibly active structures subsequently controlled the local course of the lower Colorado River (LoCR). Structural patterns summarized below suggest that the CMA absorbed transpressional strain caused by left-stepping segments of dextral faults of the San Andreas fault system and/or the eastern California shear zone and Gulf of California shear zone. For this hypothesis to be correct, no more than 200 to 300 m of post-6 Ma, pre-~5.3 Ma uplift along the CMA crest would be required to cut off a marine inlet.

The 220kmlong CMA, cored by the early Paleogene Orocopia Schist subduction complex, extends from the Orocopia Mountains (CA) southeastward through the Chocolate Mountains (parallel to the southern San Andreas fault). Where Highway 78 crosses the Chocolate Mountains (Fig. 1), the CMA turns eastward through the Black Mountain–Picacho area (CA) and Trigo Mountains (AZ) into southwest Arizona. It separates southernmost Bouse Formation outcrops of the Blythe basin from subsurface Bouse outcrops to the south in the Yuma area. South of Blythe basin the CMA is transected by the lower Colorado River along a circuitous path.

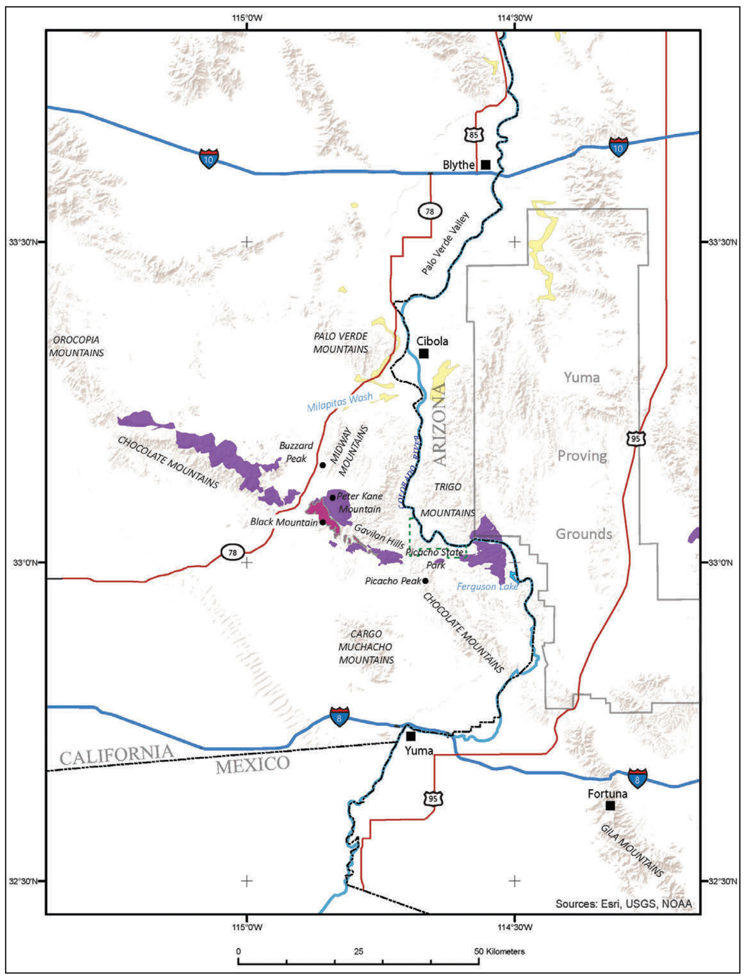


Figure 1. Overview of eastern Chocolate Mountain region showing features referenced in text. Purple shading shows exposures of Orocopia Schist, yellow are Bouse Formation outcrops, dark red are Black Mountain basalt.

Here we focus on the geology of an area between the central Chocolate Mountains and the Yuma Proving Grounds in Arizona. Specific landmarks include the southeast Chocolate Mountains, Midway Mountains, Peter Kane Mountain, Black Mountain, Picacho Peak, and Gavilan Hills (Fig. 1). For simplicity, we refer to this as the eastern Chocolate Mountains.

Late Miocene to Pliocene stratigraphy

The latest Miocene to early Pliocene Bouse Formation (>6.1-4.8 Ma) is exposed on the north flank of the Chocolate Mountain anticlinorium at the southernmost end of the Blythe basin (for distribution of Bouse basins see Fig. 1 in McDougall and Miranda-Martinez, this volume). Bouse deposition may have begun in a restricted marine estuary slightly before 6.1 Ma, as suggested by interpretation of foraminifers, mollusks and ostracods (McDougall and Miranda-Martinez, 2014). Foraminifera species are consistent with water depth at the estuary sill that was probably no more than 30 to 50 m below sea level (bsl), although the basin itself could have been significantly deeper. The marine facies of the Bouse Formation are found up to about 200 m above sea level (asl) at Milpitas Wash and 120 m asl near the Palo Verde Mountains and Cibola. Demise of clearly marine fauna and the arrival of Colorado River deltaic sands occurred at or before 5.3 Ma (McDougall and Martinez, this volume). At highest and southernmost exposures of the Bouse near Buzzards Peak, the 4.8 Ma Lawlor Tuff is intercalated with strata interpreted as lacustrine Bouse Formation at about 300 m elevation (Harvey, 2014).

The late Neogene Bear Canyon conglomerate (BCC) is a coarse clastic sequence underlying the Bouse Formation and flanking the CMA. The BCC post-dates earliest Miocene (23 Ma) volcanism and is at least partly synchronous with growth of the CMA. They divide the BCC into three informal age sequences that filled a north-south structural trough across the CMA; the youngest member is interstratified with and overlies the Black Mountain basalt (9.45 ± 0.27 Ma; Muela, 2011). Overlying the Black Mountain basalt is a distinctive conglomerate unit containing clasts of granodiorite gneiss and distinctive kyanite- and dumortierite-bearing rocks derived from a source much like the present Cargo Muchacho Mountains (Dillon, 1975; Haxel, 1977; Haxel et al., 2002). Conglomerate containing similar distinctive crystalline clasts forms a small fault-bounded sliver within the Golden Dream fault along the Lower Colorado River, which suggests that post-9-Ma conglomerate near Black Mountain originally extended at least locally across the CMA (Haxel et al., 2002, Fig. 6).

Structural patterns

The complex structural pattern of the eastern Chocolate Mountain region represents the superposition of multiple Cenozoic events, including formation of early Paleocene Orocopia subduction complex, now exposed in the core of the Chocolate Mountain anticlinorium; late Oligocene (28-24 Ma) exhumation/extension that was an early phase of mid-Miocene crustal extension (Jacobson et al., 2002); volcanism at 23 and 9 Ma (Needy et al., 2007; Ricketts et al., 2011); and dextral deformation within or along the Miocene-Pliocene Eastern California and Gulf of California shear zones and the Pliocene to Quaternary San Andreas fault system.

We focus on late Neogene deformation, and interpretation of a pattern of dextral and sinistral fault systems, with linked normal and reverse faults, based largely upon previously mapped structures (Fig. 2). Sorting out ages of individual structures within this fault complex is problematic and necessarily provisional, owing to limitations of timing data and widespread reactivation of faults. Therefore, much of our structural interpretation is speculative until more detailed kinematic and timing studies are completed.

In the Black Mountain-Picacho area, the CMA is defined by several subparallel to enechelon east-west antiforms and synforms. Orocopia Schist is exposed in tectonic windows below early and middle Cenozoic faults. Geologic units defining the CMA are the Orocopia Schist (structurally lowest), several packages of Mesozoic continental magmatic arc and post-arc rocks; earliest Miocene (23 Ma) volcanic rocks; and the Bear Canyon conglomerate, interstratified in its upper part with the 9 Ma Black Mountain basalt. The first three units display similar moderate to steep dips related to late Neogene folding along the CMA. Thermal histories from the Gavilan Hills indicate two cooling events: early Cenozoic (~56–50 Ma) subduction-related exhumation, and middle Cenozoic (~28–24 Ma) unroofing related to the start of regional extension (Jacobson et al., 2002, 2007). These events correlate to two distinct fault systems, the Chocolate Mountain and Gatuna/Sortan, both folded by the anticlinorium. Therefore, most growth of the anticlinorium postdates the younger 28–24 Ma unroofing event. Girty et al. (2006) and Ricketts et al. (2011) use facies relations of the BCC to suggest folding of the CMA began after 25 Ma. Younging sequences of the Bear Canyon conglomerate are progressively less folded and exhibit upward decreasing

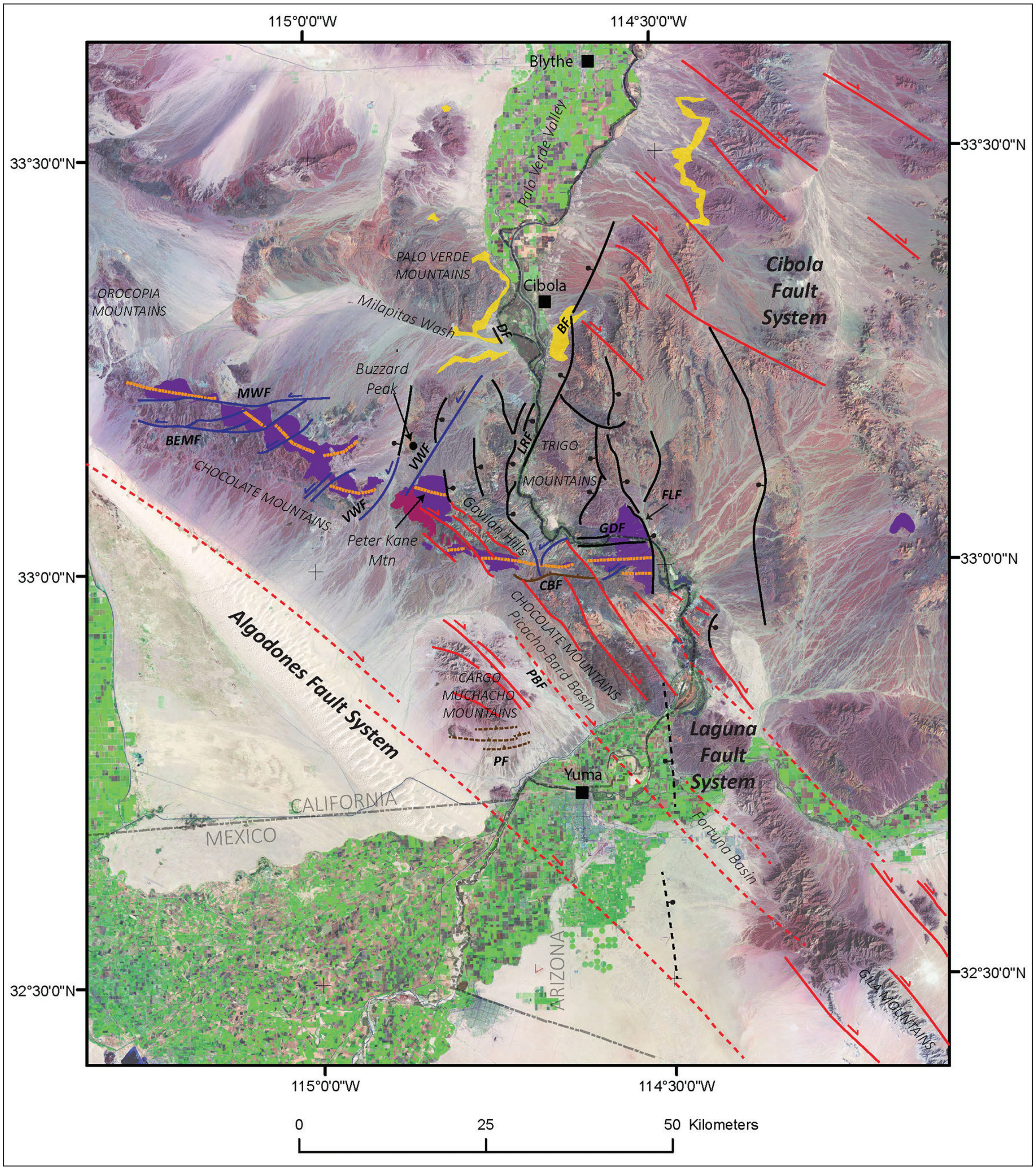


Figure 2. Regional structural pattern interpreted from previous studies (Dillon, 1975; Haxel, 1977; Girty et al., 2006; Richard, 1993; S.M. Richard, unpublished mapping; Ricketts et al., 2011; Sherrod and Tosdal, 1991), satellite imagery, and Google Earth imagery. Base is Landsat 7 imagery. Purple shading shows outcrops of Orocopia Schist, dark red is Black Mountain basalt, and yellow is Bouse Formation. Known and inferred faults colored as follows: red – dextral faults, blue – sinistral faults, black – normal faults, brown – reverse faults. Thick dashed orange line is axis of anticlinorium. BEF – Black Eagle Mine fault, BF – Big fault, CBF – Copper Basin fault, DF – 'Drive-by' fault, GDF – Golden Dream fault, FLF – Ferguson Lake fault, LRF – Lighthouse Rock fault, MWF – Mammoth Wash fault, PBF – Pichacho-Bard fault, PF – Patton faults, VWF – Vinagre Wash fault.

dips. Latest folding postdates the Black Mountain basalt at 9.4 Ma (Girty et al., 2006; Ricketts et al., 2011).

Regional tectonic events

Earlier studies suggested that growth of the anticlinorium was coeval with middle Cenozoic extension (NE–SW directed) and detachment faulting, or younger Neogene dextral faulting and transpression of the Miocene–Pliocene East California shear zone (ECSZ), or most likely both (e.g., Sherrod and Tosdal, 1991; Jacobson, 2007; Ricketts et al., 2011). According to Sherrod and Tosdal (1991), formation of the CMA post-dated eruption of a 26-Ma ignimbrite, and was perhaps emergent by 22 Ma. Middle Cenozoic volcanism and regional NE-directed normal faulting in the region was active about 24 Ma; extension continued past magmatism to perhaps 13.4 to 9.6 Ma (Needy et al., 2007). Sherrod and Tosdal (1991) describe decreasing extensional strain from the northern Trigo Mountains southward toward the CMA, manifested as homoclinal ridges of tilted Miocene and older rocks in the northern Trigo Mountains transitioning southward to less-tilted or untilted horst and graben structures. By 13 Ma coarse clastic sequences such as the BCC filled extension-related basins (Dillon, 1975; Ricketts et al., 2011).

Regional middle Cenozoic extensional structures are overprinted and perhaps reactivated by NW- and NE-striking dextral faults of the Eastern California shear zone. A reconstruction of parts of California and Arizona at 10 Ma by Richard (1993) limited estimated dextral slip between ~10 and 4.5 Ma to no more than 16 km in the Mohave Desert east of the Transverse Ranges. He placed 9 km of slip on the Cibola and Laguna fault systems. The Cibola fault system is a NW-striking array of dextral and normal faults that Richard (1993) linked across the Trigo and eastern Chocolate Mountains to the Laguna fault system. The Laguna system then extends SE as a dextral system bounding the Laguna and Gila Mountains, where it may offset the course of the Gila River as much as 15 km in a dextral sense (Fig. 2). Richard (1993), Beard et al. (2016) and Bennett et al. (this volume) suggest fault segments of the Laguna fault system and other structures controlled segments of the LoCR between Cibola and Yuma.

The Gulf of California shear zone is a ~50–100 km wide NNW-trending dextral transtensional belt with large vertical axis block rotation (Bennett and Oskin, 2014) in northwestern Mexico. It initiated ca 9 to 7 Ma and most likely linked northward to the ECSZ in the Chocolate Mountain region along the Arizona–California border (Bennett et al., this volume). Bennett and Oskin (2014) suggested that by 6 Ma there was a shift from the broad shear zone of the Gulf of California shear zone to the narrow plate boundary of the Gulf of California rift and San Andreas fault system.

Post-10 Ma fault patterns

A pattern of structures known or inferred to be post-10 Ma (Fig. 2) in the eastern Chocolate Mountain region is interpreted from previous mapping and topical studies (Dillon, 1975; Haxel; 1977; Haxel et al., 2002; Olmsted et al., 1973; Richard, 1993, unpublished mapping; Ricketts et al., 2011). Structures include inferred and certain dextral, sinistral, reverse, and normal faults that cut the Bouse, the BCC and/or the CMA. Relative timing of fault displacement is only locally known; future studies are needed to understand the time-sequence of faulting in this region.

Importantly, many of these faults terminate laterally or structurally downward against the CMA or offset it, indicating post-10 Ma movement. Structures younger than 6 Ma include those that cut the Bouse Formation or Quaternary to Pliocene pediments overlying the Bouse Formation (e.g. Homan, 2014). Buising (1990) described numerous faults as 'syn-Bouse', including at least three in the Cibola area in southernmost Blythe Basin. In addition, USGS and AZGS geologists have mapped the north-striking , east-side-down, 'Big Fault' normal fault near Cibola (first described by Metzger et al., 1973), and the 'Drive-by' fault, a NNW-striking vertical fault on the east side of the Palo Verde Mountains that cuts lower Bouse but is overlapped by an upper limestone unit in the Bouse (see Dorsey et al., this volume). A Bouse outcrop that laps onto bedrock on both sides of of Buzzard Peak (Fig. 2) is also slightly kinked by a NNW-trending fold. In addition, the Mammoth Wash and Black Eagle Mine sinistral faults that offset the CMA west of Highway 78 cut the BCC and deform the unconformably overlying Plio-Pleistocene pediment gravels that overlie the Bouse in Milpitas Wash (Dillon, 1973).

Broader-scale warping of the Bouse Formation was described by Sherrod and Tosdal (1991) in Palo Verde Valley (northerly axis; also called Cibola basin in some reports), in Milpitas Wash by Metzger et al. (1973; east–west axis), and in the Picacho–Bard basin (NW axis) by Olmsted et al., 1973) (Fig. 2). Both warping in the Milpitas Wash area (which Metzger et al., 1973, attributed to uplift of the Chocolate Mountains) and possible gentle northeastward dip of about 0.4 to 0.6 degrees of the Bouse upper limestone unit (Fig. 3; also Dorsey et al., this volume) between the Palo Verde Mountains and Buzzard Peak may record post-Bouse gentle tilting due to fold growth on the north limb of the CMA.

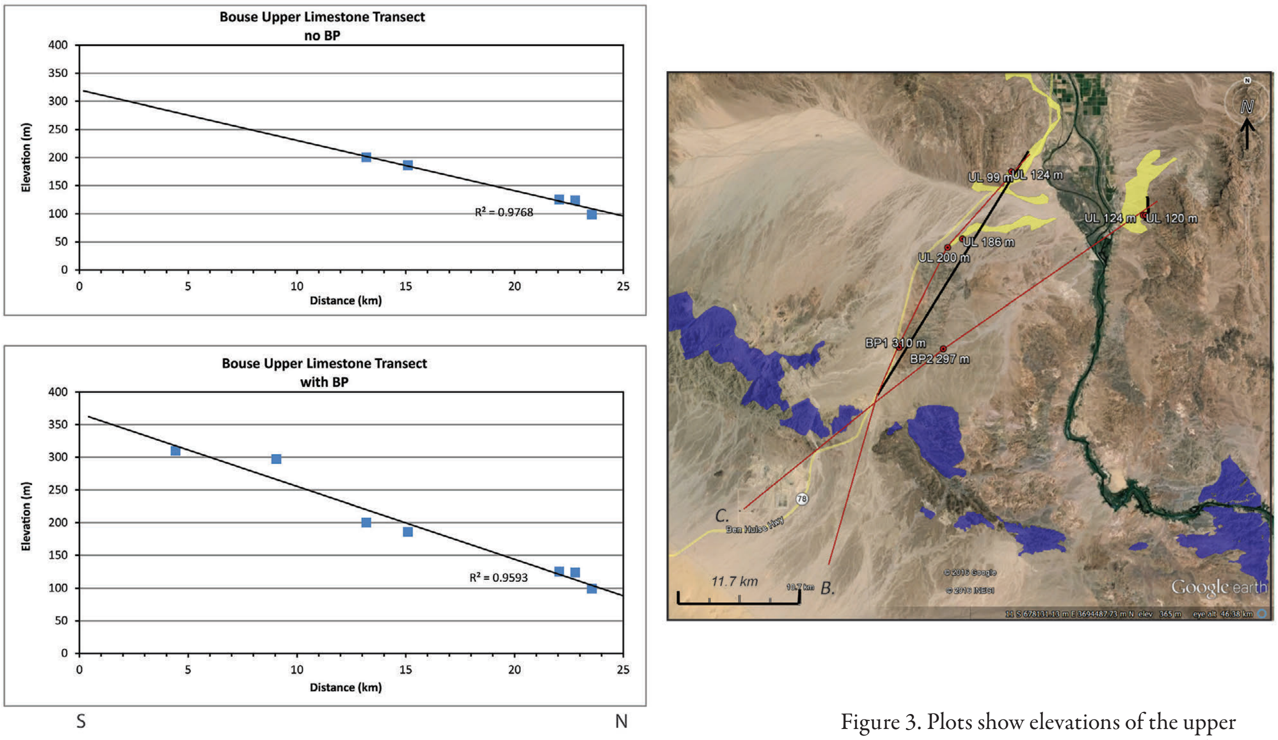
The emerging pattern is one of dominantly NW-trending dextral faults, NE-trending sinistral faults, north-striking normal faults, and key east-west faults of known or inferred reverse separation, all of which terminate at or splay into short segments near the CMA (Fig. 2). To the west, the CMA is cut by mostly sinistral faults, from the Mammoth and Black Eagle Mine faults east to Highway 78 (Dillon, 1975, estimated offset of 8 and 5 km, respectively). This system of sinistral faults ends at the Vinagre Wash fault system of Richard (1993), who estimated as much as 3.5 km sinistral offset of the axis of the CMA. Ricketts et al. (2011), in a detailed study within the CMA in the Indian Pass—Picacho area, show a pattern of paired dextral and sinistral faults offsetting the anticlinorium axis north of the Copper Basin reverse fault; they attribute this pattern to folding of the CMA in response to north-south shortening. West of there, a series of short en-echelon dextral faults ends eastward against the Vinagre Wash faults. Overall, this map pattern is very suggestive of the presence of two structural domains: a domain consisting of left-stepping dextral faults and kinematically linked reverse faults from the Yuma area to Peter Kane Mountain that transitions northwestward to a domain dominated by sinistral faults from near Buzzard Peak to the Orocopia Mountains (Fig. 2).

Normal faults in and east of the Trigo Mountains likely link the Cibola and Laguna faults through a transtensional right step. From the north, normal faults linked to the Cibola fault system end southward against or cut the CMA. From the south, the Laguna dextral fault system on the east side of the Gila Mountains splays northward against the south side of the CMA into at least two normal–separation faults that lose displacement northward. The northern of these is the Ferguson Lake fault, an east-side-down normal separation fault that parallels the LoCR east of Picacho State Park. The fault cuts the CMA, placing Orocopia Schist in the footwall to the west against coarse clastic alluvial fan deposits that may correlate to the BCC; fault steps and possible triangular facets on this fault suggest to us that the latest movement on the fault is late Pliocene or younger. Richard (1993) inferred less than 2 km dextral offset on the Laguna system based on estimating extension across associated basins. However, there could be a lot more strain unaccounted for if the Gila River is offset by 15 km. We speculate that some of the strain could have been transferred to the NW along other short dextral fault segments and some absorbed by transpressional growth of the CMA in the overall left-stepping dextral system described above.

Similarly, the Cargo Muchacho Mountains may be a transpressional feature in a left-step between dextral faults. Henshaw (1942) suggested that the Cargo Muchacho Mountains were uplifted between two NW-striking strike-slip faults, the buried Picacho–Bard fault to the northeast (underlying the Picacho–Bard basin of Olmsted et al., 1973), and the Algodones fault to the southwest (Fig. 2). Dillon (1975) mapped several NW-striking dextral faults cutting through the range with a total separation of about 3 km and several thrust faults confined between the dextral faults. In addition, he described several east-west striking, south-dipping faults, collectively called the Patton faults, that offset Pliocene Colorado River deposits as much as 120 m on the south side of the range; the deposits are locally tilted as much as 10 degrees southward adjacent to one of the faults. Direction of offset is unknown because the faults are only locally exposed, but based on faults with similar trends such as the Copper Basin fault, they could be reverse faults consistent with transpression. The Picacho–Bard fault likely links southeastward to faults that bound the northeast side of the Fortuna basin west of the Gila Mountains (Fig. 3; Olmsted et al., 1973).

Discussion

Ricketts et al. (2011) concluded that the CMA grew episodically during deposition of the Bear Canyon conglomerate due to north–south compression. Shortening was attributed to deformation in the dextral Eastern California Shear zone as part of a larger pattern of east–west extension and spatially and temporally variable north–south shortening. In addition, Ricketts et al. (2011) noted that shortening strain in the CMA is not accompanied by large-slip dextral faults. We build on their ideas by noting that the shortening strain they document is located where dextral fault segments are short, discontinuous, and step left (westward) around the CMA. This pattern suggests to us that there were kinematic linkages between late Miocene to Pliocene strike-slip faults and late-stage subtle growth of the CMA.



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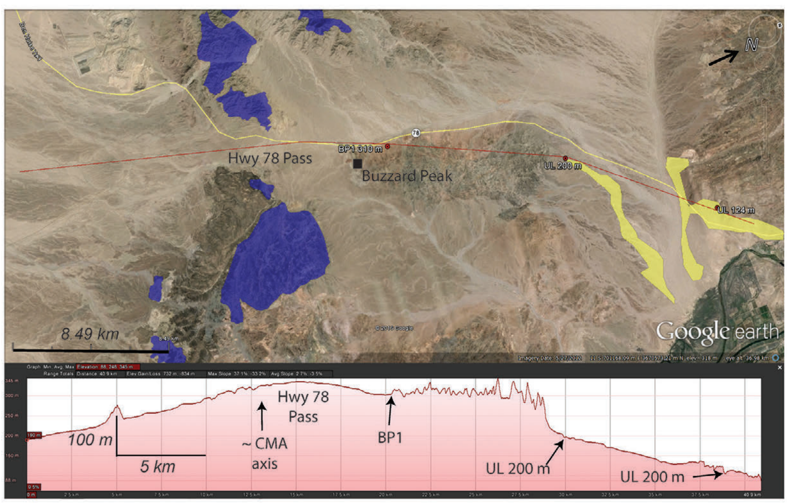

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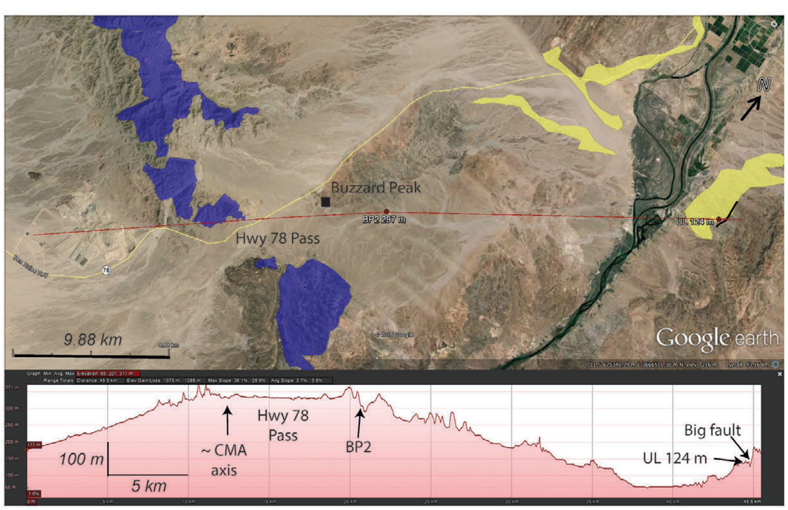

Figure 3. Plots show elevations of the upper limestone unit of the Bouse Formation (Dorsey et al., this volume) along a SSW transect from the Palo Verde Mountains to the Highway 78 pass; note the symmetric topography is roughly coincident with the CMA axis. Purple shade shows Orocopia Schist outcrops, yellow is Bouse Formation exposures. BP1 and BP2 are Bouse exposures at Buzzard Peak, west and east of the peak respectively. *A.* Slope is calculated from elevation of the upper limestone unit, interpreted by Dorsey et al. (this volume), as deposited in a lake or estuary after first arrival of the early Colorado River deltaic sediments. Blue squares are upper limestone unit (see stratigraphic sections in Homan, 2014). Upper left plot: slope is calculated from known outcrops of the upper limestone unit in the Palo Verde Mountains and Milpitas Wash. Lower left plot: slope is calculated assuming the Buzzard Peak localities BP1 and BP2) are correlative to the upper limestone unit (see Dorsey et al., this volume for discussion of correlation – this correlation is controversial but does not change the dip significantly). Google Earth Image on right shows spatial distribution of points used for slope calculation. Black line is transect line that outcrops are projected into for slope calculation. Profiles for *B.* and *C* are red lines. *B.* Topographic profile across Highway 78 pass transects the Buzzard Peak 1 locality and highest and lowest upper limestone unit outcrops; the profile ends north at the Palo Verde Mountains. *C.* Topographic profile from south to north across Highway 78 pass transects Buzzard Peak 2 locality and ends east of Big fault (black line) south of Cibola. Map base and profiles in B and C derived from Google Earth software.

Pliocene (Fig. 3 in Bennett et al., this volume) and, by inference, produced the transpressional steps into the Chocolate Mountains. That stress was probably relieved by the subsequent Cargo Muchacho transpressional step to the Algodones fault, which is along strike with the San Andreas fault and was likely a major plate boundary until the last few million years (Howard et al., 2014). Additional post-5 Ma faulting and gentle fold-related tilting is suggested by numerous faults that are known to cut and post-date the Bouse Formation.

Did late Neogene deformation of the CMA block an estuary inlet?

No direct data indicate where a Bouse estuary inlet or inlets could have crossed the Chocolate Mountains south of the Blythe basin. Two possibilities are topographic lows such as the Highway 78 pass or the Carrizo Wash—Bear Canyon divide (Fig. 4). Alternatively, the crossing could have been roughly coincident with the modern course of the LoCR (Figs. 4). The Highway 78 pass seems the most likely candidate because the highest (~310 m) and southernmost Bouse outcrops at Buzzard Peak are within about 4–5 km of the pass, which is roughly coincident with the westerly axis of the CMA at about 335 m elevation (Figs. 2, 3). In comparison, marine shoreline facies of the lower Bouse and the upper limestone unit are at about 100 to 120 m asl in exposures at Cibola and the Palo Verde Mountains (Homan, 2014) and rise to about 200 m asl about 20 km north of Buzzard Peak. We assume in Figure 3a that the Bouse deposits were deposited horizontally and the upper limestone correlates to the Buzzard Peak outcrops, although this second assumption is controversial. Slopes fitted to the outcrops (with and without the Buzzard Peak correlation) project close to the elevation of the Highway 78 pass. This suggests a post-depositional tilt about one-half a degree on the north flank of the CMA (Fig. 3).

Combining rock uplift due to tilting on the flank of the CMA of about 190 m between Buzzard Peak and the Palo Verde Mountains with a broader uplift of 120 m (~ elevation of the outcrops at both Cibola and the Palo Verde Mountains) suggest that the marine connection would have to be below about 310 m asl today. Based on foraminiferal data, McDougall and Miranda-Martinez (2014) suggested that the estuary sill was no more 30–50 m below late Miocene sea level, which would correspond to below about 280–260 m asl today. This is lower than the 335 m elevation of the alleviated pass at Hwy 78 but does not rule out a possible inlet there, because the magnitude and timing of relative uplift is poorly constrained. More importantly, if this is the inlet, only a couple hundred m of relative uplift between the marine shoreline deposits at Cibola and Palo Verde Mountains and the crest of the CMA is needed to block the connection.

The lowest point along the Carrizo Wash—Bear Canyon divide, at about 255 m asl, is well below the

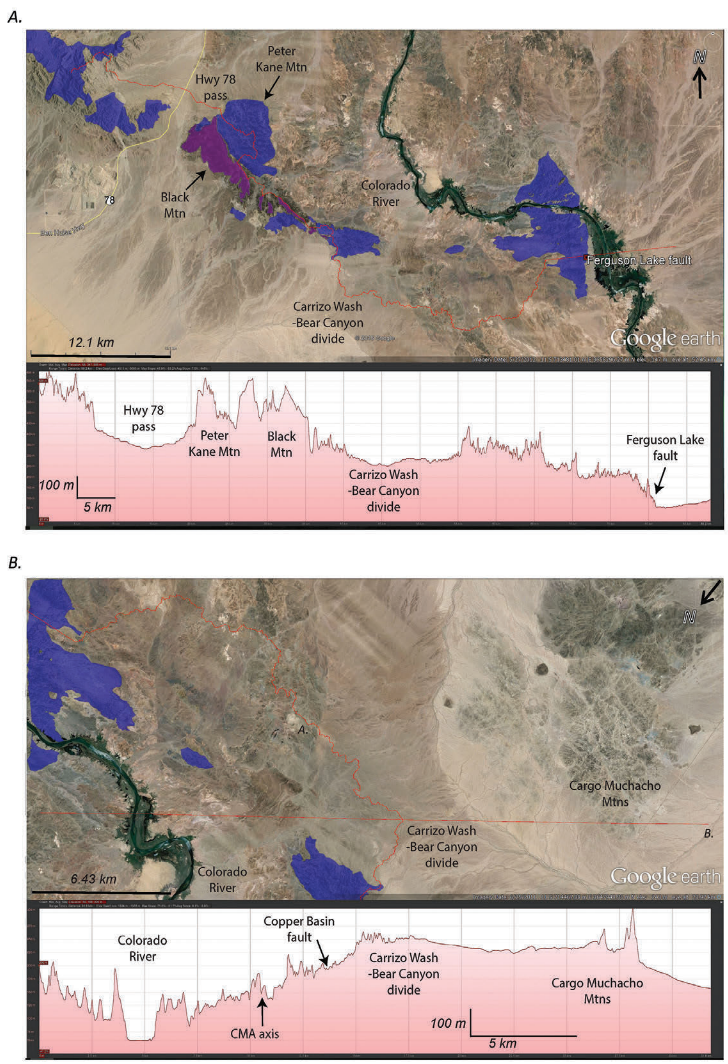

Figure 4. Transparent purple shows Orocopia Schist exposures. *A.* West to east topographic profile along the topographic crest of the eastern Chocolate Mountains from Highway 78 pass to Ferguson Lake fault. Line of profile follows drainage divides derived from USGS National Hydrography Dataset [http://nhd.usgs.gov/]. *B.* North to south topographic profile across Cargo Muchacho Mountains and Carrizo Wash – Bear Canyon divide. Note steep rugged topography of Lower Colorado River gorge on north side of divide. Vertical red line on map base is profile line for *A*. Map base and profiles derived from Google Earth software.

Highway 78 pass (Fig. 4a). The divide is underlain by south-dipping Bear Canyon conglomerate on the south flank of the CMA; the CMA axis is about 4 km km north of the divide (Fig. 4b; Ricketts et al., 2011). The BCC at the divide includes the kyanite- and dumortierite-bearing deposits, found to the north as a fault sliver in the Golden Dream fault and that we infer once extended as a continuous deposit across the CMA and has since been eroded. Drainage patterns and the asymmetry of the divide (Fig. 4b) indicate the divide is migrating southward and erosionally lowering due to incision by the nearby Colorado River. Therefore, the divide is likely degraded from its configuration during Bouse deposition. Although it could have been an estuary inlet during Bouse deposition, its paleo-position relative to late Miocene sea level is difficult to evaluate because of the erosional lowering and because unlike the Highway 78 pass, there are no Bouse outcrops nearby.

Structures controlling the course of the Lower Colorado River

The LoCR has a structurally controlled course from Cibola to Yuma. South from Cibola it follows a structural depression in Tertiary volcanic rocks between a west-dipping fault (herein the Lighthouse Rock fault) on the west side of the Trigo Mountains and east-dipping faults west of the river. Near the south end of the Lighthouse Rock fault where fault offset diminishes, the river turns SE along a zone of short NE and NW fault segments before turning due east where it cuts deeply into Orocopia Schist in the footwall of the Ferguson Lake fault. There, its easterly course is controlled by sheared and hydrothermally altered Orocopia Schist along the east-west striking Golden Dream fault zone. Upon crossing the Ferguson Lake fault where it exits a deep gorge cut into the Orocopia Schist, the river turns abruptly southward again in the hanging wall of the Ferguson Lake fault to where the fault ends (Fig. 4b). From there southward it again follows and crosses short discontinuous dextral fault segments before turning southwest toward Yuma on the north side of the Laguna Mountains.

The Lightening Rock, Ferguson Lake, and unnamed dextral faults likely have experienced late Miocene to possibly Pleistocene movement, based on their youthful tectonic geomorphology such as well-preserved triangular fault facets, but further studies are needed to test this hypothesis and determine the age of faulting in this region. In addition, the question of whether any of these faults offset the course of the river or its deposits presently is not known. Metzger et al. (1973) suggested that 'gentle uplift of the ranges' may have helped entrench and erode the LoCR into the Chocolate Mountains. Howard et al. (2014) show 100 m of possible subsidence of the ca 4.5–3.5 Ma Bullhead Alluvium (an early Colorado River aggradational deposit) at the top of the Bouse Formation in the Blythe basin, and several hundred meters of sediment accumulation in the subsided Fortuna Basin. These relations provide further support that young, post-5 Ma diffuse regional strain that could have gently tilted the CMA and may have controlled opening and closing of an estuary outlet during deposition of the Bouse Formation. This suggestion is speculative and needs to be tested in future work.

Conclusion

In summary, a hypothesis for a complex system of transtensional and transpressional strain related to the transition from broadly distributed late Neogene dextral shear to the opening of the Gulf of California may explain the complex pattern of faulting, folding and uplift in the eastern Chocolate Mountains region. The Chocolate Mountains anticlinorium likely imposes a major discontinuity in late Miocene to Pliocene dextral shear into which shortening, manifested by uplift, folding and reverse faulting is concentrated. Many faults lose displacement, splay, step over, or terminate laterally or structurally downward against the Orocopia Schist core of the CMA; only a few faults cut entirely across it. This pattern is highly suggestive of a major discontinuity in dextral strain accommodation along the plate boundary. Low systematic dips (<1°) on the Bouse upper limestone unit further suggests to us that very gentle, post-5 Ma tilting was associated with regional fold growth.

There is ample evidence of deformation in the eastern Chocolate Mountain region that overlaps with deposition of the Bouse Formation and inception of the lower Colorado River system. Whether folding, faulting and uplift along the CMA disrupted an estuary inlet and formed a dam for subsequent Bouse lacustrine deposition awaits results of: (1) ongoing studies of the Bouse Formation depositional systems; and (2) detailed mapping and fault studies in the Chocolate Mountains (e.g., Ricketts et al., 2011). Finally, the close correspondence between the course of the Colorado River and structures of this diffuse regional fault system is clear, but it is not clear *when* those structures and folding and uplift were active, and how they affected lake spillover and development of the lower Colorado River.

References

Beard, L. Sue, Haxel, Gordon B., McDougall, Kristin, Jacobson, Carl E., House, P. Kyle and Crow, Ryan S., 2016, Did late deformation of the Chocolate Mountains anticlinorium affect deposition in the southern Bouse basin and the subsequent course of the lower Colorado River? Geological Society of America Abstracts with Programs, v. 48, No. 4. doi: 10.1130/abs/2016CD-274580

Bennett, S.E.K., and Oskin, M.E., 2014, Oblique rifting ruptures continents: Example from the Gulf of California shear zone: Geology, v. 42, p. 215–218, doi: 10.1130/G34904.1.

Bennett, Scott E.K., Darin, Michael H., Dorsey, Rebecca J., Skinner, Lisa A., Umhoefer, Paul J., Oskin, Michael E.' this volume; Animated Tectonic Reconstruction of the Lower Colorado River Region: Implications for Late Miocene to Present Deformation: Desert Symposium

Buising, A.V., 1990, The Bouse Formation and bracketing units, southeastern California and western Arizona: Implications for the evolution of the proto–Gulf of California and the lower Colorado River: Journal of Geophysical Research, v. 95, p. 20,111–20,132.

Dillon, J. T., 1975, Geology of the Chocolate and Cargo Muchacho Mountains, Southeasternmost California; PhD dissertation, Santa Barbara, University of California, Santa Barbara, 442 p.

Dorsey, Rebecca J., O'Connell, Brennan, Homan, Mindy, and Howard, Keith, this volume, Upper Limestone of the Southern Bouse Formation: Evidence for Unsteady Origins of the Colorado River: Desert Symposium

Girty, G.H., Stephenson, D., Candfield, A., Marsh, J., Middleton, T., Rayburn, J., Sisk, M., Verdugo, D., Moniz, R., Gunter, J., Nielson, J., Gasca, C., Rowland-Smith, A., Smith, M., Lovering, K., Campbell, K., Castenada, F., Gray, R., and Campbell, C., 2006, Geology of the Picacho State Recreation Area, SE California: Implications for the timing of formation of the Chocolate Mountains anticlinorium, in Girty, G.H.,and Cooper,J., eds.,Using Stratigraphy,Sedimentology, and Geochemistry to Unravel the Geologic History of the Southwestern Cordillera: A volume in honor of Patrick L. Abbott: Pacific Section, SEPM, Book 101, p. 77–96.

Harvey, Janet C., 2014, Zircon age and oxygen isotopic correlations between Bouse Formation tephra and the Lawlor Tuff: Geosphere, v. 10, p. 221–232.

Haxel, G. B., 1977, The Orocopia Schist and the Chocolate Mountain thrust, Picacho-Peter Kane Mountain area, southeasternmost California: California Univ., Santa Barbara, Ph.D. dissertation, 277 p.

Haxel, G.B., Jacobson, C.E., Richard, S.M., Tosdal, R.M., and Grubensky, M.J., 2002, The Orocopia Schist in southwest Arizona: Early Tertiary oceanic rocks trapped or transported far inland, in Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 99–128.

Henshaw, P. C., 1942, Geology and mineral deposits of the Cargo Muchacho Mountains, Imperial County, California: California Jour. Mines and Geology, v. 38, no. 2, p. 147-196.

Homan, M.B., 2014, Sedimentology and stratigraphy of the Miocene-Pliocene Bouse Formation near Cibola, Arizona, and Milpitas Wash, California: Implications for the early evolution of the Colorado River: M.S. thesis, Eugene, University of Oregon, 116 pp.

Howard, K.A., House, P.K., Dorsey, R.J., and Pearthree, P.A. (2015) River-evolution and tectonic implications of a major Pliocene aggradation on the lower Colorado River, the Bullhead Alluvium: Geosphere, v. 11, p. 1–30; doi:10.1130/GES01059.1.

Jacobson, C.E., Grove, M., Stamp, M.M., Vuc´ic´, A., Oyarzabal, F.R., Haxel, G.B., Tosdal, R.M., and Sherrod, D.R., 2002, Exhumation history of the Orocopia Schist and related rocks in the Gavilan Hills area of southeasternmost California, in Barth, A., ed., Contributions to crustal evolution of the southwestern United States: Geological Society of America Special Paper 365, p. 129–154.

Jacobson, C.E., Grove, M., Vućić, A., Pedrick, J.N., and Ebert, K.A., 2007, Exhumation of the Orocopia Schist and associated rocks of southeastern California: Relative roles of erosion, synsubduction tectonic denudation, and middle Cenozoic extension: Geological Society of America Special Paper 419, p. 1-37.

McDougall, K. and Miranda-Martínez, A.Y., 2014, Evidence for a marine incursion along the lower Colorado River corridor: Geosphere, 10, p. 842–869.

McDougall, K. and Miranda-Martínez, A.Y., this volume, Bouse Formation along the lower Colorado River corridor: Tracking the transition from marine estuary to saline lake: Desert Symposium

Metzger, D. G. and Loeltz, O.J., 1973, Geohydrology of the Parker-Blythe-Cibola Area, Arizona and California: U.S. Geological Survey Professional Paper 486-G.

Muela, K.K., 2011, Timing and style of Miocene deformation, Indian Pass and Picacho State Recreation Area, SE California, U.S.A.: MS thesis, San Diego State University, San Diego, California, 44 p.

Needy, S.K., Wooden, J.L., Barth, A.P., and Jacobson, C.E., 2007, Geochronology of igneous rocks in the Chocolate Mountains region as a means to interpret tectonic evolution of southeastern California: Geological Society of America Abstracts with Programs, Vol. 39, No. 6, p. 407.

Olmsted, F.H., Loeltz, O.J., and Irelan, B., 1973, Geohydrology of the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 486-H, 227 p.

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

Ricketts, J.W., Girty, G.H., Sainsbury, J.S., Muela, K.K., Sutton, L.A., Biggs, M.A., and Voyles, E.M., 2011, Episodic growth of the Chocolate Mountains anticlinorium recorded by the Neogene Bear Canyon Conglomerate, southeastern California: Journal of Sedimentary Research, v. 81, p. 859-873.

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