

Animated tectonic reconstruction of the Lower Colorado River region: implications for Late Miocene to Present deformation

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Introduction

Although the majority of late Miocene to present Pacific–North America plate boundary strain has been accommodated by faults of the San Andreas and Gulf of California systems, growing evidence of dextral shear east of the San Andreas Fault indicates that a component of plate boundary deformation occurred in the lower Colorado River (LoCR) region. Large-scale tectonic reconstructions across the Gulf of California and Salton Trough (GCAST) region (Fig. 1), a ~500 km-wide zone of deformation that affected the western margin of North America, provide important constraints on the location, timing, style, and magnitude of crustal deformation in the LoCR region (Fig. 2). Characterizing Miocene to present deformation in the LoCR region is important to resolve the presence and kinematics

of upper crustal structures that accommodated intracontinental strain and improves our understanding of the processes that promoted localized or diffuse strain during reorganization of the Pacific–North America plate boundary.

Map-view translations of crustal blocks influence the relative motions of adjacent blocks, an approach adhered to in global plate-circuit models (Atwater and Stock, 1998; 2013). Thus, a synthesis of the magnitude and timing of horizontal strain across a broad zone of distributed deformation can provide insight into processes of strain partitioning and potential kinematic links between adjacent structural domains. Furthermore, it can help prioritize and guide future work by identifying gaps in our understanding of plate boundary deformation and provide a degree of predictability

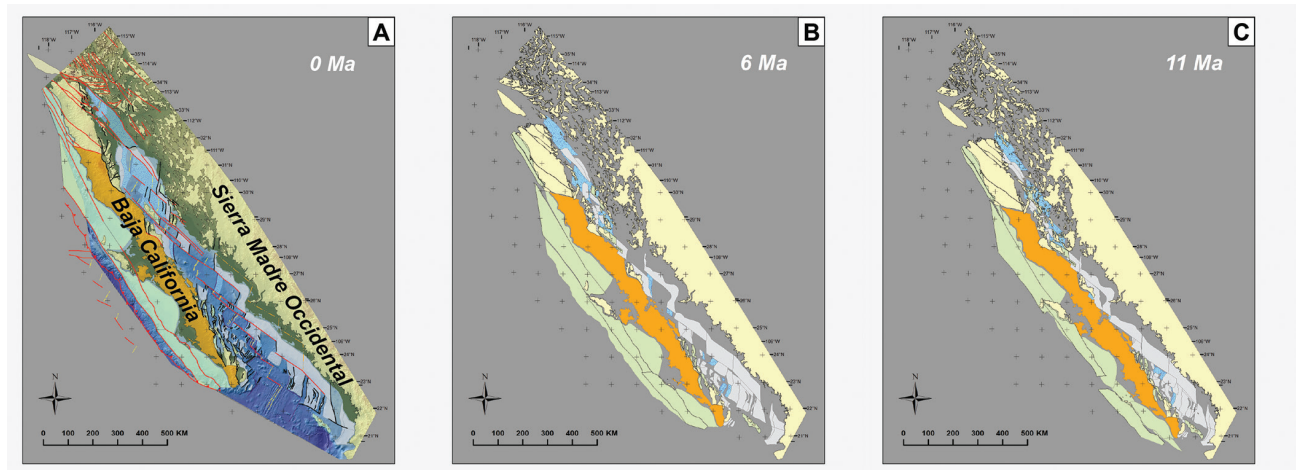


Figure 1. The GCAST tectonic reconstruction model (modified after Bennett et al., 2013a) at (A) present day, (B) 6 Ma, and (C) 11 Ma. The GCAST model synthesizes and retrodeforms evidence for crustal deformation over the past 11 Myr along a ~2,000 km-long, 400–500 km-wide swath of the Pacific–North America plate boundary, from San Bernardino, California (United States) to Puerto Vallarta, Jalisco (México). On present-day map (A), faults with >1 km of post-11 Ma map-view relative motion are shown: red–strike-slip faults; black–normal faults; dashed yellow–oceanic spreading center or center of pull-apart basin; orange dash/dot–speculative strike-slip faults. On all maps (A–C), crustal blocks consist of pre-Quaternary rocks: orange–Baja California microplate; yellow–onshore continental crust, including the Sierra Madre Occidental of stable North America; gray & pale green–offshore continental crust; blue stippled–hyperextended continental crust underlain by sills. Uncolored rhombic-shaped regions in the Salton Trough and Gulf of California (centered on dashed yellow lines) are regions where young (<5 Ma) oceanic crust has been interpreted from geophysical studies. See text and Bennett et al. (2013a) for further details. Animation of full Gulf of California–Salton Trough tectonic reconstruction can be viewed at: https://youtu.be/zRerSXoC_4c

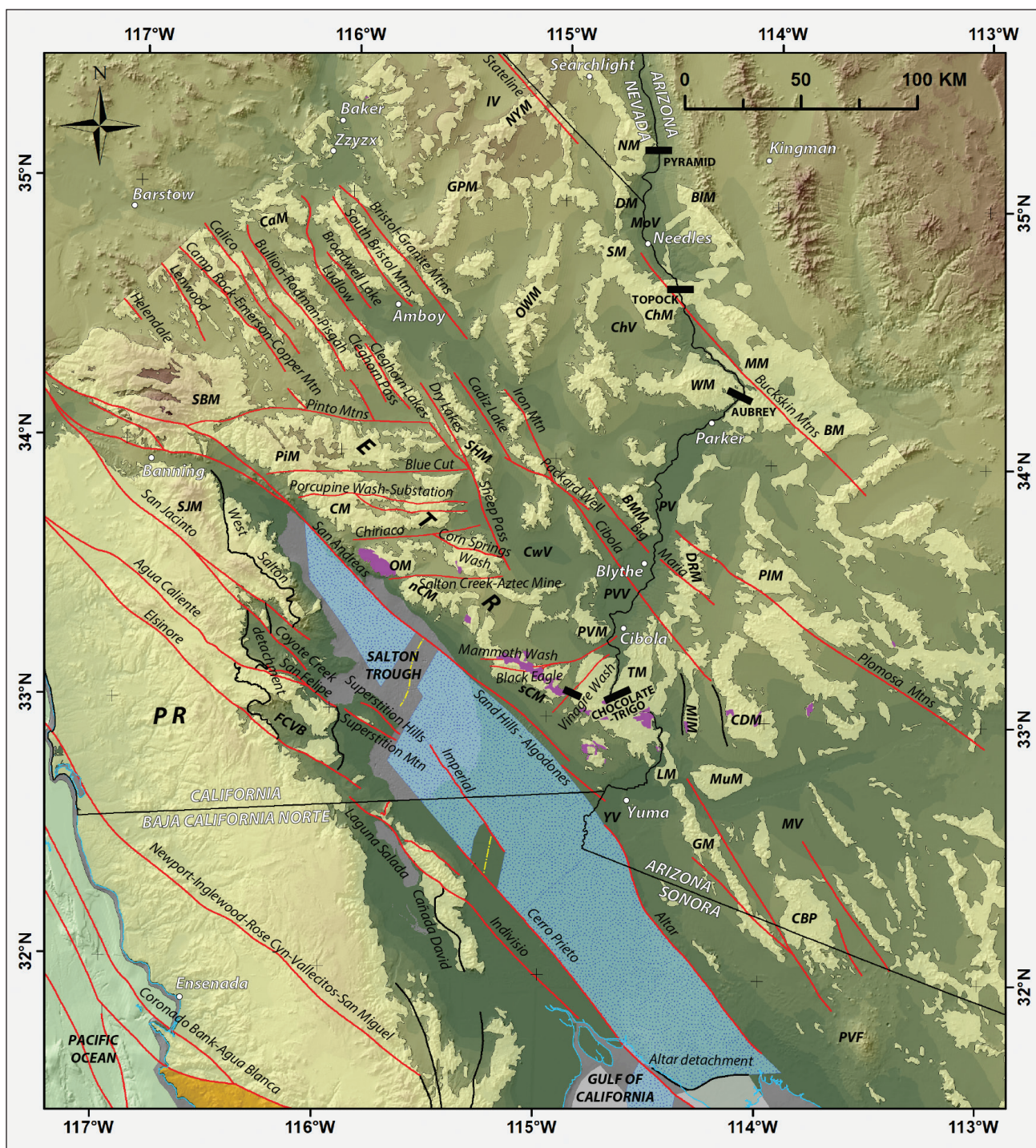


Figure 2A. Physiographic map showing the present-day arrangement of faults and modeled crustal blocks (yellow polygons) in the lower Colorado River (LoCR) region. Faults and crustal blocks as in Figure 1. Outcrops of Orocopia Schist (purple polygons) exposed along the Chocolate Mountains anticlinorium after Ludington et al., (2005). Paleodams (thick black bars) after Spencer and Patchett (1997), Pearthree and House (2014), and Sherrod and Tosdal (1991). Selected towns (white circles) and state boundaries (thin black lines) are shown. **Valleys:** ChV - Chemehuevi Valley; CwH - Chuckwalla Valley; IV - Ivanpah Valley; MoV - Mohave Valley; MV - Mohawk Valley; PV - Parker Valley; PVV - Palo Verde Valley; YV - Yuma Valley. **Mountain Ranges:** BMM - Big Maria Mtns; BLM - Black Mtns; BM - Buckskin Mtns; CBP - Cabeza Prieta Mtns; CaM - Cady Mtns; CM - Cottonwood Mtns; CDM - Castle Dome Mtns; ChM - Chemehuevi Mtns; DM - Dead Mtns; DRM - Dome Rock Mtns; ETR - eastern Transverse Ranges; GM - Gila Mtns; GPM - Granite-Providence Mtns; LM - Laguna Mtns; MM - Mohave Mtns; MiM - Middle Mtns; MuM - Muggins Mtns; nCM - northern Chocolate Mtns; NM - Newberry Mtns; NYM - New York Mtns; OM - Orocopia Mtns; OWM - Old Woman Mtns; PVM - Palo Verde Mtns; PR - Peninsular Ranges; PiM - Pinto Mtns; PIM - Plomosa Mtns; SBM - San Bernardino mtns; SM - Sacramento Mtns; SHM - Sheep Hole Mtns; SJM - San Jacinto Mtns; sCM - southern Chocolate Mtns; TM - Trigo Mtns; WM - Whipple Mtns. **Geologic features:** FCVB - Fish Creek-Vallecito Basin; PVF - Pinacate Volcanic Field

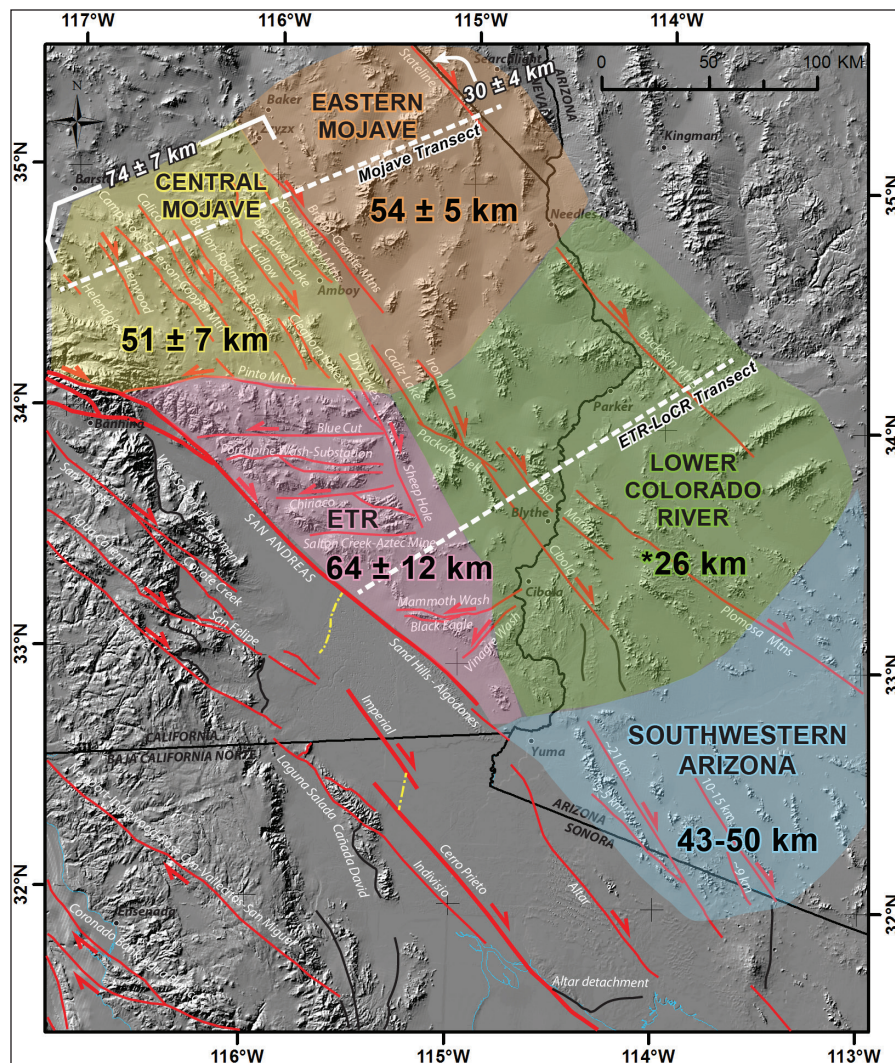


Figure 2B. Dextral shear domains within the greater eastern California shear zone. Numbers indicate documented cumulative post-10 Ma dextral shear within each domain, except for the Stateline fault which is only constrained as post-13 Ma (Guest et al., 2007). These values are exclusive of dextral slip on the San Andreas Fault (*sensu stricto*). Dashed white lines represent transects referred to in Table 1. Note that discrepancy in documented dextral shear between the adjacent eastern Mojave and lower Colorado River domains, which suggests that up to ~30–35 km of distributed shear may be currently undocumented in the lower Colorado River domain. Asterisk (*) indicates that cumulative shear in the lower Colorado River domain is based on the preferred estimates from published data (see Table 1). ETR - eastern Transverse Ranges; LoCR - lower Colorado River

for palinspastic reconstructions in areas where little information exists. At present, detailed geologic studies of crustal deformation related to the Pacific–North America plate boundary in the LoCR region are limited, leading to considerable uncertainty in the late Cenozoic tectonic evolution of the region. This uncertainty limits our understanding of how plate coupling evolves during the transition from a convergent margin to a transform margin.

In this paper, we utilize animated palinspastic fault-based reconstructions to evaluate the tectonic

evolution of the LoCR region and to examine potential inconsistencies of the spatio-temporal evolution of the late Cenozoic Pacific–North America plate boundary. Based on revised palinspastic reconstructions and remaining inconsistencies, we hypothesize that (1) late Miocene transtensional faulting related to the Gulf of California shear zone and eastern California shear zone promoted tectonic subsidence in the LoCR region that permitted the subsequent southward lake spillover of the Colorado River and connection with the northern Gulf of California, (2) distributed Pliocene transtensional faulting likely occurred within the southern LoCR region, and is presently unaccounted for in most studies of geologic units related to the Pliocene Colorado River, and (3) the Chocolate Mountains anticlinorium can be reconstructed to a broadly linear, E–W-oriented structure at ca. 11 Ma, consistent with reconstruction of several other strain markers along the southern San Andreas Fault system.

Constraints on plate boundary deformation

Inputs for tectonic reconstruction model

In this paper, we update the GCAST tectonic reconstruction model of Bennett et al., (2013a), which synthesized numerous datasets for crustal deformation over the past 11 Myr along a ~2,000 km-long, 400–500 km-wide swath of the Pacific–North America plate boundary, from San Bernardino, California (United States) to Puerto Vallarta, Jalisco (México). This GIS-based tectonic reconstruction¹ sequentially restores crustal deformation

¹ Animations of tectonic reconstructions can be viewed at: Full Gulf of California–Salton Trough: https://youtu.be/zRerSXoC_4c
Lower Colorado River region: <https://youtu.be/htzdDLW3-aQ>

between tectonic blocks and incorporates fundamental constraints on the magnitude and direction of Pacific–North America relative dextral-oblique motion provided by the updated global plate-circuit model (Atwater and Stock, 2013). At more local scales, the GCAST model incorporates all published accounts of late Miocene to present crustal deformation, including contemporary deformation rates from GPS studies (e.g., Meade and Hager, 2005; Plattner et al., 2007), the location, timing, style, and magnitude of late Cenozoic faulting from geologic and marine geophysical studies (e.g., Howard and Miller, 1992; Richard, 1993; Umhoefer et al., 2002; Aragon-Arreola and Martin-Barajas, 2007; Guest et al., 2007; Lease et al., 2009; Bennett et al., 2013b), information about crustal structure from magnetic and gravity studies (e.g., Sandwell and Smith, 2009), estimates of the age and width of new oceanic crust in the Gulf of California (e.g., Lizarralde et al., 2007), and unique geologic formations that serve as strain markers across the Pacific–North America plate boundary (e.g., Crowell, 1962; Powell, 1993; Matti and Morton, 1993; Oskin et al., 2001; Darin and Dorsey, 2013). This reconstruction is limited to published information about the geometry, timing, and magnitude of fault activity.

Pacific–North America plate boundary

The global plate-circuit postulates that Pacific–North America dextral-oblique plate motion initiated in northwest México ca. 12.3 Ma, however direct evidence of significant dextral shear east of the Baja California peninsula prior to ca. 9–10 Ma is sparse (Gans, 1997; Herman, 2013; Garcia-Martinez et al., 2014), suggesting that shear likely occurred at a low strain rate. Geologic studies in the Mojave Desert and eastern Transverse Ranges of southern California suggest that plate boundary dextral shear within the eastern California shear zone (ECSZ) initiated ca. 10–5 Ma (Dokka and Travis, 1990; Richard, 1993; Schermer et al., 1996; Dokka et al., 1998). More recent studies indicate that the Gulf of California shear zone (GCSZ; Bennett and Oskin, 2014), located east of the Baja California microplate, initiated ca. 9–7 Ma (e.g., Dorsey et al., 2007, 2011; Seiler et al., 2010, 2011; Bennett et al., 2013b, 2015; Miller and Lizarralde, 2013). The GCSZ and ECSZ were likely a continuous zone of late Miocene to early Pliocene distributed transtension, kinematically linked somewhere in the LoCR region near the California–Arizona border. The late Miocene onset of significant transtensional strain coincides

with a clockwise azimuthal shift in the direction of Pacific–North America relative plate motion at ca. 8 Ma (Atwater and Stock, 1998). This change resulted in an increase in rift obliquity, which promoted the development of strike-slip faults and transtensional sedimentary basins throughout the GCAST region.

By ~6 Ma, the Pacific–North America plate boundary south of ~33.5°N latitude had localized into the core of the GCSZ, marking an important transition from diffuse transtension in the GCSZ to localized plate boundary motion with linked transform faults and spreading centers. Subsequent oblique plate boundary motion opened the Gulf of California, such that the geologic record of the GCSZ is now preserved in late Miocene to early Pliocene sedimentary basins that flank the modern-day Gulf of California. In contrast, the ECSZ continues to accommodate diffuse plate boundary shear today north of ~33.5°N latitude. Late Miocene (6.4–6.1 Ma) tuffs, now offset ~250 km across the northern Gulf of California, serve as cross-Gulf strain markers and indicate that ~90% of plate motion has been accommodated within the Gulf of California since latest Miocene time (e.g., Oskin et al., 2001; Oskin and Stock, 2003). Similarly, GPS studies (e.g., Plattner et al., 2007) indicate ~93% of modern Pacific–North America plate motion is localized between the Baja California microplate and mainland México, suggesting that the residual plate motion shear is accommodated on structures west of Baja California. Thus, the Baja California microplate has yet to become completely coupled to the Pacific plate.

Collectively, these observations suggest that the Pacific–North America plate boundary was initially moderately oblique and diffuse, with strain partitioned east and west of the Baja California microplate, progressively localized into a belt of highly oblique relative plate motion in the GCSZ and ECSZ during latest Miocene time, and culminated with the opening of Gulf of California–Salton Trough basins. With these constraints in mind, our preferred GCAST reconstruction model uses 25% Baja–Pacific coupling between 7 and 11 Ma. The residual 75% of Pacific–North America strain is accommodated on structures offshore, west of Baja California. Between 6 and 7 Ma the GCAST model uses 60% Baja–Pacific coupling, followed by 93% Baja–Pacific coupling from 6 Ma to the present day. This gradual increase in Baja–Pacific coupling reflects the geologic evidence for progressive localization of the plate boundary. Our approach differs

from previous reconstructions (Wilson et al., 2005; Fletcher et al., 2007), which imply higher magnitudes of Baja–Pacific percent-coupling and thus restored larger amounts of Baja–North America relative motion. The advantage of our methodology is that unacceptable overlap of continental crust does not occur in two locations along the eastern Gulf of California margin (Fig. 1): (1) crustal blocks now located on Isla Tiburón, in the Sierra Libre, and in the Sierra El Bacatete, east of the Empalme graben near Guaymas, Sonora (N28°–N29°), and (2) extended crustal blocks now submerged offshore in the southern Gulf of California, between Mazatlán, Sinaloa and Puerto Vallarta, Nayarit (N21°–N24°).

The GCAST reconstruction model includes minor clockwise rotation of the Baja California microplate that occurred during oblique rifting, and captures how total Baja–North America relative motion increases from north to south due to latitudinal variation in Euler pole distance. Total preferred Baja–North America dextral-oblique motion since 11 Ma varies from ~385 km in the southern Gulf of California to ~365 km at the Midriff Islands in the northern Gulf of California. Because no trans-peninsular faults exist to transfer strain from the Gulf of California westward across the Baja California microplate to offshore structures, all this plate-boundary motion must have been transmitted along strike into the Salton Trough and LoCR region (e.g., southern San Andreas Fault system and ECSZ; Fig. 2). Accordingly, this south-to-north gradient of decreasing offset estimates is consistent with a recent estimate of 340 ± 40 km of cumulative relative dextral plate motion across southern California and the ECSZ (Darin et al., 2013).

Colorado River region

Despite sparse geologic constraints and an incomplete record of crustal deformation in the lower Colorado River region since late Miocene time, existing knowledge provides important insight into the diffuse but measureable influence of Pacific–North America relative plate motion as much as ~200 km inboard of the primary plate boundary (i.e., San Andreas Fault).

Available geologic constraints for dextral shear across the ECSZ, along a transect from the central Mojave Desert to the eastern Mojave Desert, suggest at least 104 ± 8 km of cumulative northwest-oriented dextral shear on a regional system of diffuse strike-slip and oblique-slip faults located east of the modern San Andreas–Gulf of California fault system since ca. 13 Ma (Fig. 2B, Table 1; Darin et al., 2013). A compilation of fault displacement

data from the central Mojave Desert reveals 53 ± 6 km of cumulative dextral shear since ca. 10 Ma (McQuarrie and Wernicke, 2005). However, considering new constraints for greater total slip on the Bristol–Granite Mountains fault system (Lease et al., 2009) and including published uncertainties for other faults increases the estimate for total dextral shear in the central Mojave to 74 ± 7 km (Fig. 2B, Table 1), identical to an independent estimate of 74 ± 17 km of cumulative dextral shear along strike to the northwest in the southern Walker Lane/Death Valley region (Renik and Christie-Blick, 2013). Approximately 90 km northeast of the Bristol–Granite Mountains fault system, Guest et al. (2007) documented 30 ± 4 km of post-middle Miocene dextral slip along the northwest-striking Stateline fault, effectively pushing the eastern boundary of the ECSZ at least as far inboard as the California–Nevada border (Fig. 2B).

A significant component of dextral shear from this central and eastern Mojave region is transmitted to the southeast into the eastern Transverse Ranges (ETR) and LoCR regions (Fig. 2B). In the ETR, paleomagnetic data from Miocene–Pliocene volcanic rocks (Carter et al., 1987) and fault reconstruction models based on geophysical data (Langenheim and Powell, 2009) indicate ~40° of clockwise vertical-axis block rotations between ca. 10 and 4.5 Ma. Transrotational shear caused by the rotation of crustal panels in the ETR only accounts for up to 64 ± 12 km of dextral northwestward relative displacement (Dickinson, 1996), significantly less than the 104 ± 8 km of offset predicted for the entire ECSZ across the Mojave Desert to the north (Fig. 2B). Thus, several tens of kilometers of additional, distributed dextral shear must be accommodated by a discontinuous system of northwest-striking dextral and dextral-oblique faults within the LoCR. An early attempt at estimating this additional shear across the LoCR reported a maximum of 16 km (Richard, 1993). Based on our compilation of fault slip data, we revise the estimate of dextral shear in the LoCR to a minimum of 26 km (Table 1). However, the magnitude of documented dextral shear in the LoCR region (26 km) remains less than the dextral shear observed in the eastern Mojave domain (54 ± 5 km) along strike to the northwest (Fig. 2B). Because we expect strain to be preserved along-strike in a dextral shear zone, this comparison and their uncertainties (Table 1) suggests that as much as 30–35 km of dextral offset could be unaccounted for in the LoCR region, between the Chocolate Mountains in southeastern California and the Buckskin Mountains

TABLE 1. PUBLISHED DEXTRAL FAULT SLIP DATA AND MODEL CONSTRAINTS FOR THE EASTERN CALIFORNIA SHEAR ZONE

DOMAIN	FAULT NAME	GCAST MODEL INPUT		PUBLISHED DATA				DATA USED (OFFSET FEATURES)	REFERENCES
		Dextral slip (km)	Timing of slip (Ma)	Preferred Slip (km)	Min (km)	Max (km)	Timing of slip (Ma)		
EASTERN MOJAVE	Stateline Fault	30	13-0	30	26	34	post-13	Observed offset of middle Miocene rhyolite dome	Guest et al., 2007
	Granite Mtns (BGMFZ)	24	10-0	24	21	27	post-11	alignment of offset mid-Miocene paleovalley	Lease et al., 2009
				21.5	-	-	initiation at 10-6	Best-fit value from reconstruction model	Dokka et al., 1998; Dokka and Travis, 1990
				-	-	9	uncertain	assumed slip; max 15 km total on BGMFZ and South Bristol Mtns fault to match offset along strike to SE	Richard, 1993
				-	0	10	uncertain	offset flow-banded rhyolite	Howard and Miller, 1992
				-	6	15	uncertain	granite outcrops and sediment provenance	Brady, 1992; Brady, 1993
	SUBTOTAL				54 ± 5				
CENTRAL MOJAVE	South Bristol Mountains	6.5	10-0	13.5	6	-	initiation at 10-6	best-fit from reconstruction model	Miller et al., 1982; Dokka and Travis, 1990
				-	-	6	uncertain	assumed slip; max 15 km total on BGMFZ and South Bristol Mtns fault to match observed offset along strike to SE	Richard, 1993
				6.5	0	6.5	uncertain	distinctive porphyritic granite; metavolcanics	Howard and Miller, 1992
	Broadwell Lake	6	10-0	1	0	1	initiation at 10-6	small observed offset; best-fit from reconstruction model	Dokka et al., 1998
				6	0	6	uncertain	unspecified offset strata; 1 km offset of Broadwell lake and up to 4-5 km offset on nearby parallel faults	Howard and Miller, 1992
	Ludlow	6	10-0	3	-	3	initiation at 10-6	small observed offset/best-fit model	Dokka, 1983
				6	6	-	uncertain	assumed slip to restore tilted Neogene(?) conglomerate with muscovite-granite clasts to presumed nearest source in Bullion Mtns	Howard and Miller, 1992
	Bullion-Rodman-Plisgah	13	10-0	10.4	6.4	14.4	initiation at 10-6	observed offset	Dokka, 1983
				15	10.7	19.3	< 13.4	82° ± 24° clockwise rotation of SW Cady Mtns	Ross, 1992
				12.9	6.4	19.3	uncertain	Average representing range of available data	This study
	Calico	9.6	10-0	9.6	-	-	initiation at 10-6	observed offset of 8 km, plus 1.6 km of dextral shear expressed as strain	Dokka, 1983
	Camp Rock-Emerson-Copper Mountain	4.5	10-0	3	1.6	4	initiation at 10-6	observed offset	Dokka, 1983; Miller, 1980
LoCR				6	-	-	uncertain	contacts between Mz meta. and granitic rocks	Dibblee, 1992
				3.8	1.6	6	uncertain	Average representing range of available data	This study
	Lenwood	2	10-0	2	1.5	3	initiation at 10-6	observed offset	Dokka, 1983
				1	0.8	1.2	post-7.33	displacement of Lenwood anticline; timing based on Ar/Ar age of offset basalt flow (A. Iriondo, unpublished data)	Frankel et al., 2008
	Helendale	3	10-0	3	-	-	initiation at 10-6	observed offset	Dokka et al., 1998
	SUBTOTAL				51 ± 7				
TOTAL SHEAR ACROSS TRANSECT		105	13-0			104 ± 8			
ETR-LoCR TRANSECT	Buckskin Mtns	9	10-6	8	7	9	post-12 (probably 12-6)	restoration of topographic trend of lower plate corrugations in Buckskin detachment with dominant extension direction	Singleton, 2015; J. Singleton, 2012, written comm.
	Plomosa Mountains	20*	10-6	6	6	>24	post-19	contacts, fold axes, dikes, other faults offset across ~8 km-wide zone of dextral shear. Maximum slip is assumed to be four times observed separation, which includes movement along another fault that may have separation several times that which is observed.	Miller and McKee, 1971
	Big Maria	4.5	10-0	4.5	-	-	uncertain	matching thrust faults and syncline	Richard, 1993
	Cibola	7	10-0	7	-	-	uncertain	offset normal faults and volcanic rocks	Richard et al., 1992
	SUBTOTAL					>26			
	ETR	64	10-0*	64	52	76	10-4.5	geometric estimation of transrotational shear based on 40° of clockwise vertical-axis rotation of crustal panels	Dickinson, 1996
	SUBTOTAL					64 ± 12			
TOTAL SHEAR ACROSS TRANSECT		105	10-0			90 ± 12			

Notes: Numbers in bold italics are our preferred best constraints based on all available data. Abbreviations - BGMFZ - Bristol-Granite Mountains fault zone; ETR - eastern Transverse Ranges; LoCR - Lower Colorado River; meta. - metamorphic

* Our model restores 20 km of dextral slip in the Plomosa Mountains because it is both permissible and the amount required to bring the total shear across each modeled transect into agreement.

† Minor post-4.5 Ma clockwise rotation (6°) of the ETR is included in our reconstruction model in order to avoid unacceptable overlap (i.e., extension) between the Pinto and San Bernardino Mountains during that time

in west-central Arizona. Although the majority of paleomagnetic data suggest that post-early Miocene tectonic rotations in the LoCR region are generally small to insignificant (Calderone and Butler, 1984; Wells and Hillhouse, 1989; Calderone et al., 1990), large local rotations ranging from 51° counterclockwise to 37° clockwise are observed (Wells and Hillhouse, 1989) that could be related to local rotations within or adjacent to shear zones. Regardless, the lack of systematic tectonic rotations in the LoCR region implies that dextral shear in this area may be expressed as translational rather than transrotational strain.

In the Southwestern Arizona domain (Fig. 2B), Nourse et al., (2005) estimated 43–50 km of cumulative latest Cenozoic dextral shear and transtension (pull-apart basin formation) across four northwest-striking structures that straddle the Arizona–Sonora border southeast of Yuma, AZ. This value is similar to dextral

offset documented in the eastern Mojave domain, and further supports the notion that current estimates of total offset across the LoCR are incomplete. However, the relative continuity of structures along the 220-km-long, ~east–west trending Chocolate Mountains anticlinorium, a discontinuous series of early to middle Miocene antiformal domes exposing Orocopia Schist (e.g., Haxel and Dillon, 1978; Sherrod and Tosdal, 1991; Jacobson et al., 2007), seems to preclude the existence of large-offset strike-slip faults in this region (Richard, 1993).

In summary, revised compilations of fault-slip data from the central Mojave Desert region and scattered evidence of post-middle Miocene dextral shear in easternmost California and western Arizona suggest that up to 30–35 km of dextral shear may be undocumented across the LoCR region (Fig. 2B). Precisely where and how this dextral shear is kinematically linked with coeval

transtensional structures in the surrounding western Arizona and Sonora regions remains uncertain.

Implications for the Lower Colorado River region

The implications discussed below are speculative and are not based on new field evidence. These hypotheses and concepts are merely permissible given existing constraints on the known timing and activity of faulting discussed above. These ideas tie together existing narratives for the lower Colorado River region with constraints from our GIS-based tectonic reconstruction and provide a holistic synthesis of crustal deformation. These hypotheses need to be tested – and refined or revised – with future field work.

Late Miocene transtension permitted Colorado River spillover

We hypothesize that transtensional faulting related to a once-continuous GCSZ–ECSZ was the mechanism responsible for late Miocene tectonic subsidence and basin isolation that set the stage for subsequent lake spillover and integration of the lower Colorado River into the northern Gulf of California ca. 5.3 Ma (e.g., Spencer and Patchett, 1997; House et al., 2008). Our map-view tectonic reconstruction for the LoCR region (Fig. 3) illustrates a permissible scenario for the style and location of late Miocene deformation across this region. Restoration of post-middle Miocene dextral slip along the northwest-striking Stateline fault (Guest et al., 2007) requires that blocks farther west and south restore to the southeast relative to North America. A portion of dextral shear from the Stateline fault was likely transmitted to the southeast and distributed onto numerous strike-slip faults in the Buckskin Mountains (Singleton, 2015) and Plomosa Mountains (Miller and McKee, 1971). This right-stepping fault geometry likely involved diffuse extension, transtension, and subsidence within pull-apart basins from Needles, CA, to Blythe, CA. Similar structural connections between the Bristol–Granite Mountains faults, Cibola fault, and unnamed dextral faults at the Arizona–Sonora border likely opened comparable basins between Blythe, CA and Yuma, AZ during late Miocene time (Fig. 3).

Specifically, our revised GCAST reconstruction model predicts opening and subsidence of several late Miocene transtensional basins in the LoCR region. These include: (1) the southern Mohave Valley near Needles, CA, between the Sacramento and Chemehuevi

Mountains west of the Colorado River and the southernmost Black Mountains east of the Colorado River (Fig. 3C,D); (2) a hypothetical late Miocene basin in the Parker Valley, 10–40 km north-northeast of Blythe, CA; (3) the Cibola basin south of Blythe, CA, which subsided on the west flank of the Trigo Mountains in a complex zone of linked dextral and normal faults (Sherrod and Tosdal, 1991; Richard, 1993; Homan, 2014); and (4) a northwest-trending series of fault-bounded basins beneath Bristol, Cadiz, Danby and Palen dry lakes that likely also have late Miocene to Pliocene faulting and subsidence histories (e.g. Howard and Miller, 1992; Jachens and Howard, 1992). Thus, it appears that transtension played an important role in the formation of isolated late Miocene basins through which lake waters related to the first-arrival of the Colorado River later cascaded through and linked together on its path towards the Gulf of California.

Pliocene deformation of the southern Lower Colorado River region

We hypothesize that, although Pacific–North America dextral shear has progressively localized onto the southern San Andreas Fault and ECSZ, dextral shear, transtension, and transpression continued in the southern LoCR region at a relatively low strain rate into Pliocene time (Fig. 3B). This deformation likely affected Pliocene geologic records (lacustrine and fluvial deposits) of the early Colorado River system, downriver of Parker Valley, in ways that presently are not well understood.

Scattered evidence exists for Pliocene faulting in the eastern Mojave and southernmost lower Colorado River domains (Fig. 2B). Generally, the timing constraints of this deformation have large uncertainties and require further research. Mahan et al. (2009) proposed that dextral slip on the Stateline fault (~30 km) and opening of Ivanpah Valley may have initiated as late as Pliocene time (5 ± 1 Ma) based on (U–Th)/He thermochronologic data that records rapid exhumation of the New York mountains. This and other post-Miocene dextral shear in the eastern Mojave Desert (e.g., Bristol–Granite Mountains fault zone) was likely transferred southeastward to dextral and normal faults east of the ETR and inboard of the San Andreas Fault (Figs. 2B, 3; Dokka and Travis, 1990; Richard, 1993). Pliocene deposits of the Bullhead Alluvium appear undeformed northeast of Parker Valley but have subsided or faulted down in the Blythe Basin (Howard et al., 2015), suggesting that structures downriver of Parker

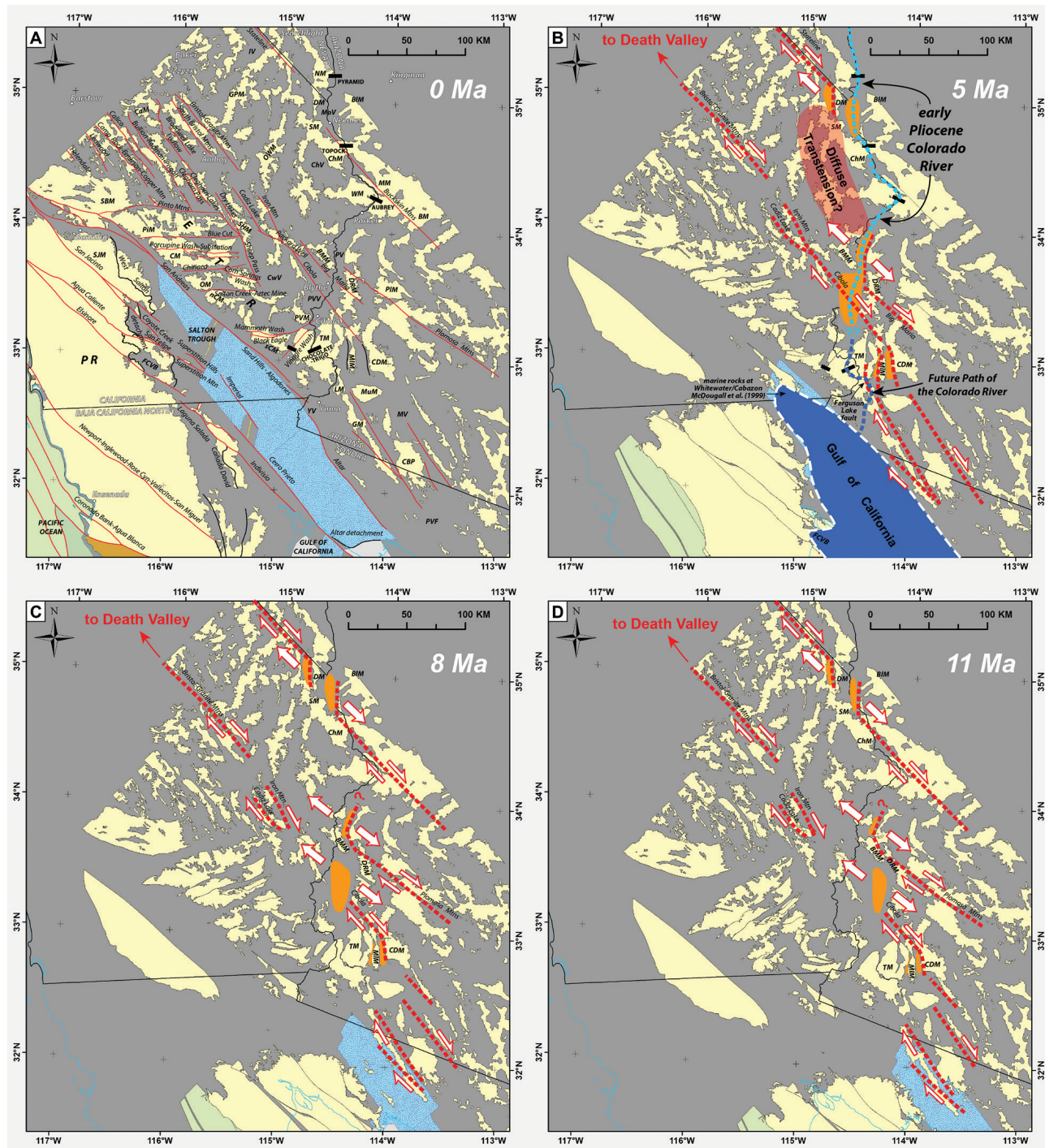


Figure 3 (A) Modern-day map of faults and crustal blocks (see Fig. 2A for details). Palinspastic reconstruction time slices showing fault activity in the eastern Mojave and lower Colorado River (LoCR) domains (see Fig. 2B) during (B) 5 Ma, (C) 8 Ma, and (D) 11 Ma. Basins that gradually open due to extension and/or transtension are shaded orange. Modern-day country and state boundaries remain fixed for reference in all four panels. Animation of Lower Colorado River region tectonic reconstruction can be viewed at: <https://youtu.be/hztdDLW3-aQ>

Valley may have been active during Pliocene time. Candidate structures include the Cibola and Laguna fault systems, which display late Miocene to Pliocene right slip (Sherrod and Tosdal, 1991; Richard et al., 1992; Richard, 1993). Other dextral faults cut deposits of the Pliocene Bouse formation in the southeastern

Palo Verde Mountains (Homan, 2014). This dextral shear was likely transferred farther to the southeast on inferred normal faults in the Indian Wash and Castle Dome basins (Richards, 1993) and/or within the Trigo Mountains (Homan, 2014; Beard et al., 2016; Beard et al., this volume). The east-dipping Ferguson Lake fault

(Beard et al., 2016; Beard et al., this volume), located ~9 km east of Picacho, CA, is likely part of this right-stepping system (Fig. 3B). These extensional structures may have connected with the northwest-striking Laguna fault system in the southeastern Trigo Mountains, which appears to continue to the southeast as unnamed dextral and dextral-oblique faults that flank both sides of the Gila Mountains and continue into northwestern Sonora (Fig. 3; (Nourse et al., 2005)).

Farther south, in the Yuma Valley, lacustrine deposits of the Pliocene Bouse Formation are observed in drill cores 150–1000 m below sea level (Olmsted et al., 1973), much lower than the deepest Bouse formation observed (-173 m) in the Blythe Basin to the north. This may support the idea that when the Colorado River reached this area, a relatively larger magnitude of late Miocene tectonic subsidence had already occurred in Yuma Valley than in the Blythe Basin. Alternatively, or in addition, the Bouse Formation in the Yuma Valley may have been deformed by post-depositional Pliocene structures and faulted down to its current elevation of 150–1000 m below sea level. In the Yuma Valley area, the Bouse Formation is cut by several northwest-striking subsurface faults along the Algodones fault system and along the southwestern flank of the Gila Mountains (Olmsted et al., 1973), supporting the notion that Pliocene faulting has occurred east of the San Andreas Fault. Additional support comes from the subsided or faulted nature of the Pliocene Bullhead Alluvium east of the Algodones fault (Howard et al., 2015). These relations suggest the possibility that post-late Miocene transtensional deformation has exerted some influence on the modern-day elevation of Bouse formation exposures in this area. If diffuse Pliocene deformation along the LoCR (from Parker Valley to Yuma, AZ has been accompanied by even very slow vertical motions and subtle tilting, existing models that interpret the modern-day elevation of Bouse Formation outcrops as a proxy for paleo-elevation may require revision.

Is the Chocolate Mountains anticlinorium a line strain marker?

The original shape and orientation of the Chocolate Mountains anticlinorium (CMA) is unknown, thus its apparent present-day continuity does not preclude the occurrence of late Cenozoic distributed dextral shear in this region. Based on our tectonic reconstruction model, we hypothesize that the pre-late Miocene CMA, long recognized as a potential strain marker across the

San Andreas Fault system (e.g., Crowell, 1962; Richard, 1993; Dembosky and Anderson, 2005), was originally an east- to east-northeast trending structural feature. Previous workers have speculated about the utility of the CMA as a linear strain marker, but no attempt has been made to palinspastically restore the CMA using independent geologic constraints. Our reconstruction model (Fig. 4), which is based on a compilation that includes fault slip data, paleomagnetically constrained block rotations, and constraints for several offset geologic markers in southern California (synthesized in Darin and Dorsey, 2013), restores dextral displacement on the San Andreas Fault (*sensu stricto*), distributed dextral shear in the southern LoCR, and rotation of the ETR. A result of this reconstruction is restoration of the axis of the CMA to an approximately east–west orientation at 11 Ma (Fig. 4B). It is important to note that this restored trace of the CMA is an independent result of the reconstruction rather than an initial constraint of the model.

Pre-11 Ma deformation along the PAC–NAM plate boundary may permit further rotation of the CMA and bring it to a more linear east-northeasterly orientation than our 11 Ma reconstruction (Fig. 4B). Paleomagnetic data from the western Transverse Ranges supports up to 50° of clockwise vertical-axis rotation of the San Gabriel Mountains ca. 15–9 Ma (Terres and Luyendyk, 1985; Dickinson, 1996), which would restore the San Gabriel block farther south, back-rotate it more in a counterclockwise sense, and orient the CMA in the Sierra Pelona east-northeast, similar to the restored trend of the eastern CMA in southwestern Arizona (Fig. 4B). It is conceivable that, prior to ~10 Ma, before displacement on the San Gabriel and southern San Andreas Faults, the ETR were rotating in a clockwise sense, similar to rotation that is documented for the western Transverse Ranges. In this case, additional clockwise rotation of similar magnitude would also need to be restored in the Orocochia and Chocolate Mountains to bring them into alignment with exposures in the restored San Gabriel Mountains and southwestern Arizona; anomalously high clockwise rotations (>100°) have been observed in the Chocolate and Orocochia Mountains, but remain poorly understood (Carter et al., 1987).

New evidence that may call into question the initial linearity of the CMA comes from a recently identified exposure of Orocochia Schist at Cemetery Ridge, AZ (Haxel et al., 2015). Assuming this exposure correlates

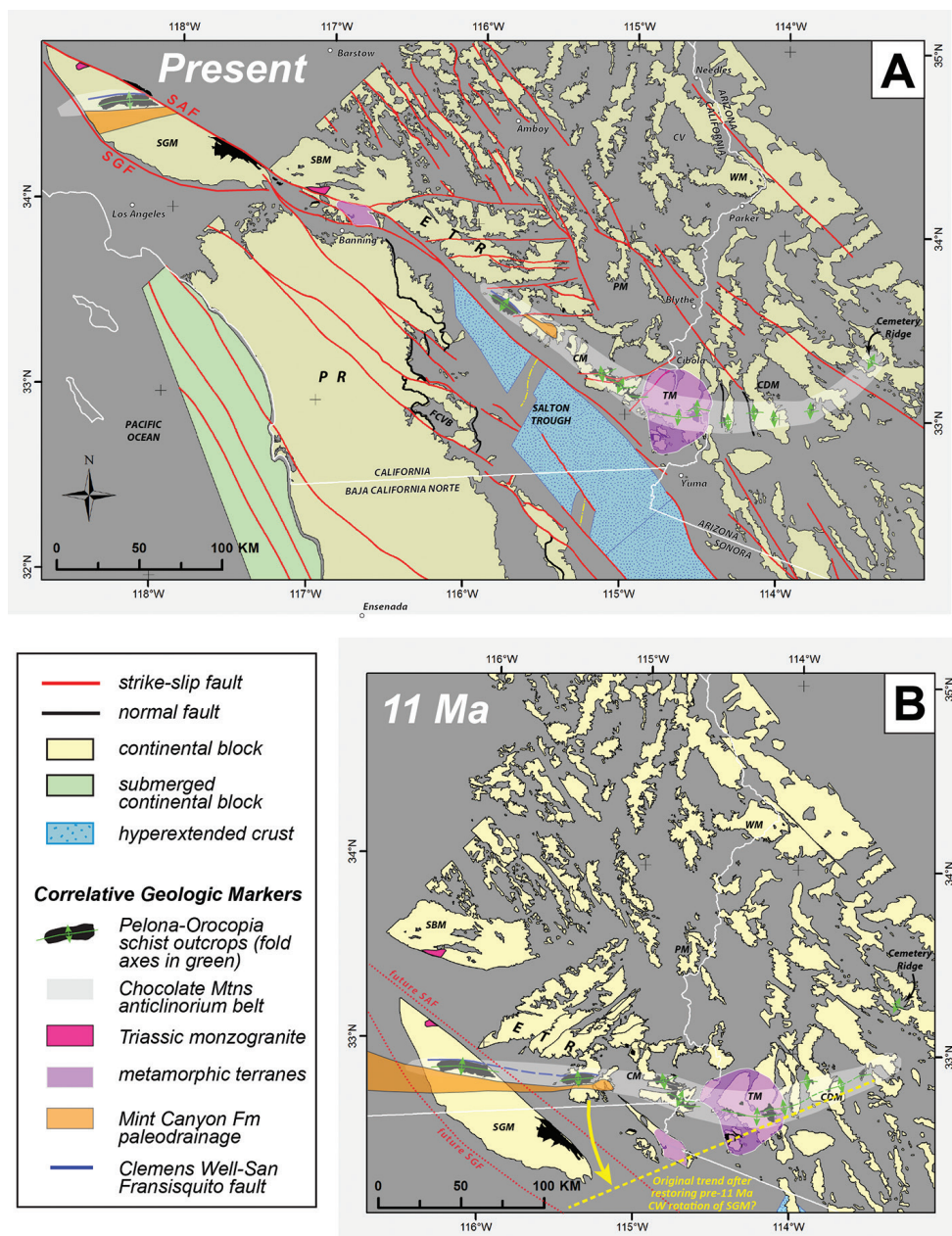


Figure 4 A) Modern-day map of faults, crustal blocks and offset geologic markers along the San Andreas Fault system. All correlative geologic markers (Darin and Dorsey, 2013), except for the Chocolate Mountains anticlinorium (CMA), are used as constraints in this reconstruction model. B) 11 Ma palinspastic reconstruction of the LoCR region. Restoration of the Chocolate Mountains anticlinorium (CMA) to a sub-linear, ~east-west trend at 11 Ma is a result of the reconstruction rather than a first-order constraint. Yellow dashed line represents a plausible initial orientation of the CMA if pre-11 Ma clockwise (CW) rotation and/or additional dextral shear were restored in the San Gabriel (SGM) and Chocolate Mountains (CM). SGF – San Gabriel fault; other abbreviations as in Figure 2.

with other exposures of the CMA to the southwest, the initial trend of the CMA could have been either more northeasterly or nonlinear. A more northeasterly initial orientation of the CMA, as we hypothesize here, would align it parallel to the early to middle Miocene extension direction (Davis and Lister, 1988; Spencer and Reynolds, 1991). Thus, the development of the CMA

may be analogous to lower plate corrugations found in the Whipple, Buckskin–Rawhide and other metamorphic core complexes in the LoCR region (e.g., Fletcher and Bartley, 1994; Singleton, 2013), lending support to models that consider the CMA to be an early to middle Miocene structure temporally and genetically related to core complex exhumation in the North American Cordillera (e.g., Haxel et al., 1985, 2002; Jacobson et al., 2007). Additional work is required to demonstrate that exposures of Orocopia Schist at Cemetery Ridge in fact correlate to the CMA.

Conclusions

In this paper we demonstrate the utility of palinspastic tectonic reconstructions to provide a paleo-tectonic framework for evaluating published concepts about the evolution of the LoCR region. An animated synthesis of crustal deformation illustrates the tectonic consequences of existing faulting constraints, and highlights gaps in our current understanding of the spatio-temporal evolution of the late

Cenozoic Pacific–North America plate boundary. From this analysis, we form three hypotheses:

(1) Progressive lake spillover of the early Pliocene Colorado River and its eventual integration with the northern Gulf of California was intimately related to, and immediately preceded by, the distributed

transtensional regime of the GCSZ and ECSZ. Late Miocene transtension produced tectonic subsidence and isolated basins through which the Colorado River was later integrated. Importantly, this hypothesis proposes a direct genetic link between tectonic subsidence in the LoCR region and integration of the Colorado River at the end of Miocene time.

(2) The region east of the San Andreas Fault system continued to accommodate a small but significant fraction of Pacific–North America relative plate motion into Pliocene time, likely accumulating tens of kilometers of distributed dextral shear across the southernmost Lower Colorado River region. This hypothesis is locally supported by observation of faults that cut Pliocene deposits (e.g., Bouse Formation and Bullhead Alluvium) downriver of Parker Valley, but otherwise it remains largely untested.

(3) The Chocolate Mountains anticlinorium (CMA) can be restored to a broadly linear, E–W to ENE-oriented structure at ca. 11 Ma, and may be a useful line strain marker for Pacific–North America plate boundary deformation. The CMA may have absorbed several tens of kilometers of distributed dextral-oblique strain and/or rotational shear since middle Miocene time. Thus, the apparent continuity of the CMA and related Pliocene–Quaternary rocks does not preclude late Miocene to Pliocene distributed deformation of the area, as assumed by previous workers.

These implications are speculative, are not based on new field evidence, and will require careful field studies to verify or reject the presence of some faults and tectonic basins. Future work is needed to improve constraints on the timing, magnitude and distribution of late Miocene to Quaternary deformation, and to seek out evidence for our prediction of up to 30–35 km of undocumented dextral shear across the LoCR region. Focused acquisition of new field data will improve our understanding of how the Pacific–North America plate boundary strain evolved over late Cenozoic time.

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