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Quaternary-Active Faults and the Role of Inherited Structures in the Sacramento-San Joaquin Delta, Western Central Valley, Northern California

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Abstract Seismic sources and their associated hazards within the Sacramento-San Joaquin Delta region of north-central California are relatively poorly characterized as compared to other, more heavily studied regions of northern California, such as the San Francisco Bay Area. Here we present a synthesis of subsurface, bedrock geology, and geodetic datasets from the Delta and from the Coast Ranges and Diablo Range to the northwest and southwest, respectively. We integrate these data and our own surface geologic and geomorphic observations to present a comprehensive review of faults in the Delta that exhibit Quaternary activity. Structural geologic data from the surrounding region highlight the significant influence that Late Cretaceous-to-Paleogene forearc structures exert on the geometry and kinematics of major Quaternary-active structures within the Delta. These inherited structures — including the Pittsburg-Kirby Hills Fault, Midland Fault, and Great Valley Fault System — exhibit a range of geometries and kinematics. Analysis of geomorphology along these structures suggests that these structures combine to accommodate Quaternary strain across the Delta region. A clearer understanding of subsurface geometries and structural relationships, built upon the regional tectonic history, provides insight into modern deformation accommodated on older structures and helps inform interpretations of seismic hazard within the Delta.

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Plain Language Summary Information about faults – for example, where they are located, their shape under the surface, how they slip, and when the last earthquake on them occurred – is important for understanding hazards from earthquakes in a region. Though the Sacramento – San Joaquin Delta (which we call "the Delta") is near the San Francisco Bay Area, a major population center, the earthquake hazards in the Delta are not well understood because we don't know much about the faults. This is partly because the faults are moving slowly and don't have earthquakes very often, and partly because the rocks and sediment that are often used to help us understand faults are not as visible due to the Sacramento River and Suisun Bay. In this paper, we bring together previous scientific studies, some of which were published and some of which were not, using many types of data to present our current best understanding of where faults in the Delta are located and how they are moving. This in turn helps to improve our knowledge about potential earthquakes in the Delta region.

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1 Introduction

The Sacramento-San Joaquin Delta region covers approximately 3,000 square kilometers in the western Central Valley of California, where the Sacramento and San Joaquin Rivers meet and enter Suisun Bay and the San Francisco Bay estuary system (Figure 1). Nearly half of California's total streamflow passes through the Delta, and approximately two thirds of California's population get some portion of their drinking water from the Delta (*Ingebritsen et al.*, 2000). The Delta and surrounding region play an important economic role in northern California and are home to Travis Air Force Base as well as some of California's most productive agricultural land, responsible for nearly $1 billion in gross revenue in 2016 (*DPC*, 2020). Earthquake effects thus have dramatic implications in the Delta region, including shaking and liquefaction that could damage levees and the islands they protect, surface rupture that could affect linear infrastructure, and the vertical deformation that could affect the very low gradient channels and water conveyance structures.

Despite its location close to the populous San Francisco Bay Area and its economic significance,

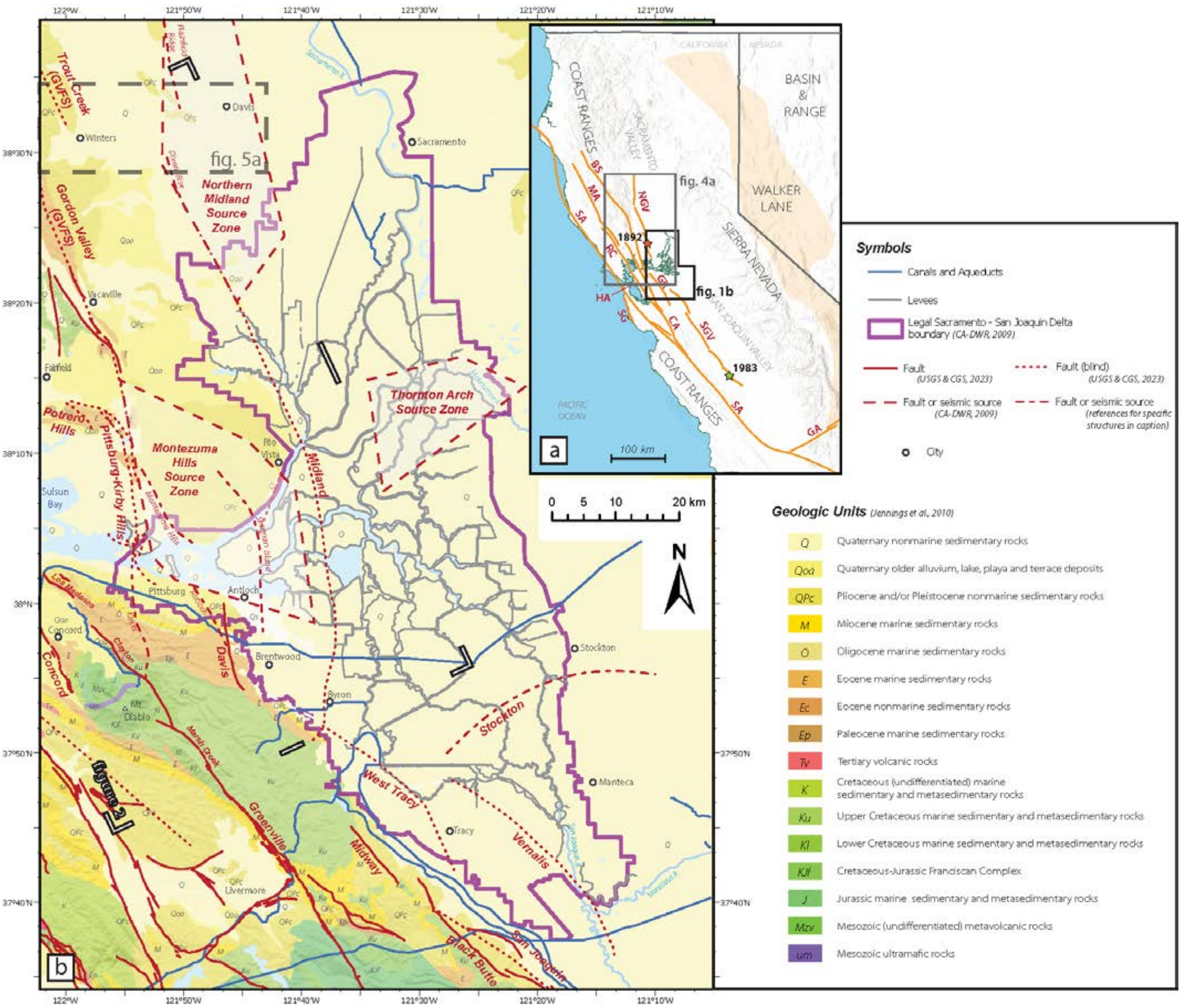

Figure 1 – **(a)** Map showing broad regional geography, including major faults within the plate boundary system (simplified from *Hatem et al.*, 2022). BS: Bartlett Springs (including the Hunting Creek-Berryessa, Green Valley, and Concord Faults); CA: Calaveras Fault; GR: Los Medanos-Clayton-Greenville Fault System; HA: Hayward Fault; GA: Garlock Fault; MA: Maacama Fault; NGV: northern Great Valley Fault System; RC: Rodgers Creek Fault; SA: San Andreas Fault; SG: San Gregorio Fault; SGV: southern Great Valley Fault System. Walker Lane extent from *Carlson et al.* (2013). Black polygon shows extent of panel (b). Stars indicate the locations of two significant historic earthquakes on the Great Valley Fault System: the 1892 Vacaville-Winters sequence and the 1983 Coalinga earthquake. **(b)** The Sacramento-San Joaquin Delta (outlined in purple) and surrounding area, highlighting potential earthquake source structures (red lines and light gray source zone areas) and water infrastructure (brown lines – levees; blue lines – canals). Seismic sources from Delta Risk Management Strategy report (CA-DWR, 2009) and USGS Quaternary Fault and Fold Database (*USGS and CGS*, 2023). Antioch Fault from *Burke and Helley* (1973). Dixon Rise and Plainfield Ridge from *Unruh and Moores* (1992). Sherman Island Fault from *Unruh et al.* (2009). Stockton Fault from *Bartow* (1991). Zone of Mercalli Intensity 8+ for the 1892 Vacaville-Winters earthquake sequence (orange shaded region) fro *O'Connell et al.* (2001). GVFS: Great Valley Fault System. Black and white corner marks indicate footprint of Figure 2; gray dashed box indicates footprint of Figure 5a.

the Delta is under-characterized as a seismic source region. Faults in the Delta region that exhibit evidence of Quaternary activity stretch as far north as the cities of Davis and Winters in the southwestern Sacramento Valley, and as far south as the city of Tracy and the northern Diablo Range (Figures 1 and 2). The geographic features that bound its western edge — the Coast Ranges, Mount Diablo, and Diablo Range — are defined by active faults and folds. Geomorphology and geodesy datasets indicate that faults within the Delta are active (Table 1 and Figure 3) (e.g., *Weber-Band*, 1998; *d'Alessio et al.*, 2005). However, regional deformation rates are low (likely on the order of millimeters per year) (Table 1) (*Prescott et al.*, 2001; *d'Alessio et al.*, 2005; *Evans*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022) and structures often have complex geometries, making it challenging to identify and constrain deformation rates on individual active faults and folds. Further complicating matters,

Table 1 – Geodetic fault slip rates in the Delta region, northern California. NSHM23 refers to the 2023 National Seismic Hazard Model (*Petersen et al.*, 2023).

Fault name	NSHM23 ID #	Geodetic Rate											
						NSHM23							
						viscoelastic fault-based model		Neokinema deformation model		dense block model		fault-based model with deep driven location sources	
		d'Alessio et al. (2005)		*Evans et al.* (2012)		*Pollitz* (2022)		*Shen and Bird* (2022)		*Evans* (2022)		*Zeng* (2022)	
		rate	rake	rate	rake	rate	rake	rate	rake	rate	rake	rate	rake
Mysterious Ridge section (GVFS)	97	∼	∼	∼	∼	2.4 ± 1.9	90	1.2 ± 0.5	114	0.9 ± 1.4	140	0.9 ± 1.0	86
Dunnigan section (GVFS)	98	∼	∼	∼	∼	0.2 ± 0.4	90	0.2 ± 0.01	91	0.9 ± 0.7	141	0.8 ± 0.9	122
Trout Creek section (GVFS)	99	∼	∼	∼	∼	1.0 ± 2.2	90	1.4 ± 1.5	58	0.0 ± 2.1	0	1.6 ± 1.2	123
Gordon Valley section (GVFS)	100	∼	∼	∼	∼	1.2 ± 1.8	90	1.4 ± 2.1	63	0.0 ± 2.1	0	1.7 ± 1.2	123
Green Valley	108	7.4 ± 1.2	161	5.0 ± 0.5	164	3.0 ± 1.7	180	2.7 ± 0.9	0	1.9 ± 1/8	145	4.2 ± 0.7	180
Los Medanos - Roe Is.	150	∼	∼	∼	∼	0.02 ± 0.1	90	0.1 ± 0.2	121	0.0 ± 0.3	0	0.014 ± 1.0	135
Pittsburg - Kirby Hills Fault	101	∼	∼	∼	∼	5.0 ± 1.5	90	1.0 ± 0.7	96	0.0 ± 1.2	0	1.4 ± 1.2	57
Midland Fault	103	∼	∼	∼	∼	0.9 ± 0.3	90	0.3 ± 0.2	86	1.0 ± 1.1	145	0.5 ± 0.9	106
Concord	44	6.9 ± 0.9	169	6.2 ± 0.5	155	4.5 ± 1.7	180	1.2 ± 0.4	0	1.6 ± 0.6	180	3.5 ± 0.7	180
Clayton	38	∼	∼	∼	∼	0.2 ± 0.4	180	0.7 ± 0.5	0	0.0 ± 0.4	0	0.6 ± 0.9	147
West Tracy	353	∼	∼	∼	∼	1.0 ± 0.5	90	0.7 ± 0.6	96	0.6 ± 1.6	90	0.6 ± 0.5	129
Midway	328	∼	∼	∼	∼	1.0 ± 0.5	90	0.8 ± 0.5	103	0.0 ± 0.6	0	0.6 ± 0.5	135
Black Butte & San Joaquin (GVFS)	105	6.0 ± 0.7	154	∼	∼	1.0 ± 0.4	90	0.7 ± 1.6	116	0.9 ± 1.1	141	1.2 ± 0.8	122

uncertainty reported as standard deviation (σ)
∼ indicates value not reported

much of the work in the Delta to date has been presented in conference proceedings, research technical reports, administrative reports, field trip guides, and unpublished student theses, rather than in widely available peer-reviewed publications. As a result, seismic source models use a simplified representation of faults in the Delta region (e.g., *CA-DWR*, 2009; *Hatem et al.*, 2022), and treat areas with complex or poorly understood structures as 'source zones' with little constraint on structure locations, geometries, or deformation histories (e.g., *CA-DWR*, 2009).

The Delta region lies along the eastern edge of the San Andreas plate boundary system, and the active faults within the Delta are a manifestation not only of modern tectonic deformation but also the tectonic history of the plate boundary. Along with the need for further characterization of seismic hazard, the Delta provides a scientific opportunity for exploration of the edge of the San Andreas plate boundary system and patterns of fault reactivation and overprinting as the tectonic regime evolved through the Cenozoic.

Here, we present a review of published and unpublished geodetic, geologic, and geophysical studies from the Delta region combined with a review of regional geologic history and new interpretations of high-resolution topographic data and geomorphic mapping. We combine these data to build a comprehensive overview of the current understanding of geologic structures within the Delta, their tectonic histories, and the role each plays in accommodating modern tectonic deformation across the region.

2 Background and Tectonic Setting

Multiple definitions exist for whether a fault is considered active, based on criteria as varied as whether a fault is "judged likely to move within the useful life of existing man-made structures" (*Brown*, 1972), exhibits physiographic evidence of recent activity (*Slemmons and McKinney*, 1977) or has associated earthquake activity (*Slemmons and McKinney*, 1977). Herein, we define an active fault as one that demonstrates geologic evidence of tectonic surface displacement within the Quaternary, consistent with the criteria for inclusion in the U.S. Geological Survey Quaternary Fault and Fold Database (*USGS and CGS*, 2023).

2.1 Regional Tectonic History

2.1.1 Pre-Neogene (> ~23 Ma)

In the Coast Ranges of northern California, to the west of the Delta, exposed pre-Cenozoic *Walker and Geissman* (prior to 66.0 Ma; 2022) rocks record significant portions of both an accretionary prism and a forearc system (Figure 1) (*Jennings et al.*, 2010). Structural geometries from this phase of tectonic history have been preserved in the Coast Ranges by the transition of the convergent plate boundary to a transform margin, rather than being destroyed by processes associated with terminal collision (e.g., *Wakabayashi*, 2015). This preserved structural architecture likely exerts an influence on the geometry of the modern transform plate boundary system, leading in some cases to reactivation of Late Cretaceous-Paleogene forearc faults to accommodate right-lateral plate motion (e.g., *Jachens et al.*, 1995; *Langenheim et al.*, 2007; *Medwedeff*, 2021; *Unruh et al.*, 2007).

The pre-Cenozoic history of the California Coast Ranges is complex, and details remain unresolved. The pre-Cenozoic rocks in the Coast Ranges can be separated into two distinct tectonic elements: the Coast Range ophiolite (sensu *McLaughlin et al.*, 1988; *Wakabayashi*, 2015) and the overlying Great Valley Group (sensu *Gilbert and Dickinson*, 1970; *Ingersoll*

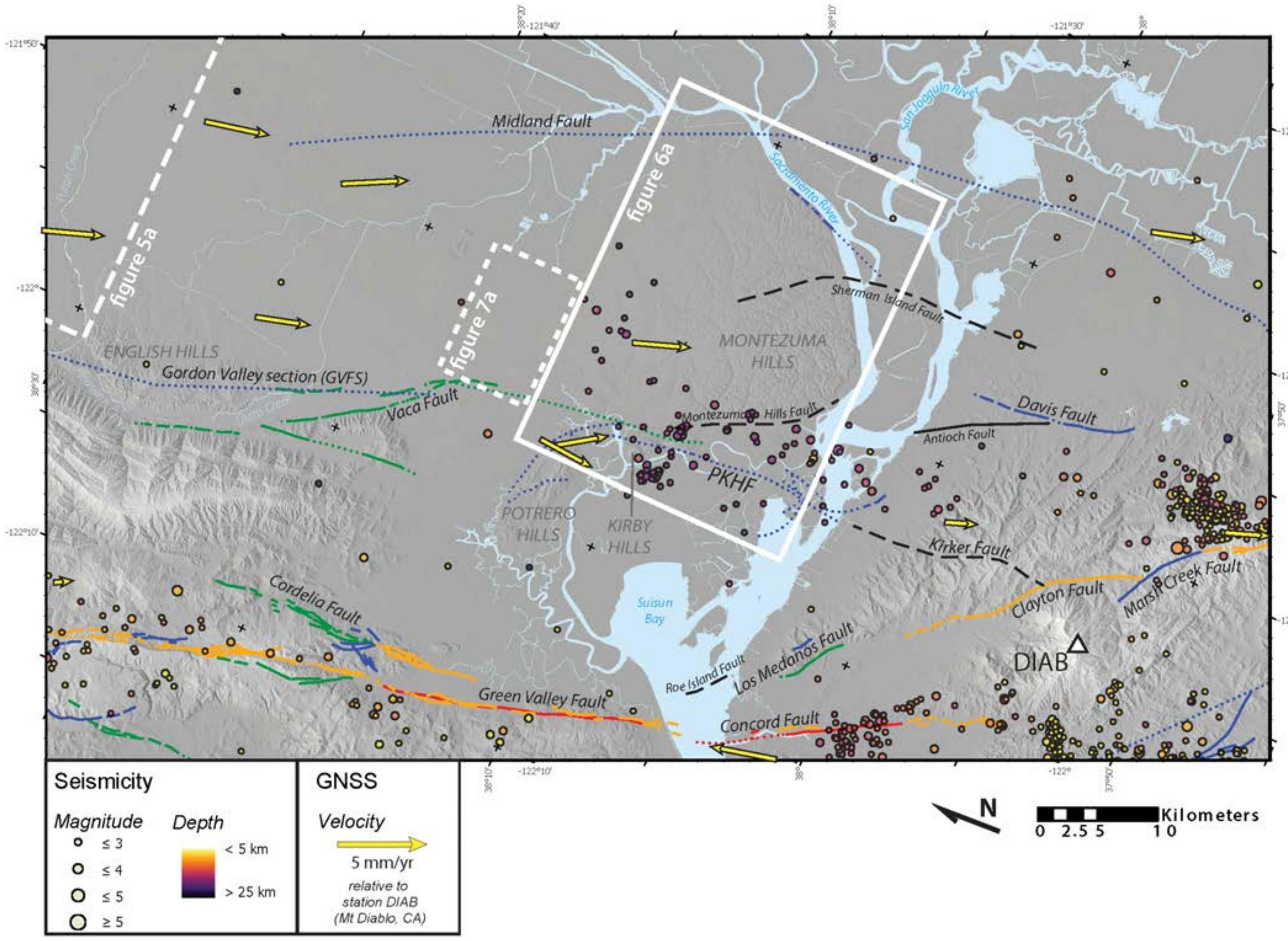

Figure 2 – Faults, plate motion, and seismicity in the central Delta and Suisun Bay region. Colored lines represent faults in the U.S. Geological Survey Quaternary Fault and Fold Database (*USGS and CGS*, 2023), with color representing age of most recent slip: red – historical (including creep), yellow – latest Quaternary (less than 15,000 years), green – late Quaternary (less than 130,000 years), blue – undifferentiated Quaternary. Fault traces are dashed where approximate and dotted where blind or buried. Black lines are faults mentioned in the text that may not be active in the Quaternary (*Burke and Helley*, 1973; *MacKevett*, 1992; *Unruh et al.*, 2007). Long dashed white box shows location of Figure 5a. Solid white box shows location of Figure 6a. Short dashed white box shows location of Figure 7a. Note that the Clayton and Marsh Creek Faults are part of the Greenville Fault System. GVFS – Great Valley Fault System. PKHF: Pittsburgh-Kirby Hills Fault. GNSS data from Geo-Gateway (*Heflin et al.*, 2020). Instrumentally recorded seismicity since 1900 (complete catalog of seismicity > M 2.5 between 1966 and 2022), shown with colored circles. Seismicity data from U.S. Geological Survey ANSS catalog (*USGS*, 2017).

and Dickinson, 1981; *Wakabayashi*, 2015), which represent the subduction forearc in the Mesozoic, and the Franciscan Complex, which represents the accretionary prism. The Franciscan Complex formed during a period of eastward subduction along the western margin of North America beginning at ~180 Ma (*Mulcahy et al.*, 2018; *Wakabayashi*, 2015). The Coast Range ophiolite, a supra-subduction-zone ophiolite complex that postdates the initiation of accretion of the Franciscan Complex (*Mulcahy et al.*, 2018), is structurally juxtaposed above and to the east of the Franciscan Complex along the Coast Range Fault (*Jayko et al.*, 1987; *Wakabayashi*, 2021). The Coast Range Fault, a name applied over a wide geographic region to structures separating Franciscan Complex and Coast Range ophiolite, is a bedrock fault with remnants found as far east as the eastern margin of the Coast Ranges and as far west as the San Andreas Fault. The Coast Range Fault has a complex kinematic history, with various datasets suggesting both thrust and normal displacement across the fault (e.g., *Medwedeff*, 2021). Juxtaposition of blueschist-grade rocks of the Franciscan Complex against zeolite-grade rocks of the Great Valley Group in the footwall and hanging wall, respectively, of the Coast Range Fault indicates that it may be the structure on which the Franciscan Complex is exhumed (e.g., *Jayko et al.*, 1987; *Unruh et al.*, 2007; *Wakabayashi*, 2021), though it has also been interpreted as a later, out-of-sequence thrust *Ring and Brandon* (1994, 1999); *Ring* (2008). The Great Valley Group, composed of well-bedded sandstones, shales, and conglomerates, was deposited in the forearc basin of the Sierra Nevada arc (*Ingersoll and Dickinson*, 1981; *Ingersoll*, 1999). In the west, the Great Valley Group is deposited atop oceanic basement now represented by the Coast Range ophiolite (*Bailey and Jones*, 1970). To the east and north, it onlaps accreted metamorphic rocks of the Sierra Nevada foothills and plutonic basement rocks associated with

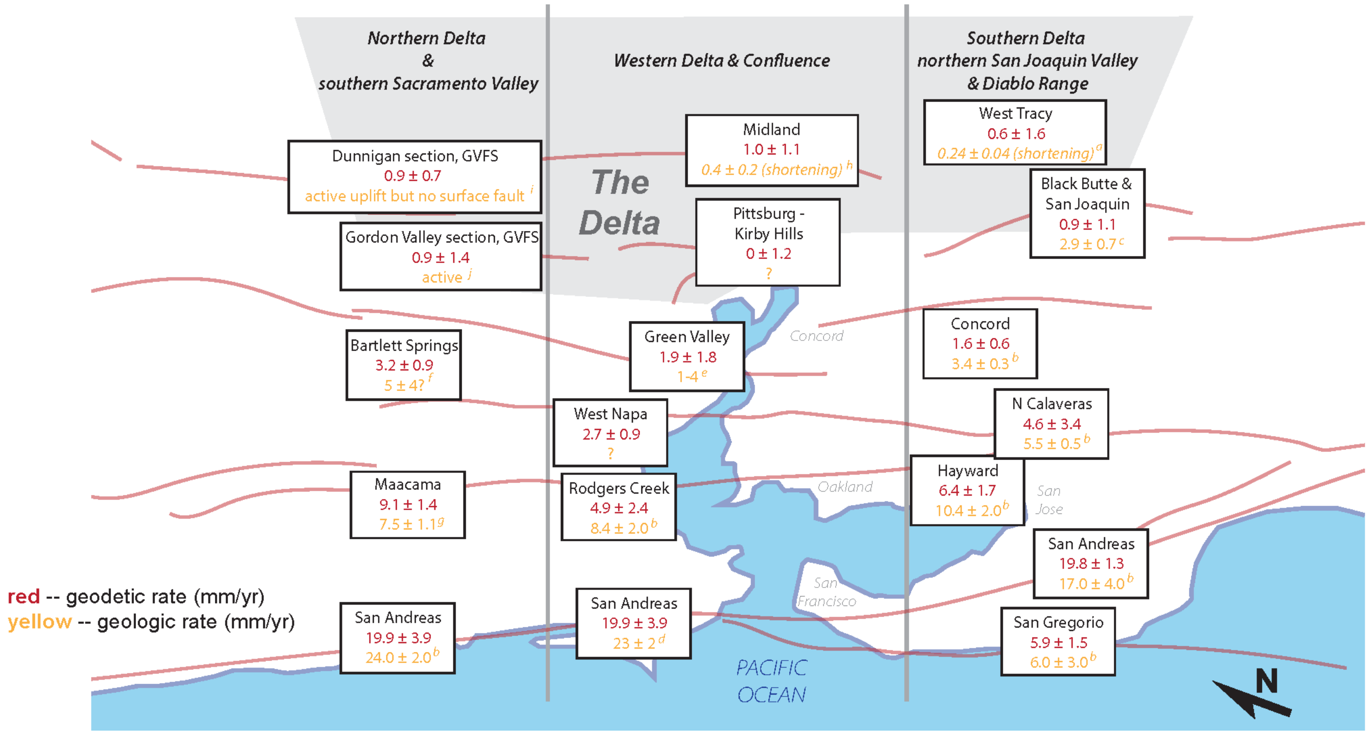

Figure 3 – Compiled geodetic (red text) and geologic (yellow text) slip rates for faults in the broader Pacific-North America plate boundary system. Unless otherwise noted, rates are fault -parallel and dextral is positive. Red lines indicate major faults in the Pacific-North America plate boundary system, simplified from *Hatem et al.* (2022). Geodetic rates are from *Evans* (2022); see Table SI-1 (Supporting Information) for a comparison of rates from other geodetic models. References for geologic rates are denoted by letters: **(a)** *LCI* (2022); **(b)** *Evans* (2018); **(c)** *Gavillot and Meigs* (2021); **(d)** *Grove and Niemi* (2005); **(e)** (*Lienkaemper et al.*, 2013); **(f)** *Murray et al.* (2014); **(g)** *Prentice et al.* (2014); **(h)** *Unruh et al.* (2009); **(i)** *Unruh et al.* (1995); **(j)** *Unruh and Moores* (1992).

the Sierra Nevada arc and Klamath terrane (*Pasquini and Milligan*, 1967; *Suchecki*, 1984; *Unruh*, 2021). The oldest rocks within the Great Valley Group are coeval with clastic units within the Franciscan Complex (e.g., *Bailey and Jones*, 1970); provenance analyses suggest that Great Valley Group and Franciscan have shared sediment sources in the Sierra Nevada arc to the east (e.g., *Ghatak et al.*, 2013; *Surpless et al.*, 2006; *Wakabayashi*, 2015) and Idaho batholith to the northeast (*Dumitru et al.*, 2015).

The depositional setting of most of the Paleogene units in the Coast Ranges and Sacramento Valley, including in the Delta, is a continuation of the setting of the Great Valley Group (e.g., *Wakabayashi and Sawyer*, 2001; *Sullivan and Sullivan*, 2012). The majority of sediment in the Paleogene section was derived from the Sierra Nevada arc and deposited by fluvial systems flowing westward off the range (e.g., the middle Eocene Domengine Formation) (*Todd and Monroe*, 1968; *Sullivan and Sullivan*, 2012). This pattern continued into the Neogene, though by the late Neogene, the section includes sedimentary units sourced from the Coast Ranges and local uplands (*Sullivan and Sullivan*, 2012). Overall, the Cenozoic section records a broad marine regression, with the onset of nonmarine deposition — a regional transition from tidal, estuarine, and shallow marine in west to fluvial and terrestrial deposits in the east — younging westward. Interbedded, geographically confined coarser units have been interpreted as migrating submarine canyons along the continental margin (*Sullivan and Sullivan*, 2012). The lateral variability and discontinuity of these units adds difficulty to interpretation and extrapolation of subsurface datasets in the region.

During the Late Cretaceous and early Paleogene, structures in the Sierra Nevada forearc accommodated both convergence and extension. This combination of approximately synchronous extensional and convergent deformation is typical of forearc settings (e.g., *Dickinson and Seely*, 1979). In the Coast Ranges of northern California, examples include the Coast Range Fault, which accommodated extension in the Late Cretaceous to exhume blueschist-grade Franciscan Complex (e.g., *Krueger and Jones*, 1989; *Unruh et al.*, 2007). The Great Valley Fault System may also be an example; some authors interpret that the system initiated as a thrust wedge on the inboard side of the forearc in the Late Cretaceous (e.g., *Wakabayashi*, 2015), though others suggest this structural system may have formed as recently as the Neogene (e.g., *Jones et al.*, 1994). Within the Delta, deformation during the late Cretaceous and early Paleogene was typified by N-S-striking (approximately plate boundary parallel) extensional faults, including those bounding the Rio Vista basin (e.g., *Johnson*, 1992; *Krug et al.*, 1992). Structures bounding this Paleogene-age extensional basin are exposed within Great Valley Group strata on the northern flanks of Mount Diablo to the south of the Delta (e.g., *MacKevett*, 1992; *Unruh et al.*, 2007). The bounding faults of this basin appear to root into a low-angle detachment that is interpreted to be the local expression of the Coast Range Fault (e.g. *Unruh et al.*, 2007).

2.1.2 Neogene (23 Ma) to Present

The northward-migrating Mendocino Triple Junction passed the latitude of the Delta approximately 10 million years ago (*Atwater and Stock*, 1998). Following the passage of the triple junction, the primary structures reflect the transition to a dextral transform plate boundary. Major faults in the Coast Ranges — including the San Andreas; the Hayward and Rodgers Creek; and the Calaveras, Green Valley, and Berryessa Faults — exhibit primarily right-lateral kinematics from the late Neogene to the present, consistent with dextral motion across the plate boundary. Other structures that initiated in the late Neogene include the Diablo Anticline, a fold 20 km wide and 40 km long and located southwest of the Delta, that forms in a restraining step in plate-boundary-parallel faults and is amplified by plate-boundary-normal compression (*Graymer and Langenheim*, 2021; *Medwedeff*, 2021).

In this new tectonic regime, preexisting dip-slip faults were in some cases reactivated as strike-slip or oblique-slip faults (e.g., *Jachens et al.*, 1995; *Langenheim et al.*, 2007; *Medwedeff*, 2021). Examples include Paleogene-age extensional faults exposed on the north limb of the Diablo Anticline, which reactivated after 10 Ma to accommodate oblique right-lateral displacement and north-south shortening around the restraining bend (*Unruh et al.*, 2007; *Unruh*, 2021). Some Paleogene-age extensional faults within the Delta also reactivated as reverse or reverse-oblique faults during this time, though with comparatively modest magnitudes of displacement (*Unruh*, 2021).

In the modern tectonic setting, faults and folds within the Delta are the easternmost structures associated with the San Andreas dextral fault system apparent in both geodetic and seismicity datasets (Figure 2 and 3) and arguably define the boundary between the Coast Ranges and the Sierra Nevada (*Wong et al.*, 2010). Structures in the Delta, and more broadly along the eastern edge of the San Andreas system, may accommodate regional transpression and partition it onto both transform and shortening structures (*Unruh and Lettis*, 1998) (Figure 2 and 3). Quaternary fold-and-thrust belts associated with plate boundary transpression are found along the inboard edge of the Coast Ranges both to the north (e.g., the Rumsey Hills and English Hills along the northern Great Valley Fault System, north of Vacaville; *Unruh et al.*, 1995) and south of the Delta (e.g., the boundary between the Diablo Range and Central Valley along the San Joaquin and Black Butte Faults; *Unruh*, 2021; *Gavillot and Meigs*, 2021) (Figure 1).

3 Faults and Folds in the Delta and Surrounding Region

Owing in part to slow rates of deformation, high rates of erosion and deposition by the Sacramento and San Joaquin Rivers, and the complex inherited structural geometries, the Delta region presents relatively few opportunities for traditional fault slip rate studies, particularly in the central and western Delta. Fault slip rate studies conducted in the Delta region to date are limited primarily to structures on the western and southern margins of Delta. Here, we draw upon a disparate array of datasets – including geologic, geodetic, geophysical, and geomorphic data – to present a synthesis of fault activity within the Delta. Because multiple structures within the central and western Delta are continuations of, and/or related to, structures that begin outside of the Delta region, we first summarize regional datasets, and then describe structures to the north and south of the Delta, respectively, before returning our focus to structures within the central and western Delta.

3.1 Regional-Scale Studies

3.1.1 Geodetic Slip Rates

In regional geodesy studies, the Delta is generally assumed to have minimal active deformation. Some geodetic models of fault slip rates either treat Delta faults as effectively inactive (e.g., *d'Alessio et al.*, 2005; *Evans et al.*, 2012) putting the easternmost active fault at the western margin of the Delta region, along the Green Valley and/or Cordelia Faults. However, these block models do not account for residual values of several mm/yr in the Delta (Table 1) (*d'Alessio et al.*, 2005; *Evans et al.*, 2012), indicating that structures in the Delta may actively accommodate a small percentage of total plate boundary motion, both as right lateral displacement and convergence. More recent geodetic models account for these residuals by assigning small magnitudes of slip to Delta structures (Table 1; Figure 3) (*Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022). A regional assessment of geodetic and geologic deformation rates suggests that up to ~5 mm/yr of dextral displacement may be accommodated on structures within the Delta (Figures 2 and 3; Tables 1 and 2), though modeled rates vary widely (Supporting Information, Table SI-1), the density of geodetic observations is low and limited by geographic factors including limited bedrock exposures and extensive anthropogenic modification.

Geodetic data record ~2-5 mm/yr of convergence within the Coast Ranges just north of the Delta (e.g., *Prescott et al.*, 2001), and ~2 mm/yr of shortening approximately normal to the plate boundary system across the Concord Fault along strike to the south (*Graymer and Langenheim*, 2021; *Graymer and Simpson*, 2012). Geodetic block models report similar

Table 2 – Geologic fault slip rates in the Delta region, northern California. NSHM23 refers to the 2023 National Seismic Hazard Model (*Petersen et al.*, 2023).

Fault name	NSHM23 ID #	Geologic Rate		NSHM23 Geologic Rate (*Hatem et al.*, 2022)	
		rate	Quaternary kinematics	rate	rake
Mysterious Ridge section (GVFS)	97	∼	reverse (f)	1.0-5.0	(undefined)
Dunnigan section (GVFS)	98	∼	reverse (g)	0.2-1.0	(undefined)
Trout Creek section (GVFS)	99	∼	reverse (g)	1.0-5.0	(undefined)
Gordon Valley section (GVFS)	100	∼	reverse (g)	1.0-5.0	(undefined)
Green Valley	108	1-4 (c)	dextral (c)	1.0-5.0	(undefined)
Los Medanos - Roe Is.	150	∼	reverse (f)	0-0.2	(undefined)
Pittsburg - Kirby Hills Fault	101	∼	oblique dextral reverse (f)	1.0-5.0	(undefined)
Midland Fault	103	0.4 ± 0.2 (e)	reverse (e)	0.2-0.6	dip slip
Concord	44	∼	dextral (c)	1.0-5.4	strike slip
Clayton	38	∼	∼	0.2-1.0	(undefined)
West Tracy	353	0.24 ± 0.04 (a)	reverse (a)	0.2-1.0	(undefined)
Midway	328	∼	∼	0.2-1.0	(undefined)
Black Butte & San Joaquin (GVFS)	105	∼	reverse (b)	0.8-1.2	dip slip

(a) *CA-DWR* (2009); (b) *Gavillot and Meigs* (2021); (c) *Lienkaemper et al.* (2013); (d) *Unruh and Hector* (1999); (e) *Unruh et al.* (2009); (f) *Unruh et al.* (1995); (g) *Unruh and Moores* (1992)
∼ indicates value not reported

residual convergence rates of ~3-5 mm/yr across the Delta and across the eastern margin of the Coast Ranges north of the Delta (e.g., *d'Alessio et al.*, 2005; *Evans et al.*, 2012). *d'Alessio et al.* (2005) argue that that this apparent convergence is a product of modeled fault orientations and suggest that a component of convergence within the eastern Coast Ranges is not required by the geodetic data. However, more recent work by *Simpson et al.* (2012) documents that the North-America-relative trajectory of the Sierra Nevada – Great Valley block is substantively different than the blocks that make up the Coast Ranges, resulting in at least ~2 mm/yr of plate-boundary-normal compression between the Coast Ranges and the Sierra Nevada – Great Valley block. We also note that the recent (Paleogene – present) geologic history along the eastern front of the Coast Ranges clearly records convergence across this boundary, even within the past few million years (after the passage of the Mendocino Triple Junction and the transition to a transform margin) (e.g., *Graymer et al.*, 2002; *Unruh et al.*, 1995). This interpretation is consistent with the larger-aperture synthesis of *Wakabayashi and Smith* (1994), who concluded that active folds and thrust faults along the western Great Valley may accommodate 1-3 mm/yr of plate-boundary-normal shortening.

Studies of vertical deformation within the Delta region use interferometric synthetic aperture radar (InSAR) to document vertical motions primarily driven by changes in groundwater level, which tend to be of greater magnitude than tectonic deformation rates and obscure tectonic signal. In the Delta, regional non-tectonic subsidence rates of up to 10 mm/yr have been documented (*Bürgmann*, 2008). Along the south and north edges of the Delta, tectonic signals can be somewhat better determined; InSAR data from the Mount Diablo region record 0.6 +/- 1.0 mm/yr of uplift (*Bürgmann*, 2008), though the uplift of this region is due to a combination of regional compression and a restraining stepover between the Greenville and Concord Faults. InSAR data also record a region of apparent tectonic uplift east of the Gordon Valley section of the Great Valley Fault system near Vacaville, kinematically consistent with convergence at the surface above this structure (Burgmann, 2008). The apparent rate of uplift reported — ~4 mm/yr — is much greater than expected given the ~2-5 mm/yr convergence rate from GPS-derived block models (e.g., *d'Alessio et al.*, 2005; *Simpson et al.*, 2012; *Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022); however, this may in part result from the selected model geometry and appears to be overprinted by significant seasonal variation driven by fluctuation in groundwater levels (*Bürgmann*, 2008).

3.1.2 Modern and Historic Seismicity

Modern seismicity within the Delta is sparse, widely distributed, and does not clearly define any mapped structures, with only a few identifiable zones of seismicity around the western edge of the Montezuma Hills and the northeast flank of Mount Diablo (*Wong et al.*, 2010) (Figure 2). Unlike further west in the Pacific-North America plate boundary system, there are relatively few shallow (<~10 km depth) events within the Delta. Deeper (>10 km) seismicity follows a broad north-south-trending zone, which follows the approximate surface trace of the Pittsburg-Kirby Hills Fault and has led to interpretations of the Pittsburg-Kirby Hills Fault as a steeply east-dipping fault that cuts through both the sedimentary section and underlying basement (*Parsons et al.*, 2002). How this proposed fault within the basement relates to, or interacts with, the Paleogene- to Quaternary-active Pittsburg–Kirby Hills Fault near the surface is not clearly answered by seismicity datasets.

Additional seismicity beneath the Delta, including a cluster of hypocenters to the west of the Pittsburg-Kirby Hills Fault and south of the Potrero Hills, are more difficult to directly attribute to structures that reach the surface. Focal mechanisms for seismicity within this system, particularly along the Pittsburg-Kirby Hills Fault and related structures, are consistent with right-lateral displacement on NNW-striking subvertical planes (*Parsons et al.*, 2002). We note that this seismicity occurs well below the base of the ~5- to 8-km-thick sedimentary section (*Parsons et al.*, 2002), and thus the kinematics may not be representative of strain accommodation at shallower depths. This deep seismicity exhibits a broad southward-shallowing trend, from an average depth of greater than 20 km at the latitude of Potrero Hills to as shallow as 15 km at the latitude of Antioch (*Weber-Band et al.*, 1997; *Parsons et al.*, 2002).

Several earthquakes in the central Delta, beneath the northwestern Montezuma Hills, have focal mechanisms consistent with thrust displacement on west to west-northwest striking, shallowly dipping planes (*Wong*, 1990; *Parsons et al.*, 2002). These focal mechanisms are kinematically compatible with dextral displacement on the orthogonal NNW-striking subvertical faults, and with the apparent uplift of the Montezuma Hills, though the depth of hypocenters (nearly all > 15 km) makes it unlikely that they are directly related.

3.2 Subregions

In the following sections, we summarize the current understanding of faults within the Delta region, organized by geographic subregion (Figure 3). In addition to faults, we also include 'seismic source zones,' which have been described by seismic hazard assessments within the Delta and encompass regions that present incomplete or qualitative evidence of active deformation that is difficult to assign to a specific structure (e.g., *CA-DWR*, 2009; *Wong et al.*, 2010, 2022). We follow this definition and use the term 'source zone' to describe an area without a clear, discrete fault trace at the surface that nonetheless has been interpreted as a potential seismic source.

3.2.1 Northern Delta and Southern Sacramento Valley

The southern Sacramento Valley and northern Delta are host to several significant faults, most notably multiple sections of the Great Valley Fault System, which parallel the western margin of the Sacramento Valley north of the city of Fairfield (Figure 1). To the east of the Great Valley Fault System, within the Sacramento Valley and northern Delta, a series of low hills follow the surface trace of the Midland Fault. Both the Midland Fault and faults within the Great Valley Fault System extend along strike southward into the western and central Delta.

Great Valley Fault System (Northern Sections)

The Great Valley Fault System traces the rangefront of the Coast Ranges along the western margin of the Sacramento and San Joaquin valleys (Figures 2 and 4). This system is a significant structure in southern Sacramento Valley and northern Delta regions. We note that its significance extends to the southern Delta (section 3.2.2) and San Joaquin Valley, but address the structural system here in its entirety.

The western margin of the Central Valley of California is defined by a marked transition in both geomorphology and in exposed bedrock geology (Figure 1): the rugged and steep Coast Ranges are made up of ophiolite, tectonic mélange, and marine rocks primarily Jurassic, Cretaceous, and early Paleogene in age, while the low-relief Central Valley has much more limited exposure of poorly lithified, primarily terrestrial Neogene and Quaternary strata. This boundary is interpreted as one of tectonic significance, dubbed the "Coast Ranges-Sierran block boundary zone" (CRSB) (*Wong et al.*, 1988; *Wong*, 1990). The CRSB, as originally defined, is a seismotectonic boundary represented by a zone of seismicity, along with compressional and right-lateral deformation, that follows the eastern edge of the Coast Ranges for nearly the entire length of the Sacramento and San Joaquin valleys (*Wong et al.*, 1988). As originally defined, the CRSB is continuous through the Delta.

The Great Valley Fault System follows the broad trend of the CRSB (Figures 1 and 4). At a crustal scale, this system is east-vergent and west dipping and typically blind, and is represented at the surface by a series of largely west-vergent thrust faults. The system is subdivided into a series of rightward-stepping en-echelon sections (Figure 4a); northwestward from the Delta, these include the Trout Creek and Gordon Valley sections (*Unruh and Sundermann*, 2006). South of the Gordon Valley section, structures directly attributed to the Great Valley Fault System are notably absent within the Delta itself. The Great Valley Fault System resumes to the south of the Delta as the Midway, Black Butte, and San Joaquin Faults. Topographic expression also changes character at the latitude of the Delta; the Coast Ranges found along the western margin of the Sacramento and San Joaquin Valleys to the north and south of the Delta give way to Suisun Bay and a series of smaller, structurally-defined hills north of Mount Diablo and the Sacramento River. Apparent growth strata – westward thinning and steepening of bedding - within Neogene units within the English Hills (to the northwest of the Delta) include units as young as the Pliocene Tehama

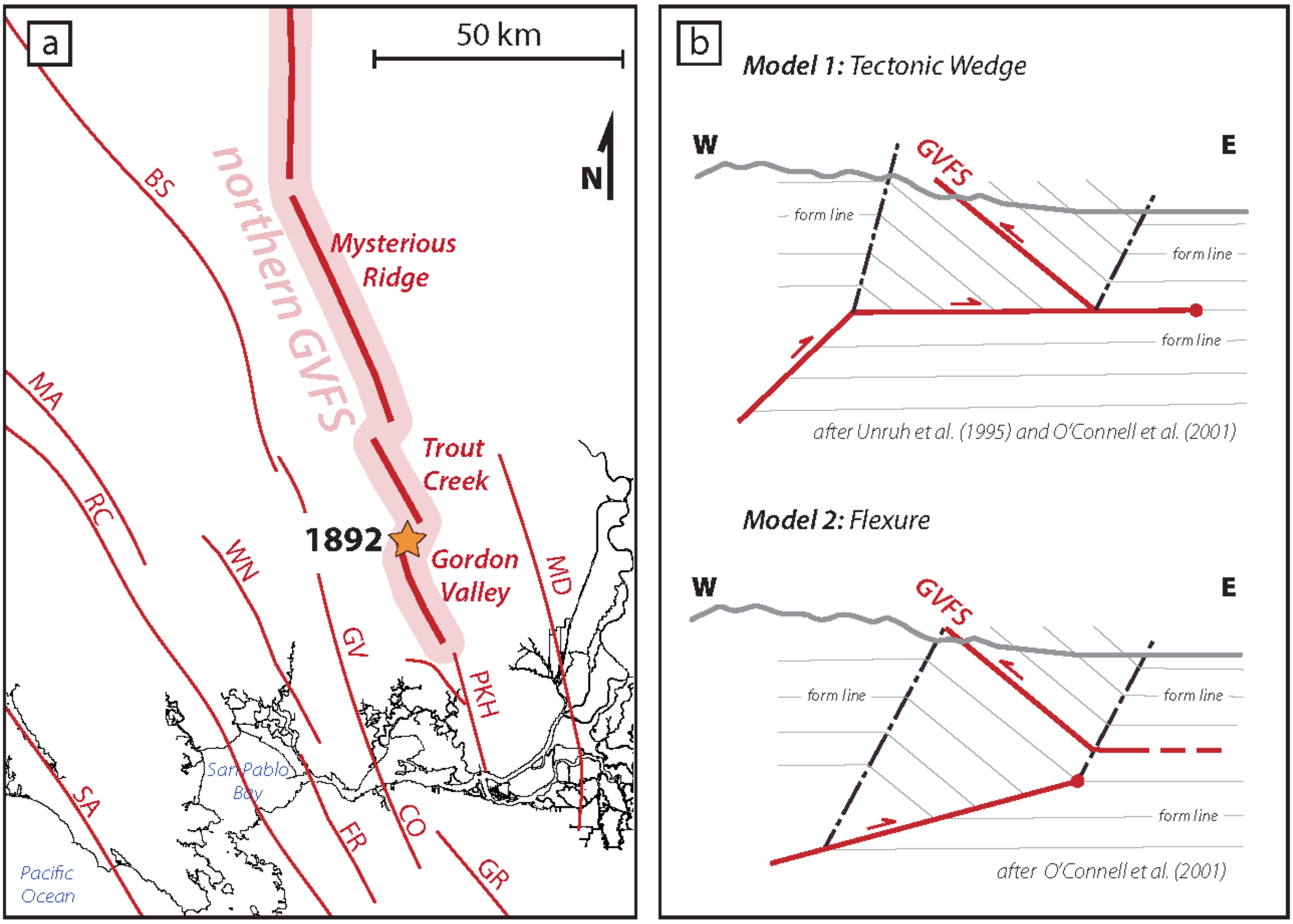

Figure 4 – **(a)** Simplified fault map of the Delta and northern Bay Area. Great Valley Fault System (GVFS) highlighted with bold red line. BS: Bartlett Springs Fault; CO: Concord fault; FR: Franklin Fault; GR: Greenville Fault; GV: Green Valley Fault; MA: Maacama Fault; MD: Midland Fault; PKH: Pittsburg-Kirby Hills Fault; RC: Rodgers Creek - Hayward Fault; SA: San Andreas Fault; WN: West Napa Fault. Yellow star shows the approximate epicenter of the 1892 Vacaville-Winters earthquake sequence. **(b)** Two proposed structural models for the Great Valley Fault System, shown in schematic cross section view.

Formation (*Graymer et al.*, 2002), suggesting that deformation on the Great Valley Fault System — which appears based on bedrock structural geometry to be related to E-W compression — postdates the northward propagation of the Mendocino Triple Junction past this latitude (e.g., *Atwater and Stock*, 1998).

Where it reaches the surface, the Great Valley Fault System is often expressed as a west-vergent, east-side-up thrust fault that emplaces Cretaceous to Paleogene strata of the Great Valley Group in a series of thrust wedges atop Jurassic-age rocks of the Coast Range ophiolite and Franciscan Complex (Figures 1 and 4) (e.g., *Suppe*, 1979; *Unruh et al.*, 1992, 1995; *Wakabayashi and Unruh*, 1995). Elsewhere, the Great Valley Fault System is expressed at the surface as an anticline above a blind fault (e.g., *LCI*, 2022). Multiple models for subsurface fault geometry have been proposed, most of which root into an east-vergent, moderately to shallowly west-dipping reverse or thrust fault at depth beneath the Coast Ranges (Figure 4b) (e.g., *Wentworth et al.*, 1984; *Unruh et al.*, 1992; *O'Connell et al.*, 2001; *Guzofski et al.*, 2007). The Great Valley Fault System is most commonly inferred to reach the surface by way of subsidiary backthrusts atop a thrust wedge, with an associated low-angle detachment tipping out beneath the Central Valley (e.g., *Unruh et al.*, 1992, 1995) (model 1, Figure 4b). This model was first suggested at the southern end of the San Joaquin Valley near Kettleman Hills (*Wentworth et al.*, 1984). A roughly north-south-striking series of low ridges known as Plainfield Ridge and the Dixon Rise, within the North Midland Source Zone in the northern Delta, may represent uplift above the eastern margin of this subhorizontal detachment (Figure 1) (*Unruh et al.*, 1992). A similar structural geometry has been proposed to explain the Dunnigan Hills, a region of uplifted and dissected Quaternary sediments that lie along strike to the north of the Midland Fault and east of the Great Valley Fault System, northwest of the city of Woodland (e.g., *Unruh and Moores*, 1992; *Munk*, 1993).

Along strike to the south, near Coalinga at the south end of the San Joaquin Valley, models derived from interpretation of seismic reflection data have challenged the existence of a subhorizontal detachment beneath the valley, and have questioned the kinematics of the Great Valley Fault System as a whole (e.g., *Constenius et al.*, 2000; *Dickinson*, 2002). However, at least at the latitude of those studies, structural cross sections constrained with surface observations, well-log data, and seismic reflection data are most consistent with the thrust-wedge model (*Guzofski et al.*, 2007).

At the latitude of the Gordon Valley section and northern Delta (Figure 1), an alternative structural model treats the Great Valley Fault System as a set of structures accommodating flexural slip in the forelimb anticline of a fault propagation fold above the tip of a propagating fault at depth (model 2, Figure 4b) (*O'Connell et al.*, 2001). At this latitude, seismic reflection data and geologic observations along the eastern margin of the Coast Ranges are equally compatible with the thrust wedge and flexural slip models (*O'Connell et al.*, 2001). The flexural slip model notably does not require (though may not preclude) the presence of a shallow detachment beneath the western valley, as the tectonic wedge model proposes. The tectonic implications of both models are generally consistent with syntheses of the structure of the Coast Ranges and Franciscan Complex as a whole, which treat the eastern margin of the Coast Ranges as an east-vergent, west-dipping fault at depth that initiated in the Late Cretaceous and remains active into the Quaternary (e.g., *O'Connell et al.*, 2001; *Unruh et al.*, 1995; *Wakabayashi*, 2015).

An 800—m-long seismic survey across the West Winters Strand, which is within the Trout Creek section of the Great Valley Fault System, documents apparent east-side-up offset of shallow strata across a set of relatively high angle (~80° E dip) faults (*Trexler et al.*, 2022) (Figure 5). The tomographic models and reflection image they report reach depths of only 300 m, and more data are required to document whether the steep fault dip is a local or near-surface phenomenon (*Trexler et al.*, 2022). The east-side-up displacement is consistent with geomorphic signatures of surface deformation at this site; however, these results don't clearly distinguish between the two structural models (Figure 4b) (*Trexler et al.*, 2022).

The northern Great Valley Fault System is the likely source structure for the most significant historic seismicity in the Delta region, the 1892 Vacaville-Winters earthquake sequence (19 April 1892 Mw 6.4 and 21 April 1892 Mw 6.2). Reports of damage and shaking are widespread along the eastern front of the Coast Ranges and western Sacramento Valley, from Vacaville north to Esparto, and are the source of moment magnitude estimates (*O'Connell et al.*, 2001) (Figure 1). Observations of ground displacement are inconsistently located and distributed throughout the region of significant shaking, and do not define a discrete rupture trace, suggesting that the rupture may have been blind, and likely occurred on the Gordon Valley section of the Great Valley Fault System just south of the eastward step to the Trout Creek section (*O'Connell et al.*, 2001). The Mw 6.5 1983 Coalinga earthquake has been suggested as a possible modern structural analogue for the 1892 Vacaville-Winters earthquake sequence, due to the similar magnitude and tectonic setting (e.g., *Wong et al.*, 1988; *Wong*, 1990). Based upon a combination of surface and subsurface data, along with interpretation of data from the main shock and aftershocks, the 1983 Coalinga earthquake is interpreted to have occurred with a thrust focal mechanism within a structural system where an east-vergent fault at depth feeds a west-vergent backthrust at shallower crustal levels (*Guzofski et al.*, 2007). This structural model is similar to the *Unruh et al.* (1995) structural cross section across the eastern front of the Coast Ranges ~50 km north of Winters (Figure 4b, model 1), lending credence to this proposed analogue.

Northern Midland Source Zone and Other Potential Seismic Sources

To the east of the Gordon Valley section of the Great Valley Fault System, the northern Midland Fault is divided into several splays that strike north-northwest (*Johnson*, 1992), referred to herein as the Northern Midland Source Zone (Figure 1) (*CA-DWR*, 2009) (the Midland Fault is covered in greater detail in section 3.2.3, below). Subtle (<5 vertical meters, over a spatial scale of tens of meters) topographic highs west of the city of Davis, known as Plainfield Ridge and the Dixon Rise (*Unruh and Moores*, 1992) (Figure 5a and b), correspond with the inferred location of several of these splays of the Midland Fault System (*Johnson*, 1992). The positive topographic expression of these features suggests shortening and uplift, at odds with the normal displacement of Late Cretaceous and Paleogene units at depth on the Midland Fault, including the multiple strands in this zone. These topographic highs may represent deformation above the blind tip of the east-vergent thrust fault that serves as the root of the 'wedge' in the Great Valley Fault System (*Unruh and Moores*, 1992), and/or may result from reverse slip on northern splays of the Midland Fault, similar to the modern reversal of slip direction on the Midland and other Paleogene extensional faults further south in the Delta (e.g., *Weber-Band*, 1998; *CA-DWR*, 2009). The Northern Midland Source Zone may serve to connect and transition strain to structures further north, such as the Dunnigan Hills Fault.

3.2.2 Southern Delta, Northern San Joaquin Valley, and Diablo Range

The northern San Joaquin Valley and southern Delta also host sections of the Great Valley Fault System (covered in more detail in section 3.2.1), which extends from the southern Delta southward along the western margin of the San Joaquin Valley (Figures 1 and 3). In the southernmost parts of the Delta, multiple structures – including the Midway,

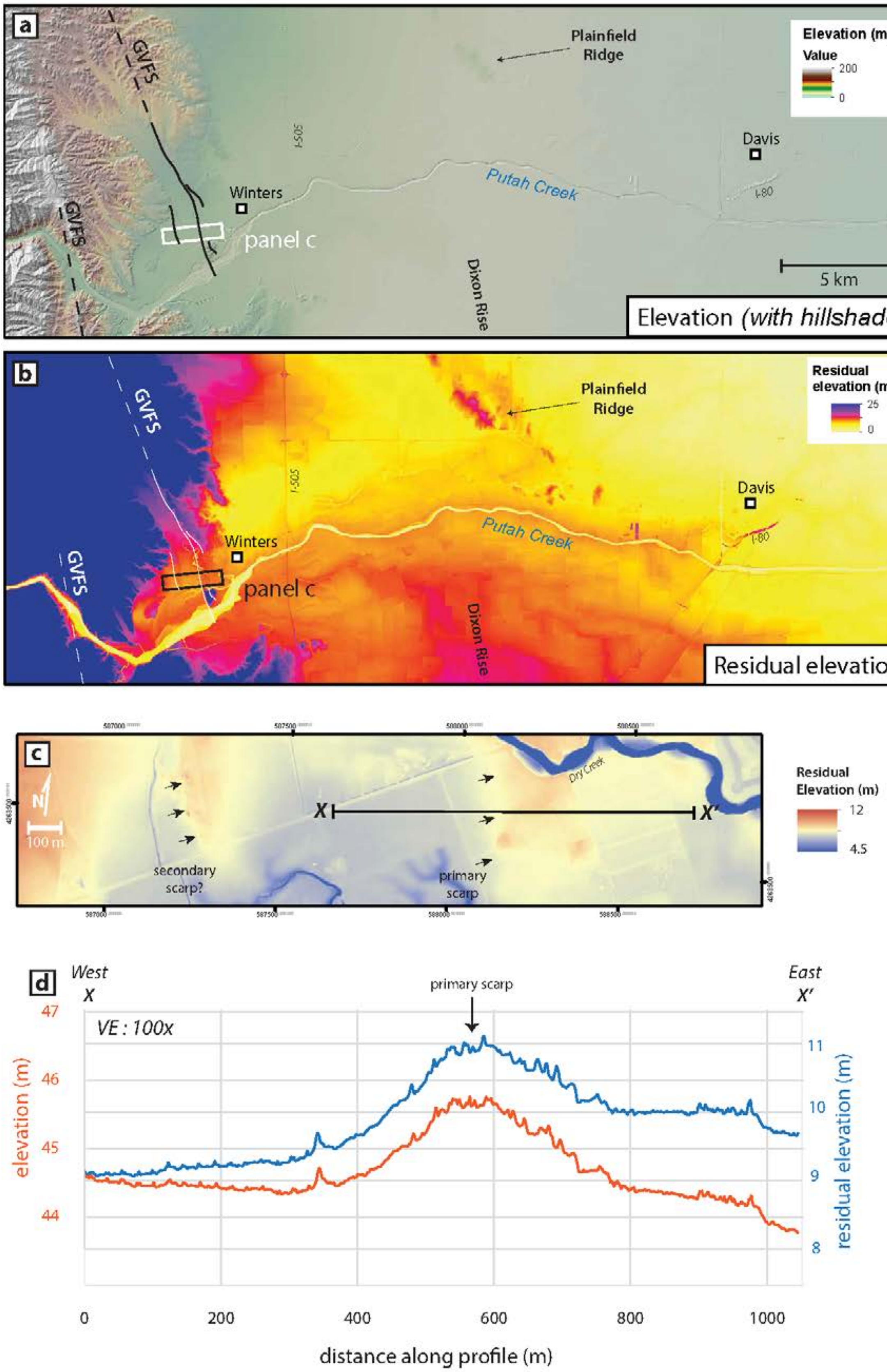

Figure 5 – **(a)** Elevation above sea level and **(b)** residual elevation map (true elevation minus elevation of modeled surface fit to active channel, after *Trexler et al.*, 2022) along Putah Creek, a tributary to the Sacramento River in the northern Delta. Lines represent faults, with dashed lines from the USGS Quaternary Fault and Fold Database (*USGS and CGS*, 2023) and solid lines from *Trexler et al.* (2022). **(c)** Residual elevation map across the West Winters strand of the Trout Creek section of the Great Valley Fault System (from *Trexler et al.*, 2022). Note two low-amplitude (< 2m) scarps in fluvial terrace north of Putah Creek channel. Coordinates are UTM meters (WGS84, UTM Zone 10N). See panels a and b for location. **(d)** Profiles of elevation (red) and residual elevation (blue) along line X-X' across the West Winters Strand of the Great Valley Fault System (see panel (c) for location). Panels (c) and (d) modified from *Trexler et al.* (2022). Digital elevation models derived from 3DEP 1-m topography data.

Black Butte, and San Joaquin faults – likely represent the Great Valley Fault System. In addition, subsurface geophysical data indicate the presence of several bedrock antiforms – the Thornton and Stockton arches – that trend approximately east-west across the northern San Joaquin Valley and may represent potential seismic sources in this region (Figure 1) (e.g., *CA-DWR*, 2009; *Wong et al.*, 2010).

West Tracy Fault

The West Tracy Fault is a southwest-dipping reverse fault or reverse oblique fault several kilometers east of the western valley margin approximately between the towns of Byron and Tracy (Figure 1) (*Unruh and Hitchcock*, 2015). Seismic reflection data suggest that the West Tracy Fault is blind, though a ~1.5-m-high fold scarp striking northwest and located northwest of the Clifton Court Forebay has been attributed to deformation on the West Tracy Fault (*Unruh et al.*, 2009; *LCI*, 2022). A ~1.5-km-long shallow seismic reflection survey across the scarp documents deformation of subsurface units to estimate a slip rate on the fault of ~0.23 ± 0.04 mm/yr (*LCI*, 2022), within the range of slip rates proposed by *Unruh and Hitchcock* (2015). The authors suggest that several small west-vergent, bedding-parallel faults may accommodate flexural slip as east-side-up deformation within the hinge of the fold that produces the scarp; the topographic uplift to the west, however, demonstrates that the root structure is a west-dipping reverse fault, as expected for the West Tracy Fault (*LCI*, 2022).

Great Valley Fault System (Southern Sections)

South of the West Tracy Fault, a series of faults — the Midway, Black Butte, and San Joaquin Faults — together represent the northernmost part of the Great Valley Fault System in the San Joaquin Valley, roughly paralleling the boundary between the Diablo Range and the San Joaquin Valley and accommodating both shortening and dextral displacement in the Holocene (Figure 1) (*Gavillot and Meigs*, 2021). The Black Butte and San Joaquin faults have a combined geologic slip rate of 2.2 – 3.7 mm/yr, with 1.7 – 3.0 mm/yr of shortening (*Gavillot and Meigs*, 2021). The Vernalis Fault is a blind, southwest-dipping fault that runs parallel to the Great Valley Fault System, within the San Joaquin Valley approximately 15 km east of the Black Butte Fault. Little is known about this structure other than its presence in seismic reflection lines (*Sterling*, 1992).

Other Potential Seismic Sources

The southern Delta also contains two recognized potential seismic sources that are less discrete. The Thornton Arch is a large-scale (~10+ km) broadly east-west trending antiform in Eocene strata observed in borehole data, located northwest of the city of Lodi in the Central Valley (Figure 1). Colocated with the antiform, the Mokelumne River makes an approximately 15-km meander to the north between where it exits the foothills of the modern Sierra Nevada foothills and where it enters the San Joaquin River. This apparent diversion in river course has been interpreted as evidence of active growth of the antiform, with rates of deformation that are unconstrained but likely extremely low (< 0.1 mm/yr) (*Wong et al.*, 2010).

The Stockton Arch is a large-scale (~10+ km) east-west trending antiform just south of the city of Stockton (Figure 1). The primary evidence for the Stockton Arch is an angular unconformity, observed in borehole data, that places nonmarine Neogene strata directly atop Great Valley Group at the crest of the fold (*Bartow*, 1991). The Stockton Arch is defined along its north edge by the Stockton Fault, a steeply-south-dipping fault that originated as a normal fault in the Cretaceous before reactivating in the latest Cretaceous or early Paleogene as a reverse fault (*Bartow*, 1991). Displacement of stratigraphy across the fault suggest it was active as recently as the Miocene (*Bartow*, 1991), but there is no evidence of Quaternary activity of either the Stockton Fault or the Stockton Arch.

3.2.3 Western Delta and Confluence: Montezuma Hills and Suisun Bay

At the confluence of the Sacramento and San Joaquin Rivers, drainages from the Sacramento and San Joaquin Valleys meet and flow westward to Suisun Bay before passing through the Carquinez Strait and into San Pablo Bay (Figure 1). The region of the Delta west of the confluence, in particular, is notable for the topographic expression of active deformation: unlike the parts of the Delta to its north, east, and southeast, which have minimal topographic relief (< 10 m), the western Delta is home to the Montezuma, Kirby, and Potrero Hills, which each reach greater than 80 meters above sea level. These large-scale topographic features within the Delta incorporate deformed Neogene and Quaternary stratigraphy. The geographic extent of topographic relief is closely mirrored by the locations of faults within the western Delta (Figure 2), suggesting that these topographic high points are at least in part structurally controlled. The most prominent structures in the western Delta are the Midland and Pittsburg–Kirby Hills Faults, which roughly follow the eastern and western margins, respectively, of the Montezuma Hills.

Seismicity datasets within the central Delta suggest a slight northward dip of the contact between the sedimentary section and Sierran basement, which is likely at ~10 km depth (e.g., *Parsons et al.*, 2002). Topographic evidence of vertical displacement observed along faults at the surface does not correlate well with seismicity at depth, which is concentrated at 15 – 25 km depth (and thus inferred to be within Sierran basement) and exhibits a mixture of strike-slip and dip-slip focal mechanisms (*Parsons et al.*, 2002). Prior work has interpreted the discrepancy between deformation patterns at the surface and focal mechanisms at depth as the result of 'vertical partitioning,' allowing for transform displacement at depth while the surface behaves somewhat independently (e.g., *Jones et al.*, 1994; *Weber-Band et al.*, 1997).

Midland Fault

The Midland Fault is an approximately north-south striking, steeply west-dipping fault that extends from the latitude of the city of Dixon southward through the city of Rio Vista, as far as the town of Byron (Figure 1). The Midland Fault divides into a series of northwest-trending splays at its north end (*Johnson*, 1992) (see section 3.2.1) and defines the east edge of the Late Cretaceous to Paleogene Rio Vista basin, an extensional basin and depocenter within the forearc of the convergent plate boundary system. The Midland Fault initiated during the Late Cretaceous (*Johnson*, 1992), and borehole and seismic reflection data record normal displacement and growth strata within Late Cretaceous and Paleogene strata across the structure (*Johnson*, 1992; *Krug et al.*, 1992). Stratigraphic displacements across the Midland Fault constrained by borehole observations suggest that extension across the structure appears to have ceased during the Oligocene (*Johnson*, 1992). South of the Sacramento River, the west-dipping Midland Fault displaces Holocene peat deposits, which record apparent west-side-up motion (*Unruh et al.*, 2009), opposite the apparent normal displacement of Cretaceous and Paleogene units across the structure. This Neogene-through-Quaternary, west-side-up relationship is also apparent in seismic reflection lines and boreholes north of Sacramento River (*Johnson*, 1992; *Krug et al.*, 1992). At its south end, the Midland Fault truncates against the Brushy Creek Fault, a structure that is not considered active in the Quaternary Fault and Fold Database (QFFD) (*USGS and CGS*, 2023). The Brushy Creek Fault may join the Marsh Creek Fault, which is included in the QFFD as part of the Greenville Fault system, but direct evidence of activity on the Marsh Creek Fault in the Quaternary is lacking. The Midland Fault has no Neogene offset south of the West Tracy Fault.

Vertical separation rates across the southern Midland Fault on the eastern margin of the Montezuma Hills, inferred from displacement in buried eolian deposits, are 0.1–1.2 mm/yr, though fault slip rates could be higher if slip is oblique (*Unruh et al.*, 2009). Structure contour and isopach maps of Holocene peat deposits in the Delta southeast of the Montezuma Hills suggest west-side-up relief across the Midland Fault (*Unruh et al.*, 2009). *Unruh et al.* (2009) document 2.4 $\pm$ 1.3 m of vertical separation across the southern Midland Fault and estimate a rate of 0.4 $\pm$ 0.2 mm/yr based on radiocarbon age control from the base of the peat deposits (*Unruh et al.*, 2009). South of the Sacramento River, seismic reflection data are interpreted to show that the Quaternary Montezuma Formation is folded over the buried Midland Fault with a west-side-up geometry, indicating approximately 200 meters of reverse displacement since the deposition of that unit (*Weber-Band*, 1998). Smaller, buried structures between the Pittsburg-Kirby Hills Fault and the Midland Fault do not appear to reach the surface and are not expressed in the geomorphology (*Unruh*, 2021).

Pittsburg-Kirby Hills Fault

The Pittsburg-Kirby Hills Fault is an approximately north-south striking, steeply-east-dipping fault that defines both the western margin of the Late Cretaceous to Paleogene Rio Vista basin and the modern Montezuma Hills (Figures 1 and 2). The Pittsburg-Kirby Hills Fault stretches northward from Pittsburg, on the south side of the Sacramento River, and parallels the western margin of the Montezuma Hills at least as far north as Fairfield. At this latitude, a prominent westward splay – the Potrero Hills Thrust (c.f. *Unruh and Sundermann*, 2006) – forms the Potrero Hills Anticline. Similar splay faults exist in the subsurface beneath Van Sickle Island, and an eastward splay may also follow the linear NNW-SSE trending margin of the southwestern Montezuma Hills between the towns of Birds Landing and Collinsville; however, this strand is not currently included in the QFFD (*USGS and CGS*, 2023). The along-strike projection of the Pittsburg-Kirby Hills Fault extends northward into the Coast Ranges at the northern margin of the Delta just west of the city of Vacaville, at approximately the same location as the southern limit of the Gordon Valley section of the Great Valley Fault System.

Various names exist in the literature for faults along the western margin of the Montezuma Hills, including the Vaca Fault (*Wong et al.*, 1988) and the Kirby Hills Fault System (*Krug et al.*, 1992). These names are mostly used interchangeably, though some works use specific names to differentiate between the extensional fault that bounds the Rio Vista basin and the late Cenozoic dextral/reverse fault that defines the northwestern margin of the Montezuma Hills (the "Pittsburg-Kirby Hills Fault" of *Weber-Band*, 1998; *Unruh and Hector*, 1999; *Unruh*, 2021). As those authors indicate, the modern dextral/reverse fault likely reactivates strands of the Paleogene extensional fault; thus, we treat these as the same structural system and use a single name, the Pittsburg-Kirby Hills Fault.

Within the Delta, the Pittsburg-Kirby Hills Fault is moderately-steeply east-dipping and may root into the same basal detachment as the Midland Fault (*Weber-Band et al.*, 1997). Like the Midland Fault, the Pittsburg-Kirby Hills Fault initiated as a forearc extensional structure in the early Paleogene, and defines the western margin of the Rio Vista basin at that time (*MacKevett*, 1992; *Krug et al.*, 1992). Exposures of the deformed stratigraphic section on the northeastern flank of Mount Diablo suggest that this fault may have a listric geometry at depth (see section 3.3, below) (*Krug et al.*, 1992; *MacKevett*, 1992; *Unruh et al.*, 2007; *Unruh*, 2021). The Pittsburg-Kirby Hills Fault has multiple subsidiary strands, and divides into systems of oblique reverse splay faults in both the north (i.e., the Potrero Hills Thrust) and the south (*USGS and CGS*, 2023). Multiple additional named faults, including the Montezuma Fault (*Krug et al.*, 1992; *Jennings and Saucedo*, 1994) and the Denverton Creek Fault System (*Krug et al.*, 1992) parallel the primary strand of the Pittsburg-Kirby Hills Fault with smaller magnitudes of apparent offset of bedrock units. Collectively, these faults within the greater Pittsburg-Kirby Hills Fault System may behave as a positive flower structure; this kinematic model is supported by geometries in seismic reflection surveys (e.g., *MacKevett*, 1992; *Krug et al.*, 1992) and is consistent with what might be expected along a transpressive strike-slip fault or along marginal faults in an inverted basin (e.g., *Weber-Band*, 1998).

Interpreted cross sections based upon seismic reflection data suggest east-side-up, reverse displacement of the base of the Montezuma Formation across the Pittsburg-Kirby Hills Fault south of the Montezuma Hills, consistent with the sense of displacement suggested by the prominent topographic escarpment that defines the southwestern edge of the Montezuma Hills, but located kilometers to the west of that feature (*MacKevett*, 1992; *Weber-Band et al.*, 1997). The Pittsburg-Kirby Hills Fault extends southward at least as far as the Sacramento River, where interpreted seismic reflection profiles indicated a steeply east-dipping fault with west-side-down displacement and erosional unconformities in strata east of the fault (*Weber-Band et al.*, 1997). Shallow marine seismic reflection data has been collected on E-W profiles along the Sacramento River (e.g., *Hart et al.*, 2002; *Parsons et al.*, 2002; *Klotsko et al.*, 2023), with a particular focus on the vicinity of the Pittsburg-Kirby Hills Fault Zone (*Parsons et al.*, 2002; *Klotsko et al.*, 2023). Reflection profiles show discontinuities in reflectors where both fault zones cross survey profiles and document deformation in the youngest sedimentary rocks in the Pittsburg-Kirby Hills fault zone (*Parsons et al.*, 2002; *Klotsko et al.*, 2023), and the Pittsburg-Kirby Hills Fault may actually deform the floor of the river channel (*Klotsko et al.*, 2023). Reflection data do not conclusively document additional modern structures in the shallow subsurface crossing the survey profiles, and apparent displacement across several minor faults may instead be attributed fluvial processes rather than Quaternary activity (*Klotsko et al.*, 2023). There is no clear surface expression of the Pittsburg-Kirby Hills Fault south of the Sacramento River. Seismicity correlated with the fault zone extends southward along strike as far as the Kirker Fault at the northern end of the Diablo Range (Figure 2), but is sparse and deep (~20km), and not easily correlated with the surface trace of any individual structures (*Parsons et al.*, 2002). Prior studies have suggested that the Kirker fault may in fact be a southward continuation of the Paleogene Pittsburg-Kirby Hills Fault on the northeast limb of the Diablo Anticline (e.g., *Krug et al.*, 1992; *MacKevett*, 1992; *Unruh et al.*, 2007; *Unruh*, 2021); however, no studies argue for Quaternary activity of the Kirker Fault.

To the north of the Delta, some prior work has interpreted that the Pittsburg-Kirby Hills Fault may connect with the Great Valley Fault System (e.g., *Jennings and Saucedo*, 1994), perhaps by rooting into the basal east-directed thrust at depth, while other work has challenged this connection based upon uninterrupted reflectors in interpreted seismic surveys (e.g., *Weber-Band*, 1998). We note that the west-directed backthrusts of the Great Valley Fault System are at a low angle to bedding in both the hanging wall and footwall in this region, thus potentially making identification of displacement in seismic reflection data difficult. Bedrock deformation, recorded in east-dipping Paleogene and Neogene stratigraphy, is present along the Great Valley Fault System from the southern extent of the Coast Ranges to the Montezuma Hills on the north bank of the Sacramento River (*Graymer et al.*, 2002), suggesting the potential for activity on either or both faults. However, the extent to which the Pittsburg-Kirby Hills Fault and Great Valley Fault Systems connect, interact, and/or transfer displacement is unclear. No Quaternary slip-rate estimates have been published for the Pittsburg-Kirby Hills Fault or other structures along the western and southwestern margins of the Montezuma Hills.

Montezuma Hills Source Zone

The Montezuma Hills Source Zone occupies a region that encompasses the southern Montezuma Hills and Sacramento River, between the Pittsburg-Kirby Hills and Midland Faults. Specific fault geometries within the source zone are not well characterized, but the deformation accommodated by structures within the Montezuma Hills Source Zone has been inferred to be responsible for the uplift of the Montezuma Hills (e.g., *CA-DWR*, 2009; *Wong et al.*, 2010). The Montezuma Hills Source Zone is typically modeled as a north-dipping plane striking west-northwest, consistent with gentle north-northeast tilting of stratigraphy, both at the surface and in seismic reflection profiles (e.g., *Weber-Band*, 1998; *Wong et al.*, 2010).

Seismic reflection profiles suggest that the Pittsburg-Kirby Hills Fault and Midland Fault may root into the same basal detachment surface (e.g. *Weber-Band et al.*, 1997), the nature of which is not clearly defined but may dip gently northeastward (e.g., *Wong et al.*, 2010). Additional sets of subsidiary bedrock normal faults also fall within the Montezuma Hills Source Zone and are typically associated with the Paleogene Rio Vista basin (*Krug et al.*, 1992; *Unruh et al.*, 2007; *Unruh*, 2021). These faults, the most prominent of which is the Sherman Island Fault System (Figure 2) (*Krug et al.*, 1992; *Unruh et al.*, 2009) are subparallel to the Pittsburg-Kirby Hills and Midland Faults and appear to be capped by Miocene and younger strata (*Krug et al.*, 1992; *Cherven*, 1983; *Weber-Band*, 1998) and do not reach the surface. As many as a dozen additional smaller structures also create minor offsets in Paleogene strata, but likely do not play a significant role in regional tectonics (*Krug et al.*, 1992; *Unruh*, 2021).

Faults in Suisun Bay and the Sacramento River

Borehole and seismic reflection data suggest that a series of WNW-ESE trending anticlines in Suisun Bay, west of the Pittsburg-Kirby Hills Fault Zone, are underlain by blind thrust faults (Figures 1 and 2) (e.g., *Unruh and Hector*, 1999). *Unruh and Hector* (1999) interpret these thrust faults to accommodate dextral shear between the Concord-Green Valley Fault System to the west and the Pittsburg-Kirby Hills Fault System to the east. They suggest that at least some of these faults may root into the Pittsburg-Kirby Hills Fault System at depth, whereas the Roe Island Fault may be a continuation of the Los Medanos Fault northwestward to the Green Valley Fault. A fault or fault system with similar structural geometry (WNW-ESE striking with a south-directed thrust component, perhaps splaying off a N-S striking structure) has been suggested along the southern margin of the Montezuma Hills (*CA-DWR*, 2009; *Weber-Band*, 1998), oblique to buried Paleogene extensional faults of the Rio Vista basin (*Unruh*, 2021).

Faults south of the Sacramento River

Immediately south of the western Delta, on the south bank of the Sacramento River, the stratigraphic section crosses a synclinal hinge, and the Paleogene stratigraphy that are shallowly east dipping within the Delta to the north are exposed in a moderately northeast-dipping fold limb on the northeastern flank of the Diablo Anticline (Figure 1). This fold limb provides a down-dip view of Late Cretaceous to Paleogene extensional structures that dissect the stratigraphic section, including the Midland and Kirker Faults that define the eastern and western margins of the Rio Vista basin at this latitude (Figures 1 and 2) (*Krug et al.*, 1992; *Crane*, 1995; *Unruh et al.*, 2007; *Unruh*, 2021). These faults are interpreted to root into the Coast Range Fault (*Unruh*, 2021).

The Davis Fault is a normal fault in the hanging wall of the Midland Fault (Figures 1 and 2). The Davis Fault offsets Paleogene and Neogene strata and is included in the QFFD (*USGS and CGS*, 2023), but there is no geomorphic evidence of Quaternary activity. The Davis Fault, along with the Sherman Island Fault north of the Sacramento River, is an antithetical splay of the Midland Fault along the eastern Rio Vista Basin (e.g., *Unruh et al.*, 2007; *Krug et al.*, 1992). The Antioch Fault, a splay of the Davis Fault with apparent right-lateral and/or normal displacement of bedrock units, runs northwest from the Davis fault through the city of Antioch. Anecdotal evidence of Quaternary activity, including potential creep, has been reported, but evidence of Quaternary slip on the Antioch Fault remains inconclusive (*Burke and Helley*, 1973). The Antioch Fault is not considered active in the QFFD (*USGS and CGS*, 2023).

The Kirker Fault strikes north–south and is typically considered to be the along-strike continuation of the Pittsburg-Kirby Hills Fault that defines the western margin of the Rio Vista basin (Figure 2) (*Krug et al.*, 1992; *MacKevett*, 1992; *Unruh et al.*, 2007). The Kirker Fault has apparent right-lateral displacement in map view, and offset of stratigraphic markers is consistently east-side down (*Unruh et al.*, 2007). The Kirker Fault offsets the base of the Pliocene Lawlor Tuff with about 300 m of apparent right-lateral displacement, but does not offset the overlying Pliocene Tehama Formation, and therefore is not considered Quaternary active. Several Tertiary units east of the fault are absent west of the fault, suggesting syndepositional deformation.

The Los Medanos Fault is a northwest-striking, northeast-dipping thrust fault located to the west of the Antioch, Pittsburg-Kirby Hills, and Kirker Faults (Figure 2). The Los Medanos Fault has been active in the Quaternary, based on deformation of Pleistocene stratigraphy in its footwall and geomorphic evidence of uplift of the Los Medanos Hills on the south bank of the Sacramento River. Similarly oriented structures within Suisun Bay, including the Roe Island Fault, appear to be the northward continuation of the Los Medanos Fault and also appear to be active in the Quaternary (*Weber-Band et al.*, 1997; *Unruh and Hector*, 1999). The Los Medanos Fault merges with, or is truncated by, the Concord Fault to the northwest. Both the Kirker Fault and the Los Medanos Fault root into the Clayton-Marsh Creek Fault System to the south (*Unruh et al.*, 2007; *Graymer and Langenheim*, 2021), which may represent, or reactivate, the basal detachment for the Late Cretaceous to Paleogene extensional graben system (*Crane*, 1995; *Unruh et al.*, 2007). In the modern tectonic regime, the Clayton and Marsh Creek Faults may connect to the northern end of the Greenville Fault System (e.g., *Medwedeff*, 2021), but the Quaternary activity of the Clayton and Marsh Creek Faults remains unconstrained.

4 Geomorphologic Evidence of Active Tectonic Deformation in the Western and Central Delta

Here we present two case studies — structures associated with the Montezuma Hills, and the northern Great Valley Fault System — that illustrate the complex role that the geologic history and evolving tectonic setting play in the manifestation of active deformation within the Delta. We focus specifically on these structures due to their geomorphic expression, which in each case both suggests Quaternary activity and provides insights into the fault geometry and kinematics of active deformation on these structures.

4.1 Pittsburg–Kirby Hills Fault System, Midland Fault, and Montezuma Hills

4.1.1 Geomorphic Indicators of Active Tectonic Deformation

Within the Delta, geomorphology provides ample evidence of active deformation at both local and regional scales, but surface deformation is often long wavelength (tens to hundreds of meters) and low amplitude (meters) (Figure 5). This deformation is clearly visible in residual elevation maps (Figure 5a) (e.g., *Trexler et al.*, 2022), but is difficult to quantify on the ground.

Recently released 1-meter-resolution lidar topographic data provides an opportunity to document signals of surface deformation across a variety of spatial scales and provides some insight into the kinematics and rates of deformation on source structures. Clear signals of active deformation are present in the geomorphology along a transect that follows Pittsburg-Kirby Hills Fault, and along-strike sections of the Great Valley Fault System to its north, from the eastern front of the Coast Ranges near the city of Winters south to the Montezuma Hills and Sacramento River. Most major channels draining eastward from the Coast Ranges, including Putah Creek, Pleasants Creek, and Ulatis Creek, appear to be antecedent to local topography (Figures 2 and 6), and form water gaps through ridges of Paleogene and Neogene bedrock. Farther south, channels between Vacaville and Suisun City, including along Denverton Creek, exhibit similar geomorphic patterns as they cross the northern Pittsburg-Kirby Hills Fault System (Figure 7). At Denverton, a water gap – an active channel that is surrounded by, and antecedent to, localized uplift – is visible in regional bedrock geologic maps (*Graymer et al.*, 2002) to the northwest of the Montezuma Hills. In this location, Denverton Creek incises a channel through an anticline of Miocene and Pleistocene bedrock, apparently deformed in the hanging wall of the Pittsburg-Kirby Hills Fault (Figure 7).

The most topographically prominent features in the Delta are the Potrero Hills and Kirby Hills, both of which reach elevations of 90 meters above base level in an otherwise extremely low-relief landscape (Figures 2 and 6), and are almost completely surrounded by tidal slough. Bedrock in the Potrero and Kirby Hills is Paleocene to Pliocene in age and extensively deformed (*Graymer et al.*, 2002). Bedrock map patterns in the Potrero Hills, specifically, define an east-west striking anticline with moderate to steep bedding dips on both limbs and a north-vergent blind thrust fault along its northern edge (*Graymer et al.*, 2002). Locally overturned bedding in the south limb also suggests the presence of a south-directed blind thrust fault defining the southern margin of the anticline. Within the Kirby Hills, bedrock units strike north-northwest and are primarily moderately to steeply west dipping, though dip direction varies (*Graymer et al.*, 2002). The Kirby Hills are typically interpreted as uplifted blocks within a positive flower structure along the Pittsburg-Kirby Hills Fault (e.g.„ *MacKevett*, 1992).

The Montezuma Hills, east of the Potrero and Kirby Hills and north of the Sacramento River, also reach elevations of ~90 m above base level at their highest points (Figure 6). Unlike the Kirby and Potrero Hills, whose steep slopes are readily explained by exposed bedrock faults and folds, the Montezuma Hills are a broad region (~20 km by ~20 km) of more subtle topography, characterized by incised fluvial channels and relatively flat hilltops. Exposed bedrock on the western edge of the Montezuma Hills is shallowly to moderately eastward-dipping and Eocene to Pliocene in age (*Graymer et al.*, 2002), suggesting that deformation has occurred since that time. A younger unit — the Montezuma Formation — is mapped but is not clearly exposed in the field, and does not provide structural orientation data. Seismic reflection data suggest that the younger units are generally very gently ENE-dipping in angular unconformity on the underlying Neogene strata (*MacKevett*, 1992).

The geomorphology of the Montezuma Hills is asymmetric, particularly from northeast to southwest (Figure 6b). The northeastern Montezuma Hills slope gently northward, with wide (i.e., 100+ meters), shallow drainages (~10 meters deep) flowing NNE. The southern and western Montezuma Hills, by contrast, are characterized by relatively deeply incised (multiple tens of meters) fluvial channels between comparatively low relief hilltops. Particularly in the southwestern Montezuma Hills, first-order streams feeding the deeply incised channels often exhibit convex profiles, with relatively low-gradient upper reaches before steepening near their confluence with the main channel (Figure 6b). The low-relief hilltops appear correlated to one another and may represent a relict Pleistocene surface that has been uplifted, deformed, and subsequently dissected by erosion along the south and west flanks of the Montezuma Hills (*Unruh et al.*, 2009; *Trexler*, 2020) (Figure 6).

At least three channels in the western Montezuma Hills are continuous across the drainage divide and have been interpreted as wind gaps — channels formed by previously throughgoing waterways that have since been abandoned, in this case most likely as a result of tectonic uplift (Figure 6a) (*Philibosian et al.*, 2022). Channel morphology suggests that these wind gaps may represent meandering former distributary channels of the Sacramento River; in this model, the preserved surface in the southern Montezuma Hills may represent a relict uplifted estuarine delta system analogous to the modern Suisun Bay (*Philibosian et al.*, 2022).

The Montezuma Hills are abruptly truncated on the south and east flanks by the westward-flowing Sacramento River (Figure 6a). A similarly abrupt margin on the southwestern flank of the Montezuma

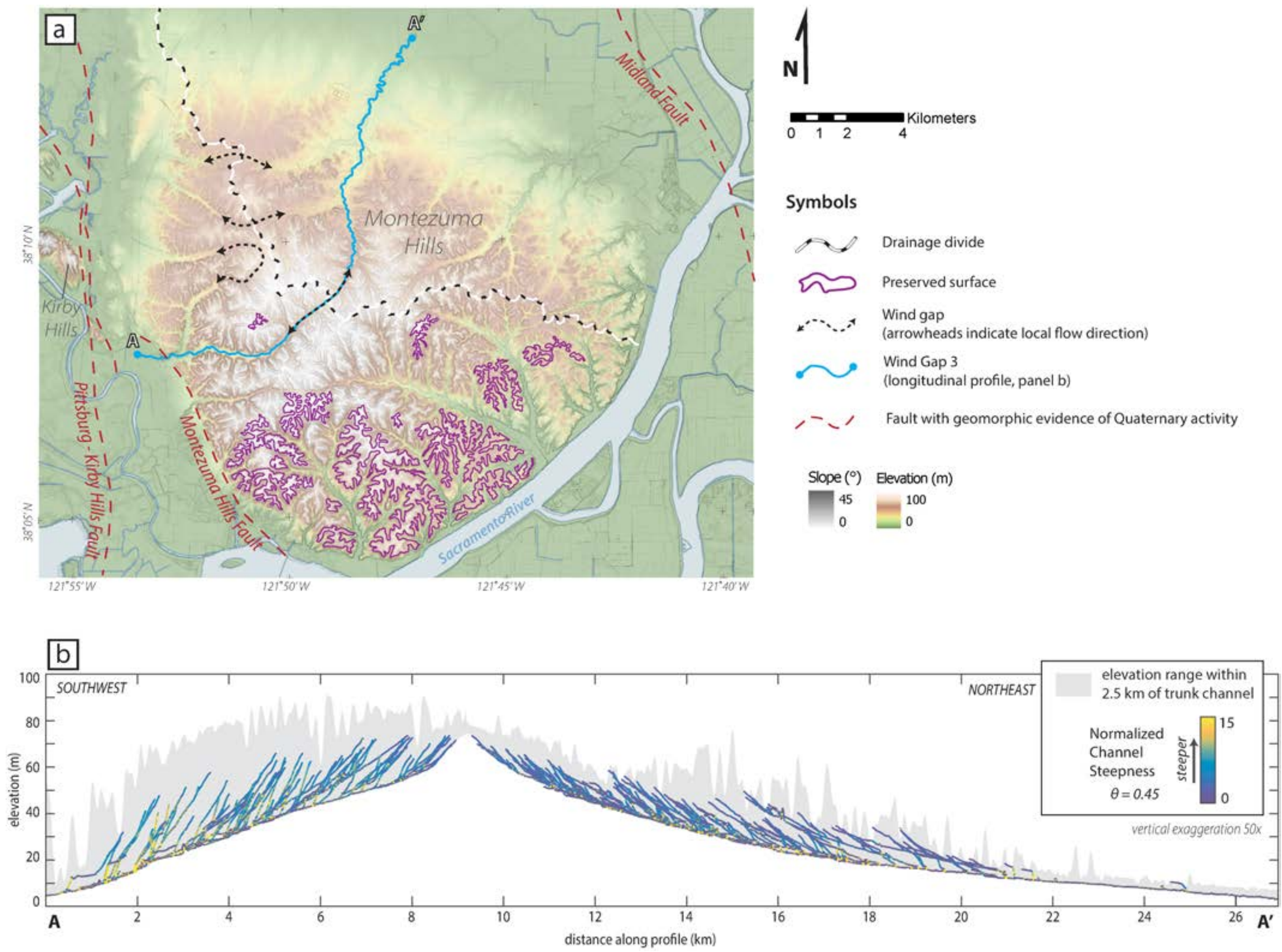

Figure 6 – **(a)** Digital elevation model of the Montezuma Hills, showing drainage divide, apparent wind gaps, and interpreted preserved surface. Inferred preserved surfaces manually mapped on 2-m slope map; mapping criteria include slope < 5 degrees, steepening break in slope on all sides, and convex geomorphology to filter out valley floors and anthropogenic modification. Elevation data and slope map derived from USGS 3DEP 1-m topography data. **(b)** Longitudinal profile of a channel and tributaries across a wind gap in the Montezuma Hills. Profile color coded by channel steepness, normalized to a reference concavity of 0.45. Grey shading shows elevation range within a 5-km-wide swatch centered on the trunk channel.

Hills diverges from the modern river channel, and is not as easily attributed to fluvial erosion. This topographic scarp, which stretches from the town of Birds Landing to the town of Collinsville, is subparallel to the Pittsburg-Kirby Hills Fault zone, raising the possibility that it may be tectonic in origin.

4.1.2 Known Structures

The Montezuma Hills occupy the central part of an uplifted tectonic block defined to the east and west by the Midland and Pittsburg-Kirby Hills Faults, which exhibit normal displacement in Paleogene strata and apparent reverse or reverse-oblique strike-slip displacement in the Quaternary. Neither kinematic mode is consistent with a simple picture of the modern tectonic regime, where both bounding structures strike approximately north-south, parallel with right-lateral faults elsewhere in the San Andreas system. However, reverse slip is consistent with apparent compression perpendicular to the San Andreas Fault System, between the Sierra-Great Valley block and blocks to the west, shown in GPS data. Both structures bounding the structural block containing the Montezuma Hills are high-angle, making reverse dip-slip displacement not particularly favored.

Both geomorphology and subsurface geophysical imaging data contribute addition details to patterns of Quaternary uplift of the Montezuma Hills. *Weber-Band* (1998) notes the apparent uplift of the Montezuma Hills in the hanging wall of the Midland and Pittsburg-Kirby Hills Faults and observes an unconformity in seismic reflection data (interpreted therein to represent the base of the Montezuma Formation) that dips 2 degrees northeast within the Montezuma Hills block. Assuming this marker was originally subhorizontal, this tilt suggests asymmetric uplift of that part of the block at least since the formation of that unconformity surface at 1.0 ± 0.5 Ma (*Weber-Band*, 1998; *Wong et al.*, 2010). The geologic controls on this asymmetric uplift are not well described, and geographic patterns in uplift rate may be attributed to differences in uplift rate, timing, or both.

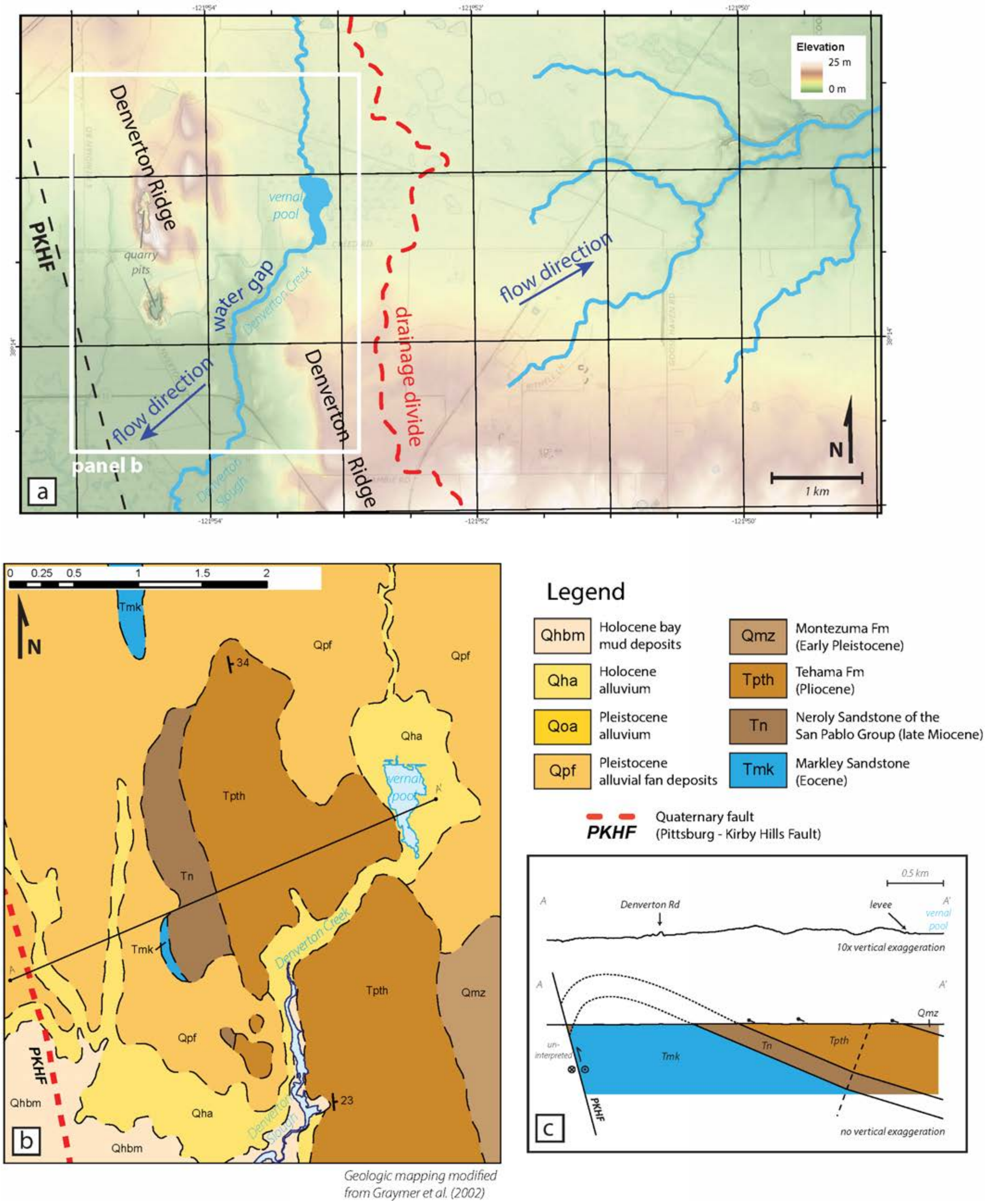

Figure 7 – **(a)** Digital elevation model of the water gap on Denverton Creek, northwest of the Montezuma Hills. PKHF: Pittsburg-Kirby Hills Fault. **(b)** Geologic map of the Denverton water gap, modified from *Graymer et al.* (2002). **(c)** Topographic profile (top) and model geologic cross section (bottom) across the bedrock fold at Denverton Creek. Bedrock orientation data from *Graymer et al.* (2002).

In detail, geomorphology of individual sites within the western Delta is somewhat more complex. For example, the Kirby Hills, which lie within the Pittsburg–Kirby Hills Fault zone to the west of (and topographically separated from) the Montezuma Hills, appear based on geomorphology and subsurface well and geophysical datasets to be a positive flower structure with down-to-the-east displacement across the easternmost strand (e.g., *Unruh and Hector*, 1999). This appears inconsistent with the larger-scale model of east-side-up displacement across a structure defining the western margin of the Montezuma Hills, suggesting that the Pittsburg–Kirby Hills Fault (or at least the strand of it that defines the Kirby Hills themselves) may not be the structure that defines the western margin of Montezuma Hills uplift.

4.1.3 "Missing" Structures: Explaining Uplift of the Montezuma Hills

Recent work on bedrock structures on the northern flank of the Diablo Anticline to the south of the Delta may offer a structural analogue for deformation within the Delta itself. On the northern limb of the Diablo Anticline, bedrock normal faults displace Paleogene units to form extensional basins which root into detachment structures associated with the Coast Range Fault (e.g., *Unruh et al.*, 2007; *Unruh*, 2021). These entire deformed packages were subsequently folded and uplifted onto the limb of the Diablo Anticline (e.g., *Unruh et al.*, 2007; *Unruh*, 2021). In this interpretation, the north-south striking, steeply dipping normal faults formed as structures associated with extensional basin(s) in the Late Cretaceous-to-Paleogene forearc. Following the passage of the Mendocino Triple Junction and reorganization of the plate boundary as a transform system, the basin-bounding normal faults were reactivated as (or overprinted by) structures accommodating dextral plate-boundary-parallel deformation. The detachment into which the extensional basin structures rooted may, too, have reactivated in the new tectonic regime. Regional folding associated with the Diablo Anticline has given the strata and associated structures a gentle northward dip, making this proposed reactivated basal detachment a gently north-dipping, south-vergent thrust.

We propose an updated model of Montezuma Hills deformation in which the Montezuma Hills block may behave similarly. In our proposed model, the Montezuma Hills block is defined on its west and east by oblique-reverse faults (to the west either the Pittsburg–Kirby Hills Fault or a structure more closely aligned with the western margin of the Montezuma Hills, and to the east the Midland Fault) accommodating uplift, and perhaps southward translation, of the Montezuma Hills block relative to the Coast Ranges and tectonic blocks to the west (Figure 8). While not favorably oriented in the current tectonic regime, these faults are pre-existing structures with a long history of motion (e.g., *MacKevett*, 1992; *Krug et al.*, 1992). Reactivation of an existing fault may be more mechanically favorable than breaking new optimally oriented faults. This modern kinematic regime is thus the latest stage in the evolution of the Pittsburg-Kirby Hills Fault System (along with associated structures, including the Midland Fault), which appears to have accommodated normal, strike-slip, and reverse displacement at different points in its geologic history (e.g., *MacKevett*, 1992; *Krug et al.*, 1992).

In our proposed model, the Montezuma Hills block is being translated southward, up onto the north-dipping flank of the Diablo Anticline, via either northward propagation of deformation associated with the northern limb of the Mount Diablo Anticline, and/or a west-northwest striking south-vergent thrust between the southern margin of the Montezuma Hills and the northern flank of Mt Diablo (Figure 8). A fault similar to the latter fault has been proposed previously as a potential seismogenic structure within the Montezuma Hills Source Zone (*CA-DWR*, 2009), but it has not been mapped. We note that its likely trace runs subparallel to and possibly beneath the Sacramento River, limiting potential for geomorphic expression of the fault. Such a structure is not clearly expressed in seismic reflection surveys that follow the river channel (e.g., *Parsons et al.*, 2002; *Klotsko et al.*, 2023), but we note that the acute angle between proposed west-northwest fault strike and approximately east-west survey profile orientations the proposed structures might obscure any apparent displacement.

In addition to the north-to-south asymmetry in the geomorphology of the Montezuma Hills, west-to-east asymmetry suggests that uplift rate on structure(s) west of the Montezuma Hills may be comparatively higher than on structures to the east (Figure 6b). The sharp western margin of the Montezuma Hills is not quite geographically coincident (or kinematically consistent) with mapped strands of the Pittsburg–Kirby Hills Fault near Montezuma Slough 3 km west (Figure 6a), suggesting the presence of an additional active structure that may define the western margin of the Montezuma Hills block at the surface. This hypothesized structure, which we refer to as the Montezuma Hills Fault (Figure 8), has been previously suggested by prior workers (e.g., *Weber-Band*, 1998; *CA-DWR*, 2009) but is not included in the current Quaternary active fault database (*USGS and CGS*, 2023). We suggest that apparent uplift across this structure may be the result of a combination of reactivation of Paleogene Rio Vista Basin structures (including, though perhaps not limited to, the Pittsburg–Kirby Hills Fault), and flexural slip as stratigraphy is folded on the north flank of the Diablo Anticline. The latter mode of deformation may be particularly apparent where the strike of the proposed Montezuma Hills Fault is WNW-ENE and approximately parallel to bedding (Figure 8). We do note, however, that this flexural slip model is not the only viable kinematic explanation; indeed, other faults with similar strike orientations appear to crosscut bedding and appear to simply represent the southward continuation of Rio Vista Basin-associated high-angle faults (e.g., the Roe Island fault; *Medwedeff* , 2021, section C-C', Figure 8).

The Midland Fault, on the eastern edge of the

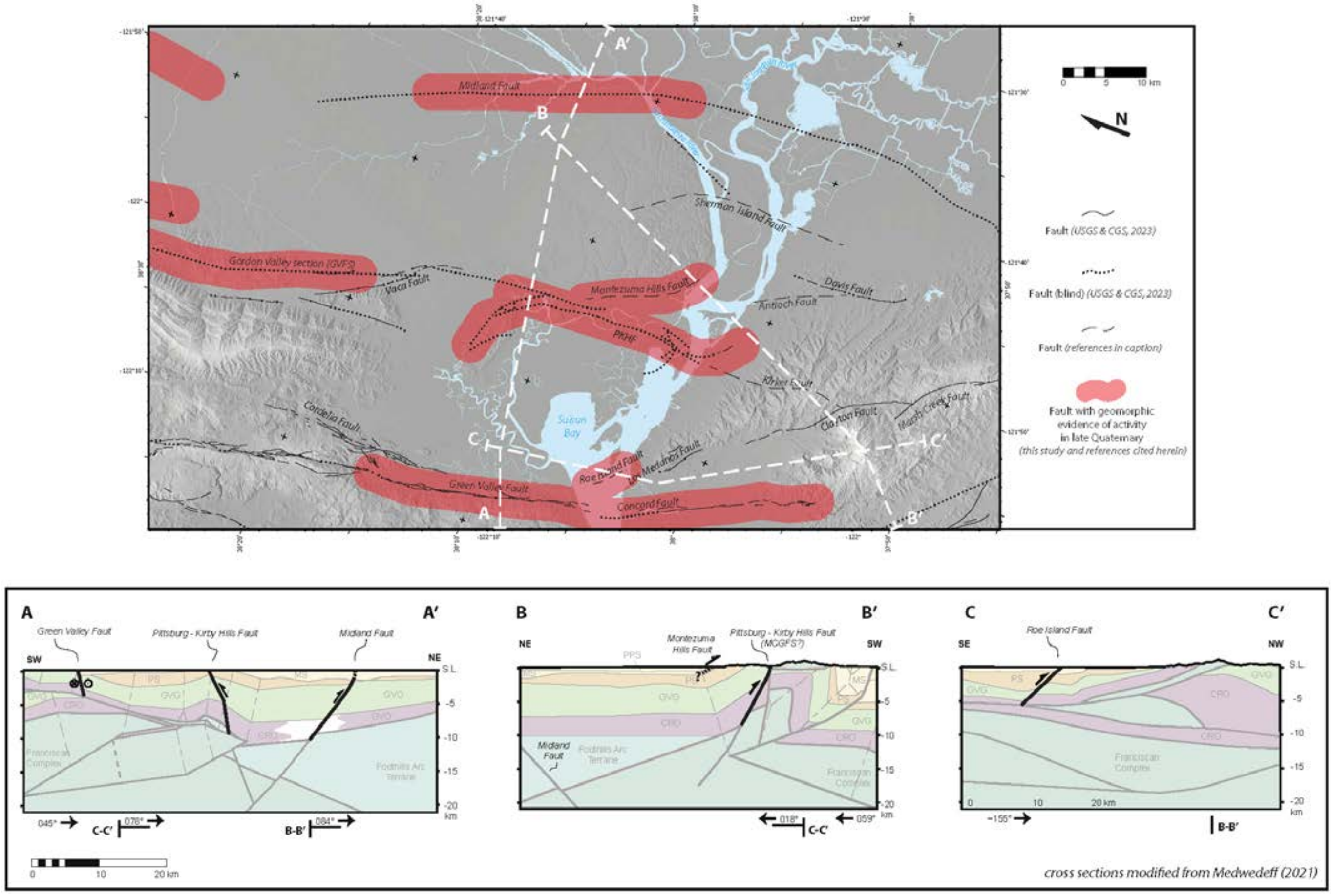

Figure 8 – Map **(top)** and structural cross sections **(bottom)** of Delta faults, with faults exhibiting clear geomorphic evidence of activity highlighted red. Structural cross sections modified from *Medwedeff* (2021). GVFS: Great Valley Fault System; PKHF: Pittsburg-Kirby Hills Fault. Generalized geologic units modified from *Medwedeff* (2021). CRO: Coast Range Ophiolite; GVS: Cretaceous Great Valley Group; PS: Paleogene marine sequence; MS: Miocene marine sequence; PPS: Plio-Pleistocene nonmarine sequence.

Montezuma Hills block, likely also accommodates vertical displacement (e.g., *Weber-Band*, 1998; *Unruh et al.*, 2009), but may not accommodate as much displacement as the Pittsburg-Kirby Hills Fault or Montezuma Hills Fault, due to its location east of the Diablo Anticline. This somewhat more limited role of the Midland Fault in our proposed kinematic model is supported by structural observations and interpreted seismic reflection data, which show a greater magnitude of deformation in the western Montezuma Hills block than in the east (e.g., *Graymer et al.*, 2002; *MacKevett*, 1992). In addition, both peak elevations and elevation of the relict surface within the Montezuma Hills block are greater in the west than the east, consistent with a greater magnitude of uplift along structures in the west (Figure 6). We suggest that the topographic scarp along the eastern margin of the Montezuma Hills south of Rio Vista may be enhanced by erosion of the Sacramento River, thus artificially amplifying the apparent role of the Midland Fault in Montezuma Hills block uplift.

4.2 Northern Great Valley Fault System

The Great Valley Fault System is widely considered to be active (e.g., *Unruh et al.*, 1995; *Wakabayashi*, 2015), yet Quaternary deformation on the structural system remains poorly constrained. Recent work along the western margin of the Sacramento Valley at the northern edge of the Delta suggests that structures associated with the Great Valley Fault System actively accommodate thrust displacement in the Quaternary (*Trexler et al.*, 2022). At their study site along Putah Creek west of the town of Winters, a surface-deforming fault defines the western margin of a bedrock hill and displaces Quaternary fluvial deposits with an east-side-up sense of offset (Figures 1 and 6) (*Trexler et al.*, 2022). This sense of displacement is opposite to the larger-scale topography in the surrounding area, where the Coast Ranges to the west meet the Sacramento Valley to the east, and there is no apparent strike-slip displacement of geomorphic features, despite the fault system being oriented subparallel to plate boundary dextral faults (Figure 5) (*Trexler et al.*, 2022). The regional history recorded in Late Cretaceous-to-Paleogene bedrock provides context for these observations. Paleogene and Neogene strata along the eastern margin of the Coast Ranges at this latitude are consistently east dipping. This deformation suggests that the Great Valley Fault System has continued to accommodate east-west convergence even in the modern characteristically transform tectonic context (e.g., *Unruh et al.*, 1995; *Wakabayashi and Unruh*, 1995), with modern kinematics similar to those prior to the passage of the northward-migrating Mendocino Triple Junction at 10 Ma and perhaps as long-lived as the Late Cretaceous (e.g., *Wentworth et al.*, 1984; *Unruh et al.*, 1995; *Wakabayashi and Unruh*, 1995; *Wakabayashi*, 2015). Within this framework, the apparent west-directed convergence on the West Winters strand of the Great Valley Fault System is consistent with the proposed structural geometry at the Rumsey Hills to the north (e.g., *Unruh et al.*, 1995), and is evidence that convergence is still actively being accommodated by this structural system (*Trexler et al.*, 2022). Deformation of Pliocene and Pleistocene-age bedrock records an average thrust slip rate on the Rumsey Hills Thrust Fault of 1.0–3.5 mm/yr over the Quaternary (*Unruh et al.*, 1995). Similar horizontal shortening rates are recorded on analogous faults within the southern Great Valley Fault System in the western San Joaquin Valley (*Bloch et al.*, 1993).

In the northern Delta, low-relief topography within the Sacramento Valley suggests that structures east of the Coast Ranges may also be active in the Quaternary (*Unruh and Moores*, 1992; *Johnson*, 1992). A ~north-south trending series of low-relief (~5 m high) topographic highs stretching from near the city of Dixon northward and to the west of the cities of Davis and Woodland — the Plainfield Ridge and Dixon Rise of *Unruh and Moores* (1992) — manifest as anomalous local high points, often associated with locally incised fluvial channels, in an otherwise nearly planar distributary fan surface. Uplift of the Plainfield Ridge and Dixon Rise may be attributed to deformation above the tip of the Great Valley thrust wedge (e.g., *Unruh and Moores*, 1992), reactivation of the northern Midland Fault (or other Late Cretaceous-to-Paleogene age extensional faults) as reverse faults, or a combination of the two.

5 Discussion

5.1 Reconciling Observations with Structural Models

Geodetic and geomorphic datasets provide clear evidence of Quaternary fault activity in the Delta, though the rates of deformation implied by these datasets vary. Geodetic models suggest that several mm/yr, and as much as 5 mm/yr, of displacement may be accommodated by structures in the Delta (Table 1; e.g., *Prescott et al.*, 2001; *d'Alessio et al.*, 2005; *Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022). While the geomorphology in the Delta is consistent with active fault displacement, it is of comparatively low amplitude relative to other regions of the world that accommodate multiple mm/yr of shortening. Gaps in our understanding of Delta structures remain, but the compilation of geologic, geomorphic, geodetic, and geophysical datasets we present here suggests that the limited evidence of active structures does not necessarily preclude active deformation on the order of mm/yr across structures in the Delta. Geologic and geomorphic evidence of tectonic activity in the Delta is obscured by a combination of low slip rates, blind faults, slip distributed across multiple parallel faults, and other factors that create adverse conditions for preserving neotectonic landforms. Alternatively, we note that more recent geodetic models of faults in the Delta and surrounding region (*Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022) report rates that are lower than the rates on those same structures from earlier studies (*d'Alessio et al.*, 2005; *Evans et al.*, 2012) (Tables 1 and SI-1). We interpret this effect as resulting from one or both of two signals: first, more individual fault segments included in the newer models, which thus distribute the same amount of strain over more structures, each accommodating a smaller percentage of the overall; and second, the pattern recognized in other settings of low relative strain where rates reduce significantly with increased length of data collection, particularly when incorporating older geodetic datasets (e.g., in the New Madrid Seismic Zone, where earlier rates were reduced by an order of magnitude to < 0.5 mm/yr with newer datasets (*Calais et al.*, 2016).

Low rates of deformation, comparatively high rates of erosion and deposition, and limited exposure of bedrock combine to limit the potential scope of datasets traditionally used to explore Quaternary deformation rates. Datasets are incomplete spatially and/or temporally, and often are insufficient to explain modern patterns of surface uplift. In addition to the limited preservation potential for active deformation, the kinematic behavior of Delta structures is obscured by the region's tectonic history of structure initiation and reactivation in an evolving tectonic regime. We agree with earlier workers that patterns of active deformation within the Delta may be largely dictated by, and deformation itself may in part be accommodated on, reactivated Late Cretaceous-to-Paleogene structures that initially formed in the subduction forearc prior to the passage of the triple junction. As a result, an understanding of the inherited structures and their geometries is key in untangling modern deformation within the region. In addition, we note that the region hosts multiple young faults with small magnitudes of accumulated slip within a region of complex and overprinted structural geometries that continue to evolve as part of the modern plate boundary system, and suggest that any modern deformation patterns may not necessarily be representative of longer-term (e.g., million-year timescale) slip rates or kinematics on any particular structures.

In combination with prior studies of displacement, kinematics and activity of Delta structures, we argue that geomorphic analyses provide clear indication of active vertical displacement across multiple structures in the western and central Delta, including the Pittsburg–Kirby Hills Fault, Midland Fault, and the proposed Montezuma Hills Fault (Figure 8). Moreover, we suggest based upon geomorphic evidence, including east-west asymmetry, that the Pittsburg–Kirby Hills Fault may play a more significant role in the late Quaternary than other faults in the region, such as the Midland Fault (Figure 6).

5.2 Fitting into Regional Context

The extent to which faults in the Delta connect to and interact with faults to the north, west, and south remains unclear, yet our observations suggest likely hypotheses. Though they are typically treated as kinematically separate systems, structures from within the Delta parallel and/or overlap in geographic space with faults from the Great Valley Fault System, faults typically associated with the San Andreas Fault System and Pacific-North America plate boundary system (e.g., the Concord-Green Valley and Clayton-Los Medanos-Roe Island Fault Systems), and the Diablo Anticline. Interactions are obviously complex, even on the scale of individual faults.

In the context of its apparent prominence as a Quaternary-active structure, the apparent overlap or interplay between the Pittsburg–Kirby Hills Fault and the Great Valley Fault System to the north is notable. The south end of the Great Valley Fault System is mapped further south than the northern end of the Pittsburg-Kirby Hills Fault System, but the two are typically treated as separate structural systems (e.g., *USGS and CGS*, 2023). Though subsurface datasets have been interpreted to suggest that these structural systems remain discrete from one another (e.g., *Weber-Band*, 1998; *Unruh*, 2021), the extent to which these faults interact and exploit one another remains a significant question. Given the similar geometries and geographic overlap, regional geodetic models assign similar displacement rates and kinematics to the two fault systems, resulting in treatment of the Pittsburg-Kirby Hills Fault System as a southward continuation of the Great Valley Fault System (Table 1; *Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022).

Geomorphology and bedrock geology do not provide clear evidence either supporting or refuting connectivity or interaction between the two structural systems. Surface faults associated with the Great Valley Fault System north of the Delta are often bedding-parallel, which obscures their location within the stratigraphic section in both surface and subsurface datasets. Within the east-dipping Paleogene and Neogene sedimentary section, more-resistant bedrock units define subtle topographic ridges along and to the east of the topographic front of the Coast Ranges. These ridges are often co-located with mapped strands of the Great Valley Fault System, including surface traces of backthrusts, along much of the western Sacramento Valley. A prominent example is found along the Gordon Valley section, where a bedding-parallel backthrust near the base of the Paleogene section (the Vaca Fault) projects into the Delta just east of the city of Fairfield. The Paleogene and Neogene strata in the hanging wall of this fault form a prominent lithologically defined ridge, the English Hills, north of the city of Vacaville. Similar bedding-defined topographic features extend southward into the Delta, along the Pittsburg-Kirby Hills Fault in the northwestern Montezuma Hills and approximately along strike from the Gordon Valley section. However, low relief (generally < 10 m) and anthropogenic modification in the region make it difficult to determine whether these bedding-defined ridges are continuous between the Gordon Valley section and the Pittsburg-Kirby Hills Fault.

While the Great Valley Fault System exhibits significant similarities in geometry and kinematics along the eastern front of the Coast Ranges both north and south of the Delta, structures easily attributed to this system are conspicuously absent within the Delta itself. Instead of the moderately dipping thrust faults observed in the Rumsey and English Hills and along the western margin of the San Joaquin Valley (to the north and south respectively), the primary faults within the Delta are steeply dipping faults that originated as normal faults in the Paleogene (e.g., *Krug et al.*, 1992; *MacKevett*, 1992). Despite these fundamental distinctions in both tectonic origin and structural geometry of these structural systems, the Paleogene extensional structures appear to play a fundamental role in modern fault activity and strain accommodation within the Delta region. We suggest that the apparent 'gap' in the Great Valley Fault System results at least in part from the presence of the Paleogene Rio Vista basin faults — specifically, the Pittsburg-Kirby Hills, Montezuma Hills, and Midland Faults — which serve to accommodate modern deformation through the Delta in place of the Great Valley Fault System (Figure 8). The Pittsburg-Kirby Hills Fault thus may represent the south terminus of the northern Great Valley Fault System, while the Midland Fault (likely including the north Midland source zone, and perhaps structures as far north as the Dunnigan Hills) represents the north terminus of the southern Great Valley Fault System.

To the south of the Delta, multiple structures accommodate both dextral displacement and shortening. The Diablo Anticline sits directly to the southwest of the Delta and sits within a restraining step between the Concord Fault, located west of the Delta, and the Greenville, Midway, and Black Butte Faults (Figure 1). A consensus has not yet been reached on the slip rates of these structures, or the nature of their interaction with the San Joaquin Fault and the southern sections of the Great Valley thrust that define the western edge of the San Joaquin Valley.

Structural and kinematic relationships between faults within the Delta and those to the north and south are significant, and have implications for seismic hazard assessments. If earthquake ruptures can propagate from structures within the Delta (e.g., the Pittsburg-Kirby Hills Fault) onto structures outside the Delta (e.g., the Great Valley Fault System or the Green Valley-Bartlett Springs Fault), this greatly increases the potential rupture length and thus the magnitude of earthquakes that may occur. The complex, multi-phase geologic history of the Delta region plays a pivotal role in how and where strain is accommodated in the modern Delta and is vital to any assessments of seismic hazard in the region. Delta faults are incorporated into the latest seismic hazard deformation models (*Evans*, 2022; *Hatem et al.*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022), but the wide range of slip rate estimates on individual Delta faults from geologic (*Hatem et al.*, 2022) (Table 2) and geodetic data (*Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022) (Table 1), which in the latter case often have uncertainties that exceed the modeled rates themselves, highlights the lack of a consensus on the significance of any particular Delta structure in accommodating active deformation. Further constraints on and refinement of fault geometries and kinematics, supported by datasets including geomorphology and geology, may help reduce these uncertainties and improve future seismic hazard assessments.

Though sections of the Great Valley Fault System are subparallel to other faults in the plate boundary system that are primarily strike-slip, we note that there is no clear geomorphic evidence of strike-slip displacement — offset channels, shutter ridges, or other features often seen along strike-slip faults (e.g., *Wallace and Dickinson*, 1968) — on faults within the Great Valley Fault System. Geomorphic and geologic datasets record eastward tilting and east-side-up displacement along some strands of the Great Valley Fault System (Figure 5), without obvious indicators of plate-boundary – parallel displacement (*Trexler et al.*, 2022). Geodetic data similarly record several mm/yr of plate-boundary-perpendicular convergence at this latitude (e.g., *Prescott et al.*, 2001), and geodetic models similarly suggest dominantly dip-slip behavior on the Great Valley Fault System in the vicinity of the Delta (Table 1 *Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022). Within the western Delta, the Potrero Hills anticline and splays of the Pittsburg-Kirby Hills Fault suggest that some component of right-lateral displacement may be accommodated at that latitude, but similarly to the Great Valley Fault System along strike to the north, landforms indicative of strike-slip displacement are lacking even where geomorphology does appear to record vertical displacement (e.g., Denverton water gap; Figure 7).

These observations raise the possibility that, at the latitude of the northern Delta, strain is partitioned across multiple structural systems, with the Great Valley Fault System accommodating convergence while another fault (likely the Green Valley-Bartlett Springs Fault) accommodates dextral slip. Similar patterns of strain partitioning at a regional scale are seen in other parts of the California Coast Ranges, as well as in other tectonic settings including New Zealand and the Arabia-Eurasia collision (e.g., *Cashman et al.*, 1992; *Jackson*, 1992; *Jones and Tanner*, 1995). The Green Valley-Berryessa-Bartlett Springs Fault and associated subsidiary structures are the furthest east structures directly associated with the San Andreas Fault System, and the primary faults accommodating strike slip in the eastern Coast Ranges at the latitude of the northern Delta according to both geologic and geodetic datasets (Table 1; *d'Alessio et al.*, 2005; *Evans*, 2022; *Pollitz*, 2022; *Shen and Bird*, 2022; *Zeng*, 2022). The primary strands of this dextral fault zone at the latitude of the Delta are the Green Valley and Cordelia Faults, located approximately 15 kilometers west of the Pittsburg-Kirby Hills Fault. Therefore, transfer of any dextral strain on the Pittsburg-Kirby Hills Fault to the Cordelia and/or Green Valley Faults would require a westward step. The Potrero Hills Anticline, a westward splay of the Pittsburg-Kirby Hills Fault accommodating north-directed compression on an east-west striking structure, could partly fill this gap, absorbing some amount of right-lateral strike-slip deformation and feeding slip northwestward onto the Green Valley-Bartlett Springs Fault System. *Weber-Band* (1998) proposes the presence of a second east-west-striking thrust structure north of the Potrero Hills Thrust that may participate in transferring strain onto the Green Valley Fault and/or Bartlett Springs Fault System; however, no other work has suggested the presence of this structure and structural observations in the northern Delta do not document such a fault. We note that our geomorphology analyses similarly do not document clear evidence of active dextral displacement across the Pittsburg–Kirby Hills Fault. We suggest that the lack of a clear structure to transfer dextral strain to structures northwest of the Delta, combined with the limited geomorphic evidence for dextral displacement across the Pittsburg–Kirby Hills and associated faults is consistent with the strain partitioning model we proposed for the Great Valley Fault System to the north of the Delta.

6 Conclusions

Synthesis and analysis of bedrock geology, geophysical data, and geomorphology provide an enhanced understanding of potential seismic sources within the Delta region. Faults inherited from prior tectonic regimes—including the forearc of the Farallon subduction zone, prior to passage of the northward-migrating Mendocino Triple Junction— play an outsized role in modern strain accommodation within the Delta, leading to modern kinematics that appear inconsistent with fault geometry and tectonic context (Figure 8). Examples include the Pittsburg-Kirby Hills Fault, which dips eastward and appears to record normal offset of Paleogene sediments, while the positive flower structure in younger sediments suggests strike-slip displacement and topography indicates a component of reverse displacement, and the Great Valley Fault System, which strikes subparallel to other dextral faults in the region but appears to accommodate reverse or thrust displacement and does not exhibit clear evidence of strike-slip displacement. Further work will help elucidate the interaction between overlapping inherited structures within the Delta, such as the Pittsburg-Kirby Hills Fault, and the Great Valley Fault System, and provide geologic constraints on deformation rates and kinematics within the region. While geologic constraints on deformation rates on Delta faults and folds remain limited, geodetic data suggest that faults within the Delta together accommodate as much as 5 mm/yr of plate-boundary-parallel dextral displacement and 3 mm/yr of plate-boundary-normal convergence. Based upon geomorphologic analyses, we suggest that in the central and western Delta, this active deformation is accommodated on the Pittsburg–Kirby Hills Fault and associated structures (including the Montezuma Hills Fault) to the west and southwest of the Montezuma Hills, in addition to the Midland Fault along the eastern margin. Faults within the Delta region have produced significant historical earthquakes, including the Mw 6.4–6.2 1892 Vacaville-Winters sequence. The fault geometries and kinematics we present here, constrained by geologic, geomorphic, geodetic, and subsurface datasets, provide context for interpretation of strain accommodation on structures in the Delta region

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Author contributions

CT conceived of this study, with assistance and input from **BP**. **CT**, **BP**, and **JW** conducted literature review, and **CT** and **JW** wrote early drafts. **CT** wrote the manuscript, with editorial assistance from **BP** and **JW**.

Data availability

All data are reproduced here from references as cited within the manuscript. Tables 1, 2, and SI-1 are available for download from the Supporting Information.

Competing interests

The authors declare no competing interests.

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