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Evidence of Active Reverse Faulting and a Left-Stepping San Andreas Fault (Mission Creek Strand) in the Eastern San Bernardino Mountains, Southern California

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EVIDENCE OF ACTIVE REVERSE FAULTING AND A LEFT-STEPPING SAN
ANDREAS FAULT (MISSION CREEK STRAND) IN THE EASTERN SAN
BERNARDINO MOUNTAINS, SOUTHERN CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Jesse Waco

May 2021

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The Designated Thesis Committee Approves the Thesis Titled

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ABSTRACT

EVIDENCE OF ACTIVE REVERSE FAULTING AND A LEFT-STEPPING SAN ANDREAS FAULT (MISSION CREEK STRAND) IN THE EASTERN SAN BERNARDINO MOUNTAINS, SOUTHERN CALIFORNIA

by Jesse Waco

This study presents a revision of mapped faults of the southern San Andreas fault, specifically the Mission Creek strand, at the latitude of northern Coachella Valley from Mission Creek to Whitewater River. Previous studies in the region indicate that as the San Andreas fault splits into the Mission Creek, Banning, and Garnet Hill strands in the Indio Hills, the Banning strand accommodates the majority of displacement across the plate boundary and forms a structurally complex zone with the Garnet Hill strand and San Geronimo Pass fault zone, while the Mission Creek is mapped as inactive. However, a recent provenance study of displaced Quaternary sediment and $^{36}\text{Cl}/^{10}\text{Be}$ burial dating indicate recent fault activity on the Mission Creek strand during the mid to late Pleistocene. Field mapping at the onset of the left-restraining bend of the Mission Creek strand reveals a series of faults that offset geomorphic features in Quaternary alluvium and deform local bedrock. These faults have: (1) tilted and uplifted a middle Pleistocene alluvial fan complex; (2) preserved dip-slip displacement in mid to late Pleistocene fan surfaces along fault scarps; and (3) laterally offset stream channels that were incised during the latest Pleistocene and Holocene. Most interestingly, I observe laterally offset ridges, drainages, and debris flows along an unmapped trace of the Mission Creek strand. These observations allow for a revised interpretation of fault evolution for the San Andreas fault in the northern Coachella Valley region of southern California.

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INTRODUCTION

The emphasis of this study is to produce updated detailed geologic and geomorphic maps, structural cross-sections, and fault displacement reconstructions for the Mission Creek fault strand (hereby referred to as the Mission Creek strand) of the southern San Andreas fault from northern Coachella Valley to the San Gorgonio Pass region of southern California (Figure 1). San Andreas fault activity (or inactivity) and its style of deformation is of high priority, as the San Andreas fault from northern Coachella Valley through the San Gorgonio Pass is overdue for a large magnitude earthquake (Fumal et al., 1993, Field et al., 2014 and references therein). Of particular importance is whether a through-going rupture on the southern San Andreas fault is permissible through San Gorgonio Pass, and if so, which fault strand will accommodate the rupture. The Mission Creek strand is currently mapped as inactive by the Earthquake Hazards Program at the USGS and UCERF3 (Uniform California Earthquake Rupture Forecast) (Field et al., 2014), but recent work east of San Gorgonio Pass, near Pushawalla Canyon, shows geologic slip rates of 20-24 mm/yr suggesting otherwise (Blisniuk et al., 2021). At present, southern San Andreas fault geometry through San Gorgonio Pass is interpreted to be a left-stepping contractional jog or “structural knot” that resists dextral motion from the boundary between the Little San Bernardino Mountains and the San Bernardino Mountains (Figure 1). This motion is transferred ~8 km to the southwest onto the Coachella Valley Banning and Garnet Hill strands and San Gorgonio Pass fault zone (Yule and Sieh, 2003; Matti and Morton, 1993). However, if slip is transferred from the Mission Creek strand across this wide zone, more recent faulting of landforms should not

be observed, as current maps of the region suggest. The proposed study area in Figure 1 has been chosen as an ideal location for field mapping to document active structures across this ~8 km-wide region during mid to late Quaternary timescales. Oblique thrust and reverse fault splays are commonly produced within left bends and left steps of right-lateral strike-slip fault (Sanderson and Marchini, 1983; Fossen et al., 1994; Cowgill et al., 2004); if these structures are documented across this ~8x20 km region near Mission Creek and Whitewater Preserves, it would suggest the Mission Creek strand is still active and a revision to hazard maps is required.

Figure 1. Regional shaded relief map of the southern San Andreas fault. This map shows currently accepted structures through San Geronimo Pass based on USGS and UCERF4 fault maps. Red lines represent active faults. Black lines represent inactive faults. Faults northeast of the San Andreas fault are not shown except for the Pinto Mountain fault. ECSZ-eastern Californian shear zone; SJFZ-San Jacinto fault zone.

The San Gorgonio Pass stepover is an ~20 km-wide region from the Coachella Valley segment of the San Andreas fault in northwest Coachella Valley to the San Bernardino strand of the San Andreas fault at the southern range front of Yucaipa Ridge (Figure 1). At the location where the Coachella Valley segment reaches the boundary between the Little San Bernardino Mountains and San Bernardino Mountains, the fault transitions to a left-restraining bend geometry consisting of several fault splays that make up the Mission Creek strand. Near the junction of the Mission Creek strand and the Pinto Mountain fault, the fault splits into the Mission Creek and Mill Creek strands (Figures 1 and 2). The continuation of the Mission Creek strand flanks the south sides of Yucaipa Ridge until it reconnects with the San Bernardino strand at Banning Canyon (Figure 2). Near Raywood Flat, the Wilson Creek fault diverges from the Mission Creek strand and takes a right bend northwestward across the crest of Yucaipa Ridge, where the fault converges with the Mill Creek strand at Mill Creek Canyon (Figure 2). In the southern zone of the stepover, the Banning strand has a slight left-bend into San Gorgonio Pass, where the fault left-steps southward to the Garnet Hill strand and merges with the San Gorgonio Pass fault zone to the west (Figure 1). The Garnet Hill strand and San Gorgonio Pass fault zone are sinuous faults that make up a thrust front at the southern boundary of the San Gorgonio Pass stepover. At Cottonwood Canyon, the Garnet Hill strand right-steps at Whitewater Hill and dextral-reverse motion transfers back to the merger of the Banning strand and San Gorgonio Pass fault zone (Allen, 1957; Matti et al., 1985; Matti and Morton, 1993). The Banning strand and San Gorgonio Pass fault zone project westward, where the Banning strand truncates the eastern fault tip of the

San Bernardino strand and the San Gorgonio Pass fault zone ends at the western edge of San Gorgonio Pass (Figure 2). North of the Banning strand, the Cox Ranch fault zone is the only major structure centrally located within the San Gorgonio Pass stepover. The Cox Ranch fault zone is a series of arching normal and right-oblique faults across the southern half of the stepover (Allen, 1957; Yule and Sieh, 2003). Faults of the Cox Ranch fault zone are variable in orientation but are predominately intramontane grabens with orientations antithetic to the Banning strand and San Gorgonio Pass fault zone thrust front (Yule and Sieh, 2003).

Several studies suggest active structures of the San Andreas fault accommodating plate motion through San Gorgonio Pass (Figure 2), and each is in agreement that a through-going Mission Creek strand is an unlikely geometry through the stepover due to lack of surface expression along the Mission Creek and Mill Creek strands (Allen, 1957; Dibblee, 1967; Matti and Morton, 1993; Yule and Sieh, 2003; Kendrick et al., 2015). Instead of a through-going Mission Creek strand, many kinematic models for the region infer a complex system of strain partitioning on a series of discontinuous strike-slip and thrust faults, where individual strands accommodate a portion of the total strain through San Gorgonio Pass (Seeber and Armbruster, 1995; Yule and Sieh, 2003; Langerheim et al., 2005).

Figure 2. Shaded relief map of the San Gorgonio Pass region with points of interest. The area marked in the box is the approximate extent of detailed field mapping for this study. Pink lines represent normal and dextral strike-slip faults of the Cox Ranch fault zone mapped by Yule and Sieh (2003). Blue lines represent newly mapped faults from this study. It should be noted that no faults have been mapped in the area between the Cox Ranch fault zone and the Mission Creek strand despite this region being a tectonically active restraining bend during the Quaternary.

Allen (1957) established most of the major strands for the San Andreas fault through San Gorgonio Pass by recognizing Holocene displacement along the east-west striking Coachella Valley Banning strand and active dextral-reverse motion along the San

Gorgonio Pass fault zone (Figure 2). The Coachella Valley Banning strand was later linked with the San Gorgonio Pass fault zone through field observations indicating dextral slip diminishes along the Coachella Valley Banning strand until it ceases and is absorbed by dextral-reverse motion on both the San Gorgonio Pass and Garnet Hill strands (Matti and Morton, 1993; Yule and Sieh, 2003). Yule and Sieh (2003) also improved upon previous studies by mapping a more precise trace of the San Gorgonio Pass-Garnet Hill-Coachella Valley Banning strands and found abundant subsidiary faults across the region. None of these previous geologic mapping studies have found any signs of Quaternary displacement on the other major strands within the San Gorgonio Pass stepover, so the San Gorgonio Pass-Garnet Hill-Coachella Valley Banning strands are generally accepted as dominant structures in accommodating most of the plate boundary motion along the San Andreas fault through the region, and therefore are likely to rupture in an earthquake on the San Andreas fault (e.g., Matti and Morton, 1993; Yule and Sieh, 2003).

Holocene offsets have been observed in alluvium along the Mission Creek strand southeast of Highway 62 near Desert Hot Springs (Matti and Morton, 1992; Blisniuk et al., 2017) (Figure 3), but offsets or tectonic geomorphic features have not been observed in Quaternary deposits along the Mission Creek or Mill Creek strands from Desert Hot Springs to Yucaipa Ridge (Figure 2). Allen (1957) first made this assessment based on undisturbed Cabezon fan conglomerate (Qc) deposits along the Mission Creek strand near Raywood Flat (Figure 2), but more recent studies at this location have observed 4-6m of offset in young alluvial deposits and the lower section of a 50-m-thick debris flow cut by

the fault (Morelan, 2018). Matti and Morton (1993) found that where the Coachella Valley segment of the San Andreas fault intersects with the Mission Creek strand near Big Morongo Valley, Holocene displacements are not observed at the base of the Little San Bernardino Mountains (Figure 3). A few kilometers northwestward along the Mission Creek strand, between the beheaded and modern Mission Creek drainages (Figure 3), Kendrick et al. (2015) further support fault inactivity within late Pleistocene-Holocene deposits with observations that Cabezon fan conglomerate alluvial deposits are undisturbed by the Mission Creek strand, citing a specific deposit of very old alluvium (middle Pleistocene) that is overlying pulverized basement rock and appears to show no signs of deformation. However, more recent studies based on detailed sedimentary provenance analyses of modern drainages and offset alluvial fan deposits suggest evidence of more recent fault activity (Fosdick and Blisniuk, 2018).

The overall uncertainty of fault activity in this region of the San Andreas fault, coupled with a lack of detailed surficial mapping due to the presumed inactivity along the Mission Creek strand, allows for a re-evaluation of geomorphic features and geologic relationships adjacent to the restraining bend. Field mapping from this study provides evidence of more recent fault activity and is used to re-interpret the style of deformation and tectonic evolution of the San Andreas fault from the Little San Bernardino Mountains to Whitewater River.

Figure 3. Google Earth image showing active drainages near the study area. These drainages were sampled by Fosdick and Blisniuk (2018) for provenance analysis which determined the sources of Cabezon fanglomerate (Qc) are Mission Creek and Morongo Valley Canyon. Reconstructions of Qc deposits to their original source show up to 8 km of offset along the Mission Creek strand.

GEOLOGIC SETTING

Tectonic Setting

The Pacific-North American plate boundary accommodates ~50 mm/yr of relative plate motion across a series of regional fault zones from southern California to western Nevada (DeMets and Dixon, 1999). Of these fault zones, the southern San Andreas and San Jacinto faults are dominant structures in accommodating present dextral motion in southern California (Bennett et al., 1996; Becker et al., 2005; Lundgren et al., 2008, Guns et al., 2020). The southern San Andreas fault is generally comprised of a chain of NW

striking segments that extend from the Salton Trough to central California (Figure 1, inset map). Since the modern southern San Andreas fault initiated ~6-8 Ma with the rifting of the Gulf of California (Frost and Martin, 1982; Dorsey et al., 2011), different strands of the fault have taken on various complexities of hard and soft linkages during its maturation (Matti and Morton, 1993).

In the northwest corner of the Salton Trough, the southern San Andreas fault cuts through Coachella Valley by linking up with the San Bernardino strand through the San Gorgonio Pass region along a series of strike slip, reverse and oblique fault strands. Near the Indio Hills in Coachella Valley (Figure 1), the linear through-going trace of the San Andreas fault splits into two different strands, the Mission Creek and Banning strands; here dextral motion is suggested to decrease on the Mission Creek strand and transfer to the Banning strand northwest of the Indio Hills (e.g., Kendrick et al., 2015 and references therein). As the Mission Creek strand continues ~30 km to the northwest along the range front of the San Bernardino Mountains, the Pinto Mountain fault places southward compressional stress on the strand and it bifurcates into the Mission Creek and Mill Creek strands near the headwaters of Whitewater River (Matti and Morton, 1993). The Mission Creek and Mill Creek strands, along with the ancestral Wilson Creek strand, have all acted as a primary plate boundaries faults in accommodating dextral motion along the San Gorgonio Pass restraining bend since the inception of the modern San Andreas fault (Allen, 1957; Matti and Morton, 1993) (Figure 2). In the San Gorgonio Pass area, fault evolution models of the San Andreas fault suggest dextral slip has now been abandoned on all three strands (Matti and Morton, 1992; Yule and Sieh, 2003). The

Mission Creek and Mill Creek strands have been active during Pliocene-Pleistocene time, but motion is thought to have ended sometime during the middle to late Pleistocene (Matti and Morton, 1992; Yule and Sieh, 2003; Kendrick et al., 2015). The abandonment of the Mission Creek and Mill Creek strands within the restraining bend of the San Andreas fault is hypothesized to be caused by initiation of oblique normal sinistral motion on the Pinto Mountain fault. The Pinto Mountain fault has been argued to offset the Mission and Mill Creek fault strands of the San Andreas fault, therefore ceasing movement of these strands and transferring this slip southward onto the Banning and Garnet Hill strands and San Geronimo Pass fault zone (Matti and Morton, 1993; Kendrick et al., 2015).

Field mapping of the Mission Creek strand along its restraining bend near Mission Creek further supported fault inactivity. Specifically, qualitative field observations of middle to late Pleistocene alluvial deposits collectively referred to as the Mission Creek alluvial complex (Cabezon fan conglomerate) (highlighted in Figure 3) were mapped to be locally sourced from Whitewater Canyon and therefore have not moved since emplacement from ~500-100 ka (Matti and Morton, 1993, Owen et al., 2014, Kendrick et al., 2015). A more recent quantitative provenance study analyzing modern drainages in the area concluded that Whitewater Canyon or a combination of Whitewater Canyon and Mission Creek are unlikely sources for the Cabezon fan conglomerate near Mission Creek (Fosdick and Blisniuk, 2018). Instead, detrital zircon ages within Cabezon fan conglomerate deposits correlate with deposits from the active Mission Creek and Morongo Valley Canyon drainages further to the east (Figure 3). Based on a reconstruction of the

westernmost Cabezon deposits to Mission Creek and Morongo Valley Canyon, a dextral displacement of ~2-8 km since emplacement is estimated.

Directly south from where the Mission Creek strand becomes inactive at Highway 62, the Coachella Valley Banning strand transfers slip to the subparallel Garnet Hill strand on its southern flank, where together they link up on their western tip and interact with the San Gorgonio Pass fault zone at the northern boundary of San Gorgonio Pass (Yule and Sieh, 2003; Gold et al., 2015) (Figure 2). The interaction of the San Gorgonio Pass fault zone, Garnet Hill strand and Coachella Valley Banning strand form an east-west striking dextral-reverse fault system. The San Gorgonio Pass fault zone contains a series of right-oblique normal faults that remained unnamed until Yule and Sieh (2003) grouped the faults with the Cox Ranch fault zone previously mapped by Allen (1957) (Figure 2). These faults produce offset ridgelines and faceted surfaces within bedrock, but tectonic features are not expressed in Holocene alluvium in the area. These observations have been used to suggest low slip rates in the Cox Ranch fault zone (Yule and Sieh, 2003). The location of the Cox Ranch fault zone marks the northernmost active structure mapped within the San Gorgonio Pass stepover (Yule and Sieh, 2003), suggesting that the area between the Cox Ranch fault zone near Cottonwood Canyon and the Mission Creek strand does not contain any active or inactive faults as currently defined by previous studies and UCERF4 hazard maps (Figure 2).

Stratigraphy of the Mission Creek Study Area

Geologic units in the study area are differentiated into three distinct groups based on ages and general rock classification: Cretaceous and older crystalline bedrock, Miocene volcanics and sediments, and Quaternary alluvium, with Miocene and Quaternary complexes being subdivided into several units (Figure 4).

Map-unit and thickness (m)		Formation and approximate age
Qdf < 100	Debris flow deposits (Holocene-Pleistocene)
	Qc 100-150	Cabezon fanglomerate (late to middle Pleistocene)
	Qd 750	Deformed gravels of Whitewater River (middle to early Pleistocene)
	Mcmd 10-20	Coachella marsh deposits (Pliocene-Miocene)
	Mcg < 60	Coachella gravels (Pliocene-Miocene)
	Mcb 200-300	Coachella basalt flows (Miocene)
	Mcl 1400	Coachella fanglomerate (Miocene) Sedimentary alluvial complex
SGg 1500-3000		San Geronio gneiss (Cretaceous and older) Strongly deformed, heavily intruded igneous-metamorphic complex

Figure 4. Stratigraphic column of the Mission Creek study area. Modified from Allen (1957).

San Gorgonio Igneous-Metamorphic Complex (San Gorgonio gneiss)

The majority of bedrock exposed between Mission Creek and the western boundary of the field area is the San Gorgonio igneous-metamorphic complex (SGg) (Plate 1). SGg is a heterogeneous, strongly deformed, and heavily intruded complex consisting of several different suites with varying compositions of igneous and metamorphic rock (Allen, 1957). In the study area, SGg is best identified by two main rock types: (1) a foliated metamorphic rock described as “migmatitic gneiss” and (2) a potassium feldspar porphyry (Allen, 1957).

Miocene Rocks: Coachella fanglomerate

The area directly northeast of Whitewater Trout Farm (now Whitewater Ranger Station) exposes the Miocene Coachella Fanglomerate (Mcl), a sedimentary alluvial complex that has not been correlated across the San Andreas fault, but several studies have speculated it has been translated ~200 km along the fault from the Split Mountain Formation, Chocolate Mountains or Cargo Muchacho Mountains near the Salton Trough (Proctor, 1968; Dillon and Ehlig, 1993; Giblin, 2019). The absolute age of the Coachella Fanglomerate is unknown, but south of the study area near the Banning strand, the Coachella Fanglomerate is unconformably overlain by the lower Pliocene Imperial Formation. Considering a lower Pliocene minimum age and the time needed for the deposition of a 1200-1500 m-thick alluvial complex, this places the Coachella Fanglomerate at Miocene in age or older (Proctor, 1968).

Overlying Mcl and SGg bedrock is a 200-300 m-thick Miocene basalt flow (Mcb). Mcb is a moderate red to dark greenish gray series of fine-grained, aphanitic basalt flows. Red basalts can be observed at Red Dome and the slopes bounding the Pacific Crest Trail just north of Whitewater River, while dark gray basalts are exposed at the base of the slopes just east of the swamp at Mission Creek Preserve (Plate 1).

Deformed gravels of Whitewater River

Unconformably overlying Miocene volcanic units and SGg is the oldest of the Quaternary alluvial units, the Deformed gravels of Whitewater River (Qd). Qd is very pale orange to grayish orange in color and weakly cemented. Qd is matrix supported by gravels to medium sand-sized sediment and is crudely stratified with layers of interbedded pebbles, cobbles and boulders that are sometimes cross-bedded. Clasts within Qd are subrounded and moderately sorted. Rock types within the unit include biotite gneiss, coarse-grained granodiorite and quartz monzonite (Allen, 1957; Dibblee, 1964; Fosdick and Blisniuk, 2018). Localized areas of the unit transition to clast-supported beds that are more abundant in cobble-sized clasts to boulders up to 1 meter in diameter. On surfaces of interfluvies and nose slopes, Qd displays white to very light gray grusification, which distinguishes it from the light brown to light orange surfaces of the younger Cabezon fanglomerate.

Cabezon fanglomerate (Mission Creek alluvial complex)

The Cabezon fanglomerate (Qc) is a middle to late Pleistocene alluvial fan complex bounding the modern Mission Creek and Whitewater River stream channels. There are variations in lithology, stratification, and clast size within each subsequent alluvial unit in

the complex, but characteristics that can be applied to all Qc fan units is that they are grayish orange to dark yellowish orange in color, exhibit cambic soil development and are poorly sorted. The unit is typically massive to weakly-stratified with bedding that consists of gravel to boulder-sized clasts. These subsurface clasts are subangular to subrounded. Rock types within the unit include biotite gneiss, granodiorite, quartz monzonite, with some diorite and sparse andesite-dacite, amphibolite, schist, hematite and quartzite (Allen, 1957; Dibblee, 1964; Fosdick and Blisniuk, 2018).

METHODS

General Field Mapping

To determine fault geometry and deformation along the Mission Creek strand in the San Geronio Pass region, geomorphic and geologic maps, cross-sections, and annotated high-resolution images were produced. Field mapping was executed on 1 m-resolution orthoimages provided by the National Agriculture Imagery Program (NAIP) divided into 1000x600 m sectors covering the entire 15 x 5 km study area. Areas that were too difficult to traverse in the field were mapped using ALSM (airborne laser swath mapping) imagery and orthoimagery provided by NCALM and USGS EarthExplorer. The few unmappable areas of extreme relief are along the southwestern field area boundary west of Whitewater River. Field maps were then digitized and transferred into digital formatting using ArcMAP. Clast counts were executed in the field to correlate

deposits of Qc alluvium using a 1x1 m grid and counting the number of each clast type until n=30.

Using terminology adapted from Behr et al. (2010), the terms *zone*, *segment*, *strand*, and *splay* help describe the scale of faults in a hierarchal manner from largest to smallest. A *zone* can describe a regional domain made up of several regional faults (e.g. the eastern California shear zone), with a *segment* representing a regional section of a single regional fault (e.g. the San Andreas fault). A fault may be made of several *strands* that can split into two or more *splays*. The term *active structure* can be applied to any scale fault that produces deflected drainages, offset ridgelines, or tectonic features in late Quaternary to Holocene units, as defined by Yule and Sieh (2003).

Mapping Alluvial Fan and Terrace Surfaces

Unit description terminology and unit names are adapted from Allen (1957) for previously mapped units. Some members within the Miocene volcanic group have been added and removed based on field observations, so my correlation of Miocene units varies slightly from Allen and will have new unit names introduced. Allen identified the two sedimentary Quaternary units, early-to-middle Pleistocene Qd and mid-to-late Pleistocene Qc. Quaternary surficial mapping is only applied to the Qc alluvial complex highlighted in Figure 3.

Alluvial deposits in the Mission Creek study area are differentiated by the overall color and textural characteristics of the surface following the nomenclature of Bull (1991). Characteristics contributing to surface color and texture include soil development, grusification, rubification and clast lithologies. The degree of soil

development and grusification (breakdown) of granitic and gneissic clasts collectively gives the greater part of a fan surface a distinct color depending on the type of parent rock being chemically weathered. The amount of oxidized minerals (or lack thereof) in the soil, and the type of minerals weathering out from the clasts may give a surface an identifiable degree of redness. For example, latest Pleistocene to Holocene age surfaces will be characterized by hues of dull grays and yellows since little time has passed since deposition, but mid to late Pleistocene surfaces will be redder with age and peak at a dark orange hue (7.5YR 6/3 to 7/6) before erosion removes the soil profile (Bull, 1991) (Figure 5).

Surface morphology in this study can further establish mappable surficial units to help place surfaces into four basic categories (from oldest to youngest) Q1, Q2, Q3, and Q4, and their alphanumeric subdivisions (from oldest to youngest) Q2a, Q2b, Q2c, etc. (Figure 5) (Bull, 1991). Commonly, fan surfaces in arid regions can be distinguished using aerial photography based on topography alone, but uplift of alluvial fans near Mission Creek and Whitewater River has placed surfaces up to 150 m above the modern stream channel, where they are no longer being actively dissected by drainages exiting the range front. As a result, the highest-standing Q1 fans near Mission Creek retain much of their original planar surface which causes them to resemble Q2 surfaces. Therefore, each alluvial fan and terrace surface in the study area was traversed and observed over 60+ days of field work to map Q1, Q2 and Q3 surfaces in the study area. The orientation and degree of channel incision on fan surfaces and location of geomorphic boundaries on 1 m-resolution LiDAR images also assisted in mapping alluvial surface contacts.

Figure 5. Photographs showing fan surfaces within the Cabezon Fanlomerate. (A) Q1a unit with a dull orange to light brown surface and predominately gravel and cobble-sized clasts. (B) Q1b unit that displays similar clast characteristics as Q1a but with abundant strongly-weathered boulders. (C) Q2 units have a light orange surface and predominately gravel-sized clasts. (D) Qt₂ terrace tread with a grayish brown surface and gravel to boulder-sized clasts. 10 x 12" map board and 13" rock hammer used for scale.

RESULTS

Summary of Mapped Units

Overview of Bedrock Units

The migmatitic gneiss member of the San Gorgonio gneiss bedrock unit, SGg, is the dominant rock type throughout the field area. The texture of SGg varies laterally from distinct mm-scale laminated mylonitic and gneissic foliation to migmatites and weakly-foliated pegmatitic dikes. Gneissic units are typically fine to medium-grained, greenish

gray to dark greenish gray in color. Outcrops of flaser gneiss display boudin and shear zones. Coarse-grained weakly-foliated to gneissic granodiorites are interspersed locally as well. The migmatitic unit is dark greenish gray to yellowish gray in color and appears dark reddish brown when weathered. This unit is a hornblende-andesine-quartz gneiss (Allen, 1957), with meter-scale potassium feldspar augen leucosomes. Meter-scale aplite veins are also present. Faulted regions of the migmatitic rocks display distinct massive, white to bluish white, fine-grained outcrops of pulverized rock. The other common but less-abundant rock type within SGg is a potassium feldspar porphyry with a dark green groundmass that weathers to grayish green. The rock is well-indurated and consists of orthoclase phenocrysts and a matrix of quartz, plagioclase, and biotite (1-2 mm in size). These porphyritic rocks are found near Rainbow Peak and the northern slopes of the Rainbow Peak fan near the gaging station (Plate 1).

The Coachella fanglomerate alluvial complex was split into an upper (Mcu) and lower member (Mcl) by Allen (1957). Observations in this study found the contact between the two members to be gradational, and the differences in composition and color that Allen (1957) used to distinguish the two members alternate throughout the unit, not just at the contact between the lower and upper member. Therefore, Mcu could not be distinguished enough to separate it from the lower member, Mcl, and the Mcl map-unit name is applied to the entire extent of the Coachella fanglomerate. Mcl is a light brownish gray to very light gray conglomerate unit with interbedded east-dipping, moderately-stratified, poorly sorted beds in a well-indurated sandy matrix. Clasts consist of gravel to boulder-sized, subrounded to subangular, porphyritic rhyolite-dacite,

greenschist, olivine basalt, quartz monzonite, and some granitoid pegmatites and gneissic clasts. A horizontal unconformity separates Mcl from SGg approximately 1 km southeast of Red Dome at the eastern banks of Whitewater River. It also has a subvertical contact with SGg directly across the Whitewater stream channel from Red Dome (Plate 1), which could be a tilted depositional contact or fault. No other exhumed Mcl-SGg contacts can be observed in the study area.

Mcb is interspersed throughout the eastern half the study area. A few small outcrops east of the swamp have been severely weathered into red clayey mud. Tan silty gypsiferous deposits overlie this mud east of the swamp and have been given the map-unit label Mcmd.

The youngest unit within the Miocene group, Mcg, is a series of previously unmapped debris flows containing clasts derived from the Coachella fanglomerate. Mcg is an unconsolidated, massive, moderately sorted conglomerate of pebble to gravel-sized sub-angular clasts that are surrounded by a grayish brown sandy matrix. Clasts consist of predominately porphyritic andesite and dacite, with some olivine basalt, rhyolite and quartz monzonite. These deposits are only found near the confluence of the Mission Creek and Beheaded Mission Creek stream channels and along a ridge overlooking the Pacific Crest Trail just west of Beheaded Mission Creek.

Overview of Mid-Quaternary Deposits

The Deformed gravels of Whitewater River, Qd, is the only Quaternary sedimentary unit in the field area that is well-stratified in some areas and allows for accurate strike and dip measurements. These well-defined bedding attitudes help determine the location of

several fault traces from Mission Creek to Wathier Hill. Qd bedding has a general dip of $\sim 30^\circ$ to the N or NE, but near tectonically active areas bedding can take on varying orientations and display steeply dipping or near-horizontal beds. Qd is thought to be early Pleistocene based on stratigraphic relationships (Allen, 1957), with the upper section showing burial ages into the middle Pleistocene (Balco et al., 2019). The upper section of Qd is exposed in a vertical cliff face along cross-section B-B' in the Beheaded Mission Creek steam channel, where interbedded sandy deposits and m-scale gravelly beds are overlain by Qc along an angular unconformity (Figure 6). Here, the exposure exhibits a change from the very pale orange, sandy planar beds of the upper section of Qd, to the massive light gray to light brown massive basal section of Qc containing abundant boulders. Total unit thickness is unknown due to the basal section being at depth, but the largest exposure is at cross-section B-B', where the unit is at least 750 m-thick (Plate 1, cross-section A-A').

Figure 6. Outcrop photo showing the Quaternary stratigraphic sequence. Location is the northern walls within Beheaded Mission Creek stream channel. 10 x 12" map board used for scale.

The mid to late Quaternary Cabezon fanglomerate, Qc, consists of 100-150 m-thick alluvial deposits derived from Mission Creek. Previous mapping grouped the deposit as a single unit; however in this study the unit is split into three different units Qc₁, Qc₂, and Qc₃, based on the mapped location. Qc₁ deposits are located on the southern slopes of Wathier Hill and the eastern slopes of present-day Whitewater Canyon across from Red Dome. These deposits generally appear as high terrace deposits 50 m above the modern

Whitewater River channel. The thickest deposits of Qc alluvium, Qc₂, are terrace deposits located on the western slopes of Whitewater Canyon just south of Red Dome. These deposits have a basal contact 0-20 m above the modern Whitewater channel, and therefore are younger than Qc₁. Qc₁ and Qc₂ deposits within Whitewater River have not been dated in previous studies, but their relative age can be assumed to be the oldest in the complex considering they have been translated the furthest distance from their source drainage at Mission Creek (Fosdick and Blisniuk, 2018). Using the depositional history by Fosdick and Blisniuk (2018), these deposits were likely emplaced by Mission Creek and dissected in an SSE flow direction, just as the orientation of the paleochannel suggests.

Qc₃ deposits are located within Beheaded Mission Creek drainage. The basal section of Qc₃ here shows a light gray sandy matrix on the south-facing slopes within Beheaded Mission Creek stream channel. In general, all Qc deposits appear very light orange to light brown in color. Clast size fluctuates throughout the unit, but there is an overall upward-fining from abundant cobbles and boulders mid-section, to a gravel to cobble dominate upper section. Stratification in the lower section of the unit is typically massive, with some interbedded weakly stratified beds. Middle and upper sections of Qc are typically weakly stratified with interbedded sandy layers. The main diagnostic characteristic separating Qc from Qd lithologically is the abundant presence of granodiorite and quartz monzonite clasts. Another distinguishing lithologic feature of Qc

is the scattered presence of pebble to cobble-sized clasts of mafic schist, amphibolite, hematite, marble, and quartzite.

Overview of Quaternary Surficial Units

Qt Surfaces

Terrace surfaces of Qc alluvium are present from Mission Creek Preserve to the channel walls of Whitewater River. These surfaces are generally mapped as Qt and include subdivisions Qt₁ and Qt₂ (from oldest to youngest). Several Qt surfaces have incised and buttressed against SGg bedrock throughout Whitewater Canyon. These Whitewater terraces are grayish orange to yellowish orange in color, weakly stratified, poorly sorted, and predominately clast-supported. Clasts on the surface are subrounded to subangular and consist of gravel to cobble-sized clasts, with some boulders up to 2 m in diameter. Clast counts indicate a correlative source for the deposits throughout the Whitewater terraces, with each terrace being dominant in biotite gneiss and granodiorite, while also containing sparse amounts of quartz monzonite and diorite. A series of terraces are located on the eastern side of Whitewater across from Red Dome (Plate 1 and Figure 7). The depositional contacts of these terraces are ~50 m above the modern channel, indicating they are an older generation of terraces than the terraces deposits approximately 0-20 m above the modern channel on the western walls of the channel in Whitewater Canyon. With similar heights above the modern stream channel, the terrace deposits at Wathier Hill and east of Red Dome are likely correlative in age, while the terrace deposits near channel base level on the eastern walls are correlative with each other.

Figure 7. LiDAR image (provided by NCALM) showing points of interest. In addition, alluvial fan surfaces of the Cabezon fanglomerate are highlighted in yellow and labeled with their according names. Bold red lines show the Mission Creek strand as mapped by USGS and UCERF.

Two Qt_2 terrace deposits are incised into Qd within the banks of Beheaded Mission Creek. These are likely cut and fill terrace deposits based on their relationship to the older San Gorgonio Overlook and Rainbow Peak alluvial fans seen upsection. Their height above the modern channel suggests the terraces are likely correlative with Q2 units flanking Mission Creek near the basin floor (Figures 8 and 9). This correlation is supplemented by Qt_2 and Q2 both being light grayish brown in color, weakly stratified, gravel to boulder conglomerates consisting of clast-supported beds of predominately biotite gneiss and granodiorite, with some quartz monzonite and diorite clasts. Interbedded medium sand-sized, matrix supported layers are also present. A third small terrace is less than a km east of Cross K Ranch (Mission Creek Preserve) and is likely correlative with the youngest Q2 units or even Q3 units since it is incised into Q2a (Plate 1).

Q1

The oldest alluvial surfaces mapped are Q1 surfaces. In this study, mapped surfaces of Q1 correlate with Qc₃ deposits and are topographically the highest surface observed in the area, generally located ~130-150 m above the modern channel (Figure 8). Q1 surfaces are generally undulating and are incised by several 30 m-deep channels, which is characteristic of Q1 surfaces mapped by Bull (1991). Localized areas of Q1 fan surfaces display Q2-type 5YR 7/3-7/4 grayish orange soil development, but most are grayish yellow 7.5YR 8/2-8/3 colors more correlative with Q1 surface colors mapped elsewhere in the western US (Bull, 1991). Due to differences in surface color and clast characteristics at several locations, this surface has been subdivided into Q1a and Q1b. Q1a consists of a small patch of deposits that is the oldest and highest-standing section of the fan surface (Plate 1). At both SGO and Mission Creek Preserve, Q1a surfaces are located at the northwest surface boundary. Q1a is grayish orange in color with moderate to strong rubification and very sparse amounts of boulder-sized clasts. Clasts on the surface are moderately grusified and pebble to gravel-sized clasts dominate the surface. Rock types consist of mostly subrounded quartz monzonite and hematite. Sparse amounts of subangular clasts of quartzite, pegmatitic granite and amphibolite are also present. The diagnostic characteristic for Q1a is that it contains a very low number of clasts in general and the surface exhibits mostly soil, grus and gravel. ³⁶Cl/¹⁰Be burial dating of Qc3 alluvium suggest emplacement 260 +/- 57 ka (Balco et al., 2019) (Figure

7), which is similar to Optically Stimulated Luminescence (OSL) ages of 320 $\pm$ 34 ka (Atace, 2019).

Figure 8. Stratigraphic column of Quaternary alluvial surfaces near Mission Creek.

In contrast to Q1a, Q1b surfaces are grayish yellow and contain abundant strongly weathered boulders that are up to 4 m in diameter. Rocks on the surface consist of quartz monzonite and gneissic boulders, with gneissic boulders being extremely weathered (Figure 5B). Other less abundant surface clasts consist of granodiorite, diorite, felsic and intermediate volcanics, and sparse quartzite. Grus is present on most areas of the surface and gravel and cobble-sized clasts are much more abundant than in Q1a.

Q2

The second oldest surficial units mapped in the study area are Q2 fan surfaces. Q2 fan surfaces are inset into Q1 and are located where the active Mission Creek stream channel drains into the alluvial plain at Mission Creek Preserve (Plate 1 and Figure 9). Q2 fan surfaces are 25-80 m above the active drainage and 3.5-4 km from the mouth of Mission Creek. These surfaces are not mapped north of the Beheaded Mission Creek-active Mission Creek confluence. The largest Q2 deposit is dissected by both the active Mission Creek channel and an abandoned paleochannel 500 m southwest of Cross K Ranch (Plate 1 and Figure 9). Q2 surfaces are subdivided into three map-units, Q2a-Q2c, with the oldest Q2a unit being a gravel dominant surface consisting of predominately granitoids and biotite gneiss, with localized areas of moderately weathered boulders and weak to moderate grusification. Infra-Red Stimulated Luminescence (IRSL) burial dates of Q2a by Kendrick et al. (2015) on samples collected ~4-5 m beneath the surface resulted in ages of 106 +/- 15 ka for fan emplacement. A more recent study applying OSL dating techniques by Ataee (2019) further support this age. These authors collected Q2a samples from ~10-20 m beneath the surface that resulted in ages of 122.68 +/- 11.81 ka for fan emplacement. Planar surfaces, shallow channel incision, and dull orange surface color are all characteristics consistent with alluvial surfaces that are late Pleistocene in age (Bull, 1991). Several studies have provided ages for the Q2b surficial unit bounding Mission Creek near Cross K Ranch (Plate 1 and Figure 9). South of Mission Creek on the Q2b surface, a series of ^{10}Be exposure dates from Owen et al. (2014) yield a mean age range of 63.01 +/- 2.57 ka for the alluvial fan surface. A later

study by Ataei (2019) applying OSL dating at collection depths of 11.1-12.6 m yields concordant depositional ages for Q2b of 65.07 $\pm$ 8.04 to 78.81 $\pm$ 9.40 ka. These studies suggest that emplacement of Q2b subsurface deposits began ~106 ka and the surface was then abandoned ~65 ka.

Figure 9. Geologic map of the southeast section of the field area. This map layered with NCALM LiDAR imagery shows the sequence of Cabezon fanglomerate alluvial fan surfaces. Q2 units have incised into Q1 alluvium and deposited distally at the basin floor. Unit abbreviations are defined on Plate 1.

The youngest Q2 unit, Q2c, is inset to Q2b on the northern side of Mission Creek and is emplaced near the eastern margin of the Qc₃ alluvial complex (Figure 9). Q2c has the same surface characteristics and clast types as Q2b but contains more abundant boulders

distributed evenly across the entire fan surface. Channel incision is very shallow compared to the well-developed channels on Q2a, so the age of Q2c appears to be significantly younger, suggesting deposition may have extended into the latest Pleistocene. A second Q2b unit, Q2bv, shows similar geomorphic development as Q2b and Q2a but it is sourced from drainages coming from the ridges to the west instead of Mission Creek. Ridges feeding the alluvial plain from west to east are entirely made up of Mcl fanglomerate, so Q2bv fan surfaces are easily distinguishable due to the presence of abundant volcanic clasts of porphyritic rhyolite-dacite and olivine basalt derived from Mcl (Figure 9). Q2bv incises and overlies Q2a and Q2b, and its degree of soil development and channel incision are very comparable to Q2c, so it is inferred to be late to latest Pleistocene age.

Q3 to Q4

Latest Pleistocene to Holocene Q3 units mapped in the study area represent the eastern margin of the Cabezon fanglomerate alluvial complex at the mouth of the active Mission Creek wash. The younger Q3c surface within the walls of the active channel is still being reworked by Mission Creek flooding events along Mission Creek road just west of Highway 62. The older Q3a unit south of Mission Creek is a preserved geomorphic surface on the southwestern banks of Mission Creek. Parts of the surface have been graded and developed during residential development. The intermediate Q3b surface north of Mission Creek is being sourced from an unnamed creek at the northern margin of the Mission Creek Preserve. Q3a and Q3b surfaces share the same degree of channel incision and both display bar and swale surface topography, so they likely

experienced coeval deposition, but Q3b can be distinguished from Q3a by its clast composition being dominant in angular clasts of migmatitic gneiss, giving this unit a light to medium gray surface. This contrasts with Q3a surfaces being very light gray to pinkish gray in color. Rock types of Q3a consist of predominately biotite gneiss, granodiorite and diorite.

The Q3c surface located at the eastern boundary of the map area, along with younger Q4 terrace surfaces bounding the active Mission Creek channel, are part of the modern floodplain. These surfaces are white to very light gray in color. Clasts on the surface of consist biotite gneiss, quartz monzonite, and granodiorite. These clasts are predominately cobble to boulder-sized and coarse sand bars are present within bar and channel topography.

Evidence of Faulting: Mission Creek strand Fault Core

At the eastern boundary of the study area near Highway 62 (Figure 3), the Mission Creek strand transitions from a single through-going trace to a series of diverging and converging discontinuous splays, until it bifurcates into the Mill Creek strand near Wathier Hill. Throughout this area, the Mission Creek strand fault core consists of distinct and well consolidated, white to yellowish gray outcrops of pulverized igneous-metamorphic complex (SGg) (Figure 10). These fault core zones range from 10-150 m wide along the main Mission Creek strand and can be both irregular and linear in shape, with one linear trace in Mission Creek Preserve providing an approximate strike and dip for the main trace (Figure 10A).

These distinct outcrops of pulverized rock are found throughout the study area and are useful tools for projecting fault traces across the map area. There are several series of aligned pulverized outcrops parallel to the Mission Creek strand, which could indicate adjacent strike-slip faults and a left-stepping geometry, as well as several isolated pulverized outcrops in areas displaying tectonic uplift, which may indicate reverse faulting. These pulverized outcrops are then correlated with geomorphic and geologic features in Quaternary alluvium in order to assess whether a fault is still active.

Figure 10. Outcrop photos of the Mission Creek strand fault core. These zones of pulverized bedrock (outlined in black) are within San Geronio gneiss bedrock.

Evidence of Active Faulting: Strike-Slip Faults and a Left-Stepping Fault Geometry

In this section, geologic maps, cross-sections and schematics based on field observations are used to provide evidence of horizontal and vertical displacement adjacent to the Mission Creek strand at four areas from Mission Creek Preserve to Wathier Landing (Plate 1 and Figure 7). From east to west, these areas are: (i) a 2-km-long zone of splays at Mission Creek Preserve, (ii) a 2-km-long continuation of splays at San Geronio Overlook and Beheaded Mission Creek, where only a single inactive strand is currently mapped (*e.g.*, Matti and Morton, 1993; Kendrick et al., 2015), (iii) the onset of a left-stepping geometry at Catpaw Ridge, and (iv) a 3-km-long zone of offset ridges at Wathier Hill.

(i) 2-km-Long Zone of Splays at Mission Creek Preserve

Near the junction of the Morongo Valley fault and Mission Creek strand just north of the Mission Creek alluvial fan complex in Mission Creek Preserve (Plate 1), right-laterally offset features are mapped in deposits of Qd and the landforms associated with Qd. Previous mapping in this region identified three splays of the Mission Creek strand (Proctor, 1968, Matti and Morton, 1992). This study extends the three northern splays and projects their continuation westward throughout the entire field area and identifies an additional two splays.

Throughout the region, the deformed gravels, Qd, were given the distinction of being “deformed” by Allen (1957) due to characteristic tilted bedding throughout the unit

compared to the sub-horizontal Cabezon Fanlomerate unconformably overlying it, but the deformed gravels at area (i) show a much different orientation and style of deformation (Figure 11). Along cross-section D-D' at study area (i): Site 1 (Figure 11), $\sim 70^\circ$ dipping beds are present and abrupt changes in dip direction are observed over a few meters, compared to the more typical $\sim 30^\circ$ northeast dipping beds observed in Qd throughout the study area. The best fit model to resolve the abrupt change in bedding at Site 1 is to place a subvertical fault truncating and folding bedding along the fault (Plate 1, cross-section D-D').

Figure 11. Study area (i) at Mission Creek Preserve. This location is identified in text as the 2-km-long zone of splays. Qd bedding attitudes near Site 1 reveal a steeply-dipping antiform structure along an inferred fault splay. Black arrows near Site 2 highlight offset rills on a north-facing side slope. A surface expression at Site 3 projects to a series of brecciated outcrops. See Figure 2 for location.

Evidence of more recent faulting is observed in area (i) at Sites 2 and 3 (Figure 11). Between the arrows near Site 2, a series of offset rills that have formed on a north-facing slope of mapped Qd deposits (Figure 11 and Plate 1). At Site 2, the fault appears to bifurcate into two splays halfway up the slope, where offset rills continue upslope and project westward to an outcrop of brecciated bedrock on the other side of the ridge, while the other splay bends to the north and appears to offset ridges and ravines (Figure 11). These splays are present in early Pleistocene gravels and Cretaceous bedrock units, so faulting through these units alone does not indicate active faulting, but the small amount of incision within the rills indicates recent faulting, possibly even Holocene in age. Additionally, a 200-m-long scarp on the pediment surface of Qd is mapped and projects to a zone of brecciated bedrock (Figure 11). This scarp also extends 125 m into the younger alluvium of Q1b at its eastern fault tip, suggesting possible middle to late Pleistocene fault activity. At Site 3, more evidence for active faulting is observed in cross-section D-D' where a thin deposit of Qd is juxtaposed to a very thick deposit of Qd. The abrupt change in thickness of Qd at Site 3, from hundreds of meters to tens of meters, suggests lateral translation of the thin deposit.

(ii) Beheaded Mission Creek and San Gorgonio Overlook

Multiples splays of the Mission Creek strand mapped in area (i) appear to continue westward to the San Gorgonio Overlook (SGO) and Beheaded Mission Creek region, area (ii). Evidence for the continuation of these splays is shown in cross-sections B-B' and C-C' of Plate 1. In the area of Beheaded Mission Creek, the main splay of the Mission Creek strand is referred to as Beheaded Mission Creek fault.

Field mapping in area (ii) within the walls of Beheaded Mission Creek indicate evidence of active faulting along Beheaded Mission Creek fault has likely obscured and buried by stream erosion and local debris flows, but fractures in a stream cut bank and a linear scarp in young debris flows suggest recent faulting through area (ii). A cut bank within Beheaded Mission Creek exposes a 5 m-high vertical face of latest Pleistocene-Holocene debris flow deposits (Figure 12A, Sites 1 and 2; Figures 12B and 12C). A 40 m-wide section of this cut bank displays a series of subvertical fractures in an unconsolidated and unstratified sandy unit (Figures 12B and 12C). This sandy unit consists of a light brown, medium to coarse sand-sized matrix that contains the same gravel-sized clasts of gneiss observed in the deformed gravels unit located directly upslope to the west; therefore the debris flow is likely derived from the drainage feeding Site 1. At the location where cross-section B-B' passes through the beheaded channel, a bifurcation of the Beheaded Mission Creek fault is inferred. Here, the southern splay projects to the aforementioned cut bank at Sites 1 and 2 and a linear scarp further to the west, while the northern splay continues along the path of Beheaded Mission Creek. The linear fault scarp to the west of the cut bank of area (ii) is clearly visible in LiDAR images of the area (Figure 13B), and projects to a linear valley further to the west (Figure 13A), and right-laterally offsets an outcrop of M_{cb} (Figure 12A).

Figure 12. Study area (ii) in Beheaded Mission Creek. (A) LiDAR image showing geology and fault geometry across cross-section B-B' as it crosses Beheaded Mission Creek. Colored stars mark location of each site. (B) Photo showing abundant fractures near Site 2 (yellow star). (C) Photo showing abundant fractures near Site 2 (yellow star).

Figure 13. Western section of study area (ii) in Beheaded Mission Creek. (A) Photo with blue arrows highlighting a linear drainage looking to the east from Site 3 in Figure 12 (red star). (B) LiDAR image with red arrows highlighting a linear scarp that aligns with the fractures at Site 2 and the linear feature at Site 3 in Figure 12.

800 m north of Beheaded Mission Creek is San Geronio Overlook (SGO). Field Mapping at SGO of area (ii) reveals three splays of the Mission Creek strand, the northern, middle and southern (Figure 14). The northern and middle splays appear to be inactive, but brecciation is observed in SGg bedrock along these splays. The southern splay appears active and offsets and deflects a series of drainages and rills. The rills are weakly-incised, indicating they are young offset geomorphic features. Along the rills at Site 1 of SGO, evidence of active faulting is observed where SGg is juxtaposed next to younger debris flow deposits (Figure 15).

Figure 14. Study area (ii) at San Gorgonio Overlook. (A) LiDAR image showing tectonic geomorphic features. Red arrows highlight linear scarps and offset rills. Blue lines highlight deflected drainages. (B) Same location with geology added for context.

Figure 15. Photo showing the juxtaposition of bedrock (SGg) and young Quaternary debris flows (Qdf).

Following the trace of the offset rills to the west, the southern splay offsets and deflects channels that are incised into Q1b deposits (Figure 14). These channels are offset by 57 to 67 m. Figure 16 summarizes the progressive offset of these channels.

Channels 1-4 at San Gorgonio Overlook have channel depths of 0.5-3.5 m and are determined to be young to intermediate in age using depth of incision criteria from Christensen and Purcell (1985), indicating offset of these channels has occurred during the late Pleistocene to Holocene. The timeline in Figure 16 proposes that Channel 2 was

incised by Drainage B, translated west along the fault, and recaptured by Drainage A for further incision, giving it a wide channel profile.

Figure 16. Fault reconstruction of offset drainages at San Gorgonio Overlook. Time 1 is the present day and Time 4 shows initial incision of Channel 1. Numbered drainages are highlighted by blue lines. Red arrows highlight offset ridgelines.

Westward along the southern splay of the Mission Creek strand at SGO, several geomorphic features are observed on the Q1b alluvial surface adjacent to the offset drainages. Near Site 5, at least two, and possibly three linear ridges appear parallel to the

southern splay (Figure 14A). Due to their linear E-W orientation along the fault splay rather than N-S in the direction of surface flow, these are likely tectonically induced geomorphic features rather than fluvial.

The fault contact along the southern trace of the Mission Creek strand at SGO also aligns with a change from a thick deposit of alluvium south of the fault to a thin deposit north of the fault at SGO (Figure 14B). Examining the different thicknesses in cross-section B-B' (Plate 1), the change in thickness can be attributed to the orientation of the two fault planes, where the southern fault dips steeply to the north while the two faults to the north are subvertical, forming a positive flower structure geometry that uplifts the thin deposit. The surface of the thin deposit, which is partially a Q1a surface, shows more soil development than the Q1b fan surface south of the fault and displays a pale orange 5YR 8/3 color.

Located west of SGO along the southern splay of the Mission Creek strand, surface displacement is projected WNW along the upper side slope of the north-facing slope of Qc3 (Figure 14B, Site 6). Most of the slope is buried in Qc3 slope debris, so it is difficult to determine the exact location of the Qc3-SGg contact, but small-scale “road cuts” are present along the Pacific Crest Trail running obliquely up the slope. These road cuts reveal small outcrops of SGg bedrock surrounded by Qc deposits. Determining whether the Qc3-SGg contact is depositional or faulted is ambiguous, though there are small 1-2 m wide outcrops of pulverized SGg along the contact that suggest it is faulted. Field observations do support a ~10 m-wide depositional contact where the inferred contact is located. Therefore, since it is assumed a contact between the units lies within the

gradational zone, and this zone is in alignment with the trend of the aforementioned linear ridge, offset streams channels, and offset rills, the fault trace is inferred along the Qc₃-SGg contact on the upper side slope. This solution also infers the Qc₃ unit has been juxtaposed to the SGg bedrock by dextral motion along the southern splay of the SGO fault.

(iii) The Onset of a Left-Stepping Geometry at Catpaw Ridge

West of Beheaded Mission Creek and SGO, evidence of continued active faulting is observed along the crest of a large ridge in an area known as Catpaw (Plate 1). The ridge at Catpaw consists mainly of Qd deposits, with the one exception being a Qc₃ deposit overlying Qd at the northern end of the cross-section. Qd deposits at Catpaw contain abundant exposures of well-preserved, moderately-stratified alluvium providing bedding attitudes throughout the area. These exposures help to locate and connect faults from SGO and Beheaded Mission Creek to the western third of the study area near Wathier Hill. Direct evidence of faulting is not preserved within exposures of Qd, so surface faulting is projected through the Catpaw area based on changes in bedding attitudes and deflected geomorphic features along mapped fault lines. Here, the southern active splay of the Mission Creek strand from SGO bifurcates into a northern and southern splay, renamed here for simplicity as the northern Catpaw fault and the southern Catpaw fault (Figure 17). Additionally, the Beheaded Mission Creek fault continues through this region and an additional fault, referred to as the Paw fault is identified.

Figure 17. Study area (iii) at Catpaw Ridge. A) LiDAR image showing geomorphic features on the terrace surface at Catpaw Ridge. For reference, the terrace has been divided into three zones (southern, middle and northern). B) Proposed offset reconstruction along the northern and southern Catpaw faults.

Along the northern Catpaw fault, several ridgelines, drainages, and head scarps realign with 50-100 m of displacement along the fault, these features are highlighted with thin blue lines in Figure 17B. The offset drainages bounding each ridgeline are incised into both Qd and Qc3. The Qc3 deposits at Catpaw have not been dated by previous studies, so these features do not provide well-constrained timing for fault activity across A-A'. Based on similar soil development and clast characteristics, along with the Qc3-Qd contact at Catpaw and SGO having similar elevations across Beheaded Mission Creek, these deposits likely correlate with Qc3 alluvium observed at SGO.

Along the southern Catpaw fault, restoring 60 m of dextral slip realigns a catchment (highlighted in green) and a head scarp at Site 1 (Figure 17B). This reconstruction also aligns the western edge of the 30 m-thick deposit of alluvium in the southern zone with a 25 m-thick isolated ridge in the middle zone near Site 2 (Figure 17B). Besides their similar thicknesses fitting together well, this realignment forms the side slopes of a considerable drainage using the south-facing slope at Site 2 and the north-facing slope of the southern zone (Figure 17B).

South of the Qc3 deposit at Catpaw, the Paw fault and the continuation of the Beheaded Mission Creek fault are two additional right-lateral faults mapped across cross-section A-A' (Figure 18).

Figure 18. (A) Geologic map showing inferred faults across cross-section A-A'. (B) LiDAR image and geologic map highlighting the Paw fault and the offset of the Paw landmark. The inset Google Earth image views the Paw fault along strike projecting to the east toward Catpaw Ridge.

The Paw is an isolated ridge just east of Catpaw at the confluence of Catclaw Flat and Whitewater River (Figure 18B). The Paw Fault appears to right-laterally offset this isolated ridge from the nose slope to the northeast (Figure 18B). The Paw could simply be a product of stream erosion from Whitewater River, but field observations show it may be a tectonically offset feature because the northern tip of The Paw and the southern end of the nose slope to the northeast both display a large leucocratic dike that may have been connected and severed by the inferred fault. There is also a small Q4b terrace on the east side of The Paw that is observed to be the same alluvium observed at the mouth of Catclaw Flat (Figure 18B).

Attitudes of Qd bedding across cross-section A-A' also suggest the presence of the Paw and Beheaded Mission Creek faults in area (iii) of Wathier Hill. As previously mentioned, Qd deposits in the study area are generally N to NE dipping at $\sim 30\text{-}35^\circ$. Within 75 m of the Paw fault there are several attitudes dipping to the east at $25\text{-}50^\circ$, suggesting the block between the Paw and Southern Catpaw fault may be rotating and deformation is occurring in close proximity to the fault. South of the Paw fault near A-A', bedding orientations change to north-dipping at $\sim 15\text{-}20^\circ$ just north of the Beheaded Mission Creek fault and abruptly become south-dipping on the south side of the fault. An anticline at this location is also possible and may explain the shallow dip attitudes. The folding therefore may result from NW-vergent motion on the thrust fault to the southeast, but this is unlikely due to the proximity of the change in bedding. The change from north to south dipping beds occurs just 10-20 m from the Beheaded Mission Creek fault, and

with the lack of competence within weakly-cemented Qd bedding a parallel fold is not likely. Therefore, bedding across the fault does not appear to be continuous, suggesting south-dipping beds have been laterally translated and juxtaposed to a set of north-dipping beds at this location.

Overall, cross-section A-A' displays four previously unmapped faults south of the Mission Creek strand. Each fault must be inferred due to the lack of direct fault exposures or fault scarps but offset geomorphic surface features and bedding attitudes for subsurface deformation provide evidence for plausible fault locations. It is essential to provide best-fit fault traces through Catpaw Ridge in order to connect evidence of active faulting observed at SGO to offset features at Wathier Hill to the west.

These observations, along with the four faults across A-A', suggest two potential major left-steps along the Mission Creek strand and a series of subsidiary P-shear faults. The first major structure, the northern Catpaw fault, is a continuation of the southern SGO splay that diverges from the main trace of the Mission Creek strand. In cross-section A-A', a series of P-shear faults trending at an $\sim 10\text{-}15^\circ$ angle to relative motion of the northern Catpaw fault are in accordance with classical simple shear models (Tchalenko, 1970). When the northern Catpaw fault reaches Catclaw Flat, the fault bifurcates and takes a left step to the south as it approaches Wathier Hill, while the Paw fault projects into Whitewater channel to the south of Wathier Hill. These are the two faults proposed as potential main structures (or alternative traces to the Mission Creek strand) accommodating dextral motion at the western boundary of the study area.

(iv) 3-km-Long Zone of Offset Ridges at Wathier Hill

The continuation of active faulting westward toward Wathier Hill along projections of the bifurcated Paw fault and the northern Catpaw fault is documented by a series of offset drainages that are incised into Wathier Hill, (area iv) (Figure 19). As these faults continue to the western third of the study area, they enter a region almost entirely made up of Cretaceous bedrock (SGg) near the confluence of the middle and south forks of Whitewater River. The only exception being Qc₁ deposits scattered along the southern slopes of Wathier Hill.

Wathier Hill is a ~3 km-wide, 1000 ft-high isolated ridge that has been translated westward at the base of the San Bernardino Mountains by the ancestral Mission Creek-Mill Creek strands (Fosdick and Blisniuk, 2018; Kendrick et al., 2015). At the base of the northern slopes of Wathier Hill, a series of pulverized outcrops of SGg bedrock can be observed from Catclaw Flat to Wathier Landing (Plate 1), and each trace of the Mission Creek-Mill Creek strand has been mapped along these outcrops on previous USGS and UCERF3 maps. Pulverized outcrops of SGg are also present on the slopes of Wathier Hill and provide two probable trends for fault traces that have not been previously mapped. The northernmost of these two faults, the northern Wathier fault, is a continuation of the northern splay of the bifurcated northern Catpaw fault. Within the Catclaw Flat paleochannel, the northern Catpaw fault splay projects to a small outcrop of pulverized bedrock exposed in a cut bank and then aligns with a series of pulverized outcrops in the northern half of Wathier Hill (Figure 19, Sites 1 and 2). Ridges and

Figure 19. Study area (iv) at Wathier Hill. (A) LiDAR image showing offset features and geology at Wathier Hill. (B) Photo of brecciated bedrock (SGg) at Site 3. (C) Photo of Qc-SGg contact downslope from Site 6. (D) Photo of the knickpoint and brecciated bedrock at Site 4. Geologist for scale is circled in red.

ravines along this trend do not appear to be offset by the fault, so slip is likely abandoned along this trace or transferred to the southern Wathier fault.

The southern Wathier fault is a continuation of the southern trace of the bifurcated northern Catpaw fault. Offset ridges, deflected channels, faceted ridges and displaced Quaternary alluvium are in alignment along an E-W trend on the south-facing slopes of Wathier Hill. Where the southern Wathier fault reaches the eastern boundary of Wathier Hill, no visible outcrops of pulverized rock are present to determine the location of the fault, but just over the crest at Site 3 a fault core is exposed on the head slope of a large drainage (Figures 19A and 19B). Adjacent to the pulverized head slope, Sites 3 through 5 mark the locations of three drainages that appear to be beheaded or deflected (Figure 19D). The two most prominent offset drainages are the channels at Sites 4 and 5, where the currently active drainage at Site 4 has been deflected by a shutter ridge and right-laterally offset ~150 m (Figure 20A). At Site 5, a beheaded paleo-channel along the same trace has been offset by ~400 m from the same point and was likely deflected by the faceted shutter ridge between Sites 4 and 5. Both channels have knickpoints along the fault trace that consist of pulverized and brecciated bedrock (Figure 19D), and these knickpoints do not coincide with any lithologic boundaries so they are likely the result of a shift in drainage location along the fault, accompanied by possible tectonic uplift. The drainage at Site 5 is presumably severed from its source since the west-facing side slope within the drainage dead-ends into the south-facing slope across the fault instead of having a head slope to feed incision. The same relationship of geomorphic features is present at Site 4, where a smaller-scale knickpoint is located where the side slopes of the

Figure 20. Fault reconstructions of the southern Wathier fault at Wathier Hill. (A) Realignment of the drainages at Sites 4 and 6. (B) Realignment of the drainages at Sites 5 and 6.

drainage meet the south-facing slope north of the fault. When reconstructed to align with the drainage at Site 6, the slopes of the knickpoints at Sites 4 and 5 simply become a continuation of the west-facing side slope of the Site 6 drainage (Figures 19A and 19B).

Near the deflected drainages at Sites 5 and 6, there are two outcrops of quaternary deposits on the northern side of the fault (Figure 19A). The deposit near Site 6 is an unstratified, matrix supported conglomerate consisting of predominately subangular clasts, suggesting a debris flow depositional environment (Wells and Harvey, 1987). There are no outcrops of Qc_1 directly upslope, so these deposits were likely sourced by a Qc_1 deposit no longer preserved. The deposit near Site 5 displays stratification, clast-supported layers, and moderate sorting common to traditional flow-type deposits (Figure 19A). The small patch of Qc_1 near Site 5 does not cross the southern Wathier fault and has the same surficial characteristics as deposits across the fault 200 m to the west at Site 7.

On the southern side of the fault at Site 7 of the Wathier Hill area (iv) (Figure 19A), a 10-30 m-thick deposit of Qc_1 sits along the crest of a ridge. This section of Qc is a much thinner than the ~150 m-thick section of Qc_1 located on a head slope north of the fault at Site 8 (Figure 19A). These deposits at Sites 7 and 8 of the Wathier Hill area (iv) seem to originate from the same source but do not match in their size and orientation. The thin deposit at Site 7 has a sub-horizontal contact with SGg bedrock, whereas the thick deposit near Site 8 appears to be cut into the slope in a channelized contact with the bedrock. The thin section of Qc_1 located south of the southern Wathier fault may be right-laterally displaced from the deposits near Site 5 or another deposit that has not been

preserved. The thick deposit of Qc₁ is likely located in its original depositional site relative to the modern Whitewater channel, where stream flow cut into Wathier Hill and deposited a thick fill terrace like the ones observed adjacent to Red Dome on the banks of Whitewater Canyon. If the thin deposit is translated from the east and is not severed from the small terrace deposit at Site 5, it could be part of a terrace deposit from when Catclaw Flat was an active stream channel and the deposit has translated ~1-2 km westward since deposition.

The offsets summarized at Wathier Hill, area (iv), combined with deflected active drainages that are incised into Wathier Hill suggests 1) strike slip faulting along the Mission Creek strand appear to step to the south along a left step and that the southern Wathier fault is a candidate for the proposed active trace of the Mission Creek strand.

Reverse, Normal and Oblique Faults to the Mission Creek Strand

This section summarizes evidence of reverse, normal and oblique faulting throughout the study area by connecting fault scarps and their traces from near Mission Creek Preserve to drainages located to the southwest of Whitewater River using field relations and a cross-section oblique to the Mission Creek strand (Plate 1, cross-section E-E'). From east to west, the two main areas are the: (i) fans at Mission Creek Preserve and (ii) Rainbow Peak fan. These mapped faults indicate fault geometry along the restraining bend of the Mission Creek strand consists of a series of NW-verging reverse faults with thrust-related extensional fractures in the propagating hanging wall.

(i) Fans at Mission Creek Preserve

At Mission Creek Preserve in the northeast section of the study area, a series of fault scarps in middle to late Pleistocene (Q1 to Q2) alluvial fan surfaces trend obliquely to the Mission Creek strand. Two southeast-facing fault scarps mapped northeast of Mission Creek in Q1 and Q2 alluvial deposits indicate reverse faulting (Figure 21, Sites 1 and 2), while a series of northwest-facing scarps are mapped south of Mission Creek as normal faults (Figure 22, Sites 1-4).

At Site 1 of the fans of Mission Creek area (i), a 5-10 m-high sinuous scarp vertically offsets a Q2b fan surface and projects to the west across present day Mission Creek to a saddle along a ridge shown in Figure 21 at Site 3. Here, the fault appears to thrust older Mcl fan conglomerate into younger alluvium of Q2b (Figure 21B). A similar relationship is observed across the paleochannel at Site 4 (Figure 21). Here, the Q2a-Mcl contact on the northwest side of the fault is 30-40 m higher than the same contact on the southeast side. This proposed fault does not appear to continue southwestward.

The larger of the two southeast-facing scarps northeast of Mission Creek is a 30-35 m slope trending $\sim 40-45^\circ$ to nearby splays of the Mission Creek strand (Figure 21, Site 2). This scarp also trends obliquely to the orientation of the Q1b fan deposit. Due to slope debris, the fault producing this scarp is not displayed in the northeastern bank of Mission Creek, but north of the fault vertical displacement is observed where a Miocene basalt flow (Mcb) is thrust onto Qc₃ alluvium (Figure 21A, Sites 6 and 7). These two fault scarps suggest faulting of the surface occurred after deposition of Q2b, which is dated to $\sim 67-106$ ka (Owen et al., 2014). These scarps trend at an expected $\sim 45^\circ$ angle to dextral

Figure 21. Evidence of reverse faulting at Mission Creek Preserve. (A) Geologic map showing reverse fault traces on the Mission Creek Preserve fan surface at Sites 1 and 2. (B) Photo of Mcl volcanics forming a structural wedge with Qc₃ (Q2b) deposits. The width of the field of view is ~275 m. (C) Bare earth LiDAR image with red arrows highlighting two scarps on the fan surface.

Figure 22. Evidence of normal faulting in the study area. (A) Bare earth LiDAR image showing well-preserved scarps on Q2a and Q2b fan surfaces. Red arrows highlight fault scarps. (B) Geologic map of the same area showing study sites and bedding attitudes of Mcl fanglomerate. (C) Photo of a down-dropped terrace surface. Site 3 is located on the southeastern surface. The width of the field of view is ~250 m. (D) Outcrop photo showing the offset of Mcl and Q2b terrace deposits.

motion within a left-restraining stepover (McClay and Bonora, 2001), and are at a similar orientation to a series of large-scale linear drainages located southwest of Whitewater Canyon (Plate 1).

Another indication of late Quaternary faulting includes a series of normal faults observed on and adjacent to Q2a and Q2b fan surfaces in the southeast section of the study area near Mission Creek Preserve. Q2a and Q2b surfaces south of Mission Creek display several northwest-facing scarps, and fault exposures are present in Miocene units in the adjacent canyons to the west.

The Q2b fan surface bounding present day Mission Creek to the south is vertically offset by ~2-3 m. Here, the scarp trends 227°, is sinuous and appears to continue along strike to the southwest (Figure 22, Site 1). Q2bv deposits on the banks of the adjacent drainage to the southwest also appear to be vertically displaced by normal faulting. In profile view, the planar surface of Q2bv on the northwest side of the fault is down-dropped ~2 m relative to the southeast side (Figure 22, Site 3 and Figure 22C). This 2 m difference is approximately the same height as the surface offset of the scarp.

Approximately 1 km to the northwest, another highly visible scarp is present on another Q2bv fan surface (Figure 22, Site 4). Surface displacement of Q2bv at Site 4 is also ~2-3 m and the fault appears to strike at approximately the same orientation, ~220°. To the northwest, ~300 m along the cut bank at Site 5 (Figure 22B), Mcl bedding is well-stratified and a normal fault exposure shows the hanging wall down-dropped ~1 meter along a northwest-dipping fault (Figure 22D). Here, the Q2bv-Mcl contact does not display a clean erosional contact to observe a well-preserved Quaternary offset, but the

northwest side of the Q2bv terrace does appear to be disturbed and down-dropped by ~1 m. In the active channel draining past Sites 5 and 6 and sourcing Q2bv, normal fault exposures within Mcl outcrops are also observed (Figure 23). The minimal displacement from normal faulting in Mcl, Qc₃ and Q2bv suggests the normal component of faulting through the restraining bend of the San Andreas fault is minor and subsidiary to reverse, strike slip and oblique-slip faulting.

Figure 23. Photos of normal fault exposures. (A) Outcrop photo showing the fault exposure in Miocene Coachella fanglomerate from Figure 22, Site 7. A hat is circled for scale. (B) Photo showing the same fault exposure. Black box represents the extent of Figure A. The width of the field of view is ~475 m.

(ii) Rainbow Peak Fan

Two fault scarps are mapped on the Rainbow Peak fan surface trending 40-45° counter-clockwise to the mapped Beheaded Mission Creek fault (Figure 24) indicate reverse faulting continues from the northeast to the west. The Rainbow Peak fan shows the same characteristics as the surfaces located at SGO and parts of Mission Creek Preserve, but this surface is 175-200 m above the modern channel, whereas SGO and Mission Creek Preserve are 125-150 m and 100 m above the modern channel, respectively. Near the confluence of Beheaded Mission Creek and Mission Creek, a pulverized outcrop of SGg bedrock on the side slope of the Rainbow Peak fan aligns with a WNW-facing scarp on the fan surface (Figure 24, Site 1). Additionally, on the fan surface further upslope from Site 1, a 2 m-high sinuous scarp is present in LiDAR imagery and surface profiles across the north-south extent of the fan (Figure 24C). The scarp profile shows slope angle of $< 10^\circ$.

Stratigraphic relationships along ridges near Site 1 also suggest reverse faulting is likely occurring through this section (Figure 24). The tilted contact between Qd-SGg is similar with Qd bedding in the area, where at Sites 3 and 4 beds dip 70-80° to the NNW. The fault trace in the drainage near Site 3 also shows a significant change in bedding orientation across the fault. Qd bedding within the drainage is consistently at 70-80° on the southeast side and 45-55° to the northwest. At Site 5, the fault also appears to displace Cabezon fanglomerate and Miocene volcanic gravels (Mcg). Here, the older Mcg unit is juxtaposed to the younger Qc₃ deposits on the head slope, and atop the head slope on the fan surface, the fault projects to a pronounced scarp that extends from Site 5

Figure 24. Study area of Rainbow Peak. (A) LiDAR image of the Rainbow Peak alluvial fan surface showing two reverse faults across the fan surface. (B) Outcrop photo at Site 3 showing an example of severely tilted Qd bedding found at several locations south of the Beheaded Mission Creek fault. (C) Bare earth LiDAR image displaying two fault scarps on the Rainbow Peak fan surface. The inset graph shows the scarp profile of the easternmost of the two scarps.

to Site 7. The best-fit solution for bedding dips and the Qd-SGg relationship in cross-section C-C' is a severely tilted Qd-SGg erosional contact and drag folding along the fault near Site 3, which caused variations in dip across the fault (Plate 1). The tilted block of Qd is assumed to be part of a translated block of Qd on the southern side of the Beheaded Mission Creek fault.

Downslope from the fan surface boundary near Site 1, a series of terraces appear vertically offset across the fault. In Figure 25, each terrace is highlighted in profile view and labeled according to age (T1 = most recent). This illustrates how T1 and T2 terraces are displaced when the hanging block is uplifted on the southeast side of the fault. On the fan surface, a 15-20 m-high slope is present along the same trace across the entire extent of the fan. The scarp is perpendicular to the southwestern flow path of deposition, so it is likely not a fluvial feature.

Figure 25. Oblique Google Earth image of vertically offset terraces at Rainbow Peak.

A mapped reverse fault along the 15-20 m-high slope is corroborated by a profile view from the south of Rainbow Peak (Figure 26), where the previously-mentioned drag folding in cross-section C-C' is affecting the Qc₃-Mcl contact exposed on the south-facing slopes of the fan. At the Rainbow Peak bench mark (Plate 1), the Qc₃-Mcl contact dips west and thins out to the east, which mimics a drag fold in the underlying Mcl unit. This is also confirmed by the steepening of west-dipping beds moving eastward towards the fault contact (Plate 1 and Figure 26). On the northwest side of the fault contact, Mcl is unstratified and the Mcl unit transitions to massive angular gravels, so it appears bedding observed throughout Mcl is folded on the southeastern side of the fault and discontinuous across the fault.

Two splays are inferred to branch off from the main trace of the Mission Creek strand in the Rainbow Peak area (ii). At Site 6 on the eastern banks of Whitewater River, a Qc₁ terrace deposit dips to the northwest, which differs from nearby terraces that are sub-horizontal or slightly dipping towards Whitewater stream channel (Figure 24). At Site 7, a second possible scarp diverges from the main scarp and is preserved within a surface unit of aeolian sand deposits (Qes). Where the scarp meets the head slope, Qc bedding is moderately stratified and dips 21° to the northeast. Qc beds in the area typically dip in the direction of the depositional flow path (ESE for the Rainbow Peak fan at 10-15°). Therefore, active faulting may have tilted Qc to the northeast. Continuing this fault downslope from Rainbow Peak and Site 7, the best-fit projection is towards a vertical SGg-Mcl contact north of Site 6 and then into Whitewater stream channel, where burial

of the active channel conceals its whereabouts to the west. The vertical contact may be an inactive fault that has juxtaposed younger Miocene deposits to SGg bedrock, indicating it is not part of a series of Quaternary reverse faults, as the nearby drag folds and scarp suggest.

Figure 26. Photo of Mcl drag fold and truncated bedding at Rainbow Peak. These two features line up with the projection of the two fault scarps on the Rainbow Peak fan surface. View is from Whitewater stream channel to the northeast.

The front section of the thrust front in area (ii) is comprised of two reverse faults located at the northwest base of the Rainbow Peak fan. Here, two faults have the same

northeast strike as the two fault scarps displacing the fan surface. At Site 1 in Figure 27, fractures are exposed in a cut bank of the modern Beheaded Mission Creek channel (Figures 14 and 27B). These fractures are located at the base of a drainage and project upslope to a strongly-pulverized outcrop of SGg at crest of the ridge (Plate 1 and Figure 27C). On the backside of the ridge, a second outcrop of pulverized bedrock is present, and the fault is likely buried at the base of the slope to the southwest. Across Whitewater stream channel, no definitive location can be found for the continuation of the fault near Red Dome (Plate 1). The large terrace deposit at Red Dome displays a horizontal Qc₂-SGg contact at the top of the terrace tread, giving way to a tilted or channelized contact on the southeast side of the fault.

In summary, I have presented evidence for two active left-stepping right-lateral strike slip faults and a series of normal and reverse faults oblique to the strike of the left-stepping faults. Geomorphic features and offsets at Mission Creek Preserve show a series of splays that diverge from the inactive trace of the Mission Creek strand and project west, where at San Gorgonio Overlook and Beheaded Mission Creek deflected Holocene channels, fractures in Holocene alluvium, and linear geomorphic features in late Pleistocene surfaces suggest active displacement along two east-west trending right-lateral faults. In the western half of the field area, these right-lateral faults offset several more ridgelines and drainages, and late Pleistocene alluvium at Catpaw Ridge and Wathier Hill. At Mission Creek Preserve and Rainbow Peak, fault scarps on late

Figure 27. Study area northwest of the Rainbow Peak fan. (A) LiDAR image showing two proposed reverse faults branching off the Beheaded Mission Creek fault. (B) Outcrop photo showing the exposed cut bank at Site 1 within the Beheaded Mission Creek stream channel. The width of the field of view is ~30 m. (C) Outcrop photo of pulverized SGg bedrock at Site 2. The width of the field of view is ~50 m.

Pleistocene alluvial fan surfaces and vertically displaced alluvial surfaces provide evidence for active normal and reverse faulting diverging from the proposed right-lateral faults. These observations demonstrate active displacement of middle to late Pleistocene alluvial fans in a region where the Mission Creek strand has been mapped as inactive. Therefore, the tectonic history of the southern San Andreas fault system can be reevaluated and presented in a schematic reconstruction of fan emplacement.

DISCUSSION

Translation and Emplacement of Cabezón Fanglomerate Deposits

Mapping conducted in this study of newly identified faults and structures, combined with published ages for alluvial fans at Mission Creek (Owen et al., 2014, Kendrick et al., 2015, Ataee, 2019) and detrital provenance studies of these fans (Fosdick and Blisniuk, 2018) allow for an alternative interpretation of faulting and fan displacement for the Mission Creek strand of the southern San Andreas fault along its restraining bend. Alluvial fan surfaces and local geomorphology within and adjacent to the Cabezón fanglomerate provide a history of sedimentation and offset of Quaternary deposits coming from Mission Creek and Morongo Valley Canyon drainages. By identifying each fan unit and realigning them with their source drainages we reinterpret a slip history along the Mission Creek strand during the middle to late Pleistocene. Previous models in the study area propose that emplacement of Qc deposits occurred via Whitewater and Hell For Sure drainages throughout their depositional history (Kendrick et al., 2015). This model suggests that Qc deposits have not been translated along the Mission Creek-Mill Creek faults during the late Pleistocene.

However, detailed detrital provenance analysis by Fosdick and Blisniuk (2018) has determined Mission Creek and Morongo Valley Canyon are a more likely source for Qc deposits. This study aims to build on that analysis using fault reconstructions along the Mission Creek strand to illustrate fan emplacement over time (Plate 2).

At Time 1, with approximately 8600 m of dextral slip, Mission Creek flows into Whitewater Canyon on the western boundary of Wathier Hill. This time is chosen as the initial starting point for the reconstructions due to Qc deposits on the southern slopes of Wathier Hill being the westernmost deposits sourced by Mission Creek (Fosdick and Blisniuk, 2018). As previously mentioned, Q1-age Qc units have been divided into three subdivisions (Qc₁, Qc₂, Qc₃), based on location, to distinguish separate generations of deposits. The deposits at Wathier Hill, along with a series of small terrace deposits ~50 m above the modern channel on the eastern slopes of Whitewater Canyon, Qc₁, are likely the oldest Qc deposits in the study area.

The alignment of channels in this model is in agreement with Panels A and B in Figure 13 of Kendrick et al. (2015), but the flow path and timing of deposition vary between my model and theirs. In Time 1, Qc₁ is only sourced from Mission Creek and flow remains within Whitewater Canyon for the deposition of Qc₁ terraces, while in the Kendrick et al. (2015) model the source for Qc₁ originates from both Whitewater and Mission Creek (Qvof2, Panel A). Additionally, Kendrick et al. (2015) interpret Q2 (Qvof3, Panel B) alluvial fans at this location to be of similar age to Qc₁. These fans are proposed to also source Whitewater Canyon through the modern Beheaded Mission Creek corridor. Instead of due east flow from Whitewater River to Beheaded Mission

Creek, my model proposes Morongo Valley Canyon drains into the vicinity of modern Beheaded Mission Creek channel, potentially incising a path captured by Mission Creek drainage at later time frames. Qc deposits coming from Morongo Valley Canyon are inferred to be the grayish brown Qc basal section which is exposed within Beheaded Mission Creek (Figure 6). Between Times 1 and 2, Wathier Hill acts as a shutter ridge and dams flow coming from Mission Creek. By Time 2, flow coming from Mission Creek is redirected through Catclaw Flat and into Whitewater Canyon. Here, younger Qc₂ terraces (0-20 m above the modern channel) are emplaced into the western slopes of Whitewater Canyon. Panel C, Figure 13 in the Kendrick et al. (2015) reconstruction agrees with the drainage configuration and deposition of terraces within Whitewater Canyon shown in Time 2, but the deposition of these terraces comes after the deposition of Q1 and Q2 units, whereas in my Time 2 model deposition of Qc₂ terraces precedes the deposition of Q1 and Q2 units. Based on evidence presented in this study for an active Mission Creek strand, our model assumes continuous dextral displacement into the late Pleistocene and the deposition of Q1 and Q2 units during Time 3 and later, as Mission Creek drainage is captured by several channels along the fault.

At Time 3, Mission Creek is translated and drains into a channel along the Mission Creek strand just north of Catpaw, emplacing a large Qc₃ alluvial fan to the southeast. This time frame is in agreement with age data from Atae (2019) and Balco (2019) that Q1 deposits are 123-260 ka in age. Using estimated slip rates of 15-30 mm/yr (Fosdick and Blisniuk, 2018, Balco et al., 2019) and the 4100 m of total displacement of Mission Creek drainage in Time 3, the age range of deposition for Qc₃ is estimated to ~137-261

ka. These deposits are the light brown upper Qc section overlying the gray basal section exposed in Figure 6 and can be correlated as surficial unit Q1b throughout the field area from Catpaw Ridge to the easternmost section of Mission Creek Preserve (Plate 1). Concurrently, Morongo Valley Canyon is inferred to drain southward towards the distal section of the fan, but the gray Qc basal section is not exposed anywhere distally and cannot be correlated with basal deposits at Beheaded Mission Creek.

The basal section could have also been incised into and eroded by the subsequent emplacement of Q2 units in Times 4 and 5. The capture of Mission Creek by the Beheaded Mission Creek stream channel leads to incision into Qc alluvium and the deposition of Q2a via the Mission Creek paleochannel. Based on Q2b dates from Kendrick et al. (2015) and Owen et al. (2014), incision into Q2a by Q2b via the paleochannel occurs from 67-106 ka. The channel then migrates northward to Mission Creek Preserve during Time 5 and into the modern Mission Creek channel. The drainage configurations in Times 3-5 correlate with Panel D of the Kendrick et al. (2015) reconstruction, with the one difference being Times 3-5 show active deposition of Qc₃ and Q2 units, while Panel D shows Mission Creek incising into a previously deposited Qc₃ and Q2.

At Time 6, Mission Creek flows directly into Beheaded Mission Creek and its downstream flow path incises into Q2b during the deposition of Q2c. During this time interval, Mission Creek paleochannel is abandoned and incision is rerouted into modern Mission Creek. Morongo Valley Canyon is now draining onto the alluvial plain in northwest Coachella Valley, where preservation of fan surfaces is minimal due to urban

development and burial from debris flow deposits coming from the San Bernardino Mountains range front.

As dextral displacement continues, the ridge of Qc₃ deposits at San Gorgonio Overlook blocks Mission Creek from depositing sediment from the upper reaches of Mission Creek into Beheaded Mission Creek during Time 7. Two flow paths for Mission Creek are considered during this period. The first is a path across San Gorgonio Overlook that reworks Qc deposits on the fan surface. This interpretation is supported by ¹⁰Be exposure dates on boulders of the Q1 surface by Owen et al. (2014), which indicate ages of 12-42 ka for the fan surface. A second potential path for Mission Creek during Time 7 is a redirection to the southwest into Beheaded Mission Creek, where it incises into the Qc₃ alluvial fan parallel to the path of the Pacific Crest Trail and flows into Whitewater Canyon. Outcrops of *in situ* alluvium are not present within the drainage leading to Whitewater, but a veneer of Cabezon deposits can be found throughout this drainage, suggesting flow may have occurred through this area.

At Time 8, ~1200 m of dextral displacement along the Mission Creek strand brings the damming of Mission Creek to the eastern end of San Gorgonio Overlook, where the reworking of fan surface material continues until ~10-20 ka and flow redirects east towards Mission Creek Preserve. Here, an unnamed channel incises into the northern boundary of the Qc₃ alluvial fan. Ridges adjacent to the unnamed channel are predominately Qd deposits, but several patches of Qc deposits present on nearby ridges confirm flow sourced by Mission Creek occurred through this area.

By Time 9, resurfacing of San Gorgonio Overlook has been abandoned and Mission Creek has been captured by the modern Mission Creek channel. In this time interval, Q3a incises into Q2b and is emplaced distally at the eastern boundary of the field area. Concurrently, Q3b is sourced from headwaters adjacent to the Mission Creek fault just north of Mission Creek Preserve. The head slopes of the source area are made up of SGg migmatites, and clasts on the Q3b surface are distinct from Qc deposits sourced from Mission Creek and Morongo Valley Canyon. Based on the path and higher volume of flow coming from Mission Creek, Q3a likely incised into Q3b during their coeval deposition.

During Time 10, Mission Creek continues along the path of modern Mission Creek as Q3c incises into Q2 and Q3 units. Total dextral displacement at this time frame is only 50-160 m, so the path of Mission Creek is almost identical to the configuration of modern Mission Creek. In Time 11, as Q4 deposits incise into several units of the Cabezon fan conglomerate, the present layout of the alluvial complex is shown.

CONCLUSIONS

Faults presented in this study have: (1) tilted and uplifted a mid-Pleistocene alluvial fan complex; (2) produced dip-slip displacement in mid to late Pleistocene fan surfaces along fault scarps; and (3) laterally offset stream channels that were incised during the latest Pleistocene and possibly Holocene. Most interestingly, laterally offset ridges, drainages, and debris flows are observed along an unmapped trace of the Mission Creek strand and several possible splays. Pulverized and brecciated bedrock and abrupt changes

in bedding attitudes of early Pleistocene gravels are then used to project the fault trace into the San Bernardino Mountains, where the fault likely connects with the San Bernardino strand near Yucaipa Ridge. These observations allow for a revised interpretation of fault evolution for the San Andreas fault in southern California along a restraining bend in northern Coachella Valley, and combined with cross-sections across the mapped region I suggest the geometry of faulting in this region is partitioned across several strands and has migrated across several unmapped strands, including an active and previously unmapped Mission Creek strand and several subsidiary reverse faults adjacent to the Mission Creek left-restraining bend.

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