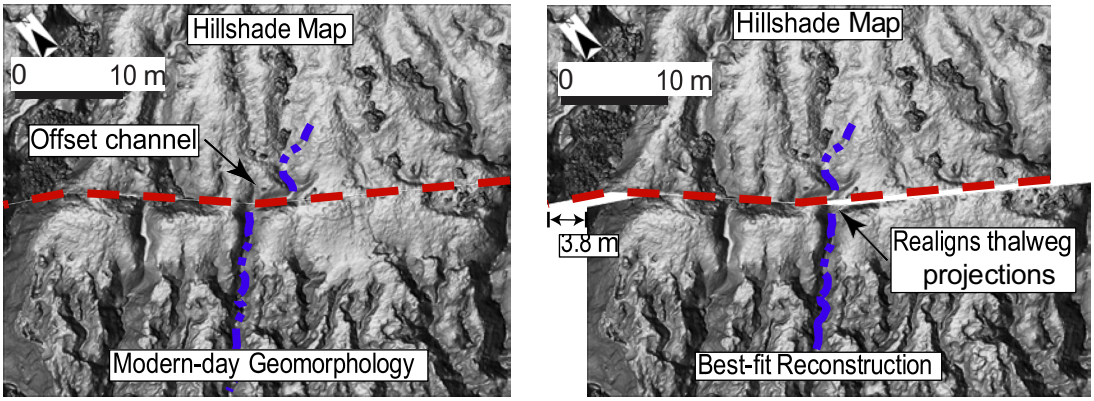
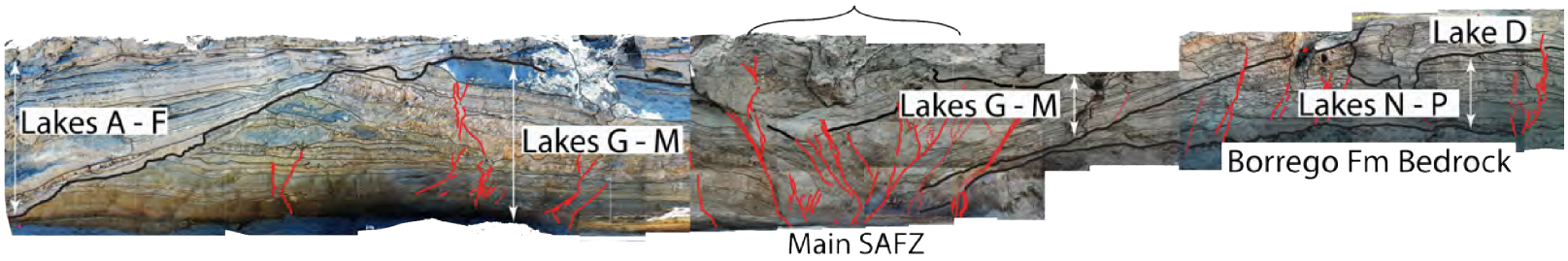
Friends of the Pleistocene Annual Field Trip 2023

Salt Creek Offset Reconstruction



Offset reconstruction representing the Most Recent Event (MRE) for a feature located at Salt Creek with modern-day geomorphology (left) and inferred reconstruction (right). Offset location: 33.4436464, -115.8366745

Salt Creek Trench Log



Trench log exhibiting the complex, 5,000-year lake history across the southern San Andreas Fault (sSAF) at Salt Creek.

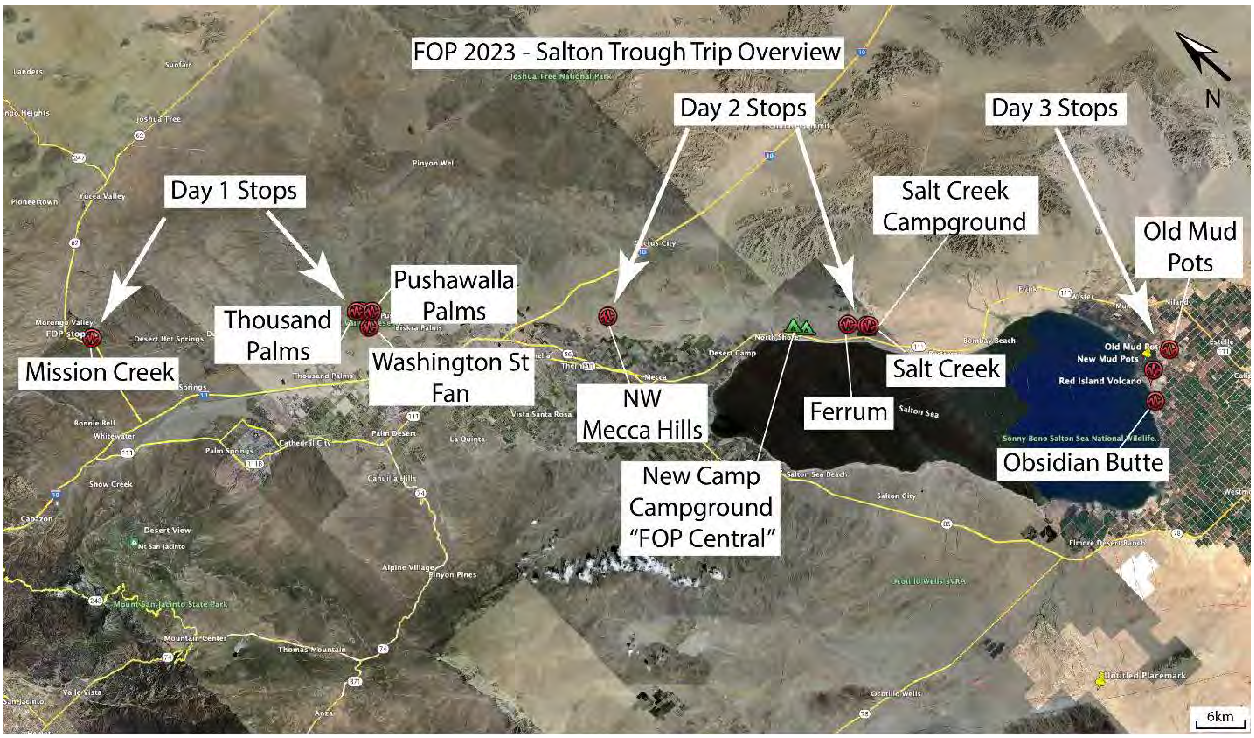
FOP 2023 Pacific Cell Guidebook Table of Contents

1. *Road Log (description of stops and how to get to/from stops) – pages 3-16*

2. *Day 1 Papers Relevant to Each Stop – pages 17-316*

3. *Day 2 Papers Relevant to Each Stop – pages 317-462*

4. *Day 3 Papers Relevant to Each Stop – pages 463-570*



FOP Field Trip Stops

First and foremost, we will be congrega ng at 'FOP Central' which is located at the New Camp Campground, located along the northeastern shoreline of the Salton Sea. Camping in this area is covered via the FOP registra on fee. This campground includes plenty of shade, bathrooms, and even showers! We will ideally be congrega ng together at 'FOP Central' before and a er our field stops each day.

FOP Central coordinates: 33.501701, -115.912130

Day 1

To kick off the trip, we will be heading into the Indio Hills where the San Andreas Fault splits off into two strands – the Mission Creek and Banning strands! First, we will be mee ng at the Pushawalla Palms Trailhead (Blisnuk). We will plan to leave New Camp Campground at 8:30am on Friday morning.

Pushawalla Palms Trailhead coordinates: 33.8353, -116.3069

Drive time from 'FOP Central': ~45 minutes

Details on how to get there from 'FOP Central' at New Camp are as follows:

1. *Make your way out of the campground toward the main road (CA-111)*
2. *Turn left onto CA-111 (follow for 13.1 miles)*
3. *Turn right onto 62nd Avenue (follow for 0.2 miles)*
4. *Turn right onto CA-86 (follow for 10.3 miles)*
5. *Merge onto I-10 W (follow for 6.6 miles)*
6. *Take exit 137 toward Washington Street (follow for 0.3 miles)*
7. *Use the middle lane to turn left onto Varner Road (follow for 0.2 miles)*

8. *Use the right 2 lanes to turn right onto Washington Street (follow for 5.0 miles)*
9. *Turn right onto Thousand Palms Canyon Road (follow for 1.8 miles)*
10. *Park at the dirt lot near the Pushawalla Palms Trailhead. If the parking lot becomes full, park along the dirt shoulders on either side of the road.*

Next, we will be heading to the Thousand Palms Oasis Preserve (Seitz).

Thousand Palms Oasis Preserve coordinates: 33.8370, -116.3101

Walking / driving time: ~5 minutes walking / ~1 minute driving

Details on how to get there from Pushawalla Palms Trailhead are below.

1. *Driving here isn't necessary, as it is a short walk from the trailhead (~0.3 miles). If you do wish to drive, follow the same instructions as below. There is a parking lot but space is not guaranteed for everyone.*
2. *From the trailhead, begin walking northeast along Thousand Palms Canyon Road for about ¼ mile.*
3. *You will then see a sign on the left-hand side of the road which says 'The Coachella Valley Preserve'.*
4. *Follow the sign by turning left onto the gravel road, and walk ~500 feet (~150 meters) towards the cluster of palm trees.*

A⍰er this, we will be heading to the Washington Street Fan/Banning Fault Site (Scharer, Blisniuk).

Washington Street Fan/Banning Fault Site coordinates: 33.8160, -116.3121

Drive time from Pushawalla Palms Trailhead: ~3 minutes

Details on how to get there from Pushawalla Palms Trailhead are as follows:

1. *Travel southwest down Thousand Palms Canyon Road (follow for 1.8 miles)*
2. *Turn left onto Washington Street (follow for 0.8 miles)*
3. *Park along the dirt shoulders on either side of the road.*
4. *Hike ~300 feet (~91 meters) northeast towards the Washington Street Fan.*

t- from Coachella Valley Preserve, California
Io Coachella Valley Preserve, California

5 min (3.0 miles)
VIDThous.ind Palmt Canyoo Rd and Washlngtoo S1
Fasl t route now due to traffic conditions

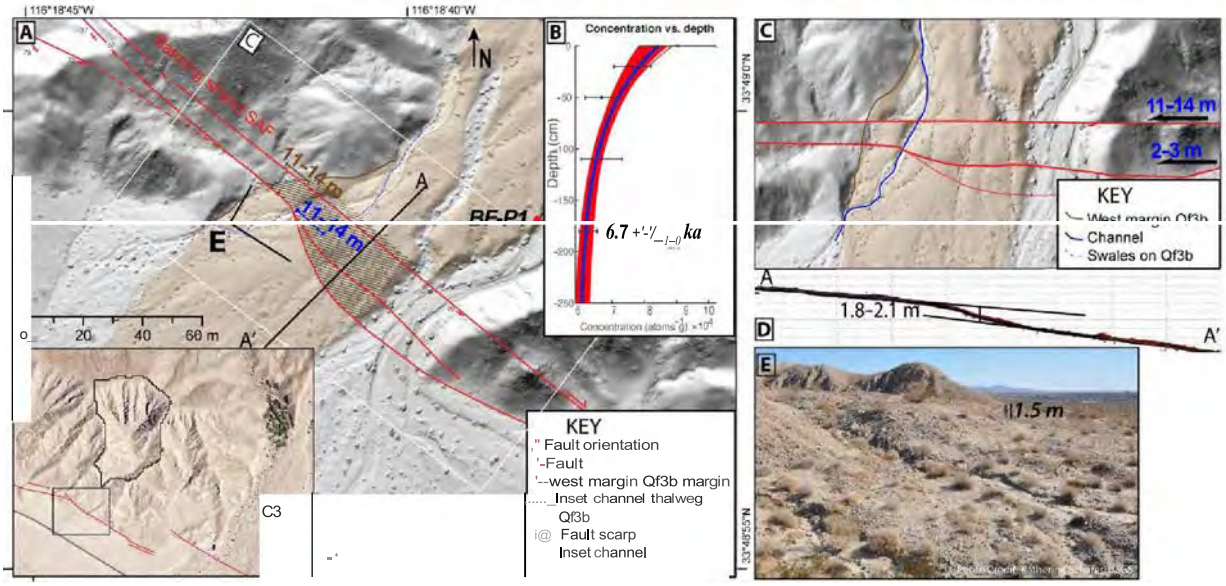
Coachella Valley Preserve
Ca1ifomia

T Head northeast toward Thoosand Palms Canyon Rd

.,_. Turn nghl onto Thousand Palms Canyon Ad

+-, Turnlel! on10 Washlng1on St
0 Oestlnttlon will be on the left

Coachella Valley Preserve
Californua



We will then head up to Mission Creek to explore/debate recent slip history along the Mission Creek strand of the San Andreas Fault (Ma et al).

Mission Creek coordinates: 34.0087, -116.5806

Drive time from Washington Street Fan: ~28-35 minutes

Details on how to get there from Washington Street Fan are as follows:

1. *Head northwest on Washington Street toward Thousand Palms Canyon Road (follow for 1.0 miles)*
2. *Continue onto E Ramon Road (follow for 3.5 miles)*
3. *Turn left onto Monterey Avenue (follow for 0.6 miles)*
4. *Turn right to merge onto I-10 W (follow for 14.2 miles)*
5. *Take exit 117 for CA-62/29 Palms toward Yucca Valley (follow for 0.4 miles)*
6. *Continue onto CA-62 E/29 Palms Highway (follow for 6.1 miles)*
7. *Slight left toward N Indian Canyon Drive/Kolbe Road (0.1 miles)*

8. *Continue onto N Indian Canyon Drive/Kolbe Road (0.2 miles)*
9. *Turn right along a restricted usage road for 0.2 miles (there are two dirt roads to turn right onto…turn right onto the 2nd possible option) and park somewhere along the dirt road.*

That will be a wrap for Day 1 at FOP! The only thing left to do is go back to FOP Central, drink some beer, and discuss/debate some of the things that have been brought up today. Slip activity along the Mission Creek strand of the fault might facilitate some interesting discussion!

Details on how to get back to FOP Central from here are as follows:

Drive time from Mission Creek to FOP Central: ~1 hour 20 minutes

1. *Head back to CA-62 W and turn right onto the highway (follow for 6.2 miles)*
2. *Keep right at the fork, follow signs for I-10 E/Indio/Palm Springs and merge onto I-10 E (follow for 28.5 miles)*
3. *Use the right 2 lanes to take exit 145 for California 86 toward Brawley/El Centro (500 ft)*
4. *Continue straight onto CA-86 S (follow for 12 miles)*
5. *Use the left lane to take the 66th Avenue ramp to CA-111 S/Niland/Calipatria (follow for 0.2 miles)*
6. *Turn left onto 66th Avenue (follow for 0.7 miles)*
7. *Turn left onto Lincoln Street (follow for 0.1 miles)*
8. *Turn right toward CA-111 S and make a slight right onto CA-111 S (follow for 10 miles)*
9. *Turn right onto State Park Road*

Day 2

We will kick off Day 2 by heading down to the Salt Creek Paleoseismic Site (Rockwell, Williams, Scharer).

Salt Creek Parking Area: 33.4457, -115.8430

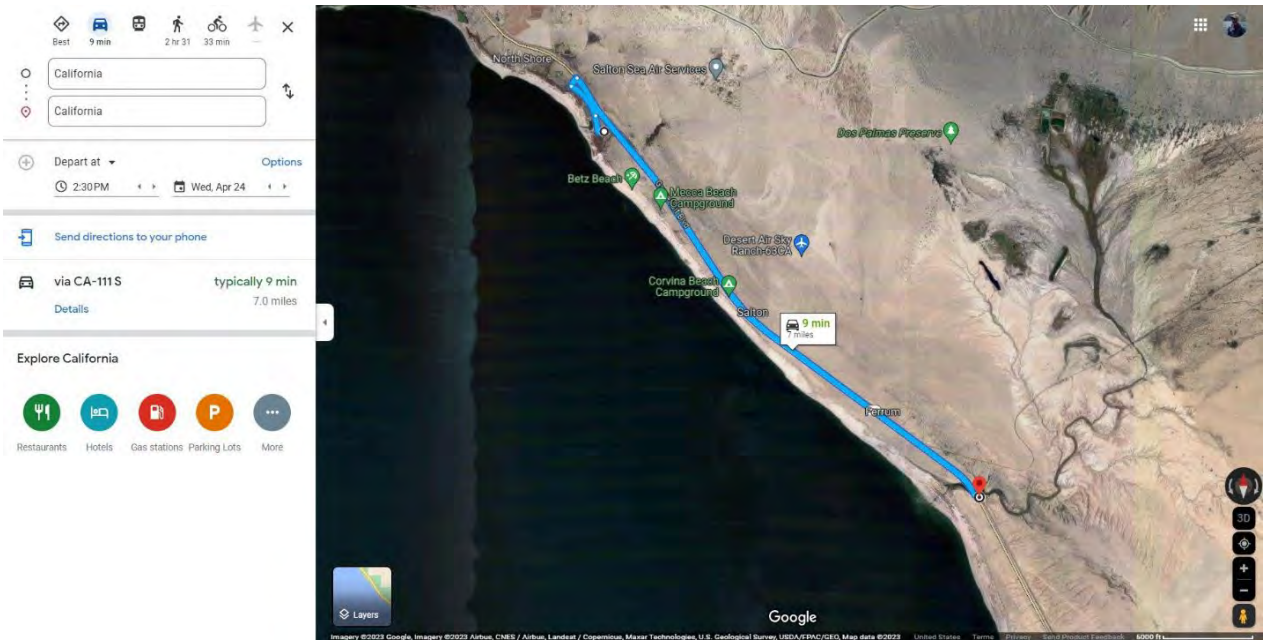
Salt Creek Paleoseismic Site: 33.4460, -115.8398

Drive time to the Paleoseismic Site: ~10 minutes

Details on how to get to the parking area from FOP Central are as follows:

1. *Make your way out of the campground toward the main road (CA-111)*
2. *Turn right onto CA-111 S (follow for 6.2 miles)*

You will see a large dirt shoulder on the le-hand side of the road, shortly a er you drive past a railroad bridge on the le . Park anywhere in this dirt area. The hike to the paleoseismic site from here will take roughly 5-10 minutes.



After this, we will head to one of Roger Bilham's creepmeters.

Creepmeter coordinates: 33.4485, -115.8436

Directions to the creepmeter are as follows:

1. *We won't need to drive, as Roger's creepmeter is fairly close to the paleoseismic site. We will instead walk over to the site, which is roughly a 0.5 mile walk from the parking area.*
2. *From the parking area, walk north-northwest along the highway until you cross the bridge.*
3. *Once you cross the bridge, walk into the large open dirt area on the right-hand side and make your way towards the railroad bridge.*
4. *Walk underneath the railroad bridge and turn left onto the existing dirt road/path.*
5. *Follow the dirt road/path for ~500 feet and you should see the creepmeter on the left-hand side.*

A⍰er the creepmeter, we will begin looking at geomorphology along the fault in the form of offset channels/streams by first star⍰ng at Ferrum (Buckley et al.). We will have to hop back in our cars briefly to meet up at this next spot.

Ferrum parking area coordinates: 33.4578, -115.8603

Ferrum offset coordinates: 33.4615, -115.8583

Drive time to Ferrum from Salt Creek: ~1 minute

Details on how to get to the parking area at Ferrum are as follows:

1. *Head northwest along CA-111 N for 1.3 miles.*
2. *You will see several turnouts on the right-hand side of the road which lead into a large open dirt area.*
3. *Turn in anywhere you see fit for parking.*
4. *To get to the offset, we will have to hike ~1/4 mile to the north-northwest.*

A⍰er Ferrum, we'll head over to the northwestern side of the Mecca Hills to look at more geomorphic offsets (Blanton et al).

Northwestern Mecca Hills parking spot coordinates: 33.6450, -116.0774

Drive time: ~26 minutes

Details on how to get to this next parking area from Ferrum are as follows:

1. *Head northwest on CA-111 N (follow for 19.4 miles)*
2. *Turn right onto 62nd Avenue (follow for 0.5 miles)*
3. *Turn left onto Buchanan Street (follow for 3 miles)*
4. *Turn right onto Airport Blvd (follow for 0.2 miles)*
5. *Turn right after crossing the canal and follow the road through the existing facilities (follow for 1 mile)*
6. *You'll see a large open dirt area on the left-hand side of the road, where we will park and meet.*

f- from California
10 Thefmal, ca11romla 92274

26 min (22.0 miles)
viaCA-111 N

Add to Calenclar

California

Heed northwe(,-1on CA-111N
18.lii,j

r+ Tum rlgtrt onto 62ml Ave
O!imi

•,, Tum leh ooto Buchanan St
IIIIII

r+ Tum rlgh1ont0Nrpon BlIJd
oIIIII

•,, Tumlert
O Destinahon will be oo tt,e left
oimi

Thermal
Calllornia92274

That's a wrap for Day 2 at FOP! We will meet back at FOP Central for more beer and discussion.

Drive time back to FOP Central: ~35 minutes Direc⍰ons

back to FOP Central are as follows:

1. *Make your way back across the canal and head west along Airport Blvd (follow for 0.2 miles)*
2. *Turn left onto Buchanan Street (follow for 1.0 miles)*
3. *Tur right at the 2nd cross street onto Avenue 58 (follow for 1.9 miles)*
4. *Turn left onto CA-111 S (follow for 15 miles)*
5. *Turn right onto State Park Road into the campground*

Day 3

We will be closing off this FOP trip with a couple unique stops, the first of which is Obsidian Bute along the southern shoreline of the Salton Sea.

Obsidian Butte coordinates: 33.1711, -115.6375

Drive time from FOP Central: ~50 minutes

Details on how to get to Obsidian Bute from FOP Central are as follows:

1. *Make your way out of the campground toward the main road (CA-111)*
2. *Turn right onto CA-111 S (follow for 37.0 miles)*
3. *Turn right onto Estelle Road/W Sinclair Road (follow for 5.5 miles)*
4. *Turn left onto Gentry Road (follow for 0.5 miles)*
5. *Turn right onto McKendry Road (follow for 1.1 miles)*
6. *Turn right onto the first dirt road that you see and follow for 0.2 miles.*
7. *Park anywhere you see fit. We will take a brief hike (~500 feet) up Obsidian Butte*

We will then head to the 'Old Mud Pots' aka mud volcanoes. These mud volcanoes are continuously flowing (erupting, if you want to call it that) and the mud temperature is relatively mild, up to about 100 degrees F or so.

Old Mud Pots coordinates: 33.2006, -115.5781

Drive time to Old Mud Pots: ~20 minutes

Details on how to get to the Old Mud Pots are as follows:

1. *Head back towards McKendry Road and turn left onto McKendry Road (follow for 1.1 miles)*
2. *Turn left onto Gentry Road (follow for 0.5 miles)*
3. *Turn right onto Estelle Road/W Sinclair Road (follow for 4.0 miles)*
4. *Turn left onto English Road (follow for 1.5 miles)*
5. *Turn left onto W Schrimpf Road (follow for 2.0 miles…….weird name for a road huh??)*
6. *Turn right onto Davis Road (follow for 0.2 miles)*
7. *Park anywhere you see fit along the dirt shoulders on either side of the road.*
8. *We will have to take a brief hike (~1/4 mile) to the mud volcanoes.*

f- from Obsidian Butte, Caltfomla 92233
to Old MudPots, Calipa1ria, CA 92233

20 min (9.5 miles)
Yla Estelle Rd/W Slndalr Rd

tl:J Add tc. Cille-ndar

Obsidian Butte
Califomia92233

t Head northeast toward McKe.idry Rd
'''''
<t--, Turn left onlo Mc:Kendry Rd

<t-, TurnleftontoGentryRd

r Turn right onto Estelle Rd/W Sinclair Rd

4--i Turn leftonto Eni;illsh Rd
'''''
+-i Turn left onto W Schrimpf Rd
' o '''
r T um right ontoDavis Rd

Old Mud Pets
Calll]ltlla, CA 92233

DAY 1 PAPERS

GEOLOGY

A revised position for the primary strand of the Pleistocene-Holocene San Andreas fault in southern California

Kimberly Blisniuk[1]*, Katherine Scharer[2], Warren D. Sharp[3], Roland Burgmann[4], Colin Amos[5], Michael Rymer[6]

Copyright © 2021 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

The San Andreas fault has the highest calculated time-dependent probability for large-magnitude earthquakes in southern California. However, where the fault is multistranded east of the Los Angeles metropolitan area, it has been uncertain which strand has the fastest slip rate and, therefore, which has the highest probability of a destructive earthquake. Reconstruction of offset Pleistocene-Holocene landforms dated using the uranium-thorium soil carbonate and beryllium-10 surface exposure techniques indicates slip rates of 24.1 ± 3 millimeter per year for the San Andreas fault, with 21.6 ± 2 and 2.5 ± 1 millimeters per year for the Mission Creek and Banning strands, respectively. These data establish the Mission Creek strand as the primary fault bounding the Pacific and North American plates at this latitude and imply that 6 to 9 meters of elastic strain has accumulated along the fault since the most recent surface-rupturing earthquake, highlighting the potential for large earthquakes along this strand.

Downloaded from http://advances.sciencemag.org/ on April 1, 2021

INTRODUCTION

Landforms offset along faults by surface-rupturing earthquakes preserve a cumulative record of fault motion over time. When combined with their ages of formation, these offset landforms may be used to calculate average long-term fault-slip rates. Slip rate data, especially over multiple time intervals, are fundamental to understanding the kinematic partitioning of deformation along an evolving plate boundary. These slip rate data are also important when evaluating earthquake hazard because in most long-term probabilistic seismic hazard models, the faster a fault slips, the greater the likelihood of a future earthquake [e.g., (*1*, *2*)].

The faults of the southern San Andreas fault system, inclusive of the San Andreas fault (SAF), San Jacinto fault, and Elsinore fault (Fig. 1A), all accommodate Pacific–North American (PA-NA) plate motion and all pose seismic hazard (*1*). Of these, the SAF poses the greatest hazard potential because the southernmost section has not ruptured since ca. 1726 CE (Fig. 1A) (*3*), and geodetic data suggest that the fault accumulates interseismic strain of up to 25 mm/year, roughly half of the motion across the PA-NA plate boundary [(*4*) and references therein]. However, the SAF is multistranded along this section so it is uncertain which strand of the SAF carries the most slip and poses the greatest rupture likelihood [e.g., (*5*, *6*)]. Furthermore, obtaining geologic slip rates for some strands of the fault has proven challenging, while geodetic slip rate models have limited resolution in places where faults are closely spaced or multistranded, as the SAF is in southern California.

In the Coachella Valley in southern California near the Indio Hills, at the Biskra Palms site, the SAF is estimated to slip at a rate of ~12 to 22 mm/year (14 to 17 mm/year, preferred) (Fig. 1A) (*7*). Northwest of this location, the SAF bifurcates into the Mission Creek and Banning strands (Fig. 1A). Farther northwest, the SAF further partitions and encompasses the Mission Creek, Banning, and Garnet Hill strands and San Gorgonio Pass fault zone (Fig. 1A). Here, the relative proportion of plate boundary deformation accommodated by each strand of the SAF remains unresolved (*7*–*11*), despite the distinct implications that slip rates would have on earthquake rupture forecasts and understanding the tectonic configuration of this complex region. Several studies suggest that the majority of plate boundary deformation is localized along the Banning and Garnet Hill strands and the San Gorgonio Pass fault zone (Fig. 1B) because kinematic models for the region infer that the Mission Creek strand and its northwest continuation as the Mill Creek strand is inactive [(*8*–*11*) and references therein]. The Banning and Garnet Hill strands and San Gorgonio Pass fault zone are assumed by current hazard models (*1*) to take up most of the lateral strain at this latitude and, therefore, are considered most likely to rupture in a future SAF earthquake (*12*).

Many kinematic models indicate that as the SAF bifurcates northwestward into the Mission Creek and Banning strands at Biskra Palms, slip on the Mission Creek strand diminishes to the northwest. For example, slip rates on the Mission Creek strand are thought to decrease from values of 14 to 17 mm/year at Biskra Palms (*7*) to ~2 to 6 mm/year (*13*) at the Thousand Palms site located in the Indio Hills and 0 to 3 mm/year near the San Bernardino Mountains ~30 km to the northwest (Fig. 1A) [(*1*) and references therein]. Near Thousand Palms, the majority of SAF slip has been inferred to occur along the Banning strand [(*7*–*11*) and references therein]. The postulated reduction in slip rate and, therefore, diminished rupture likelihood on the Mission Creek strand has been explained by a model of regional fault reorganization that attributes transfer of slip off the Mission Creek strand to a change in fault geometry as the SAF evolves to a restraining bend near the southern Little San Bernardino Mountains (*9*–*11*). This transfer of plate boundary deformation off of the Mission Creek strand is thought to have occurred ~500 to 100 ka, as deformation migrated westward onto the Banning and Garnet Hill strands, San Gorgonio Pass fault zone, and northward into the Eastern

[1]Geology Department, San Jose State University, San Jose, CA 95192-0201, USA. [2]U.S. Geological Survey, Earthquake Science Center, Pasadena, CA 91106, USA. [3]Berkeley Geochronology Center, Berkeley, CA 94709, USA. [4]University of California, Berkeley, Berkeley, CA 94720-4767, USA. [5]Western Washington University, Bellingham, WA 98225, USA. [6]U.S. Geological Survey, Earthquake Science Center, Menlo Park, CA 94025, USA.
*Corresponding author. Email: kimberly.blisniuk@sjsu.edu

Downloaded from gsabulletin.gsapubs.org on July 6, 2010

Uncertainties in slip-rate estimates for the Mission Creek strand of the southern San Andreas fault at Biskra Palms Oasis, southern California

W.M. Behr[1,†], D.H. Rood[2], K.E. Fletcher[3], N. Guzman[4], R. Finkel[2], T.C. Hanks[5], K.W. Hudnut[6], K.J. Kendrick[6], J.P. Platt[1], W.D. Sharp[7], R.J. Weldon[8], and J.D. Yule[4]

[1]*Department of Earth Sciences, University of Southern California, Los Angeles, California 90089, USA*
[2]*Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[3]*Department of Earth and Planetary Science, University of California, 307 McCone Hall, Berkeley, California 94720-4767, USA*
[4]*Department of Earth Sciences, California State University, 18111 Nordhoff Street, Northridge, California 91330, USA*
[5]*U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA*
[6]*U.S. Geological Survey, 525 South Wilson Avenue, Pasadena, California 91106, USA*
[7]*Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, California 94709, USA*
[8]*Department of Geological Sciences, 1272 University of Oregon, Eugene, Oregon 97403, USA*

ABSTRACT

This study focuses on uncertainties in estimates of the geologic slip rate along the Mission Creek strand of the southern San Andreas fault where it offsets an alluvial fan (T2) at Biskra Palms Oasis in southern California. We provide new estimates of the amount of fault offset of the T2 fan based on trench excavations and new cosmogenic ^{10}Be age determinations from the tops of 12 boulders on the fan surface. We present three alternative fan offset models: a minimum, a maximum, and a preferred offset of 660 m, 980 m, and 770 m, respectively. We assign an age of between 45 and 54 ka to the T2 fan from the ^{10}Be data, which is significantly older than previously reported but is consistent with both the degree of soil development associated with this surface, and with ages from U-series geochronology on pedogenic carbonate from T2, described in a companion paper by Fletcher et al. (this volume). These new constraints suggest a range of slip rates between ~12 and 22 mm/yr with a preferred estimate of ~14–17 mm/yr for the Mission Creek strand of the southern San Andreas fault. Previous studies suggested that the geologic and geodetic slip-rate estimates at Biskra Palms differed. We find, however, that considerable uncertainty affects both the geologic and geodetic slip-rate estimates, such that if a real discrepancy between these rates exists for the southern San Andreas fault at Biskra Palms, it cannot be demonstrated with available data.

†E-mail: behr@usc.edu

INTRODUCTION

This study builds upon a long history of estimating the geologic slip rate of the Coachella Valley segment of the southern San Andreas fault where it offsets an alluvial fan at Biskra Palms Oasis, California (Fig. 1) (Keller et al., 1982; Dorsey, 2003; van der Woerd et al., 2006). Keller et al. (1982) first used displaced fan remnants at Biskra Palms to propose a late Quaternary mean slip rate of 23–35 mm/yr, a rate that for more than two decades remained the benchmark for long-term geologic slip on the southern San Andreas fault. Because of increasing interest in late Quaternary strain budgets and seismic hazard evaluation for the southern San Andreas fault zone, the Biskra Palms site has been recently reevaluated, leading to conflicting interpretations of both the amount of offset and the age of the fan, and to apparent discrepancies of up to 10 mm/yr between geologic and geodetic slip rates for this region (Dorsey, 2003; van der Woerd et al., 2006).

We continue this reevaluation and complement existing geologic and geochronologic data with new estimates of the amount of offset based on new trench excavations and new age determinations for the T2 fan. This unusually complete and diverse data set allows us to focus on the uncertainties in the geologic slip rate at this important location on the Coachella Valley segment of the southern San Andreas fault. Rather than choosing a single estimate of fault offset, for example, we present three alternative offsets. We also consider different surface-exposure–age sampling strategies, which provide different ages of the offset fan surface, and we compare these results to those obtained from U-series age determinations of pedogenic carbonate developed in the deposits of this fan, described in a companion paper by Fletcher et al. (this volume). The different offsets and ages we consider here lead to a wide range of permissible geologic slip rates for the Coachella Valley segment of the southern San Andreas fault at Biskra Palms, 12–22 mm/yr.

This study also revisits the "slip-rate discrepancy" at Biskra Palms, as it is thus far the only site on the southern San Andreas fault where a long-term (millennial) slip-rate estimate can be obtained and compared to short-term (decadal) slip-rate estimates from geodesy. Recent comparisons of slip-rate data worldwide have highlighted discrepancies between long-term and short-term slip-rate estimates. The best-known examples are for the great strike-slip faults of Tibet, where geologic slip-rate estimates are commonly greater than those inferred from geodetic data (Meriaux et al., 2004, Meriaux et al., 2005; Thatcher, 2007). These discrepancies, if common for active crustal faults, have profound implications for how the crust accumulates and releases elastic strain and potentially for seismic clustering and seismic hazard (Peltzer et al., 2001; Dolan et al., 2007; Oskin et al., 2008). In many instances, however, a more fundamental question is whether these slip-rate discrepancies are real, given the uncertainties in geodetic modeling choices and capabilities and in the offsets and ages from which geologic slip rates are calculated. On the Altyn Tagh fault, for instance, considerable concern has recently arisen as to whether the slip-rate discrepancy of ~15 mm/yr is more a function of uncertainties in the geologic data rather than temporal variations in slip rate (e.g., England and Molnar, 1997; Brown

GSA Bulletin; September/October 2010; v. 122; no. 9/10; p. 1360–1377; doi: 10.1130/B30020.1; 15 figures; 3 tables.

For permission to copy, contact editing@geosociety.org
© 2010 Geological Society of America

Solid Earth, 13, 1169–1190, 2022
https://doi.org/10.5194/se-13-1169-2022
© Author(s) 2022. This work is distributed under
the Creative Commons Attribution 4.0 License.

Solid Earth
Open Access

Tectonic evolution of the Indio Hills segment of the San Andreas fault in southern California, southwestern USA

Jean-Baptiste P. Koehl[1,2], **Steffen G. Bergh**[3], **and Arthur G. Sylvester**[4]

[1]Centre for Earth Evolution and Dynamics (CEED), University of Oslo, 0315 Oslo, Norway
[2]Department of Earth and Planetary Sciences, McGill University, H3A 0E8 Montreal, Canada
[3]Department of Geosciences, UiT The Arctic University of Norway in Tromsø, 9037 Tromsø, Norway
[4]Department of Earth Science, University of California, California, 93106, Santa Barbara, USA

Correspondence: Jean-Baptiste P. Koehl (jeanbaptiste.koehl@gmail.com)

Received: 17 January 2022 – Discussion started: 2 February 2022
Revised: 3 July 2022 – Accepted: 5 July 2022 – Published: 1 August 2022

Abstract. Transpressional uplift domains of inverted Pliocene–Pleistocene basin fill along the San Andreas fault zone in Coachella Valley, southern California (USA), are characterized by fault linkage and segmentation and deformation partitioning. The Indio Hills wedge-shaped uplift block is located in between two boundary fault strands, the Indio Hills fault to the northeast and the main San Andreas fault to the southwest, which merge to the southeast. Uplift commenced about or later than 0.76 million years ago and involved progressive fold and faulting stages caused by a change from distributed strain to partly partitioned right-slip and reverse/thrust displacement on the bounding faults when approaching the fault junction. Major fold structures in the study area include oblique, right-stepping, partly overturned en echelon macro-folds that tighten and bend into parallelism with the Indio Hills fault to the east and become more open towards the main San Andreas fault to the west, indicating an early and close relationship of the macro-folds with the Indio Hills fault and a late initiation of the main San Andreas fault. Sets of strike-slip to reverse step-over and right- and left-lateral cross faults and conjugate kink bands affect the entire uplifted area, and locally offset the en echelon macro-folds. Comparison with the Mecca Hills and Durmid Hills uplifts farther southeast along strike in Coachella Valley reveals notable similarities, but also differences in fault architectures, spatial and temporal evolution, and deformation mechanisms. The present work contributes to better understand the structure and tectonic history of a major fault system along a transform plate boundary.

1 Introduction

This paper describes and evaluates structural patterns of the Indio Hills uplift in the northwestern part of Coachella Valley along the San Andreas fault zone (SAFZ) in California, southwestern USA (Fig. 1), where the fold–fault architecture, evolution, and partitioning of deformation compared to Mecca Hills and Durmid Hills are not well understood (e.g., Keller et al., 1982; Dibblee and Minch, 2008). The main goal of this study is to analyze internal macro- and meso-scale folds and related faults and to outline the kinematic evolution in relation to major SAFZ-related fault strands in the area (Fig. 1: Keller et al., 1982; Guest et al., 2007). These include the Indio Hills fault in the northeast (Allen, 1957; Tyley, 1974) and the main San Andreas fault along the southwest flank of the Indio Hills and of the Mecca Hills, and along the northeast flank of the Durmid Hills (Janecke et al., 2018; Fig. 1). The progressive tectonic evolution model for the Indio Hills uplift is then compared and correlated with other major uplifts and SAFZ-related fault strands along strike in the Mecca Hills and Durmid Hills (Sylvester and Smith, 1987; McNabb et al., 2017; Janecke et al., 2018; Bergh et al., 2019). We also briefly discuss the potential northwestward continuation of the Indio Hills fault into the eastern California shear zone and its role as a possible transfer fault (Dokka and Travis, 1990a, b; Thatcher et al., 2016). The variable fault and fold architectures and associated ongoing seismic activity in these uplift areas underline the need for persistent along-strike studies of the SAFZ to characterize the fundamental geometry, resolve the kinematic development, and correlate regionally major fault strands (see Janecke et

Earthquake Geology and Paleoseismology of Major Strands of the San Andreas Fault System

Thomas Rockwell
Geological Sciences, San Diego State Univ., San Diego, CA 92182
Katherine Scharer
U.S. Geological Survey, Pasadena, CA 91106
Timothy Dawson
California Geological Survey, Menlo Park, CA 94025

ABSTRACT

The San Andreas fault system in California is one of the best-studied faults in the world, both in terms of the long-term geologic history and paleoseismic study of past surface ruptures. In this paper, we focus on the Quaternary to historic data that have been collected from the major strands of the San Andreas fault system, both on the San Andreas Fault itself, and the major sub-parallel strands that comprise the plate boundary, including the Calaveras-Hayward- Rogers Creek-Maacama fault zone and the Concord-Green Valley-Bartlett Springs fault zone in northern California, and the San Jacinto and Elsinore faults in southern California. The majority of the relative motion between the Pacific and North American lithospheric plates is accommodated by these faults, with the San Andreas slipping at about 34 mm/yr in central California, decreasing to about 20 mm/yr north of its juncture with the Calaveras and Concord faults. The Calaveras-Hayward-Rogers Creek-Maacama fault zone exhibits a slip rate of 10–15 mm/yr, whereas the rate along the Concord-Green Valley-Bartlett Springs fault zone is lower at about 5 mm/yr. In southern California, the San Andreas exhibits a slip rate of about 35 mm/yr along the Mojave section, decreasing to as low as 10–15 mm/yr along its juncture with the San Jacinto fault, and about 20 mm/yr in the Coachella Valley. The San Jacinto and Elsinore fault zones exhibit rates of about 15 and 5 mm/yr, respectively. The average recurrence interval for surface-rupturing earthquakes along individual elements of the San Andreas fault system range from 100–500 years and is consistent with slip rate at those sites: higher slip rates produce more frequent or larger earthquakes. There is also evidence of short-term variations in strain release (slip rate) along various fault sections, as expressed as "flurries" or clusters of earthquakes, as well as periods of relatively fewer surface ruptures in these relatively short records. This is reflected by non-periodic coefficients of variation in earthquake recurrence of 0.4 to 0.7 for the various paleoseismic sites.

Introduction

General tectonic setting – The San Andreas Fault is the primary boundary between the Pacific and North American lithospheric plates, although the 50 mm/yr of relative motion between these plates is accommodated by many faults that trend sub-parallel to or splay away from the San Andreas Fault. In north and central California, the onshore elements of the

Long-term slip rate of the southern San Andreas Fault from ^{10}Be-^{26}Al surface exposure dating of an offset alluvial fan

Jérôme van der Woerd,[1,2] Yann Klinger,[3,4] Kerry Sieh,[3] Paul Tapponnier,[5] Frederick J. Ryerson,[1] and Anne-Sophie Me´riaux[1,3,6]

Received 30 November 2004; revised 21 December 2005; accepted 12 January 2006; published 15 April 2006.

[1] We determine the long-term slip rate of the southern San Andreas Fault in the southeastern Indio Hills using ^{10}Be and ^{26}Al isotopes to date an offset alluvial fan surface. Field mapping complemented with topographic data, air photos and satellite images allows precise determination of piercing points across the fault zone that are used to measure an offset of 565 ± 80 m. A total of 26 quartz-rich cobbles from three different fan surfaces were collected and dated. The tight cluster of nuclide concentrations from 19 samples out of 20 from the offset fan surface implies a simple exposure history, negligible prior exposure and erosion, and yields an age of 35.5 ± 2.5 ka. The long-term slip rate of the San Andreas Fault south of Biskra Palms is thus 15.9 ± 3.4 mm/yr. This rate is about 10 mm/yr slower than geological (0–14 ka) and short-term geodetic estimates for this part of the San Andreas Fault, implying changes in slip rate or in faulting behavior. This result puts new constraints on the slip rate of the San Jacinto and on the Eastern California Shear Zone for the last 35 kyr. Our study shows that more sites along the major faults of southern California need to be targeted to better constrain the slip rates over different timescales.

Citation: van der Woerd, J., Y. Klinger, K. Sieh, P. Tapponnier, F. J. Ryerson, and A.-S. Me´riaux (2006), Long-term slip rate of the southern San Andreas Fault from ^{10}Be-^{26}Al surface exposure dating of an offset alluvial fan, *J. Geophys. Res.*, *111*, B04407, doi:10.1029/2004JB003559.

1. Introduction

[2] The rate of horizontal translation between the Pacific and North American plates has averaged at about 50 mm/yr over the past 3 Myr [*DeMets*, 1995; *DeMets and Dixon*, 1999] and 48 ± 5 mm/yr over the past decade [*Bennett et al.*, 1996]. Many have attempted to understand how this deformation is partitioned between the numerous active faults of southern California because such knowledge is critical to understand the mechanics of this complex plate boundary. The details of slip rates distribution are also important input for estimating local seismic hazards because seismic productivity generally increases with increasing fault slip rate.

[3] Attempts to measure the partitioning of slip across the plate boundary have relied on either short- or long-term measurements. Geodetic data enable calculation of rates spanning a few years or decades; stratigraphic, geomorphologic and geochronologic information yield rate averages that span thousands to tens of thousands of years. Heretofore, measurements of long-term slip rates have been sparse because they have depended on the presence of clearly offset landforms datable by the radiocarbon method. Only at Cajon Pass and Wallace Creek (Figure 1, inset) is the millennially averaged slip rate well constrained along the San Andreas Fault (SAF) [*Weldon and Sieh*, 1985; *Sieh and Jahns*, 1984]. The rates there, 24.5 ± 3.5 and 34 ± 3 mm/yr, respectively, suggest that the fault currently bears about 50 to 70% of the entire relative plate motion.

[4] Use of the Cajon Pass rate to establish the nature of slip partitioning farther south in southern California is probably inappropriate because the geometry of active faults there differs greatly from their geometry at the latitude of Cajon Creek (Figure 1, inset). South of Cajon Pass, several other active strike-slip faults lie west of and subparallel to the San Andreas [*Allen*, 1957]. Structural, stratigraphic and geochronologic data show that among these faults, the San Jacinto and San Andreas have long been the principal structures. Geodetic measurements show that this continues to be the case, with the two faults carrying well over half of the total relative plate motion.

[5] The relative degree of current activity of these two faults remains controversial, however. Although the total Miocene slip across the SAF (215 km) is clearly much larger than that across the San Jacinto fault (SJF) (20 km), some interpretations suggest that the slip rate of the SJF

[1]Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California, USA.
[2]Now at Ecole et Observatoire des Sciences de la Terre, Institut de Physique du Globe de Strasbourg, Strasbourg, France.
[3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.
[4]Now at Laboratoire de Tectonique, Institut de Physique du Globe de Paris, Paris, France.
[5]Laboratoire de Tectonique, Institut de Physique du Globe de Paris, Paris, France.
[6]Now at School of Geosciences, Institute of Geography, Edinburgh, UK.

Copyright 2006 by the American Geophysical Union.
0148-0227/06/2004JB003559$09.00

2023 FRIENDS OF THE PLEISTOCENE FIELD TRIP, PACIFIC CELL, SALTON TROUGH

DAY 1: SLIP RATES FOR THE SAN ANDREAS FAULT SYSTEM

STOP 3: San Andreas Fault, Mission Creek strand in the NW Coachella Valley—San Gorgonio Pass regions: fast slip or slow slip?

Intersection of California State Highway 62 and Indian Canyon Drive (dirt road leading northwest from Highway 62)

Discussion leaders (honoring the memory & contributions of J. Douglas Yule)

Jonathan C. Matti, U.S. Geological Survey (emeritus), Geology, Minerals, Energy, and Geophysics Science Center, Tucson, AZ 85719, USA (jmatti@usgs.gov)

Richard V. Heermance, Department of Geological Sciences, California State University Northridge, Northridge, CA 91330-8266, USA (richard.heermance@csun.edu)

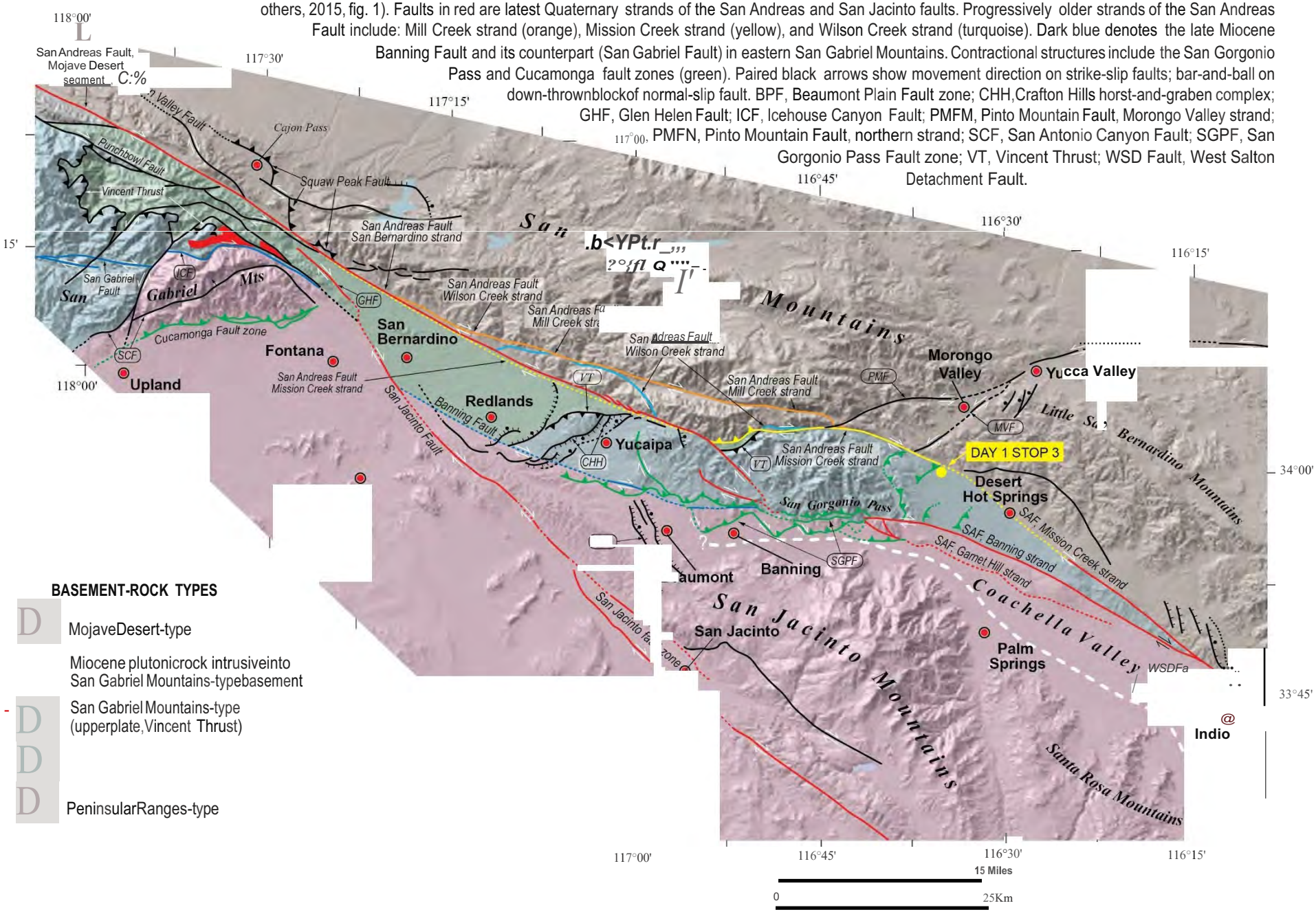
Katherine J. Kendrick, U.S. Geological Survey (emeritus), Earthquake Science Center, Pasadena, CA 91106, USA (kjkendrick1499@gmail.com)

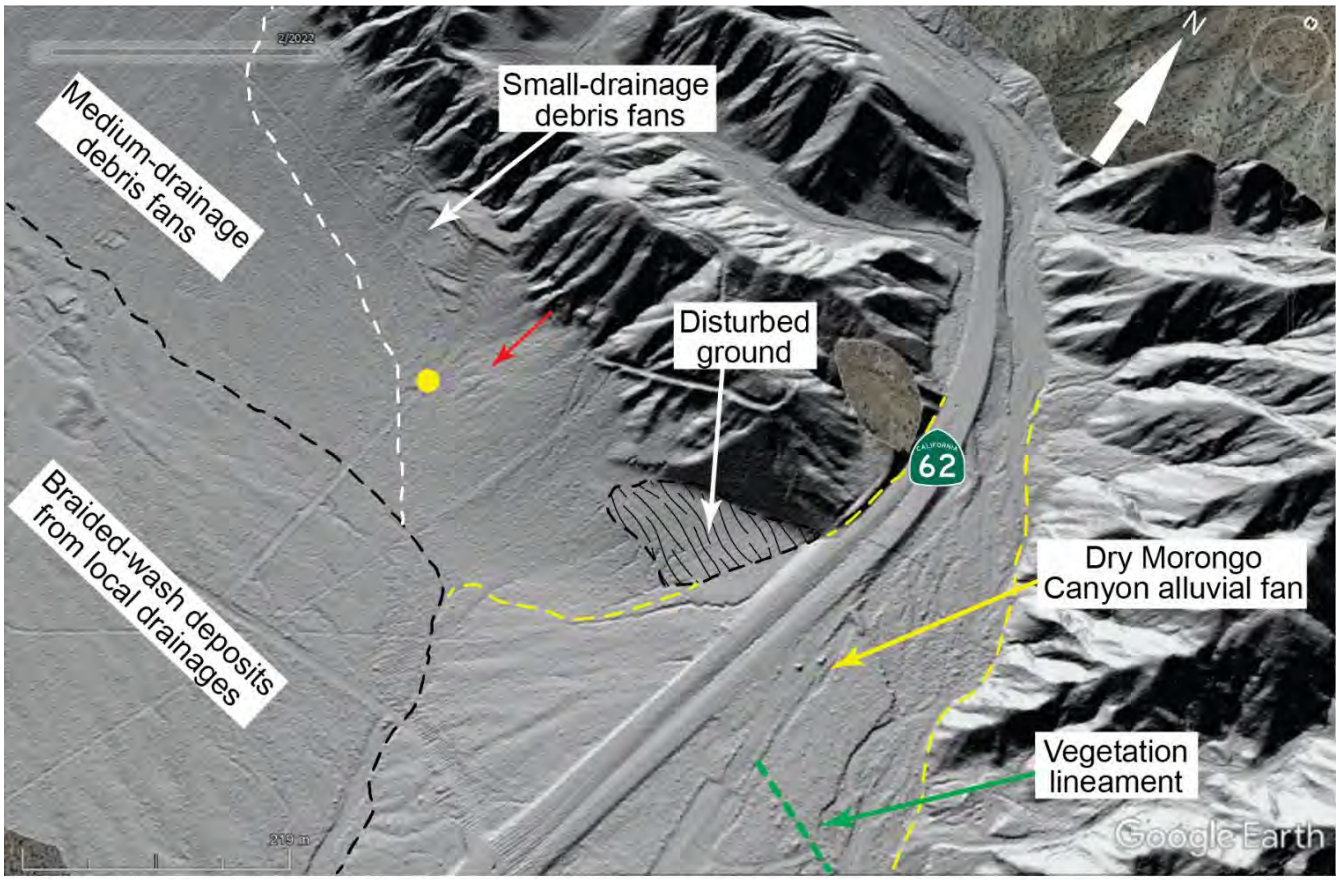
Michael E. Oskin, Department of Earth and Planetary Sciences, University of California, Davis, Davis, CA 95616 (meoskin@ucdavis.edu)

BACKGROUND

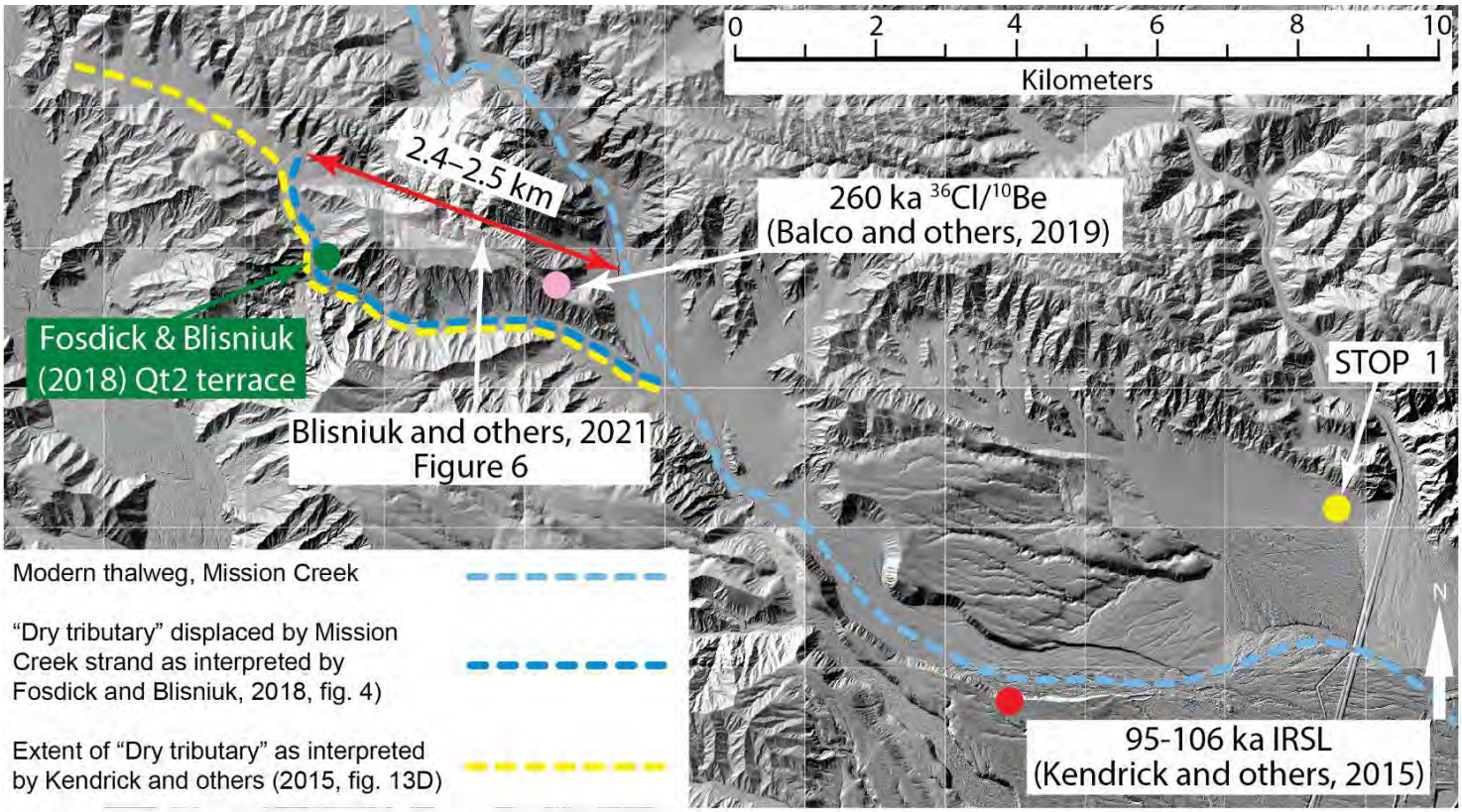
How does the 20-25 had mm/yr slip rate in Imperial and Coachella Valley (from geologic and geodetic studies) make it through the San Gorgonio Pass "knot"? Here, slip rates are controversial: some workers conclude that principal SAF strands (Mission Creek and Mill Creek faults) have minimal rates during the last 500 ka or longer (Matti and others, 1992; Matti and Morton, 1993; Kendrick and others, 2015, 2022; Matti and Yule, 2020); alternatively, recent workers (Fosdick and Blisniuk, 2018; Balco and others, 2019; Blisniuk and others, 2021) suggest that 20-25 mm/yr rates interpreted for the main San Andreas strand in the Indio Hills region (Mission Creek Fault) persist northwestward to the eastern San Gorgonio Pass portal, thence connecting directly to the modern SAF trace northwest of the Pass (San Bernardino strand). Implicit in the recent work is that the Mission Creek Fault in the northwestern Coachella Valley and San Gorgonio Pass regions remains a major plate boundary susceptible to future throughgoing large-magnitude earthquakes. Alternatively, in the vicinity of the SG Pass "knot", is strain now accommodated mainly by structures other than the major SAF strands? At STOP 3 we explore some of these issues—recognizing that field-trip time does not allow us to visit specific sites 5-10 km northwest where geologic and geomorphic evidence in support of fast-slip or slow-slip paradigms can be evaluated. Hence, STOP 3 represents a "teaser" that hopefully will promote friendly discussion among field-trip participants.

Friends of the Pleistocene DAY 1 STOP 3 location (yellow dot) relative to major faults and regional basement terranes (revised slightly from Kendrick and others, 2015, fig. 1). Faults in red are latest Quaternary strands of the San Andreas and San Jacinto faults. Progressively older strands of the San Andreas Fault include: Mill Creek strand (orange), Mission Creek strand (yellow), and Wilson Creek strand (turquoise). Dark blue denotes the late Miocene Banning Fault and its counterpart (San Gabriel Fault) in eastern San Gabriel Mountains. Contractional structures include the San Gorgonio Pass and Cucamonga fault zones (green). Paired black arrows show movement direction on strike-slip faults; bar-and-ball on down-thrownblockof normal-slip fault. BPF, Beaumont Plain Fault zone; CHH,Crafton Hills horst-and-graben complex; GHF, Glen Helen Fault; ICF, Icehouse Canyon Fault; PMFM, Pinto Mountain Fault, Morongo Valley strand; PMFN, Pinto Mountain Fault, northern strand; SCF, San Antonio Canyon Fault; SGPF, San Gorgonio Pass Fault zone; VT, Vincent Thrust; WSD Fault, West Salton Detachment Fault.

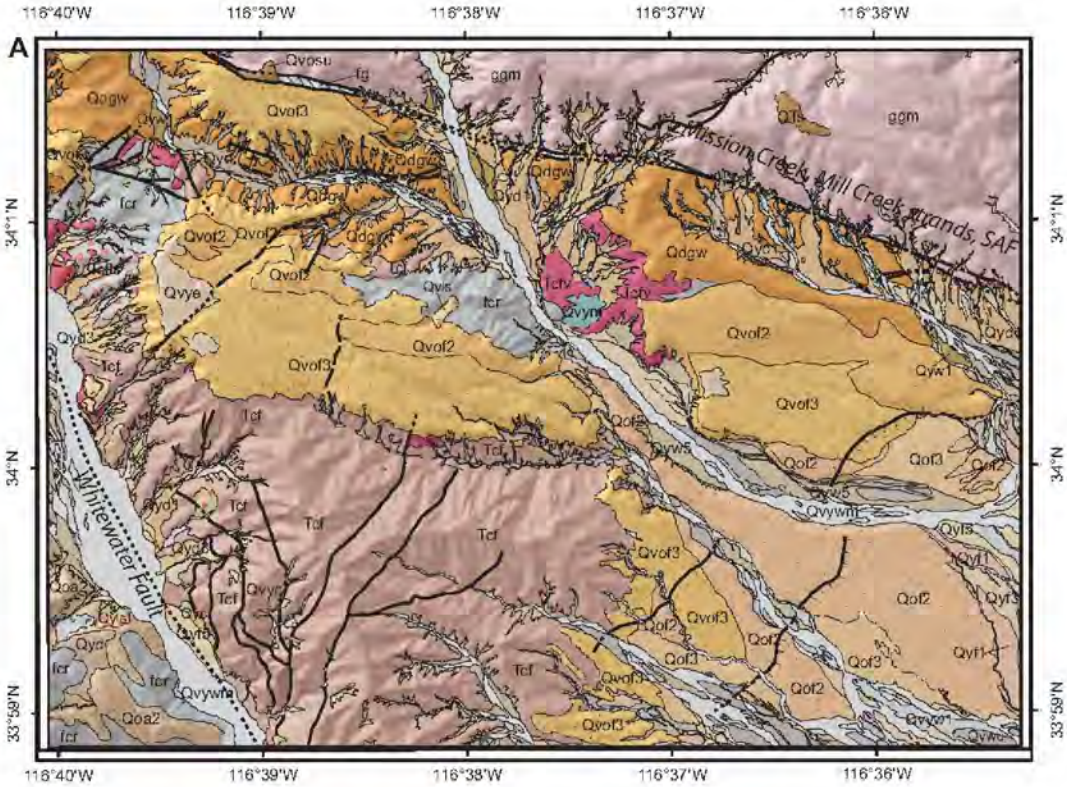




DAY 1 STOP 3 (Jonathan C. Matti, Richard V. Heermance, Katherine J. Kendrick, Michael E. Oskin, discussion leaders)—Bare-earth image from B4 lidar (45° sun angle) processed to remove vegetation (Bevis and others, 2017). Yellow dot indicates stop location. Squiggly black lines = disturbed ground that obscures original geologic and geomorphic features; 1953 Agricultural Stabilization and Conservation Service ASCS AXM imagery reveals that the disturbed area originally consisted of crystalline basement rocks of Mojave Desert-type. Red arrow points to a degraded fault scarp discernable in this image and on 1953-vintage Agricultural Stabilization and Conservation Service aerial photographs (ASCS, 1953, series AXM). The north-facing scarp bounds an area of warped ground underlain by dissected youthful surficial deposits. Younger surficial materials (debris-fan deposits) derived from the adjacent hillslope of crystalline rocks buttress depositionally against the warped landform, and elevation contrasts between the higher- and lower-standing land surfaces are so slight that the scarp is difficult to discern. The buttressing materials are part of a restricted domain of localized debris fans radiating from small gullies and canyons heading into the crystalline mountain front; the white dashed line bounds the toes of the localized debris fans and separates them from debris-fan deposits derived from somewhat larger drainages to the northwest. The black dashed line separates all the mountain-front debris-fan deposits from throughgoing braided-wash deposits sourced to the northwest. Where State Highway 62 enters the mountain front a large alluvial-fan landform debouches from the mouth of Dry Morongo Canyon (referred to by Fosdick and Blisniuk, 2018, as “Morongo Valley Canyon”); yellow dashed lines demarcate the approximate boundary of the fan landform. All surficial materials at STOP 3 appear to be Holocene in age, although no dates here have been published.



Lidar image of the Mission Creek area, showing geomorphic and geochronologic information pertaining to the age and displacement history for the Mission Creek strand of the San Andreas Fault as interpreted by Fosdick and Blisniuk (2018), Balco and others (2019), and Blisniuk and others (2021). Lidar source: U.S. Geological Survey, 2017).



Qvywm	Very young wash deposits, modern (latest Holocene)
Qvyw1	Very young wash deposits, unit 1 (latest Holocene)
Qvyc	Very young colluvial deposits (latest Holocene)
Qvye	Very young eolian deposits (latest Holocene)
Qvym	Very young marsh deposits (latest Holocene)
Qyc	Young colluvial deposits, undifferentiated (Holocene and latest Pleistocene)
Qywu	Young alluvial-wash deposits, undifferentiated (Holocene and latest Pleistocene)
Qyw5	Young alluvial-wash deposits, unit 5 (late Holocene)
Qyw1	Young alluvial-wash deposits, unit 1 (early Holocene and latest Pleistocene)
Qyf5	Young alluvial-fan deposits, unit 5 (late Holocene)
Qyf3	Young alluvial-fan deposits, unit 3 (middle Holocene)
Qyf1	Young alluvial-fan deposits, unit 1 (early Holocene and latest Pleistocene)
Qyd	Young debris-fan deposits, undifferentiated (Holocene and latest Pleistocene)
Qyd3	Young debris-fan deposits, unit 3 (middle Holocene)
Qyd1	Young debris-fan deposits, unit 1 (early Holocene and latest Pleistocene)
Qyls	Young landslide deposits (Holocene and latest Pleistocene)
Qoa2	Old axial-valley deposits, unit 2 (late Pleistocene)
Qof3	Old alluvial-fan deposits, unit 3 (late Pleistocene)
Qof2	Old alluvial-fan deposits, unit 2 (late and middle Pleistocene)
Qvof3	Very old alluvial-fan deposits, unit 3 (middle Pleistocene)
Qvof2	Very old alluvial-fan deposits, unit 2 (middle Pleistocene)
Qvosu	Very old surficial deposits, undifferentiated (middle Pleistocene)
Qdgw	Deformed gravels of Whitewater River (early Pleistocene)
QTs	Sedimentary rocks, undifferentiated (Quaternary and Tertiary)
Tcf	Coachella Fanglomerate (Miocene)
Tcfv	Coachella Fanglomerate, volcanic unit
Tcfls	Coachella Fanglomerate, landslide unit
fcr	Foliated crystalline rocks of San Gabriel Mountains-type (Cretaceous and older)
ggm	Granitic and gneissic rock of Mojave Desert-type (Cretaceous and older)
fg	Crushed and sheared rock in fault zone

Contact—Solid where meets map-accuracy standard; dashed where may not meet map-accuracy standard; dotted where concealed

Fault—Solid where meets map-accuracy standard; dashed where may not meet map-accuracy standard. Dotted where concealed by mapped covering unit. Hachures indicate scarp, with hachures on down-dropped block.

Geologic map of the Mission Creek Preserve of the Wildlands Conservancy (figure 7A of Kendrick and others, 2015). Note that Pleistocene stratigraphic units mapped here as various subunits of Qo and Qvo are shown as "Cabezon Fanglomerate" by Fosdick and Blisniuk (2018; Balco and others, 2019; Blisniuk and others, 2021). Application of the "Cabezon" nomenclature follows Allen (1957) and Proctor (1968), but we doubt correlation of the Mission Creek Pleistocene deposits with the "type" Cabezon Fanglomerate in San Gorgonio Pass because the unit there occupies a different stratigraphic position than deposits mapped as "Cabezon Fanglomerate" in the Mission Creek drainage, and by correlation throughout the San Gorgonio Pass region most of the formation can be shown to have reversed magnetic polarity (Matti and others, 2015).

Yule, D., Matti, J., Kendrick, K., and Heermance, R., 2019, Evidence for inactivity since ~100 ka on the northern route of the San Andreas fault , southern California: Geological Society of America Cordilleran Section Meeting, Paper 16-8 https://gsa.confex.com/gsa/2019CD/meetingapp.cgi/Paper/329441.

From San Bernardino to Indio, CA, the San Andreas fault (SAF) follows two distinct routes. A northern route (NR) follows the Mill Creek and Mission Creek strands and a southern route (SR) follows the San Bernardino, Banning, and Garnet Hill strands, and San Gorgonio Pass (SGP) fault zone. We think that reconfiguration of the SAF zone in the SGP region at ~100 ka shifted motion from the NR to the SR. Surprisingly, the complex SR has experienced low slip rates and relatively infrequent paleoearthquakes, particularly in SGP. SR complexity and low slip rates in part led Fosdick & Blisniuk (F&B) (2018) to propose that the NR has generated 2.5 km of dextral slip since ~100 ka, yielding a slip rate of 20-30 mm/yr. Their offset and its timing are based on correlating a small strath terrace (Qt2) with an expansive fill terrace (Qf2) 5-7 km away that has a published OSL age of ~100 ka, then using those deposits to define a paleodrainage that has been offset along the NR since that 100 ka—thereby showing that the NR remains a major active plate boundary. We question this proposal using four arguments that support little, if any, slip on the NR since ~100 ka: (1) The Qt2/Qf2 correlation is implausible because of (a) differences in soil development, elevation above modern channel, and genetic terrace styles (strath vs fill), (b) the lag on Qt2 consists of material cannibalized from older alluvial deposits into which the strath was carved, and (c) a profile connecting the Qt2-Qf2 terraces defines a gentle gradient much different from steeper profiles on Pleistocene fan remnants in the area. (2) The NR does not deform Holocene units for most of its route (Matti et al., this session). In contrast there is abundant evidence for Holocene deformation along the SR over the same distance. (3) Stream deflections of ~50 m in >>60 ka fill proposed on the NR near Mission Creek (F&B, 2018) equate to slip rates of <<1 mm/yr. (4) Dextral motion of ~6 mm/yr on the SR through SGP (Heermance & Yule, 2017) matches estimates from geodetic models for SAF motion here. Thus, there is no reason to require significant motion on the NR. Though the NR once carried ~20 mm/yr of SAF motion, it shut down following the latest SAF reorganization at ~100 ka. This relatively recent event created the geometrically complex SR and its traits characteristic of a poorly organized, youthful fault system.

Geological Society of America Abstracts with Programs. Vol. 51, No. 4, ISSN 0016-7592
doi: 10.1130/abs/2019CD-329441

© Copyright 2019 The Geological Society of America (GSA), all rights reserved.

Matti, J.C., Kendrick, K.J., Yule, J.D., and Heermance, R.K., 2019, The Mission Creek Fault in the San Gorgonio Pass region—A long-abandoned strand of the San Andreas Fault, or a major player in the latest Quaternary San Andreas strain budget? Geological Society of America Cordilleran Section Meeting, Paper 329432 https://gsa.confex.com/gsa/2019CD/meetingapp.cgi/Paper/329432.

The San Andreas Fault (SAF) zone in the San Gorgonio Pass (SGP) region is geologically and geomorphically more complex than perhaps anywhere else in southern California. Here, the zone consists of at least six separate strands that, acting together, record the fault's entire movement history since inception at ~6 Ma. In addition, interaction between the SAF and associated sinistral, contractional, and extensional fault sets has significantly impacted the geometry and slip history of individual SAF strands—especially the Mission Creek strand (MCS), which generated most of the total SAF slip during Pliocene and Pleistocene time. Many workers view the MCS in SGP as an abandoned structure that has produced no dextral slip for >0.5 Ma. This contrasts with the MCS in the Indio Hills, where the fault has generated 12-22 mm/yr of slip during the late Pleistocene. Slip-rate contrasts between SGP and the Indio Hills suggest that—between the two regions—latest Quaternary slip on the MCS does not project NW through SGP but instead must step left (and/or right) from the MCS onto other components of the SAF system. Recently, Fosdick & Blisniuk (F&B) (2018) challenged this paradigm, based on work in the Mission Creek area of NE SGP. They conclude that the MCS here has generated ~20-30 mm/yr of dextral slip over the last 100 ka. A companion abstract (Yule et al., this session) explores the basis for this proposal, and presents detailed evidence refuting the idea that the MCS in SGP has generated significant dextral slip over the last 100 ka. We also refute F&B (2018) by citing the MCS's geologic character between the Indio Hills and San Gorgonio River in northern SGP: (1) Throughout much of this 45-km extent, the MCS trace is concealed by undisrupted Holocene surficial deposits. (2) Fault scarps and other tectonogeomorphic features occur locally along the strand's extent, but these are discontinuous and are not convincingly youthful. (3) We see no evidence for young Quaternary dextral slip on the MCS in the critical footprint between Mission Creek and the headwaters of San Gorgonio River. (4) Some workers propose that—in NE SGP—20-30 mm/yr of slip steps abruptly south off the MCS and onto faults in crystalline rocks that connect directly to the SAF San Bernardino strand to the NW. We see no evidence for this, but we do see slip stepping left well SE of SGP.

Geological Society of America Abstracts with Programs. Vol. 51, No. 4, ISSN 0016-7592
doi: 10.1130/abs/2019CD-329432

© Copyright 2019 The Geological Society of America (GSA), all rights reserved.

Matti, J.C., and Yule, J.D., 2020, Does a "structural knot" in the Quaternary San Andreas Fault exist in San Gorgonio Pass? Traditional and recent views provide conflicting answers: Geological Society of America Cordilleran Section Meeting, Paper 17-1 https://gsa.confex.com/gsa/2020CD/meetingapp.cgi/Paper/347317.

Abstract

Traditional geologic models for Quaternary (Q) strain within the southern San Andreas Fault (SAF) zone invoke a "structural knot" centered on San Gorgonio Pass (SGP). The "knot" concept grew out of Allen's (1957) recognition that Q thrusting now predominates in SGP: older dextral-slip faults have been disrupted, and the "modern" SAF trace is disguised. We now know that several SAF strands occur in the SGP region and have evolved sequentially ("switched on and off") throughout the zone's ~6-Ma lifespan. Later workers also have shown that late Q SAF motion carries through SGP in complex but understandable ways *via* oblique thrust and tear faults of the SGP Fault Zone (SGPFZ). Oblique convergence in SGP also is supported by the first-order observation that its mountainous landscape rises abruptly above adjacent lowlands. These factors all led to a traditional time-space model where the SAF system at SGP is a left-oblique regime within which Q slip steps progressively from the Mission Creek strand (MCS, on the NE) to the Banning and Garnet Hill strands (to the SW), accompanied by the following constraints: (1) in mid-Pleistocene (PL) time the MCS in SGP was abandoned, leading to mid-PL contraction within the SGPFZ and uplift of high-standing parts of the SGP landscape; (2) in mid-PL time the Mill Creek strand bypassed this older "knot" in the SAF, but ultimately even it was abandoned by the SAF; (3) today, the late Q framework of SGP reflects left-oblique SAF slip trying to work through SGP in order to "connect" young SAF strands to the NW and SE. Recent reports by Fosdick and Blisniuk, 2018 (https://doi.org/10.1038/s41598-018-30622-3) and Balco et al., 2019 (https://doi.org/10.5194/gchron-1-1-2019) challenge this paradigm. These reports assert that—over the last ~100 ka years—20-30 mm/yr of SAF slip projects through SGP on the MCS and on fault structures associated with the MCS. To us, this poses a pressing question: is there any need for a late Q San Gorgonio Pass "knot" in the SAF? We answer "yes": (1) interaction among ALL geologic structures in the SGP region is consistent with a long-lived Q knot; (2) in SGP we see no evidence for youthful dextral offset on the MCS itself; (3) in SGP we see no evidence for dextral-slip faults SW of the MCS (e.g., Waco et al., 2017, https://files.scec.org/s3fs-public/SCEC2017Proceedings.pdf).

Geological Society of America Abstracts with Programs. Vol. 52, No. 4, 2020
doi: 10.1130/abs/2020CD-347317

© Copyright 2020 The Geological Society of America (GSA), all rights reserved.

Heermance, R., Matti, J.C., and Kendrick, K.J., 2023, Holocene slip rates along the San Andreas Fault through the San Gorgonio Pass: Geological Society of America Cordilleran Section Meeting, Paper 15-9, https://gsa.confex.com/gsa/2023CD/meetingapp.cgi/Paper/387451.

Abstract

As it traverses NW Coachella Valley the San Andreas fault (SAF) splits into multiple, divergent strands that enter the "enigmatic" San Gorgonio Pass (SGP). Large, historical earthquakes have not ruptured through SGP, thus creating debate about the rupture length and location of a future event on the southern SAF. Relatively continuous faults have been mapped in two zones through the SGP: a *southern-route* (SR) involving the Banning strand, Garnet Hill strand, and San Gorgonio Pass Fault zones and a *northern route* (NR) involving the Mission Creek and Mill Creek strands and/or associated structures. Any large earthquake on the southern SAF through SGP must follow one of these two routes, and only the southern route shows convincing geologic and geomorphic evidence for repeated throughgoing earthquake ruptures during the Holocene. Only two sites provide published Holocene slip-rates within SGP: along the Banning strand and the San Gorgonio Pass fault zone, both along the SR. An oblique slip rate of 5.7 (+2.5, -1.5) mm/yr was calculated across fault scarps within Millard Canyon in the central SGP, where fan terraces were dated (10Be exposure) as Holocene. At the eastern edge of SGP the Banning strand has a comparable slip rate of 3.9-4.9 mm/yr from an offset mid-Holocene fan surface. Together, these data suggest that the SR is active but accommodates <50% of slip along the SAF system. In contrast, there are no published Holocene slip rate sites along the NR through SGP. Notably, fault scarps and dextral stream offsets are sparse, discontinuous and developed in alluvium of undocumented age; dextral stream offsets developed on one uplifted Pleistocene terrace NW of Mission Creek cannot convincingly be attributed to Holocene slip. At Dry Tributary, a 45 m-deep canyon reveals a strath surface beneath 25 m sedimentary fill that buries the Mission Creek strand of the SAF. Although the NR undoubtedly was active during the Pleistocene, during the Holocene it has shut down and slip has been transferred to the southern route or is accommodated by diffuse off-fault deformation.

Geological Society of America Abstracts with Programs. Vol. 55, No. 4, 2023
doi: 10.1130/abs/2023CD-387451

© Copyright 2023 The Geological Society of America (GSA), all rights reserved.

Matti, J.C., Kendrick, K.J., and Powell, R.E., 2023, Tectonic evolution at the intersection of the San Andreas, Pinto Mountain, and Morongo Valley Fault zones, southern California: implications for Quaternary San Andreas Fault slip rates: Geological Society of America Cordilleran Section Meeting, Paper 15-7, https://gsa.confex.com/gsa/2023CD/meetingapp.cgi/Paper/387523.

Abstract

In the San Gorgonio Pass (SGP) region, dextral slip rates for northern strands of the San Andreas Fault Zone (SAFZ) are hotly debated. Some workers maintain that dextral slip on the Mission Creek strand (MiCS) of the northern route (NR) slowed at ~1.5 Ma as a "structural knot" evolved in the SAFZ, with slip approaching zero before ~500 ka (Matti and Morton, 1993); in SGP the MiCS has an E-W bend that formed a 9-15 km left step in the Pleistocene SAFZ. At ~500 ka, slip initiated on the Mill Creek strand (MCS) and produced ~8 km of displacement before ~100 ka, when slip ended (Kendrick and others, 2015). In contrast, recent workers contend that the SAF NR has 20-30 mm/yr of slip during the last 100 ka and longer (e.g., Blisniuk and others, 2021). Here, we argue that interaction between the SAF NR and intersecting sinistral faults (Pinto Mountain Fault [PMF] and Morongo Valley Fault [MVF]) allows only minimal slip on the SAF NR over the last 1.5 Ma. Specifically: when slip on the MCS is reconstructed, the MiCS left bend aligns with the MVF—suggesting that sinistral slip on the latter is coeval with and caused the MiCS left bend (Kendrick and others, 2022). We use these relations to propose the following tectonic scenario: (1) At ~1.5 Ma, dextral slip on the MiCS gradually was impeded by sinistral slip on the MVF. (2) During this period, the MiCS was deformed into its E-trending bend. (3) The MVF thus is as a major strand of the PMFZ. (4) The PMFZ is widely viewed as the northern boundary for clockwise-rotating blocks of the Eastern Transverse Ranges (ETR); we see the MVF as part of that boundary during middle Pleistocene time. (5) Following interaction between the MVF and the MiCS, dextral slip punched through the "structural knot" in the SAFZ, allowing the MCS to displace the MiCS left bend NW to its current location. (6) In late Pleistocene time, sinistral slip on the PMF truncated and displaced an abandoned MCS by ~1.2 km. (7) Geometric relations and sequencing of major dextral and sinistral faults at the NE portal to SGP suggest that they have interacted together for the last ~1.5 Ma to produce the current geologic framework. *Implication*: The original spatial arrangement of these faults has been disrupted only by 8 km of dextral slip on the MCS, requiring that the SAF NR has not produced significant dextral slip in middle and late Quaternary time.

Geological Society of America Abstracts with Programs. Vol. 55, No. 4, 2023
doi: 10.1130/abs/2023CD-387523

© Copyright 2023 The Geological Society of America (GSA), all rights reserved.

Matti, J.C., Morton, D.M. and Cox, B.F., 1992, The San Andreas fault system in the vicinity of the central Transverse Ranges province, southern California: U.S. Geological Survey Open-File Report 92-354, 40 p., scale 1:250,000. https://pubs.er.usgs.gov/publication/ofr92354. NOTE: Oversize plates 1 and 2 can be downloaded at the URL in this citation.

DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

THE SAN ANDREAS FAULT SYSTEM IN THE VICINITY OF THE CENTRAL TRANSVERSE RANGES PROVINCE, SOUTHERN CALIFORNIA

By

Jonathan C. Matti[1], Douglas M. Morton[2], and Brett F. Cox[3]

OPEN-FILE REPORT 92-354

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, product, or firm names is for descriptive purposes only nd does not imply endorsement by the U.S. Government.

[1]U.S. Geological Survey
Department of Geosciences
Gould-Simpson Building
University of Arizona
Tucson, Arizona 85721

[2]U.S. Geological Survey
Department of Earth Sciences
University of California
Riverside, California 92521

[3]U.S. Geological Survey
345 Middlefield Road, MS 975
Menlo Park, California 94025

1992

SUMMARY

The vicinity of the central Transverse Ranges is a structurally complex region that is traversed by several major fault zones. The Banning, San Jacinto, and San Andreas faults are right-lateral strike-slip faults of the San Andreas transform system. The San Gorgonio Pass and Cucamonga fault zones are compressional thrust- and reverse-fault complex s. The Crafton Hills horst-and-graben complex, the Tokay Hill and Peters faults in the Cajon Pass region, and the Beaumont Plain fault complex are extensional fault zones. The compressional and extensional fault complexes owe their origin and kinematics to complications within the San Andreas transform fault system.

The Banning fault has had a complex history that in ludes th left: and right-lateral displacements. During middle Miocene tlme the ancestral Banning fault zone may have generated left-lateral displacements that juxtaposed the Peninsular Ranges block against the San Gabriel Mountains block along a regionally extensive fault system that included the Malibu Coast-Santa Monica fault. During late Miocene time the Banning fault was incorporated into the San Andreas transform system and generated 16 to 25 km of right-lateral displacement; during this period the Banning probably was the eastward continuation of the San Gabriel fault in the San Gabriel Mountains. The Banning fault was abandoned by the San Andreas system in earliest Pliocene time. In San Gorgonio Pass the Banning fault has been obscured and reactivated by low-angle Quaternary faulting of the San Gorg?nio Pass fault zone.. In the Coachella Valley the Banmng fault has been reactivated by Quaternary strike-slip faulting related to the San Andreas fault, and has generated about 3 km of right-lateral displacement that largely has been absorbed by convergence within the San Gorgonio Pass fault :zone.

The San Andreas fault in the vicinity of the central Transverse Ranges consists of three segments--the Mojave Desert, Coachella Valley, and San Bernardino Mountains seg ents. The omplex San Bernardino Mountains segment consists of multiple strands that had sequential movement histories. To the northwest and southeast these strands merge to form the simpler Mojave Desert and Coachella Valley segments.

The San Bernardino Mountains segment of the San dreas fault co!1s sts of three paleotectonic strands (the Wilson Creek, M1ss1on Creek, and Mill Creek faults) and a neotectonic strand (the San Bernardino strand). Together, ese four strands have generated about 160 km of right-lateral displacement and record the total history of the San Andreas fault *(sensu stricto)* since its inception 4 or 5 m.y. ago. The Wilson Creek and Mission Creek faults together generated about 130 km of right-lateral displacement during Pliocene and Pleistocene time. The Wilson Creek fault, the older strand, generated about 40 km of displacement before it was deformed into a sinuous trace in the vicinity of the San Bernardino Mountains; this displacement estimate is based on our proposal that the Wilson Creek fault is the offset continuation of the Punchbowl fault in the San Gabriel Mountains--a structure that has about 40 km of right slip documented by other workers. In Pliocene time the Wilson Creek strand was succeeded by the Mission Creek strand which enerated the balance of the 130-km displacemen before it was deformed and abandoned in late Pleistocene time. The Mill Creek strand subsequently evolved inboard (east) of the locked-up Mission Creek fault and generated about 8 km of right-slip during late Pleistocene time. Ultimately, the Mill Creek strand was abandoned as right-lateral activity shifted to the southwest front of the San Bernardino Mountains, where the neotectonic San Bernardino strand developed. The San Bernardino strand is aligned with the Coachella Valley segment of the Banning fault, but these two neotectonic right-lateral faults are separated by the San Gorgonio Pass fault zone and it is not clear that they ever formed a single throughgoing trace between the Coachella and San Bernardino valleys.

Two compressional fault complexes and an extensional fault system have evolved in the vicinity of the south-central Transverse Ranges in association with the San Andreas fault. The San Gorgonio Pass and Cucamonga fault zones consist of late Quaternary thrust and reverse faults that have evolved where neotectonic strands of the San Andreas and San Jacinto faults interact with the southeastern San Bernardino Mountains and San Gabriel Mountains respectively. Northwest of the San Gorgonio Pass fault zone' crustal extension in the San Bernardino valley and vicinii;, has created normal dip-slip fault complexes like the Beaumont Plain fault zone, the Crafton Hills horst-and-graben complex, and the Tokay Hill and Peters faults in the Cajon Pass region.

The Quaternary tectonic framework of the central Transverse Ranges can be viewed as a regionally integrated response to an evolving left step in the San Andreas transform-f ult system. The left step was initiated during Pleistocene time, and was accompanied by left-slip on the Pinto Mountain fault that gradually projected the San Bernardino Mountains westward across the path of the Mission Creek strand of the San Andreas fault and offset the Coachella Valley and Mojave Desert segments of the fault. The modern San An eas fault has adjusted to this inherited left step, and various neotectonic fault complexes in the vicinity of the central Transverse Ranges have evolved in response to this adjustment. During latest Quaternary time, right-slip on the San Andreas fault has stepped left from the Coachella Valley segment to the Banning fault and thence into San Gorgonio Pass, where right-slip is absorbed by convergence within the San Gorgonio Pass fault zone. Some slip may step farther west onto the San Jacinto fault, where accelerated right-slip ma have con ibuted to subsidence of the San Jacinto graben. Ultimately, shp steps back from the San Jacinto fault to the modem San Andreas fault, giving rise to the San Bernardino strand by reactivation of the Mission Creek fault. This right step has created a right-lateral shear couple and extensional strain field in the greater San Bernardino valley, with extension giving rise to normal dip-slip faults like those in the Crafton Hills horst-and-graben complex and the Tokay Hill and Peters faults.

alfflii rm© @ llD©ii a© lM

In this report we describe the tectonic framework and geologic history of faults in the vicinity of the central Transverse Ranges, southern California (fig. 1). The fault zones discussed include right-lateral faults of the San Andreas transt:orm system (including the San Andreas fault itself), assoc1a ed reverse and thrust faults in the vicinity of San Gorgomo Pass and the southeastern San Gabriel Mountains and associated normal faults that occur between the S Jacinto and San Andreas faults in the vicinity of the San

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088532

Key Points:
- End-member model examines the fewest, but longest, ruptures required by ages of ground-rupturing earthquakes from 31 paleoseismic sites
- Regional clustering emerges, with largest moment release ruptures similar to the historic record with ruptures breaking much of the system
- Ruptures through San Gorgonio Pass are infrequent, and anticorrelated with episodes when fault sections near Cajon Pass are active

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Table S1
- Table S2

Correspondence to:
K. M. Scharer,
kscharer@usgs.gov

Citation:
Scharer, K. M., & Yule, D. (2020). A Maximum Rupture Model for the Southern San Andreas and San Jacinto Faults, California, Derived From Paleoseismic Earthquake Ages: Observations and Limitations. *Geophysical Research Letters*, *47*, e2020GL088532. https://doi.org/10.1029/2020GL088532

Received 22 APR 2020
Accepted 27 JUN 2020
Accepted article online 8 JUL 2020

©2020. The Authors.
This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

A Maximum Rupture Model for the Southern San Andreas and San Jacinto Faults, California, Derived From Paleoseismic Earthquake Ages: Observations and Limitations

Katherine M. Scharer[1] and Doug Yule[2]

[1]Earthquake Science Center, U.S. Geological Survey, Pasadena, CA, USA, [2]Department of Geological Sciences, California State University, Northridge, CA, USA

Abstract Paleoseismic rupture histories provide spatiotemporal models of earthquake moment release needed to test numerical models and lengthen the instrumental catalog. We develop a model of the fewest and thus largest magnitude earthquakes permitted by paleoseismic data for the last 1,500 years on the southern San Andreas and San Jacinto Faults, California, USA. The largest geometric complexity appears to regulate the system: Only two ruptures break the San Gorgonio Pass region, followed by episodes of ruptures that could bridge the northern San Jacinto Fault and the San Andreas Fault. When tested against independent data on slip per event, the model produces comparable values indicating the end-member model does not underpredict rupture rates. Rupture of >85% of the fault length in the historic period between 1800 and 1857 and the subsequent quiescence is similar to epochs of activity in the prehistoric model, suggesting that regional clustering of seismicity could be a trait of the system.

Plain Language Summary Large, damaging earthquakes are rare, so geologic data are essential to supplement the record of earthquakes from seismographs. We use the geologic record to determine the magnitude and timing of past earthquakes on the San Andreas and San Jacinto Faults. A pattern emerges in which the biggest bends and splays control the length of most ruptures. Because the model estimates the largest-possible earthquakes on this system, it is useful as an upper limit on earthquake size used in engineering and earthquake forecasting.

1. Introduction

A single, large magnitude earthquake can devastate a region, but a sequence of significant earthquakes will magnify the social challenges of mitigation, emergency response, and reconstruction. In the historic record of plate boundary regions, large earthquakes occurring in isolation appear rare, whereas there are a number of well-documented examples of regional sequences in which several hundreds of kilometers of a fault system have ruptured in a few earthquakes over multiple decades. Examples on strike-slip faults include the 20th century progression along the North Anatolian Fault in Turkey (Barka et al., 2002) and the cluster of Mw > 7 events along the Kunlun Fault culminating in the 2001 Kokoxili earthquake in Tibet (Xie et al., 2014). The 21st century seismic events on the Sumatra-Andaman Sunda Megathrust provide a classic cascade example from subduction zones (Philibosian & Meltzner, 2020). The causes of rupture sequences on a fault network have been explored in terms of static stress conditions such as Coulomb stress transfer (King et al., 1994), cumulative Coulomb stress transfer (Mildon et al., 2019), heterogeneous prestress (Duan & Oglesby, 2007), elapsed time since previous ruptures (Schwartz et al., 2012), and time-dependent behavior of the lithosphere (Bürgmann & Dresen, 2008), though no single approach has been shown to be a definitive predictor (e.g., Freed, 2005; Harris & Simpson, 1998). Understanding if isolated ruptures, cascades, or clusters typifies large ruptures on a fault system is of interest because it may reveal complex time evolution of stress on faults and fault networks, effects that are not currently incorporated into seismic hazard assessments. There are a few papers that explore lithospheric mechanisms that would produce regional clustering (e.g., Ben-Zion et al., 1999; Scholz, 2010), but additional work is warranted if this is a robust feature of fault networks.

Several studies, from relatively short records for the San Francisco Bay Region in California, USA (Schwartz et al., 2014), moderate length records in the central Italian Apennines (Mildon et al., 2019), and longer

Late Quaternary slip history of the Mill Creek strand of the San Andreas fault in San Gorgonio Pass, southern California: The role of a subsidiary left-lateral fault in strand switching

K.J. Kendrick[1,†], J.C. Matti[2], and S.A. Mahan[3]
[1]*U.S. Geological Survey, Earthquake Science Center, Pasadena, California 91106, USA*
[2]*U.S. Geological Survey, Geology, Minerals, Energy, and Geophysics Science Center, Tucson, Arizona 85719, USA*
[3]*U.S. Geological Survey, Crustal Geophysics and Geochemistry Science Center, Denver, Colorado 80225, USA*

ABSTRACT

The fault history of the Mill Creek strand of the San Andreas fault (SAF) in the San Gorgonio Pass region, along with the reconstructed geomorphology surrounding this fault strand, reveals the important role of the left-lateral Pinto Mountain fault in the regional fault strand switching. The Mill Creek strand has 7.1–8.7 km total slip. Following this displacement, the Pinto Mountain fault offset the Mill Creek strand 1–1.25 km, as SAF slip transferred to the San Bernardino, Banning, and Garnet Hill strands. An alluvial complex within the Mission Creek watershed can be linked to palinspastic reconstruction of drainage segments to constrain slip history of the Mill Creek strand. We investigated surface remnants through detailed geologic mapping, morphometric and stratigraphic analysis, geochronology, and pedogenic analysis. The degree of soil development constrains the duration of surface stability when correlated to other regional, independently dated pedons. This correlation indicates that the oldest surfaces are significantly older than 500 ka. Luminescence dates of 106 ka and 95 ka from (respectively) 5 and 4 m beneath a younger fan surface are consistent with age estimates based on soil-profile development. Offset of the Mill Creek strand by the Pinto Mountain fault suggests a short-term slip rate of ~10–12.5 mm/yr for the Pinto Mountain fault, and a lower long-term slip rate. Uplift of the Yucaipa Ridge block during the period of Mill Creek strand activity is consistent with thermochronologic modeled uplift estimates.

[†]E-mail: kendrick@usgs.gov.

INTRODUCTION

Statement of Problem

Accurately evaluating seismic hazard is critical to societies worldwide (e.g., Jordan et al., 2011). A key element to seismic hazard assessment is knowledge of fault system complexity. The distribution and length of active faults in a complex fault system likely affect rupture termination, and thus earthquake magnitude potential (Wesnousky, 2008). Determination of the history, evolution, and timing of most recent movement along fault strands, and thus their activity level, is key to understanding complex fault systems. Continental transform fault systems, such as the North Anatolian, Alpine, and San Andreas faults, represent significant seismic hazard, but vary in their complexity.

The slip history of the San Andreas fault (SAF) becomes increasingly challenging to resolve and also more relevant to hazard analysis when considered in progressively greater spatial detail. At a global scale, the fault is routinely explained as a continental transform fault that simply resolves the motions of the North American and Pacific plates (e.g., Wallace, 1990). At the scale of the state of California, the fault trace is evidently divided into segments with different strike directions and seismic histories (e.g., Jones, 1988; Weldon et al., 2004). It also becomes clear that relative plate motion must be partitioned between the SAF and other right- and left-lateral strike-slip faults. Within the Transverse Ranges of southern California, the trace of the SAF deviates from its general N35°–40°W strike direction, and estimates of the amount of right-lateral slip vary significantly from place to place (Powell, 1993a). Many of these discrepant estimates are reconciled by evidence that the trace of the SAF through the Transverse Ranges is a braid of four successive right-lateral, strike-slip fault strands (Matti et al., 1985; Matti and Morton, 1993).

Why does slip switch from one strand to another in the Transverse Ranges? We present evidence of the role of subsidiary left-lateral faults in the switching process, a view that has broad relevance for the evolution of strike-slip fault systems in general, but must be developed from detailed geologic and geomorphic mapping. Our study focuses on the interaction of the left-lateral Pinto Mountain fault with the SAF where the latter changes strike direction in San Gorgonio Pass (SGP; Fig. 1). The time-space history of the SAF in SGP is critical not only to understanding the modern seismotectonic framework of the southern SAF system, but also to evaluating how various components of that system have interacted since inception of the SAF proper in the Pliocene (ca. 5 Ma). Previous workers have outlined key elements of this time-space history (Allen, 1957; Matti et al., 1985, 1992; Matti and Morton, 1993; Yule and Sieh, 2003), and the modern SAF in the SGP region recently has been the focus of considerable debate among seismologists concerned with fault-rupture scenarios and attendant seismic risk (e.g., Carena et al., 2004; Plesch et al., 2007; Yule, 2009, 2010; Dair and Cooke, 2009; Cooke and Dair, 2011). Despite this recent interest, little is known about the Quaternary slip history of the SAF in the SGP region. We address this issue by investigating the slip history for the Mill Creek strand of the SAF. The response of four drainages to strike-slip offsets between four fault blocks provides crucial evidence of slip history, recorded in the form of wind gaps, underfit drainages, and orphan alluvial deposits. We have remapped the geology, geomorphology, and alluvial stratigraphy of three critical locations along the trace of the Mill Creek strand of the SAF to reconstruct slip history. To place the new evidence in context, we must introduce

GSA Bulletin; May/June 2015; v. 127; no. 5/6; p. 825–849; doi:10.1130/B31101.1; 13 figures; 7 tables; published online 22 January 2015.

For permission to copy, contact editing@geosociety.org
© 2015 Geological Society of America

wnloaded from http://pubs.geoscienceworld.org/gsa/gsabulletin/article-pdf/127/5-6/825/3410110/825.pdf
by USGS Library user

GEOSPHERE

GEOSPHERE

https://doi.org/10.1130/GES02424.1

14 figures; 2 tables

CORRESPONDENCE: kendrick@usgs.gov

CITATION: Kendrick, K.J., Matti, J.C., and Barth, N.C., 2022, Geologic and geomorphic evidence for multi-phase history of strands of the San Andreas fault through the San Gorgonio Pass structural knot, southern California: Geosphere, https://doi.org/10.1130/GES02424.1.

Science Editor: Andrea Hampel
Guest Associate Editor: Michele Cooke

Received 25 February 2021
Revision received 30 September 2021
Accepted 29 November 2021

Published online 18 February 2022

GOLD OPEN ACCESS

THE GEOLOGICAL SOCIETY OF AMERICA®

This paper is published under the terms of the CC-BY-NC license.

© 2022 The Authors

Geologic and geomorphic evidence for multi-phase history of strands of the San Andreas fault through the San Gorgonio Pass structural knot, southern California

Katherine J. Kendrick[1,*], Jonathan C. Matti[2,*], and Nicolas C. Barth[3,*]

[1]U.S. Geological Survey, 525 South Wilson Avenue, Pasadena, California 91106, USA
[2]U.S. Geological Survey, 520 North Park Avenue, Tucson, Arizona 85719, USA
[3]University of California, Riverside, 900 University Avenue, Riverside, California 92521, USA

ABSTRACT

The San Gorgonio Pass region of southern California is a locus of extensive Quaternary deformation within a multi-strand section of the San Andreas fault zone. The geomorphology of the San Gorgonio Pass region reflects the complicated history of geologic events in the formation of this structurally complex region. We define fault-bounded blocks in San Gorgonio Pass and focus on two that are characterized by extensive crystalline bedrock outcrops with similar bedrock lithologies. These two blocks are separated by the San Bernardino strand of the San Andreas fault. Morphometric variables, including local relief, slope, slope distribution, and surface roughness, consistently demonstrate distinctions between the bedrock upland regions of the two blocks. Geologic observations of the region highlight differences in Quaternary units within the two blocks, reflective of the differing surficial processes active in each block. Within the Kitching Peak block, the morphology highlights a lineament that we informally name the Lion Canyon lineament. This boundary more clearly differentiates the two regions, as compared to the mapped San Bernardino strand, and may represent the previously active strand or bounding structure in this section. The distinction in morphology and surficial processes leads to our interpretation that the Kitching Peak and Pisgah Peak blocks have experienced different uplift histories. This further leads to the conclusion that the San Bernardino strand, broadly defined, has been integrated, at some point in the past, with the Banning strand, allowing for through-going rupture along the fault system. This connectivity may have occurred along the Burro Flats section of the San Bernardino strand or the Lion Canyon lineament. The fault connection along the mapped trace of the San Bernardino strand is not currently evident at the surface, however, suggesting that the integration has been disrupted. We propose this is due to intervals of N-S compression in the region, manifest as slip along the San Gorgonio Pass fault zone and other regional faults. We present evidence for lateral displacement along the San Bernardino and Banning strands of the San Andreas fault, discuss the implications of these displacements, and propose a sequence of fault activity, including multiple phases of activity along the San Bernardino and Banning strand pathway to account for the structural complexity and lack of surficial fault continuity.

*E-mail: kendrick@usgs.gov; jmatti@usgs.gov; nic.barth@ucr.edu

INTRODUCTION

The San Andreas fault (SAF) zone is uniquely complex through the San Gorgonio Pass region (SGPr) (Fig. 1) and, despite numerous investigations, remains incompletely understood. This complexity, demonstrated by multiple subparallel fault strands, bends, kinks, or offsets of individual fault strands, along with an orientation that is rotated in a counterclockwise sense relative to the overall strike of the fault system, led to previous descriptions of this region as a "structural knot" (Matti et al., 1992a). Allen (1957) recognized this complexity and questioned the continuity of faulting through the SGPr, citing the apparent absence of large displacements and the lack of youthful tectonic geomorphology associated with the most likely path of the modern SAF. Many of the questions posed by Allen (1957) persist, in spite of numerous investigations designed to better understand this enigmatic region. Among the questions remaining are how the SAF resolves itself through the SGPr, and whether there is a pathway for fault rupture to propagate through the SGPr, or if instead, this region serves as a barrier to rupture along the SAF initiating from the southeast or northwest. Additionally, it is important to know both the three-dimensional geometry and the kinematic evolution of the SAF through the region in order to fully characterize the earthquake hazards of the system.

Principal geologic structures within the SGPr landscape (Fig. 1) include (1) strands of the SAF zone, including the Mission Creek, Mill Creek, San Bernardino, Gandy Ranch, Banning, and Garnet Hill strands, that have been active at different intervals in the recent geologic past (Matti et al., 1992a; Matti and Morton, 1993; Kendrick et al., 2015); (2) the transpressive San Gorgonio Pass fault zone (SGPFZ); (3) the Crafton Hills fault complex; and (4) the Whitewater fault (nomenclatural usage for all of these faults follows Matti et al., 1985, 1992a, 2003; Kendrick et al., 2015). Throughout this study, we will refer to the strands of the SAF simply as strands without designating that they are strands of the

Downloaded from http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02424.1/5548351/ges02424.pdf
by USGS Library user

WHAT HAPPENS TO THE REAL SAN ANDREAS FAULT AT COTTONWOOD CANYON, SAN GORGONIO PASS, CALIFORNIA?

Gary S. Rasmussen
Gary S. Rasmussen & Associates, Inc.
1811 Commercenter W.
San Bernardino, CA 92408

Wessly A. Reeder
Gary S. Rasmussen & Associates, Inc.
1811 Commercenter W.
San Bernardino, CA 92408

INTRODUCTION

The San Andreas fault has been difficult to trace through the San Gorgonio Pass, despite numerous efforts to precisely define its location and style of movement. In this paper we have attempted to provide an alternate explanation for the fault through the San Gorgonio Pass. At this time, our field work has been primarily confined to the terrain between Millard Canyon and Cottonwood Canyon, the easternmost portion of the area where the fault is most elusive. In describing the geologic features of the San Andreas fault from Burro Flats to Cottonwood Canyon, the convention of describing the fault from north to south has been followed. The fault itself and most of the structural features associated with it, however, were created by forces imposed from south to north as the oceanic plate collided with the continental plate.

This paper is the result of several years of observations of the fault in this area. It is based on time and effort unrelated to any outside funding. The increasing pressure of development in the upper Coachella Valley is resulting in many more site specific geologic studies that rely on the published literature. The interaction of man with geologic forces makes it mandatory that we more completely understand the geologic facts prior to modifying or building on the natural terrain.

The purpose of this paper is to off er a possible explanation for most, if not all of the puzzling aspects related to where and what is the real San Andreas fault between Burro Flats and Cottonwood Canyon.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. B11, 2548, doi:10.1029/2001JB000451, 2003

Complexities of the San Andreas fault near San Gorgonio Pass: Implications for large earthquakes

Doug Yule[1] and Kerry Sieh

Seismological Laboratory, California Institute of Technology, Pasadena, California, USA

Received 13 February 2001; revised 30 December 2002; accepted 27 February 2003; published 29 November 2003.

[1] Geologic relationships and patterns of crustal seismicity constrain the three-dimensional geometry of the active portions of San Andreas fault zone near San Gorgonio Pass, southern California. Within a 20-km-wide contractional stepover between two segments of the fault zone, the San Bernardino and Coachella Valley segments, folds, and dextral-reverse and dextral-normal faults form an east-west belt of active structures. The dominant active structure within the stepover is the San Gorgonio Pass-Garnet Hill faults, a dextral-reverse fault system that dips moderately northward. Within the hanging wall block of the San Gorgonio Pass-Garnet Hill fault system are subsidiary active dextral and dextral-normal faults. These faults relate in complex but understandable ways to the strike-slip faults that bound the stepover. The pattern of crustal seismicity beneath these structures includes a 5–8 km high east-west striking step in the base of crustal seismicity, which corresponds to the downdip limit of rupture of the 1986 North Palm Springs earthquake. We infer that this step has been produced by slip on the linked San Gorgonio Pass-Garnet Hill-Coachella Valley Banning (SGP-GH-CVB) fault. This association enables us to construct a structure contour map of the fault plane. The large step in the base of seismicity downdip from the SGP-GH-CVB fault system probably reflects a several kilometers offset of the midcrustal brittle-plastic transition. (U/Th)/He thermochronometry supports our interpretation that this south-under-north thickening of the crust has created the region's 3 km of topographic relief. We conclude that future large earthquakes generated along the San Andreas fault in this region will have a multiplicity of mostly specifiable sources having dimensions of 1–20 km. Two tasks in seismic hazard evaluation may now be attempted with greater confidence: first, the construction of synthetic seismograms that make useful predictions of ground shaking, and second, theoretical investigations of the role of this complexity in retarding the propagation of future seismic ruptures. *INDEX TERMS:* 8102 Tectonophysics: Continental contractional orogenic belts; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8107 Tectonophysics: Continental neotectonics; 8110 Tectonophysics: Continental tectonics—general (0905); 8115 Tectonophysics: Core processes (1507); 8124 Tectonophysics: Earth's interior—composition and state (1212); *KEYWORDS:* San Andreas fault zone, San Gorgonio Pass, neotectonics, three-dimensional fault geometry, transpression, fault interaction

Citation: Yule, D., and K. Sieh, Complexities of the San Andreas fault near San Gorgonio Pass: Implications for large earthquakes, *J. Geophys. Res.*, *108*(B11), 2548, doi:10.1029/2001JB000451, 2003.

1. Introduction

[2] Discontinuities of crustal dimension are rare along the 1100-km length of the San Andreas fault (Figure 1, inset). This scarcity of large structural irregularities may, in fact, encourage lengthy seismic ruptures like the 360- and 420-km-long events of 1857 and 1906 [*Sieh*, 1978], since geometrical complexities appear to play a critical role in impeding rupture propagation [for example, *Barka and Kadinsky-Cade*, 1988; *Harris and Day*, 1993; *Wesnousky and Jones*, 1994; *Rice and Ben-Zion*, 1996; *Sieh and Natawidjaja*, 2000]. The largest irregularity in the San Andreas fault occurs in southern California, in the vicinity of San Gorgonio Pass (Figure 1). Here at a contractional left step [*Matti et al.*, 1985, 1992a; *Matti and Morton*, 1993], the surface trace of the San Andreas fault disaggregates into a family of irregular and discontinuous faults [*Allen*, 1957; *Dibblee*, 1968, 1982; *Hill*, 1982; *Matti et al.*, 1985, 1992a; *Matti and Morton*, 1993].

[3] The exceptional complexity of the San Andreas fault zone in the region of San Gorgonio Pass, southern California, presents a formidable challenge to forecasting the source characteristics of future earthquakes there. Recent earthquakes in structurally complex regions provide two general insights, however. First, the nearly synchronous failure of several faults can lead to unusually complex earthquakes. The complex Spitak, Armenia, earthquake of

[1]Now at Department of Geological Sciences, California State University, Northridge, California, USA.

Copyright 2003 by the American Geophysical Union.
0148-0227/03/2001JB000451$09.00

DAY 2 PAPERS

Quaternary Science Reviews 282 (2022) 107456

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

The late Holocene history of Lake Cahuilla: Two thousand years of repeated fillings within the Salton Trough, Imperial Valley, California

Thomas K. Rockwell [a, *], Aron J. Meltzner [b, c], Erik C. Haaker [d], Danielle Madugo [e]

[a] Dept. Geological Sciences, San Diego State University, San Diego, CA, 92182, USA
[b] Earth Observatory of Singapore, Nanyang Technological University, 639798, Singapore
[c] Asian School of the Environment, Nanyang Technological University, 639798, Singapore
[d] G3Soilworks, Inc., 350 Fischer Avenue, Costa Mesa, CA, 92626, USA
[e] Garrick Institute for the Risk Sciences, University of California Los Angeles, Engineering VI, Phase 1, 404 Westwood Plaza, Los Angeles, CA, 90095, USA

a r t i c l e i n f o

Article history:
Received 11 November 2021
Received in revised form
26 February 2022
Accepted 6 March 2022
Available online xxx

Handling Editor: Dr I Hendy

Keywords:
Lake Cahuilla
Lake chronology
Radiocarbon
Paleoseismology
Archaeology

a b s t r a c t

To constrain the timing of the past seven lake highstands in the Salton Trough, we compiled 423 radiocarbon dates, of which 284 are reliable and have good stratigraphic control, from paleoseismic and archeological sites in the basin. We developed two OxCal models that assume most charcoal, wood, seeds, and twigs recovered from organic mats at or near the shoreline are derived from material that grew within the lake footprint, and therefore date a dry period between lakes. Charcoal samples collected from lacustrine clastic strata may have also been derived from fires burned during a dry period. As an initial constraint, we assume that samples older than those in earlier lake deposits have age inheritance. Assuming the dates are accurately described by their respective 2s uncertainties, we ran all dates that would run in a preliminary OxCal model, and then removed those with a poor agreement index as defined in OxCal. From this, of the 423 total dates in the compilation, 151 dates are used in the base model and 149 dates are used in an alternative model, with the differences in the models resulting from choices of whether to include or exclude specific dates that may or may not be representative of a particular dry period between lakes. Where the two models agree, the results are robust, but where the models differ, any differences are taken as uncertainty in the lake ages. Historical accounts and a high-resolution paleohydrologic reconstruction allow us to refine some lake ages.

The age windows for the past seven Lake Cahuilla highstands are 1731e1733 CE (Lake A), 1618 e1636 CE (Lake B), 1486e1503 CE (Lake C), 1118e1165 or 1192e1241 CE (Lake D), 1007e1070 CE (Lake E), 930e966 CE (Lake F), and 612e5 BCE (Lake G). These ages represent the maximum allowable ranges during which a lake may have filled the basin up to the þ13 m highstand elevation; the basin may have been dry for significant portions of each time window, though the lake filling and desiccation episodes may have extended beyond the stated highstand age range for each lake. If the paleohydrologic constraints are ignored, some of the lakes may have initiated earlier, by up to three decades. Additional dates would be needed to further bracket the ages of the earlier lakes. Notably, 120 of the original 284 reliable dates were rejected because they clearly violate stratigraphic ordering, implying that more than 40% of all radiocarbon dates in the Salton Basin exhibit statistically significant age inheritance.

© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Lake Cahuilla was a freshwater lake that filled the Salton Trough in southeastern California many times during the Holocene, up to the sill elevation at ~13 m above sea level (Sykes, 1937; Wilke, 1978; Waters, 1983; Philibosian et al., 2011). Each filling of Lake Cahuilla followed an avulsion of the Colorado River (Waters, 1983; Li et al., 2008), away from its usual southerly course to the Gulf of California, with flow instead directed west and north along the Alamo and New Rivers (Fig. 1). Six filling episodes resulting in full lakes have been recognized in the past ~1100 years, all of them from before written history in the Salton Basin, although there are oral Indigenous American accounts that record the latest filling (Modesto and

* Corresponding author.
E-mail addresses: trockwell@sdsu.edu (T.K. Rockwell), meltzner@ntu.edu.sg (A.J. Meltzner), ehaaker@g3soilworks.com (E.C. Haaker), daniellemadugo@gmail.com (D. Madugo).

https://doi.org/10.1016/j.quascirev.2022.107456
0277-3791/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Bulletin of the Seismological Society of America, Vol. 108, No. 5A, pp. 2634–2649, October 2018, doi: 10.1785/0120170392

Dates of the Two Most Recent Surface Ruptures on the Southernmost San Andreas Fault Recalculated by Precise Dating of Lake Cahuilla Dry Periods

by Thomas K. Rockwell, Aron J. Meltzner,* and Erik C. Haaker

Abstract The past two southernmost San Andreas fault (SAF) ruptures occurred when ancient Lake Cahuilla was full, based on faulted lake sediment relationships and extensive liquefaction at sites near the shoreline. The times of the past two southern SAF ruptures have been reevaluated with new radiocarbon data on *in situ* stumps that grew between the past three Lake Cahuilla highstands, which, when taken in combination with historical accounts and modeling of the time to fill and desiccate the lake, provide more precise and accurate ages for the past two SAF earthquakes. The ^{14}C dates on inner and outer rings combined with historical observations show that the dry period prior to the last lake ended after 1706 C.E., leaving a narrow window of less than 25 yrs to fill and begin desiccating the most recent lake, and that the penultimate lake began dropping from a highstand around 1640 C.E. or earlier. Our analysis shows that the most recent earthquake occurred about 1726 ± 7 C.E., whereas the timing of the penultimate event is slightly older at 1577 ± 67 C.E. (both at 2σ). These new dates, when combined with previous age estimates of earlier southern SAF events, suggest more regular recurrence of surface-rupturing events, with an average interval of about 180 yrs, but leave the open interval at nearly 300 yrs.

Introduction

Assessment of earthquake hazard from fast-moving faults using time-dependent forecast models is critically dependent on knowing the timing of the most recent large earthquake (Gomberg *et al.*, 2005; Petersen *et al.*, 2007; Field *et al.*, 2015). This is particularly true for the southern San Andreas fault (SAF), where the published average recurrence interval for the past millennium is on the order of 116–221 yrs, with a best estimate of 180 yrs (Philibosian *et al.*, 2011), whereas the last large surface rupture has been estimated to have occurred 330–340 yrs ago (Sieh, 1986; Sieh and Williams, 1990; Fumal *et al.*, 2002; Philibosian *et al.*, 2011). All of these studies used radiocarbon dating to resolve the timing of past earthquakes, but the radiocarbon calibration curve for the time period after about 1680 C.E. fluctuates about a horizontal axis, resulting in multiple age intercepts and discrete, broad ranges for predicted earthquake ages. The historical record has been used to trim these dates, but the historical observations are sparse, allowing for substantial uncertainty in the timing of the most recent large southern SAF earthquake.

The southern SAF crosses the shoreline and lake deposits of ancient Lake Cahuilla (Fig. 1), a freshwater lake that covered much of the Salton trough, up to its sill elevation of 13 m above sea level, at least six times in the past 1000–1200 yrs (Waters, 1983; Gurrola and Rockwell, 1996; Philibosian *et al.*, 2011). The two most recent southern SAF surface ruptures are interpreted to have occurred during the two most recent highstands of Lake Cahuilla, based on the presence of extensive liquefaction, plastic slumping, and soft-sediment deformation of lake deposits in association with upward termination of fault splays and accumulation of growth strata (Sieh, 1986; Sieh and Williams, 1990; Philibosian *et al.*, 2011).

The timings of these past earthquakes are based, in part, on radiocarbon dates on detrital charcoal recovered from the lake sediments. Because wood in this region neither grows under water nor burns in the water, most of the detrital charcoal is either derived from outside the lake basin or represents wood growth below the lake shoreline during a dry period between lakes. Consequently, the published dates of large SAF earthquakes almost certainly are older than the actual dates of the events because they do not account for the inherited age of the wood, which includes the time between plant growth and death, the burning of the wood, and the transport and burial of the charcoal in the lake sediments.

*Also at Asian School of the Environment, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.

wnloaded from https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/108/5A/2634/4345479/bssa-2017392.1.pdf
13598
30 September 2018

Estimating slip distribution along the southernmost ~80 km of the San Andreas Fault by examining tectonically offset features

***William C. Buckley[1], Patrick L. Williams[2], Thomas K. Rockwell[1], and Allen M. Gontz[3]**

[1]Department of Geological Sciences, San Diego State University, 5500 Campanile Drive, San Diego, California 92182

[2]Patrick Williams & Associates, P.O. Box 1437, Alpine, California 91903

[3]Department of Civil and Environmental Engineering, Clarkson University, 8 Clarkson Avenue, Potsdam, New York, 13699

ABSTRACT

We measured tectonically offset geomorphic features along approximately 80 km of the southernmost San Andreas Fault (sSAF) between Bombay Beach and Indio Hills in the Salton Trough to obtain a better estimate for slip distribution and slip-per-event for the past several large, surface rupturing earthquakes along this segment of the fault. In addition to gathering aerial imagery from previously published B4 light detection and ranging (LiDAR) and uncrewed aerial vehicle (UAV) imagery, we constructed new high-resolution orthomosaics and digital surface models (DSMs) generated from Structure-from-Motion-Multiview Stereo (SfM-MVS) techniques from UAV imagery at multiple localities along the San Andreas fault in the Salton Trough region of California, which include areas at Durmid Hill, Salt Creek, Ferrum, Mecca Hills, and Indio Hills. The aerial imagery, along with field mapping, were used to identify and measure a total of 146 offset features with lateral displacement measurements ranging between 2 to 23 m. Investigation of offset features suggests that the last several large, surface rupturing events produced average displacements of 3.1-4.4 m per event, with lower overall lateral slip values where multiple fault strands are present. Offset features displaying less than ~1 m of lateral displacement were not considered in our study as these features likely reflect modern creep and triggered slip events, which post-date the most recent surface rupturing event in ca 1726 AD.

INTRODUCTION

The southernmost San Andreas Fault (sSAF), extending from approximately Bombay Beach to Banning Pass in the Salton Trough (Fig. 1), has been the focus of several notable paleoseismic studies in the Coachella Valley and Salt Creek regions (Sieh and Williams, 1990; Fumal et al., 2002; Philibosian et al., 2011; Rockwell et al., 2018; Castillo et al., 2021), but information on displacement in the paleo-events is much more limited. Some displacement information was included in UCERF3 (Field et al., 2014; Field et al., 2015), and two recent studies in and near the Mecca Hills provide local information on displacement for the past few ruptures (Dingler et al., 2016; Blanton et al., 2020), but information on the distribution of slip in the past several earthquakes has not been constructed for the length of the southern SAF in the Salton Trough. In this paper, we present new information of the amount of displacement

Geomorphology 357 (2020) 107064

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Refining the spatial and temporal signatures of creep and co-seismic slip along the southern San Andreas Fault using very high resolution UAS imagery and SfM-derived topography, Coachella Valley, California

Chelsea M. Blanton [a,b,*], Thomas K. Rockwell [a], Allen Gontz [a], Joshua T. Kelly [a,c]

[a] Department of Geological Sciences, San Diego State University, San Diego, CA, 92182, USA
[b] Lettis Consultants International, Inc., 27441 Tourney Road, Suite 220 Valencia, CA 91355, USA
[c] Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA

article info

Article history:
Received 21 July 2019
Received in revised form 28 January 2020
Accepted 31 January 2020
Available online 13 February 2020

Keywords:
Paleoseismology
Tectonic geomorphology
El Niño Southern Oscillation (ENSO)
Photogrammetry

abstract

The current interseismic period for an event on the Coachella Valley segment of the San Andreas Fault (SAF) is ~300 years, much greater than the best-estimated average recurrence interval of ~180 years, prompting questions regarding earthquake recurrence and fault behavior. Digital Surface Models (DSMs) generated using Structure-from-Motion-Multiview Stereo (SfM-MVS) techniques on unmanned aerial systems (UAS) imagery and very-high resolution UAS orthomosaics were used to identify and measure fault-related offsets of small geomorphic features and develop a model of late Holocene slip-per-event for the southern SAF (sSAF) in the Coachella Valley. We aim to better constrain slip estimates from recent earthquakes along the sSAF and combine new slip data with ages of past earthquakes from paleoseismic studies to understand earthquake recurrence. Slip-per-event for paleoearthquakes, which ruptured this segment of the sSAF, and the relationship between co-seismic slip events, creep or afterslip, and triggered slip were evaluated. Examination of offsets suggests that five (5) large, surface rupturing events produced average displacements of 2.6−3.1 m per event. Gaussian distribution analysis revealed small-scale offset clusters that we attribute to climate-modulated channel incision across the fault and subsequent creep. These offset clusters support a creep rate of ~3 mm/yr in the Mecca Hills averaged over the past ~160 years.

© 2020 Elsevier B.V. All rights reserved.

1. Introduction

1.1. Earthquake recurrence

The Coachella Valley segment of the San Andreas Fault (SAF) in the Salton Trough (Fig. 1) has been the subject of many paleoseismic studies (e.g. Fumal, 2002; Philibosian et al., 2011; Rockwell et al., 2018; Sieh and Williams, 1990). Average recurrence intervals for paleoearthquakes rupturing the Coachella Valley range from 116 to 240 years with a best estimate of 180 years (Philibosian et al., 2011), leaving the current open interval of ~300 years curiously long. Rockwell et al. (2018) re-evaluated the timing of the most recent and penultimate events on the southern San Andreas Fault (sSAF), supporting an average recurrence interval of about 180 years, but this average recurrence interval is biased by the open interval of about 300 years. The current approximately 300-year-long period of quiescence could be a deviation from the normal behavior of shorter intervals and more frequent events, or it could reflect a lower rate of elastic loading (van der Woerd et al., 2006). The extended period of dormancy has led some to speculate that an abnormally large amount of elastic strain has accumulated along the sSAF segment (Fialko, 2006; Philibosian et al., 2011), which provokes questions concerning earthquake recurrence models. If the average interseismic period is 180 years and the current open interval is ~300 years, is it possible that earthquakes follow a quasi-periodic recurrence model with a relatively high coefficient of variation? Is it more likely that this long open interval is producing a buildup of elastic strain energy that will result in an unusually large (infrequent) earthquake in terms of magnitude-frequency distributions? This is a complex relationship that warrants further exploration.

1.2. Creep rate

The sSAF in the Coachella Valley is known to creep at rates that vary between 1 and 4 mm/yr (Bilham, 2019; Lindsey et al., 2014; Sieh and Williams, 1990). Sieh and Williams (1990) calculated an average creep rate of 3.4 ± 0.7 mm/yr at Indio for the past 300 years and a creep rate of only 1.9 ± 0.2 mm/yr for an ~81 year period from ~1906 to 1987 at Salt Creek (Fig. 1). Creep rates near Indio and the Salton Sea have

* Corresponding author at: Lettis Consultants International, Inc., 27441 Tourney Road, Suite 220 Valencia, CA 91355, USA.
E-mail address: blanton@lettisci.com (C.M. Blanton).

https://doi.org/10.1016/j.geomorph.2020.107064
0169-555X/© 2020 Elsevier B.V. All rights reserved.

Bulletin of the Seismological Society of America, Vol. 101, No. 1, pp. 13–38, February 2011, doi: 10.1785/0120100050

San Andreas Fault Earthquake Chronology and Lake Cahuilla History at Coachella, California

by Belle Philibosian, Thomas Fumal, and Ray Weldon

Abstract The southernmost ~100 km of the San Andreas fault has not ruptured historically. It is imperative to determine its rupture history to better predict its future behavior. This paleoseismic investigation in Coachella, California, establishes a chronology of at least five and up to seven major earthquakes during the past ~1100 yr. This chronology yields a range of average recurrence intervals between 116 and 221 yr, depending on assumptions, with a best-estimate average recurrence interval of 180 yr. The most recent earthquake occurred c.1690, more than 300 yr ago, suggesting that this stretch of the fault has accumulated a large amount of tectonic stress and is likely to rupture in the near future, assuming the fault follows a stress renewal model. This study also establishes the timing of the past 5–6 highstands of ancient Lake Cahuilla since A.D. 800. We found that earthquakes do not tend to occur at any particular stage in the lake cycle.

Introduction

The Coachella Valley section of the San Andreas fault (SAF), between San Gorgonio Pass and the Imperial Valley, is the only noncreeping portion of the 1300-km-long fault that has not ruptured in a major earthquake during historical time (Fig. 1). For this reason, the hazard potential and likely timing of its next earthquake are poorly constrained in comparison to other sections of the fault, since these parameters must be determined solely from paleoseismology. Paleoseismic analysis of the southernmost SAF is particularly important because a rupture on this fault segment has the potential to severely damage the adjacent Los Angeles metropolitan area, particularly if the rupture propagates northward through the San Gorgonio Pass (Olsen *et al.*, 2006). In addition, rupture history is key to resolving important issues in fault behavior such as periodicity, segmentation, and characteristic versus random rupture behavior (discussed in Weldon *et al.*, 2004). Toward these ends, we have constructed an earthquake chronology for the past ~1200 yr for the southernmost SAF based on a new paleoseismic investigation conducted in the city of Coachella, California.

To date, there have been three other paleoseismic investigations on the SAF south of the San Gorgonio Pass (Fig. 1c), two of which have yet to be completely published. Sieh (1986) reported four earthquakes since A.D. 1000 from an investigation in the city of Indio, only a few kilometers northwest of the Coachella site. An ongoing investigation at Salt Creek, 45 km to the southeast of the Coachella site, includes evidence for six earthquakes since A.D. 800 (Williams, 2009), but specific dates for these have not yet been published. To date, the best record of Coachella Valley earthquakes comes from an extensive investigation 20 km to the northwest of the Coachella site at the Thousand Palms oasis, where Fumal, Rymer, and Seitz (2002) described evidence for five earthquakes since A.D. 800. However, in that region there are at least two active strands of the fault (Banning and Mission Creek), and only the Mission Creek strand passes through the Thousand Palms site. The Mission Creek strand gradually dies out to the northwest, with slip becoming concentrated on the Banning strand. While the Mission Creek strand has a slip rate between 12 and 22 mm=yr at the Biskra Palms site, which is located in the junction zone between the two strands (Behr *et al.*, 2010), its slip rate at the Thousand Palms site is only a few millimeters per year (Fumal, Rymer, and Seitz, 2002), with the Banning strand likely accommodating the majority of the slip. The two strands probably move in concert, but it is possible that the Thousand Palms site record is missing earthquakes that produced surface rupture only on the Banning strand. The Coachella site, located to the southeast in the region where the SAF is singly stranded, does not suffer from this source of ambiguity.

The most recent earthquake recorded at the Indio site has been dated to approximately A.D. 1680 (Sieh, 1986), more than 300 yr ago. This is significantly longer than most estimates of average recurrence interval of on other segments of the fault, which range from ~100 to 250 yr (e.g., Sieh *et al.*, 1989; Weldon *et al.*, 2004; Weldon *et al.*, 2005; Kelson *et al.*, 2006; Goldfinger *et al.*, 2008; Akciz *et al.*, 2009). This open interval is about as long as the longest interval between earthquakes estimated by Sieh (1986) at the Indio site, and longer than any of the estimated interseismic intervals at the Thousand Palms site (Fumal, Rymer, and Seitz, 2002).

GEOSPHERE

GEOSPHERE, v. 17, no. 3

https://doi.org/10.1130/GES02237.1

13 figures; 7 tables; 1 plate; 1 supplemental file

CORRESPONDENCE: bryan.castillo@csusb.edu

CITATION: Castillo, B.A., McGill, S.F., Scharer, K.M., Yule, D., McPhillips, D., McNeil, J., Saha, S., Brown, N.D., and Moon, S., 2021, Prehistoric earthquakes on the Banning strand of the San Andreas fault, North Palm Springs, California: Geosphere, v. 17, no. 3, p. 685–710, https://doi.org/10.1130/GES02237.1.

Science Editor: Andrea Hampel
Associate Editor: Craig H. Jones

Received 27 January 2020
Revision received 19 August 2020
Accepted 23 February 2021

Published online 6 May 2021

GOLD OPEN ACCESS

THE GEOLOGICAL SOCIETY OF AMERICA®

This paper is published under the terms of the CC-BY-NC license.

© 2021 The Authors

Prehistoric earthquakes on the Banning strand of the San Andreas fault, North Palm Springs, California

Bryan A. Castillo[1], Sally F. McGill[1], Katherine M. Scharer[2], Doug Yule[3], Devin McPhillips[2], James McNeil[3], Sourav Saha[4], Nathan D. Brown[4,*], and Seulgi Moon[4]

[1]Department of Geological Sciences, California State University, San Bernardino, California 92407, USA
[2]Earthquake Science Center, U.S. Geological Survey, Pasadena, California 91106, USA
[3]Department of Geological Sciences, California State University, Northridge, California 91330, USA
[4]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California 90095, USA

ABSTRACT

We studied a paleoseismic trench excavated in 2017 across the Banning strand of the San Andreas fault and herein provide the first detailed record of ground-breaking earthquakes on this important fault in Southern California. The trench exposed an ~40-m-wide fault zone cutting through alluvial sand, gravel, silt, and clay deposits. We evaluated the paleoseismic record using a new metric that combines event indicator quality and stratigraphic uncertainty. The most recent paleoearthquake occurred between 950 and 730 calibrated years B.P. (cal yr B.P.), potentially contemporaneous with the last rupture of the San Gorgonio Pass fault zone. We interpret five surface-rupturing earthquakes since 3.3–2.5 ka and eight earthquakes since 7.1–5.7 ka. It is possible that additional events have occurred but were not recognized, especially in the deeper (older) section of the stratigraphy, which was not fully exposed across the fault zone. We calculated an average recurrence interval of 380–640 yr based on four complete earthquake cycles between earthquakes 1 and 5. The average recurrence interval is thus slightly less than the elapsed time since the most recent event on the Banning strand. The average recurrence interval on the Banning strand is thus intermediate between longer intervals published for the San Gorgonio Pass fault zone (~1600 yr) and shorter intervals on both the Mission Creek strand of the San Andreas fault (~215 yr) and the Coachella section (~125 yr) of the San Andreas fault.

INTRODUCTION

The San Andreas fault is the longest fault (~1300 km) and has the highest slip rate of all faults in California. The northern section of the fault ruptured in 1906, and the south-central section ruptured in 1857. Only the southernmost section of the San Andreas fault has not ruptured during the historical record. The Banning strand of the San Andreas fault is located within a complex portion of the southernmost section of the San Andreas fault zone (Fig. 1). Within the San Gorgonio Pass region, the fault bends to a west-northwest orientation, resulting in a complex zone of transpressional faults (Yule and Sieh, 2003). In addition, faults diverge northward from the southernmost section of the San Andreas fault toward the Eastern California shear zone (Fig. 1). This geometry triggers many questions about the southernmost section of the San Andreas fault system, such as: (1) How is plate-boundary slip accommodated within this region? (2) How have earthquake ruptures in this region made use of the various fault strands within this complex region?

The geometry of the southernmost San Andreas fault becomes more complex from southeast to northwest; the Coachella section is a single strand, but it splits as it approaches the San Bernardino Mountains (Fig. 1). Near Indio, California, the Banning strand diverges from the Mission Creek strand, and farther to the northwest, the Garnet Hill strand deviates from the Banning strand. In the San Gorgonio Pass region, the southernmost San Andreas fault comprises an intricate network of right-lateral, oblique thrust and reverse faults known as the San Gorgonio Pass fault zone (Allen, 1957; Matti et al., 1985; Matti and Morton, 1993; Yule and Sieh, 2003), which connects in turn with the San Bernardino strand of the southernmost San Andreas fault. None of the strands southeast of the San Bernardino section has ruptured in a major earthquake during the historical period, with the exception of the 1986 North Palm Springs earthquake of M_w 6.0, which produced minor fracturing, as discussed below. The Mill Creek strand, which diverges from the Mission Creek strand within the San Gorgonio Pass region, also connects to the San Bernardino strand, but its recency of motion is less clear (cf. Kendrick et al., 2015; Fosdick and Blisniuk, 2018). Given this complexity and limited slip rate data, it is has long been debated whether earthquake ruptures on the southernmost San Andreas fault have propagated through the faults within the San Gorgonio Pass region (Allen, 1957; Yule and Sieh, 2003).

The distribution of slip among various strands of the southernmost San Andreas fault is poorly known. The southeastern portion of the Mission Creek strand seems to accommodate the majority of the slip: The slip rate is 12–22 mm/yr (14–17 mm/yr preferred) at Biskra Palms (Fig. 1; Behr et al., 2010; Fletcher et al., 2010) and is 21.6 ± 2 mm/yr at Pushawalla Canyon (Blisniuk et al., 2021). The slip rate of the Banning strand has been proposed to be 2–6 mm/yr in the Indio Hills (Scharer et al., 2016), and it has been measured

*Present address: Department of Earth and Planetary Science, University of California, Berkeley, California 94709, USA

wnloaded from http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/17/3/685/5319464/685.pdf
by 19162

DAY 3 PAPERS

Recently discovered warm springs at Obsidian Butte, Imperial County, California

Paul M. Adams[1] and David K. Lynch[2]
[1]126 South Helberta Ave. #2, Redondo Beach, CA 90277, paul.m.adams@aero.org
[2]Thule Scientific, P. O. Box 953, Topanga, CA

abstract—Obsidian Butte is one of the Salton Buttes, which are five Holocene rhyolitic volcanic domes associated with a relatively shallow (~4 km) magma body in the Salton Sea Geothermal System. Late in 2020, several small springs were discovered flowing into the sea along the shore north of Obsidian Butte. The springs span about 150 m along the shore and were recently exposed as the sea level has dropped. They have water temperatures as high as 27°C and form small channels that cross mud flats and bars before entering the sea. Over the period of one year the outflow channels from the springs have changed as the sea level has further dropped, as have the flow rates and temperatures of some of the springs. The combined flow of several of the springs in the main outflow channel is significant (~400 liters/min) with a velocity of nearly 30 cm/s. Thermal imagery showed that water in spring channels with significant flow retained elevated temperatures as it traversed the mud flats. In view of the many geothermal features in the vicinity, the springs' slightly elevated temperatures may be geothermal in origin. We note, however, that spring temperature may be influenced by the region's mean annual temperature of 25°C, which controls the near-surface temperature of the rock and sediment through which the water flows before emerging.

1. Introduction

The Salton Buttes are five rhyolitic volcanic domes associated with the Salton Sea Geothermal System (SSGS) located near the southeast shore of the Salton Sea in Imperial County, California. The SSGS lies in the Salton Trough, a pull-apart basin located at a tectonic stepover between the San Andreas and Imperial faults (Gurbuz, 2010) and has a high geothermal gradient anomaly that is related to the numerous geothermal plants of the Salton Sea Geothermal Field (SSGF) (Hulen et al., 2002). The Salton Buttes, from north to south, are Mullet Island, north and south Red Hill, Rock Hill, and Obsidian Butte. They collectively form a roughly north-northeast trending line about 7 km long. The buttes were thought to have formed during the late Pleistocene (Muffler and White, 1969), but recent work suggests eruptions as recent as 2.45 ka for Red Hill and Obsidian Butte (Schmitt et al., 2013; Wright et al., 2015). Hulen et al. (2003) give a detailed description of the subsurface geology of the Obsidian Butte sector of the SSGF based on analysis of several thousand feet of borehole rock samples. Obsidian Butte is the surface expression of the Obsidian Butte flow-dome-tuff complex (Robinson et al., 1976) which consists of glassy to stony, sparsely porphyritic, flow-banded and pumiceous to perlitic rhyolite. It is underlain by the Pleistocene to Holocene Brawley Formation and uppermost Borrego Formation. The former contains a several-hundred-meter-thick evaporitic anhydrate-bearing mudstone that forms a natural cap to the geothermal system. In the conceptual model of Hulen et al. (2003), the source of the geothermal energy for the Obsidian Butte sector of the SSGF is a still-cooling granitic pluton 2 km in diameter and 3.5 km below the surface. The production fluids are circulating hypersaline brines with temperatures generally greater than 290°C. At depth, the interaction of the brines with the wall rocks has led to hydrothermal alteration and development of epidote, actinolite and clinopyroxene.

Obsidian Butte is located in the Brawley seismic zone and from 28 August to September 2, 2005 a swarm of more than 550 earthquakes with magnitude 1.0 or greater occurred near Obsidian Butte (https://www.cisn.org/special/evt.05.09.01/). Eight events were greater than magnitude 4.0 with the largest being 5.1. Its epicenter was 9.7 km deep and was located 1.6 km south of the butte and 2.3 km south of the wells. Analysis of earthquake data indicated that seismic faulting was restricted to a depth of about 4–6 km along a 10 km-long NE striking near-vertical fault segment. In a cross section based on drill core data, Hulen et al. (2003) show a high angle fault near the zone defined by the earthquake epicenters. Surface deformation was observed by two nearby GPS stations, as were some surface breaks in the field (Lohman and McGuire, 2007).

Obvious surface expressions of geothermal activity in the SSGS occur at fumarole fields 1 km SE of Mullet Island (Lynch et al., 2013; Adams et al., 2017) and at the intersections of Davis and Schrimpf Roads, 4 km SE of Mullet Island (Onderdonk et al., 2011), with the former being currently the most active. The fumarole field 1 km SE of Mullet Island consists of vents with boiling water and mud and small gryphons that are emitting ammonia (Tratt et al., 2016), which produced

AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1002/2015GC005714

Key Points:
- Five rhyolite obsidian domes form the Salton Buttes, CA
- We use Ar/Ar, U-Th, and paleomagnetism to date all five domes
- All domes are mid-late Holocene in age, erupted in three separate episodes

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2
- Table S3

Correspondence to:
H. M. Wright,
hwright@usgs.gov

Citation:
Wright, H. M., J. A. Vazquez, D. E. Champion, A. T. Calvert, M. T. Mangan, M. Stelten, K. M. Cooper, C. Herzig, and A. Schriener Jr. (2015), Episodic Holocene eruption of the Salton Buttes rhyolites, California, from paleomagnetic, U-Th, and Ar/Ar dating, *Geochem. Geophys. Geosyst.*, *16*, 1198–1210, doi:10.1002/2015GC005714.

Received 2 JAN 2015
Accepted 12 MAR 2015
Accepted article online 20 MAR 2015
Published online 30 APR 2015

© 2015. American Geophysical Union. All Rights Reserved.

Episodic Holocene eruption of the Salton Buttes rhyolites, California, from paleomagnetic, U-Th, and Ar/Ar dating

Heather M. Wright[1], Jorge A. Vazquez[2], Duane E. Champion[2], Andrew T. Calvert[2], Margaret T. Mangan[2], Mark Stelten[2,3], Kari M. Cooper[3], Charles Herzig[4], and Alexander Schriener Jr.[5]

[1]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA, [2]U.S. Geological Survey, Volcano Science Center, Menlo Park, California, USA, [3]Department of Earth and Planetary Sciences, University of California-Davis, Davis, California, USA, [4]Department of Earth Sciences, El Camino Community College, Torrance, California, USA, [5]CalEnergy Operating Corporation, Calipatria, California, USA

Abstract In the Salton Trough, CA, five rhyolite domes form the Salton Buttes: Mullet Island, Obsidian Butte, Rock Hill, North and South Red Hill, from oldest to youngest. Results presented here include $^{40}Ar/^{39}Ar$ anorthoclase ages, ^{238}U-^{230}Th zircon crystallization ages, and comparison of remanent paleomagnetic directions with the secular variation curve, which indicate that all domes are Holocene. ^{238}U-^{230}Th zircon crystallization ages are more precise than but within uncertainty of $^{40}Ar/^{39}Ar$ anorthoclase ages, suggesting that zircon crystallization proceeded until shortly before eruption in all cases except one. Remanent paleomagnetic directions require three eruption periods: (1) Mullet Island, (2) Obsidian Butte, and (3) Rock Hill, North Red Hill, and South Red Hill. Borehole cuttings logs document up to two shallow tephra layers. North and South Red Hills likely erupted within 100 years of each other, with a combined ^{238}U-^{230}Th zircon isochron age of: 2.83 6 0.60 ka (2 sigma); paleomagnetic evidence suggests this age predates eruption by hundreds of years (1800 cal BP). Rock Hill erupted closely in time to these eruptions. The Obsidian Butte ^{238}U-^{230}Th isochron age (2.86 6 0.96 ka) is nearly identical to the combined Red Hill age, but its Virtual Geomagnetic Pole position suggests a slightly older age. The age of aphyric Mullet Island dome is the least well constrained: zircon crystals are resorbed and the paleomagnetic direction is most distinct; possible Mullet Island ages include ca. 2300, 5900, 6900, and 7700 cal BP. Our results constrain the duration of Salton Buttes volcanism to between ca. 5900 and 500 years.

1. Introduction

Age determination of Holocene volcanic rocks is inherently difficult, especially where carbon that could be used for ^{14}C dating is not present or the relation of the organic material to the eruption is difficult to establish [e.g., *Schmitt et al*., 2010a; cf. *Capra et al*., 2007]. At monogenetic volcanic fields, where there is only one phase of eruptive activity at each center, eruptive deposits from all centers likely do not form a single stratigraphic section. Thus, detailed mapping is required in order to resolve relative age relationships, if at all possible. Indeed, the use of a variety of dating techniques in combination with geologic mapping may be required in order to resolve the eruptive chronology at monogenetic volcanic fields in general [*Connor and Conway*, 2000]. Apart from ^{14}C dating, radioisotope dating of Holocene rocks is challenging due to small accumulated quantities of radioactive decay daughters, but analytical advances and high-resolution sampling techniques yield meaningful dates for late Pleistocene-Holocene eruptions [e.g., *Lanphere et al*., 2007; *Vazquez and Lidzbarski*, 2012]. In cases where uncertainties are large, paleomagnetic directions of primary volcanic deposits can be used to refine age determinations [*Hagstrum and Champion*, 2002]. Here we use the results from multiple dating techniques to resolve the timing and episodicity of rhyolitic volcanism that generated the five obsidian domes that compose the Salton Buttes, southern California, and scrutinize the advantages and shortfalls of each geochronologic technique.

2. Salton Trough Magmatism

The Salton Buttes consist of five rhyolitic obsidian domes located at the southern margin of the Salton Sea, California, USA. The domes are aligned subparallel to the axis of spreading along the boundary between the

Journal of Volcanology and Geothermal Research 347 (2017) 15–43

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Sulfate mineralogy of fumaroles in the Salton Sea Geothermal Field, Imperial County, California

Paul M. Adams *, David K. Lynch, Kerry N. Buckland, Patrick D. Johnson, David M. Tratt

The Aerospace Corporation, P. O. Box 92957, Los Angeles, CA 90009, United States

article info

Article history:
Received 4 March 2017
Received in revised form 8 August 2017
Accepted 26 August 2017
Available online 31 August 2017

Keywords:
Salton Sea
Fumaroles
Sulfates
Mascagnite
Remote sensing
Mako

abstract

The Salton Trough lies in the transition between the San Andreas Fault and oblique spreading centers and transform faults in the Gulf of California. The Salton Sea Geothermal Field is the northernmost expression of those spreading centers. In ~2007 two ammonia-emitting fumarole fields that had been submerged beneath the Salton Sea were exposed for the first time in nearly 50 years. As the sea level continued to drop these fields have developed a number of boiling pools, mud pots, gryphons and a unique suite of ammonium sulfate minerals. These have been studied over time with long-wave infrared remote sensing coupled with ground truth surveys backed by laboratory analyses of the minerals. Many vents lie at the center of concentric rings of mineralization with systematic occurrence of different minerals from center to edge. Three semi-concentric zones (fumarole, transition and evaporite) have been defined with respect to ammonia-emitting vents and bubbling pools. The scale of these zones range from several meters, localized around individual vents, to that of the fumarole fields as a whole. The fumarole zone is closest to the vents and locally contains cavernous sulfur crystals and significant deposits of gypsum, mascagnite, boussingaultite and other ammonium sulfates. The transition zone comprises a dark brown surficial band of inconspicuous sodium nitrate underlain by anhydrite/bassanite that is thought to have formed by ammonia-oxidizing microbes interacting with the ammonium sulfates of the outer fumarole zone. The evaporite zone is the outermost and contains blödite, thenardite and glauberite, which are typical of the sulfates associated with the shoreline of the Salton Sea. Remote sensing has shown that the mineral zones have remained relatively stable from 2013 to 2017, with minor variations depending on rainfall, temperature and levels of agricultural runoff.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The Salton Trough is a topographic low in southern California and northern Baja California, Mexico that represents a tectonically active, sedimentary pull apart basin (Lonsdale, 1989; Brothers et al., 2009; Gurbuz, 2010). Except for minor contributions from the surrounding mountains and aeolian sources, most of the sediments in the Salton Trough represent Colorado River sediments and are as thick as 6 km (Muffler and White, 1969). The trough is structurally controlled and lies in the transition between the right lateral San Andreas Fault system to the north and a series of oblique spreading centers and transform faults in the Gulf of California to the south (Macdonald, 1982). The area is dominated by a number of contiguous right lateral, right stepping (releasing) transform faults including the Imperial and Cerro Prieto faults (Meltzner et al., 2006) and those of the Sierra Cucapah in Mexico (Hauksson et al., 2011).

Within the Salton Trough lies the Salton Sea Geothermal Field where the geothermal gradient averages ~0.3 °C/m (Younker et al., 1982), reaching a maximum of 4.3 °C/m (Lee and Cohen, 1979). About 11 commercial geothermal electricity generating plants operate in the area with a combined output of about 340 MW. The high geothermal gradient is the result of a shallow magma body from one or more spreading centers (Lachenbruch et al., 1985; Schmitt and Vazquez, 2006). Extruded magma produced the Salton Buttes, five late Quaternary rhyolitic volcanic necks near the southeastern end of the Salton Sea (Robinson et al., 1976; Newark et al., 1988). From south to north they are Obsidian Butte, Rock Hill, Red Island (north and south) and Mullet Island. The age of some of these volcanic structures has recently been dated to 2400 ybp (Schmitt et al., 2013). Recent thermal surveys have located moderate temperature (30 °C) thermal vents on Red Island north (Lynch and Adams, 2014) but the majority of higher temperature surface thermal features are concentrated southeast of Mullet Island (Lynch et al., 2013).

The Salton Sea occupies the lowest part of the Salton Trough. It is a saline, eutrophic, endorheic rift lake (Dangermond, 2003; Hurlbert, 2008) that was created when a canal breach diverted the Colorado River into the Salton Trough in March 1905 and fresh water flowed north through the New and Alamo Rivers (Kennan, 1917). After the canal was repaired in Feb 1907, the high water level of −59 m MSL decreased rapidly to around −76 m MSL in 1917. Rain and agricultural

* Corresponding author.
E-mail address: paul.m.adams@aero.org (P.M. Adams).

https://doi.org/10.1016/j.jvolgeores.2017.08.010
0377-0273/© 2017 Elsevier B.V. All rights reserved.

CRUSTAL STRUCTURE AND TECTONICS OF THE SALTON TROUGH
A SUMMARY

Gary Fuis and many collaborators

Seismic imaging of the Salton Trough (Fig. 1) began with the publica>on of Biehler et al. (1964) and con>nued with surveys conducted by the U.S. Geological Survey in 1979 (Fuis et al., 1984; Fig. 2), 1992 (Parsons and McCarthy, 1996; Fig. 2), and 2011 (Fuis et al., 2017; Fig. 3).

Key discoveries in the first USGS survey were 1) "basement" beneath the Imperial Valley is rela>vely low in velocity (5.6-5.8 km/s), 2) there is no reflec>on between sedimentary rocks and basement, and 3) basement shoals beneath known geothermal areas (Fig. 4). These discoveries led to the interpreta>on that "basement" was not pre-Cenozoic grani>c metamorphic rocks, as exposed on the flanks of the Imperial Valley, but young metamorphosed Colorado river sedimentary rocks. Another discovery was that there was a "subbasement" at ~ 10-km depth beneath the Imperial Valley with veloci>es of mafic rocks (6.8-7.2 km/s); this layer could be modeled with a density of 3.1 g/cc (Fig. 5; purple layer), that compensated for the rela>vely low-density sedimentary and metasedimentary rocks above and could be interpreted as gabbroic rocks of an oceanic spreading center. Seismicity in the "Brawley Seismic zone" (Johnson and Hadley, 1976; Lin et al., 2007), extending between the Imperial fault and San Andreas fault (SAF), and also in the Cerro Prieto geothermal area of Mexico, are interpreted as surface manifesta>ons of such spreading centers (Figs. 1, 2).

Key discoveries in the third USGS survey were that the subsurface geometry of the SAF, in the Coachella Valley, is not ver>cal or even planar. The fault dips steeply in the upper 6 km of the crust and then dips moderately NE below that (Fig. 6). This shape was revealed by at least 4 independent data sets, including seismic refrac>on and reflec>on data, gravity and aeromagne>c data, and seismicity data. This geometry is a refinement of the subsurface geometry of the southeast "blade" of the propeller-shaped SAF that had been interpreted in Fuis et al. (2012). Flower-structure faults in the hanging wall of the SAF include the Painted Canyon and Placorm faults. A similar subsurface geometry is seen for the Banning branch of the SAF in the northern Coachella Valley.

Figures 7a and 7b represent a summary of the crustal structure and tectonics of the southern Coachella, Imperial, and Mexicali Valleys. Figure 7a is an older, colored interpreta>on. Figure 7b is an updated interpreta>on, where 1) the "Extra fault zone" of Brothers et al., (2009, 2011) has been added and 2) well data in Mexico has been added and the interpreta>on of buried pre-Cenozoic basement rocks has been extended into Mexico.

Figure 8 represents an updated version of the crustal and upper-mantle structure along a NW-SE cross sec>on extending through the Coachella Valley, Salton Sea, Imperial Valley, Mexicali Valley, and Altar basin from Han et al. (2016a). Note that a thin (~ 5-km) layer of stretched con>nental crust, perhaps intruded by sparse mafic rocks, may or may not be present between the young metasedimentary rocks cons>tu>ng "basement" in the Imperial Valley and

the prominent lower-crustal layer of mafic rocks above the mantle. Similar stretched con>nental crust is interpreted farther south in the Gulf of California as well as blocky extended con>nental crust observed in both the Imperial Valley (above this layer) and farther south (Gonzalez-Fernandez et al., 2005; Lizarralde et al., 2007; Mar>n-Barajas et al., 2013). The Conclusions of Han et al. (2016a) are reproduced below describing a revised interpreta>on of lower crustal structure in the Salton Trough.

Conclusions of Han et al. (2016a):

"The SSIP data constrain the crust to be 17–18 km thick and roughly one-dimensional from the northern Salton Sea to the southern end of the Imperial Valley. In the central Salton Trough, crystalline rocks (>5 km/s) occur at ~4 km depth and are interpreted to be sediment metamorphosed by high heat flow to ~8 km depth. Crystalline rocks with velocity of ~6.2–6.6 km/s are ~4.5 km thick and are interpreted to be either stretched preexisting continental crust or high-grade metamorphosed sediment, with possible minor basaltic intrusion. A high velocity of 6.7–6.8 km/s in the lower crust is interpreted as rift-related mafic intrusion by underplating. The upper mantle velocity is 7.85 km/s, indicative of high heat and partial melting. In contrast, in the Coachella Valley, sediment thins to the north, the crust thickens, and the basement is interpreted to be granitic continental crust. The Mexicali Valley is also interpreted to be underlain by thicker stretched continental crust. North American crust has been essentially rifted apart with steep continental margins. Since breakup, an ~100 km wide zone of new crust in the extensional direction has been created by magmatism from below, sedimentation from above, and metamorphism of the sediment. The active rift zone is interpreted to be at least ~100 km wide in the lower crust and upper mantle, despite the much narrower volcanic, thermal, and seismic features in the uppermost crust. The Salton Trough and northern Gulf of California emphasize the important role of river delta sedimentation upon late-stage rifting."

On the origin and evolution of the Salton Sea

David K. Lynch[1] and Brian McNeece
[1]*dave@caltech.edu*

abstract—It is widely written and generally believed that the Salton Sea was created by an engineering accident. Many called it a blunder, gross negligence by Charles Rockwood. But we argue that the catastrophic inundation of 1905 was a natural event. Triggered by the Gila River's largest flood on record, Colorado River water would have reached into the Salton Trough whether or not Rockwood's California Development Company (CDC) had been there at all. Indeed, historical records show that the Colorado River flowed into the trough as early as 1840, long before the CDC. After the 1905-1907 flood subsided, the Salton Sea might have been expected to evaporate and percolate away in a few years. And it would have if the Alamo Canal had not continued to bring in river water, more in fact than was needed. For the past 115 years, the sea has been maintained by river water, not as the primary goal, but as the only practical way to dispose of irrigation runoff. The original Salton Sea may have been formed catastrophically, but the modern sea's existence is intentional, an inevitable result of Imperial Valley agriculture. Today's Salton Sea has little or nothing to do with the 1905 flood and should not be called an accident.

1. Introduction

The dramatic formation of the Salton Sea in 1905 has been much discussed and extensively studied[1-7]. The usual story is this: poor water management of the Colorado River and Alamo Canal near Yuma diverted the river water into the Salton Trough, creating the Salton Sea. Many narratives assign blame to Charles Rockwood, who allowed water from the river to flow into the Alamo Canal through open cuts without constructing head gates to control the flow. When the Colorado flooded as a result of floods on the tributary Gila River, it coursed unchecked through Rockwood's Lower Mexican Heading and into the Imperial Valley. This is the basis for the prevalent notion that the sea was Rockwood's fault. Yet the story is more complicated, and an examination of historical records leaves room for other interpretations.

We will not repeat the many fascinating accounts of the 1905 floods and subsequent return of the Colorado River to its natural bed in Mexico. Instead we will investigate two different though related topics: (1) The cause of the sea's 1905 inundation, and (2) some seldom-considered aspects of the sea's continued existence.

2. Origin of the Salton Sea

Water in the Salton Trough is nothing new. The geological record reveals that as a major body of water, Lake Cahuilla existed there episodically during the late Pleistocene and

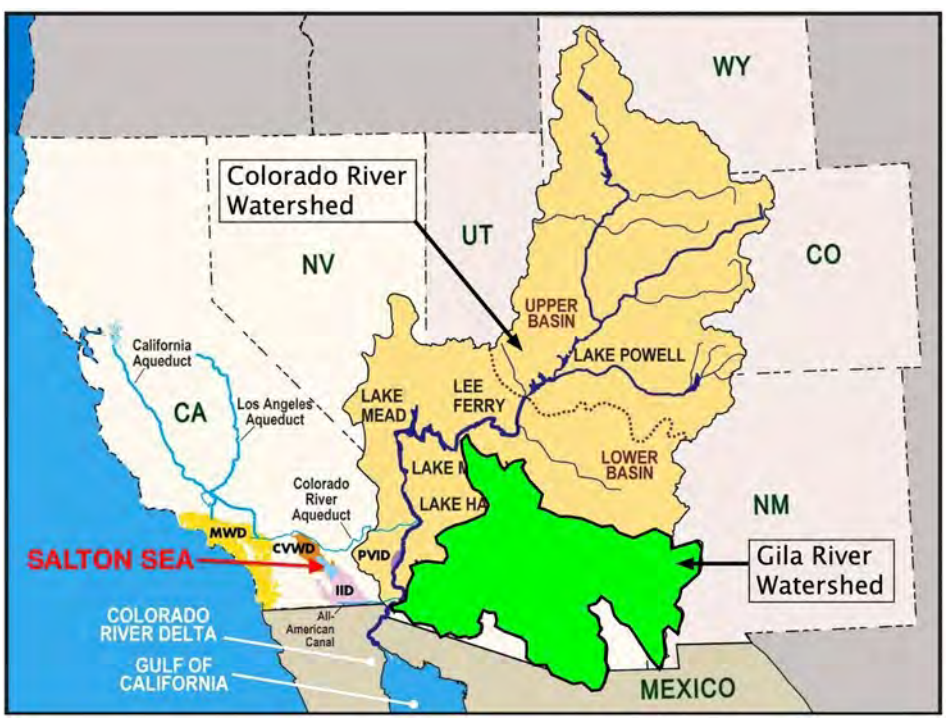


Figure 1. Drainage Basins of the Colorado and Gila rivers. Colorado River watershed includes the Gila's. Due to elevation, climate and latitude differences, the Gila River watershed is much warmer than the Colorado's. In winter, rain in the Gila's drainage basin runs off, but snow in the Colorado drainage basin stays on the ground. In summer, the Gila basin often experiences flash floods due to monsoons, less so in the upper Colorado basin because it is farther north and less likely to have monsoons. Figure adapted from the Central Basin Water District.

Nelson, S. M., Lynch, D. K.,and Rivas, T., 2023 The Colorado River (Mexico) tidal bore: persistent phenomenon in a changing estuary , in Mines of the Mojave, D. Miller and S. Rowland (eds), Proceedings of the 2023 Desert Symposium, April 21-24, 2023, Zzyzx, 143-153

The Colorado River (Mexico) tidal bore: persistent phenomenon in a changing estuary

Steven M. Nelson,[1,*] David K. Lynch,[2] and Tomás E. Rivas Salcedo[3]
[1] *Independent Scientist, 6101 NE 102nd Avenue, Apt. 5, Vancouver, WA 98662-6321,* snelson467@gmail.com
[2] *Thule Scientific, P. O. Box 953, Topanga CA 90290*
3 Sonoran Institute, Blvd. López Mateos SN, Zona Industrial, Mexicali, Baja California, C.P. 21010, Mexico

abstract — The macro-tidal estuary of the Colorado River, Mexico has been disconnected from the river's fluvial supply by the operation of upstream dams and diversions. Since the last major period of fluvial delivery in the 1980s and 90s an emergent and growing tidal sandbar has obstructed the river channel 40 km upstream from the Gulf of California. The estuary has assumed the characteristics of a blind tidal channel system where tidal sediment is transported landward, leading to decreased channel depth and width. Loss of fluvial flow diminished but did not eliminate tidal bores which continue to ascend the estuary channel at the head of flooding spring tides. Spring tide flood currents saw increased power after a large area of the intertidal mudflats subsided up to 1m following the 2010 M7.2 El Mayor-Cucapah earthquake, resulting in extensive channel bank erosion and headcut incision of new tidal channels. We conducted field visits and used satellite imagery to detect tidal bores over the 12-year post-earthquake period in order to estimate the frequency of tidal bores and gain a better understanding of their contribution to both erosion and aggradation of estuary channels and the surface of the intertidal flats.

1. Introduction

The estuary

The Colorado River estuary is situated at the northern end of the Gulf of California (Figure 1). The mean spring tide range in the upper Gulf is 6.4 m (Lavin and Marinone, 2003), reportedly increasing to 8 to 10 m within the estuary (Thompson, 1968) although no tide monitoring stations are maintained therein. In the mixed semidiurnal tidal regime of the upper Gulf, each day's lower low tide immediately precedes the higher high, contributing a maximum range to one of the day's tides. The convergent estuary is hypersynchronous, compressing the flood tidal wave into a smaller cross-sectional area as it ascends the narrowing/shallowing estuary channel, enhancing tidal effects until friction ultimately dissipates the wave at the tidal limit. Compression of the flood wave also steepens it and delays its arrival, resulting in highly asymmetrical flood-dominant tide cycles: the authors' observations at various locations within the estuary have recorded spring-tide flood periods ranging from 2.5 to 4 hours, with the ebb lasting 8 to 9.5 hours. These factors combine to create conditions favoring the formation of a tidal bore wave at the head of one and sometimes both daily flood tides during spring tide (full and new moon) periods.

Figure 1. Regional map showing the study area in the Colorado River Estuary.

The tidal bore

Lynch (1982) and Graber (2012) provide introductory information and scientific theory of tidal bores. A bore is a tidally generated water wave advancing upstream and represents the instantaneous turning of the tide from ebb to flood. It occurs during spring tides when the tidal range is at its monthly maximum. Tidal bores have been documented in the Colorado River estuary since the earliest Spanish explorers visited the area in the 16th century (Freeman, 1923).

Perhaps the best introduction to the Colorado River bore is found in the description provided by James H. Gordon of the U.S. Weather Bureau who witnessed a bore at the tiny seaport of La Bomba on the south bank of