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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.

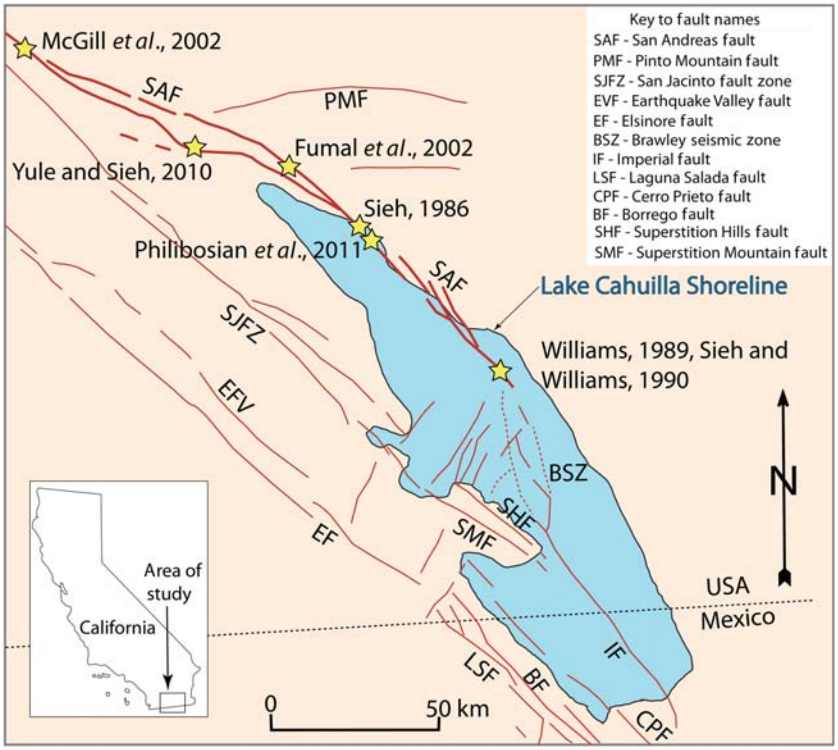


Figure 1. Map of the southern San Andreas fault (SAF) system showing paleoseismic sites (stars) on the SAF above, at, and below the shoreline of Lake Cahuilla that is shown at $+13$ m elevation. The color version of this figure is available only in the electronic edition.

To better date the past two southern SAF earthquakes, we apply a new approach to date the lake sediments that display evidence of faulting. We dated the dry interval between the past two lake highstands by collecting several dead mesquite stumps that were inundated by the most recent lake (lake A), and we add dates from one stump (SB 3DIII-23; Orgil, 2001) from below the penultimate lake (lake B). We also add radiocarbon ages obtained on two particularly young detrital charcoal samples associated with the filling of lake B and inferred to be derived from wood that grew and burned during the preceding dry period, between lakes B and C. The first sample (C25b/P3; Gurrola and Rockwell, 1996) was extracted from a shoreline peat-like organic layer, whereas the second (IFD-T2-C67; Rockwell *et al.*, 2011) was embedded within the penultimate lake-filling sequence at a site at -32 m elevation. These new data place tight constraints on when there was no water at various elevations within the basin. Finally, we add radiocarbon ages from young detrital charcoal samples embedded within the lake B deposits at a site at the shoreline (Philibosian *et al.*, 2011); these samples provide a maximum age on when lake B began to recede. We then combine these data with modeling of the time required to completely fill and desiccate a lake based on reasonable rates of discharge from the Colorado River and estimates of local and regional desiccation rates that we combine with the historical observations to more precisely date the most recent two lake stands that together improve both the accuracy and precision of the ages of the two most recent large southern SAF earthquakes.

Collection and Dating of *In Situ* Stumps

Stumps of dead mesquite (*Prosopis* sp., probably *P. glandulosa*) that were inundated by the most recent highstand of Lake Cahuilla are recognized in two ways. Some are now buried by lacustrine sediments, and we exposed them in trenches or by hand digging around the remnant tops of the bushes to expose the entire buried bush (Fig. 2a) (Haaker, 2012). More commonly, stumps were found in areas of little or no sedimentation from the last lake and exhibited coppice dunes around their bases. The coppice dunes appear to have been washed by water and are covered in gastropod shells (*Physa humerosa*; Fig. 2b).

In each case, we collected the entire stump by sawing it from its base, and we cut cross sections though it is in the lab. From the cross section with the most complete set of rings, we sampled the innermost and outermost 2–3 rings for radiocarbon dating. The wood samples were pretreated with the standard acid–base–acid rinses and dated at the Center for Accelerator Mass Spectrometry facility at University of California Irvine. For our age model, we assumed the growth rings were annual, and we counted the number of rings between the samples to provide an estimate of the expected number of years between the paired dates, allowing for reasonable uncertainties (Table 1).

In most cases, the core of the stump had been eaten away by termites, so the older part of the age range for these stumps is missing. We attempt to account for this by estimating the number of missing rings based on how much of the core is gone (Table 1). For the missing core of each stump, we used the documented growth rate of *P. glandulosa* for young trees with ample water supply of 4 cm/decade (Ansley *et al.*, 2010). We assumed that the initial growth of the mesquite likely initiated with the drawdown of Lake Cahuilla and that the mesquite taproot could keep up with the drawdown, initially maintaining rapid growth, although the mesquite could have started growing at any time after recession, which we also account for in our model. We hypothesize that the reason that most of the mesquite samples we collected had the heartwood eaten by termites is that the initial wood growth was from the early period of rapid growth and was likely softer than the outer rings, as is common in trees that formed after the water table dropped sufficiently to slow

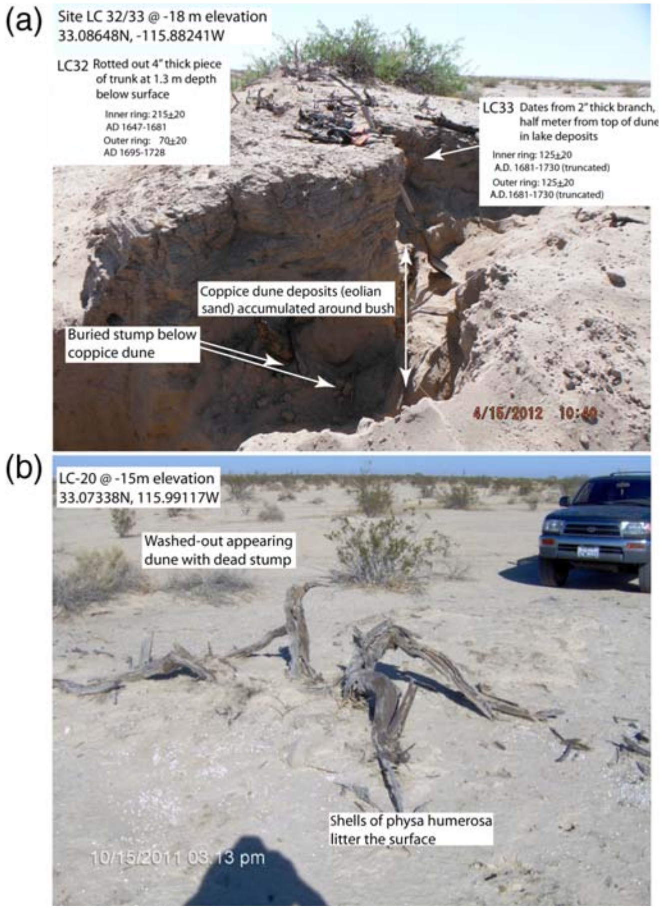


Figure 2. (a) Coppice dune with a thin capping of fine-grained sediments interpreted as lacustrine in origin. The mesquite is rooted in eolian sand near the base of the pit. (b) Dead mesquite bush surrounded by a small coppice dune with gastropod shells (*Physa humerosa*) scatted around and on the dune deposits, indicating that this bush was inundated by Lake Cahuilla (from Haaker, 2012). The color version of this figure is available only in the electronic edition.

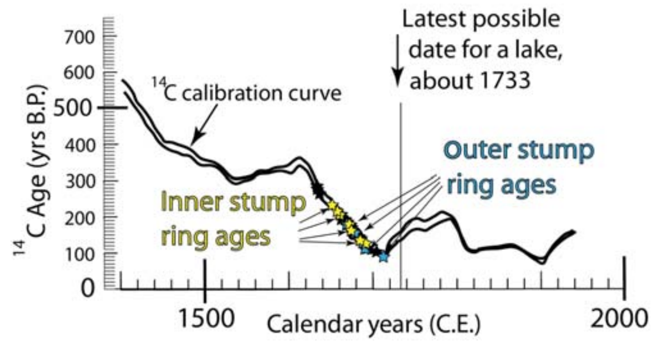


Figure 3. Inner and outer stump ages plotted on the ^{14}C calibration curve (Reimer *et al.*, 2013). Only the earliest descending part of the curve is consistent with the historical record. The color version of this figure is available only in the electronic edition.

growth. Using this model, there is probably no more than a decade or two of missing wood in any of the stumps that we dated. We note, however, that this assumption is conservative, because it avoids biasing the age of the penultimate lake. An alternative assumption that the growth rate of the stumps was more uniform throughout the lifetime of the tree would imply more missing rings in the core of each stump and would necessarily push the age of the penultimate lake farther back in time.

Dating Results

The results of dating the inner and outer rings of the drowned mesquite bushes appear in Table 2. All of the stumps that were drowned by lake A yielded dates of 1650 C.E. or younger, although the inferred missing rings could push the initiation of wood growth back a decade or two earlier. For all of these stumps, the outer rings yielded younger ^{14}C ages than the inner rings, which require that the bushes grew during a descending period on the ^{14}C calibration curve (Reimer *et al.*, 2013). The only descending periods during the past 400 yrs are for the calendar periods of about 1620–1700, 1790–1815, and 1860–1900 (Fig. 3), and only the earliest of these is consistent with the historical record, as discussed below. The apparent lack of wood growth at any

Table 1
Mesquite Stump Samples from between the Two Most Recent Lake Cahuilla Highstands

Stump Name	Latitude (°N)	Longitude (°E)	Elevation (m.a.s.l.)	Years to Fill Lake after Drowning Stump*	Years (Rings) between Inner and Outer Samples†	Missing Years (Rings) before Inner Sample‡	Years to Desiccate Full Lake down to Stump Elevation§	Total Number of Years before Inner Sample‖
LC13	33.00240	−115.95739	8	2.5 ± 0.4	21.5 ± 5.5	0.5 ± 0.3	2.9 ± 0.2	3.4 ± 0.4
LC17	33.05792	−115.97720	−14	9.5 ± 1.2	21.5 ± 5.5	8.0 ± 2.2	15.5 ± 1.1	23.5 ± 2.5
LC19	33.07330	−115.99456	−12	9.0 ± 1.2	34.3 ± 8.8	2.0 ± 0.7	14.3 ± 1.1	16.3 ± 1.3
LC20	33.07338	−115.99117	−15	9.7 ± 1.3	12.5 ± 3.3	10.0 ± 2.7	16.0 ± 1.2	26.0 ± 2.9
LC32	33.08648	−115.88241	−18	10.4 ± 1.3	62.5 ± 15.9	15.0 ± 6.3	17.8 ± 1.3	32.8 ± 6.4
LC33	33.08648	−115.88241	−18	10.4 ± 1.3	7.0 ± 2.1	22.0 ± 6.3	17.8 ± 1.3	39.8 ± 6.4

All uncertainties given at 1σ significance.
*Based on our model. See Figure 5.
†Based on our counting estimate.
‡Based on missing wood in the center of the stump.
§Based on a net desiccation rate of 1.52–2.05 m/yr.
‖The sum of the number of missing rings before the inner sample and the number of years to desiccate a full lake down to the stump elevation.

Table 2
Radiocarbon Dates Used in the OxCal Model

Sample*	Lab ID Number	$\delta^{13}C$ (‰)	Conventional ^{14}C Age (yr B.P.)	Calibrated Date Range (C.E.)†	Source
LC13-outer	UCI 111434	−23.3 ± 0.1	180 ± 20	1664–1685 1731–1808 1927–1950‡	Not previously published
LC13-inner	UCI 101757		180 ± 15	1666–1683 1734–1784 1795–1806 1930–1950‡	Not previously published
LC17-outer	UCI 111435	−23.6 ± 0.1	115 ± 20	1683–1735 1805–1895 1903–1931	Not previously published
LC17-inner	UCI 101759		130 ± 15	1681–1710 1717–1739 1750–1762 1802–1890 1909–1938	Not previously published
LC19-outer	UCI 111436	−22.5 ± 0.1	115 ± 20	1683–1735 1805–1895 1903–1931	Not previously published
LC19-inner	UCI 101761		205 ± 15	1654–1680 1764–1801 1939–1950‡	Not previously published
LC20-outer	UCI 111437	−24.3 ± 0.1	155 ± 20	1668–1696 1725–1782 1797–1815 1835–1877 1917–1949	Not previously published
LC20-inner	UCI 101762		160 ± 15	1668–1691 1728–1781 1797–1811 1920–1947	Not previously published
LC32-outer	UCI 111439	−23.7 ± 0.1	70 ± 20	1695–1726 1813–1838 1842–1853 1868–1918	Not previously published
LC32-inner	UCI 111438	−24.4 ± 0.1	215 ± 20	1647–1680 1763–1801 1938–1950‡	Not previously published
LC33-outer	UCI 111441	−24.5 ± 0.1	125 ± 20	1681–1739 1750–1762 1802–1893 1906–1938	Not previously published
LC33-inner	UCI 111440	−24.0 ± 0.1	125 ± 20	1681–1739 1750–1762 1802–1893 1906–1938	Not previously published
Sb3m45A-c	UCI 35427		310 ± 15	1516–1595 1618–1644	Philibosian *et al.* (2011)
Sb2m10A-c	UCI 35412		335 ± 15	1486–1532 1538–1604 1607–1635	Philibosian *et al.* (2011)
Sb3m44A-c	UCI 35426		335 ± 20	1484–1637	Philibosian *et al.* (2011)
Sb2m10B-c	UCI 35413		360 ± 25	1452–1527 1553–1633	Philibosian *et al.* (2011)
Sb3m48A-c	UCI 35428		380 ± 15	1449–1515 1598–1617	Philibosian *et al.* (2011)
C25b (P3)	QL4651		310 ± 40	1473–1653	Gurrola and Rockwell (1996)
IFD-T2-C67	UCI 48820	−27.6 ± 0.1	320 ± 15	1496–1506 1512–1601 1616–1642	Rockwell *et al.* (2011)

(*continued*)

Table 2 (*Continued*)

Sample*	Lab ID Number	$\delta^{13}C$ (‰)	Conventional ^{14}C Age (yr B.P.)	Calibrated Date Range (C.E.)†	Source
SB 3DIII-23B			350 ± 15	1470–1525 1557–1632	Orgil (2001)
SB 3DIII-23A			350 ± 40	1456–1637	Orgil (2001)

*Samples LC-13 through LC-33 are stump ages, and their elevations are listed in Table 1. The other dates are on detrital charcoal, and elevations are provided in the cited references. All results have been corrected for isotopic fractionation, and conventional radiocarbon ages are reported following the conventions of Stuiver and Polach (1977).

†Calibrated date ranges are 2σ ranges from Calib rev. 7.1.0 (Stuiver and Reimer, 1993).

‡These ranges are suspect due to impingement on the end of the calibration data set.

site prior to 1630–1650 C.E. suggests that all the sites were under water until shortly before that time.

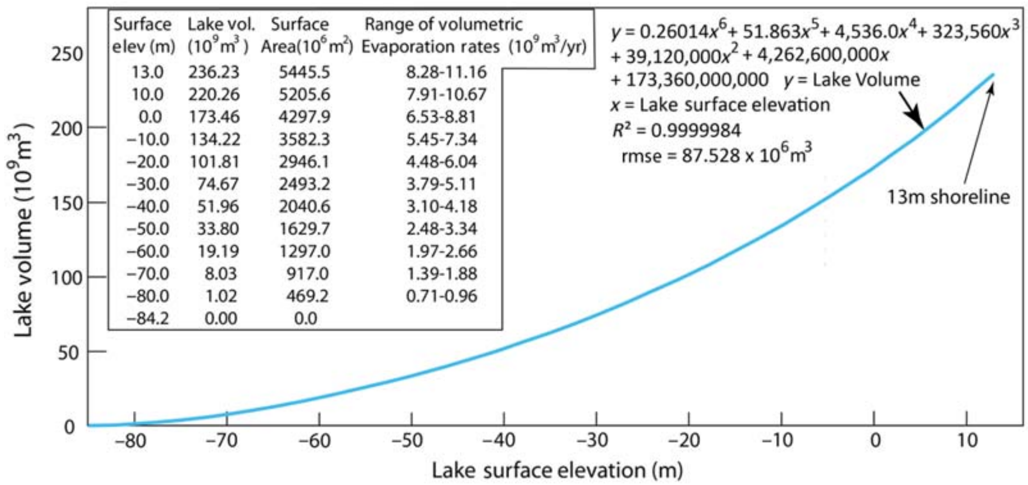
Two dates on the older stump below lake B calibrate to between 1470 and 1525 C.E. or between 1557 and 1632 C.E. (Table 2), with two intercept peaks due to the calibration curve. The ^{14}C date on detrital charcoal from the Rockwell *et al.* (2011) Dogwood site at −32 m (sample IFD-T2-C67 in Table 2) may be slightly younger, calibrating to between 1496 and 1506 C.E., between 1512 and 1601 C.E., or between 1616 and 1642 C.E. The actual date of wood growth in these cases would have been during a dry period between fillings of Lake Cahuilla. The youngest date on detrital charcoal within the lake B deposits at the +13 m shoreline (sample Sb3m45A-c in Table 2) calibrates to between 1516 and 1595 C.E. or between 1618 and 1644 C.E. This provides a maximum constraint on the age of the end of the lake B highstand, when lake B began to recede.

Rates of Lake Filling and Desiccation

The range of possible dates for the timings of the most recent Lake Cahuilla highstands must account for both the amount of time required to fill the basin and the time required for its desiccation. To estimate these values, a number of input parameters must be considered: the volumetric capacity of the Salton trough below various topographic contours, from the bottom of the Lake Cahuilla at ~84.2 m below sea level to its highstand elevation ~13 m above sea level; the average rates of Colorado River discharge entering the basin over a given period; and the average rates of evaporation. Estimates of Salton trough capacity required a digital elevation model, available above the present elevation of the Salton Sea, and bathymetric data below that. Colorado River discharge and evaporation rates were evaluated from historical and proxy data.

The fill volumes above the present level of the Salton Sea (70.28 m below sea level) were estimated using 1 arcsec (~30 m horizontal resolution) elevation data for the Salton trough (National Elevation Dataset; U.S. Geological Survey, 2017 ,2016 ,2013a) that are based on the North American Vertical Datum of 1988 (NAVD 88). Using Global Mapper GIS software by Blue Marble Geographics, the volumetric capacity was calculated at 1 m increments from the −70 m elevation contour to the +13 m shoreline elevation. Below the surface of the Salton Sea, fill volumes were obtained from surface elevation–capacity data derived from Global-Positioning-System-based bathymetric surveys reported relative to the National Geodetic Vertical Datum of 1929 (NGVD 29; Ferrari and Weghorst, 1997). These two data sets were combined by applying an orthometric height correction of +0.7 m to the bathymetric survey data to adjust contour elevations relative to the NAVD 88 reference datum. The combined elevation–capacity data for the Salton trough (summarized in the inset table in Fig. 4) were used to generate a sixth-order polynomial line of best fit and regression equation (Fig. 4) in Microsoft Excel 2010. Using the regression equation, lake volumes calculated as a function of surface elevation agree closely with the combined surface elevation–capacity data, with an R^2-value of 0.9999984 and a root mean square error (rmse) of 87.528×10^6 m^3 (< 0.04% of total lake capacity). Our lake model is based on this regression equation that we used to approximate lake volume as a function of surface elevation.

For filling the lake, the Colorado River would have been the primary source of water for Lake Cahuilla. Other sources of water entering the basin would have included direct precipitation, surface runoff from lesser streams and canyons, and groundwater inflow. We assume that inflows from direct precipitation, groundwater seepage, and all other channels are insignificant compared with annual flows of the Colorado River and recognize that any additional inflows from such sources would likely be offset by evaporative losses, losses resulting from surface water infiltration, and groundwater recharge during the initial stages of lake filling. For example, using a precipitation value of 6.4 cm/yr from Weide (1974) and a surface area of 5.4455×10^9 m^2, we estimate the average annual volume of rainfall into a full Lake Cahuilla to be 0.349×10^9 m^3; combined estimates of annual inflow from the Whitewater River, Salt Creek, and San Felipe Creek for the years 1961–1962 (Hely *et al.*, 1966) range between 57.99 thousand acre-feet (0.072×10^9 m^3) and 74.38 thousand acre-feet (0.092×10^9 m^3), with greater than 92%–93% of these combined flows derived from the Whitewater River. Combining these estimates of direct precipitation and surface runoff from lesser streams and canyons, we estimate a net inflow of 0.441×10^9 m^3, which is an order of magnitude less than estimated rates of volumetric evaporation at the present level of the Salton Sea, −70 m, and approximately 2 orders of magnitude less than at the highstand elevation of Lake



Surface elev (m)	Lake vol. ($10^9 m^3$)	Surface Area($10^6 m^2$)	Range of volumetric Evaporation rates ($10^9 m^3$/yr)
13.0	236.23	5445.5	8.28-11.16
10.0	220.26	5205.6	7.91-10.67
0.0	173.46	4297.9	6.53-8.81
−10.0	134.22	3582.3	5.45-7.34
−20.0	101.81	2946.1	4.48-6.04
−30.0	74.67	2493.2	3.79-5.11
−40.0	51.96	2040.6	3.10-4.18
−50.0	33.80	1629.7	2.48-3.34
−60.0	19.19	1297.0	1.97-2.66
−70.0	8.03	917.0	1.39-1.88
−80.0	1.02	469.2	0.71-0.96
−84.2	0.00	0.0	

Figure 4. Plot of lake volume as a function of lake-surface elevation. Inset table shows lake volume versus surface area with the range of volumetric evaporation rates. In our model, we assumed that Lake Cahuilla filled up to +13 m, based on the sill elevation (Sieh and Williams, 1990). However, given the resolution of the digital elevation model, we cannot independently resolve the elevation of the sill of the basin to better than a few meters. The color version of this figure is available only in the electronic edition.

Cahuilla at +13 m (inset table, Fig. 4). Furthermore, we recognize that, as the lake expanded northward and southward into the Coachella and Mexicali valleys, some additional capacity for water storage would have been afforded by the presence of coarse-grained alluvial deposits along the basin's margins and delta distributary deposits near the apex of the ancestral Colorado River Delta (Van de Kamp, 1973). We assume that this additional capacity would also serve to offset inflows from precipitation and surface runoff, and we therefore use average annual rates of Colorado River discharge as the sole source of water for Lake Cahuilla in our calculations.

Weide (1974) estimated an annual rate of discharge for the Colorado River of 16.96 million acre-feet (20.92×10^9 m^3), based on normal flow conditions, averaged over the years 1902–1916. This is similar to the estimate of Wilke (1978, pp. 36–39) of 16.3 million acre-feet (20.11×10^9 m^3), based on Colorado River flow data over the longer period 1896–1966 at Lee's Ferry, Arizona, upstream of major dams, combined with estimates of discharge from tributaries downstream of Lee's Ferry. To better assess the temporal variability of Colorado River discharge, we supplemented those studies with our own analyses of historical stream flow statistics for (1) the Colorado River near Yuma, Arizona, for 1906–1963 C.E. (32°43′45″ N, 114°37′15″ W, NAD27, Gage datum 102.86 ft above NGVD 29 sea level; U.S. Geological Survey, 2017b); and (2) a combination of historical stream flow data from the Colorado River at Lee's Ferry, Arizona, for 1906–2004 (Woodhouse *et al.*, 2006a,b,c; Meko *et al.*, 2007; stream flow data were obtained from TreeFlow, an online database of stream flow reconstructions from tree rings—see Data and Resources) from the Gila River near Solomon, Arizona, for 1915–2006 (Meko and Hirschboeck, 2008; stream flow data were obtained from TreeFlow, see Data and Resources) and from tributaries of the Gila including the Salt River, the Verde River, and Tonto Creek for 1914–2004 (Meko and Hirschboeck, 2008; stream flow data were obtained from TreeFlow, see Data and Resources). Combining annual flow data for Lee's Ferry and the Gila River tributaries and comparing those values with flow statistics for the Colorado River near Yuma for the years 1906–1930, we note a relatively strong and positive linear correlation between the two data sets ($R^2 = 0.6816$; rmse $= 3.527 \times 10^9$ m^3). In contrast, we note that the two data sets diverge after 1930, with significant declines at Yuma, presumably due to anthropogenic modifications to the Colorado River upstream (e.g., construction of Hoover Dam, Parker Dam, and Imperial Dam, 1931–1938). For the purposes of utilizing longer records of annual stream flow that are less encumbered by the effects of anthropogenic modification, we used the combined flow data for Lee's Ferry and the Gila River tributaries as the basis of our model, along with estimates of normal flow conditions by Weide (1974).

We therefore adopt the Weide (1974) estimate of Colorado River discharge over the period 1902–1916 as our preferred rate, but we allow for the possibility that, during wetter periods, the discharge was higher. Based on our evaluation of the combined annual stream flow data (see table in Fig. 5), we assign a maximum plausible rate of 23.54×10^9 m^3/yr, based on an 11-yr running average over the period 1906–1995; the wettest 11-yr period was 1912–1922, assuming a Gila River contribution of 2% relative to the observed flows at Lee's Ferry for 1912–1914. We also assign a historical (1906–1995) mean of 19.19×10^9 m^3/yr, neglecting Gila River contributions for the years 1906–1914, which we take as a lower bound on annual discharge in our model. A summary table of combined historical stream flow statistics for 6-, 11-, 16-, and 23-yr running averages is included in Figure 5 for reference.

The other key parameter necessary to calculate the filling time of Lake Cahuilla is the evaporation rate of lake

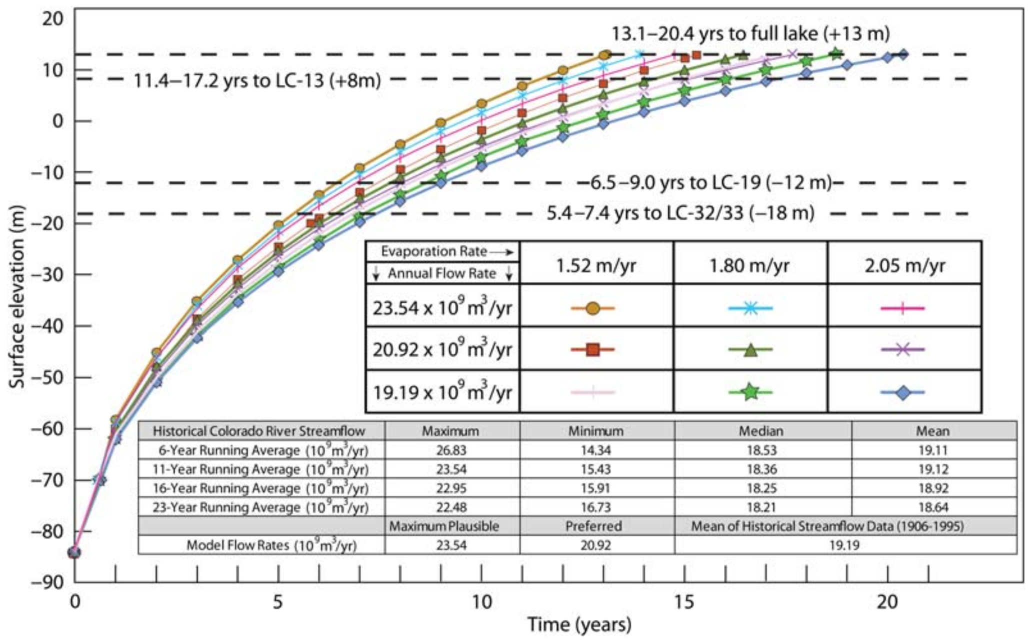


Figure 5. Lake filling model results and estimated ranges of historical Colorado River stream flow (1906–2004 C.E.). Surface elevations reported relative to mean sea level (as defined by North American Vertical Datum 1988). Historical ranges of Colorado River stream flow derived from combined annual flow rates observed on the Colorado River at Lee's Ferry (Woodhouse *et al.*, 2006a,b,c; Meko *et al.*, 2007), on the Gila River near Solomon, on the Salt River, on the Verde River, and at Tonto Creek (Meko and Hirschboeck, 2008). Our preferred Colorado River stream flow is that determined by Weide (1974), as discussed in the Rates of Lake Filling and Desiccation section. The color version of this figure is available only in the electronic edition.

water. Evaporation rates for the desiccation of Lake Cahuilla have been variously estimated at 1.52–1.55 m/yr (Sieh and Williams, 1990) to 1.8 m/yr (Wilke, 1978, p. 38). A faster evaporation rate was directly measured from a water surface in a tank in Calexico from 1904 to 1906 with an average annual rate of 2.05 m/yr (Blake, 1915, p. 21), although over those 3 yrs alone the evaporation ranged from 1.6 to 2.6 m/yr. An even faster evaporation rate of ~2.08 m/yr is estimated for the Salton Sea on the U.S. Weather Bureau's *Evaporation Maps for the United States* (Kohler *et al.*, 1959, plate 2; Meyers and Nordenson, 1962, plate 3; Hely and Peck, 1964, plate 2). However, as Hely *et al.* (1966, pp. C18–C19) note, the evaporation rates shown on the *Evaporation Maps for the United States* should be approximately correct for evaporation from small bodies of fresh water; the larger effective diameter of the Salton Sea (and Lake Cahuilla) would increase the humidity of the air moving across the water surface, thereby decreasing the evaporation rate from that predicted by Kohler *et al.* (1959), Meyers and Nordenson (1962), and Hely and Peck (1964). In light of the aforementioned estimates, we adopt 1.52, 1.80, and 2.05 m/yr as plausible evaporation rates in our model.

Hydrologic Modeling and Time Required to Fill Lake Cahuilla

Using the input parameters described above, we developed a hydrologic model for estimating the time required to partially fill Lake Cahuilla to the elevations of our dated stump samples and to completely fill it to the +13 m shoreline. The sixth-order polynomial regression equation generated from the 1 m elevation–capacity data for the Salton trough $Q_{net} = f(H_{eq})$ was used to convert lake volumes (Q_{net}) to equivalent lake-surface elevations (H_{eq}). Complete capture of annual Colorado River discharge (Q_{in}) was assumed constant for each year and added to the net volume of lake water (Q_{net}) from the previous year; this yielded the initial volume of lake water ($Q_{initial}$) for each year, prior to evaporation. Starting with an empty basin ($Q_{net} = 0$, $H_{eq} = -84.2$ m), water entering the basin each year (Q_{in}) would result in an initial lake volume ($Q_{initial}$), causing the surface elevation of the lake (H_{eq}) to rise to an initial surface elevation ($H_{initial}$); values of $Q_{initial}$ were converted to values of $H_{initial}$ ($Q_{initial} \rightarrow H_{initial}$) by linear interpolation of the regression equation calculated at 0.1 m increments of equivalent surface elevation. After the value of $H_{initial}$ was determined, evaporation would lower the surface of the lake linearly by an amount equal to the average annual evaporation rate (ΔH_{evap}), assumed to be constant for each year, resulting in the final surface elevation of the lake at the end of each model year. To repeat the calculation for the following year, values of H_{eq} were converted back to equivalent lake volumes using the regression equation $Q_{net} = f(H_{eq})$. This process was repeated for subsequent years until H_{eq} for the final year equaled or exceeded the 13 m shoreline elevation. To approximate the amount of time (t) required to fill the lake completely ($H_{eq} = +13$ m) and partially fill it to the elevations of our stump samples (H_{eq} = stump elevation), we used linear interpolation to approximate the value of t as a function of H_{eq} between model years bracketing the desired value of H_{eq}. A total of nine simulations were run using annual Colorado River discharge rates of 23.54×10^9, 20.92×10^9, and 19.19×10^9 m^3 in combination with annual evaporation rates of 1.52, 1.80, and 2.05 m/yr. The results of our hydrologic modeling are summarized in Figure 5.

The results of the model suggest it would have taken between 13.1 and 20.4 yrs to completely fill Lake Cahuilla, and using our "preferred" discharge rate (20.92×10^9 m^3), we provide a best estimate of 15.3–17.7 yrs. It would take only 5.4–7.4 yrs to fill the basin to the elevation of our lowest dated stump (LC-32/33) at approximately −18 m. If the previous lake had not fully desiccated, less time would have been required.

Historical Constraints

Several early Spanish explorers made expeditions to the mouth of the Colorado River, starting with Francisco de Ulloa in 1539 (Bancroft, 1884, pp. 78–81; Wagner, 1929, pp. 19–20 and 307) and Hernando de Alarcón in 1540 (Bancroft, 1884, pp. 90–93; Hammond and Rey, 1940, pp. 124–155). This continued 65 yrs later with Don Juan de Oñate and Father Francisco de Escobar in 1605 (Bolton, 1916, pp. 268–280; Bolton, 1919a) and then 95 yrs after that with a series of expeditions by Father Eusebio Francisco Kino between 1700 and 1706 (Venegas, 1759, Vol. 1, pp. 300–311; Bolton, 1919b, Vol. 1, pp. 246–256, 312–320, 340–345, and Vol. 2, pp. 205–214). Finally, Father Juan de Ugarte reached the mouth of the Colorado River in 1721 (Venegas, 1759, Vol. 2, pp. 46–62), as did Father Ferdinand Konščak (Fernando Consag) in 1746 (Venegas, 1759, Vol. 2, pp. 308–353). Details are in Appendix A, and locations mentioned here in the Historical Constraints section are shown in Figure A1. None of these explorers reached the Salton trough, but in 1540, 1605, and 1700–1706, their accounts indicate that the Colorado River was flowing to the Gulf of California at those times.

Another European explorer, Jacobo Sedelmayer (Jocobo Sedelmair), made a number of overland expeditions to the Gila and Colorado Rivers between 1744 and 1750 (Venegas, 1759, Vol. 2, pp. 181–211; Bancroft, 1884, pp. 536–543; Dunne, 1955). It appears that the only time during which Sedelmair followed the Colorado for any significant distance downstream of its confluence with the Gila River was in 1750, when he reached a point west of the sand dunes of the Gran Desierto de Altar that he subsequently crossed (Dunne, 1955, pp. 69–72). Sedelmair's journey along the Colorado River almost to the Gulf of California suggests the river was, once again, flowing southward to the Gulf. However, an unusual story related to Sedelmair in 1748 suggests that the Colorado River flowed, at least partially or intermittently, into the Salton trough. Sedelmair recounts a story told to him by Yuma Indians, while he was stationed just east of the confluence of the Colorado and Gila Rivers: "Here they informed me that if one crossed the Colorado and traveled northwest for two days one would touch once again the banks of the same river" (Dunne, 1955, p. 60). Later, Bancroft (1884, pp. 541–543) discusses a letter written in 1751 to the king of Spain, in which Captain Fernando Sanchez Salvador "advances the theory that the Colorado before reaching the gulf throws off a branch to the westward, which flows into the Pacific between Monterey and Point Concepcion." Although the details of a river reaching the Pacific are clearly impossible, the theory was likely based on the reports of the natives, and it suggests that, at least in what was then recent memory, the Colorado River had flowed, in part, into the Salton trough. And although Kino had visited with the same tribes at the same location in 1700, 1701, and again in 1702, no stories emerged during any of Kino's visits of a westward distributary of the Colorado River.

A series of expeditions between 1771 and 1776 unequivocally demonstrate the absence of a lake in the Salton trough at that time. In 1771, although Father Francisco Garcés was confused about his location at the time, he followed the Colorado River from its confluence with the Gila southward to the head of tidewater, near Heintzelman's Point (Bolton, 1917, pp. 322–325). From there, Garcés traveled northwestward, reaching a point about three leagues east of present-day Yuha Well; at that point, he was forced to turn around because he was out of water and had lost hope of finding water farther along (Bolton, 1917, pp. 325–328; Bolton, 1930, Vol. 1, pp. 45–47 and opposite p. 120, and Vol. 2, pp. 337–338).

Starting in 1774, Juan Bautista de Anza, Father Francisco Garcés, Father Pedro Font, and Juan Díaz continued to explore the region, searching for a land route to the west coast. On 10–11 March and 7–8 May 1774 (Bolton, 1930, Vol. 2, pp. 81–85, 113–114, 194–197, 228, 280–281, 296, 338–341) and again on 13–18 December 1775 and 7–8 May 1776 (Bolton, 1930, Vol. 3, pp. 56–62, 172–174, 195, 229–230, 295–296, and Vol. 4, pp. 129–140, 478–481), Anza and his party camped at a site they named San Sebastián, on San Felipe Creek near its confluence with Carrizo Wash, at an elevation of −40 to −35 m, near 33.099° N, 115.925° W. On 8 May 1774, both Anza and Díaz wrote in their diaries about looking for watering holes to the east or southeast of San Sebastián (Bolton, 1930, Vol. 2, pp. 114, 228, 296); exactly 2 yrs later, on 8 May 1776, Anza and Font described searching once again for a watering hole in that vicinity (Bolton, 1930, Vol. 3, pp. 173–174, 296, and Vol. 4, pp. 479–481), and this time they made it to Kane Spring, at 33.110° N, 115.836° W and −43 m. Despite their efforts, Font stated definitively on 8 May 1776 that the water at Kane Spring was "all the water we found" until they reached some wells at Pozo Salobre del Carrizal, where Font found "the water as red as if it had vermilion [and] very salty" (Bolton, 1930, Vol. 4, p. 481; see also, Vol. 3, p. 174). Bolton places the Pozo Salobre del Carrizal site on the old Paredones River, south of Cocopah in Baja California; Cocopah (Estación Cucapah) is present-day Ejido Tamaulipas, at 32.550° N, 115.232° W, and in the early twentieth century the Paredones

River was 5–10 km south of that point (Bolton, 1930, Vol. 1, opposite p. 120; see also Cory, 1915, p. 1219). No mention is ever made in any of the diaries of finding a body of water of any size in the center of the Salton trough, indicating that the most recent lake (lake A) must have desiccated completely or nearly completely by 1774. Furthermore, in his diary on 10 March 1774, Díaz described the diet of the natives who lived near the San Sebastián site, and it included mesquite beans (Bolton, 1930, Vol. 2, p. 280); if mature mesquite trees were growing at −35 m in 1774, the lake must have desiccated to below that elevation many years before then.

We use the historical accounts to place constraints on when the Colorado River was flowing to the Gulf, in which case we interpret that the lake was not in a filling phase. We also use Anza's traverse of the region as a hard constraint as to when the lake was mostly or completely dry, which limits how recently a complete filling could have occurred.

Climate Proxy Data

The stump ages (Table 2) require that the most recent Lake Cahuilla (lake A) must have filled around or after the beginning of the eighteenth century, and if we account for the time required to desiccate the lake from +13 m to −84.2 m, then historical accounts limit the filling of the most recent Lake Cahuilla to the early eighteenth century or earlier. We are therefore particularly interested in rainfall on the Colorado River catchment area in the early eighteenth century. Climate proxy records from the lower and upper Colorado River basin reveal decadal variations in rainfall. Precipitation on the lower Colorado River basin averaged 30.0 cm/yr over 1902–1916; the period 1707–1717 was drier, with precipitation averaging 26.3 cm/yr, whereas 1718–1727 was wetter, with precipitation averaging 33.8 cm/yr (Salzer and Kipfmueller, 2005a,b). For the upper Colorado River, annual flows at Lee's Ferry were reconstructed from tree rings (Woodhouse *et al.*, 2006a,b,c; Meko *et al.*, 2007; stream flow data were obtained from TreeFlow,see Data and Resources). The period 1902–1916 saw an average annual flow at Lee's Ferry of 19.4×10^9 m^3/yr, whereas 1707–1717 was drier, with an average flow of 17.5×10^9 m^3/yr, and 1718–1727 was wetter, with an average flow of 20.9×10^9 m^3/yr. These paleoclimate reconstructions consistently show that the Colorado River catchment area was ~10% drier in 1707–1717, and ~10% wetter in 1718–1727, relative to the 1902–1916 baseline. This implies that, depending on the exact timing of the most recent filling of Lake Cahuilla, it may have been possible to trim a year or so off the time required to fill the lake, but at other times it might have required an extra year. In any case, if the most recent lake did not begin filling until after Kino's final visit in 1706, the full lake highstand is not likely to have occurred until after 1721 C.E. or perhaps a year or two earlier if there was already some water in the basin in 1706; if the most recent lake did not begin filling until 1718 C.E., the full lake highstand is not likely to have occurred until after 1731 C.E. or perhaps a year or two earlier if there was already some water in the basin. Although it seems reasonable to infer that an avulsion of the Colorado River would be more likely during the wet period from 1718 to 1727 than during the dry period from 1707 to 1717, we do not impose this as a prior constraint in our model.

As stated previously, desiccation rates for evaporation of Lake Cahuilla are estimated at 1.52–2.05 m/yr (Blake, 1915, p. 21; Wilke, 1978, p. 38; Sieh and Williams, 1990), implying that between 47 and 64 yrs is required for full desiccation from +13 to −84.2 m. If the Cahuilla basin had completely desiccated by 1774, then the lake would have had to start drying up between 1710 and 1727. However, if some saline water was still resident in the basin in 1774, then the date of avulsion of the Colorado River back into the Gulf of California (and the onset of desiccation) could be advanced by several years. Alternatively, if the faster, historically documented evaporation rate from Lake Mead is applied (2.18 m/yr; Hely *et al.*, 1966, p. C18), then a slightly later date of 1731 is allowable for the end of lake A at +13 m. In any case, the historical constraints provided by Kino's and Anza's visits, along with the limits on the filling and desiccation rates, provide strong bounds on the timing of filling and desiccation of lake A and therefore on the timing of the most recent large SAF earthquake.

Chronological Modeling and Final Ages

We constructed an OxCal model (Bronk Ramsey, 2008; Fig. 6 and Fig. A2) that incorporates four sets of constraints. Working backward in time, we impose a historical prior of 1730 ± 3 C.E. (2σ) that represents the last date at which Lake Cahuilla could have been full (at +13 m elevation) if it had mostly or completely desiccated by the time of Anza's visit in 1774. The second set of constraints comes from the dated mesquite (*Prosopis* sp.) stumps that were growing in the footprint of Lake Cahuilla but which, we infer, were drowned by the last filling of the lake; these date the dry period between lakes A and B. The third set of constraints consists of five samples from the lake B shoreline deposits that provide a maximum limit on the age of the end of the lake B highstand. The oldest set consists of four additional radiocarbon dates that date the dry period prior to lake B (Fig. 6).

For each of the stumps that were killed by the filling of lake A, we ran radiocarbon dates on both the outermost and the innermost preserved growth rings (Fig. 3), and we visually counted the number of rings separating the outermost and innermost preserved rings (Table 1). Because the central core of some of the stumps was missing, presumably eaten by termites, we also crudely estimated (with appropriately large uncertainties) the number of years of growth that were missing from the center of the stump, based on the growth rate of mesquite (Ansley *et al.*, 2010; Table 1). To overcome the complication that the various stumps grew at different elevations and therefore could have begun growing at different times, we estimated the number of years that it

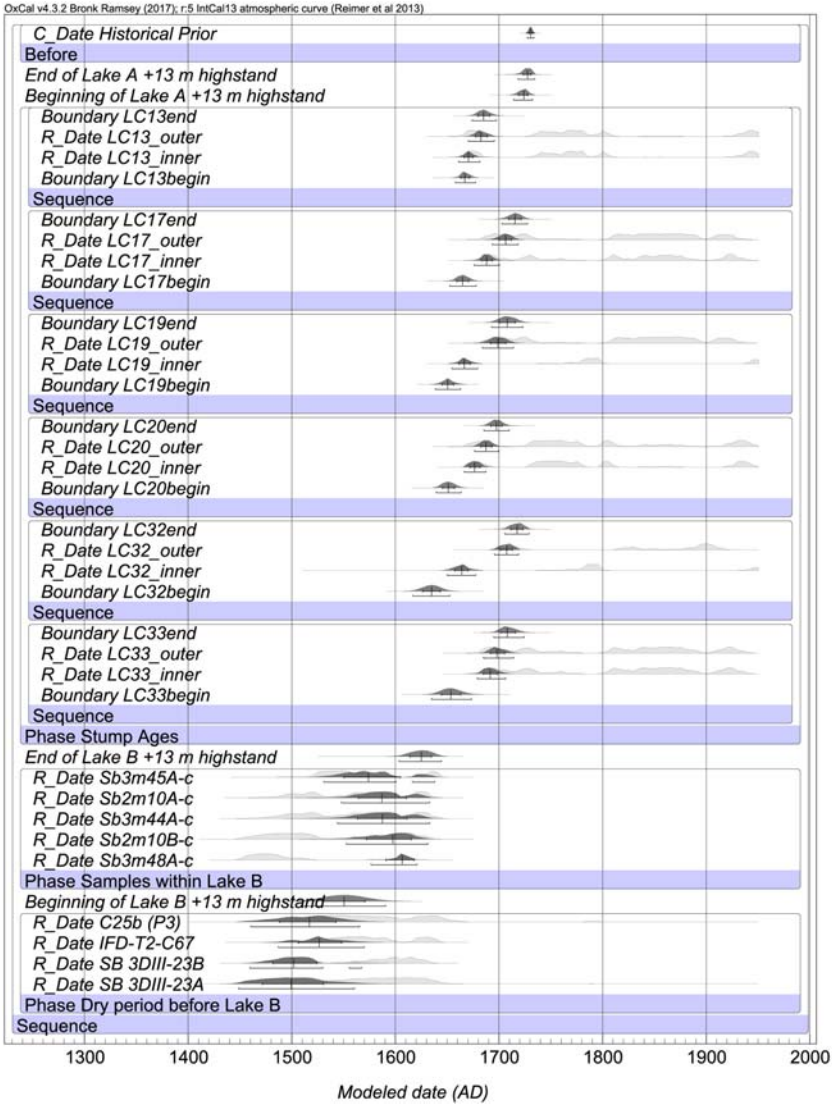


Figure 6. OxCal model of stump ages and detrital ^{14}C dates that constrain the timing of the past two lake stands and, therefore, the dates of the two most recent large southern SAF earthquakes. The color version of this figure is available only in the electronic edition.

would have taken for lake B to drop from its highstand elevation of +13 m down to the elevation of each stump. Lastly, we used the elevation of each stump to estimate the number of years it would have taken for lake A to complete its filling up to +13 m after it drowned the respective stump.

In OxCal, for each stump, we ordered the inner and outer dates as a Sequence(), and we used the Interval() function to impose, with appropriate uncertainties: (1) the number of growth rings separating the two dated samples, (2) the amount of growth inferred to be missing from the center of the stump, (3) the amount of time estimated for the lake to fall from its highstand elevation to the elevation of the stump, and (4) the amount of time estimated for the lake to complete its filling after drowning the stump. Imposition (1) forces the model to limit the posterior probability distribution to reasonable segments of the radiocarbon calibration curve (the dry period between lakes A and B must have occurred during a descending part of the calibration curve); impositions (2) and (3) force the model to extend the dry period between lakes A and B back an appropriate amount of time; and imposition (4) forces the model to allow an appropriate amount of time for lake A to fill. Because of the way the nested OxCal model is constructed, the results should not be biased if a stump did not begin growing immediately after lake B receded below its elevation or if a stump died from other causes before lake A rose to the stump's elevation.

The oldest set of radiocarbon constraints includes two dates from a mesquite stump inferred to have been drowned by the filling of lake B (Orgil, 2001): a date from a shoreline peat inferred to comprise material that had grown within the Lake Cahuilla footprint prior to the filling of lake B (Gurrola and Rockwell, 1996), and a date from charcoal at the base of the filling sequence of lake B at a site at −32 m elevation (Rockwell *et al.*, 2011). The wood being dated in each of these four cases necessarily grew prior to lake B, and therefore these samples provide a maximum age of the lake B filling event; however, because the radiocarbon calibration curve is essentially flat at that time (Fig. 3), this maximum age may overestimate the true age of the filling event by many decades, possibly even by a century.

To these we add dates from five particularly young samples embedded within lake B deposits at a site at the shoreline (Philibosian *et al.*, 2011); these samples constrain the maximum age of the end of the lake B highstand, but because these samples may have grown above the +13 m shoreline, we caution that we have no *a priori* reason to assume they grew during a lake stand versus during a dry interlude. Unfortunately, these samples also grew during a flat part of the radiocarbon calibration curve, leaving ambiguity in the interpretation. If at least some of these lake B shoreline samples have no more than a few decades of inherited age, then the samples' true ages, and the age of the lake B deposits, must fall near the younger end of the samples' probability density functions, as indicated in Figure 6. If, however, all of the lake B shoreline samples have more than a few decades of inherited age, then the samples' true ages may fall near the older end of their probability density functions; the OxCal results for Phase("Samples within Lake B") may not be valid, and the modeled age of the end of the lake B highstand may

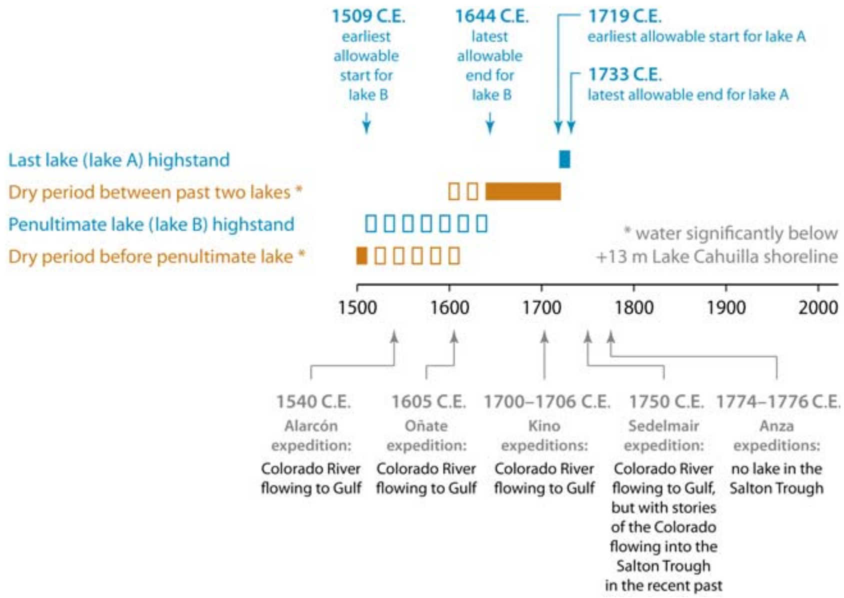


Figure 7. Timeline showing possible timings of the two most recent highstands of Lake Cahuilla and the intervening dry period. Solid bars denote periods of high confidence for the timing of the event; open bars indicate possible timing for the event. There is considerable uncertainty in the date range of lake B because of the double hump in the radiocarbon calibration curve. The color version of this figure is available only in the electronic edition.

underestimate the true age by many decades, possibly even by a century. In spite of the aforementioned complications, we can robustly conclude that the lake B highstand began no earlier than 1550 ± 40 C.E. (2σ) and ended no later than 1624 ± 20 C.E. (2σ). The actual timing of lake B could be anywhere in that interval, and the duration of the lake B highstand is not tightly constrained by these data (Fig. 7).

The OxCal model suggests that the lake A highstand occurred sometime between 1723 ± 9 and 1726 ± 8 C.E. (2σ). This is driven primarily by the ages of the LC17 and LC32 stump samples. This is consistent with the argument that lake A did not begin filling until after Kino's final visit in 1706, even though that information is not included in the model as a prior. If we now add the constraints (discussed previously) from Kino's observation that the Colorado River was still flowing southward in 1706 and from Anza's inability to find water during the treks across the basin in 1774–1776, then the earliest the lake A highstand could have begun is ~1719 C.E., and the latest it could have ended is ~1733 C.E. (Fig. 7). This leaves 1719–1733 C.E. as the maximum allowable time span for the lake A highstand, although it may have lasted only a year or two during that period. We place the highstand at 1726 ± 7 C.E.

Discussion and Conclusions

The two most recent surface-rupturing earthquakes on the southern SAF in Coachella Valley occurred when Lake Cahuilla was full, or nearly so. Sieh (1986) and Sieh and Williams (1990) reported from a shoreline site at Indio that the most recent earthquake (MRE) occurred when the lake was full, because the rupture broke up through shoreline berm sediments and was capped by topset beds associated with the most recent lake. Similarly, Philibosian *et al.* (2011) reported that the MRE produced slumping at the Coachella site that they interpreted could only have happened if the site was saturated, or nearly so. They also report that the rupture is capped by fine, well-sorted eolian sand that we reinterpret as recessional shoreline sand. These two observations are consistent with each other and argue that the MRE occurred between about 1719 and 1733 C.E., or about 1726 ± 7 (2σ). This moves forward in time the MRE on the southernmost SAF by 30–50 yrs, because prior studies placed the event at about 1680 (Sieh, 1986) to 1690 C.E. (Philibosian *et al.*, 2011).

The penultimate event at the Coachella site produced massive liquefaction that again requires the presence of water, and upward fault terminations occur in the lake B sediments (Philibosian *et al.*, 2011). After the liquefaction, additional lake deposits accumulated, which suggests that the earthquake occurred sometime during the middle of lake B, so we place a 1509–1644 C.E. age range for that earthquake, which we simplify to 1577 ± 67 C.E. (2σ). Philibosian *et al.* (2011) dated this event to between 1588 and 1662, so the timing of the penultimate event is shifted older by a several decades.

These new dates for the timing of the two MREs on the southernmost SAF even out the distribution of event ages by expanding the time between the two events to about 150 yrs, and they decrease the open interval to just under 300 yrs. Using the dates of earlier events in Philibosian *et al.* (2011), the average recurrence interval remains at about 180 yrs. Thus, by all accounts, the southern SAF is probably late in the earthquake cycle because it has now accumulated on the order of 6 m of elastic strain and potential slip (Fialko, 2006) that is more than inferred for the 1857 M_w 7.8 Ft. Tejon earthquake (Zielke *et al.*, 2010).

Data and Resources

All radiocarbon data and site elevation data used in this article were collected by the authors or appropriately cited. The websites https://www.ncdc.noaa.gov/paleo-search/study/6387, http://www.treeflow.info/content/colorado-r-lees-ferry-az-meko, http://www.treeflow.info/content/gila-river-near-solomon-az, and http://www.treeflow.info/content/salt-river-verde-river-tonto-creek-az (last accessed June 2018). All other data sources are cited.

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Appendix A

Summary of Observations of the Colorado River Delta up to 1750 C.E. and the OxCal Model Used in Our Analysis

Figure A1 shows site locations. Figure A2 shows the OxCal model used in this study. A summary of historical observations follows, below.

In September 1539, Ulloa sailed up the Gulf of California to the Colorado River Delta. Ulloa got about as far north

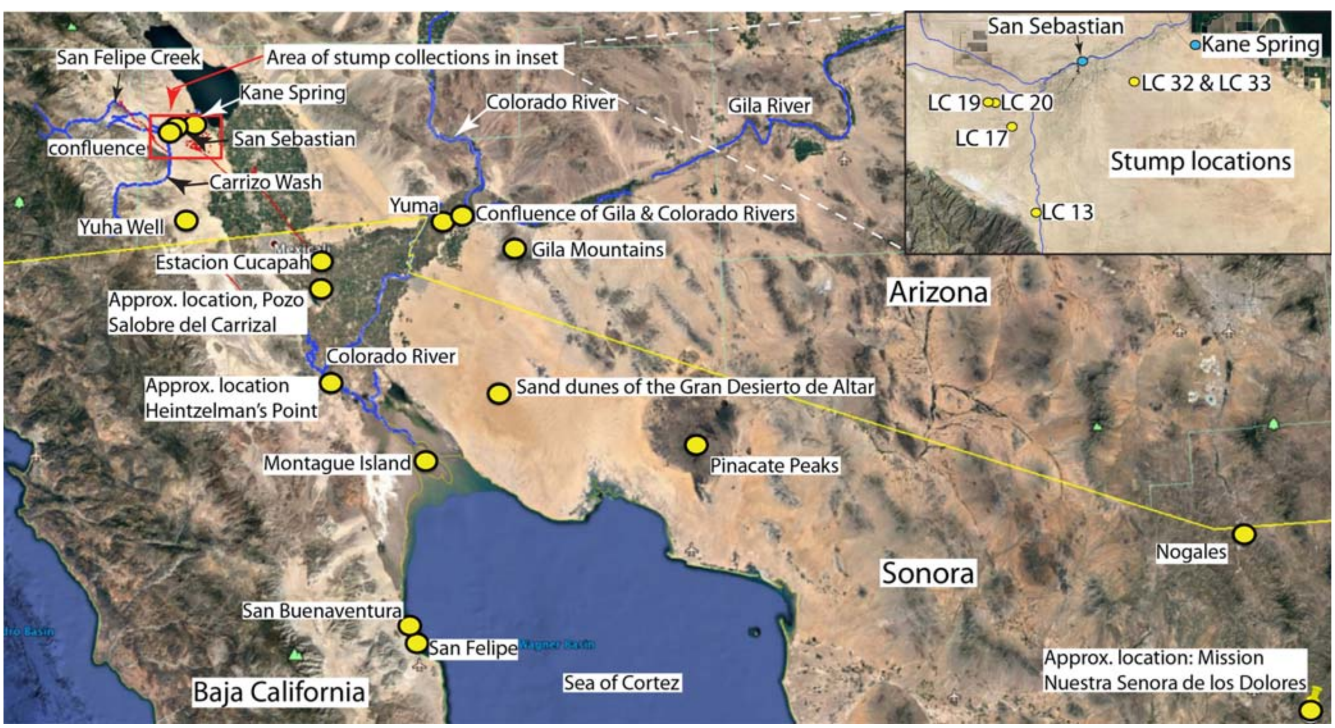

Figure A1. Location of site names used in the Historical Constraints section. The inset shows the location of stumps of dead mesquite that grew between lakes A and B and were inundated by Lake A. The color version of this figure is available only in the electronic edition.

as present-day Montague Island, at the southern edge of the Delta, but that was not northward enough to determine whether the full Colorado River was flowing southward into the Gulf. He described the sea there as "reddish and turned to mud," as if the Colorado River was actively dumping sediment nearby, yet the channels he attempted to navigate were entirely tidal and were left dry at low tide (Ulloa, in Wagner, 1929, p. 20). This was no different from conditions there in the nineteenth and twentieth centuries, where a tidal range approaching 10 m creates strong currents and a tidal bore exceeding 1 m during spring tides (United States Hydrographic Office, 1918, pp. 155–157). In the end, Ulloa abandoned his northward journey near Montague Island because his boats could not go further.

In 1540, Alarcón sailed up the Gulf of California, in an attempt to extend Ulloa's exploration northward. By August, Alarcón reached the shoals where Ulloa had turned back, but Alarcón pushed onward. Eventually, with much difficulty, his crew "found a mighty river with such a furious current that [they] could scarcely sail against it" (Alarcón, in Hammond and Rey, 1940, pp. 125–126). Determining the upstream extent of Alarcón's journey has been an elusive task ever since; Alarcón described reaching "some very high mountains among which the river flowed in a narrow canyon" (Alarcón, in Hammond and Rey, 1940, p. 153), which would imply he had passed the confluence of the Gila and Colorado Rivers above present-day Yuma, but other estimates suggest a shorter upstream traverse (Alarcón, in Hammond and Rey, 1940, p. 154; Pedro de Castañeda, in Hammond and Rey, 1940, p. 211; Bancroft, 1884, p. 93). Regardless, it is clear that in 1540 the Colorado River had strong currents to the Gulf of California, indicating that Lake Cahuilla was not filling at that time.

In 1604 and 1605, Oñate and Escobar explored overland westward from New Mexico, following the Bill Williams River to the Colorado River at present-day Lake Havasu; from there, they followed the Colorado River downstream past the Gila River (Bolton, 1919a, pp. 27–32). Below the confluence with the Gila River, Escobar estimated that the river continued 20 leagues (~110 km) to the sea and that "the river bottom appeared wider [and] the river has some branches which all the year carry water" (Escobar, in Bolton, 1919a, pp. 32–33). They reached the Cocapa settlement that "extends to the sea, or to the place reached by the salt water, which enters the river from the sea some four or five leagues" (Escobar, in Bolton, 1919a, p. 33) before continuing to Montague Island and the Gulf of California (Bolton, 1916, pp. 276–278; Bolton, 1919a, pp. 34–35). In January 1605, as in 1540, the Colorado River was clearly flowing to the Gulf of California.

In 1687, Kino founded Mission Nuestra Señora de los Dolores in what is now the inland parts of Sonora, Mexico, south of Nogales; he continued to live there for the next 24 yrs, until his death. In 1700, Kino explored the Gila River valley westward to its confluence with the Colorado River. He climbed two hills just east of the confluence (likely in the Gila Mountains), from which he could see that "the two rivers, below the confluence, ran united about ten leagues to the west, and then, turning southward, about twenty leagues farther on emptied into the head of the Sea of California" (Kino, in Bolton, 1919b, Vol. 1, pp. 249, 253). He also saw "a large stretch of country in California" (Kino, in Bolton, 1919b, Vol. 1, p. 253), but it is unclear whether he would have climbed high enough to be able to see a full Lake Cahuilla, had it existed at the time. Nonetheless, Kino made no notes of reports or descriptions of a lake in the Salton trough.

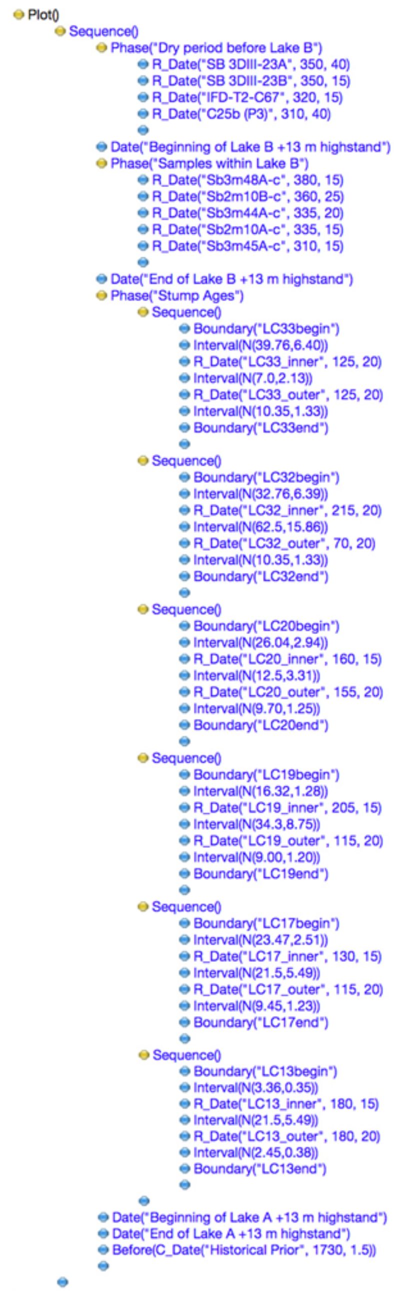

Figure A2. OxCal model used to calculate the ages of lakes A and B. The color version of this figure is available only in the electronic edition.

In 1701, Kino returned to the confluence of the Gila and Colorado Rivers and continued onward, following the river more than 18 leagues (∼100 km) toward the Gulf of California. There, Kino crossed the river on a raft, and he described the river as "very large volumed" and "about two hundred *varas* [∼170 m] wide," noting that people "did not touch the bottom except at the two banks" (Kino, in Bolton, 1919b, Vol. 1, p. 316). The next year, Kino returned to the Colorado River near where it "empties into the head of the Sea of California." There, he again described the river as "very large volumed and very wide" and difficult to cross (Kino, in Bolton, 1919b, Vol. 1, pp. 341–344).

In 1706, Fray Manuel de Oyuela traveled with Kino and climbed the highest of the Pinacate Peaks. From there, Oyuela could see as far as the Gulf of California, and he described "the very large volumed Rio Colorado which enters into the sea" at the head of the Gulf (Oyuela, in Bolton, 1919b, Vol. 2, p. 212). During all of Kino's visits to the Colorado Delta, from 1700 to 1706, it is clear that the Colorado River was flowing to the Gulf of California.

One driving question of Kino's expeditions was determining whether California was a peninsula or an island. At one point in 1702, Kino acknowledges in his diary that there were reports of a body of water northwest of the Colorado Delta, but he summarily dismisses those reports as describing the Pacific Ocean: "if some hostile and obstinate persons should maintain that some Quiquima Indians say that farther west the sea still extends to the northwest, these Quiquima speak of the other sea, on the opposite coast, and not of this our Sea of California …" (Kino, in Bolton, 1919b, Vol. 1, p. 354). Thus, it is possible that some water may have been present in the Salton trough between 1700 and 1706, but the Colorado River was clearly flowing into the Gulf at that time.

In 1721, Ugarte sailed up the Gulf of California to the mouth of the Colorado River but, like Ulloa 182 yrs earlier, was unable to pass through the shoals, where there were strong, tidally driven currents (Venegas, 1759, Vol. 2, pp. 56–58). Ugarte proceeded to Montague Island, where he observed that the river "ejected into the sea grass, leaves, weeds, trunks of trees, burnt logs, the timbers of cottages and the like" (Venegas, 1759, Vol. 2, p. 59). While this would be consistent with a full-flowing Colorado River emptying into the Gulf, Ugarte also noted that "on the two preceding nights the weather had been very tempestuous with thunders and lightnings and violent rains, which had occasioned the two inundations they had observed in the river" (Venegas, 1759, Vol. 2, p. 59). Our assessment, therefore, is that the evidence is inconclusive as to whether the full Colorado River was flowing to the Gulf in 1721.

In 1746, Consag sailed up the Gulf of California to the mouth of the Colorado River, where he described similar challenges with the tides as the previous explorers; he reached Montague Island but was unable to travel much further upstream due to strong tidal currents (Consag, in Venegas, 1759, Vol. 2, pp. 342–349). Meanwhile, Consag's crew explored limited distances overland by foot: they spent a day and a half looking for drinking water near a place they called San Buenaventura (∼10 km north of present-day San Felipe, Baja California; see map of Consag, in original Spanish text of Venegas, 1757, Vol. 3, after p. 194), and they briefly explored the land near Montague Island (Consag, in Venegas, 1759, Vol. 2, pp. 346, 348). Again, the evidence is inconclusive as to whether the full Colorado River was flowing to the Gulf of California in 1746. Furthermore, it appears Consag did not reach a place where he could have seen a lake in the Salton trough, had it existed at the time.

Father Sedelmair explored the region of the Gila and Colorado Rivers on several expeditions between 1744 and 1750. In 1744, he explored both rivers upstream of their confluence but did not explore downstream (Venegas, 1759, Vol. 2, pp. 181–185; Bancroft, 1884, pp. 536–537; Sedelmair, in Dunne, 1955, pp. 15–53). Sedelmair returned to the region in October and November 1748, although he oddly reported the dates of that trip as being in October and November 1749; regardless, he explored only a short distance downstream of the confluence of the Colorado and Gila Rivers (Sedelmair, 1750; Venegas, 1759, Vol. 2, pp. 209–210; Bancroft, 1884, p. 540; Dunne, 1955, pp. 55–66). Finally, in 1750, Sedelmair went farther downstream, to a point west of the sand dunes of the Gran Desierto de Altar, apparently almost reaching the Gulf of California (Bancroft, 1884, pp. 540–541; Dunne, 1955, pp. 67–75).

Appendix B

Online Access to Historical Accounts

Some historical accounts consulted in this study are available online:

Sedelmair (1750):
https://books.google.com/books?id=HJgEAAAAQAAJ
http://cdigital.dgb.uanl.mx/la/1080023894_C/1080023894_T1/1080023894_MA.PDF
http://cdigital.dgb.uanl.mx/la/1080023894_C/1080023894_T1/1080023894_03.pdf

Venegas (1757):
Volume 1: https://archive.org/details/cihm_18688
Volume 2: https://archive.org/details/cihm_18689
Volume 3: https://archive.org/details/cihm_18690
All: https://catalog.hathitrust.org/Record/100258713

Venegas (1759):
Volume 1: https://archive.org/details/naturalcivilhist01vene
Volume 2: https://archive.org/details/naturalcivilhist02vene
All: https://catalog.hathitrust.org/Record/100268375

Bancroft (1884):
https://archive.org/details/thenorthmexivol115bancmiss
https://archive.org/details/worksofhuberthow15bancrich

https://archive.org/details/historynorthmex02nemogoog
https://archive.org/details/historynorthmex03nemogoog
https://archive.org/details/annalsofspanishn01oakhrich

Blake (1915):
https://archive.org/details/imperialvalleya00blakgoog

Cory (1915):
https://archive.org/details/imperialvalleya00blakgoog

Bolton (1916):
https://archive.org/details/spanishexplorati00bolt
https://archive.org/details/spanishexplorat03boltgoog

Bolton (1917):
https://archive.org/details/pacificoceaninhi00panaiala
https://archive.org/details/pacificoceaninhi00panauoft

Bolton (1919a):
http://www.jstor.org/stable/25011616
https://archive.org/details/fatherescobarsre00boltrich

Bolton (1919b):
Volume 1: https://archive.org/details/kinoshistoricalm00kino
Volume 2: https://archive.org/details/kinoshistoricalm02kinouoft

Bolton (1930):
Volume 1: https://archive.org/details/anzascaliforniae01bolt
Volume 2: https://archive.org/details/anzascaliforniae02bolt
Volume 3: https://archive.org/details/anzascaliforniae03bolt
Volume 4: https://archive.org/details/anzascaliforniae04bolt
Volume 5: https://archive.org/details/anzascaliforniae05bolt

Dunne (1955):
https://catalog.hathitrust.org/Record/001652279

United States Hydrographic Office (1918):
https://archive.org/details/mexicoandcentra00offigoog

Kohler *et al.* (1959):
https://catalog.hathitrust.org/Record/101740906
http://www.nws.noaa.gov/oh/hdsc/Technical_papers/TP37.pdf

All websites were last accessed on June 2018.

Department of Geological Sciences
San Diego State University
San Diego, California 92182
trockwell@mail.sdsu.edu
(T.K.R.)

Earth Observatory of Singapore
Nanyang Technological University
50 Nanyang Avenue
Singapore 639798
Singapore
meltzner@ntu.edu.sg
(A.J.M.)

G3SoilWorks, Inc.
350 Fischer Avenue Front
Costa Mesa, California 92626
ehaaker@g3soilworks.com
(E.C.H.)

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