Title: Geomorphic evidence for the geometry and slip rate of a young, low-angle thrust: Implications for hazard assessment and fault interaction in complex tectonic environments

Abstract: We present surface evidence and displacement rates for a young, active, low-angle (~20°) reverse thrust fault in close proximity to major population centers in southern California (U.S.A.), the Southern San Cayetano fault (SSCF). Active faulting along the northern flank of the Santa Clara River Valley displaces young landforms, such as late Quaternary river terraces and alluvial fans. Geomorphic strain markers are examined using field mapping, high-resolution lidar topographic data, 10Be surface exposure dating, and subsurface well data to provide evidence for a young, active SSCF along the northern flank of the Santa Clara River Valley. Displacement rates for the SSCF are calculated over 1,000-10,000 year timescales with maximum slip rates for the central SSCF of 1.9 ±1.0/-0.5 mm/yr between ~19-7 ka and minimum slip rates of 1.3 ±0.5/-0.3 mm/yr since ~7 ka. Uplift rates for the central SSCF have not varied significantly over the last ~58 ka, with a maximum value of 1.7 ±0.9/-0.6 mm/yr for the interval ~58-19 ka, and a minimum value 1.2 ±0.3 mm/yr since ~7 ka. The SSCF is interpreted as a young, active structure with onset of activity at some point after ~58 ka. The geometry for the SSCF presented here, with a ~20° north-dip in the subsurface, is the first interpretation of the SSCF based on geological field data. Our new interpretation is significantly different from the previously proposed model-derived geometry, which dips more steeply at 45-60° and intersects the surface in the middle of the Santa Clara River Valley. We suggest that the SSCF may rupture in tandem with the main San Cayetano fault. Additionally, the SSCF could potentially act as a rupture pathway between the Ventura and San Cayetano faults in large-magnitude, multi-fault earthquakes in southern California. However, given structural complexities, including significant changes in dip and varying Holocene displacement rates along strike, further work is required to examine the possible mechanism, likelihood, and frequency of potential through-going ruptures between the Ventura and San Cayetano faults. Confirmation of the SSCF in a previously well-studied area, such as the southern California,
demonstrates that identification of young faults is critical for accurate seismic hazard assessment. We suggest that many young, active faults remain undetected in other structurally complex and tectonically active regions globally, and that significant seismic hazards can be overlooked.
Highlights

• Young faults often undetected but potentially key for seismic hazard assessments.
• First geomorphic evidence for the Southern San Cayetano fault (SSCF).
• $^{10}$Be dating on offset terraces records Holocene slip rate of $1.3^{+0.5/-0.3}$ mm yr$^{-1}$.
• SSCF has major implications for seismic hazard in southern California.
Geomorphic evidence for the geometry and slip rate of a young, low-angle thrust: Implications for hazard assessment and fault interaction in complex tectonic environments

A. Hughes¹, D. H. Rood¹,², A. C. Whittaker¹, R. E. Bell¹, T. K. Rockwell³, Y. Levy³, K. M. Wilcken⁴, L. B. Corbett⁵, P. R. Bierman⁵, D. E. DeVecchio⁶, S. T. Marshall⁷, L. D. Gurrola², C. Nicholson⁸

1 Department of Earth Science and Engineering, Imperial College, London, U.K.
2 Earth Research Institute, University of California, Santa Barbara, California, U.S.A.
3 San Diego State University, San Diego, California, U.S.A.
4 Australian Nuclear Science and Technology Organization (ANSTO), Lucas Heights, New South Wales, Australia.
5 Department of Geology and Rubenstein School of the Environment and Natural Resources, University of Vermont, Burlington, Vermont, U.S.A.
6 School of Earth and Space Exploration, Arizona State University, Phoenix, Arizona, U.S.A.
7 Department of Geological and Environmental Sciences, Appalachian State University, Boone, North Carolina, U.S.A.
8 Marine Science Institute, University of California, Santa Barbara, U.S.A.

Corresponding author: Alex Hughes (a.hughes15@imperial.ac.uk)

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**Keywords**

Thrust faults, Beryllium-10, surface exposure dating, lidar, southern California

1 Introduction

A growing body of evidence indicates that large-magnitude earthquakes can involve slip on multiple faults with complex geometries and kinematics (e.g. Hubbard et al., 2010; Yue et al., 2005). Several recent examples of large-magnitude multi-fault ruptures involve slip on young faults that were unrecognized prior to the earthquake, but acted as key rupture pathways and enhanced fault connectivity during the event (Fletcher et al., 2014; Hamling et al., 2017). Previously unrecognized faults have also been identified as the seismic source for many recent, devastating, moderately-sized earthquakes, including the 2015 M_w 6.5 Pishan earthquake, China (Lu et al., 2016), and the 2011 M_w 6.2 Christchurch earthquake, New Zealand (Beavan et al., 2011). Consequently, identifying young, structurally immature faults and accurately characterizing key fault parameters, such as location and deformation rate, is a fundamental prerequisite for accurate seismic hazard assessment (e.g. Field et al., 2015).

Fault slip rates are key first-order inputs into seismic hazard assessment as they provide quantitative information on both the magnitude and frequency of potential earthquakes (e.g. Field et al., 2015). Records of fault slip rates over multiple timescales can be used to detect spatial and temporal variations in fault activity, thereby enhancing our ability to forecast future fault behavior.
(Friedrich et al., 2003; Rood et al., 2011). However, the processes that govern spatial and temporal variations in fault slip rates are poorly understood, partly because long-term records of fault slip often lack sufficient resolution (e.g. Friedrich et al., 2003). Improved understanding of fault activity within major fault systems is particularly important given new insights into how young, previously unrecognized, faults can potentially act as rupture pathways in large-magnitude earthquakes (Fletcher et al., 2014; Hamling et al., 2017; Hubbard et al., 2014).

Young faults can have little stratigraphic offset and subtle geomorphic expression making them difficult to identify prior to earthquake rupture and can, therefore, be overlooked in seismic hazard assessments. For example, the Papatea fault in the northern South Island, New Zealand, is a recently identified, structurally immature fault with small stratigraphic offset that potentially enhanced fault connectivity and increased earthquake magnitude during the 2017 Mw 7.8 Kaikōura earthquake (Hamling et al., 2017; Hollingsworth et al., 2017). Accordingly, identification of young faults prior to an earthquake can in theory improve understanding of structural connectivity in fault systems where no historical large-magnitude (\(> M_w 7\)) earthquakes are documented, and facilitate a more rigorous assessment of future potential earthquake magnitudes (e.g. Hubbard et al., 2014).

The Ventura Basin, southern California, provides an ideal location to investigate the significance of the identification of young faults to seismic hazard assessment for several reasons. The Ventura fault (Fig. 1) is a young, structurally immature fault within the Ventura Basin with as little as 200–300 m of stratigraphic offset since 200–300 ka observed in subsurface well data (Hubbard et al., 2014). The geometry of the Ventura fault has proved controversial as small stratigraphic offsets within the upper 2–3 km made the Ventura fault difficult to identify in subsurface well data (Sarna-Wojcicki and Yerkes, 1982; Yeats, 1982). A proposed model for the Ventura fault, based on well-log and seismic reflection data, indicated that the Ventura fault may be deep-rooted and potentially
connects with the San Cayetano fault (Hubbard et al., 2014) (Fig. 1). However, modeling required an additional, steeply-dipping (45–60°) linking structure, which was referred to as the Southern San Cayetano fault (SSCF) (Hubbard et al., 2014) (Fig. 1). Connection of the Ventura and San Cayetano faults via a model-derived SSCF creates a continuous ~150 km long fault system, between which the SSCF potentially acts as a rupture pathway during large-magnitude multi-fault ruptures (Hubbard et al., 2014; Marshall et al., 2017; Rockwell et al., 2016).

Previous geological mapping has included minor unnamed fault segments along a section of the proposed SSCF with no indication of the subsurface geometry or connectivity (Yerkes et al., 1987). Additionally, a structure named the Pagenkopp fault is mapped from well data at the eastern end of the proposed surface trace of the SSCF (Çemen, 1989; Hopps et al., 1992). However, despite much previous mapping within the Santa Clara River Valley (e.g. Dibblee Jr, 1990a; Hopps et al., 1992; Rockwell, 1988) (Fig. 1), a continuous fault along the northern Santa Clara River Valley has not been characterized by any geological or geomorphic field evidence, or subsurface data. Furthermore, the proposed geometry of the SSCF (whether north or south-dipping) is unknown, and the age, surface expression, subsurface-dip, activity, and slip rate have not been thoroughly investigated. Without accurate characterization of the SSCF, a rigorous assessment of seismic hazard in this densely populated and tectonically active area of southern California remains incomplete.

In this paper, we use lidar topographic data, cosmogenic $^{10}$Be surface exposure ages, and subsurface data to provide compelling evidence for the SSCF and characterize the surface trace, subsurface geometry, and deformation rate for the SSCF through time. Our results bring into focus the importance of accurately characterizing easily overlooked, young faults for seismic hazard assessment in densely populated areas. Confirmation of the SSCF in a previously well-studied
area, such as the Ventura Basin, leads us to suggest that unrecognized, young active faults could remain undetected in many other tectonically active regions globally and result in incomplete and inaccurate seismic hazards assessments.

1.1 Regional setting

The Ventura Basin is located within the Western Transverse Ranges, a fold and thrust belt in southern California, U.S.A, resulting from regional transpression and 7-10 mm yr$^{-1}$ of north-south directed crustal shortening (Marshall et al., 2013) caused by the restraining bend in the San Andreas fault (e.g. Wright, 1991). Range-front topography throughout most of the Ventura Basin is fault controlled and associated with uplift in the hangingwall of active, east-striking reverse faults (Fig. 1). One such fault, the San Cayetano fault, is often mapped as the most southerly fault along the northern flank of the Santa Clara River Valley (e.g. Rockwell 1988) (Fig. 1). However, recent fault modelling has suggested the existence of the SSCF farther south in the footwall of the San Cayetano fault (Hubbard et al., 2014). The SSCF is not included in current seismic hazard mapping for California (e.g. Jennings and Bryant, 2010), published geological maps (e.g. Dibblee Jr, 1990a), or the UCERF3 report for California (Field et al., 2015). However, the model-derived interpretation of the SSCF is included in the latest version of the Community Fault Model for Southern California (Nicholson et al., 2015).

A series of uplifted and tilted strath terraces, fill terraces, and alluvial fan deposits are preserved along the northern flanks of the east-west trending Santa Clara River Valley, in close proximity to the proposed SSCF (Fig. 2). Uplift has previously been attributed to activity on a 25 km long, south-dipping fault zone referred to as the Lion fault set, which includes the Sisar, Big Canyon, and Lion faults (e.g. Huftile and Yeats, 1995) (Fig. 1). Alternatively, uplift of terraces along the
eastern section of the range front has been attributed to footwall deformation from the north-
dipping San Cayetano fault (Rockwell, 1988).

1.2 Study location

We focused on Orcutt Canyon (Figs. 1 & 2) to investigate range-front faulting along the northern
Santa Clara River Valley because several geomorphic observations point to active faulting in this
area. Orcutt Canyon is a north-south-trending incised valley along the southern flank of San
Cayetano Mountain (Fig. 1) that drains into the Santa Clara River Valley. The Canyon is located
in the central portion of the range front, and thus likely records close-to-maximum displacement
if the range front were bounded by a laterally continuous fault (Fig. 2). Alluvial fans that cross the
range front at the mouth of Orcutt Canyon are warped parallel to the range front creating north-
side-up scarps (Fig. 3). A series of bedding plane parallel flexural slip faults such as the Rudolph,
Culbertson, and Thorpe faults are well-established in the footwall of the San Cayetano fault at
Orcutt Canyon (e.g. Rockwell, 1983; Rockwell, 1988) (Figs. 2, 3, & 4). Additionally, ~3 km
southeast of Orcutt Canyon in the Santa Clara River Valley, a ~2 km east-west trending fold is
mapped warping Quaternary alluvial fan deposits above the valley floor (Dibblee Jr, 1990b;
Rockwell, 1983) (Fig. 2b).

A sequence of uplifted and tilted alluvial fill and strath terraces at various elevations within Orcutt
Canyon have previously been mapped and numerically age dated (Rockwell, 1983; Rockwell,
1988). The existing terrace chronology for the Santa Clara River Valley and Upper Ojai Valley is
based upon dendrochronology, soil development, radiocarbon, and comparative rates of faulting
on the Arroyo-Parida-Santa Ana fault (DeVecchio et al., 2012a; Rockwell, 1983; Rockwell, 1988)
(Fig. 1). Terraces are assigned a number that increases with increasing age, i.e. Q1 (youngest) to
Q7 (oldest), and the existing terrace chronology is included in Figure 2. Terraces previously mapped at Orcutt Canyon range from Q3 (0.5-5 ka) to Q6 (38-92 ka) (Rockwell, 1983; Rockwell, 1988).

## 2 Methods

### 2.1 Depth profiles

To improve the accuracy and precision of age estimates for the Q4, Q5, and Q6 terraces and accurately quantify slip rates at Orcutt Canyon, we measured \textit{in-situ}-produced cosmogenic \(^{10}\text{Be}\) surface exposure ages using depth profiles (e.g. Anderson et al., 1996; DeVecchio et al., 2012a). \textit{In-situ} \(^{10}\text{Be}\) is formed via the interaction of cosmic rays with minerals at the Earth’s surface and the concentration of \(^{10}\text{Be}\) decreases exponentially with depth. The surface \(^{10}\text{Be}\) concentration represents the build-up of \(^{10}\text{Be}\) since the time of surface abandonment and, if minimal erosion has occurred, the age of the surface. A depth profile accounts for substantial \(^{10}\text{Be}\) acquired prior to deposition (inheritance) by estimating \(^{10}\text{Be}\) concentration below the attenuation length of cosmic rays (Anderson et al., 1996).

Depth profile locations were selected based on the quality and completeness of soil profile development. A complete soil profile is interpreted to indicate a stable surface that has not undergone significant erosion since time of abandonment (Rockwell, 1983). We collected samples for depth profiles from alluvial fans with Q4 soil development at Orcutt Canyon (Fig. 3) and Bear Canyon (Fig. 2a). Further samples for depth profiles were collected from a Q5 alluvial fill terrace at Orcutt Canyon (Fig. 3), the top surface of a folded Q5 alluvial fan in the Santa Clara River Valley (Fig. 2b), and an uplifted Q6 alluvial fan at neighboring Timber Canyon (Fig. 3). A full description of field sampling methods is included in the supplement (S1).
2.2 Laboratory methods

Quartz separation was undertaken in the CosmiC laboratory at Imperial College London. Bulk sediment samples were sieved to isolate the 250–1000 μm fraction and ~20 g aliquots of quartz were isolated and purified from the samples following the methodology of Kohl and Nishizumi (1992). Beryllium isolation was carried out at the University of Vermont following the methods of Corbett et al. (2016). $^{10}$Be/$^9$Be AMS measurements were made at the Centre for Accelerator Science at the Australian Nuclear Science and Technology Organization using the 6 MV Sirius tandem accelerator (Wilcken et al., 2017). Measured $^{10}$Be/$^9$Be ratios were calibrated to standard 01-5-2 with an assumed $^{10}$Be/$^9$Be ratio of 8.558 x 10^-12 (Nishizumi et al., 2007). Measured AMS $^{10}$Be/$^9$Be ratios were converted to concentrations and samples were blank corrected relative to the batch-specific process blank. The mean total $^{10}$Be atoms for all process blanks was 9307 +/- 2487 atoms (1σ). This background equates to a total of 0.2–9.9% of the total $^{10}$Be atoms in the individual samples. A summary of sample details and concentrations are included in Table 1.

We calculated exposure ages and associated uncertainties by modelling depth profiles of measured $^{10}$Be concentrations using a Monte Carlo simulator (Hidy et al., 2010). Simulations employed a constant production rate model (Stone, 2000) with a reference spallogenic $^{10}$Be production rate of 4.24 +/- 0.12 atoms g^-1 yr^-1 based on inputting the Promontory Point reference production rate calibration dataset from Lake Bonneville, Utah, U.S.A (Lifton et al., 2015) to the CRONUS online exposure age calculator version 2.3 (Balco, 2009). Density was modelled using a range of 1.7–1.8 g cm^-3 and we employed an attenuation length of 160 g cm^-2. We used a $^{10}$Be half-life of 1.387 +/- 0.012 My (Chmeleff et al., 2010), but apply a greater uncertainty of 5% to the half-life in our simulations. Muonogenic $^{10}$Be production was modeled after Heisinger (2002a, 2002b). Further
details on both laboratory methods and data reduction are included in the supplements S2 and S3, respectively, and full samples parameters are included in Table ST1.

2.3 Mapping

Lidar data covering Ventura County was acquired from the Ventura County Watershed Protection District (Airborne1, 2005) and imported into ArcGIS to create a 1.5 m digital elevation model (DEM). Digital geomorphic maps comprising bare earth hillshade images and topographic slope maps were extracted from the DEM and used to reinterpret the spatial extent and increase the resolution of existing terrace maps (Rockwell, 1983; Rockwell, 1988) (Figs. 2 & 3).

2.4 Scarp identification and fault activity

We extracted topographic profiles from the DEM and used these topographic profiles in combination with our digital geomorphic maps and field observations to confirm the presence of north-side-up tectonic scarps in Q4 and Q5 alluvial fans at the mouth of Orcutt Canyon (Fig. 3). Topographic profiles, geomorphic maps, and field observations were also employed to identify further alluvial surfaces offset by active faulting along the length of the proposed fault (Figs. 2 & 3).

Monte Carlo simulations, which account for uncertainties in all input parameters, were utilized to calculate slip rates and throw rates across the fault scarps. Monte Carlo simulations output a non-normally distributed frequency histogram (Figs. 4a & b) encompassing all possible slip rate values calculated during 100,000 trial runs. The modal value was selected from the output frequency histogram to represent the most likely slip rate (e.g. Rood et al., 2011). Input parameters used in Monte Carlo simulations to calculate slip rates at Orcutt Canyon were surface age, fault position,
near-surface fault dip, geomorphic surface slope, and intercepts. See supplement S4 for full details of how each input parameter is modeled during the simulation.

Uplift for a Q6 strath terrace at Orcutt Canyon was calculated by measuring incision of the terrace relative to the current stream level and assuming that uplift is in equilibrium with incision (Fig. 4c). We improved the spatial resolution of our dataset by quantifying uplift rates for Q6 alluvial fans at Timber Canyon and Santa Paula Creek (Fig. 2) east and west of Orcutt Canyon, respectively. At these locations Monte Carlo simulations were again utilized to calculate uplift rates (Figs. 4d & 4e); however, no Q6 deposits are preserved in the fault footwall at either Timber Canyon or Santa Paula Creek (Fig. 2). Therefore, our Monte Carlo simulations combine the hangingwall surfaces for Q6 alluvial fans with the top of the corresponding Q3 alluvial fans preserved in the footwall (Figs. 4d & 4e). The most likely modal value for fault throw from the Monte Carlo simulation was taken to represent minimum uplift of Q6 surfaces relative to the modern-day Santa Clara River Valley.

For the fold in the Santa Clara River Valley floor, we were unable to identify a burial depth for the top of the Q5 surface exposed at the crest of the fold beneath Q2 deposits that currently comprise the valley floor (Fig. 4f). Consequently, a topographic profile across the fold was used to calculate the maximum elevation of the fold relative to the current elevation of the Q2 surface on the modern valley floor and the value of maximum elevation of the fold was taken to represent minimum uplift (Fig. 4f).

Rates were calculated during Monte Carlo simulations by dividing either the total fault slip, fault throw, or uplift at each location by our new cosmogenic exposure ages. We assumed a fault dip at the surface of 50–90° and modeled uncertainties accordingly from the simulation results. The basis
for the 50–90° range in fault dips is provided in section 3.4 and a full breakdown of all equations and parameters used in displacement rate calculations is included in the supplement (S5). We calculated tilt of geomorphic surfaces by plotting a linear regression for topographic profiles extracted from lidar data for both the modern-day channel and the geomorphic surface. The slope of the modern-day stream was subtracted from the slope of the older geomorphic surface to give the tilt of the older geomorphic surface. Tilt calculations assumed that the older surface was deposited at the same angle as the current stream level.

2.5 Subsurface data

An approximately north-south oriented well-correlation section through Orcutt Canyon includes subsurface data for five wells down to ~3 km (Hopps et al., 1992). We reinterpreted well-log, lithological, and structural data contained in the correlation section to identify subsurface evidence for faulting at Orcutt Canyon. Additionally, two geotechnical reports encompassing trenching and/or shallow boreholes provide subsurface data along the western section of the range front and at Timber Canyon (Earth Consultants Earth Consultants International, 2015; Earth Systems Southern California, 2013).

3 Results

3.1 Scarps

Bare earth hillshade imagery, topographic slope maps, topographic profiles, and field investigations confirm the presence of a north-side-up tectonic scarp in Q4 and Q5 alluvial fans at the mouth of Orcutt Canyon (Figs. 3, 4a, & 4b). The scarp warps Q4 and Q5 alluvial fans for ~420 m parallel to the trend of the range front and the surface trace of a range-front fault (Figs. 3, 4a, & 4b). Additionally, soil profiles exposed in road cuts perpendicular to the scarp have Q4 soil profile
development both north and south of the scarp. We take the fact that the scarps follow the orientation of the potential range-front fault, along with the similarity of soil profiles north and south of the fault, to indicate a tectonic rather than erosional origin for the scarp. We suggest the Orcutt Canyon scarp is a hangingwall collapse scarp based on our interpreted steep dip (>50°) for the fault at the surface and the poorly consolidated nature of the alluvial fan deposits in which the scarp is preserved (Carver and McCalpin, 1996) (Fig. 4). This model implies that faulting is emergent at Orcutt Canyon.

The flexural slip faults at Orcutt and Timber Canyon create south-side-up scarps that are easily identifiable in both hillshade maps and in the field (Figs. 2, 3, & 4). The flexural slip faults clearly offset Q6 surfaces at Orcutt and Timber Canyons. However, only one flexural slip fault (the Thorpe fault) offsets Q5 terraces at Orcutt Canyon, and none of the flexural slip faults offset Q4 or younger deposits. Moreover, paleoseismic trenching of a Q5 terrace that crosses the Culbertson fault revealed no evidence of Holocene activity (Earth Consultants Earth Consultants International, 2015).

There is no clear surface deformation in the numerous alluvial fans along the eastern stretch of the range front between Timber Canyon and Sespe Creek (Fig. 2). A lack of surface deformation suggests either faulting is blind or inactive along the range front east of Timber Canyon.

3.2 ^10^Be terrace geochronology

Our new surface cosmogenic exposure-age determinations generally fall within the range of published soil age estimates, but with improved precision (DeVecchio et al., 2012a; Rockwell, 1983) (Table 2, Fig. 2). Our ages for both Q5 deposits of 19.3 ± 2.7 ka (all ages are Bayesian most probable value with 2σ uncertainties throughout) for the Q5 terrace at Orcutt Canyon (Fig. 5b) and
17.1 $^{+3.5/-2.5}$ ka for the folded Q5 fan in the Santa Clara River Valley (Fig. 5c) show good
agreement, and overlap with the existing age for Q5 deposits within the Ventura basin (15-30 ka)
(Rockwell, 1983). We revise the original designation of the uplifted fan surface at Timber Canyon
from Q7 (160–200 ka) to Q6 (38–92 ka) (Rockwell, 1983). Revision is based on reevaluation of
the soil profile in the field, the close match of the existing Q6b age of 54 ±10 ka (Rockwell, 1983)
to our new cosmogenic numerical age (58.4 $^{+12.7/-9.0}$ ka), and the similar value of tilt between a Q6
surface at Orcutt Canyon and the uplifted fan surface at Timber Canyon (Table 2). However, it is
possible the Q6 fan surface we dated at Timber Canyon may include remnants of Q7 soils in places,
as described in Rockwell (1983). We discount our age of 2.2 $^{+1.4/-1.2}$ ka for the Q4 alluvial fill
terrace at Orcutt Canyon (Fig. S2). Further investigation of the soil profile in the Q4 sample
location leads us to suggest that a gravel channel in the top 1.5 m of the soil profile is a local,
anomalously-young deposit and not representative of the age of the Q4 terrace we sampled as a
whole. Therefore, we use our age of the Q4 fan at Bear Canyon of 7.3 $^{+1.8/-1.7}$ ka (Fig. 2a) for our
slip rate calculations at Orcutt Canyon.

All samples used in the depth profiles show a good fit to an exponential profile, within individual
sample 2σ measurement uncertainties (Figs. 5 & S2). Best-fit inheritance values are low with a
maximum value of 11,500 atoms g$^{-1}$ in the Q4 sample at Orcutt Canyon (Fig. S2) and minimum
values that are indistinguishable from zero in both the Q5 sample locations (Fig. 5). Sediment
stored deep within the hill slopes, beneath the attenuation length of cosmic rays, will not
accumulate significant $^{10}$Be prior to erosion and subsequent deposition within the terrace.
Therefore, low inheritance values indicate that source material is rapidly eroded from material
stored deep within the landscape. A slightly higher inheritance value for the Q4 depth profile at
Orcutt Canyon (11,500 atoms g$^{-1}$ compared to 2,500-0 atoms g$^{-1}$ for all other samples) (Figs. 5 &
S2) is indicative of a potentially shallower source material or a slower erosion rate for source material within the gravel channel contained within the Q4 terrace.

3.3 Fault Geometry

Various datasets provide evidence for a north-dipping fault at Orcutt Canyon with 50–90° dip from the surface to ~100 m depth, below which the fault dip decreases to ~20° (Fig. 7). We employ a fault dip of 50–90° in our Monte Carlo simulations and do not use the proposed subsurface dip of 20° in slip rate calculations as our displacement rates are calculated from surface offsets. On the well-correlation section through Orcutt Canyon, we note an abrupt change in dips that occurs at progressively shallower depths southwards for wells in the footwall of the San Cayetano fault (Hopps et al., 1992) (Fig. 7). The change in dips correlates to a fault with a shallow (~20°) north dip in the subsurface, with ~100 m of stratigraphic offset (Fig. 7). However, when projected to the surface, a fault with 20° north-dip that passes through the sections of variable dips observed in subsurface well-log data would steepen in dip in the upper ~100 m if it intersects with our preferred fault surface trace (Fig. 7). Fault evidence from borehole logs contained in a geotechnical report along the western section of the range front suggests a north-side-up sense of movement on three steeply-dipping northwest-southeast zones of faulting, with the majority of faults recording dips between 70–90° (Earth Systems Southern California, 2013) (Table ST2). Additionally, we suggest the linear nature of the range front (Fig. 2) is indicative of a steep fault dip at the surface (assuming that the location of the range front is fault controlled) and analysis of the intersection of the fault trace with the scarps suggests a range of apparent dips at the surface between 51–64° (Fig. S2).

The fault we present in Figure 7 offsets the overturned Sisar fault and connects with the San Cayetano fault at ~3 km depth (Fig. 7). We show the Sisar fault as offset, as we observe no
evidence of Holocene activity on the Sisar fault in both digital geomorphic maps and in the field, which suggests that the Sisar fault is potentially inactive at Orcutt Canyon. Conversely, both the main strand of the San Cayetano fault and the range-front fault at Orcutt Canyon demonstrate evidence for Holocene activity in the form of fault scarps cutting Holocene alluvial fans (Rockwell, 1988, This study).

3.4 Fault deformation rates

Within the resolution of our data, our results indicate that long-term average fault activity (fault uplift, throw, or slip) at Orcutt Canyon has remained relatively constant for the last ~58 ka (Table 2, Fig. 6). Uplift amounts at Orcutt Canyon decrease with decreasing surface age, with 9.0 ± 1.4 m fault throw across the youngest Q4 scarp at the mouth of Orcutt Canyon and 99.7 ± 12.4 m average uplift of the oldest Q6 strath terrace relative to the modern-day stream level (Table 2). All uplift or fault throw rates at Orcutt Canyon overlap within uncertainties, with a maximum value of 1.7 +0.7/-0.4 mm yr⁻¹ for the interval ~19–7 ka (deformation rates are mode and 95% confidence interval throughout) and a minimum value of 1.2 +/- 0.3 mm yr⁻¹ since ~7 ka (Table 2).

Fault slip rates also reflect a relatively constant rate of activity. The average fault slip rate from ~19 ka to the present day is 1.7 +0.6/-0.2 mm yr⁻¹ and from ~7 ka to the present day the average slip rate is 1.3 +0.5/-0.3 mm yr⁻¹. The interval fault slip rate between ~19 ka and ~7 ka is 1.9 +1.0/-0.5 mm yr⁻¹.

Q6 surfaces at Orcutt and Timber Canyons are tilted southwards more than the younger Q5 and Q4 surfaces (Table 2). Tilt rates at Orcutt Canyon remained constant during the Late Pleistocene at 0.14° ka⁻¹ since ~58 ka and 0.12° ka⁻¹ since ~18 ka (Table 2). Tilt rates at Orcutt Canyon then increased during the Holocene to 0.33° ka⁻¹ since ~7 ka (Table 2). Additionally, we note that Q6
fan surfaces along the western range front, are tilted southwards by \( \sim 6^\circ \) relative to Q3 surfaces in the footwall.

The uplift rate for the Q6 alluvial fans at Timber Canyon and Santa Paula Creek are \( 0.4 \pm 0.2/0.1 \text{ mm yr}^{-1} \) and \( 0.9 \pm 0.3/0.2 \text{ mm yr}^{-1} \) since \( \sim 58 \text{ ka} \), respectively (Table 2). Both are lower than the Q6 uplift rate at Orcutt Canyon since \( \sim 58 \text{ ka} \), although the Q6 Timber Canyon fan is tilted slightly more than the Orcutt Canyon Q6 surface (Table 2). We consider the uplift rates for the Q6 alluvial fans at Timber Canyon and Santa Paula Creek to be minimum rates, as uplift is measured relative to younger Q3 deposits in the fault footwall (Fig. 6). All rates assume that multiple terrace treads are not sharing the same strath, therefore, overprinting the initial age signal with a younger age. We have not determined the burial depth for the top of the Q5 surface below the fold in the Santa Clara River Valley, therefore, our uplift rate is a minimum (Fig. 6).

4 Discussion and Implications

Our results provide the first geomorphic and subsurface well-log evidence for a young fault beneath Orcutt Canyon. Despite a large amount of previous geologic, geomorphic, and subsurface investigation, the fault described here was previously undetected beneath Orcutt and Timber Canyons (Dibblee Jr, 1990a; Hopps et al., 1992; Rockwell, 1988). As young faults have little stratigraphic offset and sometimes subtle geomorphic expression, they can often be overlooked in seismic hazard assessment (e.g. Field et al., 2015). This gives rise to the possibility that young, active faults, such as the SSCF, could have gone undetected in numerous other tectonically active, earthquake-prone regions globally. Consequently, seismic hazard assessments in many tectonically active regions could be missing key structures and associated hazards.

4.1 Fault activity
Given the subtle nature of geomorphic and subsurface expression associated with young faults, various datasets must be examined in detail to provide compelling fault evidence. Uplifted Late Pleistocene and Holocene alluvial surfaces, tectonic scarps, faults observed in shallow boreholes, and subsurface dip-data provide evidence for the existence of a young, continuous, north-dipping, low-angle fault along the northern Santa Clara River Valley (Figs. 6 & 7).

We suggest that our shallow, north-dipping, range-front fault at Orcutt Canyon could be the westward continuation of the Pagenkopp fault because the geometry we present in Figure 7 for the range front fault is almost identical to the Pagenkopp fault to the east (Çemen, 1989; Hopps et al., 1992). However, the lack of surface scarps east of Timber Canyon, combined with a lower uplift rate at Timber Canyon compared to Orcutt Canyon, suggests that the section of the range-front fault previously mapped as the Pagenkopp fault is either inactive or blind. We suggest that active deformation steps southwards east of Timber Canyon on a blind en-echelon fault splay beneath the Q5 fold in the Santa Clara River Valley (Fig. 6). Furthermore, we speculate that this blind fault splay continues eastwards in the subsurface, potentially as far as the eastern strand of the San Cayetano fault at Fillmore.

Evidence for faulting along the western range front, west of Santa Paula Creek, comprises steeply-dipping fault segments observed in trenching and borehole studies and southward tilting of Q6 fan surfaces (Fig. 6). We map very few uplifted and tilted alluvial terraces along the western section of the range front compared to the central and eastern sections (Fig. 6). The decrease in preservation along the western section is probably due to the lack of coarse clastic sediments being shed from Sulphur Mountain (Fig. 1).
We interpret our results to suggest that the low-angle SSCF has been active since at most ~58 ka. A maximum ~58 ka age explains the small stratigraphic offset for the SSCF and why the SSCF has previously been overlooked in subsurface data at Orcutt Canyon. Our results indicate a decrease in activity on bedding parallel flexural slip faults at Orcutt and Timber Canyons since ~58 ka. In Figure 7, the Orcutt, Rudolph, and Culbertson flexural-slip faults are offset by the SSCF. We speculate that the decrease in activity on the flexural-slip faults results from onset of activity on the SSCF, because the SSCF cut across the flexural-slip faults. The decrease in activity in the flexural-slip faults implies that the onset of activity on the SSCF occurred at some point after ~58 ka, the age of the Q6 fan at Timber Canyon, which is offset by the Culbertson fault (Fig. 3). A decrease in activity on the flexural slip faults is also demonstrated by a lack of evidence for active faulting recorded in paleoseismic trenching within Q5 soils that cross the Culbertson fault at Timber Canyon (Earth Consultants Earth Consultants International, 2015).

We have adopted the name “Southern San Cayetano Fault” for the shallow north-dipping fault along the northern Santa Clara River Valley described here, as this is the most recent name suggested for a continuous, active fault in this area (Hubbard et al., 2014). However, we stress our interpretation of the SSCF, with a ~20° north subsurface-dip along the range front, has a drastically different geometry from that used in previous modelling, which incorporated a continuous 40-65° north-dip down to ~7 km and outcrops farther south in the center of Santa Clara River Valley (Hubbard et al., 2014). Additionally, the presence of north-side-up scarps and confirmation of a north-dip in subsurface data leads us to discount a south-dipping model of the SSCF (Hubbard et al., 2014).

4.2 Seismic hazard implications
Confirmation of an active, young, low-angle thrust in the well-studied Santa Clara River Valley provides a good example of how significant seismic hazards, in the form of young faults, can be overlooked in geologic, geomorphic, and subsurface datasets. The seismic source of the 1994 Northridge earthquake could potentially have been identified prior to the earthquake if it had been recognized that uplift of the footwall of the Santa Susana fault was a result of activity on the Northridge blind thrust (Yeats and Huftile, 1995). The footwall of the central San Cayetano fault is uplifted to high elevations above the Santa Clara River Valley, and footwall uplift has previously been attributed to activity on south-dipping blind thrusts, such as the Sisar fault (Yeats and Huftile, 1995). Here, we suggest that footwall uplift of the central San Cayetano fault prior to ~58 ka could have occurred on south-dipping faults, but a component of any current footwall uplift must be due to fault activity in the hangingwall of the SSCF. This implies that any future earthquake could result from activity on the active SSCF, or some combination of the SSCF and the main strand of the San Cayetano fault.

4.3 Implications for multi-fault ruptures

In addition to posing significant individual seismic hazards, young faults can potentially act as rupture pathways during large-magnitude multi-fault ruptures (Fletcher et al., 2014; Hamling et al., 2017). For example, the Papatea fault is a structurally immature fault in central New Zealand, which was unrecognized prior to the 2017 Mw 7.8 Kaikōura earthquake, but played a key role in stress transfer during the event (Hamling et al., 2017; Hollingsworth et al., 2017). Our results provide confirmation of a young SSCF along the northern Santa Clara River Valley that fills in a 23 km gap that previously existed between the Ventura and San Cayetano faults at the surface (Fig. 1). The result is a continuous ~150 km surface trace including the Pitas Point, Ventura, Southern San Cayetano, and San Cayetano faults. Previous work has suggested that this fault system could
potentially act as a pathway for large-magnitude multi-fault earthquakes (Hubbard et al., 2014; Marshall et al., 2017; Rockwell et al., 2016).

The only existing slip rate estimates for the SSCF are mechanical model-calculated slip rates based on a regional GPS derived strain rate tensor (Marshall et al., 2017). Our slip rates for the SSCF show good agreement with slip rates predicted by the Marshall et al. (2017) ‘ramp’ model and are significantly lower than slip rate estimates for the ‘no ramp’ model (Fig. 8). The ramp model of Marshall et al. (2017) (Fig. 8a) implies that the Pitas Point, Ventura, Southern San Cayetano, and San Cayetano fault system forms a single through-going plane at depth that may provide a potential multi-fault rupture pathway for past and future large earthquakes (Hubbard et al., 2014; Marshall et al., 2017). However, the interpretation of the SSCF used in three-dimensional mechanical models was not confirmed by geological field data and the results presented here suggest a change in dip of ~20–40° from the Ventura fault along-strike to the SSCF (Fig. 8a). A 20–40° change in dip does not represent a single through-going buried surface and could act as a potential stress barrier and decrease the likelihood of persistent through-going ruptures between the Ventura fault and the SSCF. Consequently, if through-going ruptures do propagate between the Ventura fault and the SSCF, then we speculate a tear fault is present, which transfers strain during through-going ruptures similar to the style of interaction previously identified between faults elsewhere in the Ventura Basin (DeVecchio et al., 2012b; Thibert et al., 2005).

Assessing the possibility of through-going ruptures between the Ventura and San Cayetano faults is further complicated by a comparison of fault slip rates along-strike. Fault slip rates are 4.6–6.9 mm yr⁻¹ since 30 +/- 10 ka for the Ventura fault (Hubbard et al., 2014) in the western Ventura Basin, 7.4 +/- 3 mm yr⁻¹ for the last 500 ka for the eastern San Cayetano fault (Huftile and Yeats, 1996) in the eastern Ventura Basin, and 1.05 +/- 0.4 mm yr⁻¹ up to 4.15 +/- 0.85 mm yr⁻¹ for the
last ~25 ka on the western San Cayetano fault (Rockwell, 1988) in the central Ventura Basin.

These values are in contrast to a lower slip rate for the SSCF of $1.7^{+0.6}_{-0.2}$ mm yr$^{-1}$ since ~19 ka (This study) in the central part of the basin. Higher slip rates for the Ventura and eastern San Cayetano faults suggest that these faults individually accommodate a greater proportion of the 7-10 mm yr$^{-1}$ of regional horizontal shortening suggested by GPS data (e.g. Marshall et al., 2013) than the SSCF or the western San Cayetano fault. However, the sum of slip rates for the SSCF and the western San Cayetano fault in the central Ventura Basin roughly equates to the individual Ventura and eastern San Cayetano faults, albeit within large associated uncertainties. Consequently, we suggest that strain in the upper ~3 km of the central Ventura Basin is partitioned between the SSCF and the western San Cayetano fault.

Alternatively, a lower slip rate for the SSCF could indicate that the SSCF is a rupture pathway that is predominantly, but not exclusively, active during through-going rupture between the San Cayetano and Ventura faults. Observations of up to 11 m coseismic uplift events on the Pitas Point/Ventura fault (McAuliffe et al., 2015; Rockwell et al., 2016) and ~5 m coseismic slip events on the eastern San Cayetano (Dolan and Rockwell, 2001) indicate that large-magnitude ($M_w$ 7–8) earthquakes can potentially occur between the Pitas Point, Ventura, and San Cayetano faults. However, these events do not necessarily always involve simultaneous rupture of all faults along-strike (McAuliffe et al., 2015). We propose that the lower slip rate for the SSCF reflects a low frequency of large-magnitude through-going ruptures between the Ventura and San Cayetano faults. The Ventura and San Cayetano faults may preferentially rupture independently or in combination with other proximal faults such as the Pitas Point, Red Mountain, or Arroyo-Parida/Santa Ana faults (Fig. 1).
5 Conclusions

We incorporated lidar topographic data and a new \(^{10}\)Be geochronology to provide geomorphic evidence for the existence of a low-angle (20°) Southern San Cayetano fault (SSCF). The SSCF is a young fault that has only been active since at most \(\sim 58\) ka. Consequently, the SSCF has little stratigraphic offset in the subsurface and has been previously overlooked in geologic or geomorphic mapping and subsurface well-log data at Orcutt Canyon. Displacement rates averaged over multiple timescales for the SSCF have remained fairly constant since the Late Pleistocene with slip rates ranging from a maximum of \(1.9^{+1.0/0.5}\) mm yr\(^{-1}\) since \(\sim 19–7\) ka to \(1.3^{+0.5/0.3}\) mm yr\(^{-1}\) since \(\sim 7\) ka.

Confirmation of an active, young, low-angle SSCF along the length of the northern Santa Clara River Valley provides new insights into the nature of seismic hazards in a densely populated area of southern California. The SSCF may rupture synchronously with the well-established main strand of the San Cayetano fault and, furthermore, it is possible that the SSCF enhances fault connectivity and facilitates multi-fault ruptures including the San Cayetano, Ventura, and Pitas Point faults. However, given structural complexities, different slip histories, and different slip rates between the Ventura, San Cayetano, and Southern San Cayetano faults, these faults may be less prone to synchronous rupture than previously suggested.

Our results demonstrate that young, active, faults, such as the SSCF, can easily be overlooked in geomorphic and subsurface data, but may represent significant individual seismic hazards or potentially enhance structural connectivity in large-magnitude earthquakes in complex thrust fault systems. Furthermore, as they are fundamentally difficult to detect, young faults like the SSCF could remain undetected in many other tectonically active areas around the globe and be overlooked in seismic hazard assessments.
Acknowledgments

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Table 1 Key sample details and \(^{10}\)Be concentrations

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Latitude (DD)</th>
<th>Longitude (DD)</th>
<th>Elevation (m)</th>
<th>Depth (cm)</th>
<th>Shielding Correction (^{a})</th>
<th>(^{10})Be (atoms g(^{-1})) (^{b, c})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q4 Fan at Bear Canyon</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>KR-1</td>
<td>34.4397</td>
<td>-119.1282</td>
<td>459</td>
<td>39</td>
<td>0.998</td>
<td>26925 +/- 1100</td>
</tr>
<tr>
<td>KR-2</td>
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<td>23559 +/- 1205</td>
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<tr>
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<td>116</td>
<td>0.998</td>
<td>14560 +/- 681</td>
</tr>
<tr>
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<td>153</td>
<td>0.998</td>
<td>10496 +/- 681</td>
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<tr>
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<td>459</td>
<td>182</td>
<td>0.998</td>
<td>8028 +/- 743</td>
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<td><strong>Q5 Fan at Orcutt Canyon</strong></td>
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<td></td>
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<tr>
<td>OCN-1</td>
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<td>42</td>
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<td>72312 +/- 2177</td>
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<td>28230 +/- 1054</td>
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<td>10135 +/- 685</td>
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<td><strong>Q7 Fan at Timber Canyon</strong></td>
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<td>TC-1</td>
<td>34.4011</td>
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<td>39</td>
<td>0.995</td>
<td>204712 +/- 6316</td>
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<td>196</td>
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<td>48588 +/- 1629</td>
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<td><strong>Q5 Fold in Santa Clara River Valley</strong></td>
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</tr>
<tr>
<td>FW-1</td>
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<td>41</td>
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<td>48179 +/- 1720</td>
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<td>FW-3</td>
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<td>139</td>
<td>116</td>
<td>0.999</td>
<td>24940 +/- 978</td>
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<tr>
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<td>139</td>
<td>150</td>
<td>0.999</td>
<td>15717 +/- 927</td>
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<td>-118.9784</td>
<td>139</td>
<td>196</td>
<td>0.999</td>
<td>10662 +/- 614</td>
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<td><strong>Q4 Terrace at Orcutt Canyon</strong></td>
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<tr>
<td>OC4 1</td>
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<td>-119.036</td>
<td>225</td>
<td>45</td>
<td>0.984</td>
<td>17849 +/- 790</td>
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<td>225</td>
<td>82</td>
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<td>16895 +/- 811</td>
</tr>
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<td>OC4 3</td>
<td>34.3859</td>
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<td>114</td>
<td>0.984</td>
<td>14733 +/- 720</td>
</tr>
<tr>
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<td>-119.036</td>
<td>225</td>
<td>160</td>
<td>0.984</td>
<td>13918 +/- 719</td>
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<td>225</td>
<td>202</td>
<td>0.984</td>
<td>12866 +/- 670</td>
</tr>
</tbody>
</table>

\(^{a}\)Calculated using the CRONUS-Earth Geometric Shielding Calculator version 1.1 (available online at: http://hess.ess.washington.edu/)

\(^{b}\)\(^{10}\)Be concentrations and associated measurement uncertainties are blank corrected relative to batch specific process blanks. Total atoms \(^{10}\)Be in process blanks (atoms): KR & OC4 = 8857 +/- 2288, OCN = 11187 +/- 2388, TC & FW = 7876 +/- 2786.

\(^{c}\)Calculated using 07KNSTD \(^{10}\)Be measurement and calibration standard number 01-5-2 with a assumed \(^{10}\)Be/\(^{9}\)Be ratio of 8.558 x 10\(^{-12}\) (Nishiizumi et al., 2007).
Table 2 Cosmogenic exposure ages, offset amounts, displacement rates, and tilting for the SSCF

<table>
<thead>
<tr>
<th>Surface</th>
<th>Age or Time interval (ka)</th>
<th>Throw (m)</th>
<th>Throw Rate (mm yr(^{-1}))</th>
<th>Slip (m)</th>
<th>Slip Rate (mm yr(^{-1}))</th>
<th>Tilt (°)</th>
<th>Tilt Rate (*/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q4 OC</td>
<td>7.3 +/- 1.8/1.7</td>
<td>9.0 +/- 1.4</td>
<td>1.2 +/- 0.3</td>
<td>9.7 +/-</td>
<td>2.6/1.7</td>
<td>1.3 +/-</td>
<td>0.5/0.3</td>
</tr>
<tr>
<td>Q5-Q4 OC</td>
<td>11.8** +/- 2.4/3.0</td>
<td>20.5 +/- 3.3/3.4</td>
<td>1.7 +/- 0.7/0.4</td>
<td>21.8 +/-</td>
<td>9.0/4.2</td>
<td>1.9 +/-</td>
<td>1.0/0.5</td>
</tr>
<tr>
<td>Q5 OC</td>
<td>19.3 +/- 2.7</td>
<td>29.5 +/- 3.0</td>
<td>1.5 +/- 0.3/0.2</td>
<td>31.7 +/-</td>
<td>8.8/3.6</td>
<td>1.7 +/-</td>
<td>0.6/0.2</td>
</tr>
<tr>
<td>Q6-Q5 OC</td>
<td>40.6** +/- 11.2/8.4</td>
<td>70.2 +/- 24.6</td>
<td>1.7 +/- 0.9/0.6</td>
<td>n/a +/-</td>
<td>n/a</td>
<td>n/a +/-</td>
<td>n/a</td>
</tr>
<tr>
<td>Q6 OC</td>
<td>58.4 +/- 12.7/9.0</td>
<td>99.7** +/- 12.4</td>
<td>1.6 +/- 0.6/0.4</td>
<td>n/a +/-</td>
<td>n/a</td>
<td>n/a +/-</td>
<td>n/a</td>
</tr>
<tr>
<td>Q5 SCRV</td>
<td>17.1 +/- 3.5/2.5</td>
<td>33.4* +/- 3</td>
<td>1.9* +/- 0.6/0.4</td>
<td>n/a +/-</td>
<td>n/a</td>
<td>n/a +/-</td>
<td>n/a</td>
</tr>
<tr>
<td>Q6 TC</td>
<td>58.4 +/- 12.7/9.0</td>
<td>24.9** +/- 6.5</td>
<td>0.4 +/- 0.1</td>
<td>n/a +/-</td>
<td>n/a</td>
<td>n/a +/-</td>
<td>n/a</td>
</tr>
<tr>
<td>Q6 SPC</td>
<td>58.4 +/- 12.7/9.0</td>
<td>51.4** +/- 14.3/8.4</td>
<td>0.9* +/- 0.3/0.2</td>
<td>n/a +/-</td>
<td>n/a</td>
<td>n/a +/-</td>
<td>n/a</td>
</tr>
</tbody>
</table>

* Uplift of the top of a folded Q5 surface relative to the corresponding unfolded Q2 surface in the fault footwall.
** Average of incision/uplift of the Q6 surface relative to the modern stream level in Orcutt Canyon or Q3 surfaces in the modern day Santa Clara River valley floor.
+ Uplift rate

All rates are calculated from the terrace age using the present day as a pin except time interval rates (indicated by++) which are calculated for the time interval between corresponding terrace ages.

OC = Orcutt Canyon, TC = Timber Canyon, SPC = Santa Paula Creek, SCRV = Fold in Santa Clara River Valley
Figure 1 Major onshore structures of the Western Transverse Ranges in the vicinity of the Southern San Cayetano fault (SSCF). The key faults discussed in this paper are highlighted with solid red lines with other major faults denoted using solid black lines. Major regional folds are indicated by dashed black lines. The location of the earthquake focal mechanism for the 1994 M 6.7 Northridge earthquake is indicated by the beach ball. Dashed blue lines are the paths of major rivers. The blue box shows location of Figures 2 & 6. SCM = San Cayetano Mountain, SM = Sulphur Mountain, BCF = Big Canyon fault, LF = Lion fault, SSMF = South Sulphur Mountain fault.

Figure 2 Hillshade map of river terraces and alluvial fans in the proximity of the Southern San Cayetano fault (SSCF). Faults are indicated with solid red lines. Triangles and semi-circles denote fault hangingwall where triangles are reverse faults and semi-circles are flexural-slip faults. Dashed lines are blind faults. Cosmogenic depth profile locations are indicated with yellow dots. The location of Figure 3 is indicated in the black box. Line of topographic profile E-E’ in Figure 4e is shown and the line of section G-G’ in Figure 7 is indicated. Terrace ages are existing ages for geomorphic surfaces taken from Rockwell [1988]. (A) Map of late Quaternary alluvial fans and location of Q4 depth profile at Bear Canyon. (B) Enlarged hillshade map of the fold in the Santa Clara River Valley. Bedding readings are from Dibblee [1992]. Line of section F-F’ from Figure 4f is indicated with a black line. SCF = San Cayetano fault, TF = Thorpe fault, OF = Orcutt fault, CF = Culbertson fault, RF = Rudolph fault.

Figure 3 Summary of active deformation at Orcutt Canyon. (A) Hillshade image with extent of mapped terraces and alluvial fans and the local surface trace of the Southern San Cayetano fault (SSCF) indicated with solid red line. Lines A-A’ and B-B’ show trace of topographic profiles through Q4 and Q5 surfaces at the mouth of Orcutt Canyon respectively. Topographic profiles are included in Figure 4. The trace of the modern-day stream used to calculate uplift of Q6 surfaces in Figure 4c is indicated by the dashed black line. (B) Hillshade map with 330° sun angle and 45° azimuth detailing scarp at the mouth of Orcutt Canyon. (C) Hillslope map with Orcutt Canyon scarp highlighted as pale green high angle slope against dark green low-angle slope detailing scarp at the mouth of Orcutt Canyon.

Figure 4 Topographic profiles used to calculate displacement across the Southern San Cayetano fault (SSCF). Equations are linear regressions through geomorphic surfaces used in Monte Carlo simulations. A and B include topographic profiles A-A’ and B-B’ across the Q4 and Q5 surfaces at the mouth of Orcutt Canyon (lines of section in Figure 3) and frequency histograms of all slip rates output during Monte Carlo simulations. C includes section C-C’ with a linear regression through the average elevation of the Q6 surface relative to the modern stream channel used to calculate average uplift and incision. The gray band either side of the regression denotes the vertical uncertainty. Bedding parallel flexural slip faults are indicated with pale gray lines. D and E are topographic profiles D-D’ and E-E’ through Q6 surfaces at Timber Canyon (D) and Santa Paula Creek (E) used to calculate minimum uplift for the Q6 surfaces relative to Q5 surfaces in the fault footwall. F is profile F-F’, a topographic profile across the fold in the Santa Clara River Valley showing parameters used to calculate minimum uplift of the Q5 surface on the fold crest relative to the Q2 surface north and south of the fold. Lines of section for D-D’ and C-C’ are shown in Figure 3. Lines of section for E-E’ and F-F’ are shown in Figure 2. VE = Vertical exaggeration, OC = Orcutt Canyon, TC = Timber Canyon, SPC = Santa Paula Creek.
**Figure 5** Cosmogenic $^{10}$Be depth profiles (see Figure 2 for sample locations). Gray circles are individual samples with error bars representing 2σ measurement uncertainties. Gray shaded area either side of the best fit profile represents the range of possible best fit solutions returned from Monte Carlo simulations. Depth profiles are calculated using a density of 1.7 - 1.8 g cm$^{-3}$ and an attenuation length of 160 g cm$^{-2}$. (a) Q4 alluvial fan at Bear Canyon. (b) Q5 alluvial terrace at Orcutt Canyon. (c) Q5 fold in the Santa Clara River Valley. (d) Q6 alluvial fan at Timber Canyon.

**Figure 6** Summary of spatial and temporal variations in slip rates and uplift rates for the Southern San Cayetano fault. Location of rate is indicated by colored circles (purple = Orcutt Canyon, yellow = Timber Canyon, green = Santa Paula Creek, and blue = Santa Clara River Valley). Vertical deformation (fault throw or uplift) is denoted using black text on a white background and fault slip rates are white text on gray background. Inset graph shows vertical deformation against surface age. Colored circles are uplift amounts with colors corresponding to the location of the rate on the map. Error bars are uncertainty in amount of vertical deformation (vertical error bars) or age (horizontal error bars) derived from Monte Carlo simulations. Deformation rates of 2.0, 1.5, 1.0, & 0.5 mm yr$^{-1}$ are indicated with gray dashed lines. The red dashed line is the long-term uplift rate and interval rates are denoted by the blue dashed lines.

**Figure 7** Cross section G-G’ showing our interpretation for the subsurface geometry for the Southern San Cayetano fault at Orcutt Canyon (after Hopps et al, 1992). Line of section is indicated in Figure 2. Surface dips and geology are from Dibblee (1990a). Well data is taken from Hopps et al (1992). Inset shows schematic for the range of steepening fault dips we interpret in the shallow subsurface compared to the ~20° dip we interpret in the deeper subsurface. The custom trapezoidal probability density function used to model uncertainty in the near surface fault dip during Monte Carlo simulations is based on a range of fault dips observed in shallow subsurface boreholes (Earth Systems Southern California, 2013), a range of potential apparent fault dips from analysis of the fault position within the scarps (Fig S1), and the dip of the SSCF utilized in previous subsurface modelling (Hubbard et al., 2014; Marshall et al., 2017).

**Figure 8** Comparison of along-strike reverse fault slip rates for the Ventura, Pitas Point, and Southern San Cayetano faults assuming either a ‘ramp’ or ‘no ramp’ subsurface geometry (adapted from Marshall et al [2017]). Dashed black lines trace best-fit model predicted along-strike reverse slip rate distributions measured from GPS data. Gray ranges reflect regional strain rate boundary condition uncertainties. Dark gray represents ‘ramp’ model and light gray represents ‘no ramp’ model. Blue circles are geologically calculated reverse slip rates at Orcutt Canyon with blue lines for error bars. (A) Schematic cross sections showing structure of the ‘ramp’ model through Orcutt Canyon comparing fault geometries used in mechanical models (Marshall et al [2017], after Hubbard et al [2014]) against the model we present here for the SSCF. (B) Schematic cross sections showing structure of the ‘no ramp’ model through Orcutt Canyon comparing fault geometries used in mechanical models (Marshall et al [2017], after Hubbard et al [2014]) against the model we present here for the SSCF. ORF = Oak Ridge fault, SCF = San Cayetano fault, SF = Sisar fault, SSCF = Southern San Cayetano fault.