Late Pleistocene rates of rock uplift and faulting at the boundary between the southern Coast Ranges and the western Transverse Ranges in California from reconstruction and luminescence dating of the Orcutt Formation

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ABSTRACT

The western Transverse Ranges and southern Coast Ranges of California are lithologically similar but have very different styles and rates of Quaternary deformation. The western Transverse Ranges are deformed by west-trending folds and reverse faults with fast rates of Quaternary fault slip (1–11 mm/yr) and uplift (1–7 mm/yr). The southern Coast Ranges, however, are primarily deformed by northwest-trending folds and right-lateral strike-slip faults with much slower slip rates (3 mm/yr or less) and uplift rates (<1 mm/yr). Faults and folds at the boundary between these two structural domains exhibit geometric and kinematic characteristics of both domains, but little is known about the rate of Quaternary deformation along the boundary.

We used a late Pleistocene sedimentary deposit, the Orcutt Formation, as a marker to characterize deformation within the boundary zone over the past 120 k.y. The Orcutt Formation is a fluvial deposit in the Santa Maria Basin that formed during regional planation by a broad fluvial system that graded into a shoreline platform at the coast. We used post-infrared–infrared-stimulated luminescence (pIR-IRSL) dating to determine that the Orcutt Formation was deposited between 119 ± 8 and 85 ± 6 ka, coincident with oxygen isotope stages 5e-a paleo–sea-level highstands and regional depositional events. The deformed Orcutt basal surface closely follows the present-day topography of the Santa Maria Basin and is folded by northwest-trending anticlines that are a combination of fault-propagation and fault-bend-folding controlled by deeper thrust faults. Reconstructions of the Orcutt basal surface and forward modeling of balanced cross sections across the study area allowed us to measure rock uplift rates and fault slip rates. Rock uplift rates at the crests of two major anticlinoria are 0.9–4.9 mm/yr, and the dip-slip rate along the blind fault system that underlies these folds is 5.6–6.7 mm/yr. These rates are similar to those reported from the Ventura area to the southeast and indicate that the relatively high rates of deformation in the western Transverse Ranges are also present along the northern boundary zone. The deformation style and rates are consistent with models that attribute shortening across the Santa Maria Basin to accommodation of clockwise rotation of the western Transverse Ranges and suggest that rotation has continued into late Quaternary time.

INTRODUCTION

The Coast Ranges of California are deformed by northwest-striking faults and folds that accommodate active transpression along the North American–Pacific plate boundary. This northwest structural grain is truncated to the south by west-striking faults and folds that accommodate north-south shortening in the western Transverse Ranges (Fig. 1). The boundary between these distinct tectonic domains is a diffuse zone ~15–20 km across that facilitates differential movement between the two domains. The boundary zone has experienced historic seismicity and large-magnitude earthquake events, but very little is known about the amount of Quaternary displacement on the major faults, slip rates, or uplift rates. This information is critical for understanding the regional tectonics and topographic development, as well as earthquake risk for the local population and critical facilities in the region, such as the Diablo Canyon nuclear power plant and Vandenberg Air Force Base.

Quantitative description of landforms and young deposits is needed to interpret the history of Quaternary landscape evolution and faulting (e.g., Bull, 1985; Kamp and Owen, 2012). Measurements of topographic development and fault slip are often dependent on localized deposits, such as fluvial terraces or alluvial fans, which can be used to bracket the timing and magnitude of offset and uplift along individual faults. However, if regionally extensive Quaternary deposits are present, deformation over a larger area can be analyzed with a single marker, which provides a more complete picture of tectonic history with less uncertainty in correlation between local deposits (e.g., DeVecchio et al., 2012). We illustrate this approach by using the Orcutt Formation, a regionally extensive late Quaternary sedimentary deposit, as a marker for investigating recent topographic growth and the structures controlling this growth at the boundary between the southern Coast Ranges and western Transverse Ranges in California.
Figure 1. Location map of the western Transverse Ranges and southern Coast Ranges showing topography, main geographic features, and faults (red lines). Fault abbreviations include: CHFZ—Casmalia Hills fault zone, LAF—Los Alamos fault, BF—Baseline fault, LHF—Lions Head fault, RMF—Red Mountain fault, SCF—San Cayetano fault, PP-VF—Pitas Point–Ventura fault. Coloring of topography shows relative elevation across the region with light green shades in lower elevation and orange shades in the higher elevations. Other abbreviations: AFB—Air Force Base, F.—fault, Pt.—Point, F.Z.—fault zone. Inset map shows location within California with the cities of Los Angeles (LA) and San Francisco (SF) for reference.
The western half of the boundary zone is a region of low hills and coastal plains called the Santa Maria Basin, which is bounded by the Santa Ynez Mountains on the south and the Santa Maria River Valley on the north (Figs. 1 and 2). The Santa Maria Basin formed during Miocene extension and has since been inverted by thrust faults and folds during Pliocene to present shortening. Retrodeformable cross sections and stratigraphic correlations of Miocene and Pliocene horizons across the basin have been used to estimate fault geometries and total convergence (Krammes and Curran, 1969; Namson and Davis, 1990; Clark, 1990; Seeber and Sorlien, 2000). However, these studies did not address the Quaternary deformation. We addressed this lack of knowledge using the Orcutt Formation to document late Pleistocene deformation and tectonic history. The Orcutt Formation is a predominantly fluvial, regionally extensive unit that was deposited on a low-relief surface that existed between the Santa Ynez and San Rafael Mountains (Fig. 2; Woodring and Bramlette, 1950; Worts, 1951; Muir, 1964; Dibblee and Ehrenspeck, 1989; Clark, 1990). The Orcutt Formation has been folded, lifted, and faulted across structures in the Casmalia and Purisima Hills, providing a rare and unique opportunity to assess multiple faults and folds with a single deposit, quantify and characterize deformation, and document the timing and rate of topographic evolution. In this study, we present nine infrared-stimulated luminescence (IRSL) dates as the first numerical ages for the Orcutt Formation. We used these dates, along with reconstructions of the Orcutt basal surface and forward modeling of balanced cross sections, to make measurements of late Pleistocene rock uplift rates across two anticlinoria and model slip rates on the underlying faults.

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**GEOLICIC SETTING**

**Regional Tectonic Context**

The Santa Maria Basin is located within the transform plate boundary zone between the Pacific plate and the North American plate. During a change from a convergent margin to the San Andreas transform system in Neogene time, broad dextral transtension across the plate boundary resulted in clockwise rotation of large crustal blocks and the formation of fault-bounded basins, including the Santa María Basin, Los Angeles Basin, Santa Barbara Basin, Ventura Basin, San Joaquin Basin, and other subbasins (Atwater and Stock, 1998; Hornafius, 1985; Luyendyk, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994). The western Transverse Ranges began to rotate clockwise at 18 Ma, and transtensional basins developed at the boundaries of the rotating domain to accommodate differential movement between the rotating crust and the nonrotating crust to the north and south (Luyendyk, 1991; Crouch and Suppe, 1993). The Santa Maria Basin developed along the northern boundary of the rotating western Transverse Ranges. Miocene transtension was replaced by transpression along the plate boundary due to changes in Pacific plate motion during Pliocene time. This change resulted in a component of shortening across the plate boundary that lifted the California Coast Ranges (Page and Engebretson, 1984; Zoback et al., 1987; Hauksson, 1990), initiated high rates of shortening across the western Transverse Ranges, and caused inversion and uplift of the rocks in the Santa Maria Basin. Shortening and uplift in the Santa Maria Basin are accommodated by a system of folds, Miocene normal faults reactivated with reverse slip, and low-angle thrust faults (Namson and Davis, 1990; Gutiérrez-Alonso and Gross, 1997). Shortening in the Santa Maria Basin may have accommodated differential rotation between the western Transverse Ranges and southern Coast Ranges (e.g., Lettis et al., 2004) as well as the southward decrease in slip on the Hosgri fault and its termination offshore of Point Arguello (e.g., Sorlien et al., 1999; Dickinson et al., 2005). Shortening has continued into Quaternary time, but the amount and rate of Quaternary deformation have not been well studied. Long-term slip rates on the southern Hosgri fault offshore are around 2 mm/yr (Sorlien et al., 1999), but there are no published Quaternary slip rates on faults within or at the boundaries of the Santa Maria Basin. The only Quaternary uplift rates come from unpublished master's theses that estimated rates of ~1 mm/yr in the central and eastern Santa Maria Basin using fluvial terraces (Farris, 2017; Tyler, 2013), and 0.012 mm/yr to 0.34 mm/yr from elevated marine terraces at Point Sal (Clark, 1993).

**Geology of the Santa Maria Basin**

**Stratigraphy**

The stratigraphy of the Santa Maria Basin consists of Miocene and younger sedimentary rocks that overlie metamorphic basement (Woodring and Bramlette, 1950; Clark, 1990). The basement rocks belong to the Mesozoic Franciscan Formation, which is an accretionary wedge complex developed during subduction along the western edge of North America prior to development of the modern transform plate boundary. These rocks are only exposed in a few locations at the margins of the Santa Maria Basin where they have been lifted to the surface by reverse faults that now bound the inverted basin (Woodring and Bramlette, 1950). The entire Late Cretaceous to Eocene forearc sedimentary sequence that overlies the Franciscan basement rocks in the southern Coast Ranges and western Transverse Ranges is missing in the Santa Maria Basin. Instead, Miocene sedimentary rocks are deposited nonconformably on the Franciscan Formation and record the development of a deep Miocene basin (Woodring and Bramlette, 1950). At the base of the Miocene section, there is the nonmarine Lospe Formation, which is overlain by the shallow-marine Point Sal Formation, and then the deeper-marine Monterey and Sisquoc Formations. The basin reached its maximum depth during deposition of the Monterey Formation, which consists of biogenic shale and chert and is the primary source of petroleum in the region (Woodring and Bramlette, 1950). The Sisquoc Formation transitions from deep-water shale to shallow-water sandstones and records the beginning of shallowing of the basin. Pliocene sedimentary units include the Foxen Mudstone overlain by the Carreaga Sand, both of which
onlap older units in some places or are missing altogether, indicating local uplift along folds that started to grow up through the shallow sea in early Pliocene time (Behl and Ingle, 1998; Woodring and Bramlette, 1950). Deposition in the Santa Maria Basin was entirely subaerial by Pleistocene time, as recorded by the terrestrial Paso Robles Formation. The Paso Robles Formation consists primarily of coarse conglomerates with clasts derived from the San Rafael and Santa Ynez Mountains (Dibblee and Ehrenspeck, 1989). This unit is present across the entire basin, as well as throughout the southern Coast Ranges, and has been interpreted to record the onset of uplift of the modern Coast Ranges of California (Page et al., 1998). In the Santa Maria Basin, the Paso Robles Formation is deposited conformably on the underlying Carreaga Sand, indicating that little deformation was occurring within the basin during the initial stages of deposition, despite the uplift of the surrounding ranges that were the source of the Paso Robles clasts. Intense deformation both within and at the margins of the Santa Maria Basin followed deposition of the Paso Robles Formation, and the unit is folded along west- and northwest-striking axes and offset by the major faults that bound the edges of the basin (Dibblee and Ehrenspeck, 1989).

Figure 2. Map of the Santa Maria Basin showing faults, anticline axes, the extent of the mapped Orcutt Formation at the surface, the Orcutt basal surface control points, cross sections, post-infrared–infrared-stimulated luminescence (pIR-IRSL) sample sites, and rock uplift rates mapped on a 5-m-resolution digital elevation model.
The Orcutt Formation is a late Quaternary unit that overlies the Paso Robles Formation in the Santa Maria Basin, and it was the focus of this study, so we describe it in greater detail than the older units. The Orcutt Formation has been mapped over an extensive area in the western portion of the Santa Maria Basin between the San Rafael and Santa Ynez Mountains (Fig. 2; Woodring and Bramlette, 1950; Dibblee and Ehrenspeck, 1989). The Orcutt Formation was first described by Woodring and Bramlette (1950), who interpreted the formation as an extensive fluvial terrace deposit that originally extended from the foot of the San Rafael and Santa Ynez Mountains to the ocean. They noted that the erosional surface upon which the Orcutt Formation was deposited merges with a shoreline platform at the coast. The formation consists primarily of poorly sorted sand with pebbles and stringers of gravel, and it has a maximum thickness of ~30 m (Woodring and Bramlette, 1950). A detailed stratigraphic description of the unit is beyond the scope of this study, but in the outcrops we observed, there was typically interbedded gravel and sand in the lower 5 m of the unit, with an increasing amount of sand and silt upward (see Fig. 3; stratigraphic columns in the Appendix). Within a few kilometers of the coast, the deposit consists of well-sorted medium to coarse sand with a basal layer of shell hash and cobbles derived from the underlying Monterey or Sisquoc Formations. These cobbles, and the surface of the Miocene formations at the contact, contain pholad borings that indicate a nearshore environment and confirm the interpretations by Woodring and Bramlette (1950) that the basal erosional surface of the Orcutt Formation merges with a shoreline platform at the coast.

The Orcutt basal contact is an angular unconformity in most places, and the Orcutt Formation overlies folded Miocene through Pleistocene rocks. This shows that most of the deformation of the Pleistocene Paso Robles Formation, and older units, occurred prior to Orcutt deposition. The basal contact of the Orcutt Formation is also deformed and has been tilted (as much as 20°) along the flanks of the topographic highs and lifted to the top of the Casmalia and Purisima Hills. The Orcutt Formation was initially deposited on a very low-relief surface (Woodring and Bramlette, 1950; McGregor, 2019) that eroded previous topography associated with deformation of the Paso Robles Formation. The fact that the Orcutt basal contact was initially a peneplain sloping to sea level that was later deformed across the modern topography makes it an excellent marker for late Quaternary deformation and topographic development.

Structures

The triangular-shaped Santa Maria Basin is structurally bound to the northeast by the northwest-striking Little Pine–Foxen Canyon fault zone, to the south by the east-striking Santa Ynez River fault zone, and to the west by the offshore north-striking Hosgri fault zone (Fig. 1). Within the Santa Maria Basin, west- and northwest-trending folds and faults show evidence of late Quaternary activity, demonstrated by the tilted basal contact of the Orcutt Formation and faulted fluvial terraces (Woodring and Bramlette, 1950; Clark, 1990; Guptill et al., 1981; Tyler, 2013). The major structures within the basin are described and geographically categorized here into two uplifted fold trends that result in topographic highs in the west-central Santa Maria Basin—the Casmalia Hills and...
the Purisima Hills (Fig. 2). Both these topographic features are anticlinoria that
deform Miocene through Pleistocene sedimentary rocks. The Casmalia Hills
fault zone is located along the north slope of the Casmalia Hills and includes
the Pezzoni, Casmalia, and Orcutt frontal faults (Fig. 2). These are south-dipping
reverse faults with similar orientations and estimates of offset and have been
described as a continuous fault zone (Sylvester and Darrow, 1979; Gray, 1980;
Clark, 1990; Namson and Davis, 1990). Previously published geologic cross
sections across the Casmalia Hills interpreted a north-vergent, asymmetric fold
overturning Miocene to late Pliocene units above the Casmalia Hills fault zone,
suggestive of fault-propagation folding (Clark, 1990; Namson and Davis, 1990).
The Casmalia Hills fault zone merges to the east with the Baseline–Los Alamos
fault, which is a south-dipping reverse fault that offsets Quaternary deposits
(Sylvester and Darrow, 1979; Guptill et al., 1981; Tyler, 2013).
A single anticline is present in the western Purisima Hills that splits into
different parallel anticlines and synclines in the eastern Purisima Hills (Fig. 2).
The Lions Head fault is interpreted to underlie the western Purisima Hills, but
it is only exposed near the coast on the south side of Point Sal, where it has
been described as a steeply northeast-dipping oblique-slip fault (Gray, 1980;
Clark, 1990; Gutiérrez-Alonso and Gross, 1997). Sylvester and Darrow (1979)
appear to be a blind Lions Head–Purisima Hills fault to merge with the Base
line–Los Alamos fault to the east. The Baseline–Los Alamos fault marks the
northern edge of the eastern Purisima Hills and extends another 30 km to the
eastern end of the Santa Maria Basin (Fig. 2). An asymmetric syncline with a
steep south limb and less steep north limb underlies the Los Alamos valley
between the Casmalia and Purisima Hills.

### METHODS

**Luminescence Dating**

We used luminescence techniques to date the Orcutt Formation. Luminescence
dating utilizes quartz or feldspar grains in sedimentary deposits younger
than ca. 300 ka to determine the last time the sediment was exposed to light
(Aitken, 1998). We collected samples from five sites in the Orcutt Formation
(Fig. 2). We took a “lower” sample at the base and an “upper” sample near the
top of the exposure for each of the five sample localities (Table 1; Appendix).
Samples were collected by removing the outer 40–50 cm of outcrop, driving
a metal pipe (capped on the outer end) into the exposure wall, excavating
around the pipe, and then capping the inner end while under a tarp to prevent
light contamination. For the North Slope Casmalia site (NSC; Fig. 2; Table 1),
we used only the lower sample collected because the upper sample returned

### TABLE 1. POST-INFRARED–INFRARED-STIMULATED LUMINESCENCE (pIR-IRSL) SAMPLE DATA

| Sample          | Location                  | K (%) | U (ppm) | Th (ppm) | Dose rate* (Gy/k.y.) | Equivalent dose (s) | No. of aliquots | Age (ka) |
|-----------------|----------------------------|-------|---------|----------|----------------------|---------------------|----------------|----------|
| NSC: North Slope Casmalia Lower | 34.89333333 120.5422222 | 2.68  | 2.81    | 7.09     | 4.98 to 5.31         | 5745 ± 136          | 24             | 96 ± 5   |
| RR: Rucker Road Upper      | 34.67555556 120.4391687 | 2.38  | 2.71    | 8.27     | 4.85 to 5.12         | 4786 ± 183          | 23             | 85 ± 6   |
| RR: Rucker Road Lower      | 34.67611111 120.4394444 | 2.13  | 3.01    | 10.43    | 4.96 to 5.15         | 5361 ± 233          | 10             | 93 ± 6   |
| LR: Lompoc Road Upper      | 34.82027778 120.525     | 2.24  | 1.15    | 5.24     | 4.56 to 4.95         | 5973 ± 128          | 16             | 111 ± 7  |
| LR: Lompoc Road Lower      | 34.82027778 120.5252778 | 2.62  | 2.15    | 6.82     | 4.56 to 4.95         | 6400 ± 168          | 12             | 119 ± 6  |
| GR: Graciosa Road Upper    | 34.85638889 120.4488889 | 2.63  | 1.67    | 6.55     | 4.4 to 4.78          | 4724 ± 115          | 24             | 91 ± 6   |
| GR: Graciosa Road Lower    | 34.85666667 120.4488889 | 2.6   | 1.81    | 6.83     | 4.38 to 4.77         | 5010 ± 99           | 24             | 97 ± 6   |
| DR: Dominion Road Upper    | 34.84305556 120.3330556 | 2.33  | 1.165   | 4.29     | 4.28 to 4.68         | 5048 ± 132          | 16             | 99 ± 7   |
| DR: Dominion Road Lower    | 34.84305556 120.3330556 | 2.61  | 1.59    | 6.4     | 4.28 to 4.68         | 5024 ± 95           | 16             | 99 ± 6   |

*Note: “Upper” and “lower” refer to relative stratigraphic position of samples at a site. Italics indicate dose rates that were considered anomalous and not used, and the
ages that would have resulted from these dose rates (see text for explanation). Bold text indicates preferred dose rate and age for two samples.

*Ranges in dose rates reflect possible range in moisture content history for each sample.
Orcutt Formation Basal Contact Reconstruction

To document Quaternary deformation across the Casmalia and Purisima anticlinoria, we used the unconformity at the base of the Orcutt Formation as a marker horizon. We constructed a three-dimensional surface representing the base of the Orcutt Formation using basal contact geometries from our own observations and existing maps (Dibblee and Ehrenspeck, 1989) along with a 4-m-resolution interferometric synthetic aperture radar (IfSAR) digital elevation model (2.2 m vertical accuracy, 4.3 m horizontal accuracy) from the National Oceanic and Atmospheric Administration’s digital topographic/bathymetric database (Fig. 4). The points used in gridding three-dimensional surfaces in Arcmap 10.4 were plotted by first georeferencing 7.5 min geologic quadrangles (1:24,000 scale) from Dibblee and Ehrenspeck (1989) to the IfSAR digital elevation models. Places where the Orcutt Formation contacted an older unit (i.e., its basal contact) were then manually digitized with points along the contacts. We determined latitude, longitude, and elevation for each point from the georeferenced IfSAR DEM. Error in the digital elevation model is a low percentage of the uplift and fault slip measurements and therefore not considered a significant source of uncertainty. We also incorporated groundwater well data from Worts (1951) to generate points for the Orcutt basal contact where it is buried in the Santa Maria Valley.

We added interpolated data points to the grid where the Orcutt Formation has been eroded off the crests of the Casmalia and Purisima Hills anticlinoria. These interpolated points were graphically determined by first calculating dip from three-point problems of the Orcutt Formation’s basal contact on either side of an anticline and then linearly projecting the basal contact orientations from both the north and south limbs of the folds to their intersection points. These points were always above the modern topography, suggesting that the pre-erosion Orcutt surface was higher than the modern crests of the Casmalia and Purisima Hills. We assume the folded Orcutt surface would have flattened closer to the anticline axes and was lower than the intersection point of our two straight-line projections. However, since we do not know the exact shape of the eroded parts of the folds and hence the exact original elevations of the Orcutt surface at the fold axes, we used the elevation of the highest topography as the elevation for our interpolated points. This assumes that there has been minimal erosion of the crests of the hills below the original Orcutt contact. Thus, the elevation of these interpolated points are most likely minimum estimates. We gridded the point array into three separate surface tiles—west, central, and east—for maximum conformance of the interpolated surface to the data. This increased the spatial distribution of data points per grid and minimized the influence of regional, west-sloping topography on calculated elevations.

We applied a tension spline interpolation method in ESRI ArcGIS 10.4 to this three-dimensional point array. Choosing an interpolation method in a geographic information system (GIS) that produces a surface of maximum conformance to the data points and is accurate in depicting the mapped geology was done through iterative constructions with both quantitative and qualitative evaluation. Qualitative evaluation was done using three-dimensional (3-D) visualizations of the surface (Fig. 4) and cross sections through the surface (Figs. 5 and 6) to view locations where the Orcutt basal surface intersected the topography and confirm that these relationships were consistent with map patterns of the Orcutt Formation’s basal contact.

Structural Analysis: Modeling Folding and Fault Slip

We used area-balanced forward modeling to estimate the amount of fault slip required to produce the observed two-dimensional fold shapes. Fault models aim to reproduce geometric attributes of structures such as horizon dips and the distribution and angle of unconformities across a section in order to describe structural development and calculate fault slip. We created six two-dimensional (2-D) cross sections from the interpolated 3-D surface representing the base of the Orcutt Formation. The orientations of these cross sections were perpendicular to the major anticlinal axes (Fig. 2). Our cross sections do not account for any lateral component of slip that may be accommodated by the faults. Structural relief (the difference between the maximum and minimum elevations of the Orcutt basal surface) was measured across the cross-section lines.
Figure 4. (A) Oblique view looking southeast at the Orcutt basal surface from a point above Point Sal. (B) Same view of the Orcutt basal surface but with a three-dimensional (3-D) representation of the topography to illustrate the similarity between the surface and the present-day topography. Contours are shown in 15 m intervals.
We used StructureSolver software (Eichelberger et al., 2015) to restore and forward model the cross sections. Forward modeling utilizes 2-D kinematic models of fault-related folding to compute fold shapes above modeled faults. Our area-balanced forward models used symmetric trishear (Erslev, 1991; Zehnder and Allmendinger, 2000) to approximate fault-propagation folding at the fault tip, with inclined shear above fault bends (Xiao and Suppe, 1992) in order to predict horizon shapes in the forelimbs and backlimbs of folds. Trishear is a preferred method of modeling propagation folding because this method can reproduce the tightening of folds and the progressive tilt of strata with depth, asymmetric folding, and the rotation of bedding toward the fault, all of which are characteristics of structures in the Santa Maria Basin. Variables that were manipulated in the fault models included the shape of the faults; trishear parameters such as initial and final fault tip depths and the triangular shear zone area (half-apical, trishear angle); the axial shear angle at fault bends; and regional horizon depths for the hanging-wall and footwall blocks. These variables allowed for modeling of pregrowth and growth stratigraphy that could incorporate simple erosion in order to specify fault displacement history and fault propagation assuming a constant propagation-to-slip ratio. This enabled us to estimate the trishear parameters, fault geometries, and amounts of displacement along a fault that provided the best visual fit to the data. A systematic approach was applied by first evaluating previous interpretations of fault geometries and depths (Namson and Davis, 1990; Seeber and Sorlien, 2000; Shaw and Plesch, 2012) and modifying model parameters to reproduce our assemblage of data. Unique structural solutions arose through an iterative process of assessing all structural solutions while prioritizing geometric constraints in the data. We chose a model that best fit the collective data and honored the key constraints, which included well data, the Orcutt basal surface, geologic contacts (controlling the fold shape of deeper Miocene to Pliocene horizons), and bedding dips. Our model error (fit of the final models to the surface and subsurface data) was 300 m or less and was mostly due to a mismatch of Miocene horizons to well data that is discussed below. Modeled fault displacement error for the base Orcutt surface was ±10 m, which is the range of variation allowed before the model began to violate key data constraints.

Figure 5. Cross-section profiles (lines 1 through 3) of the basal Orcutt surface across the Casmalia and Purisima Hills. Red lines are the Orcutt Formation basal contact, and black lines are the topographic profile. Dip indicators of the underlying geologic units are shown where they were available on geologic maps. Maximum structural relief (m.s.r) is labeled and is defined as the vertical distance between the highest and lowest points of the Orcutt surface. Interpolation data points are displayed along line 2 to show conformance of the surface to the basal contact point array derived from borehole data and geologic mapping. F.—fault; F.Z.—fault zone; SL—sea level.
RESULTS

Luminescence Dating

We obtained pIR-IRSL ages from the Orcutt Formation that indicate an age of ca. 120 ka for its base and an age of ca. 85 ka for its top. The Lompoc Road site (Fig. 2) returned the oldest ages with a lower sample age of 119 ± 8 ka (Table 1). This site was located at the base of the Orcutt Formation, and thus this age most closely represents the start of Orcutt deposition. The youngest ages were from the Rucker Road site, where the upper sample returned an age of 85 ± 6 ka. This site was the thickest exposure (13 m) we sampled, and the base of the formation was not exposed at the site. The top surface of the Orcutt Formation at this site is an expansive terrace that extends ~15 km west to the coastline (Vandenberg Terrace on Fig. 2), and this surface probably represents the original upper surface of the Orcutt Formation. This geomorphic feature and the young dates from this site suggest to us that the ca. 85 ka age likely represents the later stages of Orcutt deposition.

For the majority of samples, aliquot data were tightly grouped, and there was no evidence of partial bleaching or bioturbation in the frequency distribution histograms (Appendix). Dose rates were consistent between sites, with most between 4.5 and 5 Gy/k.y. Two sites, however, had inverted ages, where the stratigraphically higher “upper” sample was 15–20 k.y. older than the “lower” sample, which is not possible (Lompoc Road Upper and Dominion Road Upper; Table 1). An apparent age inversion could be caused by partial
bleaching of the upper samples or by inaccurate determination of dose rates. Neither of the two samples showed strong evidence of partial bleaching, which would normally be expressed as an asymmetric PDF plot of aliquot equivalent doses (Appendix). We therefore believe that the age inversion was most likely due to inaccurate determination of dose rates at these two sites. Dose rates for the upper samples at both sites were anomalously low compared to the other samples in this study, which results in an older age. This may be due to an inaccurate measurement of the U, Th, or K concentrations in the dose rate sample or error in our estimation of water content over the lifetime of the deposit, all of which affect the final dose rate determination. Although we cannot confidently attribute the apparent age inversion of samples at the Lompoc Road and Dominion Road sites to a specific cause, we believe the dose rates for the upper samples at these locations are not representative and are not consistent with the lower samples, and we therefore adopted dose rate values from the lower samples at each of these locations to get a more equal approximation of the ages of the upper and lower samples.

**Deformation of the Orcutt Basal Contact**

The geometry of the Orcutt basal surface (Figs. 4, 5, and 6) generally reflects the modern topography. The horizon is folded over the Purisima and Casmalia Hills and shows a distinct northeast-vergent asymmetry, with steeper dips on the north side of the Casmalia Hills and eastern Purisima Hills (Figs. 5 and 6). One area of uncertainty is the northwest end of the study area, where a lack of Orcutt deposits preserved in the hanging-wall block of Point Sal made it impossible for us to confidently reconstruct the Orcutt surface. Our contoured surface, based on control points on the edges of the elevated area, intersected the high topography of Point Sal (Fig. 5, line 1), which suggests that this topographic high existed during Orcutt deposition, and the Orcutt fluvial system flowed around it. This may not be accurate, however, because our Orcutt surface interpolation does not account for Quaternary dip-slip displacement along the Pezzoni and Lions Head faults that bound the high topography of Point Sal on the north and south sides. The Pezzoni fault is a south-dipping reverse fault with an approximately 3000 m of displacement of Miocene units across the fault (Woodring and Bramlette, 1950). Little is known about the recency of faulting, but the fault appears to truncate Orcutt deposits on the north side of Point Sal, and an unpublished consulting report (Woodward-Clyde Consultants, 1988) noted apparent offset geomorphic surfaces that led them to infer late Pleistocene displacement. On the south, the Lions Head fault is a steeply north-dipping reverse fault that offsets a late Quaternary marine terrace by up to 9 m along the coast (Clark, 1993). We therefore infer that the Orcutt Formation was likely lifted above the current topography of Point Sal by reverse slip on the Pezzoni and Lions Head faults and was subsequently eroded. We did not include this area in our measurements of rock uplift, however, because of the uncertainties associated with post-Orcutt offset along these faults and whether the Orcutt Formation abutted or was lifted over the older rocks at Point Sal. To the southwest of Point Sal, the Orcutt basal surface flattens in the Vandenberg Terrace area and transitions into a shoreline platform along the coast.

The six cross sections through the Orcutt surface provided reference points for rock uplift measurements and deformation modeling along transects through the Casmalia and Purisima Hills. Structural relief between the lowest and highest Orcutt basal surface points ranges from 238 m across line 3 (eastern Casmalia Hills) to 400 m across line 5 (central Purisima Hills).

**Fault Displacements from Structural Forward Modeling**

Two cross sections (lines 2 and 4) were used to construct area-balanced solutions for fault geometries at depth, position of the main fault tip, regional horizon depths, fault displacement, and the distribution of contractional strain across each section (Figs. 7 and 8). The locations of these lines were chosen where we had the greatest density of surface and subsurface data. The resultant models contain deformed horizon geometries that most accurately conform to independent geometric constraints from oil and gas wells, groundwater wells, geologic maps, and 3-D structure contour data.

**Cross-Section Line 2**

Our preferred model for the regional structure responsible for folding of the western Casmalia anticlinorium includes a southwest-dipping reverse fault with the fault tip buried beneath 1.5 km of sediment (Fig. 7). Incline shear fault-bend-folding was used to model the backlimb shape and symmetric trishear fault propagation folding (Erslev, 1991) with less than a kilometer of propagation for the forelimb.

Computed fault displacements to account for the deformation of stratigraphic horizons are shown on Figure 7 and include 731 m for the late Pleistocene base Orcutt horizon. The uncertainty of these fault displacements is ±10 m, which comes from the variability in fault slip allowed by the model to best fit the data constraints. We note that the model required greater fault displacement in the Pliocene Foxen mudstone than in the older and deeper Sisquoc and Monterey Formations (Fig. 7), which implies earlier normal slip along the fault. This agrees with previous interpretations, which inferred that many faults in the region were originally Miocene normal faults that were reactivated as reverse faults in Pliocene time (e.g., Namson and Davis, 1990; Crouch and Suppe, 1993; Sorlien et al., 1999). Average dip of the upper section of the fault is 17° to the southwest, decreasing to 10° dip near a depth of 2743 m. Depths to the Orcutt, Paso Robles, and Careaga stratigraphic horizons in Santa Maria Valley and the location and orientation of the distinct late Pleistocene angular unconformity on the northern Casmalia Hills were reproduced in this model. The fold shape of the base Orcutt horizon, depths to deeper horizons on the fold crest and forelimb, dip meter data, geologic contact locations on the forelimb and backlimb, and bedding dips across the structure were also honored by this model.
Cross-Section Line 4

In our preferred model for line 4, the late Pleistocene and older horizons are folded above a north-dipping reverse fault and a deeper south-dipping, reverse detachment (Fig. 8A). This cross section was split into two models (Figs. 8B and 8C), and both models require fault propagation above the fault tip to reproduce observed asymmetric folding. The north-dipping fault beneath the western part of the Purisima Hills anticlinorium soles into a midlevel detachment within mid-Miocene deep-marine strata, while the south-dipping regional fault continues to dip through the section at a low angle beneath the Purisima Hills and the north-dipping fault. The moderate northeast dip of the late Mesozoic–early Cenozoic rocks below the midlevel, north-dipping fault is produced by fault-bend-folding over a deep fault ramp (~5000 m depth) along the deeper, south-dipping fault. Slip along the deeper fault also contributes to the structural relief and northeast tilting of overlying units in the northern Purisima Hills and controls the moderate south dip and thickness of Pliocene to Pleistocene units in the backlimb of the eastern Casmalia Hills anticlinorium.

Shallow deformation and tight, asymmetric folding within the Purisima Hills anticlinorium could only be reproduced by a combination of trishear fault propagation and fault-bend-folding above a listric, north-dipping reverse fault (Fig. 8B). Symmetric trishear was used to model propagation at the fault tip and was preferred over the south-dipping fault ramp model of Namson and Davis (1990). We prefer the trishear model because the amount of structural relief, strong south-vergent asymmetry of folded units, bedding dips, and distribution of the geologic contacts among the Sisquoc Formation, Foxen mudstone, and Careaga Formation exposed on the northern limb of the anticline could not be reproduced from only fault-bend-folding above a south-dipping ramp. This model does not discount the existence of a fault.

Figure 7. Area-balanced, fault-related fold model solution for the western Casmalia Hills. Shear axes, trishear parameters, and horizons depths were adjusted to fit the shown geometric constraints and produce fault displacements. The fault displacement arrows show the direction (fault parallel) and magnitude (m) of displacement along the fault that produces the above fold shape of a particular horizon in our preferred geometric models. For some horizons, there is a greater amount of displacement in younger units relative to older units beneath, which is the result of an earlier episode of normal slip along the fault. Note that geologic and subsurface data indicate very steep, and in some places overturned, bedding dips on the north side of the Casmalia Hills anticline, showing that a significant amount of folding occurred prior to planation and deposition of the Orcutt Formation. SL—sea level.
Forward modeling of structural cross-section Line 4

Figure 8. (A) Combined fault-related fold model showing the spatial relationship between the south-dipping deep detachment and north-dipping reverse fault across line 4. (B, C) Area-balanced forward model solutions that constitute the composite with: model attributes, fault displacements of stratigraphic horizons, and geometric data used in the modeling. The fault displacement arrows show the direction (fault parallel) and magnitude (m) of displacement along the fault that produces the above fold shape of a particular horizon in our preferred geometric models. Note that geologic and subsurface data indicate very steep, and in some places overturned, bedding dips, showing that a significant amount of folding occurred prior to planation and deposition of the Orcutt Formation. For the Miocene units, there is a greater amount of displacement in younger units relative to older units beneath, which is the result of an earlier episode of normal slip along the faults. Refer to explanation on Figure 7 for units and symbols. SL—sea level.
ramp along a deeper south-dipping detachment (which may contribute to the northward dip of basement rocks below this fault), but a fault in the upper section is still needed to best match the data. Other model iterations with different geometry or dip directions for this fault did not accurately conform to the collective data. For example, decreasing the detachment depth of our north-dipping fault model increased the fault planarity and angle between the fault and the shear axis. This resulted in a decrease in concavity of folding across the axis, more vertical displacement of horizons than folding, and incongruence with Pliocene to Pleistocene stratigraphic contacts and dip in the backlimb (north side) of the fold. Our preferred model also honored the magnitude and dip direction of dip meter data and depth to horizons determined from lithologic logs (Fig. 8).

The computed fault displacements across the north-dipping fault needed to account for the deformation of stratigraphic horizons in cross-section line 4 are shown on Figure 8B and include 249 m for the base Orcutt horizon. The depth of the main fault tip (~1500 m) and <1 km of fault tip propagation were a direct result of reproducing the data. The average dip of the upper section of the faults is 24° to the north, and the fault decreases dip to a near-flat detachment at ~3000 m depth.

To the north, the eastern Casmalia Hills anticlinorium is deforming above a southwest-dipping reverse fault with a deep ramp contributing to northeast regional tilt in the backlimb. Fault propagation caused the north-vergent asymmetric folding above the fault tip, and the broad and flat crestal geometry results from small inflections in the fault geometry at depth. The upper section of the fault dips ~34° to the southwest (Fig. 8) and decreases to a 10° dip at a depth of 4900 m. This model was able to reproduce the distinct late Pleistocene angular unconformity between the Orcutt and Paso Robles Formations on the north slope of the Casmalia Hills, as well as obey the folded base Orcutt horizon geometry, depths to the older horizons, geologic contacts, and bedding dips across the structure. The location of the fault beneath the eastern Casmalia Hills anticlinorium matches the depth of a major fault observed in the Union Dome 18 well (Fig. 8C). Fault displacements needed to create the observed deformation related to this fault are shown in Figure 8C and include 481 m for the base Orcutt horizon. Like the displacements modeled in cross-section line 2, this model produces less slip in older units in the Miocene section, which reflects earlier normal slip on this fault during Miocene time.

**DISCUSSION**

**Quaternary Rock Uplift Amounts and Rates**

The correlation between the modern topography and Orcutt basal surface shows that the topographic evolution of the Casmalia and Purisima Hills has occurred since deposition of the Orcutt Formation (Figs. 4, 5, and 6). We therefore used the Orcutt basal stratigraphic surface to measure rock uplift across the Casmalia and Purisima Hills at six locations along the crests of the hills (Fig. 2). Two different methods were used, and the results for each method are summarized in Table 2.

In the first method, we measured incision of the Orcutt basal stratigraphic surface to a local base level represented by the elevation of the nearest active river channels (along profiles parallel to the coast from the uplift measurement points). We inferred that the incision of these rivers, the Santa Maria, Los Alamos, and Santa Ynez rivers, has kept pace with uplift because they have equilibrium channel profiles that are graded to sea level (Kelty, 2020), and therefore the incision amount is a proxy for rock uplift amount (Pazzaglia et al., 1998). Because the Orcutt Formation in the western Santa Maria Basin was deposited on a regional erosional surface that has been incised by multiple rivers, we cannot attribute planation of the basal surface at one of our measurement points to a specific active channel in the modern topography. Therefore, maximum and minimum rock uplift amounts reported in Table 2 correspond to differences in the present-day elevation of the modern channels on either side of the Casmalia and Purisima Hills and represent our uncertainty in uplift (incision) amount.

For the second method, we measured rock uplift relative to sea level by comparing the lifted Orcutt basal surface on top of the Purisima and Casmalia Hills to an inferred projection of its original slope to sea level. As mentioned previously, the fluvial Orcutt Formation grades into beach deposits near the coast, and the Orcutt basal surface that was beveled by fluvial processes inland becomes an elevated shoreline platform (marine terrace) along the coastal sections of the Vandenberg Terrace (Figs. 2 and 9). This unique situation allowed us to tie the Orcutt basal surface directly to sea level at the time of its formation. The precise location of the paleoshoreline is not exposed, but exposures of the Orcutt basal surface in canyons along the north side of the Santa Ynez River show that the shallow-marine deposits transition to fluvial deposits somewhere between 5 and 6 km inland from the coast. The gradient of the Vandenberg Terrace varies from 6 m/km (0.006) along a line parallel to the Santa Ynez River to 10 m/km (0.01) along a straight line from the coast to the western nose of the Purisima Hills. These slopes are steeper than the modern rivers (0.002–0.004) but shallower than the gradients measured on paleoshore platforms along coastal California (0.02–0.04; Bradley and Griggs, 1978). The gradient of the Vandenberg Terrace is more consistent with a surface formed by fluvial processes that graded to sea level, but some westward tilting has most likely occurred since its formation.

To calculate rock uplift amounts, we projected the Orcutt basal contact on the Vandenberg Terrace inland and compared this projected reference surface to the present-day elevation of the Orcutt basal surface on top of the Casmalia and Purisima Hills (Fig. 9). To account for the possibility of regional tilting of the Vandenberg Terrace, we calculated maximum and minimum uplift amounts based on inferred original slope angles for the Orcutt basal contact projection in this area (Table 2). Our minimum slope was the minimum of the present-day stream gradients (0.002), and our maximum was the present-day slope of the Vandenberg Terrace perpendicular to the coast and parallel to the Santa Ynez River (0.006), where we believe it is least likely to be deformed or
TABLE 2. UPLIFT AMOUNTS AND RATES

| Reference point          | Present elevation (m) | Elevation of reference* (m) | Elevation above reference surface (m) | Rock uplift at coast† (m) | Total rock uplift (elevation above paleo–sea level† or active channel) (m) | Age of Orcutt base§ (ka) | Uplift rate (mm/yr) | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min |
|--------------------------|-----------------------|-----------------------------|---------------------------------------|---------------------------|-----------------------------------------------------------------------------|--------------------------|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Relative to modern rivers |                       |                             |                                       |                           |                                                                             |                          |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Casmalia crest line 1    | 300                   | 32                          | 26                                    | 274                       | 268                                                                         | Not applicable           |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Casmalia crest line 2    | 285                   | 66                          | 55                                    | 230                       | 219                                                                         | Not applicable           |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Casmalia crest line 4    | 290                   | 166                         | 79                                    | 211                       | 124                                                                         | 230                      | 219               | 127 | 111 | 2.5 | 2.1 |     |     |     |     |     |     |     |     |
| Purisima crest line 2    | 305                   | 83                          | 19                                    | 286                       | 222                                                                         | 236                      | 222               | 127 | 111 | 2.5 | 2.1 |     |     |     |     |     |     |     |     |
| Purisima crest line 6    | 600                   | 184                         | 73                                    | 527                       | 416                                                                         | 527                      | 416               | 127 | 111 | 4.7 | 3.3 |     |     |     |     |     |     |     |     |
| Relative to projected marine terrace/peneplain surface |           |                             |                                       |                           |                                                                             |                          |                     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Casmalia crest line 1*   | 300                   | 128                         | 96                                    | 204                       | 172                                                                         | 282                      | 228               | 127 | 111 | 2.5 | 1.8 |     |     |     |     |     |     |     |     |
| Casmalia crest line 2    | 285                   | 131                         | 97                                    | 188                       | 154                                                                         | 286                      | 210               | 127 | 111 | 2.5 | 1.8 |     |     |     |     |     |     |     |     |
| Casmalia crest line 4    | 290                   | 190                         | 130                                   | 160                       | 100                                                                         | 258                      | 176               | 127 | 111 | 2.5 | 1.8 |     |     |     |     |     |     |     |     |
| Purisima crest line 2    | 160                   | 92                          | 74                                    | 86                        | 68                                                                           | 149                      | 109               | 127 | 111 | 2.5 | 1.8 |     |     |     |     |     |     |     |     |
| Purisima crest line 4    | 305                   | 190                         | 150                                   | 155                       | 115                                                                         | 283                      | 221               | 127 | 111 | 2.5 | 1.8 |     |     |     |     |     |     |     |     |
| Purisima crest line 6    | 600                   | 272                         | 172                                   | 428                       | 328                                                                         | 548                      | 426               | 127 | 111 | 4.9 | 3.4 |     |     |     |     |     |     |     |     |

*Reference is modern active river channels for first group and the projected shoreline platform/fluvial strath surface for second group.
†To correct for uplift of reference surface at the coast and the difference in sea level between 119 ka and present (+12.9 ± 11 m from present; Simms et al., 2016).
§We used the age of the lower Orcutt Formation sample collected just above the base of the formation (119 ± 8 ka) as an estimate of the beginning of Orcutt deposition.
*The elevation of the paleoshoreline at the coast and associated rock uplift assume the Lion’s Head fault has not been active since Orcutt time, which is based on geologic maps that show no offset of the Orcutt Formation by the fault.

Figure 9. Schematic cross section showing how rock uplift measurements were made relative to sea level. Inland projection of the Orcutt basal contact on the Vandenberg Terrace surface (green dashed line) is compared to the present-day elevation of the Orcutt basal contact (orange line) at a point on top of the uplifted topography. This difference (A) is added to the uplift of the Orcutt basal surface under the Vandenberg Terrace since the development of the surface at 119 ± 8 ka (B).
tilted since it formed. Because the Vandenberg Terrace is a shoreline platform at its coastal extent, we added the uplift of the inferred paleoshoreline since formation of the shoreline platform to the elevation of the Orcutt base at our calculation points above the reference surface to get a total rock uplift value. We approximated the elevation of the paleoshoreline by estimating the elevation of the Orcutt basal surface (3–5 m below the surface elevation) at the inferred paleoshoreline 5.5 km inland from the coast.

We believe an age of 119 ± 8 ka to be the best approximation of the Orcutt basal surface because this date came from a sample collected less than 2 m above the Orcutt basal contact, and it was the oldest Orcutt age we measured in this study (Lompoc Road locality in Table 1). We therefore used this age to calculate uplift rates and to determine paleo–sea level when the Orcutt basal surface was beveled. Sea level at 119 ka was +12.9 ± 11 m relative to modern sea level based on a glacial-isostatic adjusted sea-level curve calculated for the area by Simms et al. (2016).

Our two separate methods resulted in similar rock uplift amounts and rates (Table 2), with neither method consistently producing faster rates than the other. The rates plotted on Figure 2 represent the full range of maximum and minimum rates from both methods. Rock uplift rates average around 2 mm/yr along the crest of the Casmalia Hills and range from 1.0 to 2.5 mm/yr. The rates are faster in the west, where the highest topography is present. Our rock uplift rates for the western Casmalia Hills are significantly higher than the uplift rates of 0.14–0.18 mm/yr previously estimated by Clark (1993) near Point Sal.

For the Purisima Hills, uplift rates vary from 0.9 mm/yr in the west, where the topography is lowest, to 4.9 mm/yr in the east, where the topography is the highest. The relatively fast rates in the eastern Purisima Hills are unexpected, and we note that this location is the only measurement point where the Orcutt basal surface is not actually present at the top of the hills, but rather projected based on our reconstruction of the Orcutt basal surface. It is possible that our projection of the Orcutt basal surface over this area is incorrect and that some high topography existed here during Orcutt time, and the Orcutt Formation was deposited as a buttress unconformity. The tilting of the Orcutt Formation along the northern and southern edge of the eastern Purisima Hills (as much as 20°), however, and the lack of any remnant Orcutt deposits in the higher elevations suggest that our interpretation that the Orcutt surface projected over the modern topography is correct and that there has been greater late Quaternary uplift here than to the west. We interpret that the high topography here is a result of the fast uplift rates, and the Orcutt Formation is not present at the top of the Purisima Hills because it has been eroded off.

The slower rates in the western Purisima Hills occur where the anticlino- nial flattens into the Vandenberg Terrace. We interpret the uplift rate of the Vandenberg Terrace to represent the regional uplift of the paleo-peneplain onto which the Orcutt Formation was deposited. This regional uplift rate is supported by research conducted for several master’s theses set in the Santa Maria Basin that used fluvial or marine terraces to determine incision and uplift rates of ~1 mm/yr in the footwall blocks of the reverse faults (Kelty, 2020; Farris, 2017; Tyler, 2013). The cause of this regional uplift rate is beyond the scope of this study, but it is likely related to deeper crustal thickening, possibly along the detachment at 12–15 km depth that has been interpreted by multiple studies (Levy et al., 2019; Huang et al., 1996; Namson and Davis, 1990). Our rock uplift rates along the crests of the Casmalia Hills and Purisima Hills are likely superposed on this regional uplift, such that the rate of rock uplift due to the underlying blind faults modeled in this study are anywhere from near 0 mm/yr at the western nose of the Purisima Hills to a little less than 4 mm/yr in the eastern Purisima Hills.

Late Pleistocene Fault Slip Rates

A range of dip-slip rates for each fault was calculated by dividing the computed fault displacements from our kinematic models by the lower age (119 ± 8 ka) of the Orcutt Formation that best approximates the age of the basal contact. For cross-section line 2, displacement along the fault is 731 ± 10 m, which results in a dip-slip rate of 5.7–6.7 mm/yr. For cross-section line 4, displacement along the north-dipping fault is 481 ± 10 m, and the dip-slip rate is 3.7–4.4 mm/yr. Dip-slip displacement of 247 ± 10 m on the south-dipping fault in line 4 results in a slip rate of 1.9–2.3 mm/yr (Fig. 8).

The total shortening of 689–708 m across the fault in line 2 since 119 ± 8 ka results in a shortening rate of 5.4–6.5 mm/yr. Cumulative shortening across the two faults in line 4 is 4.9–6 mm/yr, i.e., slightly less than the rates calculated across line 2. These late Pleistocene shortening rates are comparable to geodetic rates of northeast-directed (N30°E) shortening across the basin, normal to the fold belt, which are 6 ± 2 mm/yr (Feigl et al., 1990). The similarity in rates suggests that the faults that underlie the Casmalia and Purisima Hills are accommodating the majority of shortening across the basin. Kelty (2020) has shown, however, that reverse slip on the Santa Ynez River fault occurred during this time period as well, and the unknown amount of shortening across that fault would need to be included in any estimate of the total north-northeast-oriented shortening across the basin since ca. 119 ka.

The 2-D forward models in this study assumed pure reverse displacement on the faults and negligible lateral displacement. Most of the Casmalia Hills fault zone and the faults that underlie the Purisima Hills do not reach the surface, so there is no way to measure lateral slip directly at the surface. Previous studies, however, have inferred a component of left-lateral slip on these faults, as well as the Lion’s Head and the Santa Ynez River faults. Sylvester and Darrow (1979) interpreted the folds in the Casmalia Hills, Purisima Hills, and along the Santa Ynez River fault to be left-stepping en-echelon folds resulting from a component of left-lateral slip along these faults at some time in their history. Clark (1993) and Sorlien et al. (1999) reported striations on fault surfaces along the Lion’s Head and Honda faults that suggested a component of left-lateral slip. Conversely, comparison of crustal velocities west of the San Andreas fault in central California from geodetic data (Feigl et al., 1990; Shen et al., 2003; DeMets, 2014; Sandwell and Wessel, 2016) with the orientation of the faults we modeled suggests a component of right-lateral shear across the...
fauls. Focal mechanisms in the northwestern corner of the Santa Maria Basin (McLaren and Savage, 2001; Hardebeck, 2010) are mainly reverse sense, but a few earthquakes include focal mechanisms that would indicate right-lateral displacement if they occurred on one of the main faults. Consequently, the faults modeled in this study likely involve a component of lateral slip that we are unable to detect. Any additional lateral slip would increase the total slip rate on these faults by some unknown amount and would mean the rates presented here are minimum estimates. The contradiction between geologic evidence for left-lateral slip versus geodetic and seismic evidence for right-lateral slip may be a result of a change in fault kinematics through time, with earlier left-lateral slip replaced by later right-lateral slip.

The true slip rates of these faults may also be larger than what we calculated here because of our uncertainties in the timing of deformation. The slip rates we report are based on the oldest ages we obtained from the Orcutt Formation, which assumes that deformation began during Orcutt deposition. The lack of unconformities or angular discordance within the Orcutt stratigraphy, however, and the widespread deposition of this fluvial deposit, which is only 30–50 m thick (Woodring and Bramlette, 1950), suggest that deformation and uplift may not have started until after the Orcutt Formation was deposited. This is supported by the fact that fluvial terrace deposits in the Santa Maria Basin that are younger than the Orcutt Formation are confined to present-day drainages, showing that topographic growth and localization of later fluvial deposits occurred after the wide peneplain-like deposition of the Orcutt Formation. If deformation and uplift did not start until the end of Orcutt deposition (ca. 85 ka), then the fault slip rates would be 8–9 mm/yr, and uplift rates along the crests of the Casmalia and Purisima Hills would increase by an average of 1 mm/yr.

Implications for Regional Active Tectonics

The deformation style and rates in the Santa Maria Basin support previous interpretations that this area is a transition zone between the southern Coast Ranges and western Transverse Ranges that is accommodating differential motion between the two tectonic domains (e.g., Hornafius, 1985; Feigl et al., 1990; Sorlien et al., 1999; McLaren and Savage, 2001; Lettis et al., 2004). High rates of shortening and uplift have been documented in the western Transverse Ranges. Marshall et al. (2013) measured an average geodetic shortening rate of 7 mm/yr, while other geodetic studies have reported rates as high as 12 mm/yr (Donnellan et al., 1993; Hagar et al., 1999). Measurements of geologic shortening rates since Miocene time vary from 6.5 to 9.1 mm/yr (Levy et al., 2019) to as high as 25 mm/yr (Yeats, 1983; Huftile and Yeats, 1995). Slip rates on faults in the western Transverse Ranges have mainly been determined in the Ventura area, where upper limits range from 7 to 11 mm/yr along the Ventura, San Cayetano, and Red Mountain faults (Fig. 1; Rockwell et al., 1988; Huftile and Yeats, 1995; Huftile and Yeats, 1986; Hubbard et al., 2014). Geodetic uplift rates vary from 2 mm/yr in the northeastern western Transverse Ranges and along the San Andreas fault to ~4 mm/yr in the actively subsiding Ventura Basin (Marshall et al., 2013; Hammond et al., 2017). Late Quaternary uplift rates determined from marine terraces near Ventura are as high as 7 mm/yr (e.g., Rockwell et al., 2016) but range from 0.5 to 2 mm/yr farther west along the Santa Barbara coast (Gurrola et al., 2014; Morel, 2018).

Deformation in the southern Coast Ranges, to the north of the Santa Maria Basin, is characterized by right-lateral transpression and slower rates of deformation and uplift than in the western Transverse Ranges. Major faults in the southern Coast Ranges include the West Huasna, Rinconada, and Hosgri faults, which are steeply dipping, north-northwest–striking faults with primarily right-lateral strike-slip geologic offsets and focal mechanisms (e.g., Page et al., 1998; Hardebeck, 2010). The Hosgri fault exhibits late Quaternary slip rates of 1–3 mm/yr at Point Buchon (Fig. 1; Hanson et al., 1992; Lettis et al., 2004), and the West Huasna and Rinconada faults together accommodate up to 1–3 mm/yr of slip (Titus et al., 2007; Hardebeck, 2010). Uplift rates in the southern Coast Ranges are also slower than in the western Transverse Ranges. In the San Luis Obispo area (Fig. 1), late Quaternary marine terraces show that individual ranges are being lifted at rates of 0.1–0.2 mm/yr along steeply dipping reverse faults with slip rates of 0.2–0.5 mm/yr (Hanson et al., 1992; Lettis and Hall, 1994; Lettis et al., 2005). These elevated areas have little to no internal folding during Quaternary time, and deformation is concentrated along the high-angle faults at the margins of the ranges. North of San Luis Obispo, the Santa Lucia Range is being lifted at 0.8 mm/yr due to slip on steeply dipping reverse faults that bound the mountain range (Ducea et al., 2003). These reverse faults are likely the result of plate boundary transpression and a restraining step geometry, where right-lateral displacement on faults southeast of the range is transferred westward to the Hosgri fault (Clark et al., 1994; Titus et al., 2007; Johnson et al., 2014).

The orientations of faults and folds in the Santa Maria Basin have a somewhat northwestward-opening fanning geometry and vary from west-striking features, like in the western Transverse Ranges, to more northwest-striking features, like in the southern Coast Ranges. The style and rates of deformation along these structures, however, are more similar to the western Transverse Ranges. The low-angle blind thrust faults that cause folding at shallower levels within the basin are similar to deformation patterns in the western Transverse Ranges and are unlike the high-angle reverse faults and right-lateral faults that characterize the southern Coast Ranges to the north (Namson and Davis, 1990; Page et al., 1998; Sorlien et al., 1999; Wirtz, 2017). Focal mechanisms and limited geologic data indicate that right-lateral shear across the Santa Maria Basin area appears to be focused on the more northerly striking faults that mark the margins of the basin, primarily the Hosgri fault to the west, but possibly the West Huasna and Foxen Canyon faults to the northeast as well (Sorlien et al., 1999; McLaren and Savage, 2001; Lettis et al., 2005; Hardebeck, 2010).

The uplift rates and fault slip rates reported here are also similar to those seen in the western Transverse Ranges and are significantly faster than those in the southern Coast Ranges. Deformation rates in the Santa Maria Basin decrease dramatically to the north across the Santa Maria River, where the northern part of the Los Osos domain of Lettis et al. (2005) near San Luis
Our data fit previous models that attributed shortening and uplift across the Santa Maria Basin to ongoing vertical-axis rotation of the western Transverse Ranges. Lettis et al. (2005) noted that a velocity gradient between the western Transverse Ranges and the southern Coast Ranges, which they observed in their geologic slip rates, agrees with a gradient observed in geodetic data (Feigl et al., 1990; Shen and Jackson, 1993) and reflects internal shortening of the Santa Maria Basin to accommodate rotation of the western Transverse Ranges relative to the nonrotating southern Coast Ranges. The fan-like orientations of variable west- to northwest-striking faults and folds and the presence of fault-propagated folding in the Santa Maria Basin mimic older structures present to the east of the Little Pine fault along the northern edge of the western Transverse Ranges. Those structures accommodated rotation through rotational folding and variations in dip-slip displacement along strike of reverse faults from late Miocene to possibly Pleistocene time (Onderdonk, 2005). This style of deformation likely also occurred in the Santa Maria Basin during the later stages of western Transverse Ranges rotation (6 Ma to present), and continued into late Pleistocene time.

Shortening across the Santa Maria Basin may also be accommodating a decrease in right-lateral slip southward on the Hosgri fault and thereby transferring some southern Coast Ranges right-lateral shear into western Transverse Ranges shortening. Estimates of total displacement on the Hosgri fault vary from 10.5 km (Sorlien et al., 1999) to 80 km or more (Hall, 1975; Dickinson et al., 2005; Langenheim et al., 2013). Sorlien et al. (1999) reconstructed Miocene horizons in the offshore part of the Santa Maria Basin and calculated 3.5 km of right-lateral displacement across the Hosgri fault, with an additional 7 km of right-lateral shear accommodated by folding and thrust faulting that facilitate small amounts of clockwise vertical-axis rotation of individual fault blocks in the Santa Maria Basin. Colgan and Stanley (2016) noted that because the Hosgri fault terminates offshore of Point Arguello, the 80 km of right-lateral displacement on the Hosgri fault proposed by previous studies would have to be absorbed by a similar amount of shortening across the Santa Maria Basin. This much shortening has not been documented in geologic reconstructions of the area (Namson and Davis, 1990; Clark, 1993). Colgan and Stanley (2016) presented data that show the geologic correlation used to infer 80 km of right-lateral displacement along the Hosgri fault is not unique and may not be valid, and they therefore inferred that total displacement on the southern Hosgri fault is most likely on the order of 10 km.

Although our forward models were constructed to evaluate Quaternary deformation, displacement of the Miocene horizons in the models indicates that total shortening across the Purisima and Casmalia Hills since mid-Miocene time is on the order of 4 km (Figs. 7 and 8). Additional post-Miocene shortening has undoubtedly occurred across the Santa Ynez River fault to the south (Wirtz, 2017; Kelty, 2020), and through layer-parallel shortening and outcrop-scale structures across the area (Gutiérrez-Alonso and Gross, 1997; Wirtz, 2017). We doubt that this additional amount is anywhere near sufficient to accommodate 80 km of displacement on the Hosgri fault, and our data fit better with interpretations of 10 km or less of displacement on the Hosgri fault at the latitude of the Santa Maria Basin (Colgan and Stanley, 2016; Sorlien et al., 1999). The model proposed by Colgan and Stanley (2016) involved right-lateral slip along the faults within the Santa Maria Basin that transferred clockwise rotation of the western Transverse Ranges into lateral slip on the southern Hosgri fault. As mentioned above, geodetic and seismic data seem to support some right-lateral slip on the faults within the basin. However, we also consider it likely that vertical-axis rotation of fault blocks within the Santa Maria Basin, through variations in dip-slip displacement along strike of the reverse faults, is accommodating some of the southward decrease in right-lateral displacement on the Hosgri fault, as proposed by Sorlien et al. (1999). In addition, we hypothesize that some displacement across the northern Hosgri fault may have been transferred eastward to the West Huasna–Foxen Canyon–Little Pine fault at a point north of the Santa Maria Basin during mid-Miocene to early Pleistocene time. This eastward transfer of right-lateral shear would have been accommodated by the large amount (tens of kilometers) of shortening that occurred across the western Big Pine–Pine Mountain fault (Fig. 1) during this time period (Onderdonk, 2003).

CONCLUSIONS

The Orcutt Formation represents deposition on a broad, flat peneplain between 119 ka and 85 ka. The Orcutt Formation was subsequently deformed by folding at the surface above blind thrust faults that underlie the Casmalia and Purisima Hills. Post–Orcutt Formation deposition on a deep south-dipping detachment ranges from 721 to 741 m since 119 ± 8 ka at a slip rate of 5.6–6.7 mm/yr. Rock uplift along the crests of the Casmalia and Purisima Hills ranges from 0.9 to 4.9 mm/yr. Our data show that the western Santa Maria Basin is actively inverting along major faults with high rates of displacement not previously documented. This Quaternary uplift and shortening are most likely due to ongoing vertical-axis rotation of the western Transverse Ranges and transfer of right-lateral slip on the southern Hosgri fault to north-south shortening in the western Transverse Ranges.

APPENDIX. LUMINESCENCE DATA AND SITE STRATIGRAPHY

Figures A1 through A5 show the luminescence data and site stratigraphy for each of the five sampling sites. Stratigraphic columns are shown on the left, with green circles denoting where samples were collected. Figure A1 includes a key for the stratigraphic columns. Two plots of the data from each sample are shown on the right—a probability density function for all aliquots run from each sample in terms of seconds of irradiation time by a beta source, with a rate of 0.088 Grays/s, and a radial plot of the same data (RadialPlotter by Vermeesch, 2009), which was used to calculate the central age of the sample (Galbraith and Roberts, 2012).
North Slope Casmalia Site Stratigraphy and Luminescence Data

Key for Appendix 1 (Figures A1 through A5)

Sedimentary Structures Key

- planar cross-lamination
- intraclasts
- current ripple cross-lamination
- hummocky cross stratification
- horizontal planar laminations
- gravitational contact
- wavelet cross stratification
- erosional contact
- trough cross stratification

North Slope Casmalia Lower Probability Density

Central value = 5745 ± 136 (1σ)
Dispersion = 11%
P(χ²) = 0.00

North Slope Casmalia Lower Radial Plot

(n=24)

Figure A1. Luminescence data and site stratigraphy for the North Slope Casmalia site. A stratigraphic column is shown on the left with a green circle denoting where the sample was collected. Two plots of the data for the sample are shown on the right: (Top) Probability density function plot for all aliquots run from the sample in terms of seconds of irradiation time by a beta source with rate of 0.088 Grays/s, and (Bottom) a radial plot of the same data (RadialPlotter by Vermeesch, 2009) that was used to calculate the central age of the sample (Galbraith and Roberts, 2012). Sand grain size: vf—very fine; f—fine; m—medium; c—coarse; vc—very coarse. Gravel size: gran—granule; pebb—pebble; cobb—cobble; boul—boulder.
Figure A2. Luminescence data and site stratigraphy for the Rucker Road site. A stratigraphic column is shown on the left with green circles denoting where samples were collected. Two plots of the data from each sample are shown on the right: a probability density function for all aliquots run from each sample in terms of seconds of irradiation time by a beta source with rate of 0.088 Grays/s, and a radial plot of the same data (RadialPlotter by Vermeesch, 2009) that was used to calculate the central age of the sample (Galbraith and Roberts, 2012). Refer to Figure A1 for key to stratigraphic column.
Lompoc Road Site Stratigraphy and Luminescence Data

Figure A3. Luminescence data and site stratigraphy for the Lompoc Road site. A stratigraphic column is shown on the left with green circles denoting where samples were collected. Two plots of the data from each sample are shown on the right: a probability density function for all aliquots run from each sample in terms of seconds of irradiation time by a beta source with rate of 0.088 Grays/s, and a radial plot of the same data (RadialPlotter by Vermeesch, 2009) that was used to calculate the central age of the sample (Galbraith and Roberts, 2012). Refer to Figure A1 for key to stratigraphic column.
Graciosa Road Site Stratigraphy and Luminescence Data

Figure A4. Luminescence data and site stratigraphy for the Graciosa Road site. A stratigraphic column is shown on the left with green circles denoting where samples were collected. Two plots of the data from each sample are shown on the right: a probability density function for all aliquots run from each sample in terms of seconds of irradiation time by a beta source with rate of 0.088 Grays/s, and a radial plot of the same data (RadialPlotter by Vermeesch, 2009) that was used to calculate the central age of the sample (Galbraith and Roberts, 2012). Refer to Figure A1 for key to stratigraphic column.
Figure A5. Luminescence data and site stratigraphy for the Dominion Road site. A stratigraphic column is shown on the left with green circles denoting where samples were collected. Two plots of the data from each sample are shown on the right: a probability density function for all aliquots run from each sample in terms of seconds of irradiation time by a beta source with rate of 0.088 Grays/s, and a radial plot of the same data (RadialPlotter by Vermeesch, 2009) that was used to calculate the central age of the sample (Galbraith and Roberts, 2012). Refer to Figure A1 for key to stratigraphic column.
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