Climate-controlled landscape evolution in the Western Transverse Ranges, California: Insights from Quaternary geochronology of the Saugus Formation and strath terrace flights

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ABSTRACT

The Las Posas and Ojai Valleys, located in the actively deforming Western Transverse Ranges of California, contain well-preserved flights of strath terraces and Quaternary strata (i.e., Saugus Formation) that when numerically dated elucidate the tectonic, geomorphic, and fluvial histories that sculpted the landscape since ca. 140 ka. This study includes 14 new optically stimulated luminescence and 16 new terrestrial cosmogenic nuclide ages from the late Pleistocene to Holocene that record two regional aggradation events and four intervals of strath terrace formation. Geochronologic data indicate that terrestrial Saugus strata in the Las Posas Valley (Camarillo Member) prograded over marine deposits at ca. 125 and 80 ka and are as young as 60–25 ka, which is an order of magnitude younger than the youngest Saugus strata elsewhere in Southern California. These results highlight the need for precise dating of Saugus strata where identified and utilized to assess rates of tectonic deformation. Based on its compositional character, thickness, stratigraphic relations, and inferred ages, the Camarillo member of the Saugus Formation is correlated with sediments of the Mugu aquifer identified in subcrop throughout the Ventura Basin and thus provides a new regional chronostratigraphic subsurface datum. The aggradation of these sediments and similar deposits in the study area between 13 and 4 ka is subsequent to the transition from humid to semiarid climate correlating to the end of the ultimate and penultimate glacial maximums. Aggradation is inferred to have resulted from increased sediment supply in response to transient vegetative and consequent hillslope destabilization. Similar to aggradational events, strath terrace cover sediments ages correlate to dry warm climate intervals, indicating straths in Southern California were cut at ca. 110–100 ka, 50–35 ka, 26–20 ka, and 15–4 ka. These results support recent mathematical and experimental models of strath formation, where increased sediment flux and decreased water discharge enhances lateral erosion rates and inhibits vertical incision. Subsequent incision and strath terrace formation is inferred to occur during intervening wet climate intervals. The correlation of strath terrace ages and aggradational events with environmental changes that are linked to global climate indicates that climate rather than tectonics exhibits first-order control of depositional, denudational, and incisional processes in the Western Transverse Ranges. Moreover, these results provide a chronostratigraphic framework that allows these landforms to be regionally correlated and used to assess rates of active tectonics where geochronologic data are unavailable.

INTRODUCTION

In actively deforming regions, landscape evolution is controlled by the interplay between tectonics and climate, which modulate depositional, incisional, and denudational processes (e.g., Whipple and Tucker, 1999; Anders et al., 2005; Wobus et al., 2006; Kamp and Owen, 2012). Consequently, quantification of the age of both erosional landforms and depositional strata provides critical insight into the effects of past climate variability and active faulting of Earth’s surface. Furthermore, an understanding of the effects of climatic and/or tectonic changes on erosion and aggradation is critical to modeling all aspects of the landscape linked to rock, ocean, and atmospheric systems, and for quantifying local and regional earthquake hazard (e.g., Rockwell, 1983; Rinaldo et al., 1995; Whipple et al., 1999; Roering et al., 2007). With increasingly widespread usage of Quaternary geochronological techniques, such as optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclides (TCNs), which are capable of numerically dating a variety of Earth materials over time scales of 10^6 yr, detailed chronologies can now be developed for regions that have previously lacked late Quaternary geochronological data (e.g., National Research Council, 2010). This study provides insight into the processes governing landscape evolution and develops a chronologic framework for estimating ages of regional geomorphic features that can be used for quantifying tectonic and geomorphic processes where site-specific geochronology is otherwise unavailable.

The Western Transverse Ranges of Southern California are an ideal location to study the driving forces of landscape evolution because the region is easily accessible and has a well-documented late Pleistocene precipitation (e.g., Kirby et al., 2006), sedimentation (Kennett et al., 1995), vegetation (Heusser, 1995), and tectonic history (e.g., Yeats, 1988a). In addition, the need for precise rates of active faulting in Southern California necessitates geochronological investigation of deformed landforms and sedimentary deposits. However, few ages based on geochronological
data of landscape features in this region exist. Therefore, this study focuses on numerical dating of late Pleistocene aggradational deposits, including the Saugus Formation, and bedrock strath terraces preserved in the Las Posas and Ojai Valleys (Fig. 1). These study areas are actively deforming (Rockwell et al., 1984; Yeats, 1988b; DeVecchio et al., 2012) and are characterized by different rates and styles of tectonic deformation, and, therefore, they are ideal for comparing the effects of local tectonics and global climate oscillations on the depositional and denudational processes that control landscape evolution.

The Saugus Formation is of particular interest because it is a regionally extensive Pliocene–Pleistocene shallow-marine and terrestrial sedimentary deposit that is deformed across numerous active faults and folds within the Western Transverse Ranges (Fig. 1) (e.g., Hershey, 1902; Kew, 1924; Yeats, 1988b). The formation is commonly cited as the youngest unit involved in tectonic deformation and has been reported in numerous consulting reports and paleoseismic trench logs, and its inferred upper age limit (200–500 ka) is typically utilized for assessing rates of tectonic deformation (e.g., Weber et al., 1976; Yeats, 1983; Yeats et al., 1988; Huftile, 1991; Huftile and Yeats, 1995, 1996; Baldwin et al., 2000; Meigs et al., 2003; Geosols, Inc., 2007). Therefore, the age of the Saugus Formation is critical for evaluating rates of deformation on numerous active structures in the Western Transverse Ranges. Unfortunately, the Saugus Formation is poorly defined, highly variable, and regionally diachronous (Blackie and Yeats, 1976; Levi and Yeats, 1993; Levi et al., 1986; Yeats, 1983). Thus, the upper age of the Saugus is poorly known.

Strath terraces are common along rivers within the Western Transverse Ranges, are shown on numerous geologic maps (e.g., Kew, 1924; Rockwell et al., 1988; Dibblee, 1992a, 1992b), and are widely used in fluvial and tectonic studies (e.g., Rockwell et al., 1984). However, the processes that control their formation are still debated (e.g., Bull, 1991; Pazzaglia et al., 1998; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2009; Finnegan and Dietrich, 2011). Strath terraces represent ancient and now-abandoned river floodplains that formed during periods of valley-bottom widening by lateral planation. Bull (1990) suggested that lateral erosion and strath cutting are the dominant processes when streams are in dynamic equilibrium, where river discharge and sediment load are in balance. Recent quantitative field studies and conceptual and numerical models predict they form in response to balanced or oscillating sediment supply (Formento-Trigilio et al., 2003; Hancock and Anderson, 2002, respectively), elevated sediment supply (Fuller et al., 2009), and/or periods of stable base level (Pazzaglia and Gardner, 1993). Experimental results indicate that during high sediment supply, transient fluvial deposits inhibit incision by armoring the channel (e.g., Sklar and Dietrich, 2001), which leads to a wider band of active erosion and lateral channel erosion (Finnegan et al., 2007). As experimental and mathematical models continue to unravel the complexities in the processes controlling strath formation, field-based studies are required to compare local driving mechanisms with predicted forcings. By focusing on high-precision numerical dating of these denudational landforms, in addition to aggradational deposits, and correlation of these features to the well-documented climate proxy records of Southern California, we illuminate the effects of water discharge and

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**Figure 1.** Simplified index map of the principal active faults in Southern California with respect to the study areas (black boxes) draped over a topographic hillshade image. The east-west structural grain of this part of California defines the Western Transverse Ranges tectonic province, with the Santa Monica fault delineating the southern boundary. Darker-gray areas show the distribution of previously mapped Pleistocene Saugus Formation, which was deposited by the ancestral Santa Clara River that drains the San Gabriel Mountains. Note that many of the faults deform the Saugus Formation, which is typically the youngest unit deformed by faulting in the region. Focal mechanisms show the approximate epicenter locations for the 1971 Mw 6.6 San Fernando–Sylmar, and 1994 Mw 6.7 Northridge earthquakes (lower-hemisphere projections), which both deform Saugus strata. Dashed polygons show the locations of selected group of strath terraces in the province that are locally faulted and folded.
river sediment load on depositional and erosional processes that sculpted the landscape in response to past climate variability.

**GEOLOGIC SETTING**

**Regional Structural and Stratigraphic Framework**

The California Borderlands west of the San Andreas fault have experienced a multiphase tectonic evolution following cessation of subduction during early Miocene time, including mioplate capture, clockwise rotation in excess of 90°, and syntectonic volcanism (e.g., Kamerling and Luyendyk, 1979; Luyendyk et al., 1980; Nicholson et al., 1994; Weigand et al., 2002), as well as transpression deformation related to the “Big Bend” of the San Andreas fault (e.g., Wright, 1991; Dolan et al., 1995; Shaw and Suppe, 1996; Yeats, 1988a). Thick sections of volcanic and volcanioclastic rocks of the Conejo volcanics and deep-marine siliceous mudstones (Monterey Formation) accumulated in middle Miocene transensional fault-bounded basins, with the Oligocene Sespe Formation on the upthrown side (Kew, 1924; Durrell, 1954; Ehrenspeck, 1972; Jakes, 1979; Williams, 1983; Ingersoll, 2001). Extensional deformation of the region continued until ca. 5 Ma, at which time development of the “Big Bend” of the San Andreas fault resulted in transpression deformation and inversion of Miocene basins (e.g., Crowell, 1976; Wright, 1991). Previous studies in the Western Transverse Ranges indicated that the rates of tectonic uplift due to Pliocene–Pleistocene shortening varied from ~1 to 15 mm/yr (e.g., Lajoie et al., 1979; Rockwell et al., 1984; Yeats, 1988a; Huftile and Yeats, 1995).

Following Miocene transtension and volcanism, deep-marine basins were filled by a progradational sequence of Pliocene–Pleistocene deep-marine turbidites, shallow-marine sandstone and mudstone, and terrestrial sandstone and conglomerate (Kew, 1924; Winterer and Durham, 1958; Weber et al., 1976; Yeats, 1965, 1977). In the Las Posas and Ojai Valleys, these strata have been given a variety of formal and local names based on stratigraphic position and inferred correlations to strata in the Los Angeles Basin (Fig. 2).

Regionally, the age of Pliocene–Pleistocene strata shown in Figure 2 is locally defined by biostratigraphy, magnetostratigraphy, tephrochronology, and fission-track dating (see Yeats, 1988b, and the references therein). However, these strata are diachronous (Yeats, 1977), vary widely in thickness along strike, and lack chronostratigraphic markers near the top of the section (Yeats, 1988a, 1988b). Consequently, the upper age limits for deformed strata within the Western Transverse Ranges are poorly defined.

The name Saugus Formation is loosely applied to regionally extensive (Fig. 1), shallow-marine, and terrestrial strata that are predominately conformable with underlying Pliocene–Pleistocene deep-marine strata (e.g., Yeats et al., 1988; Levi and Yeats 1993). The Saugus Formation is up to 2000 m thick in the Santa Clara River Valley and thins to the north and south toward each of the study regions (Fig. 3). In the Santa Clara River Valley and on the Oak Ridge–South Mountain uplift (Fig. 4A), the Saugus Formation is dominated by metamorphic and plutonic clasts originating from four locations in the Western Transverse Ranges from north to south illustrating Pliocene–Pleistocene stratigraphic relations and thickness variability of the Saugus Formation (shaded). Note that the Saugus Formation (shaded gray) thins significantly to the north and south of the Santa Paula, California, which is located in the Santa Clara River Valley. Generalized column location names are shown within the study areas on Figure 4. Important aquifer unit names are shown between the Santa Paula and Oak Ridge stratigraphic columns. Qa—Alluvium; Qs—Saugus Formation; QTp—Las Posas Sand; QTp—Pico Formation/Fernando Group; Tm—Monterey Formation; Ts—Sespe Formation.

![Figure 2. Stratigraphic nomenclature table illustrating the diversity of local lithologic naming of Pliocene–Pleistocene to Holocene strata in the Los Angeles and Ventura Basins. Ojai Valley nomenclature is shaded gray.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/4/2/110/3049965/110.pdf)
Landscape evolution in the Western Transverse Ranges

Figure 4. Geologic maps of the two study areas showing the distribution of Tertiary bedrock units, including the Saugus Formation, and numerical ages (white boxes). (A) The Las Posas Valley and Camarillo fold belt (hollow white polygon), south of the Oak Ridge/South Mountain uplift, are the main areas of focus for this study. Pliocene–Pleistocene bedrock mapping was compiled from Yeats (1988b), Dibblee (1990, 1992a, 1992b), and modified in this study. Two distinct late Pleistocene strath terrace levels are shown (Qt1 and Qt2). A third discontinuous remnant intermediate terrace level is present, but is too small to be depicted here, yet is shown in Figure 7A. MM—Moorpark mammoth site. (B) Geologic map of the Ojai Valley. Tertiary bedrock mapping was compiled from Dibblee (1990, 1992b), with modified late Pleistocene strath terrace levels of Rockwell et al. (1984) shown along the Ventura River. Note that the nomenclature of Rockwell uses ascending numbers for increasing terrace age, which is the reverse for the Las Posas Valley.
from the San Gabriel Mountains, reflecting deposition by the ancestral Santa Clara River (e.g., Kew, 1924; Yeats et al., 1994; Yeats, 1988a; Levi and Yeats, 1993).

The Saugus Formation is Quaternary in age (Fig. 2). Levi and Yeats (1993) utilized magnetostratigraphy to estimate a lower age of 2.3 Ma and upper age of 0.5 Ma of the Saugus in the Santa Susana Mountains (Fig. 1). The lower age limit on Saugus strata to the west is unknown; however, amino acid racemization (AAR) data from overlying terrace deposits near Ventura suggest an upper age of ca. 200 ka (Lajoie et al., 1979, 1982; Yerkes et al., 1987). Because few Quaternary numerical ages exist within the region, the upper age of the Saugus Formation and other correlated sedimentary strata (Fig. 2) is commonly utilized for estimating the timing and rates of deformation on numerous active faults and folds in the region (e.g., Yeats, 1988a; Huftile, 1991; Baldwin et al., 2000). Therefore, these studies and other unpublished consulting reports give the impression that deformation began synchronously everywhere west of the San Gabriel Mountains at 200 ka.

A regional unconformity separates the Saugus Formation from overlying sediments that constitute the upper aquifer system (Figs. 2 and 3) in the Santa Clara River Valley and on the south flank of the Oak Ridge uplift, as well as offshore (Turner, 1975; Greene et al., 1978; Yeats, 1988a; Hanson et al., 2003). The Mugu aquifer sediments have a thickness of ~60 m, and the sediments are differentiated from the Saugus Formation in the Las Posas Valley by being less indurated, finer grained, having a lower hydraulic conductivity, and being actively uplifted in the hanging wall of the Oak Ridge fault, a reverse fault estimated to have a late Quaternary slip rate of 5.9–12.5 mm/yr (Yeats, 1988a). Regional correlation and lithostratigraphic nomenclature of geologic units in the Las Posas Valley are summarized in Figure 3 (unshaded).

Much of the existing geologic mapping within the Las Posas Valley area is built upon regional-scale mapping by Kew (1924), which accurately illustrates most of the Oligocene to Pleistocene bedrock formations. In the Camarillo fold belt, Jakes (1979) correlated post-Miocene shallow-marine and terrestrial sandstone, siltstone, and conglomerate to the Saugus Formation. In contrast, Pressler (1929) and Dibblee (1990, 1992a, 1992b) differentiated the marine and nonmarine Saugus Formation, assigning the terrestrial sediments to the Saugus Formation and the Las Posas Sand to underlying shallow-marine sediments (Fig. 4A). Our study utilizes the nomenclature of the latter; however, we further subdivide the terrestrial sediments of the Saugus Formation into chronostratigraphic units, Qs1 through Qs4 (oldest to youngest) based on our geochronology investigation. Although the upper age of Pleistocene sedimentary rock in this region is poorly defined, a biostratigraphic age of 850–780 ka at the Moorpark mammoth site (MM on Fig. 4A) indicates that Qs1 strata north of the Camarillo fold belt were deposited during the early middle Pleistocene (Wagner et al., 2007).

During the early Pleistocene, the Camarillo fold belt occupied what Yeats (1965) referred to as the Camarillo shelf, where most of the late Tertiary sediments (Monterey Formation) were removed and Pliocene deep-marine sediments (Pico Formation and Fernando Group) did not accumulate. Consequently, Pleistocene strata in the Camarillo fold belt are significantly thinner (~80 m) compared to those to the west in the Oxnard Plain and to the north, where thicknesses exceed 1 km (Fig. 3; Jakes, 1979; Yeats, 1988b). Although the entire Pleistocene section thickens westward along the axis of the Camarillo fold belt, the Saugus Formation maintains a near-uniform thickness of 40–60 m where observed in outcrop (McNamara et al., 1991; Lopez, 1991; Kile et al., 1991; this study).

Overlying the Saugus Formation, the uppermost Pleistocene to Holocene sedimentary units are composed of a thin veneer of dissected and weakly deformed surficial deposits termed Quaternary older alluvium (Qoa of Dibblee, 1992a) or Quaternary terrace deposits (Qt of Kew, 1924). These previously mapped older alluvial and fluvial deposits are composed of geomorphic and geologic units, including two terrace levels (Qt1 and Qt2) and an older Quaternary alluvial unit (Qa1) identified in this study (Figs. 4A and 5). No detailed study of these landforms and sediments has been conducted; however, a paleoseismic investigation undertaken on the southernmost Qt2 exposure described a younger alluvial deposit that unconformably overlies Saugus strata and has a calibrated radiocarbon age 23,000 ± 1000 cal. yr B.P. (Buena Engineers, 1987) (Fig. 4A; Table 1).

### Table 1. Compilation of existing age estimates discussed in text

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Age (ka)</th>
<th>Geochronological technique</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>Las Posas Sand</td>
<td>Camarillo fold belt</td>
<td>450–750</td>
<td>Amino acid racemization</td>
<td>Wehmiller (2010, personal commun.)</td>
</tr>
<tr>
<td>Saugus Formation</td>
<td>Santa Susana Mountains</td>
<td>2300–0.5</td>
<td>Magnetostratigraphy</td>
<td>Levi and Yeats (1993)</td>
</tr>
<tr>
<td>Saugus Formation</td>
<td>Near Ventura</td>
<td>&gt;200</td>
<td>Amino acid racemization</td>
<td>Lajoie et al. (1982)</td>
</tr>
<tr>
<td>Saugus Formation</td>
<td>Las Posas Valley</td>
<td>850–780</td>
<td>Biostratigraphy</td>
<td>Wagner et al. (2007)</td>
</tr>
<tr>
<td>Mugu aquifer</td>
<td>Offshore Ventura</td>
<td>60–75</td>
<td>Marine isotope stage correlation</td>
<td>Dahlen (1992)</td>
</tr>
<tr>
<td>Qt2</td>
<td>Camarillo fold belt</td>
<td>23 ± 1</td>
<td>Radiocarbon</td>
<td>Buena Engineers (1981)</td>
</tr>
<tr>
<td>Qt6c</td>
<td>Ojai Valley</td>
<td>94 ± 13*</td>
<td>Relative displacement</td>
<td>Rockwell et al. (1984)</td>
</tr>
<tr>
<td>Qt6b</td>
<td>Ojai Valley</td>
<td>56 ± 10*</td>
<td>Relative displacement</td>
<td>Rockwell et al. (1984)</td>
</tr>
<tr>
<td>Qt6a</td>
<td>Ojai Valley</td>
<td>40*</td>
<td>Radiocarbon</td>
<td>Rockwell et al. (1984)</td>
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<tr>
<td>Qt5b</td>
<td>Ojai Valley</td>
<td>32 ± 1*</td>
<td>Radiocarbon/correlation†</td>
<td>Rockwell et al. (1984)</td>
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<tr>
<td>Qt5a</td>
<td>Ojai Valley</td>
<td>16–22*</td>
<td>Radiocarbon/correlation†</td>
<td>Rockwell et al. (1984)</td>
</tr>
<tr>
<td>Qt4</td>
<td>Ojai Valley</td>
<td>8–12*</td>
<td>Relative displacement</td>
<td>Rockwell et al. (1984)</td>
</tr>
</tbody>
</table>

*Calibrated radiocarbon ages of Rockwell et al. (1984). Calibration was conducted using online calculator (www.calpal.de).
†Based on average of two calibrated radiocarbon ages 39,117 ± 1188 and 41,587 ± 2101 cal yr B.P.
*Calibrated radiocarbon ages from samples collected from terraces south of study area near Ventura, California, and correlated to the Oak View area.
Ojai Valley

The Ojai Valley is a complex, structurally controlled intramontane basin bounded by the Topatopa Mountains to the north and Black/Sulfur Mountains to the south (Fig. 4B). The lower Ojai Valley closes to the east, where the San Cayetano fault overrides the Arroyo Parida fault. The San Cayetano fault is a north-dipping active reverse fault that Yeats (1981) suggested flattens at depth, where it joins with a regional mid-crustal detachment. In contrast, the Oak View faults, which offset several strath terrace levels and the Saugus Formation along the Ventura River (Fig. 4B), were interpreted by Rockwell et al. (1984) to be a series of flexural slip faults related to synclinal folding that do not root into high-strength pre-Miocene bedrock. Fault-slip rates near the Ojai Valley on the San Cayetano fault are estimated to be ~1.05 mm/yr (Rockwell et al., 1988), whereas slip rates on the Oak View faults are estimated to be between 0.3 and 1.1 mm/yr (Rockwell et al., 1984).

Similar to the Las Posas Valley, late Pleistocene strata in the Ojai Valley have been given a variety of different names (Fig. 2, shaded). This study utilizes the nomenclature of Huftile (1991, 1992), who referred to late Pleistocene conglomeratic units that are unconformable with the underlying Pliocene–Pleistocene strata, as Saugus Formation. The Saugus is compositionally unique in the Ojai Valley, containing predominantly clasts from the Eocene Coldwater and Matilija Sandstone that compose much of the Topatopa Mountains to the north (Fig. 4B; Huftile, 1991). In contrast to the Las Posas Valley and Santa Clara River Valleys, the Saugus Formation is angularly discordant with the underlying Pliocene and older strata, indicating that deformation of Sulfur Mountain is younger than deformation to the south (Huftile, 1991; Huftile and Yeats, 1995) or that the base of the Saugus Formation is younger to the north. Estimated from uplift rates, Rockwell et al. (1984) provided an age estimate of ca. 100 ka for the oldest strath terrace that is cut into the Saugus Formation, places an upper age limit on the formation.

The seminal work on soil chronosequences by Rockwell (1983) in the Ojai Valley defined six late Pleistocene to early Holocene strath terrace levels, named Qt6c, Qt6b, Qt6a, Qt5b, Qt5a, and Qt4 (oldest to youngest) (Figs. 4B and 5). The chronosequence is tied to four radiocarbon dates from three terraces, two from the Qt6a terrace (40,000 cal yr B.P.) near Oak View, one from a terrace near Ventura correlated to Qt5b (32,000 ± 1000 cal yr B.P.), and a lower terrace near Ventura correlated to Qt5a (15,000–20,000 cal yr B.P.) (Rockwell et al., 1984). Strath terraces are variably deformed by the Oak View faults and deeply incised by the Ventura River (Fig. 5).

METHODS OF INVESTIGATION

Geologic Mapping

We focused our geologic mapping on late Pleistocene strata previously interpreted as Saugus Formation, Las Posas Sand, strath terraces, and Quaternary older alluvium. Because the Saugus Formation in the Las Posas and Ojai Valleys has been mapped and described in detail (e.g., Jakes, 1979; Yeats, 1988b; Huftile, 1992; Dixble, 1987a, 1987b, 1992a, 1992b; McKay, 2011), the focus of mapping of the Saugus Formation was carried out in the Camarillo fold belt. There, mapping and numerical dating focused on the contact between the Las Posas Sand and the Saugus Formation exposed along most of the folds within the Camarillo fold belt to characterize the nature of the contact and the compositional variability of the two different geologic units (Fig. 4A). Stratigraphic relations described in outcrop were then compared with data from more than 50 subsurface wells compiled by Jakes (1979) and Hanson et al. (2003) in the Las Posas Valley and Camarillo fold belt (fig. 4B of DeVecchio et al., 2012).

Due to extensive agricultural use and urbanization on strath terraces in the Las Posas Valley, Qt1 and Qt2 were mapped based on geomorphic expression and altitudinal continuity using a high-resolution (3 m) digital elevation model (DEM). In the Ojai Valley, we relied upon terrace mapping, nomenclature, and age estimates of Rockwell (1983) and Rockwell et al. (1984) (Table 1).

Geochronological Approaches and Technique

We used optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN) to constrain the absolute ages of Saugus Formation strata and strath terraces in the Las Posas and Ojai Valleys. We combined these new data with preexisting chronologies to chronicle the upper Pleistocene terrestrial depositional and erosional history of these areas. Next, we outline a brief primer on these techniques and their applicability to dating Quaternary sediments and landforms in the Western Transverse Ranges.

Optically Stimulated Luminescence

We utilized OSL dating on quartz mineral separates and infrared stimulated luminescence (IRSL) dating on feldspar mineral separates. The luminescence signal derived from OSL and IRSL records the elapsed time...
since the sediment was last exposed to sunlight during transportation and/or as it is deposited and, therefore, represents the depositional age (e.g., Aitken, 1998).

Due to the relatively high radiogenic dose rate (≥2.6 Gy/ka) of sediments in the Camarillo fold belt, rapid saturation of luminescence signal in quartz OSL samples limited the maximum resolvable age to ca. 45 ka (Table 2). Where the quartz luminescence signal was saturated or near saturation, age estimations are only minimums; therefore, we utilized IRSL on feldspar mineral separates at these sites. Because feldspar saturates at higher doses than quartz (Aitken, 1998), IRSL analyses of feldspar separates are capable of resolving a greater burial duration and thus older ages. For a more thorough discussion of the OSL and IRSL technique employed in this study and examples of quartz and feldspar luminescence characteristics, see DeVechchio et al. (2012).

**Cosogenic Nuclides**

TCNs, such as beryllium-10 ($^{10}\text{Be}$), are isotopes that form from the interaction of cosmic particles with elements in Earth’s atmosphere and surface. $^{10}\text{Be}$ forms from the interaction of cosmic particles with quartz (Lal, 1991). TCN production decays exponentially with depth as the penetration of cosmic rays attenuates below the ground surface. Thus, production of TCNs is negligible a few meters below Earth’s surface. Furthermore, $^{10}\text{Be}$ is radiogenic, with a half-life of $1.3 \times 10^6$ yr (Nishiizumi et al., 2007), and thus it is not present in buried rocks more than a few million years old. The concentration of $^{10}\text{Be}$ in rocks or sediments at Earth’s surface is a function of the production rate (known) and the time (what we wish to determine) the rocks or sediments have been exposed to cosmic rays, modeled for a particular latitude and altitude. Knowing these key components, we can calculate exposure ages based on measured $^{10}\text{Be}$ concentrations summarized in Table 3 (see Appendix A for expanded table 1). Either in situ boulder ages or depth profiles, outlined herein, were used to define surface ages within the Las Posas and Ojai drainages.

**Exposure dating.** Exposure dating was undertaken on five boulders on the Qi6a surface in the Ojai Valley (Fig. 4B). Samples were 2 cm thick and collected from the top of each boulder. Shielding corrections were made for each sample from field measurements and calculated using the CRONUS online calculator (Balco et al., 2008). All boulder samples were prepared at the University of Arizona (UA) cosmogenic laboratory. Sandstone samples were crushed to 250–500 µm grain size for processing. Approximately 50 g aliquots of quartz grains were separated from the sample following the method of Kohl and Nishiizumi (1992). Prior to dissolution, samples were analyzed for purity on the inductively coupled plasma–optical emission spectrometer (ICP-OES) in the Department of Hydrology at UA. Samples were spiked with an in-house ultrapure beryllium carrier ($^{10}\text{Be}/^{9}\text{Be} \approx 2 \times 10^{-16}$), and a blank was processed along with the samples to account for background contamination in the laboratory. Samples were dissolved and run through chromatography columns to extract the beryllium hydroxide, which was later combusted over a Bunsen burner for 20 min to produce beryllium oxide. Targets were packed with a mixture of niobium powder and the beryllium oxide sample in accordance with procedures from Lawrence Livermore National Laboratories (LLNL) Center for Acceleration Mass Spectrometry (AMS). AMS ratios from LLNL were compared to in-house ultrapure beryllium carrier ($^{10}\text{Be}/^{9}\text{Be} \approx 2 \times 10^{-16}$), and the beryllium oxide sample in accordance with procedures from Lawrence Livermore National Laboratories (LLNL) Center for Acceleration Mass Spectrometry (AMS). AMS ratios from LLNL were compared to in-house ultrapure beryllium carrier ($^{10}\text{Be}/^{9}\text{Be} \approx 2 \times 10^{-16}$), and a blank was processed along with the samples to account for background contamination in the laboratory. Samples were dissolved and run through chromatography columns to extract the beryllium hydroxide, which was later combusted over a Bunsen burner for 20 min to produce beryllium oxide. Targets were packed with a mixture of niobium powder and the beryllium oxide sample in accordance with procedures from Lawrence Livermore National Laboratories (LLNL) Center for Acceleration Mass Spectrometry (AMS). AMS ratios from LLNL were converted to concentrations and exposure ages calculated using the online

**TABLE 2. ANALYTICAL RESULTS FROM OPTICALLY STIMULATED LUMINESCENCE GEOCHRONOLOGY FROM THE LAS POSAS VALLEY AND CAMARILLO FOLD BELT**

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Location</th>
<th>Age (ka)</th>
<th>Method</th>
<th>Age Estimation</th>
<th>Equivalent Dose (DE) (ppm)</th>
<th>Dose Rate (DR) (Gy/ka)</th>
<th>Age Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Qi6a</td>
<td>&gt;45</td>
<td>OSL</td>
<td>Min. 129</td>
<td>1.18 ± 0.05</td>
<td>4.29 ± 0.17</td>
<td>2.85 ± 0.21</td>
</tr>
<tr>
<td>2</td>
<td>Qi6a</td>
<td>&gt;45</td>
<td>OSL</td>
<td>Min. 129</td>
<td>1.48 ± 0.11</td>
<td>8.25 ± 0.41</td>
<td>3.42 ± 0.25</td>
</tr>
<tr>
<td>3</td>
<td>Qi6a</td>
<td>35 ± 10</td>
<td>OSL</td>
<td>Min. 129</td>
<td>1.59 ± 0.04</td>
<td>5.14 ± 0.04</td>
<td>2.87 ± 0.24</td>
</tr>
<tr>
<td>4</td>
<td>Qi6a</td>
<td>84 ± 7</td>
<td>IRSL</td>
<td>Min. 129</td>
<td>2.71 ± 0.03</td>
<td>7.82 ± 0.04</td>
<td>3.79 ± 0.28</td>
</tr>
<tr>
<td>5</td>
<td>Qi6a</td>
<td>85 ± 6</td>
<td>IRSL</td>
<td>Min. 129</td>
<td>4.75 ± 0.05</td>
<td>7.32 ± 0.03</td>
<td>4.27 ± 0.28</td>
</tr>
<tr>
<td>6</td>
<td>Qi6a</td>
<td>141 ± 10</td>
<td>IRSL</td>
<td>Min. 129</td>
<td>4.05 ± 0.03</td>
<td>10.42 ± 0.03</td>
<td>5.13 ± 0.28</td>
</tr>
<tr>
<td>7</td>
<td>Qi6a</td>
<td>97 ± 7</td>
<td>IRSL</td>
<td>Min. 129</td>
<td>3.05 ± 0.03</td>
<td>9.04 ± 0.06</td>
<td>4.13 ± 0.28</td>
</tr>
<tr>
<td>8</td>
<td>Qi6a</td>
<td>25 ± 2</td>
<td>IRSL</td>
<td>Min. 129</td>
<td>2.71 ± 0.05</td>
<td>7.93 ± 0.05</td>
<td>3.25 ± 0.28</td>
</tr>
<tr>
<td>9</td>
<td>Qi6a</td>
<td>13 ± 1</td>
<td>OSL</td>
<td>Min. 129</td>
<td>3.15 ± 0.06</td>
<td>11.80 ± 0.09</td>
<td>3.25 ± 0.28</td>
</tr>
</tbody>
</table>

1GSA Data Repository Item 2012077, three alternative CRONUS Calculator results for cosmogenic radionuclide exposure and depth profiles analyses utilizing alternative erosion rates, and one expanded geochronology table, is available at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
### TABLE 3. ANALYTICAL RESULTS OF TERRESTRIAL COSMOGENIC NUCLIDE $^{10}$Be GEOCHRONOLOGY

<table>
<thead>
<tr>
<th>Sample *</th>
<th>Location†</th>
<th>Sample type</th>
<th>Elevation (m)</th>
<th>Thickness (cm)</th>
<th>Production Rate§ (atoms/g*yr)</th>
<th>Shielding factor</th>
<th>Denudation Rate# (cm/k.y.)</th>
<th>Quartz (g)</th>
<th>AMS values</th>
<th>$^{10}$Be concentration (atoms/gram)</th>
<th>$^{10}$Be error (1σ)</th>
<th>$^{10}$Be error (2σ)</th>
<th>Apparent age** (yr)</th>
<th>Apparent age error†† (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt5b-1L</td>
<td>292153</td>
<td>3812042</td>
<td>depth profile 227</td>
<td>10</td>
<td>5.09</td>
<td>0.20</td>
<td>0.9994</td>
<td>0-0.1</td>
<td>36.7800</td>
<td>0.4153</td>
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<td>1.76E+03</td>
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<tr>
<td>Qt5b-2L</td>
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<td>3812042</td>
<td>depth profile 227</td>
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<td>5.09</td>
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<td>0.9994</td>
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<td>0.4153</td>
<td>5.38E-14</td>
<td>1.50E-15</td>
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<td>292153</td>
<td>3812042</td>
<td>depth profile 227</td>
<td>10</td>
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<td>0.20</td>
<td>0.9994</td>
<td>0-0.1</td>
<td>38.6800</td>
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<td>1.62E-15</td>
<td>3.22E+04</td>
<td>1.19E+03</td>
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<td>3812042</td>
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<td>0.9994</td>
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<td>6a-1a</td>
<td>290216</td>
<td>3813527</td>
<td>boulder 228</td>
<td>2</td>
<td>4.66</td>
<td>0.19</td>
<td>0.9989</td>
<td>0-0.006</td>
<td>49.3600</td>
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<td>3813531</td>
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<td>6a-3</td>
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<td>0-0.1</td>
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<td>4.25E-15</td>
<td>4.98E+04</td>
<td>2.00E+03</td>
</tr>
</tbody>
</table>

*"L" or "A" at end of name indicates where the sample was run on the accelerator mass spectrometer (AMS); at Lawrence Livermore Laboratories or at the University of Arizona, respectively.
†Locations are given in Universal Transverse Mercator (UTM) coordinates system zone 11, using World Geodetic System 1984 (WGS84) datum.
§Production rates are from the CRONUS calculator and the script of Hidy et al. (2010).
#Denudation rates show the ranges used in models. Please see text for details.
**Apparent age is based on Chronus calculator results (0 erosion model). In parentheses, 6 mm/ka erosion model. Depth profile ages are shown in Appendix Table 2 (see text footnote 1).
††Apparent error is based on Chronus calculator results (0 erosion model). In parentheses, 6 mm/ka erosion model. Depth profile ages are shown in Appendix Table 2 (see text footnote 1).
§§Sample 6a-2a was not used for calculation of terrace age because this sample was run in duplicate at two laboratories and has a larger error that completely encompasses its duplicate 6a-2L. See text for details.

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CRONUS calculator (Balco et al., 2008). Surface age was calculated as the weighted mean of the five samples. Boulder inheritance and post-depositional boulder erosion are considered in our calculations and are discussed in the results section.

**Depth profiles.** We used depth profiles to constrain the ages of the Qt1 and Qt5a surfaces in Moorpark and Ojai, respectively. TCN depth profiles provide an effective method for determining the age of abandonment of fluvial and marine terraces (e.g., Hancock and Anderson, 1998; Hidy et al., 2010). The $^{10}$Be concentration theoretically should decrease with depth along an exponential curve that represents the production in the near surface since deposition. For young (~10,000 yr), pristine terrace surfaces, muonogenic production at depth is insignificant, and the concentration within the deepest samples represents the “inheritance” acquired prior to deposition in the deposit.

Samples were collected from the terrace surfaces along an incised arroyo in Moorpark and along a road cut at the Villanova School in Ojai, California. At each site, we excavated >75 cm into the vertical face (Fig. 6A) to ensure samples had not accumulated TCNs from the side wall. Samples were collected from 10 cm intervals spaced ~40 cm apart (Fig. 6A). At least 30 pebbles (1–5-cm-diameter clasts) were analyzed to avoid any bias in the profile due to migration of sand through the soil profile. Clast-size distributions are shown in Appendix A (see footnote 1).

Pebbles were described and then crushed to the 250–500 µm size fraction for processing as per the boulder samples. Qt5a samples were prepared at UA and analyzed at LLNL in August 2008. Samples Qp1 01, 03, and 05 were processed at UA and analyzed at LLNL in December 2008. Samples Qt1–02, 04, and 06 were processed at the University of California, Santa Barbara, cosmogenic laboratory and at California State University, Northridge, and run at LLNL in August 2010.

Depth profile ages were determined from two methods: simple linear regression and Monte Carlo simulations. The underlying assumption for both methods is that production of TCNs decreases exponentially with depth as a function of sediment density ($\rho$), depth below the surface ($z$), and the absorption mean free path ($\Lambda$; ~160 g/cm² for these samples). The equation for decrease in production rate ($P$) at any depth below the surface ($z$) is based on the following equation (Lal, 1991):

$$P(z) = P(0)e^{-\frac{z}{\rho \Lambda}}.$$  \hspace{1cm} (1)

$P(0)$ is the surface production rate scaled for altitude and latitude.

The linear regression method fits a line to our data points via the following methodology. Nuclide concentration $C$ (atoms) at any depth $z$ is the product of the production rate at that depth (Eq. 1) and time (yr B.P.) plus the $^{10}$Be concentration within the sample prior to deposition (called...
nuclide inheritance, $I$). We assume that, on average, each amalgamated sample has the same transport history. The concentration of any sample can thus be written as:

$$C(z) = (\text{Age} \times P[z]) + I.$$  

(2)

Further substitution of Equation 1 into Equation 2 leads to:

$$C(z) = (\text{Age} \times P[0] e^{-\rho z}) + I.$$  

(3)

Equation 3 defines a line with a slope of Age times $P(0)$ (known). Therefore, we can regress a line through our data points plotted with $C(z)$ on the $y$-axis and $e^{-\rho z}$ on the $x$-axis. Errors are based on 2σ linear regression errors of the line fit. This method assumes no erosion of the surface, and it does not account for errors in other parameters such as production rate or half-life.

The second, more quantitative, analysis is after the method of Hidy et al. (2010). This method includes a rigorous analysis of all errors (i.e., production rate, erosion or inflation of the surface, and $^{10}$Be half-life) included in the analysis and provides a specified number (100,000 for our analysis) of probable fits at 2σ confidence. The Monte Carlo simulation was run for both the Qt1 and Qt5 surfaces in Moorpark and Ojai, respectively. Only the data from the Qt1 Moorpark surface provided a result within the 2σ confidence limits. For the Qt5 surface in Ojai, the data do not provide a result at 2σ confidence, but nonetheless we show the best-fit profile of our data for comparison with the linear regression model.

RESULTS

Stratigraphy and Age of the Saugus Formation and Las Posas Sand in the Camarillo Fold Belt

The basal contact of the Saugus Formation (Qs2) with the underlying Las Posas Sand is exposed in most folds in the Camarillo fold belt (Fig. 4A) and is easily identifiable. The two formations are both un lithified yet easily distinguished based on color, composition, and sedimentary structures (Fig. 7). The Las Posas Sand is composed of interbedded greenish mud, and thinly cross-bedded, white quartz-richer sand with abundant well-rounded pebbles composed of plutonic, metamorphic, and metavolcanic clasts (Fig. 7C). Bivalve hash is ubiquitous in exposures of the Las Posas Sand and can be identified even in engineered urban landscapes. In contrast, the Qs2 and Qs3 strata are composed of thickly bedded (>2 m), reddish, massive, pebble-bearing silt with clasts that are dominantly composed of Miocene Monterey Shale and Conejo volcanic clasts, with less common granitic and metamorphic clasts. Paleosols with carbonate-cemented rhizoliths are common (Fig. 7E). The original thicknesses of Qs2 and Qs3 strata are not known and may have been variable across the Camarillo fold belt. However, where the base and apparent top are exposed within folds of the Camarillo fold belt, terrestrial strata have a near uniform thickness of 40–60 m.

Our initial OSL geochronology investigation of the basal age of Qs2 strata using OSL on quartz mineral separates was inconclusive. With the exception of sample 4 (Table 2), all OSL analyses indicated the strata were saturated with respect to the luminescence signal, indicating that the onset of Saugus deposition occurred prior to 45 ka (time of quartz OSL saturation). The apparent younger age of sample 4 (35 ± 10 ka) is inconsistent with all other OSL samples from Qs2, including the bed that sample 3 was taken from, which lies stratigraphically above the former. Sample 4 also had a high equivalent dose ($D_{eq}$) scatter (28% of the mean) compared to all other samples in this study (mean = 10%; Table 2), which is an indication of insufficient bleaching or contamination by younger sediments (see Discussion section in Devvecchio et al., 2012).

Due to saturation or near saturation of quartz samples, we utilized IRSL on feldspar mineral separates from the same sample sites where quartz separates were collected to determine the depositional age of the base of the Qs2 deposits (Fig. 4A). IRSL samples 5–7 gave ages of $84 ± 7$ ka, $78 ± 6$ ka, and $85 ± 6$ ka, indicating that the base of the Saugus Formation in the central and western part of the Camarillo fold belt is ca. 80 ka in age (Table 2; Fig. 4A). In the eastern part of the Camarillo fold belt, a slightly older IRSL age of $125 ± 9$ ka (sample 8, Table 2) was obtained from the base of the Saugus Formation (Qs3). A sample collected ~30 m down section from sample 8 from near the base of the Las Posas Sand gave a stratigraphically consistent age of $141 ± 10$ ka (Fig. 4A; sample 9, Table 2).

Stratigraphy and Age of Qt1 Terrace in the Las Posas Valley

The Qt1 strath is cut on the south limb of the Oak Ridge anticline, extends for >10 km in an east-west direction (Fig. 4A), and is the highest terrace level in the Las Posas Valley (Fig. 5). The planar surface of Qt1 is well preserved and is easily mapped on topographic maps and in the field (Fig. 8A), and it presently dips $2°–3°$ southwestward, which is, in part, likely due to tectonic tilting. The strath is beveled onto tilted Oligocene Sespe and Pleistocene Saugus Formation (Qs1) strata (Fig. 4A). With the exception of the easternmost remnants of the Qt1 strath, sediments are absent; therefore, we mapped the strath surface. However, where terrace cover sediments are present, they are as thick as 3.5 m (Fig. 8A) and characterized by one to two depositional units of trough cross-bedded sand and pebble gravel composed of igneous, metamorphic, volcanic, and sedimentary rocks.

A single IRSL sample and six TCN samples (one depth profile) were collected from the same exposure in the eastern part of the study area, where the strath cover sediments were well exposed and the terrace surface showed no evidence of degradation (Figs. 4A and 8A). Results from the IRSL analysis showed very good luminescence properties, with bright luminescence signals, very good growth curve properties, and small errors of the individual recycling points, and gave an age of $97 ± 7$ ka (sample 10, Table 2). We utilized the lower four points of the Qt1 depth profile, which linear regression determined to be a very good fit, and gave an age of $98 ± 5$ ka (Fig. 8B; Table 3). We excluded the surface sample due to the poor fit, assuming that it may have been affected by postdepositional processes such as bioturbation or slope wash from adjacent topography, and assumed no change in the surface over time (e.g., no erosion or inflation). Monte Carlo simulations after Hidy et al. (2010) of these four samples produced an age of $102 ± 13$ ka (Fig. 8C). Larger errors result from our input parameters, which include variable sediment density, minor changes in surface erosion (0–5 cm), and variable erosion rates (0–0.4 cm/k.y.). Additional Monte Carlo simulations of the points using larger erosion/inflation uncertainty estimates for the surface (+0.1 to −0.5 m, respectively) produced similar best-fit and mean age profiles, but with larger resulting errors (Appendix B [see footnote 1]).
Figure 7. Photographic collage highlighting several of the important key distinguishing sedimentological characteristics of the Qs3 and the Las Posas Sand in the Camarillo fold belt. (A) Photo mosaic of deformation on the northern and central splays of the Santa Rosa fault zone (see DeVecchio et al., 2012). Note the strath that truncates the deformation zone. The strath is fragmented and discontinuous and covers less than 100 m². Although it could not be dated, we estimate an age of 37 ka (see discussion for details). (B) Contact between terrestrial Q3 strata and the marine Las Posas Sand. (C) Cross-bedded granitic sand of the Las Posas Sand containing abundant shell fragments. (D) Carbonate-cemented bivalve hash excavated from the Las Posas Sand near the upper contact. (E) Close-up photo of stacked paleosols characteristic of Qs3 and Qs2 units. (F) Infrared stimulated luminescence (IRSL) sample site location near the base of Qs2 (sample 7, Table 2).
Stratigraphy and Age of the Qt2 Terrace in the Las Posas Valley

The Qt2 terrace level is exposed along both sides of Calleguas Creek in both Las Posas Valley and within the Camarillo fold belt (Fig. 4A). The Qt2 strath dips less than 1° westward, parallels the profile of Calleguas Creek, and is cut into the Sespe, Las Posas Sand, and the Saugus Formation (Qs1, Qs2, and Qs3). Local faulting has variably uplifted the strath within the study area (see fig. 12 in DeVecchio et al., 2012). The surface has been extensively urbanized, and few exposures of the terrace gravels persist. Where present, sand and gravel beds are thin (<3 m) and contain clasts composed of Monterey Shale and volcanic and plutonic rocks.

Two quartz OSL ages were collected from Qt2 cover sediments in two different locations separated by 15 km (Fig. 4A). Sample 11, collected from eastern part of the study area, gave an age of 25 ± 2 ka, while the downstream sample gave an age of 27 ± 4 ka (Table 2, sample 12). Both OSL ages are within error of previous radiocarbon results of (23,000 ± 1000 cal yr B.P.; Table 1).

Stratigraphy and Age of the Qa1 Fill in the Las Posas Valley

The Qa1 deposit forms a broad geomorphic surface in the West Las Posas Valley and fills paleodrainages cut into the south flank of the Oak Ridge uplift, forming flat-floored valleys that extend to within 150 m of the range crest (Fig. 9). These sediments are currently being incised by modern drainages and have an exposed thickness of ~15 m (Fig. 5). Based on subsurface data of Hanson et al. (2003), Qa1 deposits do not exceed 20 m in the Las Posas Valley. Where exposed, the unit is composed of massive greenish silt and sand and contains fragments of Monterey Shale, which are exposed along the crest of the Oak Ridge uplift (Fig. 4A).

Two OSL samples were collected and dated from the Qa1 surface (Fig. 4A). Due to greater incision of the surface toward the East Las Posas Valley, sample 13 was collected from a deeper stratigraphic position below the Qa1 surface, which was likely near the base of the deposit and gave an age of 13 ± 1 ka (Table 2). Sample 14 was collected 9 km to the west from within the upper 1 m of the Qa1 surface and gave an age of 5 ± 1 ka (Fig. 4A).

Figure 8. Sample location and TCN data from Qt1 in the Las Posas Valley. See Figure 4A for location. (A) Photograph of the sample site location showing the location of the IRSL sample and TCN profile. The uppermost TCN depth profile sample was excluded, see text for discussion. TCN—terrestrial cosmogenic nuclide. (B) Age interpretation based on conventional linear fit to data assuming an exponential decay of production rates (5.52 atoms/g/yr for this site) with depth. Gray shaded area shows 2σ error on linear fit. (C) Age results from analysis of 100,000 Monte Carlo simulations after Hidy et al. (2010). See Table 3 for production rates and model parameters and text for method details. Linear fit and Monte Carlo simulations suggest an age of ca. 100 ka for the Qt1 surface.

Figure 9. View of the top of Qa1 fill deposits on the south flank of South Mountain (view to the north). See Figure 4A for location. Note the broad flat-floored valley composed of Qa1 deposits that locally extend from the west Las Posas Valley northward to within 150 m of the crest of South Mountain. Qa1 deposits fill incised paleodrainages on the uplifting Oak Ridge hanging wall and structural lows north of the Camarillo fold belt.
Exposure Ages for Qt6a Terrace Boulders in the Ojai Valley

Six boulders from the Qt6a terrace were sampled for exposure dating in order to constrain the stabilization ages for the surface. All the boulders stand >0.5 m tall above the surface of the grassy terrace tread (Fig. 10A). The boulders are made up of very hard, Eocene sandstone that outcrops north of the terraces in the Topatopa Mountains (Fig. 4B), and they are interpreted to have been rapidly exhumed and transported from a nearby hillslope source area in the Topatopa Mountains. These boulders were likely deposited during floods or by debris flows while the Ventura River was laterally abrading the underlying bedrock. As such, we interpret these boulders to have little to no inheritance, although the absolute inheritance value is unconstrained. The boulders have the same composition and are similar in size to boulders found in the active channel and floodplain of the Ventura River (Fig. 10B), although the terrace boulders are much more rounded than those in the active channel. The rounded nature of the boulders may be due to in situ erosion or spallation since they were deposited (e.g., Zimmerman et al., 1994), although there is no evidence for boulder toppling or movement since deposition.

Six numerical dates were obtained from five boulders on the surface and are shown on Figure 10C. Boulder samples 6a-1a, 6a-2a, and 6a-6a were run on the accelerator mass spectrometer at the UA Accelerator Mass Spectrometry Laboratory (Table 3). Samples 6a-2l, 6a-3l, and 6a-5l were run at LLNL Center for Acceleration Mass Spectrometry (CAMS). Samples 6a-2l and 6a-2a are aliquots from the same boulder and have overlapping age errors (Table 3). We chose to use the age and error for 6a-2l for our calculations because it has a smaller error, and the average falls within the error range of 6a-2a. The weighted mean for the five boulders, assuming no erosion, is 36 ± 3.5 ka (Fig. 10C). This result based on zero erosion represents the minimum boulder age. A second age was determined for the boulders by assuming 26 cm of erosion from the surface. This 26-cm-erosion model corresponds to an erosion rate of 6 mm/k.y. and represents an arbitrary, but plausible, erosion amount for boulders sitting at the surface during the late Pleistocene and can account for the obvious rounding of the boulders. For example, such a rate would account for 26 cm of erosion over 42,000 yr and is within the range of the rates interpreted for boulder spallation from fires (Zimmerman et al., 1994). The resulting weighted mean age for the surface is 43.4 ± 5.7 ka. Thus, the age of 36 ± 3.5 ka should be considered a minimum age for the surface.

Depth Profile Ages from the Qt5a Terrace in the Ojai Valley

For the Qt5a data in the Ojai Valley, the data do not fit an exponential curve (Fig. 6B). We can still use the data, however, because they do decrease with depth. We added 35 cm and 51 cm to the profile because there has been some erosion of the surface (Figs. 6C and 4D). A value of 35 cm of erosion was determined based on reconstructing the rounded edge of the road cut (Fig. 6A), and 51 cm was reconstructed by adding the A soil horizon back onto the surface based on detailed soil description from the same surface at another location by Rockwell (1983). A simple linear regression for the Qt5 data provides ages of 5.6 ± 5.4 ka (2σ error) and 7.2 ± 7 ka (2σ error) for 35 and 51 cm, respectively. Large errors are due to the poor linear fit of the data, but this nonetheless places the terrace surface as Holocene in age.

Figure 10. TCN surface data from boulders on the Qt6a strath. (A) View of boulder 6a-5. Notice the roundness of the boulder, suggesting postdepositional spallation. (B) Active Ventura River channel (right) and young (<250 yr) terrace showing modern example of boulder sampled from the Qt6a surface. (C) Data points show age values with 2σ error for all samples assuming no erosion of the surface. Age in zero-erosion model is weighted mean of all samples except 6a-2 (l) (see text for explanation). LLNL—Lawrence Livermore National Laboratories; UA—University of Arizona.
The Monte Carlo approach described here was applied to the technique of Hidy et al. (2010) and yields a best-fit age of 6.5 ± 4 ka. The solution, however, does not fit within a 2σ error envelope and is only an approximation, although this result does fall within the range of the linear regression fits.

DISCUSSION

Effects of Southern California Paleoclimate on Landscape Evolution

We compared the geochronology results to late Pleistocene to Holocene climate proxy data and local sedimentation rates in Southern California. The paleoclimatology of Southern California is moderately well constrained through field-based geologic studies (Bull, 1991), paleolimnology (Kirby et al., 2006, 2007; Bird and Kirby, 2006), pollen records and precipitation proxies (Heusser, 1995, 1998), sedimentation rates tied to isotope stratigraphy (Kennett, 1995), and eustatic sea-level estimates (Chappell et al., 1996). These records are graphically illustrated in Figure 11 and were used to infer the effects of late Pleistocene climate oscillation on the evolution of depositional and erosional processes that have sculpted the landscape of the Western Transverse Ranges. For example, aggradation events in the San Gabriel Mountains, Mojave Desert, and central California are widely recognized across the Pleistocene-Holocene transition beginning ca. 15 ka and continuing until ca. 4 ka (Fig. 11; e.g., Melton, 1965; Ponti, 1985; Wells et al., 2003; Rennae et al., 1990; Bull, 1991; Harvey et al., 1999). In the Las Posas Valley, this aggradation event is recorded by accumulation of 20 m of Qa1 sediments between ca. 13 ka and 5 ka (Table 1). Aggradation is inferred to be the result of transient vegetative conditions in response to warmer, drier climate during the termination of the Last Glacial Maximum (Termination I) (Fig. 11) and consequent moderate hillslope destabilization (i.e., Bull, 1991). This is supported by an interval of 13 k.y. of rising eustatic sea level (18–5 ka) and pollen records from the Santa Barbara Channel, which indicate a flora change from pine forest through oak/juniper woodland to chaparral, delineating the change from relatively wet, cool Pleistocene climate to dry, warm, semiarid Holocene climate (Fig. 11). Although slightly out of phase with other environmental changes, sedimentation rates in the Santa Barbara Channel increase from 1.4 mm/yr to 1.9 mm/yr from ca. 20 to ca. 10 ka, suggesting links between deep-marine sedimentation, terrestrial aggradation, and increased river sediment loads (Fig. 11). Unfortunately, no published proxy records for Southern California precipitation exist for the period from 65 ka to 150 ka; therefore, we inferred precipitation over this interval (Fig. 11) and, where needed, these inferences are discussed more extensively below.

Saugus Formation Deposition in the Las Posas Valley and Camarillo Fold Belt

Situated on the Camarillo shelf during the Pleistocene (Yeats, 1965), the depositional and erosional environments of the Camarillo fold belt evolved differently than regions to the north (Fig. 12A). The lack of accumulation and/or preservation of Qs1 in the Camarillo fold belt is arguably the most significant difference due to its importance to assessing rates of active tectonics. Uplift of the Santa Susana Mountains northeast of the Camarillo fold belt occurred at ca. 800 ka (Saul, 1975; Treiman, 1982), by which time, progradation of Santa Clara River sediments (Saugus sediments) from the San Gabriel Mountains had reached to the Las Posas Valley area, as indicated by deposition of Qs1 at the Moorpark mammoth site (Fig. 12B). Yet, shallow-marine sediments in the central part of the Camarillo shelf continued to be deposited until 450–750 ka, based on AAR analysis of shells from the Las Posas Sand (Fig. 12B; Table 1).

Uplift of Oak Ridge hanging wall at 500–200 ka (Yeats, 1988a) produced no change in depositional environment or sediment composition preserved in the Las Posas Sand accumulating on the Camarillo shelf (Fig. 12C). The absence of any lithologic change in the Las Posas Sand subsequent to tectonic uplift to the north likely reflects recycling of Santa Clara River sediments from the unlithified Qs1, now being eroded from the Oak Ridge hanging wall. In addition, longshore currents may have carried Santa Clara River sediments to the shelf through the isolated shallow-marine embayment (Fig. 12C). We interpret the absence of any volcanic material derived from the Santa Monica Mountains to indicate that fairly low local erosion rates and sediment input to the shelf were overwhelmed by the volume of sediment from the Santa Clara River and/or from erosion of unlithified Qs1.

Erosion of the eastern part of the Camarillo shelf during the middle Pleistocene is indicated by the relatively young basal age of the Las Posas Sand compared to the older AAR age farther west (Fig. 12C). Erosion likely occurred ca. 140 ka in response to relatively low sea level (115 below msl), correlating to the penultimate glacial maximum at the end of marine oxygen isotope stage (MIS) 6 (Fig. 11). Marine transgression during Termination II at ca. 130 ka is indicated by the OSL age of 141 ± 10 ka from the base of the Las Posas Sand (Fig. 11). Although it is not known whether Qs1 sediments had previously prograded across the eastern part of the shelf and were eroded away during the middle Pleistocene, the conformable contact between the Las Posas Sand and Q3 strata to the west suggests Q1 did not prograde across the central and western Camarillo shelf. We suspect that the central and western part of shelf did not experience significant erosion during the penultimate glacial maximum due to a down-to-the-west Pleistocene topographic break in the shelf, which corresponds to the location of a late Miocene fault (Fig. 12C) (DeVecchio et al., 2012).

After a relatively short interval (~10 k.y.) of marine deposition on the eastern shelf, Qs2 sediments began prograding westward, and by ca. 80 ka, Saugus strata had completely capped the Las Posas Sand (Fig. 12D). We do not have enough numerical data to determine whether westward progradation of terrestrial sediment was continuous from ca. 125 ka to 80 ka or whether progradation of Qs2 and Qs3 represents discrete depositional events. However, what is surprising is that all four numerical ages from the bases of Qs2 and Qs3 indicate that the transition from marine to terrestrial sedimentation was everywhere coincident with periods of relatively high sea level (MIS5e and MIS5a, respectively; Fig. 11). This strongly argues against eustatic sea-level forcing of terrestrial progradation. Accompanying the change in depositional environment, there was a change in sediment composition, from a predominantly plutonic source to a local source at Oak Ridge and the Santa Monica Mountains, which could suggest a tectonic control. For example, uplift of the Santa Susana Mountains is inferred from a synchronous change from a plutonic source to a local source and rapid progradation of the Saugus Formation in the Simi Hills (Saul, 1975; Treiman, 1982) (Fig. 1). Such a tectonic model in the Camarillo fold belt, however, is not preferred for two reasons. First, if uplift of the Oak Ridge did not begin until ca. 125 ka, shortening rates would be in excess of 20 mm/yr, which is not supported by geologic (Yeats, 1993) or geodetic surveys across the region (Donnellan et al., 1993; Argus et al., 1999). Second, uplift of the Oak Ridge hanging wall could not explain the synchronous appearance of volcanic clasts coming from the Santa Monica Mountains at that time. Therefore, we suggest that the change in sediment composition and progradation of terrestrial strata across the Camarillo shelf were the result of a climate-driven increase in denudation of topographic highs and increased sedimentation rates in topographic lows.

Using the well-documented aggradation event in response to Termination I as an example (see previous section), we infer that climate-
Figure 11. Geochronology, paleoclimate proxy data, and sedimentation data in Southern California. Hillslope vegetation from ca. 140 ka to the present is inferred from pollen records from the Santa Barbara channel (Heusser, 1995). Precipitation proxy data from the past 65 k.y. are inferred from paleolimnology data from Baldwin and Elsinore Lakes in Southern California (Kirby et al., 2006; Bird and Kirby, 2006), and pollen record of Heusser (1995). See text for discussion of inferred precipitation from 140 ka to 60 ka and for links between the disparate data sets. All numerical ages from this study and terrace ages of Rockwell et al. (1984) were plotted using “Camel plot” geochronology script downloaded and methodology described at: http://cosmognosis.wordpress.com/2011/07/25/what-is-a-camel-diagram-anyway. Bold gray dotted and solid lines show total probability distribution functions for all numerical data and just strath terrace ages, respectively. Shaded bars correlate to intervals of relatively dry climate inferred from vegetation changes and paleolimnology studies. Note that most strath terrace levels and aggradational events (Qs3, Qs2, Qa1) are well correlated to intervals of dry climate. MIS—marine oxygen isotope stage.
driven aggradation in response to similar environmental changes occurred following the end of the penultimate glaciation ca. 125 ka. Figure 11 clearly shows a change from conifer forest through oak/juniper woodland to chaparral at both glacial-interglacial transitions; therefore, we infer a similar change from semihumid to semiarid climate conditions following Termination II. We suggest that progradation of Q2 sediments at 125 ka was the result of climate-controlled environmental changes that resulted in destabilized hillslopes and consequent increased local erosion rates and elevated river sediment loads. This is supported by a contemporaneous 10 k.y. period of 5× increase in sedimentation rate, from 0.3 m/k.y. to 1.6 m/k.y., in the Santa Barbara Channel (Fig. 11). Although somewhat less clear, progradation of Q3 beginning at ca. 80 ka was, similarly, contemporaneous with a decrease in nonarbooreal pollen in sediment cores, suggesting drying of the atmospheric regime and a potential for transient hillslope conditions, which may have led aggradation at that time. These results, together with aggradation of Qa1 at the Pleistocene-Holocene transition, suggest that climate likely exhibited a first-order control on the evolution of Pleistocene stratigraphy within the actively deforming Western Transverse Ranges. The upper age of Qs2 and Qs3 is based on correlation of these deposits with similar strata mapped throughout the Ventura Basin, which is discussed below.

Saugus Correlation in the Camarillo Fold Belt and Las Posas Valley

Based on the conformable contact between Qs2 and Qs3 with the underlying Pleistocene Las Posas Sand in the Camarillo fold belt, terrestrial sediments in the Camarillo fold belt are lithostratigraphically correlatable with the upper Saugus Formation, as previous researchers have suggested (e.g., Kew, 1924; Pressler, 1929; Jakes, 1979; Dibblee, 1992a). Yet, significant differences in age and composition warrant additional scrutiny. The oldest Saugus stratum in the Camarillo fold belt (125 ka) is 85–375 k.y. younger than the well-cited upper age limit of the Saugus Formation (200–500 ka). Additionally, in the southern Camarillo fold belt, sediment identified as Saugus Formation (Qs4, Fig. 4A) in consulting reports (Earth Systems Southern California, 2005; Geosoils Inc., 2007) has an upper age limit of 125 ka. Therefore, the Saugus Formation in the Camarillo fold belt does not have a San Gabriel source and therefore is compositionally different from Qs1 in the Las Posas Valley (Fig. 4A). Although formally defining a new stratigraphic member of the Saugus Formation is beyond the scope of this paper, we, however, use the name “Camarillo member” of the Saugus Formation when referring to Qs2 and Qs3, which are exposed within the Camarillo fold belt, to avoid temporal and genetic inferences associated with Saugus strata elsewhere in the Ventura Basin.

Figure 12. Schematic diagram illustrating the stratigraphic evolution of the Las Posas region from the early Pliocene until ca. 75 ka. Darkly shaded areas represent topographic features during the different time slices, whereas lightly shaded areas represent modern topographic features that have not yet developed. (A) Shallow-marine sediments accumulate on the Camarillo shelf, while thick accumulations of Pliocene–Pleistocene marine strata accumulate elsewhere. (B) Santa Susana Mountains begin uplifting. Terrestrial Saugus Formation (Qs1) progrades across the Santa Clara River Valley and future location of the Oak Ridge uplift, while to the south and west marine deposition continues. Black star illustrates the approximate location of the Moorpark mammoth site, whereas hollow star shows the location of amino acid racemization (AAR) age estimate on fossil bivalve. (C) Uplift along the Oak Ridge fault isolates the Las Posas Valley from the Santa Clara River. At ca. 130 ka, Las Posas Sand accumulates on a shallow embayment between the Santa Monica Mountains and the South Mountain–Oak Ridge uplift. (D) Progradation of Qs2 and Qs3 across the shelf occurs between ca. 125 ka and ca. 75 ka. During this interval, a single large strath (Qt1) is cut on the south flank of the Oak Ridge hanging wall.
A compelling similarity exists between the Camarillo member and the sediments of the Mugu aquifer identified in countless subsurface wells (Fig. 3). Within the Santa Clara and Las Posas Valley groundwater basins, the upper aquifer system is composed of the Mugu, Oxnard, and Shallow aquifers, which unconformably overlie the lower aquifer system, consisting of the Hueneme and Fox Canyon aquifers (Fig. 3) (Hanson et al., 2003). The lower aquifer system has a Santa Clara sediment source and is correlated to the Saugus Formation of Kew (1924) (Fig. 2), with the Fox Canyon aquifer characterizing the lower Saugus member, the Las Posas Sand of Dibblee (1990, 1992a, 1992b) (Hanson et al., 2003). The upper aquifer system, including the Mugu, has a local source south of the Oak Ridge fault and a Santa Clara River source north of the fault (Hanson et al., 2003), indicating accumulation of the upper aquifer sediments after the uplift of the Oak Ridge hanging wall (<200 ka, post-Qs1 Saugus). Similar to the Camarillo member of the Saugus Formation, the Mugu aquifer sediment consists of interbeds of sand, gravel, and silt that have a near-uniform thickness (40–60 m) and that accumulated during a period of oscillating highstand sea level (Turner, 1975; Greene et al., 1978; Dahlen et al., 1990; Dahlen, 1992). Finally, an offshore marine terrace that is correlated to highstand sea-level events at 75 ka or 60 ka (Fig. 9 of Dahlen, 1992) overlies the Mugu aquifer, suggesting that the age of the Mugu sediments is similar to that of the Camarillo member (<200 ka to 75 ka). Therefore, we suggest that the Camarillo member of the Saugus Formation exposed in the Camarillo fold belt is represented by the Mugu aquifer sediments in the subsurface.

The main difference between the sediments of the Mugu aquifer and the Camarillo member is that the base of the Mugu is defined by a late Pleistocene angular unconformity (Turner, 1975; Dahlen, 1992), whereas the Camarillo member is concordant with the Las Posas Sand in the Camarillo fold belt. We suggest that this difference has simply to do with the local timing of deformation in the Ventura Basin. Specifically, deformation in the Santa Clara River Valley and in the Las Posas Valley (Oak Ridge hanging wall) is older than the Mugu sediments, in contrast to deformation in the Camarillo fold belt, which postdates the Mugu/Camarillo member sediments. It seems likely that the regional Pleistocene unconformity at the base of the Mugu aquifer in the Ventura Basin is the same unconformity observed at the base of the Las Posas Sand in the eastern Camarillo shelf, correlating to lowstand sea level during the penultimate glacial maximum. Therefore, we suggest a lower age of 140 ka for Mugu aquifer sediments throughout the Ventura Basin, which provides a new chronostratigraphic datum from which to estimate the timing and rates of deformation from subsurface data in this part of the Western Transverse Ranges.

Cosmogenic Geochronology of Strath Terraces

New TCN data from both the Las Posas and the Ojai Valleys provide quantitative age estimates for strath terrace formation. The Qt1 depth profile age in the Las Posas Valley agrees well with age results from IRSL indicating the surface has an age of ca. 100 ka (Table 2). This age overlaps the age estimate of 94 ± 13 ka for Qt6a, the highest preserved terrace surface above the Ventura River (Rockwell et al., 1984). Although we cannot be certain that these extensive preserved terrace remnants correlate, the similar ages within different tectonic settings suggest a climatic origin for these broad erosional surfaces.

Surface exposure ages from boulder samples collected on terrace Qt6a along the Ventura River suggest a surface age of 36 ± 3.5 ka to 43 ± 5.7 ka, based on zero erosion and maximum erosion rate estimates (6 mm/k.y.) for the boulders (Table 3; Appendix C). The actual erosion rate for the boulders on Qt6a is unconstrained. A study of moraine boulders in Wyoming, however, determined that fire-induced erosion rates of boulders during the late Pleistocene ranged from 6 to 0.3 m/m.y. (Zimmerman et al., 1994). Although the Wyoming boulder composition and climate are different than in Southern California, we know of very few other examples of in situ boulder erosion rate studies, and we use the maximum erosion rate to provide a range for the Qt6a boulders. This erosion-corrected age overlaps newly calibrated 14C ages (~40,000 cal yr B.P.; Table 1) from the same surface (Rockwell et al., 1984).

Surface Qt5 in the Ojai Valley yielded a depth profile that did not fit an exponential curve (Fig. 6B; Appendix E [see footnote 1]). This could be due to the low number of clasts (<50) per sample (for discussion of this problem, see Hidy et al., 2010), or because of the variable clast sizes used in the analysis (1–5 cm). Nonetheless, linear regression and Monte Carlo simulation of the data suggest a Holocene age for the terrace formation. The cosmogenic age of ca. 6 ka from terrace surface Qt5 in the Ojai Valley is problematic because it is much younger than the previously reported age range for the Qt5 surfaces (16–32 ka; Table 1; Rockwell et al., 1984). This surface (preserved at the Villanova Preparatory School adjacent to San Antonio Creek in Ojai, California), although correlated to Qt5b in the Ventura River Basin (Rockwell, 1983), may in fact be correlative with the Qt4 (8–12 ka) surface observed by Rockwell et al. (1984). This age discrepancy highlights the complexity in the local timing of strath formation within discrete drainage basins.

Strath Terrace Formation

One of the most challenging aspects of field-based studies of strath terraces is the interpretation of the genetic relationship between the terrace cover sediments and underlying strath surface. Most terrace deposits in the study areas are thin (one channel depth) and assumed to have been deposited during strath cutting (Gilbert, 1877; Mackin, 1948). In this case, the sediments represent the tools responsible for cutting the strath, and hence the age of the sediments overlaps with the timing of valley-bottom widening. However, because straths might take 103–104 yr to develop (Hancock and Anderson, 2002), progressive lateral migration of the channel across the strath would result in the replacement of older deposits with younger alluvial fill (e.g., Wegmann and Pazzaglia, 2009). Therefore, multiple terrace ages from a single terrace level should represent the minimum interval of strath formation (e.g., Wegmann and Pazzaglia, 2002). Age results from Qt2 in the Las Posas Valley, which was dated in three locations along a 20 km profile of Calleguas Creek, indicate a relatively short period of strath cutting (~9 k.y.) when geochronological confidence intervals are considered (Fig. 11). However, all numerical ages are within error, suggesting the strath cover sediments may record a specific event at 23 ka (Fig. 11), such as incision and abandonment of the strath. In either case, geochronologic results from terrace deposits in the study area appear to place close temporal constraints on the minimum age of strath cutting.

The mechanism for strath cutting is more problematic to interpret from our data. Montgomery (2004) showed that in areas of weak bedrock and where extreme wet-dry cycles existed, lateral stream erosion rates are equal to or greater than incision rates (mm/yr to cm/yr). Similarly, the formation of strath terraces in northern Italy appears to be strongly influenced by bedrock type, which consequently affects the volume of sediment in the channel (Wegmann and Pazzaglia, 2009). These results are supported by numerical and mathematical models that suggest changes in sediment and water supply have causative effect on the formation of strath terraces (i.e., Hancock and Anderson, 2002; Finnegan et al., 2007). The new geochronology presented in this study combined with Southern California climate proxy records enables us to test assumptions related to the effects of river sediment load and discharge driven by climate variability on the formation of straths.
Numerical ages from this study were obtained from four different bedrock terrace levels in the Las Posas Valley (Qt1 and Qt2) and the Ojai Valley (Qt6a and Qt6a) and are combined with six terrace levels of Rockwell et al. (1984) and shown on Figure 11. Within the resolution of the data, no good correlation exists between beveling of strath terraces and stable eustatic base level (e.g., Pazzaglia and Gardener, 1993), with terrace ages correlating to periods of rising and falling sea level. Over the past 60 k.y., however, strath terrace ages are reasonably well correlated to relatively dry and/or stormy climate intervals characterized by extreme wet-dry cycles, compared to intervening periods when the climate is inferred to have been wetter and more stable (Fig. 11; Heusser, 1998; Bird and Kirby, 2006; Kirby et al., 2006). If the age of Qt6c from the Ojai Valley is coeval with Qt1, as suggested previously, the highest terrace in both study areas are, similarly, correlated to an inferred relatively dry climate interval ending ca. 100 ka. These observations support models that suggest decreased river discharge plays an important role in establishing equilibrium between sediment load and river transport capacity and consequent strath formation (i.e., Bull, 1979; Hancock and Anderson, 2002).

Placing field constraints on river sediment load during strath cutting is difficult and remains a significant obstacle to evaluating the effect of changing sediment supply on strath formation in the Western Transverse Ranges. The ages of the Qt1 and Qt2 surface in the Las Posas Valley are contemporaneous with an increase in sedimentation rate in the Santa Barbara Channel from 0.7 mm/yr to 1.7 mm/yr and 1.3 mm/yr to 1.7 mm/yr, respectively, suggesting straths are cut during periods of elevated river sediment load (Fig. 11). Similarly, Qt4 in the Ojai Valley is contemporaneous with aggradation events in the Las Posas Valley and elsewhere in Southern California that resulted from increased sedimentation rates due to destabilized hillslopes following the transition to a drier climate. Although we have no evidence to support increased river sediment load for the remaining terrace levels, we suggest that similar climate and hillslope conditions following wet to dry transitions could have resulted in similar increases in transient river sediment loads. This suggests that hillslopes are not weathering-limited and thick soils are capable of developing during intervening wet climate intervals, which typically last between 10 k.y. and 30 k.y. Furthermore, this assumption suggests that hillslope sediments are not transport-limited following the wet-dry transition and that a significant percentage of the stored hillslope sediments is moved through the fluvial network at these times. If these assumptions are valid, it is not possible to deconvolve the combined effects of decreased discharge and increased transient river sediment loads on the formation of strath terraces in the Western Transverse Ranges.

Although we are unable to independently evaluate the effects of discharge and sediment flux on the formation of strath terrace, it is clear that strath formation is the result of climate-controlled effects on the landscape, and, therefore, regional correlation of these landforms and use of these surfaces as strain markers may be appropriate where numerical data are absent. These results are consistent with previous models suggesting that decreased sediment transport capacity, either by increased sediment flux or decreased discharge, leads to channel armorung, which minimizes vertical incision while enhancing lateral channel erosion (i.e., Bull, 1979; Sklar and Dietrich, 2001; Hancock and Anderson, 2002; Finnegan, et al., 2007). With the exception of the Qt5b terrace in the Ojai Valley, the absence of terrace ages during semihumid climate intervals suggests that incision and terrace formation likely occur when elevated water discharge results in incision (Fig. 11). However, if climate change is the only forcing mechanism, then why do the terrace records differ? Specifically, only one strath terrace developed in the Las Posas Valley in the past 65 k.y., whereas five terrace levels developed in the Ojai Valley over that same interval. Furthermore, the Qt2 terrace in the Las Posas Valley has no age-equivalent surface in the Ojai Valley (Fig. 11). The simplest conclusion that explains both why the Qt2 has no age equivalent and why the Qt5b surface is out of phase with a dry climate interval is that the Qt5b radiocarbon age of Rockwell et al. (1984) overestimates the age of the surface by 5–7 k.y. Radiocarbon age overestimates are not uncommon because charcoal can be stored in hillslope deposits for thousands of years and remobilized and incorporated in the terrace sediments. This seems particularly probable in our conceptual model of strath formation, where there is strong evidence for significant mobilization of stored hillslope sediments during the transition from wet to dry periods. Therefore, we suspect that the Qt5b terrace is coeval with the Qt2 terrace, which formed during a semi-arid climate interval at ca. 25 ka (Fig. 11). Alternatively, Qt5b may represent a complex response terrace (Bull, 1991) or may have resulted from pulsed evacuation of hillslope and colluvial hollow sediments (Reneau et al., 1990) due to transport-limited erosional process (see following discussion).

The dearth of strath terraces in the Las Posas Valley is likely a reflection of low preservation due to the local bedrock type (e.g., Garcia, 2006), or it may be the result of its relative proximity to the high topography. Any straths developed in the past 65 k.y. would likely have been cut along Calleguas Creek, which parallels the structural grain of the region and flows through a synclinal valley between the Oak Ridge anticline and Camarillo fold belt (DeVecchio et al., 2012). Pre-Qt2 erosion surfaces would have been cut onto un lithified Qs2, Qs3, and the Las Posas Sand, which are highly deformed in the Camarillo fold belt and are easily erodible. Although not discussed in detail, a discontinuous and fragmented higher-level terrace in the Camarillo fold belt is exposed along the Santa Rosa fault zone and shown in Figure 7. However, because there were no alluvial sediments preserved with which to date the strath, we can only estimate the age of the surfaces. Based on ~100 m of vertical separation between the strath fragment and Calleguas Creek and an uplift rate on the Santa Rosa anticline of 2.7 ± 0.11 mm/yr (DeVecchio et al., 2012), we estimate an age of 37 ± 1 ka, indicating correlation with Qt6a in the Ojai Valley and an interval of semi-arid climate (Fig. 11). Alternatively, aggradation in the Las Posas Valley rather than strath formation may have been the primary geomorphic response to climate change due to its proximal position along the fluvial network compared to the more distal position of the Oak View terraces. This may explain why Qa1 sediments were aggregating and backfilling incised drainages on the south flank of Oak Ridge in the Las Posas Valley while Qt4 was being cut in the Ojai Valley. Similar relationships are observed in Cuyama Valley, north of Ojai in the Western Transverse Ranges, where proximal alluvial-fan deposits prograded ca. 45 ka, 25 ka, and ca. 3 ka (DeLong et al., 2007), which are coeval with strath terraces in both the Las Posas and Ojai Valleys and overlapping in age with relatively dry climate intervals (Fig. 11).

Although we are confident that the combined effects of climate-controlled decreases in precipitation and high transient river sediments are largely responsible for the processes driving lateral planation and the formation of straths in the Western Transverse Ranges, the model does not consider the complexities of hillslope and fluvial processes and the formation of complex response terraces (i.e., Bull, 1991). The presence of multiple terrace levels developed in each of the dry climate intervals in the Ojai Valley between 50 ka and 20 ka (Fig. 11) is not surprising and is likely a manifestation of such dynamic surficial processes. It has been documented that sediment pulses in response to large landslides may drive local strath formation (Fuller and Perg, 2005; Fuller et al., 2009). In this case, transport-limited hillslopes and colluvial hollows may not be completely evacuated following the wet to dry transition (e.g., Reneau et al., 1990), which could result in multiple avulsion events during a single semi-arid climate interval. Such a model suggests that transient river sediment loads may be integral to strath formation and that the effect of
decreased discharge does little more than affect the stability of hillslopes. Conversely, discharge variation may be exclusively responsible for strath terrace formation, in which case, dry intervals may be punctuated with wet periods that enhance river incision rates, enabling a terrace to develop before the river returns to equilibrium during the remainder of the dry interval. In either case, the strong correlation of the strath terrace ages with global climate variability in tectonically discrete regimes indicates climate rather than tectonics is paramount in controlling the formation of these landforms.

CONCLUSIONS

The Western Transverse Ranges tectonic province of California is composed of a discontinuous sequence of late Pleistocene to Holocene sedimentary strata that are being actively deformed along a suite of east-trending reverse and strike-slip faults. Unfortunately, many of these Quaternary strata fall outside the applicability of many geochronological techniques, and therefore numerical dates from the youngest strata are few. Consequently, the timing and rates of Quaternary deformation in the province are poorly defined. However, younger geomorphic features such as strath terraces and late Quaternary aggradational strata, which are ideal for OSL and TCN geochronology, provide a new opportunity to quantify the timing and magnitude of deformation and understand the effects of past climate on the landscape.

Age constraints on the Saugus Formation and equivalents (e.g., Ojai Conglomerate, Santa Barbara and San Pedro Formation) are needed because they are exposed along the entire length of the Western Transverse Ranges and are typically the youngest unit involved in deformation. Geologic mapping, stratigraphic correlation, and numerical dating of the Saugus Formation in the Las Posas Valley allow us to conclude:

1. The Camarillo member of the Saugus Formation in the southern Las Posas Valley and Camarillo fold belt, although lithostratigraphically equivalent to Saugus strata elsewhere in the Ventura Basin, accumulated significantly later. In contrast to terrestrial Saugus strata north of the Camarillo fold belt, which have an age range 2300 ka to 200–500 ka (e.g., Levi and Yeats, 1983), the Camarillo member accumulated from ca. 125 ka until ca. 65 ka. Hence, the entire Camarillo member is half the age of the youngest cited age for the Saugus Formation in the published literature, and locally sediments in the southern Camarillo fold belt identified as Saugus (Qs4) are an order of magnitude younger (25 ka, DeVecchio et al., 2012). These results are not overwhelmingly surprising because the formation is known to be diachronous. However, it is troubling because tectonic rate estimates based on the inferred upper age of the Saugus Formation (>200 ka) appear both in professional reports and in the published literature. These results exemplify the need for caution when interpreting and correlating young deformed terrestrial strata in the Western Transverse Ranges.

2. Because the Camarillo member of the Saugus Formation is significantly younger than Saugus strata north of the study area, the Camarillo member likely evolved by different processes. We correlate the Camarillo member with the Mugu aquifer sediments encountered in numerous water and petroleum wells in the Las Posas Valley, based on similar thickness, lithologic character, local provenance, and overlapping ages. The Mugu aquifer sediments are identified throughout the Ventura Basin in the subsurface, suggesting that a regional aggradation event occurred during the late Pleistocene beginning ca. 125 ka. Aggradation of both the Camarillo member and Mugu aquifer sediments appears to have been in response to increased sediment flux due to destabilized hillslope sediments following the transition from the penultimate glaciation to interglacial MIS5e. This correlation provides a new chronostratigraphic datum for estimating deformation rates from regional subsurface data.

Geochronology results of strath terrace dating in the Las Posas Valley and Ojai Valley were combined with previous age estimates in the Ojai Valley (i.e., Rockwell et al., 1984) and compared to late Pleistocene to Holocene climate proxy data and sedimentation rates in Southern California to assess causative links. Correlation of strath terrace ages with climate-controlled environmental changes enables us to make the following conclusions.

3. In the Western Transverse Ranges, valley-bottom widening in response to lateral bedrock planation occurs during relatively dry climate intervals. Strath formation is interpreted to be in response to decreased incision (vertical erosion) rates due to reduced precipitation and increased river sediment load, which brings fluvial discharge and sediment transport capacity into balance. Strath terraces develop during intervening wet intervals when stream power is increased in response to either decreased sediment load or increased discharge. However, aggradation may predominate in proximal alluvial environments during dry climatic intervals because of high sediment discharge from hillslopes and a lack of upstream drainage basin area.


ACKNOWLEDGMENTS

The initial field work and analytical costs for research in the Las Posas Valley were funded by the U.S. Geological Survey (USGS) National Earthquake Hazard Reduction Program (NEHRP, awards 8HQR0073 and 08HQR0073) and the Southern California Earthquake Center (SCEC, award 120044), a consortium of earthquake scientists funded by the National Science Foundation. Additional support was provided by the University of California, Santa Barbara, in the form of teaching assistantships to support DeVecchio during his dissertation. Ojai field work and cosmogenic laboratory analysis was supported by a USGS Mendenhall research fellowship to R. Heermance. Additional funding was provided by a California State University, Northridge, research grant to Heermance. We thank Villanova Preparatory School and Oak Grove School in the Ojai Valley for allowing us permission to sample on their property. We thank Colin Amos, Frank Pazzaglia, and anonymous reviewers for their constructive comments, which greatly improved this paper.

REFERENCES CITED

Bailey, T.L., 1951, Geology of a portion of Ventura basin: Los Angeles and Ventura Counties, California, scale 1:48,000.
Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., and McAninch, J., Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Micro...


