Research Article

Spatiotemporal Rates of Tectonic Deformation and Landscape Evolution above a Laterally Propagating Thrust Fault: Wheeler Ridge Anticline, California, USA

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The Wheeler Ridge anticline, located in the southern San Joaquin Valley of California, USA, is a well-studied and classic example of a laterally growing fault propagation fold. New high-resolution lidar elevation data combined with nine infrared stimulated luminescence (IRSL) ages of discrete geomorphic surfaces that are bounded by prominent transverse wind and river gaps allow for investigation of tectonic topography through time. Luminescence ages from four of the six surfaces yield depositional ages that range from 32 ka to 153 ka, which are broadly consistent with a previously published soil chronosequence. Our graphical modeling indicates an average surface uplift rate of ~2.1 mm/yr and an average along-strike fold propagation rate of ~20 mm/yr. However, our probabilistic modeling and topographic analysis suggest a rate decrease of both uplift and lateral propagation toward the fault tip from ~2.4 to 0.7 mm/yr and from ~49 to 14 mm/yr, respectively. Rate decreases are not progressive but rather occur in punctuated deformational intervals across previously documented structural barriers (tear faults) resulting in a fold that is characterized by discrete segments that exhibit a systematic deformational decrease toward the east. The punctuated tectonic growth of Wheeler Ridge has also locally controlled the topographic evolution of the anticline by affecting the formational timing and position of at least seven wind and river gaps that result from multiple north-flowing antecedent streams that traverse the growing structure. We quantify the timing of wind and river gap formation, based on IRSL results and inferred incision rates, and present a model for the spatiotemporal evolution of transverse drainages and the topographic development of Wheeler Ridge. Our chronology of gap formation broadly correlates with regional Late Pleistocene dry climate intervals suggesting that both tectonics and climate were integral to the geomorphic development of the Wheeler Ridge anticline.

1. Introduction

The double-restraining bend (the Big Bend) in the plate-bounding San Andreas fault system in Southern California has resulted in broad regions of transpressional deformation both north and south of the bend (Figure 1(a)). Deformation is characterized by numerous east-west trending oblique-slip reverse faults and fault-related folds (Figure 1(a)) [1, 2]. South of the Big Bend in the populous Los Angeles and Ventura Basins, many of these faults are buried by alluvium (i.e., [3–8]). Consequently, faults and folds concealed beneath Quaternary deposits in urban areas expose communities to significant earthquake hazards [1, 9–11]. In fact, some of the largest and most damaging historic earthquakes in Southern California have occurred on these poorly understood structures in urban areas, including the 1952 Kern County (MW 7.3), 1971 Sylmar (MW 6.5), 1987 Whittier Narrows (MW 6.0), and 1994 Northridge (MW 6.7).
earthquakes (Figure 1) [12–17]. In order to better quantify the temporal and spatial growth of such concealed and active (i.e., Holocene) tectonic structures, it is necessary to focus on areas where Quaternary surfaces have been deformed by concealed faults over time, especially in rural areas with minimal post-depositional disturbance by urban expansion.

The Wheeler Ridge anticline, in the southern San Joaquin Valley of California, is the surface expression of a fault propagation fold resulting from transpression north of the Big Bend in the San Andreas fault (Figure 1(b)). On the northern flanks of the San Emigdio Mountains, Wheeler Ridge exhibits clear topographic evidence of both vertical and lateral growth [18–23]. Several seminal studies of Wheeler Ridge were conducted in the 1990s on the subsurface fault and fold structure [20] as well as the landscape evolution of the tectonic topography [18, 19, 21, 23]. Prominent river gaps (stream channels that cut across the structure, also called water gaps) and wind gaps (river gaps abandoned due to uplift) divide Wheeler Ridge into geomorphic domains that record the time-transgressive vertical and lateral (eastward) tectonic growth.
of the fold. Keller et al. [19] developed a soil chronosequence using age control for the youngest surfaces and estimated ages of the older surfaces based on Late Pleistocene climate intervals correlated to marine isotope stages. These projected surface ages were used to estimate rates of tectonic uplift (~3 mm/yr) and lateral (along-strike) fault growth (~30 mm/yr). However, without precise age control of tectonically isolated deposits along the entire length of Wheeler Ridge, the geomorphic evolution of the fold and the timing, magnitudes, and rates of fold growth are unclear.

This paper presents nine new infrared stimulated luminescence (IRSL) ages from uplifted and isolated alluvial fan surfaces, and new geomorphic mapping and topographic analysis based on a high-resolution lidar dataset to better constrain the evolution of this well-known fault propagation fold. New mapping expands and refines the extent of numerically dated geomorphic surfaces isolated by tectonic uplift, as well as identifies previously unrecognized landforms. The IRSL ages suggest that the youngest uplifted deposits are older than previously reported. We calculate more precise rates of surface uplift and propagation along the fold, shedding light on the interplay between complex tectonic topography and geomorphic evolution of Wheeler Ridge. Combining geomorphic mapping, IRSL geochronology, and previous studies, we present an updated model of fold growth and surface process response along the Wheeler Ridge anticline. We compare our model with the most cited models of evolution of surface geomorphology at Wheeler Ridge (i.e., [18, 19, 21]), as well as use deformation rates to quantify the timing of river and wind gap formation (i.e., [24]).

2. Background

The northern extent of thrust deformation at the San Emigdio range front is driven by transpression related to the Big Bend in the San Andreas fault (e.g., [25–28]; Figure 1(a)). The onset of transpressional deformation, northward folding, and thrust-related displacement by the buried Pleito thrust fault along the San Emigdio front is estimated to have initiated 450–700 ka [29]. Uplift rates estimated from retro-deformed sedimentary strata identified in hydrocarbon exploration wells suggest northward propagation of the deformational front onto the Wheeler Ridge fault initiated between 250 and 400 ka (Figure 1(b); [20, 29]). Transfer of strain into the foreland would have resulted in a local decrease in slope within the newly formed piggyback basin, thereby setting up a competition between the erosive power of northward flowing streams from the San Emigdio Mountains and the east-propagating tectonic topography of the Wheeler Ridge fault [18].

The Wheeler Ridge anticline is an east-plunging fault propagation fold [20] with a maximum topographic relief of 455 m at its western extent. The magnitude of surface uplift progressively decreases toward the east along the 12 km long fold axis before disappearing beneath the undeformed modern valley floor at an elevation of ~300 m (Figure 2(b)). The fold is north-vergent and asymmetric with a steeply dipping northern forelimb (50°–70°) and gently dipping southern backlimb (10°–20°) [19]. Folded strata exposed at the surface are composed of Plio-Quaternary medial-to-distal fanglomerates and interbedded sands sourced from small drainages emanating from the San Emigdio Mountains, as well as two larger drainages: Salt Creek and Tecuya Creek (Figure 1(b)). Several prominent wind and river gaps cross-cut Wheeler Ridge (Figure 2(b)); the locations of which have been suggested to be controlled by tear faults that strike perpendicular to the fold axis and accommodate differential uplift and folding of the hanging wall [20, 21, 30]. A fold propagation rate of 25–30 mm/yr has been estimated from the ages of the youngest deformed alluvial fan surfaces at Wheeler Ridge [19, 21].

The most well-known model for evolution of tectonic geomorphology of Wheeler Ridge with respect to growth of the underlying fault was initiated by Zepeda [23] and later expanded upon by Keller et al. [19, 29]. Previous studies identified three geomorphic domains based on their relative location: the western, central, and eastern domains (Figure 2(b)). Domains are differentiated by elevation changes (10s of meters), degree of folding, and drainage densities [19, 21, 31]. Domain boundaries are characterized by the presence of prominent wind and/or river gaps, which traverse the fold roughly perpendicular to its axis. Within and around the three domains, deformed (Q2–Q5) and undeformed (Q1) Quaternary alluvial surfaces were identified, mapped, and correlated based on degrees of soil pedogenesis [19, 23]. Soil pits and mapping of the surfaces were completed partially along the fold crest where erosional incision was at a minimum [23]. Zepeda reported radiocarbon dating results from detrital charcoal and uranium series dating on pedogenic carbonate to quantify soil ages. With the exception of the Q3 surface, numerical ages were obtained from pedogenic carbonates for all surfaces; however, these data produced significant age inconsistencies in comparison to relative geomorphic age relations and largely reflected processes related to later soil development. Consequently, Keller et al. [19] approximated the ages of the different geomorphic surfaces by assuming a climatically driven soil formation model which was correlated to marine isotope stages (MIS) tied to radiocarbon and/or uranium series ages from Zepeda [23] (Q2, 17 ka; Q4, 105 ka or 125 ka) or fold propagation rates (Q3, 60 ka; Q5, 185–400 ka). Using limited data, previous work provided an excellent model for the evolution of Wheeler Ridge; however, no robust geochronology nor detailed geospatial exploration of the uplifted surfaces existed until this study.

3. Methodology

3.1. Mapping and Topographic Analysis. Mapping and topographic analyses were based on digital elevation models (DEMs) derived from an airborne lidar survey (80 km², ~9 pnts./m²), extending from west of the study area to east of Interstate 5 (Figure 2(a); 10.0.19.205/G99K485N). Half-meter bare-earth DEMs were generated from classified airborne lidar data, and derivative products were created including slope, aspect, hillshade, and slope-shade models, as well as elevation contours (Figure 2(b)). Derivative DEM
products were created with Blue Marble GlobalMapper, exported, and used in ESRI ArcMap to complete mapping. The derivative DEMs were used to refine the extents of Quaternary surfaces Q1–Q5 defined by Zepeda [23] and identify wind and river gaps (Figures 2(a) and 2(c)). Field observations and data collection included soil profile descriptions, lidar-based Quaternary mapping using GPS-enabled tablet running GIS software (ArcGIS), as well as structural measurements along the fold axis [32].

Observing and quantifying topographic changes along Wheeler Ridge were critical to this study. Using the half-meter bare-earth DEM in GlobalMapper, numerous topographic profiles were measured in order to interrogate features from the submeter scale to the entire fold. The maximum heights of different domains within the Wheeler Ridge anticline do not occur on a single azimuth (Figure 2(b)). In order to define the maximum topographic envelope, a fold-axis-parallel elevation profile was created using TopoToolbox in MATLAB [33] to show the highest points along the anticline axis. The swath object tool was used to extract a 200 m wide profile along a kinked path connecting the highest points of topography for each domain (Figure 2(b)).

Uplifted alluvial surfaces (Q5–Q2) locally preserve relict alluvial morphology being characterized by broad planar surfaces along the crest and backlimb of the fold. Preservation of
the geomorphic surfaces generally increases toward the younger eastern domain; however, locally incised wind gaps removed large areas of the paleo-surface. Quaternary surfaces were correlated based on numerical ages (this study) and, where present, previous soil chronologies (i.e., [23]), as well as local geomorphic characteristics (e.g., slope, degree of dissection, and relative elevation). Wind gaps were identified by using topographic profiles to show asymmetric saddles at the crest of Wheeler Ridge between correlated surfaces. River gaps were mapped as active channels between uplifted surfaces.

3.2. Luminescence Dating. IRSL dating provides an age estimate for the last time feldspar sand grains were exposed to sunlight by surface processes and thus can be used to infer depositional ages [34–36]. IRSL dating of feldspar was chosen over optically stimulated luminescence (OSL) dating of quartz due to known problems with quartz from Southern California [37] and signs of weak fast-decay components of quartz, which can lead to age underestimates (e.g., [38]). IRSL samples were collected from alluvial fan deposits by driving metal tubes into sand lenses with the exception of one sample that was collected into a light-proof container at night using red-light headlamps (WR2083). Special care was taken to avoid soils and poorly sorted debris-flow deposits, where sediments may have been mixed due to bioturbation or not completely exposed to light prior to deposition. Samples were analyzed at the Utah State University Luminescence Laboratory using the single-aliquot regenerative-dose method of Wallinga et al. [39] on 1 mm small aliquots of 150-250 μm potassium feldspar at 50°C. IRSL results were corrected for anomalous fading (loss of signal over time) using the method by Auclair et al. [40] and the correction model of Huntley and Lamothe [41]. Equivalent dose (D_e) and fading corrected IRSL ages were calculated using the central age model (CAM) of Galbraith and Roberts [42] (Table S-1). Environmental dose rates were calculated from radioisotope concentrations using ICP-MS and ICP-AES techniques and conversion factors (Table S-2). Further details on IRSL measurements and results are found in the Supplementary Materials.

4. Results

We present our IRSL results (Table 1) and geomorphic mapping (Figure 2(c)) in the context of the western, central, and eastern domains at Wheeler Ridge. While previous studies tended to limit mapping of Quaternary surfaces to the crest of the fold, we interpret these terraces on the western backlimb (Figures 2(b) and 2(c)). However, we note that many of the backlimb interfluves are relatively flat-topped suggesting the Q5 surface may extend farther down slope than our mapping illustrates.

At an elevation of ~530 m, a prominent bench wraps around the western backlimb and into the aqueduct gap along the west side (Figures 2(b) and 2(c)). Although 30–40 m higher than the maximum elevation of Q4 in the central domain, we suggest that these may represent the paleo-alluvial Q4 surface deformed in across the central domain. The greater elevation of these benches likely reflects the paleo-slope of the piggyback basin and is consistent with the modern slope of the piggyback basin deposits and the westward projection of Q4 from the central domain (Figure 2(b) inset). Similarly, we map Q4 deposits along broad flat-topped backlimb interfluves of the western domain that increase in elevation from 530 m to 590 m toward the west (Figure 2(c)), which is consistent with the slope of the modern piggyback basin (Figure 2(b) inset).

Two prominent topographic lows that isolate Q5 surfaces on the eastern part of the domain are interpreted to be the oldest wind gaps along Wheeler Ridge (Figure 2(c)). Wind gaps have a relatively flat bottom that have no clear linkage to any stream systems that are currently incising the fore- and backlimb of the western domain (Figure 2(c)). The bottom of the western wind gap lies ~30 meters below Q5 surfaces on either side, whereas the eastern gap is more deeply incised lying ~80 meters below Q5. IRSL sample WR2085 was collected west of the wind gaps from the same place that Zepeda [23] dug a Q5 soil pit. The sample was collected from below a well-developed soil horizon and yielded an age of 153.1 ± 24.0 ka (Figure 2(c); Table 1). The eastern extent of the western domain terminates at the aqueduct wind gap, which is 135 m below Q5.
Table 1: Luminescence age information. IRSL results from Wheeler Ridge, California.

| Q-surface | Domain | Location (UTM) | Elevation (ASL) | Sample number | Depth below Q-surface (m) | Number of aliquots\(^*\) | Dose rate (Gy/kyr) | Equivalent dose \(\pm 2\sigma\) (Gy)\(^7\) | Fading rate g\(^2\)days (%/decade)\(^9\) | Age \(\pm 2\sigma\) (ka)\(^8\) |
|-----------|--------|----------------|-----------------|---------------|--------------------------|--------------------------|--------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Q2        | Eastern| 321703 3875114 | 309             | WR2086        | 2.5                      | 11 (11)                  | 4.36 ± 0.48         | 104.0 ± 6.2                                    | 3.0 ± 0.5                                      | 32.0 ± 4.6                                    |
| Q3        | Eastern (Q3\(_{\text{low}}\)) | 320705 3875089 | 343             | WR2082        | 9\(*\)                    | 11 (11)                  | 3.96 ± 0.43         | 279.8 ± 22.0                                   | 5.0 ± 0.6                                      | 119.9 ± 18.3                                  |
| Q3        | Eastern (Q3\(_{\text{mid}}\)) | 320705 3875089 | 358             | WR2088        | 4.5\(*\)                  | 15 (15)                  | 4.35 ± 0.48         | 272.9 ± 17.7                                   | 6.1 ± 0.7                                      | 120.3 ± 17.6                                  |
| Q3        | Eastern (Q3\(_{\text{top}}\)) | 320500 3875073 | 374             | WR2090        | 7\(*\)                    | 10 (11)                  | 4.56 ± 0.50         | 217.3 ± 16.7                                   | 3.9 ± 0.7                                      | 70.3 ± 10.7                                   |
| Q3/Q4     | Eastern/water gap | 320253 3874554 | 329             | WR2081        | 21                       | 15 (15)                  | 4.53 ± 0.50         | 227.3 ± 21.7                                   | 5.6 ± 0.7                                      | 90.6 ± 14.7                                   |
| Q3        | Central/piggyback | 319778 3874588 | 348             | WR2089        | 4                        | 14 (14)                  | 4.90 ± 0.54         | 195.0 ± 12.0                                   | 4.0 ± 0.3                                      | 59.2 ± 8.6                                    |
| Q4        | Central | 319575 3875516 | 478             | WR2083        | 3                        | 15 (15)                  | 4.42 ± 0.48         | 308.1 ± 27.6                                   | 5.6 ± 0.7                                      | 126.0 ± 20.0                                  |
| Q4        | Central | 319290 3875228 | 443             | WR2084        | 8                        | 22 (23)                  | 4.25 ± 0.46         | 316.0 ± 22.4                                   | 5.4 ± 0.7                                      | 131.4 ± 19.6                                  |
| Q5        | Western | 316136 3876040 | 621             | WR2085        | 16\(*\)                  | 21 (23)                  | 4.13 ± 0.45         | 433.7 ± 37.2                                   | 3.8 ± 0.5                                      | 153.1 ± 24.0                                  |

\(^*\) Number of aliquots used in age calculation and number of aliquots analyzed in parentheses. \(^7\) Infrared stimulated luminescence (IRSL) age analysis at 50°C following Wallinga et al. (2000). Equivalent dose (DE) calculated using the Central Age Model (CAM) Galbraith and Roberts (2012). \(^9\) Average fading rate calculated following the method by Auclair et al. (2003). \(^8\) IRSL age corrected for fading following Huntley and Lamothe (2001). \(*\) Q-surface is modified from mining or oil and gas extraction activities.
4.2. Central Domain. The central domain includes geomorphic surfaces of Q4 and Q3 age that are incised by two prominent wind gaps (Figure 2(c)). The easternmost wind gap within the central domain is ~450 m wide and ~60 m deep. The western wind gap is ~260 m wide and ~20 m deep. Two IRSL samples (WR2083, WR2084) were collected within the upper 3–8 m of the Q4 surface and returned numerical ages that overlap within error (Figure 2(c); Table 1). The eastern sample was collected from the fold crest (WR2083; Figure 2(c)), and the western sample was collected from the top of the backlimb (WR2084; Figure 2(c)). Due to limited coarse-grained sand at the WR2083 sample site, a bulk sample was taken at night and yielded an age of 126.0 ± 20.0 ka (Figure 2(c); Table 1). Sample WR2084 was collected from a drill pad outcrop and yielded an age of 131.4 ± 19.6 ka (Figure 2(c); Table 1).

The Q3 surface is mapped from the lower-backlimb to the piggyback basin south of the central domain. The top of Q3 extends from an elevation of 395 m in the major river gap across the central backlimb into the aqueduct wind gap, where it terminates at a prominent bench at ~400 m of elevation (Figure 2(b)). An IRSL age of 59.2 ± 8.6 ka (WR2089; Figure 2(c); Table 1) from the base of the central backlimb supports the mapping of Q3 from the central backlimb into the piggyback basin.

4.3. Major River Gap. The major river gap, separating the eastern and central domains, was cut by the ancestral Salt Creek prior to diversion by the California Aqueduct in the 1960s, and other piggyback basin streams farther west (Figures 1(b) and 2(a)). Entrenchment of the piggyback basin south of the major river gap by the ancestral Salt Creek has isolated several high surfaces that we correlate to Q2 based on a similar elevation to Q2 south of the eastern domain and degree of dissection (Figure 2(c)). IRSL sample WR2081 was collected from an exposure within the river gap located about 21 m below the Q3 surface on the backlimb of the fold and yielded an age of 90.6 ± 14.7 ka (Figure 2(c); Table 1).

4.4. Eastern Domain. The eastern domain of Wheeler Ridge includes the Q2 and Q3 geomorphic surfaces. There are at least two wind gaps, with the western gap incising into the Q3 surface and the eastern gap separating Q2 from Q3 (Figure 2(c)). The Q3 surface extends west for ~700 m before it is crosscut by the major river gap between the eastern and central domain (Figure 2(b)). The Q3 slopes along the fold axis are tilted ~2–3° and reach a maximum elevation of ~380 m (Figure 2(b)). Q3 is the most continuous and unmodified at the western edge where it is incised into by the major river gap (Figure 2(c)).

Prior to this study, no age control existed for the Q3 surface. Consequently, we dated multiple samples from different stratigraphic depths to validate the age consistency of the Q3 surface. Samples were taken from stratigraphically low (Eastern Domain; Q3_low, WR2082), middle (Q3_mid, WR2088), and upper (Q3_top, WR2090) deposits (Figure 2(c); Table 1). All samples were taken from well-exposed quarry walls (see Figure S-1). The Q3_low (WR2082) outcrop yielded an IRSL age of 119.9 ± 18.3 ka. Q3_mid (WR2088) collected from 16 m below Q3_top (358 m) returned an IRSL age of 120.3 ± 17.6 ka. The Q3_top sample (WR2090) yielded an age of 70.3 ± 10.7 ka. We use the Q3_top numerical age as the representative age for the previously undated Q3 surface as it is coincident with the fold axis, along with other fold-isolated Quaternary surfaces.

Q2 is mapped on the lowest uplifted surface of the eastern domain. It is mapped from just above the valley floor on the forelimb (~300 m) up to the approximate fold axis location (~340 m; Figure 2(b)). Between these elevations, the Q2 and Q3 surfaces are separated by a broad (100+ m) and shallow (3–5 m) wind gaps (Figure 2(c)). The easternmost IRSL sample site is adjacent to the 10 m high eastern escarpment separating Q2 and a Q1 Salt/Tecuyca Creek terrace (Figure 2(c)). The sample site was selected for its proximity to Zepeda’s [23] U-series date and soil description site on the Q2 surface and ease of access to unmodified, sandy-rich deposits ideal for IRSL analysis. Previous age control produced U-series ages ranging from 8 to 12 ka [23], although Keller et al. [19] interpreted these as minimum ages, citing that it can take about 5 kyr to develop carbonate rinds in the region [43]. Our IRSL results yielded an age of 32.0 ± 4.6 ka (Figure 2(c); Table 1).

4.5. Deformation Rates. IRSL age results and fold-axis perpendicular topographic transects were used to bracket surface uplift rates for the western, central, and eastern domains (Figure 3). The magnitudes of surface uplift were estimated based on the difference between the maximum height along the anticlinal crest and a line drawn from the undeformed sediments in the piggyback basin to the foreland of the fold (Figure 3(a)). Magnitudes of uplift were measured at the minimum and maximum heights of Quaternary surfaces along the fold crest (i.e., at the eastern and western extents of each domain), based on geomorphic mapping. These values (Table 2) were plotted as red boxes in Figure 3(b) to illustrate the range of surface uplift along eastward-titled Quaternary surfaces (Q2–Q5) (right-hand axis), and the IRSL ages of those surfaces including the associated analytical errors (horizontal axis). If the rate of uplift was constant along the length of the fold, a rate of ~2.1 mm/yr would be the only solution for all Quaternary surfaces (Table 3; Figure 3(b)). The propagation rate from the graphical method is ~20 mm/yr (Figure 3(b)). Additionally, average surface uplift rates were calculated of the minimum and maximum magnitudes of surface uplift for each Quaternary surface (Table 2, right column).

In order to assess variability in tectonic rates among adjacent Quaternary surfaces (e.g., Q3 to Q2) and domains (e.g., western to central), probabilistic modelling using Monte Carlo sampling of the age (normal) and uplift (Figure S3–S11) and horizontal propagation (uniform; Figure S12–S17) probability distribution functions were determined (see supplementary material). A summary of these results is shown in Figures 3(c) and 3(d). Both Figure 3(c) (uplift rate) and Figure 3(d) (propagation rate) show a systematic decrease. These trends suggest a decrease in tectonic rates from west to east, with the most common modeled uplift rate decreasing from 2.5 mm/yr to 0.7 mm/yr (Figure 3(c))...
Figure 3: Surface uplift and propagation rate calculations using IRSL ages and lidar elevation data at Wheeler Ridge. (a) Topographic profiles taken from the piggyback basin across Wheeler Ridge to the undeformed deposits in the foreland to measure surface uplift between the maximum height of a given Quaternary surface (solid red line) and the projected profile of the inferred undeformed paleo-surface (dashed red line). (b) Graphical calculations of surface uplift and propagation rates at Wheler Ridge using age vs. distance along strike (left y-axis) and magnitude of surface uplift (right y-axis). Red rectangles illustrate the spatial and temporal extents of Quaternary surfaces (Q5–Q2). Assuming a constant rate of deformation along Wheeler Ridge, a best-fit linear regression that passes through all red rectangles suggests an average surface uplift and propagation rate of ~2.1 mm/yr and ~20 mm/yr, respectively (dashed red line). (c, d) Modeled probability distribution functions of surface uplift (c) and lateral propagation (d) rates sampled from uniform surface uplift distributions and normally distributed surface. The resulting sequential histories from surface-to-surface are normalized and trimmed for significance, as well as concatenated to develop this cumulative rate distribution (full pdf is upper solid line). A significance level of 1-sigma (top of grey area) trims the resulting pdf outliers. See text and supplement for more information.
and the most common propagation rate decreasing from 50 mm/yr to 13 mm/yr (Figure 3(d)). However, the ratio of propagation to surface uplift remains relatively constant at ~20:1 within each of the domains (Table 3).

5. Discussion

The goal of this work to build a more robust model of the tectonic and geomorphic evolution of Wheeler Ridge, scaffolded on previous studies, by using IRSL geochronology and airborne lidar data; tools that have become critical to studying actively deforming landscapes in recent decades. Our mapping and topographic analysis suggest a more complicated history of deformation and river and wind gap development than previously presented (Figure 4). We compare our modelled and graphical uplift and lateral propagation rates with a geomorphic model proposed by Hetzel et al. [24] to bolster our field mapping and digital topographic analysis of the occurrence of wind gaps that traverse the topography of Wheeler Ridge (Figures 4(a) and 4(b)). In addition, application of the Hetzel model between geomorphic domains of Wheeler Ridge allows us to evaluate the spatiotemporal geomorphic evolution of the structure and make some inferences about the specific role of the piggyback basin sedimentation to the formation of wind and river gaps.

5.1. Geomorphic Development. There is extensive literature pertaining to the timing of wind gap formation as a proxy for quantifying spatial and temporal development of laterally propagating folds [18, 19, 24, 44–49]. The “Hetzel Criterion” [24] suggests that the position of a river gap with respect to the most recently developed wind gap should be located at or near the intersection of the wind gap elevation, projected horizontally in the direction of fold propagation, and the “topographic envelope,”—the projection of a tectonically isolated geomorphic surface along the strike of the fold (Figure 4(a)). Specifically, when a river gap is abandoned and a wind gap develops, the modeled position of the resulting new river gap should be located near to where the sloping topographic envelope intersects base level elevation (Figure 4(a)). The Hetzel Criterion, similarly, can be applied between older wind gaps to evaluate past positions of antecedent streams which traversed the growing fold (Figure 4(a)). However, the idealized model by Hetzel et al. [24] only accounts for a single antecedent drainage system traversing the active structure, which is not true of Wheeler Ridge today nor was it likely to have been true in the past. In addition, the model does not account for the effects of variability in along strike uplift rates like those indicated in our study. However, by combining the Hetzel Criterion with these unique tectonic and geomorphic conditions at Wheeler Ridge, we are able to shed light on not only the geomorphic evolution of the fold but also aspects of the structural style of deformation (tear faults) and tectonic rates.

Figure 4(b) illustrates the lidar-derived elevation swath profile of the Wheeler Ridge anticline annotated with the position of river gaps, as well as the relative timing of wind gap formation based on our mapping and analysis. It is clear from the stepped topography of Wheeler Ridge crest that there is no simple reconstruction of a single topographic...
envelope that can be fit across the three geomorphic domains, or even within some domains (Figure 4(b)). Yet because the rate ratio of propagation to uplift is constant along strike (~20:1, Table 3), all topographic envelope lines are drawn parallel. These steps in the profile suggest that uplift of Wheeler Ridge was not progressive but was rather...
punctuated in space and time. For example, there is more than a 50 m topographic step between each adjacent domain (blue bars) and a ~24 m step within the central domain (magenta bar). These steps in the topographic envelopes consistently step downward toward the east, and all correspond to the positions of wind and/or river gaps. This could suggest that erosion by the antecedent streams traversing the growing fold beveled the topography of the fold tip before ultimately incising a river gap. Alternatively, as others have suggested, fault perpendicular tear faults (Figure 4(b)) may have limited the lateral growth of the fault through time resulting in punctuated lateral growth of the fold [20, 21]. This is discussed in more detail in the deformation rate section, below. Regardless of the process, application of the Hetzel Criterion to Wheeler shows a strong correlation with the position of river gaps with respect to local topography in the direction of propagation (Figure 4(b)). The validity of this construction of the Hetzel model for Wheeler Ridge is further bolstered by noting that uplift rates (rates in blue) estimated from offsets in the topographic profile (Figure 4(b)) agree well with modelled surface uplift rates (Figure 3) suggesting a rate decrease from west to east.

By combining our modelled surface uplift rate, age results, and the Hetzel model, we infer ages of an undated surface and formation times of wind and river gaps along Wheeler Ridge (Figure 4(c)). Our IRSL ages from the Q4 surface come from samples that were collected from either side of the western wind gap (Figure 4(b), red dots; Figure 3(c)), suggesting an average age of 129 ka for the upper western Q4 surface (Figure 4(b)). The eastern part of the central domain is separated from the western part by a prominent wind gap and downward step in the topography (Figure 4(b)). Based on the 24 m offset in the topographic envelope and using the most common uplift rate between the central and eastern domain of 1.8 mm/yr, we suggest that the eastern region of the central domain is approximately 13 kyr younger than the western region, suggesting an ~116 ka age for the surface, herein referred to as Q4b (Figures 3(c) and 4(b)).

Similar to the technique applied to quantifying the age of the Q4b surface, we use the depth of incision of water and wind gaps into numerically dated surfaces to quantify the timing of gap formation along Wheeler Ridge (Table 4). The relative timing of wind gap formation is shown as a circled number on Figures 4(b) and 4(c), with the highest wind gap (1) being the oldest gap. Because multiple streams traverse the growing fold (e.g., Tecuya and Salt Creek), the timing of wind gap formation is not always sequential in the direction of propagation (Figure 4(c)) as the idealized Hetzel model illustrates in Figure 4(a).

Due to the greater degree of dissection and mass wasting of the western domain, it is difficult to reconstruct the topographic envelope of the fold crest in this region, and therefore, we focused on the eastern part of the domain. We infer that the two prominent topographic lows incised into the Q5 surface to be the oldest wind gaps in the study area. At ~150 ka, two antecedent streams were incising into the western domain (Figure 4(c), lowest panel). From east to west, both of these streams had been defeated by ~120 ka, with their subsequent drainage now being diverted into the aqueduct gap (dashed blue lines, Figure 4(c)), while the ancestral Salt Creek was cutting a river gap through the central domain (red dashed line, Figure 4(c)). By ~90 ka, wind gaps 3 and 4 had developed, and Salt Creek had been diverted into the major river gap that still separates the central and eastern domains today. The aqueduct gap likely remained active until ~75 ka before streams being diverted into the major river gap (Table 4). This age estimate agrees well with the Keller et al. [19] suggestion that the aqueduct gap and the Q3 surfaces should be similar in age based on their similar elevations (Figure 2(b)). Between 75 ka and the present, Tecuya Creek cut two channels (now wind gaps 6 and 7) across the eastern domain of Wheeler Ridge as the creeks were progressively pushed eastward by the growing fold (Table 4 and Figure 4(c)).

It has been previously suggested that wind gaps from antecedent river gaps can form without being strictly controlled by tectonic-driven isolation. Burbank et al. [18] suggests that aggradation in the hinterland and avulsion and stream capture in the piggyback basin are potential causes of abandonment of river gaps at Wheeler Ridge and elsewhere. Our IRSL ages of Q3 and related deposits in the central domain are supportive of this model as they suggest a two-fold increase in the rate of sedimentation on the backlimb closer to the piggyback basin (Table 5, see Discussion in next section). Moreover, our estimates of the timing of wind gap formation broadly correlate to dry climate intervals in Southern California (Table 4) (see also summary Fig. 11 in [50] and the references therein; [51]), which we suggest would likely have resulted in a loss of stream power due to decreased discharge and consequent aggradation in the

**Table 4: River and wind gap formation ages based on IRSL chronology of Quaternary surfaces and inferred incision rates (surface uplift rates, Table 2), correlated to precipitation records around Southern California.**

| Wind gap # | Surface age (ka) | Incision (m) | Rate of incision (mm/yr) | Formation age estimate | Precipitation |
|------------|-----------------|-------------|-------------------------|------------------------|---------------|
| 1          | 153             | 30          | 2.5                     | 141                    | MIS 6 peak (wet?) |
| 2          | 153             | 80          | 2.5                     | 121                    | Dry           |
| 3          | 129             | 20          | 1.7                     | 117                    | Dry           |
| 4          | 129             | 60          | 1.7                     | 94                     | Wet           |
| 5          | 129             | 135         | 2.5                     | 75                     | Dry           |
| 6          | 70              | 25          | 0.9                     | 42                     | Extreme wet-dry cylces |
| 7          | 32              | 5           | 0.8                     | 26                     | Wet to dry transition |

*See Figure 11 in DeVecchio et al. [9].
piggyback basin that may have facilitated stream capture and consequent river gap abandonment.

5.2. Surface Deformation Rates. Surface uplift rates along the crest of Wheeler Ridge, calculated both across Quaternary domain boundaries (e.g., western to central) and within domains (e.g., eastern), show a wide range of rates (~0.7–2.6 mm/yr); with an average of ~2.1 mm/yr (Figure 3). However, based on the observed topographic steps of the fold axis across and within domains, combined with our detailed chronology and probabilistic modelling, we do not support using a simple average surface uplift rate along the length of the fold, as previous studies have done (e.g., [19]). Although the range is wide, the variability is not random, but rather shows a systematic rate decrease from west to east (Figures 3(c) and 3(d)). We consider the topography and surface processes at Wheeler Ridge, as well as various tectonic, surface uplift, and lateral propagation rates, to shed light on the surface deformation rates.

Downward-stepped topography and decrease in uplift rate along Wheeler Ridge toward the east may have resulted from surface beveling of the actively growing fold crest, prior to uplift and isolation from the zone of erosion and the formation of Quaternary surfaces (e.g., Q3). Differential erosion of the fold crest toward the east could be explained by greater stream power resulting from larger drainages emanating from the San Emigdio Mountains farther east (Figures 1(b) and 4(c)). Furthermore, numerical ages collected from the crest and backlimb of the eastern domain from different stratigraphic depths with respect to the Q3 surface could be interpreted to support an erosional model, rather than increased aggradation in the piggyback basin as suggested in the Geomorphic Development section, above. Samples WR2088 and WR2082 were collected at 16 and 31 meters, respectively, below the uppermost Q3 sample and returned overlapping ages (~120 ka, Table 1, and Table 5) suggesting a sedimentation rate of ~0.42 mm/yr between ~120 ka and ~70 ka. In contrast, sample WR2089 (Table 1) collected from the backlimb of the fold, adjacent to the piggyback basin (Figure 2(c)), was collected 21 meters below the Q3 surface suggests a sedimentation rate of ~1 mm/yr between ~60 ka and ~70 ka (Table 5). These results could be interpreted to reflect a greater degree of erosion of the actively uplifting fold crest rather than higher rate of deposition in the piggyback basin, as suggested in the previous section. Unfortunately, without better exposure, we are unable to determine which interpretation is more valid; however, we prefer increased aggradation in the piggyback basin model to explain the observed differences in sedimentation rates at crest of Wheeler Ridge. Assuming that surface uplift scales with fault length, as many studies have shown for fault displacement and fault length, we would not expect these relations to have persisted had the if tectonic topography been eroded during uplift. Specifically, an increase in fault length with respect to surface uplift would be expected if the crest of the fold were eroded during uplift because total lateral propagation would not have been affected by erosion, and therefore, the 20 : 1 ratio of propagation to uplift would not have remained constant (Table 3).

Although not completely understood, the ability of tear faults to limit the lateral propagation at Wheeler Ridge (e.g., [20, 21]) and other faults in Southern California (e.g., [9]) may be common. However, at some point, the shear strain at the fault tip must reach a critical threshold resulting in breach of the tear fault and consequent lateral growth of the fault and the overlying hanging wall anticline. In the case of the Wheeler Ridge anticline, the ratio between lateral growth and uplift (20:1) appears clear, providing some insight into the critical shear stress necessary at the fault tip for lateral propagation. Although beyond the scope of this study, an important unanswered question for the Wheeler Ridge fault is why the rate of deformation appears to be decreasing toward the east, away from the Pleistocene-recent fault system responsible for uplift of the San Emigdio Mountains. However, transfer of strain from the Wheeler Ridge fault onto the northeast striking White Wolf fault zone which extends to the east is the most likely explanation. This is supported by source parameter modeling of reverse slip for 1952 Mw 7.3 Kern County earthquake on the White Wolf fault zone, which underlies the Wheeler Ridge fault and is better aligned with the northeast-striking structural grain of the region (Figure 1(b); [16]).

6. Conclusions

This study builds on existing research of a laterally propagating fold developed above a blind reverse fault at Wheeler Ridge, California. We utilize new airborne high-resolution topographic data, IRSL geochronology, and deformation rate calculations to better quantify vertical and lateral growth of the geomorphic development of tectonic topography. IRSL-based probabilistic modelling indicates a systematic decrease in rates of deformation toward the propagating fold tip that occurred in discrete punctuated intervals. Deformation appears to have been controlled by transverse tear faults

| Location | IRSL sample | Depth below Q3 (m) | Approx. age (ka) | Error | Sedimentation rate (mm/yr)* |
|----------|-------------|--------------------|-----------------|-------|----------------------------|
| Q3 crest | WR2090      | 3                  | 70              | 11    | 0.42 ± 0.16                |
| EDmid    | WR2088      | 16                 | 120             | 18    |                            |
| Q3low    | WR2082      | 31                 | 120             | 18    | 1.00                        |
| Backlimb | WR2081      | 21                 | 91              | 15    |                            |

*Sedimentation rate calculated by determining the maximum uplift from Q3mid and Q3low.

Table 5: Sedimentation rate calculations of the eastern domain on the crest and the backlimb. These values indicate that there has been erosion at the crest while Wheeler Ridge has been uplifting.

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which limited growth of the fold through time resulting in a down-stepping topography in the direction of propagation. We utilize our IRSL-derived rates to construct an evolutionary model for wind and river gap formation that illustrates the spatiotemporal geomorphic growth of the fold. This study furthers our understanding of the growth and evolution of mostly buried thrust faults, which have produced some of the largest magnitude modern earthquakes in Southern California.

**Data Availability**

High-resolution airborne lidar data used in this work can be found in the NSF OpenTopography data portal (doi:10.5069/G99K485N).

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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**Supplementary Materials**

The supplementary material for this manuscript includes (1) additional information about IRSL methods and age determinations and (2) an exploration of the geologically reasonable surface uplift and horizontal propagation rates at Wheeler Ridge, accounting for secular variations in rates and clarifying nuance of the resulting history. (Supplementary Materials)

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