Active tectonics at Wheeler Ridge, southern San Joaquin Valley, California

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ABSTRACT

Wheeler Ridge is an east-west–trending anticline that is actively deforming on the upper plate of the Pleito–Wheeler Ridge thrust-fault system. Holocene and late Pleistocene deformation is demonstrated at the eastern end of the anticline where Salt Creek crosses the anticlinal axis. Uplift, tilting, and faulting, associated with the eastward growth of the anticline, are documented by geomorphic surfaces that are higher and older to the west.

Faulting and associated folding is propagating eastward, as indicated by increases in both the degree of surface dissection and the degree of soil development from east to west. Distinct topographic areas having distinct degrees of surface dissection, bounded by tear faults, suggest that faulting and folding have propagated eastward in discrete segments.

Numerical dates indicate (1) the anticline is propagating eastward at a rate of about 30 mm/yr (about 10 times the rate of uplift); (2) folding was initiated about 400 ka; (3) a prominent wind gap was formed during Q3 time (about 60 ka) when an antecedent stream was defeated, forcing the stream east around the nose of the fold; today drainage through the ridge is by way of two antecedent streams (water gaps) east of the wind gap; and (4) the rate of uplift at the easternmost and youngest (past 1 k.y.) part of the fold is at least 3 mm/yr.

Investigations of the tectonic geomorphology of Wheeler Ridge support the hypothesis that climatic perturbations are primarily responsible for producing geomorphic surfaces such as alluvial fan segments and river terraces—tectonic perturbations deform the surfaces.

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INTRODUCTION

Buried reverse faults associated with actively deforming folds are known to produce large earthquakes. Several recent, large California earthquakes are examples: M = 6.7, Northridge, 1994; M = 6.1, Whittier Narrows, 1987; M_S = 6.4, Coalinga, 1983, and M_S = 7.7, Kern County, 1952. Detailed investigations of folding associated with concealed reverse faults are therefore necessary in order to better understand earthquake hazards associated with these areas.

The goals of earthquake hazards research are to characterize earthquake sources likely to produce future events by determining fault-slip rate, average recurrence intervals, and timing of past events. Active faults have generally been studied where geologically young surficial deposits are observed to be displaced at the surface. Landforms associated with strike-slip, normal, and reverse faults may include fault scarps, offset streams, sag ponds, or offset terraces. However, in areas where active reverse faults do not break through to the surface, young surficial deposits are not ruptured. Therefore, the underlying fault may be either unknown or incorrectly identified as inactive, unless independent geophysical data demonstrate that activity (Stein and King, 1984).

The recent earthquakes identified here have resulted in a concerted effort by researchers to evaluate the potential seismic hazards in areas of active folding (Stein and King, 1984; Zepeda et al., 1986; Yeats, 1986; Keller and Pinter, 1996).

The Wheeler Ridge anticline, located in the southern San Joaquin Valley, California (Figs. 1 and 2), was chosen for study because it is possible to determine rates of uplift associated with active folding above a buried reverse-fault system. Holocene and latest Pleistocene activity has been demonstrated at the east end of Wheeler Ridge, where geomorphic surfaces are folded over the anticlinal axis (Zepeda et al., 1986). In addition, the 1952 Kern County earthquake was centered below Wheeler Ridge, but not on the Wheeler Ridge thrust fault; therefore the potential earthquake hazard in the area is clear.

The primary goals of the research at Wheeler Ridge are (1) to characterize the tectonic geomorphology; (2) to develop the Pleistocene chronology; and (3) to test the hypothesis that climatic perturbations are responsible for most Pleistocene and Holocene aggradational events that produce alluvial fan segments, and that tectonic perturbations primarily deform the fan segments.

Testing the hypothesis concerning climatic and tectonic perturbations is important in understanding the origin and significance of landform evolution in tectonically active regions (Bull, 1991). The question is, How significant are tectonic perturbations? At the regional scale over several million years, tectonic processes may produce mountain ranges that cause climatic change, for example, through the development of a rain shadow. At a more local scale, a study of terraces of the Ventura River, California, indicated that the terrace sequence has a climatic signature, whereas deformation of the terraces resulted from tectonic activity (Rockwell et al., 1984). As a second example, tectonic tilting of alluvial fan segments may cause a threshold of fan slope stability to be exceeded (Schumm, 1977) and fan-head entrenchment to occur (Rockwell et al., 1985). In turn, entrenchment will cause a new fan segment to develop. However, the development of thick alluvial deposits through aggradational events may be the result of climatic perturbations. The study of landscape evolution at Wheeler Ridge spans a sufficient length of time that both tectonic and climatic perturbations have influenced the landform evo-

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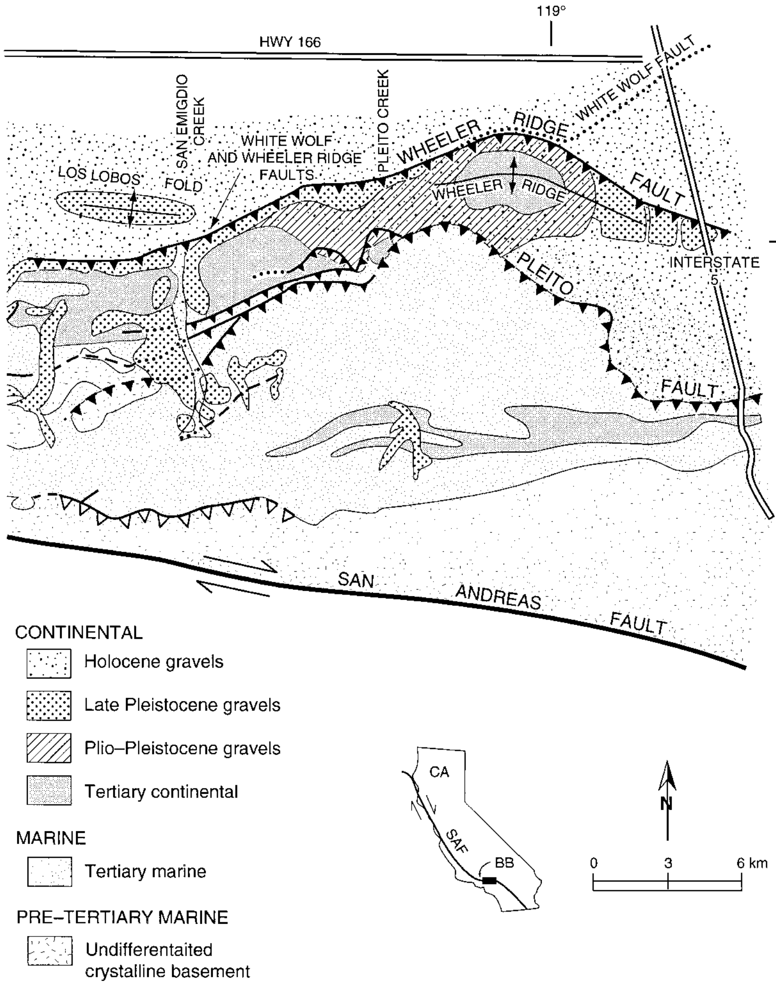

Figure 1. Location of study area and generalized geologic setting at Wheeler Ridge. SAF—San Andreas fault, BB—"Big Bend" of the fault. After Davis (1983); Dibblee (1973); Morton and Troxel (1962).

lution. As a result, this study helps delineate the relative importance of climatic versus tectonic perturbations in an area characterized by relatively high rates of tectonic activity.

METHODS

The approach to the investigation included photogeologic analysis to characterize the structure and geomorphology of the anticline; geologic mapping; surveying with engineering level to document deformation (folding) of geomorphic surfaces; sampling and description of soil profiles in backhoe trenches, road cuts, hand-dug pits, and natural exposures; numerical dating of charcoal and pedogenic carbonate by radiocarbon and/or uranium-series techniques; and laboratory analysis of soil samples.

Sample preparation of pedogenic carbonate rinds for radiocarbon and uranium-series analyses included (1) removal of soft outer carbonate; (2) scraping and collection of the hard, innermost carbonate rinds from undersides of clasts; and (3) viewing with a microscope for signs of leaching or reprecipitation (not included for radiocarbon-dated carbonate rinds).

Soil properties were described according to the methods and terminology described by the Soil Survey Staff (1975). Stages of carbonate morphology were described using the nomenclature developed by Gile et al. (1966) and Bachman and Machette (1977). Figure 3 shows the locations of 23 soil profiles described in the Wheeler Ridge area; three or more soils were described and sampled for each characteristic geomorphic surface.

CLIMATE

There are large topographically controlled variations in climate in the vicinity of Wheeler Ridge (Soil Conservation Service, 1988). The average climate at Wheeler Ridge (~300 m elevation) is warm and semiarid to arid with one wet season during the year (winter). Of all precipitation, 90% falls between October and April. Summers are generally cloudless, hot, and dry. Temperatures often exceed 38 °C and rarely fall below 20 °C. Minimum temperatures during the winter months sometimes are below freezing. The mean annual temperature is about 19 °C. Precipitation ranges from 15 to 16 cm in the San Joaquin Valley to 27 cm in the San Emigdio and Tehachapi Mountains south of Wheeler Ridge.

GEOLOGIC SETTING

The east-west–trending Wheeler Ridge anticline is located along the north flank of the San Emigdio Mountains at the boundary between the Transverse Ranges and the San Joaquin Valley (Figs. 1 and 2). The San Emigdio Mountains are part of the east-west–trending, western Transverse Ranges, in contrast to the predominantly northwest-southeast structural grain of California. The western Transverse Ranges are bounded on the north and south edges by fold-and-thrust belts (Keller et al., 1987).

Wheeler Ridge is located in the "Big Bend" region of the San Andreas fault, where the generally northwest-southeast–trending fault strikes more east-west (Fig. 1). Within the Big Bend, north-south compression and resulting shortening are observed (Savage, 1983; King and Savage, 1984). The driving force for the uplift of the San Emigdio Mountains and Wheeler Ridge is thought to be compression generated by the left step in the San Andreas fault produced by the Big Bend and accompanying strain partitioning, resulting in displacement on reverse faults along range fronts (Rodgers, 1980; Lettis and Hanson, 1991; and Working Group on California Earthquake Probabilities, 1995).

Nodal planes for five earthquakes in the Wheeler Ridge area are consistent with the orientation of the generally east-west–striking faults mapped in the area (Webb and Kanamori, 1985). The focal mechanisms for these events agree well with those expected from the local geology and the general north-south compression. Shallow-dipping nodal planes associated with these focal mechanisms, as well as the shallow-dipping listric faults that were inferred by Davis (1983) to flatten with depth, support the hypothesis of a regional decollement located below the San Emigdio Mountains (Webb and Kanamori, 1985).

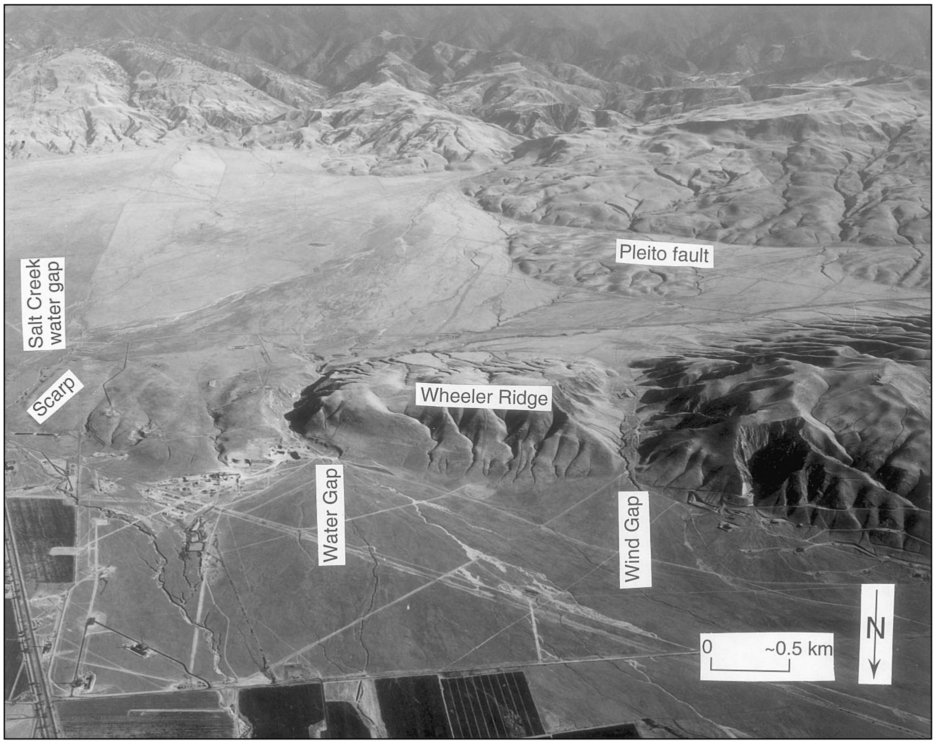

Figure 2. Aerial photograph of Wheeler Ridge looking to the south. Degree of surface dissection is greatest to the west (right) and decreases in stages to the east (left). This evidence, together with the observed east to west increase in the degree of soil profile development, indicates that the anticline is propagating eastward in a segmented fashion. Note the Pleito thrust fault and landslides at top of photograph (see Fig. 9; photograph courtesy of J. Shelton).

The southern San Joaquin Valley is a seismically active area that has a generally diffuse pattern of activity. Seaver (1986) attributed the diffuse pattern to multiple active faults and/or inaccurate location of events. Continued seismic activity in the area is demonstrated by the M = 4.8 earthquake that occurred in the vicinity of Wheeler Ridge at a depth of 21 km on May 19, 1993 (T. Hong-Kie, 1993, personal commun.).

The San Emigdio Mountains have accommodated about 7 km of shortening since late Pliocene time, during which the southernmost San Joaquin Valley was an actively subsiding sedimentary basin (Davis, 1983). Uplift of the San Emigdio Mountains has occurred along the southward-dipping Pleito–Wheeler Ridge thrust-fault system (Fig. 1). The leading topographic edge of this uplift has migrated northward with time toward the San Joaquin Valley (Davis, 1983; Seaver, 1986). The Wheeler Ridge anticline is the northernmost topographic expression of the Pleito–Wheeler Ridge thrust-fault system in the study area (Fig. 1) (Davis, 1983), where active deformation is occurring simultaneously along the Wheeler Ridge thrust fault (Zepeda et al., 1986) and the Pleito thrust fault (Hall, 1984) (Fig. 1). Seaver (1986), working 20 km west of Wheeler Ridge in San Emigdio Canyon (Fig. 1), determined that uplift was initiated along the Pleito fault in mid-Pleistocene time. The Pleito fault is currently inactive in San Emigdio Canyon, and uplift has shifted northward to the buried Wheeler Ridge fault at the present mountain front. In late Pleistocene time, topographic expression of folding has stepped farther northward to the Los Lobos folds (Fig. 1).

The other major fault in the study area is the White Wolf fault, which merges with the Pleito–Wheeler Ridge thrust-fault system at Wheeler Ridge (Fig. 1). The White Wolf fault has traditionally been considered to be the cause of the M_S = 7.7, 1952 Kern County, California, earthquake; researchers now suggest that it was due to a deep, concealed member of the Pleito–Wheeler Ridge thrust-fault system (Davis and Lagoe, 1987; Medwedeff, 1988). The source of the 1952 Kern County earthquake was located 15 ± 6 km below the Wheeler Ridge anticline (Gutenberg, 1955). Ground rupture and displaced features were observed along a 64 km section of the White Wolf fault northeast of Wheeler Ridge. In the epicentral region, however, the surficial expression consisted of minor fractures oriented obliquely to the anticline (Buwalda and St. Amand, 1955). Although the major displacement that occurred at depth did not reach the surface at Wheeler Ridge, the earthquake produced about 1 m of uplift along and south of the anticline (Stein and Thatcher, 1981).

GENERAL STRATIGRAPHY

Rocks exposed south of the Wheeler Ridge anticline consist of a Mesozoic and older crystalline basement complex that forms the core of the San Emigdio Mountains (Fig. 1). The northern flank of the mountains is overlain by a predominantly sedimentary section as thick as 9.2 km (Nilsen et al., 1973). Strata generally dip northward and flatten toward the San Joaquin Valley, where they are subhorizontal. Strata of Eocene to Miocene age are composed of a series of marine shale and sandstone and terrestrial sandstone and conglomerate units.

Wheeler Ridge is underlain by about 4.5 km of Tertiary sediments that unconformably overlie the crystalline basement (Dibblee, 1973). These Tertiary sediments are overlain by about 600 m of Pliocene–Pleistocene Tulare Formation and late Pleistocene to Holocene gravelly deposits. The gravels are predominantly granitic, poorly consolidated, conglomeratic sandstone, deposited northward by streams in an alluvial fan complex, the source of which was the San Emigdio Mountains. Deposition of the coarse-clastic Tulare Formation was initiated by uplift of the San Emigdio Mountains (Davis, 1983). In the southern San Joaquin Valley the formation varies in age from 1.5–3.0 Ma (Davis, 1983) to younger than 0.615 Ma (Sarna-Wojcicki et al., 1979).

Distinct soil profiles have developed on five major geomorphic surfaces (segments of alluvial fans) underlain by the gravel deposits described above. The geomorphic surfaces, designated Q1 for the lowest to Q5 for the highest, are located along the Wheeler Ridge anticline (Figs. 4 and 5). These geomorphic surfaces have been uplifted and isolated from continued alluvial fan deposition during the growth of the anticline. Wind and water gaps located along the anticlinal axis serve as surface boundaries for the geomorphic surfaces, which also correspond with distinct changes in the degree of surface dissection observed along the crest of the anticline (Figs. 2, 4, and 5). Soils developed on the four younger geomorphic surfaces were used in this study to correlate the surfaces at Wheeler Ridge. Soils were not used to determine or date late Pleistocene–Holocene chronology.

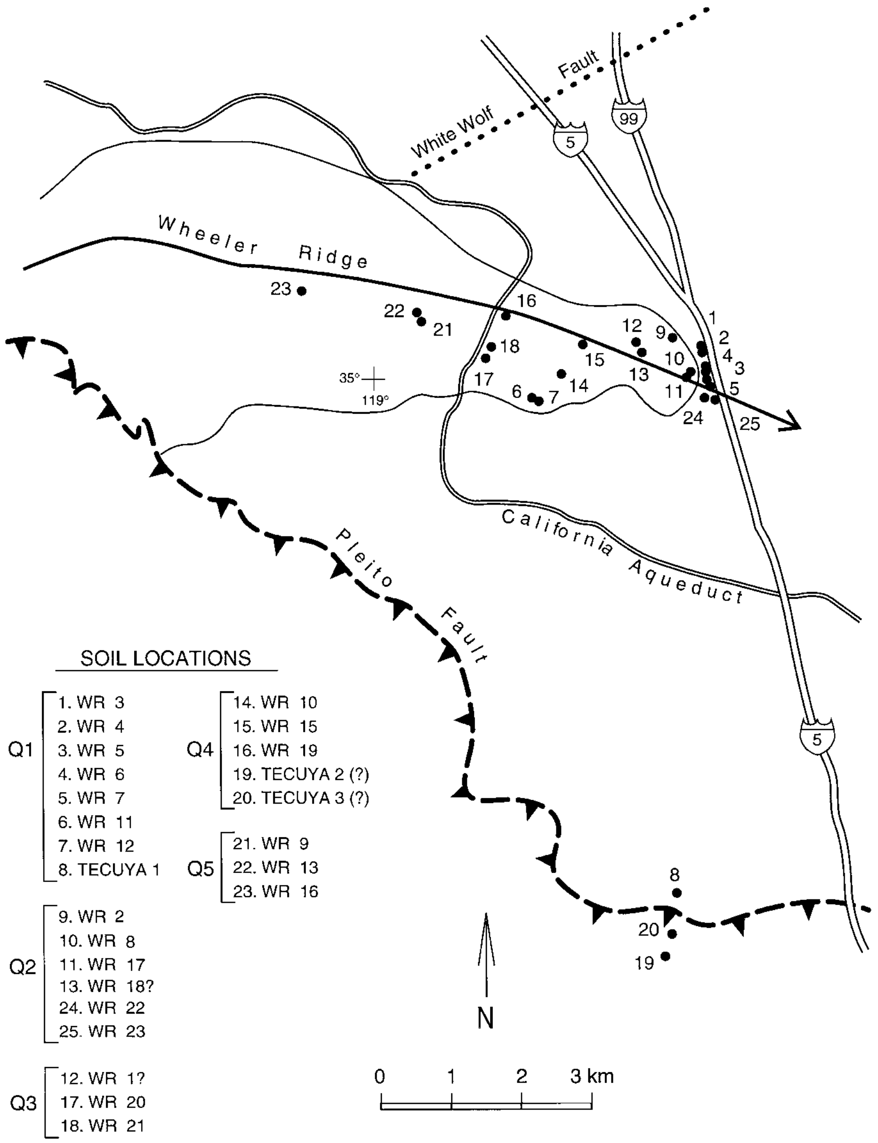

Figure 3. Map of the Wheeler Ridge study area, showing locations where soils were sampled.

STRUCTURE AND GEOMORPHOLOGY

The east-west–trending Wheeler Ridge anticline is an unusually prominent asymmetric fold that has a steeper north limb. The fold is about 12 km long and as wide as 3 km; it has a maximum topographic and structural relief of 500 m and about 1 km, respectively (Figs. 1 and 5). The maximum topographic and structural relief are within the western portion of the fold and decrease eastward (Medwedeff, 1988, 1992). The topographic expression of Wheeler Ridge is greatest to the west and gradually decreases from the prominent wind gap eastward to the termination of the fold near Salt Creek (Figs. 2 and 5). The Wheeler Ridge anticline is asymmetrical and has a steeply north-dipping limb (50°–70°) and gently south-dipping limb (10°–20°).

The five primary geomorphic surfaces, Q1 through Q5, have been deformed during the development of the anticline. This deformation is illustrated at the eastern terminus of the fold where the Q1 and Q2 surfaces are folded (Fig. 6).

At Wheeler Ridge the geomorphic surfaces and their associated deposits and soils are assumed to be approximately the same age. This is probably a valid assumption in an environment such as Wheeler Ridge, characterized by active deposition of sediment that forms geomorphic surfaces, followed by uplift and erosion that isolates the surfaces.

As noted above, the wind and water gaps located along the anticlinal axis serve as the boundaries for most of the geomorphic surfaces, which also correspond with apparent changes in the degree of surface dissection observed along the crest of the anticline (Figs. 2, 4, and 5). Surface dissection is greatest west of the prominent wind gap (Fig. 4) and decreases eastward, until relatively undissected surfaces are found at the eastern end of the anticline. Shelton (1966) concluded that this decrease in dissection from west to east suggested that the Wheeler Ridge anticline grew in that direction. The wind and water gaps have also been found to correspond to tear faults that have developed during the lateral propagation of the anticline (Medwedeff, 1988, 1992). A steep, straight escarpment at the east end of Wheeler Ridge (where Salt Creek crosses the fold hinge [Fig. 2]) is the topographic expression of a buried tear fault, as are the boundaries between Q2 and Q3, Q3 and Q4, and Q4 and Q5 (Medwedeff, 1988, 1992). Existence of a folded Q2 surface just east of Salt Creek suggests that the Q1 surface through the fold is a water gap (Fig. 4). Q2 is part of a fan segment, but Q1 in the water gap (Fig. 4) is an approximately 2-m-thick deposit on eroded Q2 gravels in the gap that has recently been entrenched several meters by Salt Creek. At some future time the stream flowing through the much deeper dissected western water gap probably will be defeated by the combination of uplift and deposition on the southern flank of the ridge, forming a new wind gap. It is this combination of events that probably produced the wind gap that today separates Q4 and Q5 (Fig. 5). At other locations (Fig. 4), Q1 forms much of the piedmont areas of the San Emigdio Mountains and Wheeler Ridge.

The structural geometry of folding in the western Transverse Ranges and southern and western San Joaquin Valley has been described by various workers in terms of either fault-bend or fault-propagation folding (Davis, 1983; Namson and Davis, 1984, 1988; Medwedeff, 1988, 1992). Such folds form in response to displacement on underlying blind reverse faults.

Medwedeff (1988, 1992) used balanced cross sections and subsurface data for Wheeler Ridge to describe folding between the prominent wind and water gaps, applying a complex fault-wedge, fault-bend fold mechanism. The fold evidently has formed at the tip of a north-verging fault wedge that has slipped several hundred meters during late Pleistocene and Holocene time (Medwedeff, 1988, 1992). The surface morphology, although apparently simple, is complex because the fold has propagated eastward, where deposition and fold-

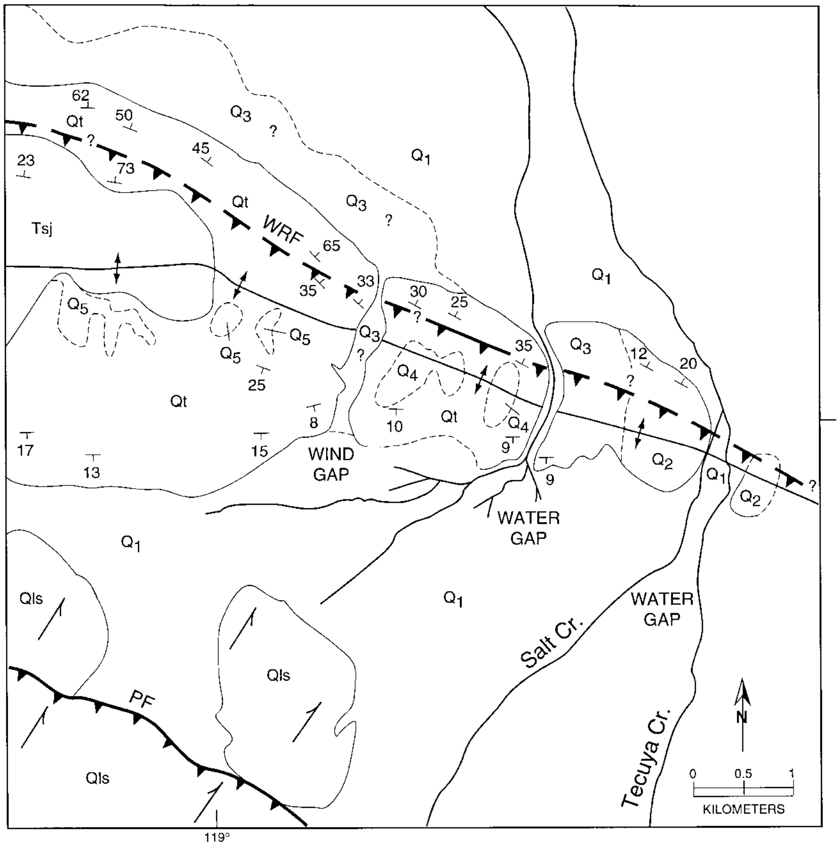

Figure 4. Generalized geologic map of Wheeler Ridge. Q1 to Q5 are geomorphic surfaces (see Table 2); Qt—Pliocene–Pleistocene Tulare formation; Tsj—Tertiary San Joaquin formation; Qls—Quaternary landslide deposits; WRF—buried Wheeler Ridge thrust fault; PF—Pleito thrust fault (bedrock geology after Dibblee, 1973).

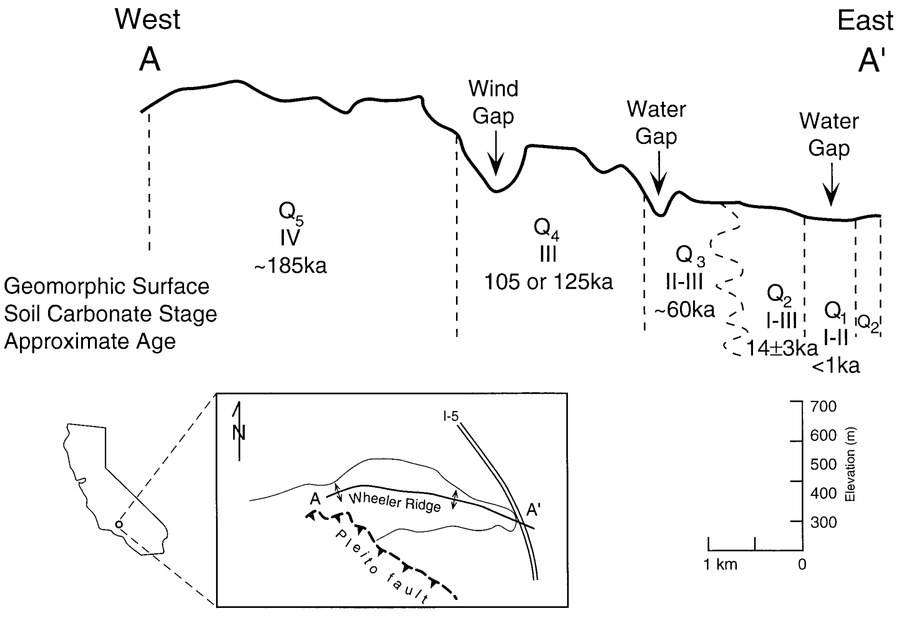

Figure 5. Topographic profile along the crest of Wheeler Ridge showing major geomorphic surfaces and Q1–Q5 soils.

ing coincide. Structural relief, fault slip, and structural complexity decrease to the east where the anticline dies out east of Salt Creek (Medwedeff, 1988, 1992). At the eastern end of Wheeler Ridge where the anticline is a simple fault-bend fold, the Wheeler Ridge thrust fault dips 36° to the south and flattens with depth.

A strand of the Wheeler Ridge thrust fault (once thought to be an entirely buried feature) is exposed in a gravel quarry at the east end of the Wheeler Ridge anticline (Fig. 7) (Zepeda and Keller, 1989), where it deforms gravels of Q2(?) or Q3 age. A highly degraded scarp is observed at the surface where the fault strikes east-southeast and dips 24° southward. Near the surface the base of a B soil horizon is offset approximately 2.5 m along dip (Fig. 7). Toward the base of the ~20-m-deep fault exposure, the amount of deformation by folding increases dramatically, although marker beds for measuring displacement are not present. In the uppermost portions of the exposed fault, bedding on the hanging wall dips gently northward, while it abruptly increases to a dip of 40° to 50° at 15 m depth (Fig. 7). These steep dips are consistent with the strong fold asymmetry generally observed at Wheeler Ridge. The amount of dip-slip displacement necessary to produce the observed 5 m vertical displacement of folded gravel beds on the thrust fault having a dip of 24° is about 12 m. Assuming that the deformation resulted from one giant earthquake, the amount of fault slip is about the 10 m per event estimated by Mueller and Suppe (1997). A more conservative interpretation is that the folding at depth (Fig. 7) represents several events that did not rupture to the surface. We prefer this latter interpretation, because 20 km to the west at San Emigdio Canyon, recent events on the buried Wheeler Ridge fault evidently produced 1 to 2 m of uplift. However, we can't eliminate the hypothesis that those events with 1 to 2 m surface uplift at San Emigdio Canyon did not, at depth, produce as much as 10 m of fault displacement as a result of subsurface folding. By the same reasoning (and geometry) the most recent 2.5 m of dip-slip displacement on this fault strand produced about 1 m of surface uplift. A small scarp, if produced by such an event, would degrade quickly, explaining the limited surface expression of the fault. We are not arguing that the displaced soil represents the most recent event at Wheeler Ridge, only that it is the most recent on this strand. Investigation of the Wheeler Ridge fault 20 km to the west suggests that there have been several events in the past 1000 yr (Laduzinsky, 1989). Alternatively, the fault may be a minor strand of the Wheeler Ridge fault, because it is apparently several hundred meters south of the near-surface rupture suggested by Medwedeff (1992) (Mueller and Talling, 1997).

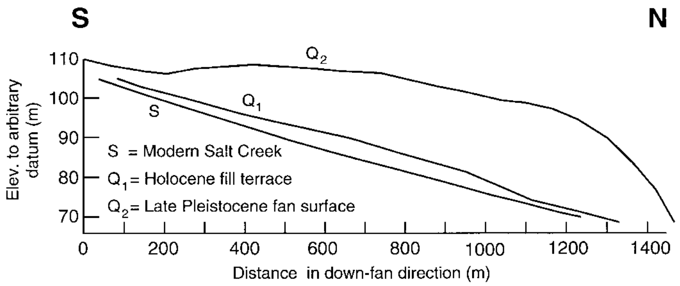

Figure 6. Topographic profiles of the present course of Salt Creek (which crosses the Wheeler Ridge anticlinal axis near its eastern terminus) and the Q1 and Q2 geomorphic surfaces. Soil horizons at the southern end of Q2 are tilted and parallel to the folded surface, providing positive evidence for folding.

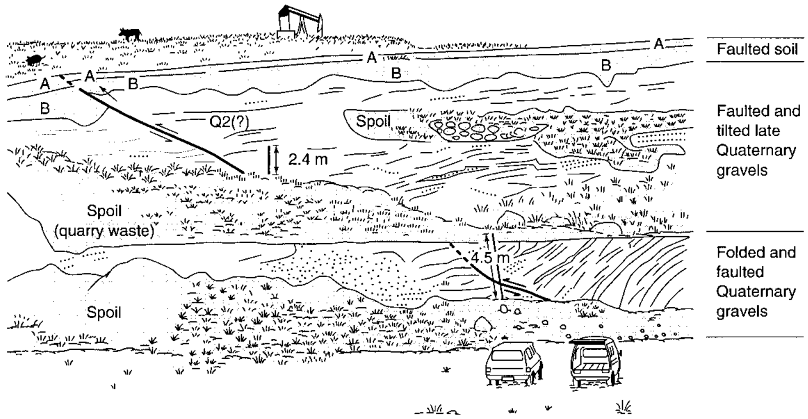

Figure 7. Sketch of exposure of south-dipping reverse fault in gravel pit near the east end of Wheeler Ridge. Notice that the B soil horizon is thicker on the downthrown block. There is thickening of the A soil horizon on the lower plate of the fault, suggesting there was probably a surface scarp present at one time. Folding of the hanging wall is the dominant process in the lower part of the exposure.

In addition to the fault exposure described here, several localized, generally east-west–striking, north- and south-dipping reverse faults with offsets of no more than a few meters were also observed in the gravel quarry. One set of faults was apparently associated with a subtle graben observed on a set of aerial photographs that recorded the surface morphology prior to development of the gravel quarry. This area, which has since been removed by quarrying, was apparently related to extension along the crest of the anticline during faulting, similar to areas observed following the 1980 Algeria earthquake (King and Vita-Finzi, 1981).

NUMERICAL DATING

Rates of deformation at Wheeler Ridge would ideally be determined by numerical dating the time when each geomorphic surface was uplifted and isolated from deposition. Initiation of soil development is assumed to approximate the time when each surface was uplifted and isolated, and active deposition of alluvial fan gravels ceased. Dating the surfaces, combined with measured deformation of the surfaces, therefore allows for the calculation of rates of uplift produced by folding and movement on the Wheeler Ridge thrust fault.

In addition to the standard ^{14}C dating of charcoal, the radiometric dating of pedogenic carbonate has proven to be valuable in Quaternary studies in the southwestern United States. Radiocarbon dating of carbonate rinds has been used successfully for latest Pleistocene deposits in New Mexico (Gile et al., 1981), and uranium-series dates have been successfully obtained on pedogenic carbonate in gravelly soils in southern California (Ku et al., 1979; Bischoff et al., 1981).

Radiometric dating of carbonate rinds provides a minimum age of the initiation of carbonate accumulation. For example, a few thousand years may be required before rinds are thick enough for sampling; consequently, continual additions of carbonate over the period of deposition will have an averaging effect on the soil age (Gile et al., 1966; Seaver, 1986). In San Emigdio Canyon, 20 km west of Wheeler Ridge (Fig. 1), accumulation over about 5 k.y. was necessary before carbonate rinds were sufficiently thick for sampling (Seaver, 1986).

Radiocarbon and/or uranium-series ages were determined for stratified charcoal underlying the Q1 geomorphic surface and for pedogenic carbonate rinds from soils of the Q2 and Q4 surfaces (Table 1). Numerical ages were determined for the uranium-series–dated samples under the closed-system assumption, i.e., no postdepositional migration of U and Th isotopes of interest. Maximum age assignments are based on the assumption that all of the ^{230}Th in the pedogenic carbonate originate from in situ decay of ^{234}U. "Probable" ages are estimated by correcting for the detrital ^{230}Th, assuming that the $^{230}Th/^{232}Th$ activity ratio of the detritus incorporated in the carbonate when formed was 1.5 ± 0.5 (Kaufman and Broecker, 1965).

Q1 and Q2 are the surfaces at Wheeler Ridge for which we are most confident of the age control. The probable uranium-series age of 76 ± 6 ka for Q4 (Table 1) is accepted as a minimum. Other age controls based on extrapolation of rates of tectonic processes are less certain, and constitute best estimates.

Three uranium-series dates for Q4 and Q5 are approximately 22–23 ka. Clustering of dates at 22–23 ka, or the time of most recent major late Pleistocene Sierra Nevada glaciation that began about 26 ka (Atwater et al., 1986), is hypothetically related to a time in the late Pleistocene at Wheeler Ridge when dissolution and reprecipitation of soil carbonate occurred. The presence of this accumulation of carbonate suggests that the climate may have been semiarid and there was sufficient precipitation to cause wetting fronts to migrate downward to depths greater than 1 m (Bull, 1991). Uranium-series dates in Table 1 were reported by Zepeda et al. (1988) and dismissed, because we could not explain the cluster

TABLE 1. RADIOCARBON AND URANIUM-SERIES AGES FOR THE WHEELER RIDGE AREA

Geomorphic surface*	Sample number	Material	^{14}C age (ka)	U-series age (ka)	
				Prob.	Max.†
Q1	WR7	Charcoal	7370 ± 140	N.D.	N.D.
Q2	WR-2	Carbonate	11410 ± 350	8 ± 2	15
	WR-8	Carbonate	11940 ± 260	12 ± 3	21
Q2(?)§	WR-18	Carbonate	N.D.	10 ± 4	23
Q4	WR-10	Carbonate	N.D.	23 ± 4	36
	WR-15	Carbonate	N.D.	76 ± 6	94
Q5	WR-9 (Stage III)	Carbonate	N.D.	23 ± 1	26
	WR-9 (Stage IV)	Carbonate	N.D.	22 ± 6	40

Note: N.D.—not determined.

*We assume the age of the geomorphic surface is approximately the same as the age of the deposits.

†Maximum uranium-series ages are based on assumption that all observed ^{230}Th is derived from in situ decay of ^{234}U. Probable ages are based on assumption that when formed, carbonate rinds incorporate Th isotopes with a $^{230}Th/^{232}Th$ activity ratio of 1.5 (Kaufman and Broecker, 1965). Radiocarbon ages determined at Illinois State Geological Survey.

§Soil development suggests a correlation with Q3.

of younger dates for Q4 and Q5 and the 10 ka age for what we then thought was Q3. At that time, we relied (perhaps) too heavily on soils as a dating tool and did not consider paleoclimatic implications of the dates. We now believe that the soils are a rough correlation tool. We can easily distinguish Q5 soils from Q4, Q4 from Q3 and Q3 from Q1. It is more difficult, on the basis of soils, to distinguish Q3 from Q2. It is possible that Q2 and Q3 are the same surface, but we have retained them as two separate surfaces on the basis of geomorphology and minor differences in the soils. We have no numerical dates for Q3. On the basis of the above discussions, we now believe the uranium-series dates may be accepted and interpreted in context of the history of Wheeler Ridge.

SOIL CHRONOLOGY

The degree of soil profile development can ideally be attributed to the variables of climate, parent material, vegetation, topography, and time (Jenny, 1941). Accordingly, it should be possible to evaluate for time (especially relative time) if the other factors are held constant. Many studies have shown a relationship between soil age and particular soil properties, such as carbonate horizon morphology (Gile et al., 1966), mass of secondary carbonate (Machette, 1978, 1985), total soil morphology (Harden, 1982), and iron oxide content (McFadden and Hendricks, 1985).

Carbonate-rich soils are common in the southern San Joaquin Valley, and carbonate morphology in Wheeler Ridge area soils was described using the terminology developed by Gile et al. (1966) and Bachman and Machette (1977). Gile et al. (1966) originally identified four stages of carbonate morphology (I, II, III, and IV) in calcic soils developed in gravelly and nongravelly parent materials. They identified the influence of parent material on the time required to form each morphologic stage; in general, less time is required to increase the morphologic stage in gravelly soils than in nongravelly soils. In addition, the type of carbonate morphology varies depending upon parent material; carbonate coatings form on clasts in gravelly soils, whereas nodules and carbonate fillings of seams and void spaces tend to form in nongravelly soils. Bachman and Machette (1977) identified two more advanced stages of carbonate morphology (V and VI) that are characterized by volume expansion of the carbonate horizons.

The source of the carbonate in Wheeler Ridge area soils is presumed to be atmospheric, from eolian dust and precipitation. Wheeler Ridge is located at the southern end of the San Joaquin Valley and the prevailing wind direction is from the northwest. In addition, wind storms carrying large volumes of dust are common in the San Joaquin Valley (Wilshire et al., 1981).

Mineral weathering is not considered a likely source of carbonate at Wheeler Ridge, although the San Emigdio Mountains contains some marble and calc-alkaline granites. Gardner (1972) calculated that it would require weathering and erosion of 37 to 90 m of material to develop a stage IV carbonate horizon, similar to those observed at Wheeler Ridge. Detailed studies using dust traps in the Las Cruces region of New Mexico indicate that significant additions of carbonate are derived from the atmosphere as dust and in precipitation (Gile et al., 1981). Most pedogenic carbonate in the semiarid and arid parts of the western United States is considered to be atmospheric in origin (Bachman and Machette, 1977; Machette, 1985; Birkeland et al., 1991; Reheis et al., 1995).

Accumulation of carbonate by upward capillary movement is not considered as a likely source at Wheeler Ridge due to the observed parent material of coarse alluvium. Capillary rise within coarse alluvium is negligible (Birkeland, 1984), and downcutting at Wheeler Ridge following deposition of the alluvium has lowered the ground-water table far below the surface and beyond the reach of the developing soils. In addition, impermeable beds, which could act to perch the ground-water table, were not identified anywhere within the Wheeler Ridge study area.

Wheeler Ridge Soil Chronosequence

Soils at Wheeler Ridge are best distinguished by the observed stage of carbonate morphology, in addition to color brightness, clay content, and clay-film abundance and thickness. Each soil of the five uplifted geomorphic surfaces can be characterized by a distinct representative soil profile. General characteristics of the Wheeler Ridge soil chronosequence are presented in Table 2, and the five members of the chronosequence are described below in the following (Zepeda, 1993).

Soils observed at Wheeler Ridge on the Q1 to Q5 geomorphic surfaces range in age from Holocene (Q1 surface) to progressively older surfaces of late to mid-Pleistocene age (Q2 to Q5 surfaces) (Figs. 4 and 5, and Table 2). Soils found on Q1 surfaces are significantly less developed (AC horizons) than those on the increasingly higher surfaces to the west (Q2 to Q5 surfaces) (Bt, Btk, and K horizons).

Use of soils in correlating geomorphic surfaces at Wheeler Ridge is complicated by the fact that uplift, folding, and deposition occur at the same time. Thus, younger soils may be found on the flanks of the fold below older surfaces. For example, sites 6 and 7 and 17 and 18 are, respectively, Q1 and Q3 soils, both below the higher Q4 surface at the crest of the fold (Fig. 3). This results because Q3 and Q1 gravels were deposited on the south flank of the fold as the Q4 gravels were uplifted (Wheeler Ridge is a growth structure). Nearly all geomorphic surfaces, with the exceptions of stream terraces in water and wind gaps, are segments of alluvial fans. Widths of the segments are variable but generally correspond to the mapped extents of Q2 to Q5 (Fig. 4).

Q1 Surfaces and Soils. Soils formed on Q1 surfaces generally consist of AC soil profiles (Table 2). The primary fluvial stratification of the sediments is generally observed, as well as mixed colors (color is observed from a sample following mechanical mixing by hand) of 10 YR 3/3 m (m = moist). For comparison, sediments from the floor of modern Salt Creek have mixed colors of 2.5 Y 4/2 m and contain about 2% to 3% clay and 2% to 4% carbonate. Soils of Q1 designation

TABLE 2. WHEELER RIDGE SOIL CHRONOSEQUENCE

Geomorphic surface*	Solum thickness (m)	B Horizon					Carbonate stage§	Approx. elevation (m)	Approximate age of deposits (ka)
		Type	Moist color†	Texture	Structure	Clay films			
Q1	0.5–0.8	AC to Cambic B	10YR 3/3	Sandy to sandy loam	Primary fluvial stratification to massive	None	Weak I	295–299	Holocene#
Q2	2.4+	Argillic	10YR 4/4	Sandy loam	Moderate coarse subangular blocky	Many thin and moderately thick on pebble-matrix interfaces	I–III	318–335	17**
Q3	2.7+	Argillic	10YR 4/4	Loam to sandy loam	Weak medium subangular blocky	Many moderately thick on pebble matrix interfaces	II–III	335–378	60††
Q4	3.1+	Argillic	7.5YR 4/6	Sandy loam	Massive breaking to fine subangular blocky	Continuous thick on pebble-matrix interfaces	III	425–500	105 or 125§§
Q5	N.A.	B horizon stripped and/or engulfed by carbonate					Strong IV	600–650	185##

Note: N.A.—not available.
*We assume that the geomorphic age is approximately the age of the deposits.
†Color terms follow Munsell Color Company (1975) notation.
§Carbonate stage terms follow Gile et al. (1966) and Bachman and Machette (1977).
#Based on soil development and ^{14}C.
**Based on ^{14}C and uranium-series.
††Based on extrapolation of fold propagation and soil development.
§§Based on uranium series.
##Based on rate of fold propagation—may be as old as 400 ka.

have a weak to strong stage I carbonate morphology, and carbonate content is generally no more than 6.5%. An increase in carbonate with depth generally coincides with increases in both silt and clay amounts (Zepeda, 1993).

Sediments upon which Q1 soils formed are of Holocene age and, for the sites sampled, range in age from Historic (buried plastic, WR 3 soil profile) to younger than 7.4 ka (^{14}C dated stratified charcoal; Table 1). The Q1 (WR7) surface, however, is thought to be significantly younger than 7.4 ka. The ^{14}C dated charcoal was collected from stream gravels at a depth of about 4 m in the present water gap formed by Salt Creek, and at this site the dated gravels are significantly older than the overlying deposits that form the Q1 surface.

Radiocarbon dates for three soil profiles in San Emigdio Canyon, 20 km to the west of Wheeler Ridge, indicate that soil profiles that still retain fluvial stratification are about 1 ka (Seaver, 1986; Laduzinsky, 1989). This suggests that the AC soil profiles of the Q1 surface in the water gap are about 1 ka. At site 2 (Fig. 3) the Q1 profile has a weak cambic B horizon and is probably mid-Holocene in age.

Q2 Surfaces and Soils. Soils observed on Q2 surfaces are developed on an alluvial fan segment. They are characterized by argillic and calcic B horizons and they have soil colors (10 YR 4/4 m) that have higher chroma than Q1 soils (Table 2). Strong stage I to stage II carbonate morphology is generally observed; individual soil horizons contain as much as 35% carbonate. Locally stage III carbonate is present. A bimodal distribution of carbonate is sometimes observed. The high carbonate content observed in the Btk horizon is associated with a corresponding increase in silt, which suggests that it may have been derived from eolian dust. This upper zone of carbonate, sometimes called the “Holocene overprint” (Rockwell, 1983), is apparently related to a shallower depth of wetting during a dryer, Holocene interglacial climate, and the deeper Bk2 horizon is related to a wetter Pleistocene glacial climate. McFadden and Tinsley (1985) developed a compartment model that simulates calcic soil development. This model supports the hypothesis that a bimodal distribution of secondary carbonate is at least partly due to changes in the depth of carbonate accumulation resulting from changes in climate at the end of the Pleistocene.

Soils developed on Q2 surfaces, as compared to soils on younger Q1 surfaces, generally have larger percentages of silt in the upper profile. This supports the hypothesis that the silt is derived from eolian dust, because the uplifted surfaces at Wheeler Ridge have been isolated from any fluvial additions. As with the carbonate associated with the Btk horizon, carbonate in the Bk2 horizon may also have been derived from additions of eolian material.

At the east end of Wheeler Ridge a subdued, folded geomorphic surface forms the east bank of the water gap formed by Salt Creek (Fig. 4). This surface is apparently a continuation of Q2 eastward across the gap, making the Q1 surface here a young strath that has a veneer of stream gravels. The degree of soil development on the surface also suggests that it is Q2.

Radiocarbon and uranium-series dates of carbonate rinds from Q2 soils range from about 8 to 12 ka (Table 1). These are minimum ages because it takes time for the rinds to develop. Seaver (1986) estimated that it takes about 5 k.y. for carbonate rinds to develop at San Emigdio Creek to the west. Consequently, an estimated age of about 17 ka for Q2 may be more realistic.

Q3 Surfaces and Soils. Soils on Q3 surfaces are developed on an alluvial fan segment. They are distinguished by argillic and calcic B horizons and mixed colors of 10 YR 4/4 m (Table 2). Strong stage II to weak stage III carbonate morphology is characteristic of Q3 soils. The Q3 geomorphic surface is estimated to be about 60 ka (oxygen isotope stage 3) (Zepeda, 1993). The age of surface Q3 was estimated by linear extrapolation of propagation of structural deformation, based on ages of adjacent surfaces. The age estimate of Q3 is discussed in greater detail in the following general discussion of rates of deformation. The boundary between the Q2 and Q3 surfaces is not as distinct for the other surfaces. Near the boundary there is a topographic scarp associated with a tear fault (Medwedeff, 1992), and aerial photographic interpretation suggests the presence of channels that may have once crossed the fold. The distinction between Q2 and Q3 is also based in part on soil development. The Q3 soils generally are stronger developed, having Bt (argillic) horizons and carbonate stages II to III, rather than the carbonate stages I–III that characterize Q2 soils.

Q4 Surfaces and Soils. Soils observed on Q4 surfaces are developed on an alluvial fan segment. They are characterized by strong stage III carbonate development, a 25-cm-thick well-developed argillic B horizon, and mixed colors of 7.5 YR 4/6 m (Table 2). Carbonate content is as high as 37% in some horizons (Zepeda, 1993).

The uranium-series date from soil carbonate (WR-15) from Q4 deposits yields a probable age of 76 ± 6 ka, and a maximum possible age of 94 ka. We therefore believe that the age of Q4 deposits, considering time necessary for carbonate to initially form, is at least 81 ka, which corresponds with oxygen isotope stage 5a. However, because a date of 81 ka is a minimum, we believe that Q4 is probably as old as 105 ka (oxygen isotope stage 5c) or 125 ka (oxygen isotope stage 5e). If the uranium-series date is a minimum, and we assume that southern California underwent a significant aggradation event at 125 ka (Bull, 1991), we can argue that Q4 is likely to be 125 ka. However, a date of 105 ka for Q4 can also be argued, because 105 ka is between the minimum uranium-series date and 125 ka, which is a maximum. Given our present data and knowledge, we can't determine if Q4 is 105 or 125 ka.

Q5 Surfaces and Soils. Soils that have formed on the Q5 geomorphic surface are characterized by thick, laminar stage IV carbonate K horizons; argillic B horizons are generally absent (Table 2). The stage IV, K horizons contain as much as 60%–70% carbonate. Stage IV carbonate (K1 horizon) is commonly observed to overlie a dense horizon of stage III carbonate (K2 horizon). A slight bimodal distribution of secondary carbonate is observed in Q5 soils, which may be associated with the general absence of B horizons. It appears that the B horizons on Q5 soils have mostly been stripped and/or engulfed by carbonate during K horizon development. Elsewhere, K horizons commonly are observed to extend to the surface and B horizons become overprinted, if the depth of wetting is relatively shallow (dry climate) or if surface erosion is sufficiently intense (Birkeland, 1984). Carbonate increases observed in Q5 soils directly correspond to increases in silt amounts. As with the other soils at Wheeler Ridge, this close relationship suggests that the carbonate is derived from windblown silt (Zepeda, 1993).

The Q5 geomorphic surface is estimated (based on extrapolation of rate of fold propagation) to be approximately 185 ka (oxygen isotope stage 7a) (Table 2). Stage IV carbonate morphology is the most characteristic feature of Q5 surface soils.

RATES OF DEFORMATION

A comparison of all structures in the fold-and-thrust belt on the north flank of the San Emigdio Mountains and along the Wheeler Ridge anticline shows that rates of deformation have varied in space and time (Keller et al., 1987). Deformation initially migrated northward from the active Pleito thrust fault to initiate the growth of Wheeler Ridge. Once folding was initiated, deformation propagated eastward along the growing anticline. This eastward growth is apparent from the varying degrees of both surface dissection and soil-profile development observed along the axis of the anticline. At the east end of Wheeler Ridge the minimum rate of latest Pleistocene–Holocene uplift, based on measured deformation of 24 m (vertical, not adjusted for sedimentation on flanks) over about 17 k.y. (Fig. 6), is about 1.4 mm/yr (Zepeda et al., 1986). After considering sedimentation during Q4 time, Medwedeff (1988, 1992) used the Keller et al. (1989) age estimate for Q4 in conjunction with the total structural relief to determine that the uplift rate at Wheeler Ridge is 3.2 mm/yr. The Q1 surface here is a strath terrace that has a veneer of gravels cut into on the present water gap of Salt Creek. As shown in Figure 6, the Q1 surface has been isolated by 1 to 2 m of post depositional incision by Salt Creek. The surveyed profile is parallel to modern Salt Creek, and the amount of folding is reasonably well constrained. Since the formation of the terrace there has been 3 m of uplift as a result of folding. On the basis of soil-profile development, we believe the age of the deposits on the terrace to be no more than about 1 ka. Pedogenesis of Q1 soils has not destroyed original fluvial stratification, which has been shown at San Emigdio Canyon to the west of Wheeler Ridge (Fig. 1) to be characteristic of deposits dated by ^{14}C to be about 1 ka (Laduzinsky, 1989). Thus, the best estimate for a very recent (minimum) rate of uplift is about 3 mm/yr.

The tear faults identified by Medwedeff (1988, 1992) correspond with the locations of wind and water gaps, and have developed during the lateral migration of the anticline. It appears, from the most reliable age information from Q4 to present, that faulting and associated folding at Wheeler Ridge developed in a segmented manner. Figure 8 shows a graph of the eastward propagation of the fold (data from Fig. 5 and Table 2). The eastern termination of surface expression of folding determined by surveying is just east of the eastern water gap (Fig. 5). This position is fixed at 8 km in Figure 8. Data points for Q2 and Q4 represent the age and location for each surface along the crest of the ridge. The error bars on the y axis represent the estimated length of the respective surface; the dot is at the center. The horizontal bar on the x axis for Q4 represents the estimated range of ages (83 to 125 ka). The point of the easternmost identified surface propagation of folding along with Q2 and Q4 in Figure 8 form a straight line, suggesting that the rate of propagation of the fold has been relatively constant during late Pleistocene time. This suggests that the slip rate on the fault has also been relatively constant. Uplift produced by faulting has probably not been constant, but is a function of the mechanics of folding (Rockwell et al., 1988). The age of Q3 is estimated to be about 60 ka, on the basis of extrapolation of its known position on the propagation line between Q2 and Q4 (Fig. 8). Interpolation to estimate the age of Q3 seems reasonable because it is between two established points (Q2 and Q4 ion Fig. 7). The rate of lateral propagation from Q4 (125 ka) to the eastern end of Q2 (data from Fig. 5 and Table 2) is about 30 mm/yr. This is about 10 times the rate of uplift determined by Medwedeff (1988, 1992).

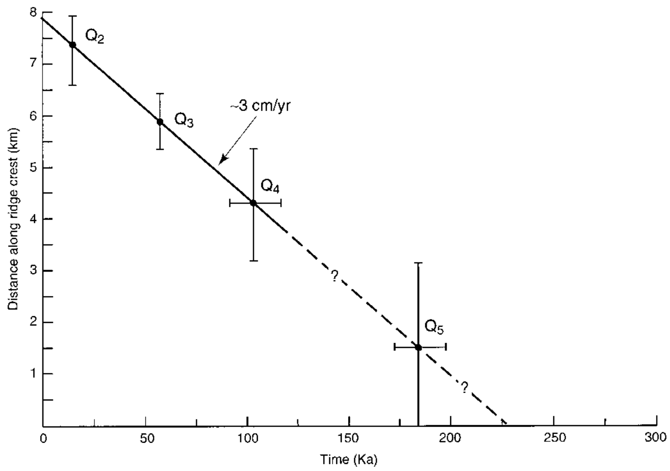

Figure 8. Propagation of Wheeler Ridge. There is acceptable age control for Q1, Q2, and Q4. Age control of Q3 and Q5 is based on extrapolation and assumption of constant rate of propagation of the fold.

Estimating the age of Q5 is problematic due to the assumption of a constant rate of propagation that is open ended (i.e., Q5 is not between two known points as is Q3). The fold is about 12 km long, and at a rate of propagation of 30 mm/yr would require 400 k.y. in order to reach its present eastward terminus east of Tecuya Creek (Fig. 4). Thus the age of Q5 could be as old as 400 ka, the age when the fold may have emerged from the alluvial fan gravels of the Tulare Formation. However, assuming a constant rate of propagation from Q5 time to present, an age assignment of about 185 ka for Q5 is our best estimate (Fig. 7).

The prominent wind gap (Figs. 2 and 4) was formed during Q3 time (ca. 60 ka), when the rate of uplift exceeded the rate of downcutting and the stream channel was abandoned. At this time gravels of Q3 age were being deposited as a stream terrace in what was then a water gap (the present wind gap) as well as around the eastern extension of the fold. We know this because the elevation of the wind gap today is about the same as that of the Q3 surface (Fig. 5). The same process is operating today because the elevation of the water gap between Q4 and Q3 (Fig. 5) is about the same as that of the easternmost water gap at Salt Creek (Figs. 4 and 5), as well as modern fan deposits directly east of Wheeler Ridge. Following defeat, the stream that occupied what is today the prominent wind gap was deflected eastward to flow through the present water gap that separates the Q3 and Q4 surfaces.

ROLE OF CLIMATE

As emphasized by Smiley (1991), a major problem in understanding relationships between geologic process and climate is the lack of accurate numerical dating. We have sufficient age control for Wheeler Ridge to make inferences concerning the role of climate related to aggradation and development of alluvial fan segments and stream terraces. There has been a fundamental question of timing of aggradation in the San Joaquin Valley (Lettis and Unruh, 1991): Is aggradation associated with glacial or interglacial time? Rivers draining the glaciated Sierra Nevada in the southern San Joaquin Valley evidently delivered the bulk of the sediment to the valley as a result of glacial-outwash aggradation (Atwater et al., 1986). We argue that, at Wheeler Ridge, the bulk of late Pleistocene aggradation delivered to the southernmost San Joaquin Valley was produced during several relatively short-duration events that correspond with rising sea level. That is, aggregation at Wheeler Ridge is apparently out of phase with aggradation from rivers draining the glaciated Sierra Nevada.

The development of Wheeler Ridge has been explained in terms of tectonic activity responsible for folding alluvial fan gravels shed from the north flank of the San Emigdio Mountains. Furthermore, the alluvial fan gravels (Tulare Formation) are the result of the uplift of the San Emigdio Mountains. However, the geomorphic development of the ridge involved both tectonic and climatic perturbations that occurred during late Pleistocene time (the last 125 k.y.). As a result, the amount of sediment produced from the mountains during the late Pleistocene certainly has not been constant as the fold developed. Nevertheless, it probably was relatively constant during specific time periods or aggradational events. For example, Q4 time was a time of extensive deposition (aggradation) of gravels that produced prominent alluvial fans at San Emigdio Canyon 20 km west of the eastern terminus of Wheeler Ridge as well as at the ridge itself. The Q4 deposits and associated alluvial fans at San Emigdio Canyon are by far the most extensive late Pleistocene aggradational event of the area. Q4 deposition correlates with initiation of the earliest of three late Pleistocene aggradational events in the Mojave Desert and elsewhere in southern California and southern Nevada (Bull, 1991). Numerical dates supporting initiation of Bull's (1991) three aggradation events center upon about 10, 55, and 125 ka, but range from about 6 to 12 ka for the Holocene event, 45 to 65 ka for the intermediate event, and 83 to 135 ka for the older event (Bull, 1991, p. 103). It is interesting that the age of Q5, as estimated from extrapolation of the propagation of Wheeler Ridge back in time, suggests that the age of approximately 185 ka correlates reasonably well with oxygen isotope stage 7 (Chappell and Shackleton, 1986), and may therefore suggest another climatically controlled aggradational event in southern California as a result of climate and associated change in vegetation. The other two regional aggradational events (discussed by Bull, 1991, p. 281) were initiated at about 55 ka and 10 ka, and may be represented by Q3-Q2 and Q1 deposits, respectively. However, these events were minor compared to Q4 deposition of alluvial fan gravels on the north flank of the San Emigdio Mountains. Even during Q4 aggradation the rate of uplift of 3.2 mm/yr exceeded the rate of fan deposition of 1.8 mm/yr, and far exceeded the estimated rate of erosion of 0.04 mm/yr (Medwedeff, 1992).

Late Pleistocene time in southern California was apparently characterized by climatically controlled aggradation events initiated by a shift toward more arid, warmer conditions in association with rising sea level (Bull, 1991). We speculate that this climatic shift resulted in a reduction and change in the species of dominant vegetation and was accompanied by a decreased effective precipitation (precipitation required to produce a given runoff), and increase sediment yield (Schumm, 1977). The aggradation events were probably of relatively short duration during the late Pleistocene, which for the most part is characterized by downcutting and incision of alluvial fan surfaces (Bull, 1991). A hiatus between Bull's (1991, p. 281) aggradation events of 55 ka and 125 ka is recorded in the Quaternary stratigraphy of southern California and southern Nevada, and this hiatus is evidently present at Wheeler Ridge between Q4 and Q3. Thus, whereas the positions of the wind and water gaps are probably fixed by the presence of tear faults that controlled episodic propagation of the fold (Medwedeff, 1992), much of the erosional relief and downcutting in the gaps may have been significantly influenced by climatically induced erosion. We suggest that the hiatus in deposition at Wheeler Ridge, between the 125 and 60 ka aggradational events, involved a return to cooler temperatures, presumably associated with an increase in effective precipitation, and more vegetation cover. In this scenario, sediment yields probably decreased and streams probably were downcutting. This climate shift would be similar to that following the most recent late Pleistocene glaciation (ca. 18 ka), when the climate was cooler and wetter along the western coast of North America from about lat 30° to 40°N (Smith, 1991). This was followed by rapid rise in sea level accompanied by warmer conditions and less precipitation. At Wheeler Ridge this would result in a change from semiarid conditions to arid. At Wheeler Ridge, the stream (at the wind gap, Figs. 4 and 5) apparently was able to downcut fast enough to keep pace with the uplift, until the climate changed about 60 ka. At that time an aggradational event was probably initiated (change from oxygen isotope stage 4 to 3), causing reduced stream erosion at the gap and eventual conversion of the landform to a wind gap. Another aggradation event was evidently initiated about 10 ka, producing the Holocene fan segments northeast and south of Wheeler Ridge. If uplift continues over the next few thousand years, the westward deep water gap (Figs. 2, 4, and 5) may be defeated forming another wind gap.

DRAINAGE DEVELOPMENT

As described earlier, surface dissection is greatest west of the wind gap and decreases in stages eastward, until relatively undissected surfaces are observed at the eastern end of the anticline (Fig. 2). Shelton (1966) was the first to conclude that the eastward decrease in dissection suggested that the Wheeler Ridge anticline was advancing eastward. The study of drainage density (length of stream channel per unit area) at Wheeler Ridge provides a rare opportunity to examine the history of drainage development on a growing anticline.

The greatest degree of dissection corresponds to the Q5 and Q4 geomorphic surfaces, intermediate dissection corresponds to the Q2-Q3 surfaces, and minimal dissection corresponds to the Q1 surface. An analysis of drainage density (Fig. 9) at Wheeler Ridge (Dinklage, 1991), based on analysis of aerial photographs and topographic maps, showed that: drainage densities on Q2-Q3 surfaces having relief <100 m and average surface slope of 4°–6° are 6.2 km^{-1} on the north flank and 0.4 km^{-1} on the south flank; drainage densities on Q4 surfaces having relief of 100–200 m and an average surface slope of >18° on the north flank and 8°–12° on the south flank are, respectively, 12.7 km^{-1} and 17.5 km^{-1}; and drainage density on Q5 surfaces having relief >200 m and an average slope of 8°–12° on the south flank is 15.7 km^{-1}. Drainage density on Q1 is essentially 0. As a result of folding, both surface slope and relief increases with the age of the geomorphic surface. Data for drainage density suggest that (1) for the younger surfaces, Q2-Q3, drainage density is maximum on the north flank, which is steeper, and (2) for the older surfaces Q4 and Q5, drainage density is greatest on the south flank. Thus, in the early development of drainage networks at Wheeler Ridge, surface slope is a significant limiting factor. However, with increasing relief and surface slope on both flanks, eventually the south flank, which has lower surface slope but longer potential stream length (length of slope), develops the greatest drainage density. We conclude that at Wheeler Ridge hillslopes equal to or greater than about 10° maximum slope (associated with a vertical interval of at least 17 m) are necessary for the initiation of stream channels and drainage network evolution.

EARTHQUAKE HAZARD

Recurrence intervals for moderate to large earthquakes along the Wheeler Ridge thrust fault may be calculated if the surface uplift per event is known or estimated. The primary assumption is that surface uplift per event and fault slip per event are directly related. This assumption is reasonable, provided that the earthquake is in the approximate range of M = 6 to 7+, as were the 1952 Kern County, 1971 San Fernando, 1983 Coalinga, 1987 Whittier Narrows, and 1994 Northridge, California, earthquakes. We are only beginning to understand how we might evaluate the earthquake hazard of faults hidden in growing anticlines. Thus Wheeler Ridge offers an important opportunity to examine this question.

Assuming a moderate to large earthquake on the Wheeler Ridge thrust fault and associated surface uplift of 1 to 2 m at Wheeler Ridge (the most recent event on a fault segment exposed in the gravel pit, Fig. 7), and assuming a 3.2 mm/yr uplift rate (Medwedeff, 1988, 1992), the average recurrence interval is about 300 to 600 yr. Recurrence intervals were derived by the method used by Stein and King (1984) in their evaluation of the 1983 Coalinga, California, earthquake. On the basis of a hydrologic model for fluid-pressure induced seismicity, Keller and Loaiciga (1993) concluded that the average recurrence for the Pleito fault system below Wheeler Ridge is 300–500 yr.

A hypothesis that could account for earthquakes of magnitudes greater than 8.0 beneath Wheeler Ridge was presented by Mueller and Suppe (1997). They suggested that the presence of fold-growth terraces on the north limb of Wheeler Ridge may indicate folding events resulting from about 10 m displacement on the underlying blind thrust, and a maximum recurrence interval (on the basis of the number of terraces) of about 500 yr. Assuming a fault dip of 20°–30°, and fault-slip rate of 10 mm/yr (Mueller and Suppe, 1997), the vertical component of slip would be 3.4 to 5 mm/yr, which at the lower range is equivalent to the estimate of 3.2 mm/yr by Medwedeff (1992). West of Wheeler Ridge at San Emigdio Canyon the total rate of uplift at the mountain front is 2.7 to 4.3 mm/yr. Assuming that the vertical rate of uplift is nearly equivalent to the vertical component of slip on the buried faults, a nearly constant rate of uplift along the entire front can be inferred. Ten meters of fault slip per event probably requires a kinematic link of the blind thrust with the San Andreas fault to the south. That is, they rupture simultaneously in a M = 8+ event (Mueller and Suppe, 1997), for example, as in the M = 8.3 Gobi-Altay earthquake in Mongolia (Bayarsayhan et al., 1996). We are unable to reject the hypothesis of Mueller and Suppe (1997) because the true nature of the

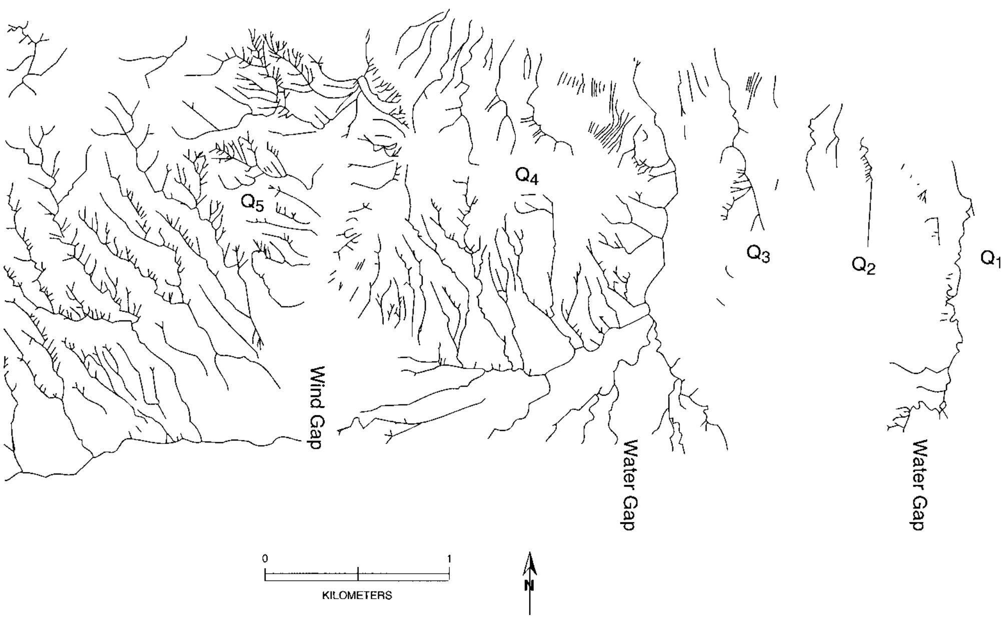

Figure 9. Streams developed on Q5 to Q2 surfaces at Wheeler Ridge. Based on aerial photographic interpretation. From Dinklage (1991).

possible fold-growth terraces is not known. Alternatively, we accept the more conservative hypothesis, that earthquakes of magnitude less than 8.0 are more consistent with established geologic relations and historic activity.

At Wheeler Ridge an uplift of about 1 to 2 m per event is a reasonable approximation for the following reasons. The 1952 Kern County earthquake, although not caused by displacement on the Wheeler Ridge fault, produced a 1 m uplift along and south of Wheeler Ridge (Stein and Thatcher, 1981). Laduzinsky (1989) documented several small, isolated fluvial terraces uplifted 1 to 2 m in San Emigdio Canyon (Fig. 1) that apparently are related to separate events on the Wheeler Ridge fault during the past 0.6 to 1 k.y. One late Pleistocene event on the Wheeler Ridge fault system, as examined in the gravel pit exposure, produced about 1 m of uplift. Hall (1984) suggested that surface uplift of approximately 1 m accompanies earthquakes of moderate magnitude along the active Pleito fault south of Wheeler Ridge.

Work by Laduzinsky (1989) suggests that, although there appears to be a spatial and temporal uniformity of earthquakes on the Wheeler Ridge fault during the past 0.6 to 1 k.y. in San Emigdio Canyon, a long period of inactivity occurred during Holocene and late Pleistocene time. However, the Los Lobos fold and associated buried reverse fault, only 1 km to the north, was active during mid-Holocene time (Seaver, 1986). Thus, faulting may have jumped north during part of the mid-Holocene, and returned to the Wheeler Ridge fault during the past 1000 yr. Swan (1988) investigated the Algerian Oued Fodda fault, which underwent surface-fault rupture during the 1980, M_S = 7.3, and found that the cumulative slip was produced by short episodes characterized by frequent surface displacements (every few hundred years) separated by long periods of inactivity.

Several lines of evidence suggest that displacements have occurred on more than one fault of the Pleito–Wheeler Ridge thrust-fault system during a particular time interval. For example, near Wheeler Ridge, the activity is currently divided among three faults: the Pleito fault (0.5 mm/yr uplift, assuming a fault dip of 20° and slip rate of 1.4 mm/yr over the past 1.5 k.y.; Hall, 1987); the Wheeler Ridge thrust fault (3.2 mm/yr uplift during late Pleistocene time; Medwedeff, 1988, 1992); and a deep thrust fault of the Pleito fault system that may have produced the 1952 Kern County, California, earthquake (Davis and Lagoe, 1987; Medwedeff, 1988). Activity on each of these faults probably varies both spatially and temporally. Other important factors are: (1) total fault displacement decreases sharply toward the eastern terminus of the anticline (Medwedeff, 1988, 1992); (2) fault displacement may be distributed along several local faults concealed in the fold; (3) faulting only recently reached the surface; and/or (4) most fault displacement occurs at depth. The fourth alternative may be the most significant, because nearly all surface deformation at Wheeler Ridge is by folding.

CONCLUSIONS

The Wheeler Ridge anticline is actively deforming above the Pleito–Wheeler Ridge thrust-fault system. Uplift, tilt, and fault displacement associated with the growth of the anticline are documented by alluvial fan segments that are systematically higher and older to the west of the eastern terminus of the fold (Figs. 4 and 5). Ages of the deformed geomorphic surfaces at Wheeler Ridge (Table 2) are determined by a combination of methods: numerical dating of charcoal and pedogenic carbonate (Q1, Q2, and Q4), and the rate of lateral propagation of the fold (Q3 and Q5). Four climatically driven Pleistocene aggradation events are recognized at Wheeler Ridge. These aggradation events were probably of relatively short duration and correlate with rising sea level, warmer conditions, less vegetation cover, decrease in effective precipitation, and a consequent increase in sediment yield. Aggradation that resulted in the Q5 and Q4 alluvial fan segments was initiated at about 185 ka and 105 ka or 125 ka, respectively. This was followed by a hiatus in aggradation until deposition of the Q3 fan segment starting about 60 ka. The most recent aggradational event appears to have started about 10 ka. The three youngest gravelly deposits roughly correlate with the three main late Pleistocene aggradational events recognized for southern California and Nevada (Bull, 1991, p. 281). At Wheeler Ridge the major aggradational events produced the alluvial fan segments that were subsequently deformed by uplift and folding.

The development of Wheeler Ridge (on the basis of back calculation from lateral rate of propagation of the fold) was apparently initiated about 400 ka. The fold is propagating eastward at a rate of about 30 mm/yr. The rate of uplift during the past 1 ka is at least 3 mm/yr.

Drainage density increases with the age of the geomorphic surface at Wheeler Ridge. As the fold propagates eastward and uplift occurs, a threshold hillslope gradient of about 10° over a vertical interval of about 17 m is apparently necessary to initiate stream channels.

The Pleito–Wheeler Ridge thrust-fault system is composed of a number of active faults. Holocene surface folding observed at the eastern extent of Wheeler Ridge is strong evidence for active faulting at depth. Rates of deformation and identification of paleoseismic events at Wheeler Ridge are not constrained well enough to determine a firm recurrence interval. However, large damaging earthquakes can be expected to occur every few hundred years within the Pleito–Wheeler Ridge thrust-fault system.

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