The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera

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ABSTRACT

Tilted Cenozoic strata in the eastern Great Valley, California, record progressive late Cenozoic uplift of the Sierra Nevada. The magnitude of tilting is combined with other geologic data, using a technique pioneered by Grant and others, to infer the rate and timing of post-late Miocene uplift between the Kings River and the Feather River.

Angular unconformities of late Neogene age have been reported throughout the east-central Great Valley. Typically, stratigraphic units of late Oligocene through Miocene-Pliocene age beneath the unconformities dip approximately 1.2°–1.6° southwest. Middle to late Pliocene units above the unconformities dip approximately 0.6°–0.9° southwest and progressively overlap younger units from east to west. These angular unconformities are interpreted to represent the onset of late Cenozoic uplift of the Sierra Nevada due to westward tilting. Dated volcaniclastic units in the east-central Sacramento Valley bracket the onset of tilting there between 3.4 and 8.4 Ma. Stratigraphic and geologic relations from the Stanislaus River area, eastern San Joaquin Valley, suggest that the late Cenozoic tilting probably began approximately 5 Ma.

Previously published tilt data from the San Joaquin Valley combined with new work in the eastern Sacramento Valley indicate that the rate of post-late Miocene tilting has been approximately uniform in the east-central Great Valley. Early to middle Pleistocene units typically dip 0.5°–0.7° southwest; middle Pleistocene units dip 0.2°–0.4°; middle to late Pleistocene units dip 0.1°–0.15°; late Pleistocene units dip 0.05°–0.1°. If it is assumed that major westward tilting began 5 Ma, these data indicate an approximately uniform tilting rate of 0.28° per million years.

These data have important implications for models of the uplift. Simultaneous inception of tilting in the east-central Great Valley at approximately 5 Ma does not support models that link uplift of the Sierra Nevada to the migration of the Mendocino triple junction. Late Cenozoic tilting of the Sierra Nevada block does not appear to coincide temporally with the onset of major Basin and Range extension. The uplift may be due to thinning of the mantle lithosphere beneath the Sierra Nevada, but the tilt data do not afford a direct test of this hypothesis.

Post-late Miocene tilting of the Sierra Nevada is temporally associated with late Cenozoic uplift of the northern Basin and Range, uplift of the Cascades, uplift of the Colorado Plateau, and uplift of the southern Rocky Mountains, supporting the contention that tilting of the Sierra Nevada may have occurred as part of a Cordillera-wide uplift event.

INTRODUCTION

The timing, magnitude, and mechanics of the late Cenozoic uplift of the Sierra Nevada range have been a matter of continuing controversy. Although most workers agree that uplift has occurred within the past 10 m.y. (Christensen, 1966; Huber, 1981, 1990; Loomis and Burbank, 1988), there is no agreement on precisely when westward tilting characteristic of the modern Sierra Nevada began, whether it began simultaneously throughout the entire range, or whether the rate and magnitude of the tilting is uniform from south to north. Constraints on the

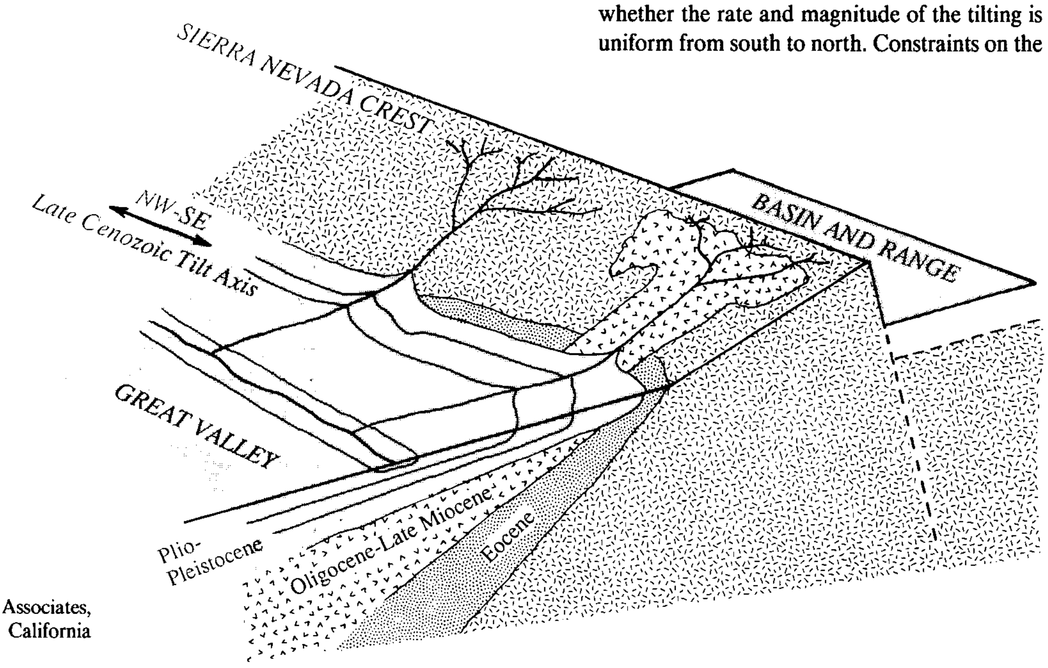

Figure 1. Schematic block diagram illustrating the simple kinematic model for uplift of the Sierra Nevada. The Sierra Nevada has been uplifted and tilted westward, forming a distinctly asymmetric profile. The northwest-southeast-striking late Cenozoic tilt axis is in the eastern Great Valley. As a consequence of the uplift, Cenozoic strata deposited along the eastern margin of the Great Valley have been tilted southwest.

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timing and kinematics of tilting are crucial for testing models that relate the deformation to time-transgressive events such as the northward migration of the Mendocino triple junction (Crough and Thompson, 1977).

Late Cenozoic tilting of the Sierra Nevada has also tilted Tertiary strata in the eastern Great Valley so that the gradient, or dip, of these units increases with age. This study utilizes a technique pioneered by Grant and others (1977) to infer the rate and timing of uplift between the Kings River and the Feather River from the progressive tilting of Tertiary strata. The data presented below indicate that westward tilting began along much of the western margin of the

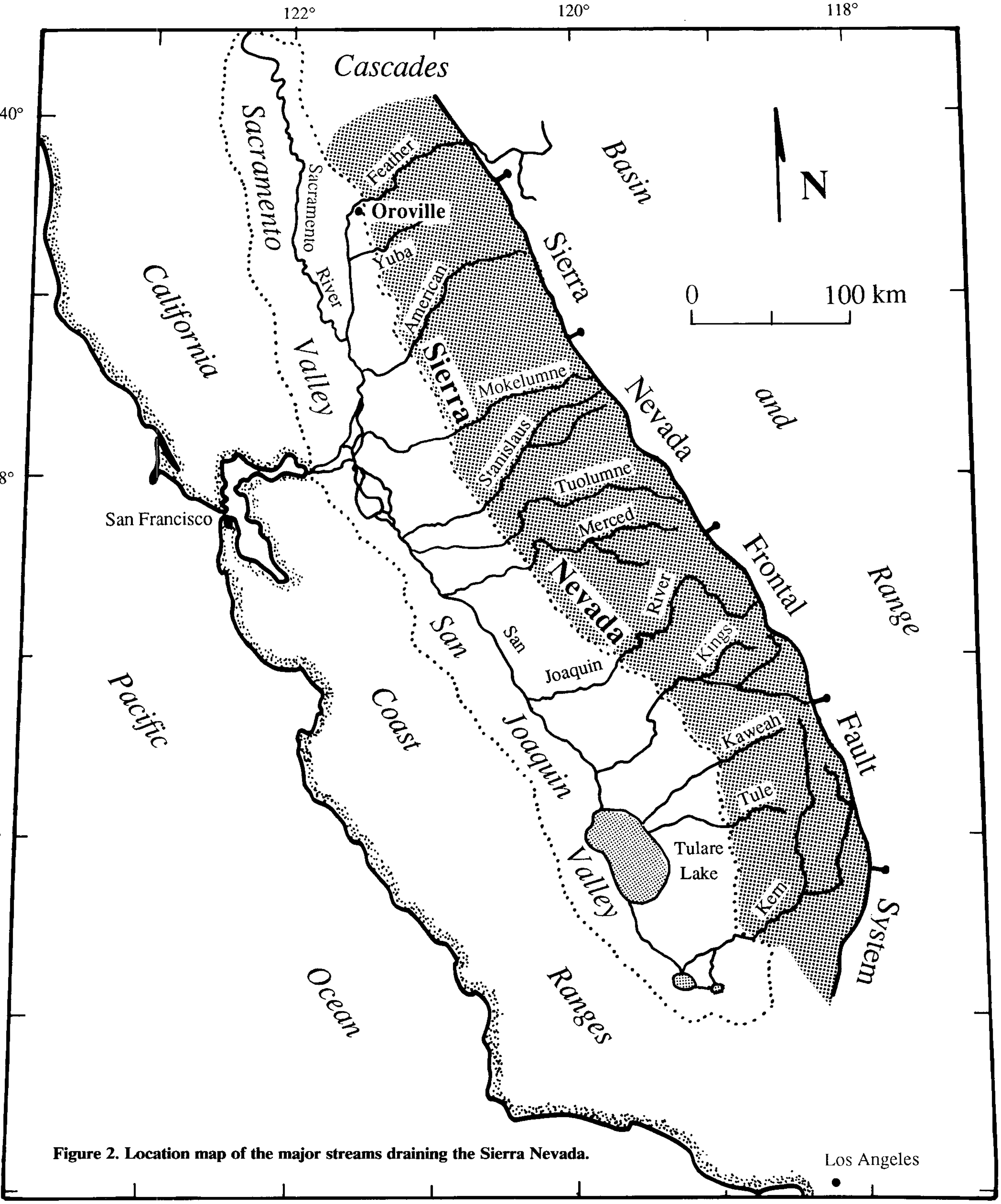

Figure 2. Location map of the major streams draining the Sierra Nevada.

TABLE 1. DIP OF MIOCENE AND OLDER TERTIARY UNITS IN THE EASTERN GREAT VALLEY, CALIFORNIA

Stratigraphic unit	Age	Oroville area	American River area	San Joaquin Valley	Merced River area	San Joaquin River area	Kings River area
		(this study)	(Department of Water Resources, 1974)	(Marchand, 1977, and other sources in Singer and others, 1977)			(Huntington, 1980)
Lovejoy Basalt	Miocene	1.4°					
Mehrten Formation	Miocene to early Pliocene		1°–2°	1.3°–1.4°	1.1°	1.26°· 1.5°	1.4° (10 Ma volcanic flow)
Valley Springs Formation	Oligocene to early Miocene		1.5°–2°	1.2°–1.35°	1.0°		
Ione Formation	Eocene		5°		1.72°	1.74°	2.46°

range at approximately 5 Ma. Models for the late Cenozoic uplift of the Sierra Nevada are examined for consistency with the tilt data. The uplift and tilting of the Sierra Nevada are also discussed in the context of epeirogenic uplift throughout the western United States since late Neogene time.

GEOLOGIC SETTING AND STRATIGRAPHY

The Sierra Nevada is most commonly and most simply characterized as an uplifted, west-tilted fault block cored by Mesozoic crystalline rocks (Bateman and Wahrhaftig, 1966). The eastern margin of the range is bounded by a steep, east-dipping frontal fault system. The western slope dips gently and uniformly to the southwest, producing a distinctly asymmetric northeast-southwest topographic profile. The asymmetry is expressed, however, only north of the Kings River. South of the Kings River, the range rises abruptly from the eastern Great Valley to a broad, irregular summit upland (Christensen, 1966).

The surface of the crystalline Sierran basement dips westward beneath the Great Valley of California and is overlain primarily by Cenozoic strata along the eastern valley margin (Fig. 1). The Great Valley is subdivided into two physiographically distinct basins: the Sacramento Valley to the north and the San Joaquin Valley to the south (Fig. 2). Although important differences exist between the two basins, some Tertiary stratigraphic units and regional depositional trends are common to the eastern margins of both. In general, the base of the Tertiary section overlying the basement consists of Eocene fluvial and deltaic deposits (Fig. 1). The Eocene deposits are unconformably overlain by a series of late Oligocene through Miocene-Pliocene volcaniclastic deposits derived from a volcanic arc that was active in the Sierra crestal region from middle to late Tertiary time (Eaton, 1984). Tertiary epiclastic and pyroclastic rocks mantling the western Sierra Nevada slope grade westward into volcaniclastic fluvial deposits in the subsurface of the Great Valley (Fig. 1). Miocene-Pliocene and older strata are unconformably overlain by a Pliocene-Pleistocene fluvial sequence, reflecting the evolution of the Great Valley from a subaerial forearc basin into an intermontane basin during late Neogene time (Unruh, 1990; Lettis and Unruh, 1991). Pleistocene strata in the northeastern San Joaquin Valley have been interpreted as a series of overlapping alluvial fans deposited during glacial outwash events (Marchand and Allwardt, 1981).

DATA PRESENTATION AND ANALYTICAL ASSUMPTIONS

The central premise of this paper is that late Cenozoic westward tilting of the Sierra Nevada has also tilted Cenozoic strata in the eastern Great Valley, a conclusion previously reached by Grant and others (1977), Marchand (1977), and Huber (1981). The data presented herein consist of new data from the east-central Sacramento Valley as well as previously published tilt values from other areas of the eastern San Joaquin Valley (Tables 1 and 2). The technique used by most workers to determine the magnitude of tilting is to draw structure contours on marker horizons in Cenozoic stratigraphic units, or draw structure contours on tilted geomorphic surfaces underlain by the units, and measure strike and dip from the contours (Woodward-Clyde Consultants, 1977; Huber, 1981; Unruh, 1990). The contacts or surfaces can typically be reconstructed over areas ranging from approximately 20 to 400 km^2, and multiple determinations of the gradients have been made using extensively preserved surfaces (Woodward-Clyde Consultants, 1977). The magnitude of tilting has also been locally determined from the dip of Cenozoic marker horizons correlated between test holes (Department of Water Resources, 1974; Woodward-Clyde Consultants, 1977; Unruh, 1990). Tilting of the Sierra Nevada block east of the Great Valley has been estimated by mapping Tertiary channel deposits and reconstructing the gradients of ancestral Sierran rivers (Lindgren, 1911; Huber, 1990).

The data in Tables 1 and 2 are tilt estimates from areas of the eastern Great Valley where, to date, Cenozoic strata have been mapped in detail. Typically, gradients are estimated from tilted geomorphic surfaces preserved over large areas between major rivers; thus, the geographic locations in Tables 1 and 2 refer to Sierran rivers closest to the individual study areas. In several cases, the data tabulated in Tables 1 and 2 were originally reported without detailed descriptions of the methods used to obtain tilt values, or discussion of the range of tilt values within individual study areas. The most thoroughly documented and discussed tilt data from the eastern San Joaquin Valley come from Woodward-Clyde Consultants (1977) and Huber (1981, 1990). Unruh (1990) discussed techniques for estimating tilt values, numbers of measurements, and local variations of tilt values in the east-

TABLE 2. DIP OF LATE CENOZOIC STRATIGRAPHIC UNITS AND GEOMORPHIC SURFACES IN THE EASTERN GREAT VALLEY, CALIFORNIA

Stratigraphic unit	Age	Oroville area	American River area	San Joaquin Valley	Merced River area	San Joaquin River area	Kings River area
		(this study)	(Department of Water Resources, 1974)	(Marchand, 1977, and other sources in Singer and others, 1977)			(Huntington, 1980)
Alluvium	Holocene				0.04°		
Modesto Fm.	Late Pleistocene		0.05°–0.12°	0.08°	0.07°–0.1°	0.05°–0.07°	
QP	Middle to late Pleistocene	0.09°–0.15°					
Riverbank Fm.					0.11°–0.15°	0.09°–0.11°	
Turlock Lake Fm.				0.2°	0.18°	0.16°	
Arroyo Seco Gravel	Middle Pleistocene		0.22°				
North Merced Gravel				0.17°–0.27°	0.2°–0.46°		
China Hat Gravels	Early to middle Pleistocene			0.6°	0.6°		
Tuffs of Oroville		0.5°–0.75°					
Tivy Surface	Middle Pliocene to Pleistocene						0.6°
Kirkman Surface							0.8°
Laguna Fm.			0.98°	0.9°			

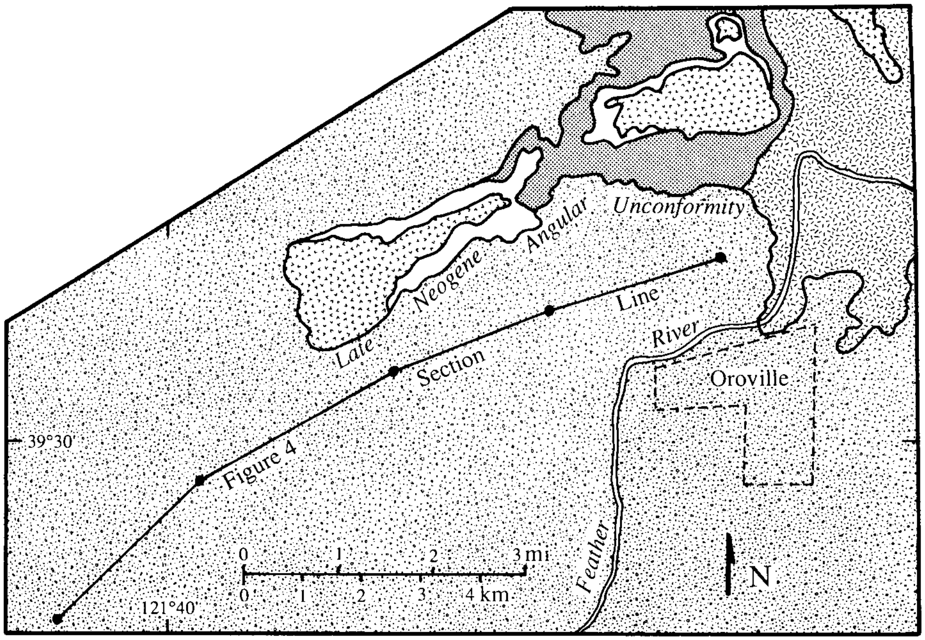

Figure 3. Generalized geologic map of the Oroville area, east-central Sacramento Valley. Map units include Mesozoic crystalline bedrock (line pattern in the northeastern corner of the map); Eocene fluvial and deltaic deposits, undivided (bold dot pattern); the early Miocene Nord Formation (unpatterned); the middle (?) to late Miocene Lovejoy Basalt (triangle pattern); and Pliocene-Pleistocene sediments, undivided (sand and gravel pattern in the southern half of the map; locally includes Quaternary gravels disturbed by dredging). Outcrop patterns north of Oroville indicate that late Miocene and older Tertiary stratigraphic units have been uplifted and tilted to the west. Pliocene-Pleistocene sediments unconformably overlie the tilted Tertiary section and, from west to east, progressively overlap older units. Mapping modified from Creely (1965); stratigraphic units are described in greater detail in Unruh (1990).

central Sacramento Valley. Gradients are most commonly reported in the literature in terms of feet per mile or meters per kilometer. For this study, all values have been recalculated to units of degrees.

To use the dip, or gradient, of Cenozoic strata to infer the timing and kinematics of Sierra uplift, the following assumptions are made.

(1) *Gradients or dips cited herein must be considered estimates of maximum tilting, because they have not been corrected for original slope.* A value of 0.04° has been reported for the Holocene gradient of the Merced River flood plain (Marchand and Allwardt, 1981; see Table 2). Presumably, all gradients could be corrected assuming that their original slope was similar to this presumed Holocene value. This exercise was not performed for middle Pleistocene and older strata, because a 0.04° initial gradient is less than the range in gradient estimates reported in the literature for older units.

(2) *The central Sierra Nevada between the Feather River and the Kings River is assumed to have been uplifted and tilted southwest as a rigid block about a single axis or hinge line.* Christensen (1966) used the elevation of upland surfaces adjacent to Tertiary stream deposits on the western Sierra Nevada slope to draw structure contours of the late Cenozoic uplift. The contours suggest that between the Yuba River and the Kings River, the Sierra Nevada was tilted as a rigid block, with no major internal tilting or flexure (see Fig. 2 for locations of Sierran rivers). Bateman and Wahrhaftig (1966) cited the evenness of west-sloping interfluves on the western slope of the northern Sierra Nevada as evidence that the northern portion of the range was tilted as a single unit. South of the Kings River, however, the Sierra may have been flexed down to the south during late Cenozoic time (Jones, 1987). Structure contours drawn on the surface of Miocene volcanic units in the east-central Sacramento Valley also indicate that late Cenozoic flexure may have occurred above reactivated basement faults, locally steepening the gradient in excess of that produced by the uplift and tilting of the Sierra (Unruh, 1990). In general, however, the assumption that the central Sierra Nevada north of the Kings River has been tilted as a rigid block has been adopted by many workers (Christensen, 1966; Bateman and Wahrhaftig, 1966; Grant and others, 1977), and it appears to be a reasonable approximation for post–late Miocene deformation.

The gradients of Cenozoic strata in the east-central Great Valley effectively record only uplift of the Sierra Nevada by westward tilting. It is probable that some Cenozoic uplift of the Sierra Nevada was not accompanied by tilting, and thus may not be reflected in the gradient data (N. King Huber, 1991, personal commun.). This paper will focus on the rate and timing of late Cenozoic uplift associated with the evolution of the Sierra Nevada as a characteristically west-tilted mountain range, with the caveat that deviations from the approximation of rigid-block tilting are not adequately addressed by this analysis.

(3) *The hinge line for tilting of the Sierra Nevada is west of the Sierra foothills and lies within the eastern Great Valley.* Marchand (1977) proposed that westward tilting associated with the uplift of the Sierra Nevada extends west into the eastern Great Valley. In the Oroville area, east-central Sacramento Valley, the Lovejoy Formation, a middle to late Miocene basalt (Wagner and Saucedo, 1990), caps an uplifted, southwest-tilted section of Cenozoic strata (Fig. 3). The intersection of the sloping basalt surface with the modern valley floor (a crude guide to the location of the tilt axis) is approximately 6 km west of the valley margin. Landsat imagery reveals that uplifted and tilted Neogene strata are in a 6- to 8-km-wide northwest-trending belt between the Sierra Nevada foothills to the east and the younger fan–flood-plain surfaces of the Sacramento Valley to the west. I consider the contact between the sloping Miocene-Pliocene deposits and less tilted younger units as evidence that the tilt axis lies within the eastern Sacramento Valley, approximately 6 km west of the valley margin.

The assumption that uplift and tilting have occurred about a single axis requires that the magnitude of tilting east of the axis be constant for all affected units. Comparison of the gradients of Miocene strata exposed in the eastern Great Valley and on the western slope of the Sierra Nevada supports this assumption. Huber's data (1990) indicate that channel deposits of the Miocene Tuolumne River exposed at elevations of 1,100 to 1,900 m (3,500–6,000 ft) in the central Sierra Nevada dip approximately 1.2° southwest normal to regional strike. Dips of Miocene strata reported from the east-central San Joaquin Valley range from 1.2°–1.5° southwest (Table 1). The similar values of tilting of the Miocene strata in both the central Sierra Nevada and east-central Great Valley suggest approximately uniform tilting at the latitude of the Tuolumne River about an axis *west* of the eastern margin of the San Joaquin Valley.

(4) *The dips of Cenozoic strata in excess of the slope of Holocene depositional surfaces in the east-central Great Valley are interpreted to reflect uplift and westward tilting of the Sierra Nevada.* The gradients of Pliocene through Holocene strata in the east-central Great Valley consistently increase with age (Table 2). If the higher gradients of the older strata are not a function of regional tilting associated with the uplift of the Sierra Nevada, then they must reflect systematic changes in stream hydraulic conditions with time.

Episodic Quaternary deposition in the east-central Great Valley has long been attributed to glaciation of the Sierra Nevada (Arkley, 1962; Marchand, 1977). Hydraulic parameters such as discharge, sediment load, and sediment caliber may have increased significantly during glacial outwash events (Shlemon, 1972; Marchand and Allwardt, 1981). Systematic variations of these parameters, tied to climatic fluctuations, could conceivably have produced the progressively decreasing gradients of late Cenozoic strata. For example, the slopes of graded streams are inversely proportional to discharge (Langbein and Leopold, 1964) and directly proportional to sediment load and sediment caliber (Schumm, 1977). Decreasing gradients with time may thus reflect some combination of increasing discharge, decreasing sediment load, and decreasing sediment caliber during subsequent glacial outwash events. Although understanding of Quaternary paleohydraulic conditions in the eastern Great Valley is imperfect (Lettis and Unruh, 1991), there is no evidence for systematic variation in hydraulic parameters during late Cenozoic time. Studies of Quaternary strata reveal that units of different ages have similar sediment textures (Marchand and Allwardt, 1981); no systematic increase in average clast size through time has been reported. The penultimate glaciation of the Sierra Nevada was the middle to late Pleistocene Tahoe glaciation (Bateman and Wahrhaftig, 1966). Presumably, Quaternary stream discharge in the eastern Great Valley was at a maximum during the Tahoe deglaciation. If the varying gradients of late Cenozoic strata reflect variations in stream discharge, middle to late Pleistocene strata in the eastern Great Valley should dip less steeply west than do early to middle Pleistocene strata. In fact, the gradients of all Quaternary units progressively decrease with decreasing age (Table 2).

Although it is possible that nontectonic processes may have produced progressively decreasing gradients with decreasing age during the Quaternary, I believe that the most parsimonious explanation is that the varying gradients of late Cenozoic strata are the result of progressive westward tilting during the uplift of the Sierra Nevada. This hypothesis is consistent with observations that older units typically occupy higher topographic positions (Marchand and Allwardt, 1981) and are more strongly dissected with increasing age (Busacca and others, 1989).

EVIDENCE FOR PRE-LATE CENOZOIC UPLIFT OF THE SIERRA NEVADA

Geomorphic and stratigraphic data indicate that uplift of the Sierra Nevada occurred prior to late Miocene time (Huber, 1981). Petrologic and stratigraphic relationships suggest that the initial uplift of the Sierra Nevada and exposure of the Mesozoic batholith may predate early Tertiary time. By Eocene time (approximately 45–50 Ma), large rivers drained from east to west across the northern and central Sierra Nevada crest (Bateman and Wahrhaftig, 1966). Channel deposits of the Eocene rivers locally rest on Mesozoic plutonic and metamorphic rocks in the northern Sierra Nevada (Durrell, 1966), indicating that the batholith had been uplifted and unroofed prior to Eocene time. Paleobarometric studies reveal that 134–140 Ma plutons in the northern Sierra Nevada crystallized at depths of approximately 8–12 km (McLeod and Day, 1991), suggesting that uplift of that magnitude or slightly less occurred between Early Cretaceous and Eocene time.

Similarly, Sams and Saleeby (1988) concluded from paleobarometric analysis that 100 Ma plutonic rocks of the southern Sierra Nevada batholith formed approximately 20 km deeper than did 100 Ma plutonic rocks in the central portion of the range. This suggests a minimum uplift of 20 km for the southern Sierra Nevada since 100 Ma. Sams and Saleeby (1988) summarized evidence that the uplift occurred prior to Eocene time. The initial uplift must have ceased well before Eocene time, because erosion had reduced the ancestral Sierra Nevada to a range of modest relief prior to the deposition of the Eocene fluvial gravels. Huber (1981) calculated that major peaks on either side of the San Joaquin Canyon, central Sierra Nevada, presently rise only 450–750 m above the reconstructed Eocene base level.

Additional or renewed uplift of the Sierra Nevada occurred between Eocene and late Miocene time (approximately 50–10 Ma). Major peaks near the central Sierra Nevada crest rise 1,500–1,700 m above the local 10 Ma base level, indicating that relief within the range had increased substantially between Eocene and late Miocene time (Huber, 1981). At least some of the post-Eocene uplift probably occurred prior to early Miocene time. In areas where tilt data have been collected, the Eocene Ione Formation in the eastern Great Valley dips more steeply southwest than does the overlying late Oligocene to early Miocene Valley Springs Formation (Table 1). Huber (1981) noted that as much as 1,300 m of uplift at the crest may have occurred between Eocene and late Oligocene time at the latitude of the upper San Joaquin River drainage, if the angular discordance between the two units in the eastern San Joaquin Valley represents tilting sustained across the width of the range.

TIMING AND KINEMATICS OF THE LATE CENOZOIC TILTING OF THE SIERRA NEVADA

Angular unconformities of late Neogene age regionally separate Miocene-Pliocene and older Tertiary strata from overlying Pliocene-Pleistocene deposits in the east-central Great Valley. Typically, the Pliocene-Pleistocene deposits successively overlie, from east to west, crystalline rocks of the Sierra Nevada, Paleogene and older Neogene fluvial sediments, and Miocene-Pliocene volcaniclastic rocks (Figs. 1 and 3). The gradient or dip of Miocene-Pliocene and older Cenozoic strata is measurably greater than that of the overlying Pliocene deposits (Tables 1 and 2). The precise age and lithology of the Miocene-Pliocene and older units varies throughout the valley, but Pliocene sedimentary rocks consistently overlap progressively younger strata from east to west. These stratigraphic relations are interpreted as a regional angular unconformity marking the onset of the late Cenozoic tilting of the Sierra Nevada.

The late Neogene angular unconformity is revealed by outcrop patterns in the eastern Sacramento Valley north of the Feather River (Fig. 3). Tertiary strata capped by the middle to late Miocene Lovejoy Basalt underlie a series of west-sloping mesas and cuestas north of the town of Oroville. Pliocene-Pleistocene sedimentary rocks unconformably overlie the west-tilted Tertiary section and from west to east progressively overlap Miocene units, Eocene strata, and Mesozoic bedrock (Fig. 3). Outcrop patterns showing similar stratigraphic relationships can be observed in maps of the Merced River area, eastern San Joaquin Valley, approximately 250 km south of the Feather River (Arkley, 1962; Marchand and Allwardt, 1981).

Correlated test-hole data from the Oroville area also reveal the late Neogene angular unconformity and permit an estimation of the timing of initial tilting. Pliocene-Pleistocene sedimentary rocks unconformably overlie a west-tilted section of Paleogene and Neogene strata (Fig. 4). Several of the units shown in Figure 4 crop out in the uplifted, west-sloping landforms north of the cross-section line in Figure 3. The oldest radiometrically dated unit above the angular unconformity in the Oroville area is the 3.4 Ma Nomlaki Tuff, which is at or near the base of the Pliocene-Pleistocene section (Busacca, 1982; Unruh, 1990). The youngest unit beneath the angular unconformity is the Neroly Formation, a late Miocene fluvial volcaniclastic deposit widely distributed in the Sacramento Valley subsurface (Redwine, 1972). The Neroly Formation is easily recognized in well logs by its beds of "black" volcaniclastic sand and its distinctive bluish colors, which result from diagenetic clay coatings on the sand grains (Unruh, 1990). Using hundreds of water-well and test-hole logs, Unruh (1990) traced the Neroly Formation from the Oroville area 35 km southeast to the Yuba River area. There, the Neroly Formation interfingers in the subsurface with the Reed's Creek Andesite, a Miocene volcaniclastic and pyroclastic deposit that crops out in the western Sierra Nevada foothills south of the Yuba River (Fig. 2). The Neroly Formation was interpreted by Unruh (1990) to be a basinal, fluvial equivalent of the lahars and pyroclastic flow deposits in the Reed's Creek Andesite. Radiometric dates obtained from volcanic clasts in the Reed's Creek Andesite range from 8.4–18.0 Ma (Wagner and Saucedo, 1990). The youngest date (8.4 Ma) was obtained from a volcanic block at the stratigraphically highest exposure of the Reed's Creek (George Saucedo, 1990, personal commun.). If the correlation of the Neroly Formation with the Reed's Creek Andesite is correct, the top of the Neroly Formation is no older than 8.4 Ma. The radiometric dates from the Reed's Creek Andesite, combined with stratigraphic and age relationships in the east-central Sacramento Valley, described above, indicate that uplift and tilting represented by the late Neogene angular unconformity began between 3.4 and 8.4 Ma.

Similar subsurface relationships have been observed in the southeastern Sacramento Valley approximately 120 km south of Oroville. Using well-log data, California Department of Water Resources (DWR) geologists constructed several east-west cross sections north of the American River in the Sacramento area (DWR, 1974; see Fig. 2 for location of the American River). The correlated subsurface data reveal an angular unconformity between Pliocene-Pleistocene strata and underlying Cenozoic deposits (Fig. 5). The youngest unit beneath the angular unconformity in the Sacramento area is the Mehrten Formation of Miocene to earliest Pliocene age (Marchand and Allwardt, 1981). The oldest unit above the angular unconformity is the Laguna Formation, thought to be latest Pliocene to early Pleistocene in age (Marchand and Allwardt, 1981).

The late Neogene angular unconformity has been observed between the Feather River and the Merced River in the eastern Great Valley (Table 3). The timing of uplift and tilting is generally bracketed by Miocene-Pliocene volcaniclastic deposits and older strata beneath the unconformity, and middle Pliocene and younger strata above the unconformity. Detailed gradient data from the Stanislaus River area, northeastern San Joaquin Valley, suggest that tilting there probably began during deposition of the Miocene-Pliocene Mehrten Formation (Woodward-Clyde Consultants, 1977; Grant and others, 1977). Table 4 lists the gradient of the base of the Mehrten Formation mudflows and the gradients of four laterally extensive lahars in the middle to upper portion of the Mehrten used by Woodward-Clyde Consultants (1977) as marker horizons. The base of the Mehrten mudflows is tilted more steeply westward than are the overlying marker horizons, and the marker horizons show a progressive increase in gradient with increasing age. These data are interpreted as evidence for syndepositional tilting of the Mehrten Formation. Wagner (1981) also reported evidence from the Stanislaus River area for an angular unconformity of Hemphillian age in the upper portion of the Mehrten Formation (Table 3).

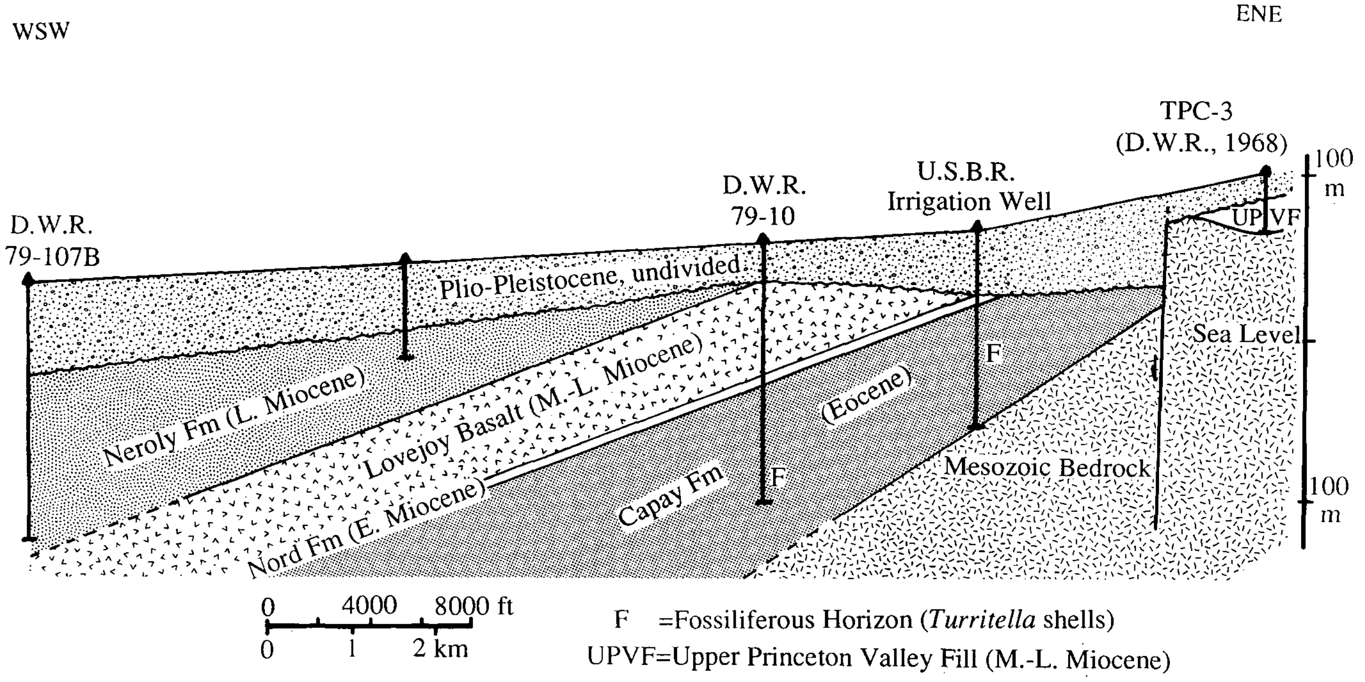

Figure 4. East-west geologic cross section in the Oroville area constructed from well-log data provided by the California Department of Water Resources (see Fig. 3 for detailed location of section line and individual drill holes). Note that Pliocene-Pleistocene strata progressively overlap younger strata from east to west, reflecting westward tilting of the Miocene and older strata in late Neogene time. Vertical exaggeration, 20×.

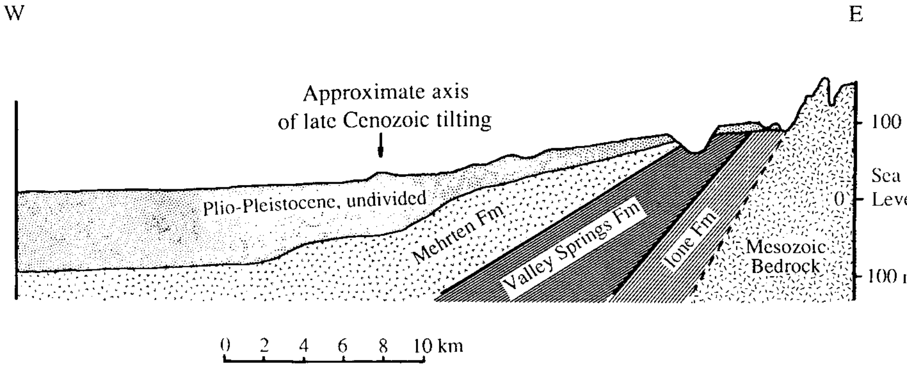

Figure 5. East-west cross section from the Sacramento area, approximately 120 km south of Oroville, modified from cross sections presented in Department of Water Resources (1974). Note stratigraphic and age relationships similar to those in the Oroville area (Mehrten Formation, late Miocene to Pliocene; Valley Springs Formation, late Oligocene to early Miocene; Ione Formation, Eocene). Vertical exaggeration, 40×.

In the Stanislaus River area, lahars of the Mehrten Formation rest on and contain clasts of the Table Mountain latite (T. A. Grant, 1990, personal commun.). The Table Mountain latite has been dated at 9 Ma by K-Ar techniques (Dalrymple, 1964). The tilted marker horizons (Table 4) are in the middle to upper portion of the Mehrten Formation (T. A. Grant, 1990, personal commun.). The middle portion of the Mehrten Formation contains the Oakdale flora, estimated to be middle Pliocene (Hemphillian) in age based on its composition and climatic indications (Axelrod, 1980). Combined paleontological, radiometric, and stratigraphic data indicate that the upper portion of the Mehrten Formation in the eastern San Joaquin Valley is probably 4.0–4.5 Ma (Axelrod, 1980; Bartow, 1980). Because the gradient of the base of the Mehrten lahars in the Stanislaus River area is similar to the gradient of the underlying Valley Springs Formation (T. A. Grant, 1990, personal commun.), tilting probably began just prior to or during deposition of the middle or upper portion of the Mehrten. I interpret these data as evidence that tilting began approximately 5.0 Ma in the east-central San Joaquin Valley, particularly if tilting began during deposition of the upper portion of the Mehrten Formation (Wagner, 1981).

The onset of uplift due to tilting can also be bracketed by independent paleobotanic and geologic data. Axelrod (1980) reported that the Mount Reba flora, a lowland plant assemblage found in volcaniclastic rocks with K-Ar ages of 6–7 Ma, is presently exposed at the crest of the northern Sierra Nevada. The displacement of the Mount Reba flora indicates that uplift began after 6–7 Ma, and possibly as recently as 5 Ma (Axelrod, 1980). Dalrymple (1963) observed that 3.9 Ma basalts crop out within the rims of the inner gorges of modern Sierran rivers, implying that canyon cutting, and hence uplift, began prior to 3.9 Ma. Christensen (1966) noted that the Tertiary Sierran canyons, now filled with late Miocene volcanic and pyroclastic flows, had flat floors and uniform gradients. In contrast, Pliocene-Pleistocene channels have deep, V-shaped canyons with numerous local changes in gradient, suggesting that uplift began or accelerated after eruption of the late Miocene volcanic rocks and initiated a new episode of canyon-cutting. I interpret these relationships as evidence that uplift related to tilting began between 4 and 6–7 Ma, consistent with the estimate of 5 Ma based on stratigraphic data from the eastern San Joaquin Valley.

The 1.2°–1.6° range in dip of late Miocene strata along the east-central Great Valley implies that the magnitude of tilting is approximately uniform between the Kings River and the Feather River (Table 1) and supports the rigid-block approximation for late Cenozoic uplift. Dip data from younger units also suggest range-parallel uniform tilting (Table 2); thus middle Pliocene to early Pleistocene strata commonly dip 0.7°–0.9°, early to middle Pleistocene strata dip approximately 0.6°, middle Pleistocene strata dip 0.2°–0.4°, middle to late Pleistocene strata dip 0.9°–0.15°, and late Pleistocene strata dip 0.05°–0.1°.

TABLE 3. LATE NEOGENE ANGULAR UNCONFORMITIES IN THE EASTERN GREAT VALLEY, CALIFORNIA

Source	Location	Ages of stratigraphic units bounding the unconformity
Redwine, 1972 (cross section A–A′)	Northeastern Sacramento Valley	Miocene/middle Pliocene
Unruh, 1990	East-central Sacramento Valley	Approx. 8.4–3.4 Ma
Department of Water Resources, 1974	Southern Sacramento Valley	Late Miocene/middle Pliocene
Marchand and Allwardt, 1981	Northeastern San Joaquin Valley	Miocene-Pliocene/middle Pliocene
Wagner, 1981	East-central San Joaquin Valley	Hemphillian/Hemphillian
Arkley, 1962 (Figs. 2 and 3)	Merced River area, east-central San Joaquin Valley	Miocene-Pliocene/early Pleistocene

TABLE 4. GRADIENTS OF CENOZOIC SURFACES AND STRATIGRAPHIC UNITS IN THE STANISLAUS RIVER AREA, EASTERN SAN JOAQUIN VALLEY (DATA FROM WOODWARD-CLYDE CONSULTANTS, 1977)

Contoured surface or stratigraphic unit	Gradient	Age
Surface of crystalline basement rocks	5.41°	Eocene or older
Base of Mehrten Formation	1.63°	9.0–5.7 Ma
Mehrten marker horizon I	1.36°	4.0- 5.7 Ma
Mehrten marker horizon A	1.31°	4.0–5.7 Ma
Mehrten marker horizon L	1.30°	4.0–5.7 Ma
Mehrten marker horizon M	1.27°	4.0–5.7 Ma
Pediment gravel	0.98°	Pliocene(?)–Pleistocene
Turlock Lake Formation	0.19°	0.6 Ma

If it is assumed that 1.4° represents a reasonable average value for the total tilting since uplift began and that the uplift of the crest has been produced by sustained rigid-block tilting across the western slope of the Sierra Nevada, a 1.4° tilt would result in uplift at the crest of 1,950 m for 80-km-long slopes and 2,440 m for 100-km-long slopes. This agrees with uplift estimates derived from independent paleobotanic data. Axelrod (1980) estimated that the lowland Mount Reba flora, now found at the northern Sierra Nevada crest, has been uplifted approximately 1,800 m since 6–7 Ma.

The gradients of Cenozoic strata can also be used to test the hypothesis that the rate of tilting has been constant during late Cenozoic time. Again, if it is assumed that a southwest gradient of 1.4° represents the average total tilting since late Cenozoic uplift began, the dip of any unit can be expressed as a percentage of total tilting by dividing the dip of that unit by 1.4°. Table 5 lists the average dips and ages reported for late Cenozoic units in the eastern Great Valley, with the dips also expressed as a percentage of the total deformation. Similarly, the ages of these units can be expressed as a percentage of total time since the uplift began. Table 5 lists the ages of late Cenozoic units as a percentage of total time elapsed since 5 Ma, the approximate onset of uplift inferred from stratigraphic and geologic relationships. For comparison, similar percentages are calculated assuming that tilting began 4 Ma and 6 Ma (Table 5). The greatest uncertainty in these calculations comes from the reported ages of middle Pliocene to middle Pleistocene strata, which are commonly inferred from stratigraphic relationships. The ages of middle Pleistocene and younger strata, particularly in the San Joaquin Valley, are reasonably well constrained by radiometric dates (Marchand and Allwardt, 1981).

Within the uncertainty of available age estimates, there is a good correlation between the percentage of total deformation expressed by the tilting of a unit and the amount of time that has passed since tilting began approximately 5 Ma, indicating that the rate of tilting has been approximately constant. Grant and others (1977) reached the same conclusion based on analysis of tilted Cenozoic strata in the northeastern San Joaquin Valley. Note that the correlation between percent total deformation and percent total time elapsed is better if tilting began 4 or 5 Ma, rather than 6 Ma (Table 5). This may indicate that the onset of tilting was slightly later than 5 Ma, rather than slightly earlier.

The history of Cenozoic westward tilting as interpreted from the gradients of Cenozoic strata adjacent to three major rivers in the east-central Great Valley (Tables 1 and 2) is summarized in Figure 6. When compared to an average long-term Cenozoic gradient, the data suggest that most of the post-Eocene tilting in the east-central Great Valley occurred during two major episodes (Fig. 6): one episode prior to the deposition of the late Oligocene–early Miocene Valley Springs Formation, and a second episode here associated with late Cenozoic uplift of the Sierra Nevada beginning approximately 5 Ma.

TABLE 5. TILTING VERSUS AGE OF LATE CENOZOIC STRATIGRAPHIC UNITS IN THE EASTERN GREAT VALLEY, CALIFORNIA

Age	Dip (gradient)	% total tilting	% total time (assuming uplift began 5 Ma)	% total time (assuming uplift began 4 Ma)	% total time (assuming uplift began 6 Ma)
Late Pleistocene (120–40 ka)	0.05°–0.1°	0.04%–0.07%	1%–2%	1%–3%	1%–2%
Middle to late Pleistocene (0.20–0.45 Ma)	0.1°–0.15°	6%–11%	4%–9%	5%–11%	3%–8%
Middle Pleistocene (0.6–1.0 Ma)	0.2°–0.4°	14%–29%	12%–20%	15%–25%	10%–17%
Early to middle Pleistocene (1.0–2.0 Ma)	0.5°–0.7°	36%–50%	20%–40%	25%–50%	17%–33%
Middle Pliocene to early Pleistocene (2.0–3.5 Ma)	0.7°–0.9°	50%–64%	40%–70%	50%–88%	33%–58%
Oligocene to late Miocene	1.2°–1.6° (ave., 1.4°)	100%	100%	100%	100%

IMPLICATIONS FOR MODELS OF THE SIERRA NEVADA UPLIFT

The tilt data have important implications for models of the late Cenozoic Sierra Nevada uplift. The following discussion compares the timing and kinematics of uplift indicated by the tilted strata in the eastern Great Valley between the Kings River and the Feather River with the predictions of several models for the uplift.

(1) *Uplift of the Sierra Nevada triggered by the northward migration of the Mendocino triple junction.* Crough and Thompson (1977) proposed that northward migration of the Mendocino triple junction and evolution of the asthenospheric "slabless window" beneath the North American lithosphere effectively thinned the upper mantle beneath the Sierra Nevada. The resulting increased buoyancy of the sub-Sierran lithospheric column is interpreted to have generated progressive uplift of the range from north to south as the asthenospheric window expanded in the wake of the migrating triple junction (Crough and Thompson, 1977).

The data presented herein do not support models for time-transgressive deformation. Tilting began simultaneously in the east-central Great Valley approximately 5 Ma. The model also predicts that Pliocene-Pleistocene strata should be progressively less tilted from south to north. The tilt data (Table 2) indicate approximately uniform tilting of Pliocene-Pleistocene strata between the Kings River and the Feather River.

(2) *Uplift of the Sierra Nevada as delayed isostatic compensation of a Mesozoic crustal root.* Chase and Wallace (1986) proposed a model for the uplift based on the assumption that the early to middle Tertiary topography of the Sierra Nevada did not fully compensate for the inferred Mesozoic crustal root beneath the range. They suggested that uplift and topographic compensation of the root was effectively prevented between Late Cretaceous and late Tertiary time by the elastic strength of the lithosphere developed during cooling of the Mesozoic batholith. Late Cenozoic uplift and tilting of the range were triggered when Basin and Range extension to the east broke the elastic lithosphere. According to this model, migration of the Mendocino triple junction and evolution of the San Andreas fault have had little effect on the uplift (Chase and Wallace, 1986).

This model assumes that no significant uplift of the rocks that form the crustal root beneath the Sierra Nevada occurred prior to late Cenozoic time. This assumption is not supported by

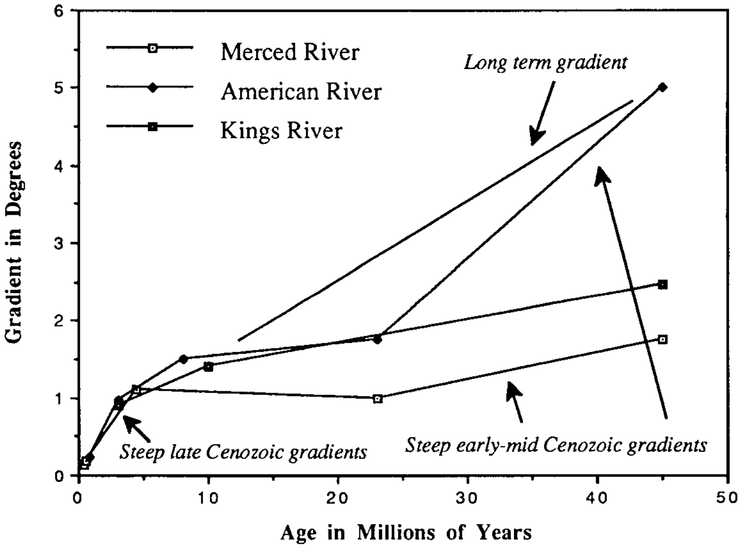

Figure 6. The gradients of Cenozoic strata adjacent to three major rivers in the eastern Great Valley as a function of time. Most of the Cenozoic tilting appears to have occurred during two episodes marked by relatively steep gradients. The steep late Cenozoic gradients reflect uplift and tilting of the Sierra Nevada beginning approximately 5 Ma. The steep early-middle Cenozoic gradients may represent an earlier period of uplift (Huber, 1981).

independent petrologic and stratigraphic data. As discussed previously, uplift and exhumation of Mesozoic plutonic rocks in the Sierra Nevada probably occurred prior to Eocene time. Estimates of the minimum pre-Eocene uplift from paleobarometry range from 8–12 km in the northern part of the range to 20 km in the south. In contrast, late Cenozoic uplift at the range crest, estimated from tilting in the eastern Great Valley, is 2.4 km or less depending on the length of the western Sierra Nevada slope. These relations indicate that significant uplift of plutonic rocks, long interpreted to form a crustal root beneath the Sierra Nevada (Bateman and Eaton, 1967), occurred 40 m.y. or more before the onset of late Cenozoic tilting. The pre-Eocene uplift of the southern Sierra Nevada may have been an order of magnitude greater than that produced by late Cenozoic westward tilting.

This model also assumes that the beginning of late Cenozoic tilting is correlated with the onset of Basin and Range extension. Stratigraphic and structural relations in western Nevada do not support this assumption. Proffett (1977) reported that Basin and Range normal faulting in the Yerington area, western Nevada, began approximately 17–18 Ma. Major crustal extension by slip on low-angle faults ceased by 8–11 Ma. Late Neogene and Quaternary extension in the Yerington area occurred by slip on high-angle faults, accounting for a third or less of the total Cenozoic extension in the region (Proffett, 1977). Data from the Yerington area show that large-scale Tertiary extension began locally in the western Basin and Range at least 12 m.y. before the onset of late Cenozoic tilting of the Sierra Nevada approximately 5 Ma and may actually have subsided in intensity before tilting began.

(3) *Uplift of the Sierra Nevada in response to thinning of mantle lithosphere.* If the uplift and tilting of the Sierra Nevada is not being driven by buoyant forces acting on a crustal root, as suggested by Chase and Wallace (1986), then the driving force for uplift may originate in the mantle. Thinning of the mantle lithosphere—by convection, by thermal erosion, or by mechanical stretching—would increase the buoyancy of the remaining lithospheric column and produce uplift. This is the mechanism proposed by Crough and Thompson (1977), but without a time-transgressive component of mantle thinning linked to the migration of the Mendocino triple junction.

Several workers proposed that the uplift of the Sierra Nevada is due to thinning of the sub-Sierran mantle lithosphere (Eaton and others, 1978; Mavko and Thompson, 1983; Jones, 1987; Humphreys,1987). Jones (1987) summarized geophysical evidence for anomalously warm and buoyant mantle beneath the southern Sierra Nevada:

TABLE 6. LATE NEOGENE EPEIROGENIC UPLIFT IN THE CORDILLERA

Region	Reference	Onset of uplift
Sierra Nevada	This study	3.4–8.4 Ma (approx. 5 Ma)
Western Cascades	Priest and others, 1983	4.0–5.0 Ma
Northern Basin and Range	Axelrod, 1956	Late Miocene–Pliocene
Southern Rocky Mountains	Sato and Denson, 1967	Late Miocene–early Pliocene
	Eaton, 1987	4.0–7.0 Ma
Western Great Plains	Trimble, 1980	Approx. 5 Ma
Colorado Plateau	Lucchitta, 1979	After 5.5 Ma

(1) Anomalously slow arrival times for teleseismic P waves traveling through the sub-Sierran lithosphere, indicating lower-mantle densities;

(2) Lower Pn mantle velocities measured by seismic refraction experiments;

(3) Regional magnetic lows over the southern Sierra Nevada, suggesting elevated temperatures and an anomalously high Curie isotherm;

(4) Correlation of Bouguer gravity anomalies in the southern Sierra Nevada–Death Valley region with late Cenozoic topography, rather than with the distribution of lower-density Mesozoic batholithic rocks that constitute the crustal root of the Sierra Nevada, suggesting that at least part of the mass deficiency that produces both the uplift of the Sierra Nevada and the corresponding gravity low originates in the mantle.

The tilt data from the east-central Great Valley provide no direct test of the mantle-thinning hypothesis. Of the three models described above, however, the mantle-thinning hypothesis is consistent with independent geological and geophysical data and does not conflict with the tilt data.

THE SIERRAN UPLIFT AS PART OF A LATE CENOZOIC CORDILLERA-WIDE EVENT

Westward tilting of the Sierra Nevada in late Cenozoic time has been accompanied by epeirogenic uplift throughout the western United States (Table 6). Virtually every physiographic region has been affected.

(1) *The western Cascade Range.* Priest and others (1983) reported that uplift of the western Cascade Range occurred approximately 4–5 Ma.

(2) *The northern Basin and Range province.* Using fossil floras as measures of paleoaltitude, Axelrod (1956) argued that the northern Basin and Range has been uplifted 470–630 m (1,500–2,000 ft) since Miocene-Pliocene time. The inferred uplift of the northern Basin and Range was either accompanied or followed shortly by a major geomorphic rejuvenation. Nitchman and others (1990) reported that low-relief erosional surfaces of regional extent in the western Basin and Range, formed between 7 and 4 Ma, were disrupted by modern Basin-and-Range–style normal faulting beginning approximately 4 Ma.

(3) *The northern and middle Rocky Mountains.* Sato and Denson (1967) interpreted the sudden appearance of basement-derived heavy minerals in late Neogene sediments east of the northern and middle Rocky Mountains as evidence for uplift and erosion of the mountains during Miocene-Pliocene time. According to Sato and Denson (1967), uplift of the mountains is also suggested by a significant increase in the grain size of the minerals appearing in the late Neogene sediments to the east of the mountains.

(4) *The southern Rocky Mountains.* Eaton (1987) presented evidence for a pulse of rapid epeirogenic uplift of the southern Rocky Mountains (that is, the "Alvarado Ridge") beginning between 4 and 7 Ma.

(5) *The western Great Plains.* Trimble (1980) cited a regional reversal of drainage direction and abrupt incision of streams in the western Great Plains as evidence for epeirogenic uplift beginning approximately 5 Ma. Trimble (1980) estimated that this uplift added 1.5 km of elevation to the western Great Plains.

(6) *The Colorado Plateau.* Lucchitta (1979) interpreted the uplift of rocks deposited near sea level in Arizona during late Neogene time as evidence that the Colorado Plateau has been uplifted at least 880 m since 5.5 Ma. This estimate is similar to the depth that the Colorado River has incised its canyon during the past 5 m.y. (approximately 760–915 m; Trimble, 1980).

The wide extent of uplift events, clustered closely in time, supports the hypothesis (Stewart, 1978) that late Cenozoic uplift of the Sierra Nevada may have been part of a Cordillera-wide event. The modern western Cordillera is a plateau approximately 1.5–2.5 km high that extends for more than 1,000 km in an east-west direction between the Sierra Nevada and the southern Rocky Mountains. Estimates of absolute late Cenozoic uplift from individual physiographic regions range among approximately 0.5 km (the northern Basin and Range; Axelrod, 1956), 1.5 km (the western Great Plains; Trimble, 1980), and 1.9–2.4 km (the Sierra Nevada; this study), suggesting that much of the present high elevation of the plateau may have developed during the past 5 m.y.

The northern Basin and Range, in the interior of the Cordilleran plateau, has an average crustal thickness of 30 km (Allmendinger and others, 1987), indicating that the relatively high topography is underlain by a thin, rather than thick, crust. The northern Basin and Range is also characterized by high heat flow, anomalously slow upper-mantle Pn velocities, and a regional, long-wavelength gravity low (Eaton, 1984; Kane and Godson, 1989). These data have been interpreted as evidence that the high elevation of the northern Basin and Range is supported by a thermally buoyant mantle (Eaton and others, 1978; Froidevaux, 1986; Kane and Godson, 1989). The co-occurrence of young uplift and elevated heat-flow values has also been observed along the eastern margin of the Cordillera plateau. Eaton (1987) discussed evidence for geologically youthful elevated heat flow beneath the "Alvarado Ridge," southern Rocky Mountains, and suggested that late Cenozoic uplift there may be due to distributed convective thinning of the underlying mantle lithosphere. Thus, late Cenozoic uplift of the margins of the Cordillera (the Sierra Nevada, the Alvarado Ridge) and a large part of the interior of the Cordillera (the northern Basin and Range province) has been attributed by a number of workers to thinning of the mantle lithosphere. If it is assumed that late Cenozoic uplifts in the Cordillera (Table 6) are genetically related, mechanical, convective, or thermal thinning of the lithosphere may have begun approximately 5 Ma beneath a large area of western North America. Deviatoric horizontal tensile stresses arising from the increased gravitational potential energy of the uplifted plateau may be partially responsible for late Cenozoic and active crustal extension in the western United States (Froidevaux, 1986; England and Houseman, 1989).

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REFERENCES CITED

Allmendinger, R. W., Hauge, T. A., Hauser, E. C., Potter, C. J., and Oliver, J., 1987, Tectonic heredity and the layered lower crust of the Basin and Range province, western United States, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: London, United Kingdom, Blackwell Scientific Publications, Geological Society of London Special Publication 28, p. 223–246.

Arkley, R. J., 1962, The geology, geomorphology, and soils of the San Joaquin Valley in the vicinity of the Merced River, California: California Division of Mines and Geology Bulletin 182, p. 25–31.

Axelrod, D. I., 1956, Mio-Pliocene floras from west-central Nevada: University of California Publications in Geological Sciences, v. 33, p. 1–321.

——— 1980, Contributions to the Neogene paleobotany of central California: University of California Publications in Geological Sciences, v. 121, 212 p.

Bartow, J. A., 1980, Constraints on the latest movements on the Melones fault zone, Sierra Nevada foothills, California: U.S. Geological Survey Professional Paper 1126-J, p. J1–J4.

Bateman, P. C., and Eaton, G. P., 1967, Sierra Nevada batholith: Science, v. 158, p. 1407–1417.

Bateman, P. C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 107–172.

Busacca, A. J., 1982, Geologic history and soil development, northeastern Sacramento Valley, California [Ph.D. dissert.]: Davis, California, University of California, 383 p.

Busacca, A. J., Singer, M. J., and Verosub, K. L., 1989, Late Cenozoic stratigraphy of the Feather and Yuba Rivers area, with a section on soil development in mixed alluvium at Honcut Creek: U.S. Geological Survey Bulletin 1590-G, 132 p.

Chase, C. G., and Wallace, T. C., 1986, Uplift of the Sierra Nevada of California: Geology, v. 14, p. 730–733.

Christensen, M. N., 1966, Late Cenozoic crustal movements in the Sierra Nevada of California: Geological Society of America Bulletin, v. 77, p. 163–182.

Creely, R. S., 1965, Geology of the Oroville quadrangle, California: California Division of Mines and Geology Bulletin 184, 86 p.

Crough, S. T., and Thompson, G. A., 1977, Upper mantle origin of the Sierra Nevada uplift: Geology, v. 5, p. 396–399.

Dalrymple, G. B., 1963, Potassium-argon dates of some Cenozoic volcanic rocks of the Sierra Nevada, California: Geological Society of America Bulletin, v. 74, p. 379–390.

——— 1964, Cenozoic chronology of the Sierra Nevada, California: University of California Publications in Geological Sciences, v. 47, 41 p.

Department of Water Resources, 1968, Final geologic report on the Thermalito power canal: State of California, Project Geology Report C-26.

——— 1974, Evaluation of ground water resources: Sacramento County: State of California, Bulletin 118-3.

Durrell, C., 1966, Tertiary and Quaternary geology of the northern Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 185–197.

Eaton, G. P., 1984, The Miocene Great Basin of western North America as an extending back-arc region: Tectonophysics, v. 102, p. 275–295.

——— 1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: London, United Kingdom, Blackwell Scientific Publications, Geological Society of London Special Publication 28, p. 355–369.

Eaton, G. P., Wahl, R. R., Prostka, H. J., Mabey, D. R., and Kleinkopf, M. D., 1978, Regional gravity and tectonic patterns: Their relations to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 51–91.

England, P., and Houseman, G., 1989, Extension during continental convergence, with application to the Tibetan Plateau: Journal of Geophysical Research, v. 94, p. 17561–17579.

Evernden, J. F., and James, J. T., 1964, Potassium-argon dates and the Tertiary floras of North America: American Journal of Science, v. 262, p. 945–974.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, J. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: American Journal of Science, v. 262, p. 145–198.

Froidevaux, C., 1986, Basin and Range large-scale tectonics: Constraints from gravity and reflection seismology: Journal of Geophysical Research, v. 91, p. 3625–3632.

Grant, T. A., McCleary, J. R., and Blum, R. L., 1977, Correlation and dating of geomorphic and bedding surfaces on the east side of the San Joaquin Valley using dip, *in* Singer, M. J., ed., Soil development, geomorphology and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Davis, California, University of California Press, Guidebook for joint field session (ASA, SSSA, GSA), p. 312–318.

Huber, N. King, 1981, Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California—Evidence from the upper San Joaquin River basin: U.S. Geological Survey Professional Paper 1197, 28 p.

——— 1990, The late Cenozoic evolution of the Tuolumne River, central Sierra Nevada, California: Geological Society of America Bulletin, v. 102, p. 102–115.

Humphreys, E., 1987, Mantle dynamics of the southern Great Basin–Sierra Nevada region: Eos (American Geophysical Union Transactions), v. 68, no. 44, p. 1450.

Huntington, G. L., 1980, Soil-landform relationships of portions of the San Joaquin River and Kings River alluvial depositional systems in the Great Valley of California [Ph.D. dissert.]: Davis, California, University of California, 147 p.

Jones, C. H., 1987, Is extension in Death Valley accommodated by thinning of the mantle lithosphere beneath the Sierra Nevada, California?: Tectonics, v. 6, p. 449–473.

Kane, M. F., and Godson, R. H., 1989, A crust/mantle structural framework of the conterminous United States based on gravity and magnetic trends, *in* Pakiser, L. C., and Mooney, W. D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 383–403.

Langbein, W. B., and Leopold, L. B., 1964, Quasi-equilibrium states in channel morphology: American Journal of Science, v. 262, p. 782–794.

Lettis, W. R., and Unruh, J. R., 1991, Quaternary geology of the Great Valley, California, *in* Morrison, R. B., ed., Quaternary non-glacial geology of the conterminous United States: Boulder, Colorado, Geological Society of America, Decade of North American Geology, v. K2.

Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada of California: U.S. Geological Survey Professional Paper 73, 226 p.

Loomis, D. P., and Burbank, D. W., 1988, The stratigraphic evolution of the El Paso Basin, southern California: Implications for the Miocene development of the Garlock fault and uplift of the Sierra Nevada: Geological Society of America Bulletin, v. 100, p. 12–28.

Lucchitta, I., 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63–95.

Marchand, D. E., 1977, The Cenozoic history of the San Joaquin Valley and adjacent Sierra Nevada as inferred from the soils of the eastern San Joaquin Valley, *in* Singer, M. J., ed., Soil development, geomorphology and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Davis, California, University of California Press, Guidebook for joint field session (ASA, SSSA, GSA), p. 39–50.

Marchand, D. E., and Allwardt, A., 1981, Late Cenozoic stratigraphic units, northwestern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1470, 70 p.

Mavko, B. B., and Thompson, G. A., 1983, Crustal and upper mantle structure of the northern and central Sierra Nevada: Journal of Geophysical Research, v. 88, no. B7, p. 5874–5892.

McLeod, M., and Day, H., 1991, Hornblende barometry of calc-alkaline plutons and movement history of the Big Bend fault zone, northern Sierra Nevada, California: Geological Society of America Abstracts with Programs, Cordilleran Section, v. 23, no. 2, p. 78.

Nitchman, S. P., Caskey, S. J., and Sawyer, T. L., 1990, Change in Great Basin tectonics at 3–4 Ma—A hypothesis: Geological Society of America Abstracts with Programs, Cordilleran Section, v. 22, no. 3, p. 72.

Priest, G. R., Woller, N. M., Black, G. L., and Evans, S. H., 1983, Overview of the geology of the central Oregon Cascade Range, *in* Priest, G. R., and Vogt, B. F., eds., Geology and geothermal resources of the central Oregon Cascade Range: Oregon Department of Geology and Mineral Industries Special Paper 15, p. 3–28.

Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266.

Redwine, L. E., 1972, The Tertiary Princeton submarine valley system beneath the Sacramento Valley, California [Ph.D. dissert.]: Los Angeles, California, University of California, 480 p.

Sams, D. B., and Saleeby, J. B., 1988, Geology and petrotectonic significance of crystalline rocks of the southernmost Sierra Nevada, California, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States [Rubey Volume 7): Englewood Cliffs, New Jersey, Prentice-Hall, p. 866–893.

Sato, Y., and Denson, N. M., 1967, Volcanism and tectonism as reflected in the distribution of nonopaque heavy minerals in some Tertiary rocks of Wyoming and adjacent states: U.S. Geological Surveyy Professional Paper 575C, p. C42–C54.

Schumm, S. A., 1977, The fluvial system: New York, John Wiley and Sons, 338 p.

Shlemon, R. J., 1972, The lower American River area, California: A model of Pleistocene landscape evolution: Association of Pacific Coast Geographers Yearbook, v. 34, p. 61–86.

Slemmons, D. B., 1966, Cenozoic volcanism of the central Sierra Nevada, California, *in* Bailey, E. H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 199–208.

Stewart, J. H., 1978, Basin-range structure in western North America: A review, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 1–31.

Trimble, D. E., 1980, Cenozoic tectonic history of the Great Plains contrasted with that of the southern Rocky Mountains: A synthesis: The Mountain Geologist, v. 17, p. 59–69.

Unruh, J. R., 1990, Stratigraphy and late Cenozoic deformation in the Oroville area, east-central Sacramento Valley, California [Ph.D. dissert.]: Davis, California, University of California, 272 p.

Wagner, D. L., and Saucedo, G. J., 1990, Age and stratigraphic relationships of Miocene volcanic rocks along the eastern margin of the Sacramento Valley, California, *in* Ingersoll, R. V., and Nilsen, T. H., eds., Sacramento Valley symposium and guidebook: Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 65, p. 143–151.

Wagner, H. W., 1981, Geochronology of the Merhrten [sic] Formation in Stanislaus County, California [Ph.D. dissert.]: Riverside, California, University of California, 342 p.

Woodward-Clyde Consultants, 1977, Site geology, *in* Early site review report for the Stanislaus Nuclear project, section 2.5.1: Report prepared for Pacific Gas and Electric Company, San Francisco, California.

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