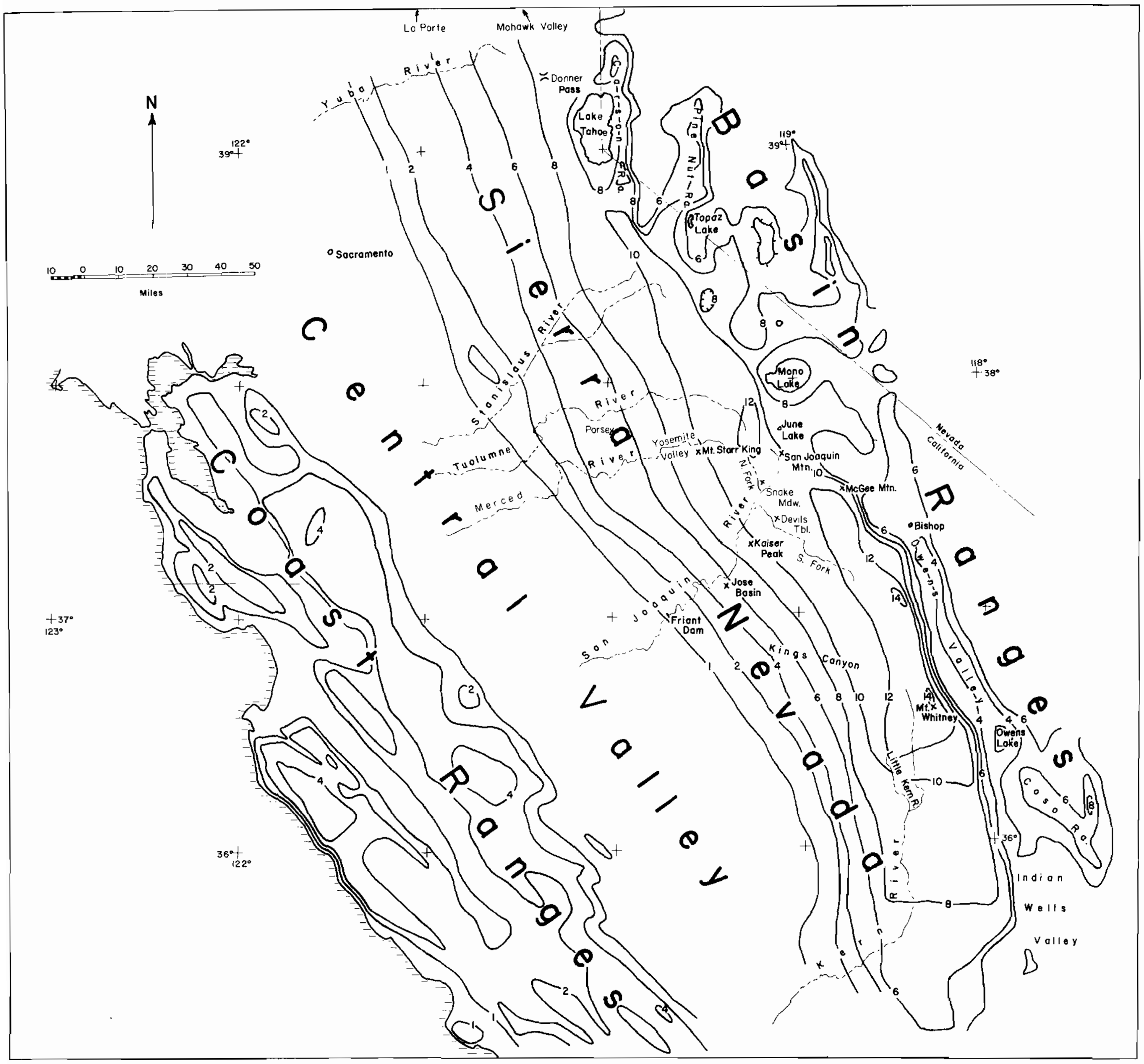

GENERALIZED TOPOGRAPHIC CONTOUR MAP OF CENTRAL CALIFORNIA AND ADJACENT PARTS OF NEVADA

Contour interval 2000 feet; 1000-foot contour is supplementary

CHRISTENSEN, PLATE 1
Geological Society of America Bulletin, volume 77

M. N. CHRISTENSEN *Dept. Geology and Geophysics, University of California, Berkeley, California*

Late Cenozoic Crustal Movements in the Sierra Nevada of California

Abstract: The geometry of the late Cenozoic uplift of the Sierra Nevada is determined from the record of Tertiary river channels and volcanic rocks and from gross physiography of the range. This geometry is described by means of a structure contour map. Fossil mammals, some spore-pollen data, physical stratigraphy, K-A dates, and physiography indicate that the last major uplift began during Pliocene time and that the eastern escarpment developed subsequently by downfaulting of the area to the east. The simple geometry of movements over a large area in the Sierra Nevada, contrasted with the complex pattern of movements to the east and west during the same interval, seems likely to be a direct expression of processes that have produced crustal material during the rise of the Sierra.

CONTENTS

Introduction 163
  Purpose and scope 163
  Geologic setting 164
  Previous work 164
Acknowledgments 166
Northern Sierra Nevada 166
Central and southern Sierra Nevada 169
History of uplift 169
Structure contour map 172
Eastern escarpment 172
  Structure and inferred movements 172
  Age of movements 174
Origin of movements 177
Conclusions 178
References cited 178

Figure
1. Topographic profiles across the Sierra Nevada 164
2. Relation of river gradients to area of upstream drainage basins for a wide variety of climates and bedrock terranes 167
3. Structure contour map, depicting rise of the Sierra Nevada, beginning in Pliocene time 173
4. Geometry of faults and warps near LaPorte, California 175
5. Topographic map of the Bishop–Long Valley area 176

Plate Facing
1. Generalized topographic contour map of central California and adjacent parts of Nevada 163

Table
1. Uplift of the Sierra Nevada inferred from Tertiary river profiles 168
2. Uplift of the Sierra Nevada calculated from the magnitude of relief during the Tertiary . . 170
3. Correlation of land-mammal ages with European epochs and with years 171
4. Inclinations of faults along the eastern escarpment 174

INTRODUCTION

Purpose and Scope

Movements of major segments of the earth's surface provide boundary conditions for models of mechanisms of mountain building. Information about these movements is rather scarce, however, because the histories of mountain ranges have been determined largely from the record of deformed rocks within deeply eroded cores of ancient mountains rather than from direct study of gross surface movements of young mountain ranges. As knowledge of the crust and upper mantle increases and as computers provide the means for studying mathematical models of mountain building, it becomes increasingly desirable to describe more precisely the superficial expressions of movements of the earth's crust. The Sierra Nevada of California is a young mountain range with an extensive geologic record of late Cenozoic crustal movements. This paper is an attempt to analyze the available evidence and to synthesize a description of the geometry and history of movements of the Sierra Nevada in late Cenozoic time. The geometry of movements is described by means of a structure contour map. The analysis confirms in general the classic work of Lindgren and Matthes and refutes

Geological Society of America Bulletin, v. 77, p. 163–182, 5 figs., 1 pl., February 1966

much of the more recent challenges to that work.

Geologic Setting

The Sierra Nevada parallels the Pacific Coast of California about 150 miles inland (Pl. 1). Its high point is Mount Whitney (14,495 feet), the inconspicuous culmination of a high, even crestline which declines gently northward to an elevation of 9000 feet west of Lake Tahoe. It is flanked on the west by the Central Valley, a structural trough that has subsided throughout late Mesozoic and Tertiary time, and on the east by the Basin Ranges. The northern Sierra Nevada is markedly asymmetric, rising gradually and evenly eastward from the Central Valley to a crestline along its eastern margin. The southern Sierra, in contrast, rises rather abruptly from the valley lowlands and has a broad, irregular summit upland (Fig. 1). The eastern margin of the range is marked by a high, steep escarpment, which in most places is a fault scarp.

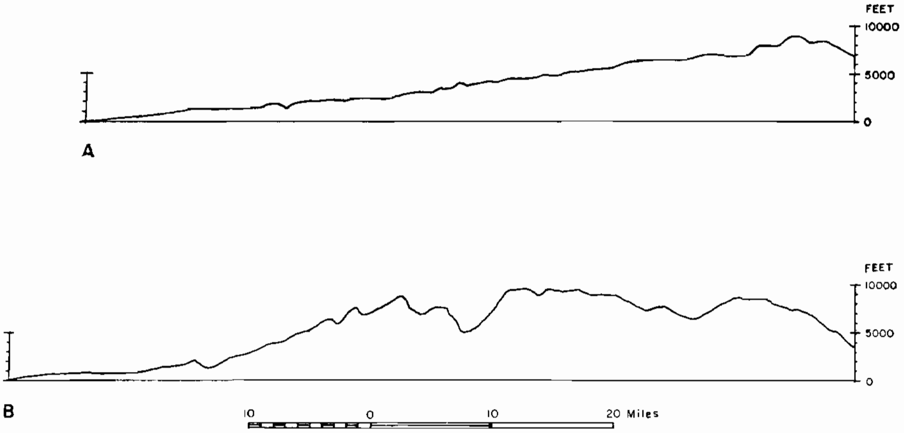

Figure 1. Topographic profiles across the Sierra Nevada, California. A, Sacramento to Lake Tahoe; B, approximately along lat. 36° N. *See* Plate 1 for location.

The basement rocks of the Sierra Nevada are metamorphic rocks and granitic plutons of Mesozoic age. These plutonic rocks were unroofed by early Tertiary time. The landscape carved upon these rocks at that time had a relief ranging from a few hundred feet in the western foothills to several thousand feet near the present summit (*e.g.*, Lindgren, 1911); highlands existed in the present summit area in early Tertiary time. The lower reaches of rivers draining westward from the highlands were filled with auriferous gravels. In Oligocene time lavas erupted along the summit swept down the rivers and buried the auriferous gravels. Volcanism culminated in Miocene-Pliocene time when a flood of andesite breccias, erupted along the summit, inundated virtually the entire landscape of the northern Sierra. During this time basaltic lavas flowed down the channels of several rivers in the southern Sierra, but the volume of these flows was small. Subsequently deep, narrow canyons were eroded through the volcanic cover, into the crystalline basement, far below the levels of the early Tertiary channels. Those ancient channels are now exposed high in the canyon walls, preserved beneath a blanket of volcanic rocks. The Tertiary river channels provide the principal measure of the late Cenozoic uplift of the Sierra Nevada.

Previous Work

Le Conte noted in 1886 that the Tertiary river channels provide evidence for uplift of the Sierra Nevada. The ancient, alluviated channels have much steeper gradients than do the modern rivers, which are vigorously eroding their beds. The old channels are high above the modern rivers in the central part of the range, decline rapidly westward, intersect the profiles of the modern rivers near the western margin of the range, and pass westward beneath the alluvium of the Central Valley.

Lindgren concluded from this geometry (work summarized in 1911) that the northern Sierra was tilted toward the west as a rigid block rather than uplifted by a simple translation, and that the hinge line lay along the present boundary between the Sierra Nevada and the Central Valley; canyon cutting, hence tilting, began during the volcanic period, but most of the cutting occurred after volcanism ceased (Lindgren, 1911, p. 28.) The magnitude of faulting along the eastern escarpment is inadequate to account for the uplift calculated from tilting of river channels, so there is no necessary connection between faulting on the eastern escarpment and uplift of the range; Lindgren expressed the opinion that faulting on the eastern escarpment occurred after the range rose. Ransome (1898) studied on old channel of the Stanislaus River which was cut into early volcanic rocks and was later filled with a distinctive latite flow. This channel provides a date for part of the canyon cutting; the geometry of its profile supports Lindgren's conclusion that the northern Sierra was tilted toward the west as if it were a rigid block.

Matthes (1930; 1933; 1939; 1960) constructed profiles of the "Miocene" and "Pliocene" predecessors of the Merced and San Joaquin rivers in the central Sierra. A volcanic mantle on the basement rocks is lacking in these areas, so there is no stratigraphic record of the Tertiary rivers. Rather, the profiles are based on nickpoints of tributaries, with the upstream gradients projected to the main river. From the profiles so constructed Matthes inferred a westward tilt of the range and uplift of the eastern crest. He believed that the deep canyons of the Merced and San Joaquin rivers had been cut nearly to their present depths before the earliest glacial moraines were deposited, whereas thousands of feet of faulting have occurred along the eastern escarpment after the earliest moraines were deposited. He therefore supported Lindgren's conclusion that the eastern escarpment developed by faulting after the range had been tilted to the west and the crestline uplifted.

Axelrod (1957; 1962) and Axelrod and Ting (1960; 1961) studied fossil floras in an effort to date the rise of the Sierra Nevada by determining the date of the advent of a rain shadow in the desert areas east of the Sierra. For this purpose Axelrod assumed that the eastern escarpment developed simultaneously with the rise of the crest of the range, hence refuting Matthes' conclusion. He concluded that most of the present height of the range was attained by uplift during the Pleistocene epoch.

Hudson (1948; 1951; 1955; 1960) rejected the conclusion that the northern Sierra was tilted as an essentially rigid block. He implicitly assumed that the Tertiary volcanic rocks had been deposited on a planar topography, rather than on an irregular surface, and concluded that extensive folding and faulting occurred within the Sierra Nevada during late Tertiary time. He restudied the Tertiary river channels in an attempt to make very precise calculations of the magnitude of uplift of the crest. By correlating physiographic features of the Merced River area within certain strata along the margin of the Central Valley, he concluded that a major uplift of the Sierra Nevada occurred in latest Pliocene or Pleistocene time.

Dalrymple (1963; 1964) applied the potassium-argon dating technique to the problems of Cenozoic chronology of the Sierra Nevada. He analyzed volcanic rocks that date various phases of canyon cutting and faulting. His data concur with the conclusions of Lindgren and Matthes that the main uplift of the Sierra occurred before the advent of glaciation.

Wahrhaftig (1962a; 1965) studied the distinctive "stepped-topography" in the granitic areas of the central Sierra. He concluded that a topography characterized by treads and risers is the product of normal processes of erosion of hillslopes in that area, that the flat treads are not remnants of erosion surfaces that were once graded to some base level of erosion. If his concept of the origin of this topography is correct, then Matthes' profiles of Tertiary rivers are probably invalid. Wahrhaftig noted that the lower course of a Tertiary predecessor of the San Joaquin River is preserved beneath a lava flow and that neither of Matthes' physiographically derived profiles is concordant with the slope of this stratigraphically recorded channel.

It will be shown further on that to a first approximation the northern Sierra between the Yuba and Tuolumne rivers did behave as if it were a rigid block and that the principal rise of the crestline began during Pliocene time, but that the magnitude and timing of uplift can be set only within rather broad limits at the present time. This brief review has touched only the papers which have dealt with the problem of the Cenozoic history of the Sierra Nevada as a whole. Additional papers concerned with specific details of individual areas are discussed in the text.

ACKNOWLEDGMENTS

This work has benefited substantially from suggestions and criticisms of C. A. Wahrhaftig, R. J. Janda, and G. H. Curtis. I have profited also from many discussions with colleagues and students. The work was supported financially by the University of California and the National Science Foundation.

NORTHERN SIERRA NEVADA

The strata that overlie the crystalline basement north of the Tuolumne River (Pl. 1) indicate that during late Cenozoic time the northern Sierra has been tilted gently toward the southwest as if it were a rigid block with, at the most, very minor warping and faulting within the block. Each of the modern rivers has a Tertiary ancestor buried beneath or within the volcanic pile. The reconstructed profiles are, if anything, more regular than their modern counterparts (Ransome, 1898, Pl. II; Lindgren, 1911, Pl. X; Hudson, 1955, Figs. 2 and 4; natural exposures combined with mining excavations along these ancient channels provide abundant data for reconstructing the longitudinal profiles of these Tertiary rivers; clearly, the amount of differential warping or faulting within the areas drained by these rivers has been small. In addition, the flat tops of ridges between the modern rivers have been interpreted as remnants of the original depositional surface of the volcanic plain that buried the bedrock topography. Piper and others (1939, Pl. 4) have drawn contours on these remnants. If their inference about the origin of the flat tops is correct, the even character of the reconstructed surface precludes warping within the range with amplitudes of greater than 500 feet along chords of 20 miles. Also, the volcanic strata and buried bedrock surface are exposed over great distances in the walls of canyons; these exposures preclude any major folding or faulting on the western slope of the range. Hudson (1948; 1951) asserted that there are folds in the base of the volcanic series near Donner Pass, but he did not consider the possibility that these might be buried topography; Curtis (1951, Ph.D. dissert., Univ. California, Berkeley) concluded that one structure described by Hudson as a tight syncline is actually a buried prevolcanic channel. The distinction between folds and initial dips in volcanic rocks can be difficult (Geotimes, cover, April 1963). At a few places minor faults do cut the volcanic strata (Lindgren, 1911, p. 108; Eric and others, 1954, Pl. 2). The classic picture of tilting as a rigid block holds up as a good first approximation. To the extent that tilting as a rigid block is valid, movements over a large area can be determined from movements at a few points.

Lindgren (1900, p. 10) estimated that tilt of the range at the latitude of Lake Tahoe totals 60–70 feet per mile. This tilt over a distance of 65–70 miles corresponds to uplift at the crest of 3900–4900 feet. Lindgren determined the amount of tilt from the profile of the Tertiary Yuba River. Southwestward-directed segments of the Tertiary river have gradients of 80–100 feet per mile, whereas a major northwestward segment has a gradient of only 20–30 feet per mile (Lindgren, 1911, Pl. 10). If one assumes that the range was tilted about a northwesterly axis parallel to the crest of the range, the northwesterly segment represents the original gradient of the river, and a tilt of 60–70 feet per mile is determined by subtraction.

The method used by Hudson (1955) to calculate uplift of the range was similar to Lindgren's but differed in an important respect. Lindgren studied the river as a whole, so that local irregularities might be minimized. Hudson studied short segments of the Tertiary Yuba River. He derived a method for calculating the amount and direction of tilt necessary to reduce the irregular gradients of short reaches of the present profile of the Tertiary Yuba River to a uniform gradient. For his calculation he had to assume that the original gradients were uniform in detail over reaches ranging from a fraction of a mile to a few miles in length, even where the river flowed on bedrock. This assumption can be refuted by examining the profile of the modern Yuba River where it flows on bedrock; in the Emigrant Gap 15-minute quadrangle (U. S. Geol. Survey, 1955) the gradient of the South Fork of the Yuba River over reaches 1 mile long varies irregularly from 450 feet per mile to 50 feet per mile; over reaches from 0.1 to 0.2 miles long it varies from 800 feet per mile to a few tens of feet per mile. This variation is fully as great as that of the present gradient of segments of the Tertiary Yuba River. Hudson's assumption of uniform gradient on bedrock is untenable, and his calculations, therefore, are invalid. He himself noted that the results of many of his calculations were "absurd" (Hudson, 1955, p. 850).

The basic premise that canyon cutting was caused by uplift of the range needs to be examined, because stream regimen is affected by a host of factors other than tectonics; it is conceivable that the canyon cutting was initiated by events other than uplift (*e.g.*, changing climate). This possibility can be tested by studying the influence of various factors on the gradients of modern streams. The gradients of modern alluviated rivers are plotted as a function of upstream drainage area in Figure 2. The rivers plotted here occur in a wide variety of climates and bedrock terranes in North America; the envelope containing these points provides a reasonable measure of maximum and minimum gradients of alluviated rivers as a function of drainage area. In the western part of the Sierra Nevada, Tertiary rivers flowed in alluviated valleys; remnants of the Tertiary drainage network are sufficiently extensive that the minimum areas of the drainage basins can be estimated with reasonable accuracy (Lindgren, 1911, Fig. 3). Whereas the maximum gradient for modern alluviated rivers with drainage areas on the order of 1000 square miles is about 30 feet per mile, the present gradients of Tertiary rivers with comparable drainage areas in the Sierra Nevada are on the order of 80–100 feet per mile (Lindgren, 1911, Pl. X). These high gradients must be due to tilting.

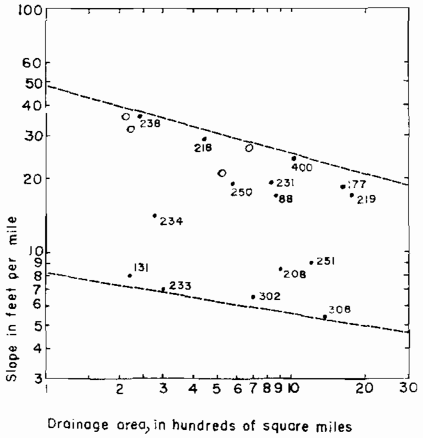

Figure 2. Relation of river gradients to area of upstream drainage basins for a wide variety of climates and bedrock terranes. Numbered points are data *from* U. S. Geol. Survey (1960). Open circles are data *from* Leopold and Miller (1956, Fig. 24).

The envelope containing the points in Figure 2 permits estimation of the maximum and minimum probable original gradients of the Tertiary rivers and thereby makes it possible to establish the limits within which the magnitude of subsequent tilting can be determined. Calculations of this kind are summarized in Table 1. The gradients of all the Tertiary streams in the northern Sierra are similar and would give similar results. The rivers selected are the Yuba and Tuolumne, which are the northernmost and southernmost rivers clearly defined by buried channels deep within the range, and the intervolcanic channels of the Stanislaus River, which provides a measure of the age of tilting. The buried channel of the lower course of the Tertiary San Joaquin River is discussed in the next section. The calculations in Table 1 suggest that if the northern part of the range behaved as if it were a rigid body, uplift at the crest could be estimated with rather high confidence within ±800 feet. The uncertainty in these calculations is, of course, greater than ±800 feet, because rigid behavior is only a first approximation. Lindgren's estimate of the gradient of the Tertiary Yuba River indicates that it was flowing on a gradient near the maximum observed for modern streams with comparable drainage areas; therefore the minimum figures for tilting are preferred.

Any vertical translation that might be superposed on the rotation discussed heretofore is small but indeterminate. The Tertiary profiles intersect the modern profiles at elevations of less than 400 feet. From these points the Tertiary rivers flowed westward to the sea across alluvial plains; hence these points were above the sea level of the late Tertiary. The uncertainty of the elevations of late Tertiary sea levels, however, renders indeterminate any changes of elevation of the hinge line with respect to present sea level.

The calculated values of uplift are rounded off to two significant figures; in view of the assumptions and the precision of the data only the first digit is significant. Axelrod (1957, p. 40) inferred 5300 feet of uplift of the summit area at Donner Pass since Miocene-Pliocene time on the basis of paleoclimatic arguments. He implicitly but clearly argued for the maximum possible uplift. In view of his assumptions only the first digit can be considered significant. His figure is in good accord with maximum uplift of 4900 feet on the Yuba River and 5300 feet on the Stanislaus River calculated from the river profiles (*see* Table 1).

TABLE 1. UPLIFT OF THE SIERRA NEVADA INFERRED FROM TERTIARY RIVER PROFILES

See Figure 3 and Plate 1 for locations.

River	Locality	Reference	Gradient (feet/mile)	Drainage area (square miles)	Estimated initial gradient (feet/mile)	Inferred tilt (feet/mile)	Width of tilted block (miles)	Uplift at crest (feet)
Northern Sierra Nevada								
Yuba	..	Lindgren (1900, p. 10; 1911, Pl. X)	80–100	..	20–30	60–70	65–70	3900 min. 4900 max.
Stanislaus	Sonora quadrangle	Ransome (1898) Eric and others (1954)	80–15	900	26 max. 6 min.	54 min. 75 max.	70	3800 min. 5300 max.
Tuolumne	Porsey	Lindgren (1911, Pl. X)	130	900	26	100 min. 125 max.	70	7000 min. 8800 max.
Southern Sierra Nevada								
Merced	Yosemite (Mountain Valley stage)	Matthes (1930, Pl. 27)	110	400	34 max. 8 min.	75 min. 100 max.	70	5300 min. 7000 max.
San Joaquin	I. Friant Dam to Jose Basin	Wahrhaftig (1965)	140	1675	22 max. 5 min.	118 min. 135 max.	25	3000 (at Jose Basin) 3400 (at Jose Basin)
	II. Jose Basin to crest	Matthes (1960, p. 2)	90	1100	24 max. 6 min.	65 min. 84 max.	40	2600 (Jose Basin to crest) 3400 (Jose Basin to crest)
	I + II	..	..	..	..	..	..	5600 min. 6800 max.

CENTRAL AND SOUTHERN SIERRA NEVADA

South of the Tuolumne River the stratigraphic record of Tertiary events is almost entirely lacking within the Sierra Nevada, and the history has been inferred largely from physiography. The Merced and San Joaquin rivers are like those of the northern Sierra in that they flow in deep canyons with sharply defined rims, cut into rolling uplands. From Kings Canyon south, the canyon rims, and uplands become obscure, but the deep canyons remain. For land forms to be properly interpreted, the processes of erosion must be understood; Wahrhaftig's recent study (1962a; 1965) of the stepped topography of the southern Sierra shows that the processes of erosion on slopes in the southern Sierra are not completely understood.

Students of the physiography of the Sierra Nevada have assumed that gentle upland surfaces originated as surfaces graded to river levels and ultimately to some base level. The present occurrence of such surfaces far above canyon levels has been assumed to be a measure of depth of canyon cutting and uplift of the range. Wahrhaftig's work indicates that the surfaces are not necessarily relicts of extensive erosion surfaces graded to a base level. Escarpments are produced by erosional processes and are not faults, as Hake (1928) inferred. As noted in the section on geologic setting Matthes (1930; 1960) used nickpoints on tributary streams and projections of upsteam gradients to determine the profiles of the Tertiary predecessors of the Merced and San Joaquin rivers. Nickpoints on streams are to be expected from tilting of the range as demonstrated in areas to the north, but they also occur on escarpments produced by processes of hillslope erosion in the stepped topography of the southern Sierra. Matthes was unaware of the need to differentiate these two kinds of nickpoints, if indeed they can be distinguished; his profiles are valid only if he fortuitously selected the proper kind of nickpoints for his constructions. In the Merced drainage, where the physiographic resemblance to the northern Sierra is most striking, calculations of tilt based on Matthes' "Mountain Valley" profile of the Merced River produce results similar to those deduced from rivers to the north (*see* Table 1). Wahrhaftig (1965) pointed out, however, that Matthes' "Pliocene" profile on the San Joaquin River is not concordant with the stratigraphically preserved Pliocene lower San Joaquin River.

The lower course of the Pliocene predecessor of the San Joaquin River was buried by a lava flow. The gradient of this channel projected onto a plane perpendicular to the trend of the range is about 140 feet per mile near Friant Dam (Wahrhaftig, 1965). This gradient is steeper than that of any of the Tertiary channels along the foothills to the north and steeper than the profiles constructed by Matthes for the Tertiary channels in the interior of the range. This high gradient may represent a warp along the western margin of the range, a departure from the rigid tilting to the north. Further evidence that the southern Sierra was not simply tilted toward the west as was the northern Sierra are the high peaks near the western edge of the range south of the San Joaquin River (Fig. 1) and the major normal fault along the western margin of the range at the point where the Kern River debouches from the mountains into the Central Valley (Gilbert, 1928, p. 86–89). In the southernmost Sierra, major faults also occur within the range (Dibblee and Chesterman, 1953, p. 47). The extent of late Cenozoic faulting and warping within the range has not been determined and, perhaps, cannot be determined because of the lack of Tertiary strata.

Dalrymple (1963) used basalt flows occurring sparsely through the southern Sierra Nevada to estimate the amount of relief at the time they were extruded and thereby to establish a limit for the maximum possible subsequent uplift. The local relief can be estimated by the difference in elevation between the base of the basalts and the highest nearby peaks. This difference sets only a minimum value of the local relief at the time of extrusion because most of the basalts are not demonstrably in the lowest parts of the Tertiary erosion surface and because relief above the basalts has subsequently been reduced by erosion of the highest summits. The elevations of the Tertiary summits can be estimated by adding to the term for the local relief a term to account for elevation of each local area as a function of distance from the Central Valley, which served as the base level for erosion. Estimates of this kind and the ages indicated by potassium-argon analyses are listed in Table 2. The estimates of uplift in Table 2 are maximum values because the estimates of Tertiary relief are strictly minimum values.

HISTORY OF UPLIFT

Paleontologic and geologic evidence indicates that the last major uplift of the Sierra Nevada began during Pliocene time, before the

TABLE 2. UPLIFT OF THE SIERRA NEVADA CALCULATED FROM THE MAGNITUDE OF RELIEF DURING THE TERTIARY

See Figure 3 and Plate 1 for locations.

Locality	Reference	Minimum relief (feet)	Time in years before present X 10^{-6}	(a) Distance from Central Valley (miles)	(b) Estimated average gradient to valley (feet/mile)	(a) X (b)	Total minimum elevation (feet)	Present elevation (feet)	Maximum subsequent increase in elevation (feet)
S. Fork San Joaquin River-Devil's Table	Dalrymple (1963, p. 387)	4000	3.5	50	30 max. 6 min.	1500 max. 300 min.	5500 4300	11,000	5500 6700
N. Fork San Joaquin River-Snake Meadow	Dalrymple (1964, p. 26)	6000	3.3	55	30 max. 6 min.	1700 300	7700 6300	13,000	5300 6700
San Joaquin River near Kaiser Park	Dalrymple (1963, p. 387)	5800	9.5	35	25 max. 6 min.	900 200	6700 6000	10,300	3600 4300
Little Kern River	Dalrymple (1963, p. 386)	5000	3.5	70	25 max. 6 min.	1800 400	6800 5400	10,900	4100 5500
Yosemite Valley Mt. Starr King	Matthes (1930, Pls. 27, 39)	2300	Mt. Valley Stage	55	30 max. 6 min.	1700 300	4000 2600	9,000	5000 6400

advent of glaciation. Potassium-argon analyses of previously undated strata support this conclusion. The major canyon-cutting in the Sierra began after eruption of floods of andesite breccias began. These andesites have yielded mammalian faunas of Clarendonian and Hemphillian age (Vander Hoof, 1933; Stirton and Goeriz, 1942; *see also* Table 3). Interpretation of fossil plants by Axelrod (1957, p. 40) suggests that the minimum (by implicit argument) height of the crest of the northern Sierra during Clarendonian time was about 2500 feet. Uplift occurred sometime after this, and deep, narrow canyons were cut through the volcanic blanket into the basement rocks. Along the western margin of the Sierra, about 40 miles north of the Yuba River such a canyon, the Magalia channel, is filled with sediments of the Tehama Formation, which contains a Blancan fauna (Stirton, 1936; Dalrymple, 1964, p. 29). The canyon of the Merced River was 2000 feet deep before the advent of the earliest glaciation recorded on the west side of the Sierra (Matthes, 1930, p. 31); the gorge of the San Joaquin River was within 300 feet of its present depth by that time (Matthes, 1960, p. 53). The oldest glaciation in the Sierra has been tentatively correlated with the Nebraskan of the mid-Continent (*e.g.*, Sharp and Birman, 1963); if this correlation is correct, a major part of the rise of the Sierra Nevada occurred well before the advent of glaciations in the United States.

TABLE 3. CORRELATION OF LAND-MAMMAL AGES WITH EUROPEAN EPOCHS AND WITH YEARS

Adapted from Evernden and others (1964) and Savage (1951)

Millions of years	Land-mammal ages	European epochs*
	Rancholabrean Irvingtonian	Pleistocene
	Blancan	
	Hemphillian	Pliocene
10		
	Clarendonian	
	Barstovian	Miocene
20	Hemingfordian	

* Sloping lines between the European epochs indicate the uncertainty of correlation with land-mammal ages.

The stratigraphic and physiographic evidence that the Sierra rose before the advent of Pleistocene glaciations is supported by potassium-argon analyses of volcanic rocks in the Sierra Nevada. The minimum age for part of the canyon cutting is most clearly documented. The sediments filling the Magalia channel include the Nomlaki Tuff, which has been dated by Evernden and others (1964, p. 180) as 3.3 m.y. Dalrymple (1963, p. 386–387; 1964, p. 26–28) analyzed basaltic rocks that occur within the rims of the inner gorges of the present canyons of the Little Kern River and the San Joaquin River (three different localities); the ages of these basalts range from 2.9 to 3.9 m.y. The last major canyon-cutting, hence uplift, began before 4 m.y. ago. This evidence does not preclude upward movements after that date.

Dates from two localities indicate a maximum age for the last major uplift of approximately 9 m.y. The intervolcanic channel of the Tertiary Stanislaus River (Ransome, 1898) was filled with a distinctive latite flow which has been dated by Dalrymple (1963, p. 383–384) as 9 m.y. old. This flow filled a channel that had been cut through earlier volcanic rocks into basement rocks, slightly below the level of the prevolcanic channels; subsequently the river has cut much deeper into the basement rocks. The intervolcanic channel had a wider, flatter floor and a more uniform gradient, even on basement rocks, than does the modern Stanislaus River, which has a V-shaped canyon. This morphologic contrast indicates that postlatite canyon-cutting was a new and separate stage, not simply a continuation of prelatite canyon-cutting. The postlatite, V-shaped canyon is much deeper than the prelatite, flat-floored canyon, indicating that most of the uplift of the Sierra in the Stanislaus area occurred after the latites were extruded.

Basalt that fills the lower course of the Tertiary San Joaquin River has also been dated as about 9 m.y. old (Dalrymple, 1963, p. 386). The deep modern canyon was cut after this basalt filled the Tertiary channel. The Sierra Nevada in that area was already a substantial mountain range 9 m.y. ago because the modern hills adjacent to the Tertiary channel still stand several thousand feet above it. Dalrymple (1963, p. 387) inferred almost 6000 feet of relief above that channel in the vicinity of Kaiser Peak.

Axelrod (1962) has recently challenged the conclusion that the Sierra rose during the Pliocene and has asserted that the major uplift occurred during Pleistocene time. He (Axelrod, 1962, p. 186; Axelrod and Ting, 1961) implicitly assumed, however, that the age of a deposit lying on an erosional surface dates the time of cutting of the surface, whereas it simply establishes a minimum age for that cutting. Potassium-argon analyses (Dalrymple, 1963) indicate that basaltic rocks of Pliocene age lie on surfaces that Axelrod inferred to have been cut during Pleistocene time. Furthermore, some or all of the surfaces that he assumed were once graded to river levels may be steps formed by hillslope processes such as those postulated by Wahrhaftig (1962a; 1965).

That the Sierra Nevada stood at approximately its present elevation during late Pliocene time is supported by Axelrod's data, in spite of his conclusions. He collected a spore-pollen flora at an elevation of approximately 10,000 feet on San Joaquin Mountain near the head of the San Joaquin River (Axelrod, 1962, p. 186; Axelrod and Ting, 1960, p. 9, 10). He regarded the age of the deposit as late Pliocene; that inference is supported by a potassium-argon age of 3 m.y. of the basalts that overlie the fossiliferous strata (Dalrymple, 1964, p. 29). The San Joaquin Mountain flora contains pollen of trees that exist over a wide range of altitudes; but the predominant grains, *Pinus murayana* and *P. aristata*, are from trees of a high altitude, subalpine flora (Axelrod and Ting, 1961, p. 123). Martin and Gray (1962) have shown that because pollen are transported long distances by wind, only the predominant grains in a sample are reliable indicators of the local flora; hence the most probable interpretation of the San Joaquin flora is that the local flora during the late Pliocene was of a subalpine type, similar to the present flora at that locality.

Interpretations based on specific identification of spores and pollen must, however, be viewed with reservation, because many palynologists assert that fossil spores and pollen cannot be identified to the species level (Martin and Gray, 1962, p. 104). Axelrod and Ting (1960, p. 42–51) acknowledged a problem in identification and stated that their method of identifying species was statistical studies of populations; almost half of their identifications, however, are based on single grains.

Hudson (1960, p. 1555) also inferred that the last major uplift of the Sierra Nevada occurred during Pleistocene time by correlating upland surfaces in the Yosemite area with late Pliocene and Pleistocene strata along the margin of the Central Valley. Matthes (1933; 1960, p. 24) had previously correlated the same physiographic features with strata of Miocene and Pliocene age. Each simply inferred an alternative possible correlation without proof. Potassium-argon ages of the basaltic rocks on the upland surface and within canyons cut into the surfaces (Dalrymple, 1963; 1964) support Matthes' general idea of the antiquity of these surfaces.

STRUCTURE CONTOUR MAP

The rise of the Sierra Nevada that began in the interval between 9 m.y. ago and 3 m.y. ago is depicted in Figure 3 by structure contours. The contours for the northern Sierra are derived from calculations in Table 1. The "0" contour is drawn through points at which the Tertiary river profiles intersect the profiles of their modern counterparts. The contours are adjusted to fit calculations derived from the Stanislaus intervolcanic channel, because that channel provides a measure of uplift within the last 9 m.y. Minimum values of tilt from the Yuba and Tuolumne rivers are used because (1) Lindgren's work suggests that the Yuba flowed on a gradient near the maximum, and (2) some of the uplift calculated for these prevolcanic channels occurred before the latites were erupted on the Stanislaus River.

The contours for the southern Sierra are based on the calculations in Table 2 and are adjusted qualitatively to indicate a higher gradient of deformation along the western margin. The geometry of deformation in the southern Sierra is much less well documented than is that for the northern Sierra.

EASTERN ESCARPMENT

Structure and Inferred Movements

The great eastern escarpment is formed by a combination of normal faults and warps. Normal faulting has long been recognized; observations are tabulated in Table 4. Movements in many places are distributed on a series of parallel faults; antithetic normal faults, dipping toward the range, have been recognized where the escarpment has been most carefully studied (von Huene and others, 1963; Moore, 1963; Thompson and White, 1964). Major normal faults change laterally into large warps in the

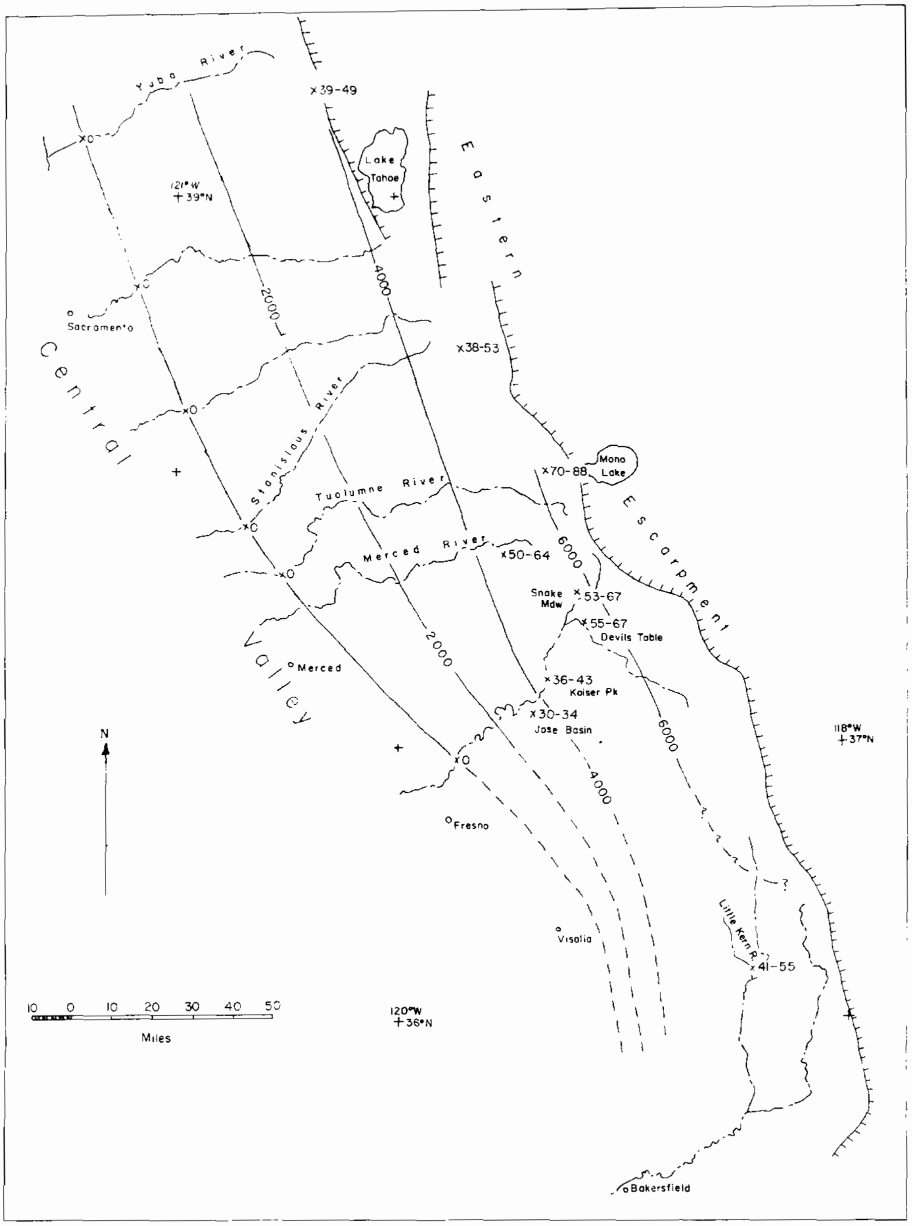

Figure 3. Structure contour map, depicting the rise of the Sierra Nevada, beginning in Pliocene time. Localities from Tables 1 and 2 are marked by X; the adjacent figures are maximum and minimum values of inferred uplift, in hundreds of feet. Contour interval, 2000 feet.

area southwest of Bishop (von Huene and others, 1963; Bateman, 1965) and at the north end of the Carson Range (Thompson and White, 1964). Topographic relief across the escarpment is a maximum of about 10,000 feet (east of Mount Whitney). Total structural relief, suggested by interpretation of gravity measurements, may be as much as 20,000 feet in several places (Pakiser and others, 1960; Kane and Pakiser, 1961; Pakiser, 1964; Pakiser and others, 1964). The interpretations of the gravity data depend on assumptions about the density of unconsolidated deposits in the valleys; if pumice constitutes a substantial part of the basin fill, the density may be substantially less than has been inferred, and the depth of fill, hence the structural relief, would also be correspondingly less.

The possibility of strike-slip movements along the escarpment has been suggested, but the sharp irregularities in the scarp as seen in map view (*e.g.*, Lawson, 1912) and the fact the major faults grade laterally into warps seem to preclude appreciable strike-slip motion. Comparison of features of the basement terranes on opposite sides of Owens Valley (Moore and Hopson, 1961; Ross, 1962; von Huene and others, 1963) has led to the conclusion that there has been no gross lateral offset across that valley. Bateman (1961) reviewed descriptions of surface movements that occurred during the earthquake of 1872 in Owens Valley and inferred a complex movement pattern with some right-lateral components but no systematic lateral shift.

Lindgren (1911, p. 108) described a series of small faults cutting a Tertiary river channel in the northern Sierra in which the height of an east-facing escarpment is largely the result of downwarping and westward tilting of the block to the east (Fig. 4). Part of the height of the main Sierran scarp is probably due to a similar pattern of movements on a larger scale, with the areas east of the scarp having been tilted downward to the west. At several localities lake beds or lake terraces east of the scarp dip westward toward the scarp. On the west side of the Pine Nut Mountains lake beds dip gently westward to the point where marshes nestle against the very foot of the steep scarp of the Carson Range. The youngest former shore lines of Pleistocene Mono Lake decline in elevation from the east side to the west, where they cut late glacial moraines (Russell, 1889, p. 302). A pluvial lake in Long Valley left a shore line that declines from 7900 feet on the south side of Glass Mountain (Fig. 5, locality B′) to 7000 feet near the foot of McGee Mountain (Fig. 5, locality B; Rinehart and Ross, 1957).

The configurations of modern lakes along the foot of the escarpment suggest that the most recent movements also involve westward tilting of areas east of the Sierra. In Topaz, Mono, and Owens lakes the deepest water is along the west side at the foot of the scarp (Blackwelder, 1933, p. 92; Russell, 1889, Pl. XIX; Gale, 1914, Pl. VI). After the earthquake of 1872, the water line in Owens Lake stood higher on the west side and lower on the east side than it had before (Hobbs, 1910, p. 368).

In summary, the movements that produced the eastern escarpment are inferred to be warping and normal faulting with relative downward movement and westward tilting of areas immediately east of the escarpment.

Age of Movements

The age of faulting as well as the magnitude of movements is determined not by demonstrable offsets of incontrovertibly correlatable horizons, but rather by physiographic arguments based on the occurrence of volcanic strata or glacial moraines adjacent to the present escarpment in situations that suggest that the escarpment either did or did not exist at the time of deposition. At the top of the escarpment at Donner Pass, Hudson (1951) described a series of mudflow breccias that seem to have been deposited before the escarpment formed; Dalrymple (1964, p. 16) dated these flows as 7.4 m.y. At the foot of the escarpment in the same area Birkeland (1963) described a series of basalt flows that were extruded on a topography similar to the present landscape; these flows have been dated by Dalrymple (1964, p. 19) as 2.3 m.y. Both Birkeland (1963, p. 1456) and Dalrymple (1964, p. 19) expressed the opinion that the scarp formed shortly before the younger basalts were extruded.

TABLE 4. INCLINATIONS OF FAULTS ALONG THE EASTERN ESCARPMENT
See Plate 1 for locations.

Locality	Dip	Reference
Indian Wells Valley	65°–70° E.	von Huene and others (1963, p. 65–66)
Owens Valley	50° E.	Knopf (1918, p. 80)
	60°–70° E.	von Huene and others (1963, p. 71)
	45°–50° E.	Moore (1963, p. 143)
June Lake	70° E.–90°	Putnam (1949, p. 1295)
Carson Range	30°–70° E.	Lawson (1912)
Donner Pass	65° W.–75° E. Average, 90°	Hudson (1948)
Mohawk Valley	65°–75° E.	Durrell (1950)

The uncertainties of this kind of interpretation are illustrated by alternative conclusions drawn from an old moraine found on the rolling, alluviated summit of McGee Mountain

(Fig. 5, locality A), the type locality of the McGee stage of glaciation in the Sierra Nevada. The McGee stage is tentatively correlated by Sharp and Birman (1963, p. 1079) with the Nebraskan of the mid-continent. The interpretation of Blackwelder (1931, p. 904), Putnam (1962, p. 205), and Rinehart and Ross (1964, p. 91) is that this moraine was deposited on a rolling topography that has subsequently been broken by faulting and dissected by deep canyons. The canyon of McGee Creek, south of McGee Mountain, now separates erratic blocks in the moraine from their source area. The canyon-cutting is presumed to have followed deposition of the moraine and to have resulted from faulting along the range front. The magnitude of movements on range-front faults, inferred from the difference in the elevation of the Mesozoic bedrock, is about 4000 feet; the maximum age of these movements would therefore be the age of the McGee stage of glaciation.

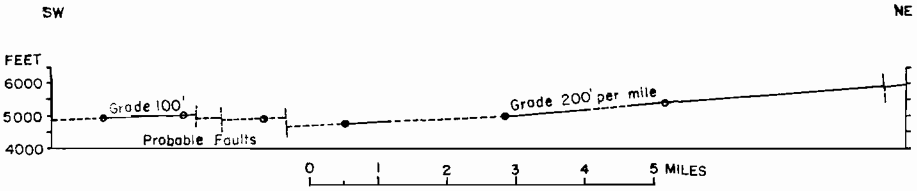

Figure 4. Geometry of faults and warps near LaPorte, California (north of the area shown on Plate 1). *From* Lindgren (1911, p. 108)

Lovejoy (1965) suggested an alternative explanation of these field relationships, namely, that the escarpment existed before the McGee stage glaciation and that the McGee Creek glacier spilled over the brink of its canyon at the outer part of the right-angle turn south of McGee Mountain, thereby depositing the moraine in an anomalous position. This explanation warrants serious consideration, but it seem improbable on two grounds, field relationships and mechanics.

Rinehart and Ross (1964, Pl. 1) mapped similar morainal material deposited on a rolling, alluviated ridgecrest on the opposite side of the canyon of McGee Creek on the inside of the right-angle bend (Fig. 5, locality A′). Piling-up of the glacier at a sharp turn cannot explain this occurrence; further, the presence of alluvium beneath the moraines at both A and A′ supports, although it does not prove, the earlier contention that the high-level moraines were deposited in an ancient valley. It can be argued that during the McGee stage of glaciation the canyon was much shallower than it now is. This argument, however, suggests that canyon-cutting, hence faulting, started only slightly before the McGee stage, thereby extending only slightly the maximum age of faulting set by previous interpretations.

The hypothesis that the escarpment in front of McGee Mountain existed during the McGee glaciation requires that the glacier in the canyon of McGee Creek have an improbably steep slope. It would have fallen about 4000 feet in less than 3 miles, from locality A in Figure 5 to the floor of Long Valley. Even if there had been a piedmont glacier 1000 feet thick in Long Valley (for the existence of which there is no evidence) the slope would be 3000 feet in 3 miles. Given the slope of the surface, one can calculate the approximate values of shear stresses in the ice for glaciers of various thicknesses (*see* Wahrhaftig and Cox, 1959, p. 401). If the canyon of McGee Creek had been 2500 feet deep then, as it is now, and filled to the rim with ice, shear stresses in the ice would have been about 15 kg/cm^2; if the canyon were 1000 feet deep and filled with a glacier, shear stresses in the ice would have been 5 or 6 kg/cm^2. The effective yield point of ice is 1 kg/cm^2 (Kamb, 1964, p. 357). It is highly unlikely that such a steep slope existed, hence also that the escarpment existed during the McGee glaciation.

Field relationships and mechanical argument both suggest that major vertical movement has occurred along the escarpment at McGee Mountain since the McGee stage of glaciation. The fact that moraines and alluvium of Wisconsin and younger age are offset only a few feet by the frontal faults indicates that most of the movement occurred before Wisconsin time (Rinehart and Ross, 1964, p. 90).

In three other places evidence suggests that the escarpment, or a major part of it, developed during Pleistocene time. At Mono Lake the

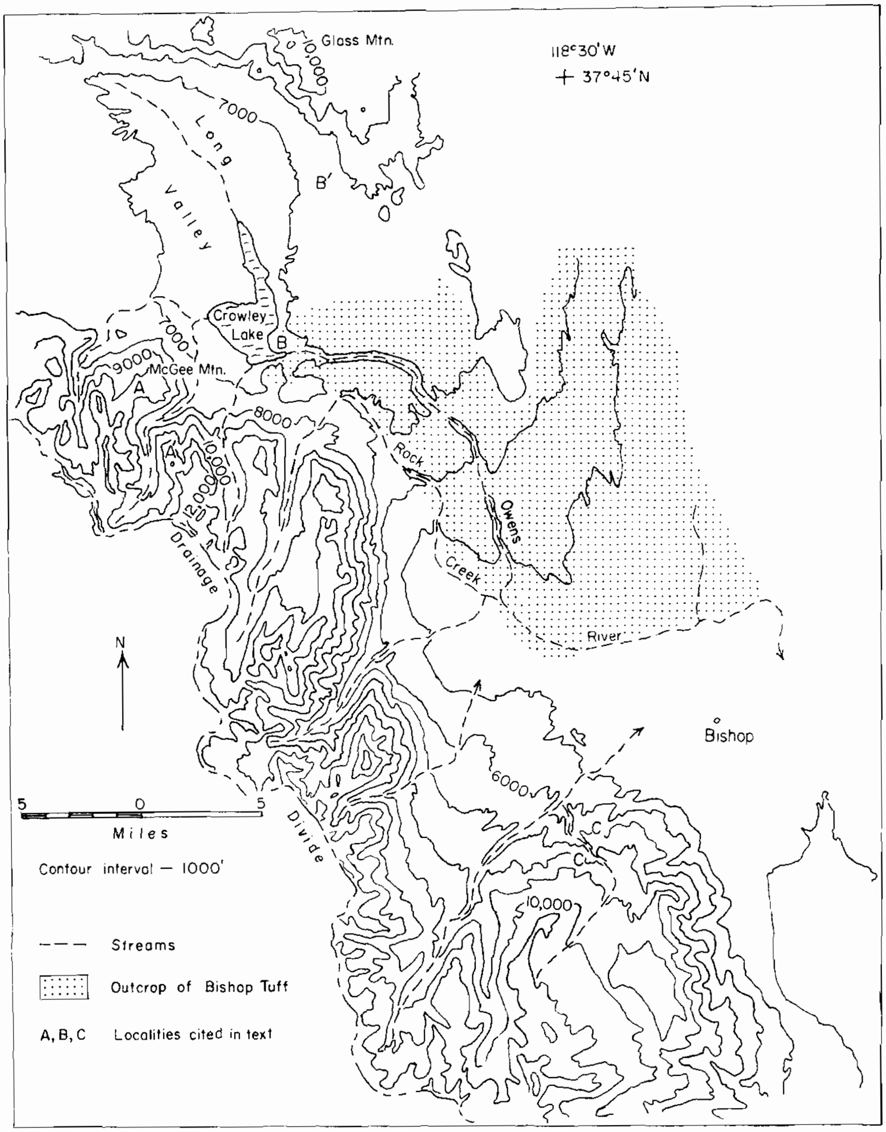

Figure 5. Topographic map of the Bishop-Long Valley area, California

oldest moraines appear to have been offset by major movement on the scarp (Matthes, 1939). At San Joaquin Mountain (Pl. 1) the escarpment truncates volcanic strata that Dalrymple (1964, p. 31) dated as 3 m.y. old. In the Coso Mountains a late Blancan mammalian fauna occurs in sediments that von Huene and Ridlon (1962) interpreted as having been deposited contemporaneously with formation of the escarpment. Recent work on the age of the Pliocene-Pleistocene boundary indicates that both of these dates fall within the Pleistocene period as defined by the 1948 International Geological Congress (Evernden and others, 1964; Fleischer and others, 1965; Evernden and Curtis, 1965).

Part of the height of the scarp may be attributable to substantial tilting of the downthrown block toward the scarp during Pleistocene time. The old shore line east of Long Valley (Fig. 5, localities B and B′) records almost 1000 feet of relative downward motion toward the scarp during the later part of Pleistocene time. This shore line is cut on Bishop Tuff (Rinehart and Ross, 1964, p. 78), an ignimbrite that overlies a morainal deposit; Dalrymple and others (1965) have dated it as about 700,000 years old. The Bishop Tuff itself has been substantially warped. The present surface of this ash flow corresponds closely to the original depositional surface; hence, generalized topographic contours on its surface represent the broad structure of the sheet (*see* Fig. 5; *also* Gilbert, 1941; Bateman, 1965). Although the present configuration is that of a broad, shallow anticline plunging southeast, old, abandoned stream courses on the surface of the ignimbrite sheet indicate that it formerly was inclined uniformly to the southeast at a more gentle slope than at present (Bateman, 1965); therefore, the southwesterly inclination of the surface in the vicinity of Owens River and Rock Creek is due to warping over the past 700,000 years. This warping produced at least 1000 feet of structural relief and possibly much more. The relative downward tilting toward the west may have been accompanied by faulting along the adjacent part of the Sierran scarp which now has 7000 feet of topographic relief.

Although much of the present relief on the escarpment probably developed during Pleistocene time, evidence suggesting that some of the structural relief east of the Sierra may have developed before early Pliocene is found on the salient in the Sierran escarpment southwest of Bishop. At localities C in Figure 5, relicts of a basalt flow define a broad, shallow valley on an old, rolling topographic surface that appears to have been tilted northward and deeply dissected after extrusion of the basalt (Bateman, 1956; 1965). The old channel, however, runs directly down the fall line of the tectonic slope, suggesting that the old drainage may have been controlled by yet earlier warping. Dalrymple (1963, p. 386) dated the basalt as 9.6 m.y. Major warping occurred after deposition although movement may have begun previously.

Because major faulting appears to have occurred on the eastern escarpment after deposition of the oldest moraines, Matthes (1933, p. 38) concluded that the eastern escarpment developed after the rise of the Sierra by downfaulting of the region east of the Sierra. More recent works generally support this conclusion, although the possibility of major movements on the escarpment during Pliocene time cannot be discounted from the available evidence.

ORIGIN OF MOVEMENTS

The sequence of uplift of the range followed by faulting on the eastern escarpment indicates that parts of the Basin Range province rose along with the Sierra. The origin of the modern Sierra, therefore, can be fully comprehended only in the context of the origin of the Basin Range structures. The Sierra Nevada is a secondary feature of a much larger primary structure in the outer skin of the earth. This view was long ago propounded by LeConte (1889). A discussion of Basin Range structures is beyond the scope of this paper, but the significance of some features of the Sierra structure can be considered.

The topographic simplicity of the Sierra Nevada results from a geometrically simple pattern of late Cenozoic movements over a large area of the earth's surface. In contrast, the topographic diversity of the Coast Ranges to the west and the Basin Ranges to the east (*see* Pl. 1) results from a complex pattern of late Cenozoic movements over much smaller domains (*e.g.*, Gilbert, 1928; Christensen, 1965). The movements at the surface may be either a direct expression of a pattern of processes at depth or an expression of the geometry of inhomogeneity of superficial rocks in combination with a pattern of processes at depth.

Both field observations and scale considerations indicate that the variation in domain size cannot be attributed to mechanical properties of the superficial rocks. In the Coast Ranges the small domain size prevails whether the basement rocks are granitic or the heterogeneous assemblage of the Franciscan formation (Christensen, 1965). In the Sierra, on the other hand, a simple pattern of movements occurred throughout a large domain in which the basement rocks consist of plutons and metamorphic bodies with a variety of shapes, sizes, and mechanical properties. A scale-model approximation, following Hubbert (1937), indicates that the uniform tilting of the northern Sierra cannot have been the result of mechanical rigidity. To reduce the Sierra Nevada to a model 100 centimeters long for an experiment lasting a few hours would require a length of reduction of approximately 10^{-5} and a time reduction of about 10^{-9}. Strength and viscosity of the model material would accordingly be reduced to the order of 10 gms/cm^2 and 10^8 poises, respectively. A material of this character could not transmit stress over a distance of 100 centimeters as would a rigid material. Uniform tilt of the surface could be accomplished only by a uniform gradient of uplift along the lower boundary of the deformed block.

These arguments support the hypothesis that the uplift of the Sierra Nevada represents primary vertical movements within the earth rather than a secondary expression of primary lateral extension or contraction. The area considered here, however, is too limited for full discussion of this problem. It is notable that uplifts of the Sierra Nevada and the Coast Ranges (Christensen, 1965) were closely associated in space and time with movements of magma.

The history of the Sierra Nevada indicates that the late Cenozoic rise is not a result of formation of a "root" during the inferred Mesozoic geosynclinal phase of this region. After sedimentation, deformation, intrusion, and metamorphism, the geosyncline, which extends beyond the limits of the present range, rose and was deeply eroded by the end of the Cretaceous period to the level of crystalline plutonic rocks (Wahrhaftig, 1962b). This deeply eroded area remained rather stable and relatively low for at least 50 m.y. before the spectacular rise beginning in Pliocene time. Crittenden's (1963) work in the Lake Bonneville area shows that the crust responds very sensitively to small loads and that, in agreement with Heiskanen and Vening Meinesz (1958, p. 369), isostatic compensation is substantially complete within less than 10,000 years. It is not credible that a buoyant tendency of the Sierran root remained latent for a period of 50 m.y., and it is scarcely more plausible that a delicate balance of forces suppressed this latent tendency for that length of time. More probably the root that is now "seen" (Byerly, 1940; Eaton, 1963), which supports the range isostatically, formed during the late Cenozoic rise of the range. The late Cenozoic rise of the Sierra Nevada is probably an expression of a synchronous process of crustal thickening.

CONCLUSIONS

LeConte's classic view of the late Cenozoic rise of the Sierra Nevada and adjacent parts of the Great Basin followed by downfaulting of the areas east of the Sierra Nevada has been substantiated by subsequent work. The view that the Sierra was tilted toward the west as a rigid, unitary block is valid only for the area north of the Tuolumne River, and not for the southern Sierra. The amount of tilt and magnitude of uplift of the crest decrease from the latitude of the Tuolumne River northward to Lake Tahoe. The magnitude of uplift can be specified at the present time, with any moderate degree of confidence, only to within ±1000 feet. In the southern Sierra Nevada the record is less clear, but it appears that part of the range rose by translation as well as rotation, with warping and faulting along the western margin as well as along the eastern. The last major increment of uplift began in the interval between 9 and 3 m.y. ago. In those places where the development of the eastern escarpment has been dated, faulting occurred since 3 m.y. ago, with as much as 4000 feet of faulting since the earliest glacial stage. The simple pattern of movements in late Cenozoic time is probably a direct expression of a similar pattern of processes of crustal thickening that occurred during the same interval.

REFERENCES CITED

Axelrod, D. I., 1957, Late Tertiary floras and the Sierra Nevadan uplift: Geol. Soc. America Bull., v. 68, p. 19–46

—— 1962, Post-Pliocene uplift of the Sierra Nevada, California: Geol. Soc. America Bull., v. 73, p. 183–198

Axelrod, D. I., and Ting, W. S., 1960, Late Pliocene floras east of the Sierra Nevada: Univ. Calif. Pubs. Geol. Sci., v. 39, p. 1–118

—— 1961, Early Pleistocene floras from the Chagoopa surface, southern Sierra Nevada: Univ. Calif. Pubs. Geol. Sci., v. 39, p. 119–194

Bateman, P. C., 1956, Economic Geology of the Bishop Tungsten district, California: Calif. Div. Mines Special Rept. 47, 87 p.

—— 1961, Willard D. Johnson and the strike-slip component of fault movement in the Owens Valley, California earthquake of 1872: Seismol. Soc. America Bull., v. 51, p. 483–493

—— 1965, The geology and tungsten mineralization of the Bishop district, California: U. S. Geol. Survey Prof. Paper 470, 208 p.

Birkeland, P. W., 1963, Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California: Geol. Soc. America Bull., v. 74, p. 1453–1464

Blackwelder, Eliot, 1931, Pleistocene glaciation of the Sierra Nevada and Basin Ranges: Geol. Soc. America Bull., v. 42, p. 865–922

—— 1933, Eastern slope of the Sierra Nevada: Internat. Geol. Cong., XVI Sess. (United States), Guidebook 16, p. 81–95

Byerly, P., 1940, The seismic determination of deep-seated crustal structure in California: Am. Geophys. Union Trans., pt. 3, p. 815–822

Christensen, M. N., 1965, Late Cenozoic deformation in the central Coast Ranges of California: Geol. Soc. America Bull., v. 76, p. 1105–1124

Crittenden, M. D., 1963, Effective viscosity of the earth derived from isostatic loading of Pleistocene Lake Bonneville: Jour. Geophys. Research, v. 68, p. 5517–5530

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

—— 1964, Cenozoic chronology of the Sierra Nevada, California: Univ. Calif. Pubs. Geol. Sci., v. 47, p. 1–41

Dalrymple, G. B., Cox, Allan, and Doell, R. R., 1965, Potassium-argon age and paleomagnetism of the Bishop Tuff, California: Geol. Soc. America Bull., v. 76, p. 665–674

Dibblee, T. W., and Chesterman, C. W., 1953, Geology of the Breckenridge Mountain quadrangle, California: Calif. Div. Mines Bull. 168, 56 p.

Durrell, Cordell, 1950, Strike-slip faulting in the eastern Sierra Nevada near Blairsden, California (Abstract): Geol. Soc. America Bull., v. 61, p. 1522

Eaton, J. P., 1963, Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic refraction measurements: Jour. Geophys. Research, v. 68, p. 5789–5806

Eric, H. H., Stromquist, A. A., and Swinney, C. M., 1954, Geology of the Angels Camp, and Sonora quadrangles, Calaveras and Tuolumne counties, California: Calif. Div. Mines Special Rept. 41, 55 p.

Evernden, J. F., and Curtis, G. H., 1965, The potassium-argon dating of late Cenozoic rocks in East Africa and Italy: Current Anthropology, v. 6, p. 343–385

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

Fleischer, R. L., Price, P. B., Walker, R. M., and Leakey, L. S. B., 1965, Fission-track dating of Bed I, Olduvai Gorge: Science, v. 148, p. 72–74

Gale, H. S., 1914, Salines in the Owens, Searles, and Panamint basins, southeastern California: U. S. Geol. Survey Bull. 580, p. 251–323

Gilbert, C. M., 1941, Late Tertiary geology of Mono Lake, California: Geol. Soc. America Bull., v. 52, p. 781–816

Gilbert, G. K., 1928, Studies of Basin Range structure: U. S. Geol. Survey Prof. Paper 153, 92 p.

Hake, B. F., 1928, Scarps of the southwestern Sierra Nevada, California: Geol. Soc. America Bull., v. 39, p. 1017–1030

Heiskanen, W. H., and Vening Meinesz, F. A., 1958, The Earth and its gravity field: New York, McGraw-Hill Book Co., Inc., 470 p.

Hobbs, W. H., 1910, The earthquake of 1872 in Owens Valley, California: Gerlands Beitr. Geophysik, v. 10, p. 352–385

Hubbert, M. K., 1937, Theory of scale models as applied to the study of geologic structures: Geol. Soc. America Bull., v. 48, p. 1459–1520

Hudson, F. S., 1948, Donner Pass zone of deformation, Sierra Nevada, California: Geol. Soc. America Bull., v. 59, p. 795–800

—— 1951, Mount Lincoln-Castle Peak area, Sierra Nevada, California: Geol. Soc. America Bull., v. 62, p. 931–952

—— 1955, Measurement of the deformation of the Sierra Nevada, California, since middle Eocene: Geol. Soc. America Bull., v. 66, p. 835–870

—— 1960, Post-Pliocene uplift of the Sierra Nevada, California: Geol. Soc. America Bull., v. 71, p. 1547–1574

Kamb, B., 1964, Glacier geophysics: Science, v. 146, p. 353–365

Kane, M. F., and Pakiser, L. C., 1961, Geophysical study of subsurface structure in southern Owens Valley, California: Geophysics, v. 26, p. 12–26

Knopf, A., 1918, A geologic reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California: U. S. Geol. Survey Prof. Paper 110, 130 p.

Lawson, A. C., 1912, The recent fault scarps at Genoa, Nevada: Seismol. Soc. America Bull., v. 2, p. 193–200

Le Conte, J., 1886, A post-Tertiary elevation of the Sierra Nevada shown by the river beds: Am. Jour. Sci., 3d ser., v. 32, p. 167–181

—— 1889, On the origin of normal faults and of the structure of the Basin region: Am. Jour. Sci., 3d ser., v. 38, p. 257–263

Leopold, L. B., and Miller, J. P., 1956, Ephemeral streams—hydraulic factors and their relation to the drainage net: U. S. Geol. Survey Prof. Paper 282-A, 37 p.

Lindgren, W., 1900, Colfax Folio, California: U. S. Geol. Survey Folio no. 66, 10 p.

—— 1911, The Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, 198 p.

Lovejoy, E. M. P., 1965, Evidence of Plio-Pleistocene faulting at McGee Mountain, Mono County, California: Critical study (Abstract): Geol. Soc. America, Cordilleran Section, Program, 61st Ann. Meeting, Fresno, Calif., p. 34

Martin, P. S., and Gray, J., 1962, Pollen analysis and the Cenozoic: Science, v. 137, p. 103–111

Matthes, F. E., 1930, Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, 137 p.

—— 1933, Geography and geology of the Sierra Nevada: Internat. Geol. Cong., XVI Sess. (United States), Guidebook 16, p. 26–40

—— 1939, History of faulting movements at the east front of the Sierra Nevada as indicated by dislocated moraines (Abstract): Geol. Soc. America Bull., v. 50, p. 1955

—— 1960, Reconnaissance of the geomorphology and glacial geology of the San Joaquin Basin, Sierra Nevada, California: U. S. Geol. Survey Prof. Paper 329, 62 p.

Moore, J. G., 1963, Geology of the Mount Pinchot quadrangle, southern Sierra Nevada, California: U. S. Geol. Survey Bull. 1130, 152 p.

Moore, J. G., and Hopson, C., 1961, The Independence dike swarm in eastern California: Am. Jour. Sci., v. 259, p. 241–259

Pakiser, L. C., 1964, A gravity study of Long Valley, p. 85–92 *in* Geology and mineral deposits of the Mount Morrison quadrangle, Sierra Nevada, California: U. S. Geol. Survey Prof. Paper 385, 106 p.

Pakiser, L. C., Kane, M. F., and Jackson, W. H., 1964, Structural geology and volcanism of Owens Valley region, California—a geophysical study: U. S. Geol. Survey Prof. Paper 438, 68 p.

Pakiser, L. C., Press, F., and Kane, M. F., 1960, Geophysical investigation of Mono Basin, California: Geol. Soc. America Bull., v. 71, p. 415–448

Piper, A. M., Gale, H. S., Thomas, H. E., and Robinson, T. W., Jr., 1939, Geology and ground water hydrology of the Mokelumne area, California: U. S. Geol. Survey Water Supply Paper 780, 230 p.

Putnam, W. C., 1949, Quaternary geology of the June Lake district, California: Geol. Soc. America Bull., v. 60, p. 1281–1302

—— 1962, Late Cenozoic geology of McGee Mountain, Mono County, California: Univ. Calif. Pubs. Geol. Sci., v. 40, p. 181–218

Ransome, F. L., 1898, Some lava flows of the western slope of the Sierra Nevada, California: U. S. Geol. Survey Bull. 89, 71 p.

Rinehart, C. D., and Ross, D. C., 1957, Geology of the Casa Diablo Mountain quadrangle, California: U. S. Geol. Surv. Map GQ 99 (scale, 1:62,500)

—— 1964, Geology and mineral deposits of the Mount Morrison quadrangle, Sierra Nevada, California: U. S. Geol. Geol. Surv. Prof. Paper 385, 106 p.

Ross, D. C., 1962, Correlation of granitic plutons across faulted Owens Valley, California, Art. 145, p. D86–D88 *in* Geological Survey Research, Short papers in geology, hydrology, and topography, articles 120 to 179: U. S. Geol. Survey Prof. Paper 450-D, 195 p.

Russell, I. C., 1889, Quaternary history of Mono Valley, California: U. S. Geol. Survey 8th Ann. Rept., pt. I, 261–394

Savage, D. E., 1951, Late Cenozoic vertebrates of the San Francisco Bay region: Univ. Calif. Pubs. Geol. Sci., v. 28, p. 215–314

Sharp, R. P., and Birman, J. H., 1963, Additions to classical sequence of Pleistocene glaciations, Sierra Nevada, California: Geol. Soc. America Bull., v. 74, p. 1079–1086

Stirton, R. A., 1936, Succession of North American Pliocene mammalian faunas: Am. Jour. Sci., 5th ser., v. 32, p. 161–206

Stirton, R. A., and Goeriz, H. F., 1942, Fossil vertebrates from the superjacent deposits near Knights Ferry, California: Univ. Calif. Dept. Geol. Sci. Bull., v. 26, p. 447–472

Thompson, G. A., and White, D. E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-A, 52 p.

United States Geological Survey, 1960, Compilation of records of surface waters of the United States through September 1950—Pacific slope basins in California; except Central Valley: U. S. Geol. Survey, Water Supply Paper 1315-B, 874 p.

Vander Hoof, V. L., 1933, A skull of *Pliohippus tantalus* from the later Tertiary of the Sierran foothills of California: Univ. Calif. Dept. Geol. Sci. Bull., v. 23, p. 183–193

von Huene, R., and Ridlon, J. B., 1962, Pleistocene Basin and Range deformation in the Coso Mountains, southeastern California, p. 71 *in* The Geological Society of America, Abstracts for 1962: Geol. Soc. America Special Paper 73, 355 p.

von Huene, R., Bateman, P. C., and Ross, D. C., 1963, Indian Wells Valley, Owens Valley, Long Valley, and Mono Basin, p. 57–110 *in* Guidebook for seismological study tour, 1963 Meeting of I.U.G.G.: China Lake, California, U. S. Naval Ordnance Test Station, 110 p.

Wahrhaftig, C. A., 1962a, Origin of stepped topography of the west-central Sierra Nevada, California, p. 71 *in* The Geological Society of America, Abstracts for 1962: Geol. Soc. America Special Paper 73, 355 p.

—— 1962b, Geomorphology of the Yosemite Valley region, California, p. 33–46 *in* Geologic guide to the Merced Canyon and Yosemite Valley, California: Calif. Div. Mines Bull. 182, 68 p.

—— 1965, Stepped topography of the southern Sierra Nevada, California: Geol. Soc. America Bull., v. 76, p. 1165–1190

Wahrhaftig, C. A., and Cox, Allan, 1959, Rock glaciers in the Alaska Range: Geol. Soc. America Bull., v. 70, p. 383–436

MANUSCRIPT RECEIVED BY THE SOCIETY OCTOBER 5, 1964