Amount and Timing of Late Cenozoic Uplift and Tilt of the Central Sierra Nevada, California — Evidence from the Upper San Joaquin River Basin

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By N. KING HUBER

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AMOUNT AND TIMING OF LATE CENOZOIC UPLIFT AND TILT OF THE CENTRAL SIERRA NEVADA, CALIFORNIA — EVIDENCE FROM THE UPPER SAN JOAQUIN RIVER BASIN

By N. KING HUBER

ABSTRACT

The upper San Joaquin River is unique among the rivers that drain the western slope of the Sierra Nevada in that it flowed westward across the present crest of the range until as recently as about 3.2 million years ago. Portions of the history of the river and of the topographic development of the central Sierra Nevada can be deciphered from tilted stratigraphic planes at the east margin of the Central Valley and dated volcanic rocks within and east of the upper San Joaquin River's present drainage basin. Uplift of the central Sierra Nevada was probably underway by 25 m.y. ago, but at a relatively low rate, probably not exceeding about 0.03 mm/yr at the present drainage divide at Deadman Pass. Uplift proceeded at an increasing rate, and is an estimated 0.3 mm/yr at present; the rate may still be increasing. Total uplift at Deadman Pass in the past 50 m.y. is estimated to be about 3450 m, of which two-thirds took place in the last 10 m.y. and one-fourth in the last 3 m.y. Of these estimates, the amounts of pre-10 m.y. uplift and post-3 m.y. uplift are the most speculative. Highlights of the uplift history, ignoring qualifications discussed in the text, include:

1. During deposition of the Eocene Ione Formation in the Central Valley, perhaps 50 m.y. ago, the San Joaquin River drained a significant area to the east of the range. Because major peaks on either side of the San Joaquin canyon presently rise only 450–750 m above the projected Eocene local base level, relief in the area was comparatively low.
2. Between 50 and 10 m.y. ago, uplift of about 1300 m occurred at the site of Deadman Pass on the present Sierran drainage divide. Major peaks stand 1500 to 1700 m above the 10-m.y. local base level, indicating that relief had increased. The stream profile at the site of Deadman Pass was about 900 m above sea level 10 m.y. ago.
3. After it began, uplift and westward tilt of the range accelerated; by somewhat more than 3 m.y. ago, the site of Deadman Pass had been uplifted an additional 1200 m, and incision of the inner canyon of the San Joaquin River in response to uplift was well advanced.
4. About 3.2 m.y. ago, the San Joaquin River was beheaded by the eruption of basalt that filled the channel near Deadman Pass. Water previously flowing in this channel was probably diverted into the already-forming Owens Valley graben.
5. An additional 950 m of uplift at Deadman Pass took place after about 3 m.y. ago, for a total of 2150 m since about 10 m.y. ago. Until about 3 m.y. ago, the area east of Deadman Pass probably rose along with the Sierran block, but then lagged behind it, resulting in relative downward displacement along faults east of Deadman Pass of about 1100 m.
6. Partial infilling of the inner canyon by basalt and the greatly reduced stream discharge, particularly in the Middle Fork, which had been the main trunk of the river, greatly reduced rates of canyon downcutting by stream erosion in the last 3 m.y. Glacial erosion consequently was the dominant mechanism for removal of the basalt, additional incision into prevolcanic bedrock, and enhancement of the concavity of the longitudinal stream profile upstream from Mammoth Pool Dam.
7. The elevation of the Sierra Nevada 3 m.y. ago may not have been high enough to permit extensive glaciation at that time. The lag deposit at Deadman Pass, previously described as a till, may be of nonglacial origin.

INTRODUCTION

Late Cenozoic uplift and westward tilting of the Sierra Nevada was convincingly demonstrated by the pioneering studies of Whitney (1880), Ransome (1898), Lindgren (1911), and others. Christensen (1966, p. 178), however, emphasized that "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," and that "the amount of tilt and magnitude of uplift of the crest decrease from the latitude of the Tuolumne River northward to Lake Tahoe." He also noted that "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." Data from the upper San Joaquin River drainage basin east of the Central Valley (fig. 1), however, suggest that tilt is the dominant effect at least that far south, although between the Tuolumne and San Joaquin Rivers there is a change in tilt azimuth from west-southwest at the Tuolumne to southwest at the San Joaquin (see Christensen, 1966, fig. 3). The fundamental difference in uplift behavior of the southern Sierra, noted by Christensen, appears to take place south of the upper San Joaquin drainage basin.

Since Lindgren's work (1911), many later workers have attempted to quantify the amount and timing of the uplift and tilting of the Sierra, mostly by trying to reconstruct stream profiles and erosion surfaces for successive epochs of the Cenozoic. Classic among such studies was that of Matthes (1930a, 1960), whose data were derived mainly from the Merced and San Joaquin River basins. Such efforts were summarized and enlarged upon by Christensen (1966), who concluded that "the last major increment of uplift began in the interval between 9 and 3 m.y. ago." Furthermore, he endorsed Dalrymple's (1964) conclusion that in the upper San Joaquin drainage basin at least, uplift had begun long enough before 3.6 m.y. ago and had been of sufficient magnitude by that time not only to initiate Matthes' (1930a, 1960) Canyon stage of erosion, but also to incise the Canyon stage deep into the preceding Mountain Valley stage, as indicated by 3.6-m.y.-old volcanic flows within the canyon. Christensen (1966) also concluded that the Sierra had reached its present elevation by the late Pliocene.

Another line of evidence cited by Christensen to suggest that major uplift had occurred earlier than 3 m.y. ago is that of ancient pollen and spores. A spore and pollen flora from elevations of 2925 and 3025 m on San Joaquin Mountain near the head of the San Joaquin River was assigned a late Pliocene age by Axelrod and Ting (1960), which is supported by an age of 3.2 m.y. for basalt overlying the fossiliferous strata (Huber and Rinehart, 1967). The flora contains pollen of trees that exist over a wide range of altitudes, but Axelrod and Ting (1960) concluded that it accumulated at a

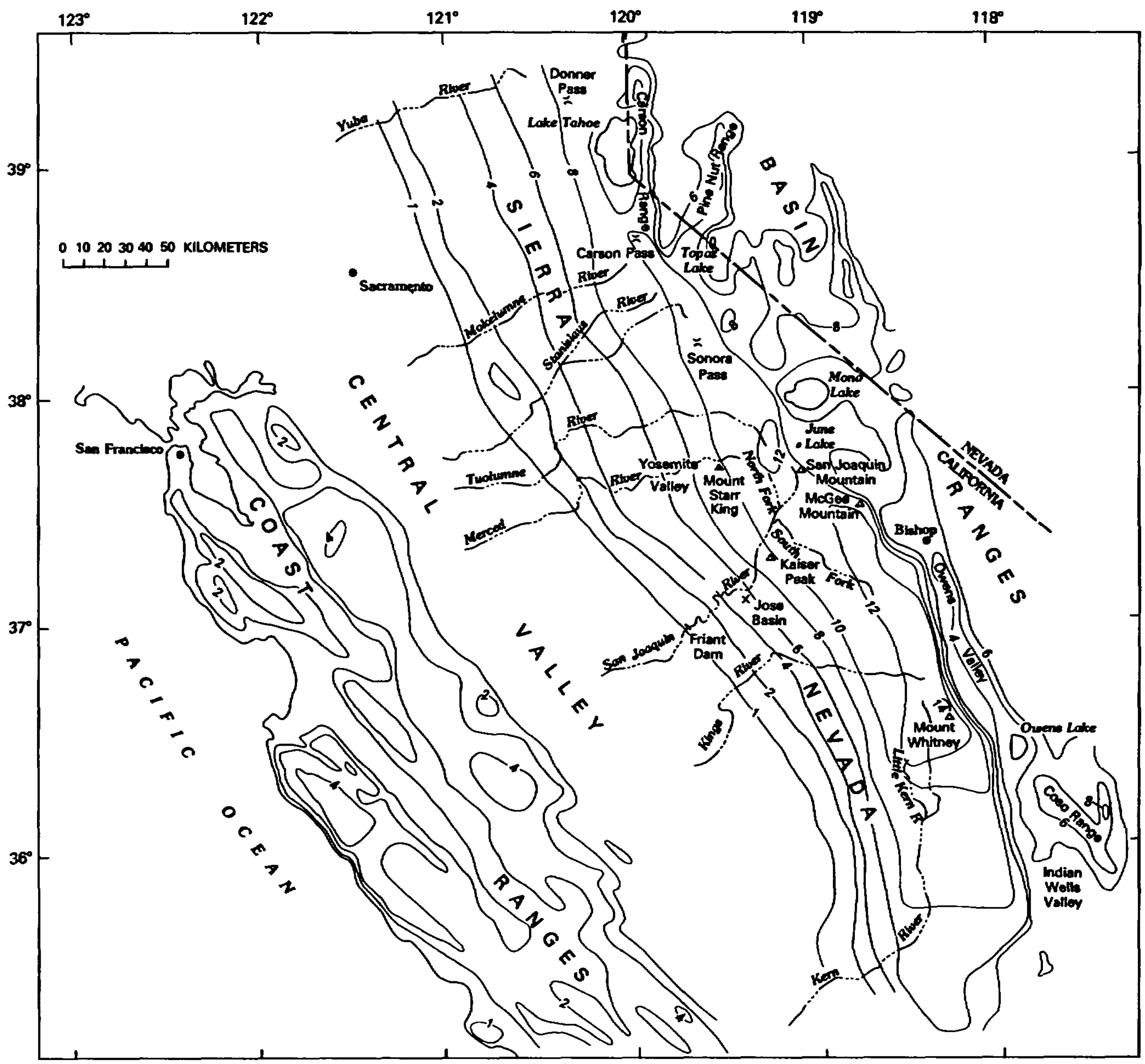

FIGURE 1.— Generalized topographic contour map of central California. Contour interval 2000 ft (610 m); 1000-ft (305 m) contour is supplementary. From Christensen (1966). "Upper" San Joaquin River is that part east of Central Valley.

moderate altitude of a thousand meters or so and was subsequently uplifted during the Pleistocene. Christensen (1966, p. 172) pointed out that the mere presence of pollen grains from trees of a high-altitude environment indicates an elevated source area somewhere in the general region whereas the middle- and low-altitude varieties could have been transported by prevailing winds from lower elevations on the western slope of the range, and he suggested that "the Sierra Nevada stood at approximately its present elevation during late Pliocene time." If the calculations presented in this study are credible, a compromise conclusion is warranted: 3 m.y. ago the collection sites had an elevation of about 2040 m and the Ritter Range, 8 km to the west with elevations of 3100 m or more, probably was high enough to supply the appropriate high-altitude pollen.

Grant, McCleary, and Blum (1977) reported that on the east side of the Central Valley between the Mokelumne and Merced Rivers, bedding planes of formations ranging in age from about 22 m.y. (Valley Springs Formation) through 9 m.y. (Table Mountain Latite) to about 5 m.y. (Mehrten Formation) in age have approximately the same dip. This led them to conclude that the Sierra Nevada was relatively stable during this time interval and that the major uplift of the Sierra Nevada began tilting the rocks along the east side of the Central Valley about 5 m.y. ago. They also concluded that uplift has taken place at a relatively uniform rate over the past 5 m.y., but their sparse data are only suggestive.

The most recent review of uplift timing is by Slemmons, Van Wormer, Bell, and Silberman (1979), who contributed some new data based on uplift of radiometrically dated volcanic rocks in the Carson Pass-Sonora Pass section of the north-central Sierra Nevada. They concluded that although minor uplift was taking place as long ago as the Oligocene, the "main uplift" in that area began about 17 m.y. ago, accelerated during the late Cenozoic, and continues today.

Hay (1976) invoked plate-tectonic theory to speculate that the late Cenozoic uplift of the Sierra began with the advent of the San Andreas transform fault system and was "***accelerated about 4.5 m.y. ago in response to the northward migration of the Mendocino triple junction and the increased rate of motion between the North American and Pacific plates." Although this scenario is appealing, he brought no new data into the argument, and any estimates of the actual timing of the uplift should be based on more direct evidence.

It is possible that uplift was started somewhat earlier in the southern part of the range and progressed northward with time (see, for example, Hay, 1976; Crough and Thompson, 1977).

The preuplift San Joaquin River headed at least as far east as the present Mono Lake basin, possibly farther north or east in Nevada, and its course across the west slope of the Sierra Nevada has changed little since the Eocene, when the Ione Formation was deposited in the Central Valley. It is this continuity of course that makes the San Joaquin River especially useful in reconstructing Sierran tectonics for at least part of the range, as all of the rivers north of Yosemite had their courses drastically altered by extensive Oligocene and Miocene volcanism. Three stratigraphic markers are available for structural analysis: the Ione Formation; a 10-m.y.-old lava flow capping a group of table mountains east of Friant; and an alluvial fan on the Kings River east of Fresno. Several critically located and dated volcanic units within the drainage basin help provide additional time constraints.

The San Joaquin River was beheaded at the present Sierran divide about 3.2 m.y. ago by a combination of volcanic activity and relative down-faulting to the east. The cumulative displacement on the eastern range-front fault system is approximately equivalent to the amount of post-3 m.y. uplift at this locality.

Estimates of the total amount of uplift at the divide depend upon choice of a model involving tilt of a rigid block or of one involving broad doming with a decrease in amount of tilt eastward from a hinge line. In either case the hinge line is assumed to lie at the east margin of the Central Valley near Friant at the intersection of the tilted stratigraphic planes of the Ione Formation (approximately 50 m.y. old) and the table mountain complex (10 m.y. old) at a present elevation of approximately 150 m above sea level (fig. 2). The simple tilt model yields a maximum post-10-m.y. uplift value at Deadman Pass on the present drainage divide of approximately 2150 m. A dome model would yield a somewhat lower but undetermined uplift value. Using present-day elevations in the range, correlative calculations permit estimation of pre-uplift elevations and relief. For example, if the uniform tilt model is applied to Mount Ritter, now at 4010 m, this peak would have had an elevation 10 m.y. ago of about 2000 m associated with a local relief of about 1050 m (these figures do not allow for erosional lowering of the mountain). This report will develop the rationale and present the analysis leading to these conclusions. It will not consider possible causes or mechanisms for the uplift.

METHODS OF STUDY AND ACKNOWLEDGMENTS

Many of the calculations in this report are based on graphic reconstruction of stream base levels and longitudinal profiles at a scale of 1:62,500 (with vertical exaggeration of about 10×) based upon 15' topographic quadrangle maps with contour intervals of 80 feet

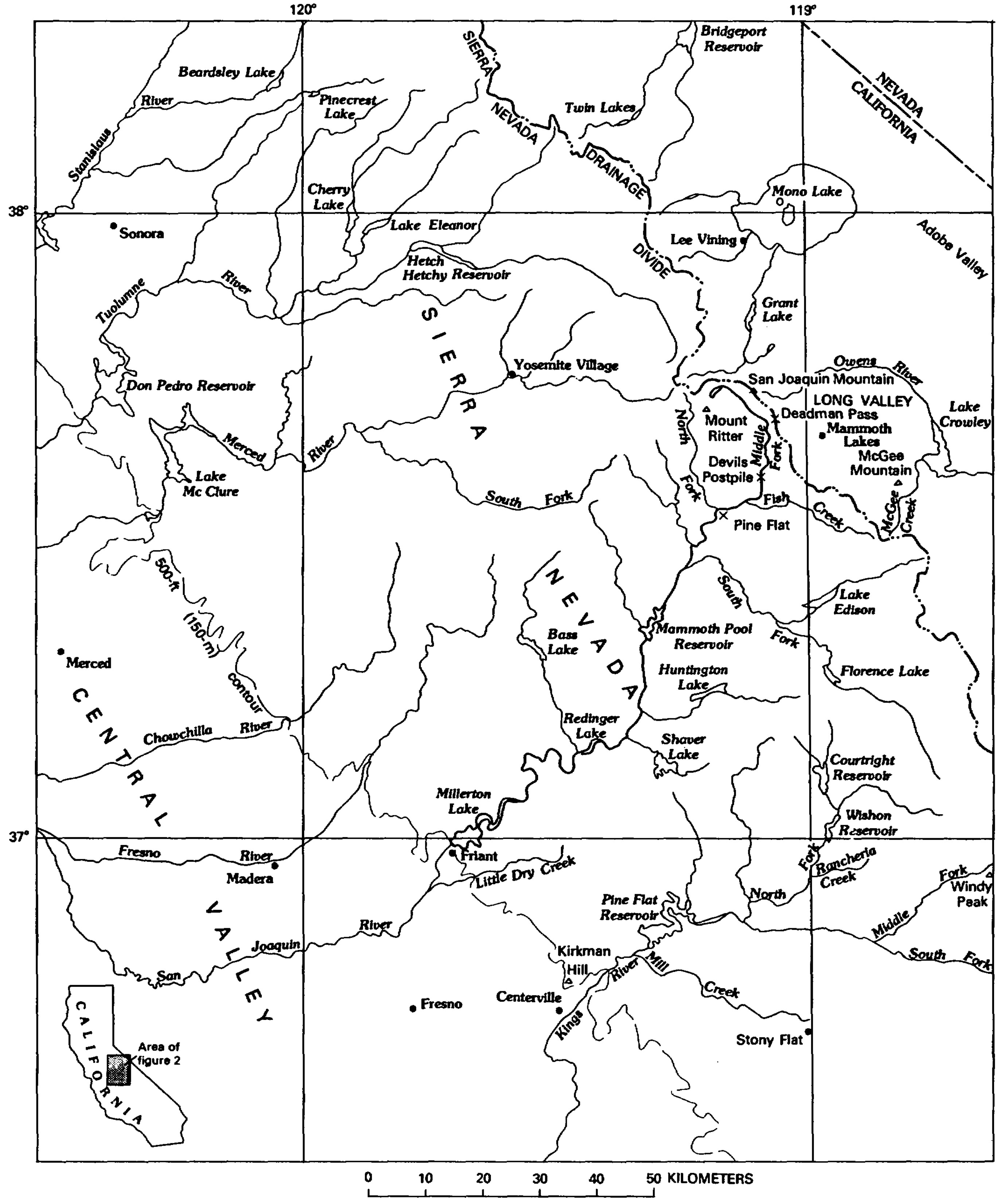

FIGURE 2.—"Upper" San Joaquin River and vicinity. The 500-ft (150-m) contour marks approximate east margin of Central Valley and assumed hinge line for Sierran tilt. Main trunk of upper San Joaquin river emphasized by heavier line weight.

(24.4 m), except for the Clovis quadrangle with a 50-foot (15.2 m) interval. The profiles were projected onto a vertical plane oriented N. 40 E., thus the slope depicted for any given reach will be greater than the actual stream gradient as measured along the stream bed. Because the topographic maps used in this study are contoured in U. S. customary units rather than metric units, the customary units were used in most calculations regarding uplift of the range. An unrealistic number of significant figures was retained to avoid multiple rounding errors during sequential calculations, but after the results were converted to the metric system, they were rounded to avoid an unwarranted aura of accuracy; even then, the conclusions are not necessarily as accurate as the numbers might imply. Because of the rounding, some of the results as presented may not sum properly. In converting elevation data to the metric system, figures have not been significantly rounded so that one can reconvert for use with the topographic maps.

J. C. Von Essen and M. L. Silberman of the U. S. Geological Survey and G. H. Curtis and R. E. Drake of the University of California, Berkeley, supplied potassium-argon age determinations. All age determinations cited from the literature have been recalculated using the new constants given in table 1 and are thus about 2.5 percent older than those in the original source. In age discussions, the Miocene-Pliocene boundary is considered to be at about 5 m.y. B. P. (Van Couvering, 1978). I have benefited greatly from discussions and data supplied by many of my colleagues, in particular J. A. Bartow, P. C. Bateman, M. M. Clark, D. S. Harwood, E. J. Helley, R. J. Janda, D. E. Marchand, and G. I. Smith; naturally I remain responsible for any errors in interpretation.

GENERAL SETTING

The trachyandesite of Kennedy Table is exposed in the upper San Joaquin River drainage basin in the western foothills of the Sierra Nevada east of Friant (fig. 3). The trachyandesite, together with underlying stream-deposited sand and gravel, marks the location of a late Miocene channel of the San Joaquin River. The trachyandesite is more resistant to weathering and erosion than the granitic rock that makes up most of the subjacent bedrock in this vicinity. Preferential erosion of the granitic rock since the eruption of the trachyandesite, coupled with uplift and tilting of the Sierra Nevada, has left erosional remnants of the trachyandesite and underlying gravel standing as a series of flat-topped "table" mountains, a classic example of topographic inversion. These table mountains allow one to reconstruct partially the drainage pattern of the late Miocene San Joaquin River, and the plane defined by the tops of the table mountains and its upstream projection allow estimates to be made of contemporary relief and the amount of uplift and tilt of the Sierra Nevada since the eruption of the trachyandesite. Such estimates have been made by Dalrymple (1963), Christensen (1966), and Bateman and Wahrhaftig (1966).

Janda (1966) included the trachyandesite (his "basalt") as a member of his proposed Auberry Formation, the remainder of which is made up of the underlying late Miocene alluvial deposits. Marchand (1976) followed this usage in a preliminary report. The trachyandesite flow, however, is the product of a single geologic event of short duration and because of its usefulness as a stratigraphic marker, it warrants its own geologic name. Trachyandesite of Kennedy Table is here used because Kennedy Table provides the largest areal exposure of the trachyandesite flow. This supersedes my informal name, San Joaquin table mountain andesite flow, used in a preliminary report (Huber, 1977). Inasmuch as the name Auberry Formation has not been proposed nor the unit described in a formal publication, the name will not be used further in this report, and the alluvial deposits beneath the trachyandesite flow will simply be referred to as pre-volcanic alluvial deposits.

PRE-VOLCANIC ALLUVIAL DEPOSITS

Late Miocene alluvial deposits can be traced discontinuously beneath the trachyandesite of Kennedy Table from the unnamed table northeast of Table Mountain (fig. 3) westward to where the deposits disappear beneath alluvial deposits of the Turlock Lake Formation of Pleistocene age at the margin of the Central Valley (Marchand, 1976). Recognition of pre-volcanic alluvial deposits east of the unnamed table is hampered by the presence of extensive talus aprons that generally conceal the base of the trachyandesite at Kennedy Table and Squaw Leap.

The easternmost "exposures" of the alluvial deposits consist mostly of scattered cobbles observed downslope from the generally concealed base of the lava flow; the alluvial deposits are probably quite thin and actual outcrops are uncommon. Near the west end of the exposures of the pre-volcanic alluvial deposits, about 3 km east of where they dip beneath younger alluvium, the deposits consist of about 45 m of interbedded stream gravels, silts and water-laid volcanic ash, overlying granodiorite (Janda, 1966). This section, on the south side of the ridge north of Little Dry Creek, is the type section for Janda's Auberry Formation and presumably reflects an interbedded mixture of channel gravels and finer grained flood-plain deposits. Approximately 42 m of similar material is exposed on the north side of the same ridge, but the base of the deposit is concealed there.

On the west side of the San Joaquin River, west and north of exposures of the Ione Formation, are scattered areas underlain by sediments that Janda (1966) and Marchand (1976) included with the pre-volcanic alluvial deposits (the lower part of their Auberry Formation). This correlation is incompatible with physiographic evidence and is now questioned by Marchand (oral commun., 1979). The true stratigraphic position of these sediments has not been established.

Abundant pumice pebbles and cobbles occur in a pumice-rich layer exposed in the pre-volcanic alluvium on the north side of the ridge north of Little Dry Creek. The abundance of the pumice pebbles within a discrete horizon of the alluvial deposit suggests that they were

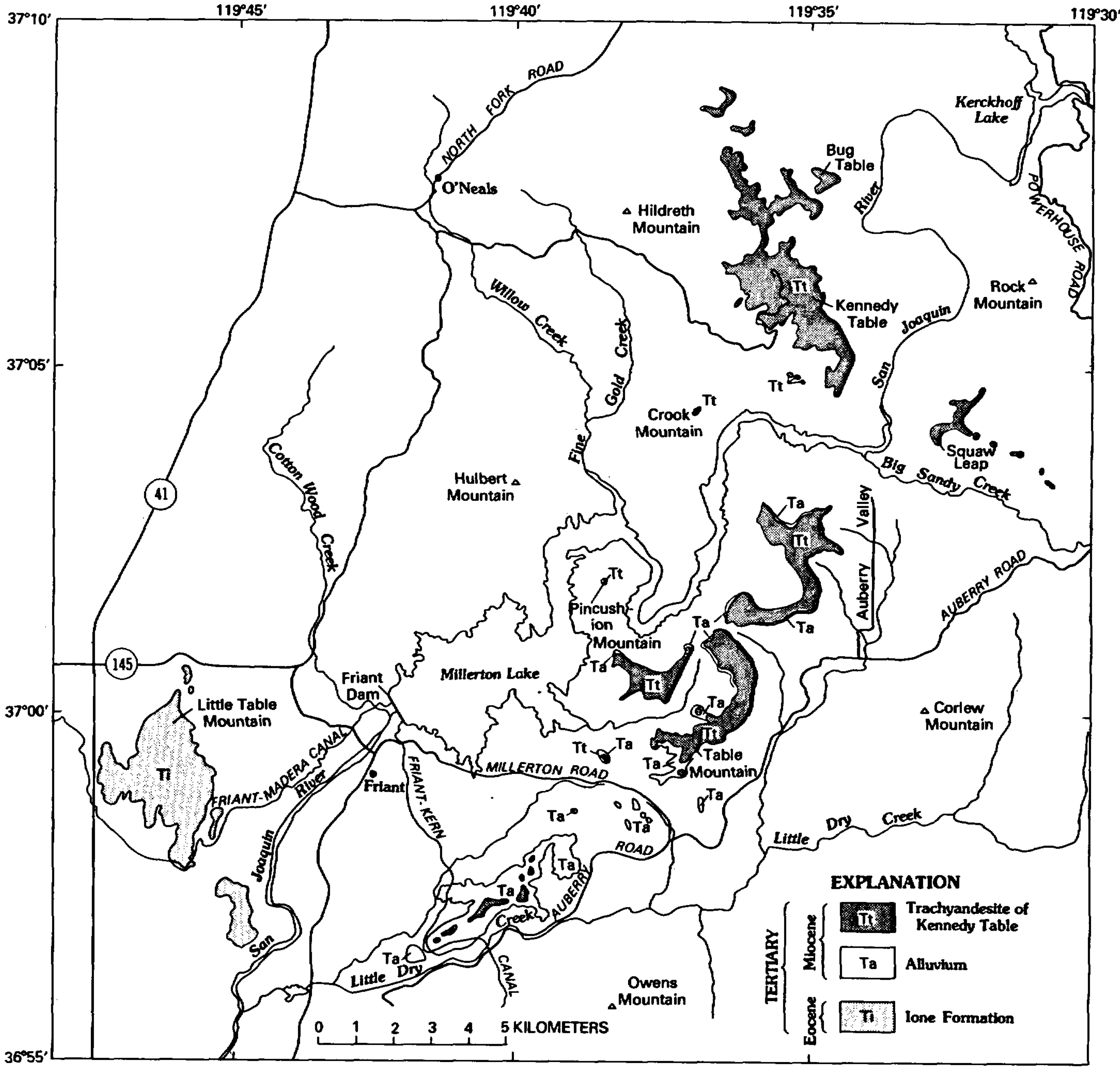

FIGURE 3.—Distribution of Tertiary units in Friant area. Modified from Macdonald (1941), Marchand (1976), and Bateman and Busacca (1980, in press).

probably deposited shortly after the eruption of the pumice at a time when the pumice was a major component of the stream bedload. Potassium-argon ages of 10.9 and 11.3 m.y. have been obtained on biotite and plagioclase from this pumice (table 1, sample A-7), and thus the volcanic source for the pumice is probably somewhat more than 11 m.y. old. There is no source for pumice of this age and composition within the present-day drainage basin of the San Joaquin River, therefore it must have come from east of the present drainage divide.

The only likely source of pumice of this general age and composition known east of the drainage divide is a welded tuff that occurs discontinuously over an area of about 400 km^2 east of Mono Lake (Gilbert and others, 1968). An analysis of a sample of this welded tuff (table 2, sample GM-41) collected from the northwest corner of the Glass Mountain quadrangle (Krauskopf and Bateman, 1977) compares very favorably with that of pumice pebble, especially when recalculated water free (table 2, sample A-7). The water-free recalculation takes into account the high water content of the pumice pebble, which has probably been in a ground-water saturated environment for a least several million years, as it was when collected.

For the unnamed welded tuff east of Mono Lake, Gilbert, Christensen, Al-Rawi, and Lajoie (1968) presented 12 K-Ar age determinations ranging from 11.4 to 12.2 m.y. (fig. 4). Multiple ash-flow units are present and mineralogy varies, so that at least some of the age spread may represent real age differences. The closest other tuff of similar composition in the region, which is exposed north of Mono Lake, has been correlated with the Eureka Valley Tuff, for which more than 10 ages of 9.0-10.3 m.y. have been reported (recalculated from Noble and others, 1974). This tuff appears to be significantly younger than the unnamed tuff and the alluvial pumice, and it was erupted from the Little Walker caldera, east of Sonora Pass (Noble and others, 1974), which is less likely to have contributed significant alluvial material to the San Joaquin River drainage. Furthermore, the alluvial pumice north of Little Dry Creek was buried by the 10-m.y. old trachyandesite of Kennedy Table before the eruption of most of the Eureka Valley Tuff (see later section). As the ages determined on plagioclase and biotite from the pumice pebble are discordant, argon loss is suggested, and the older age (11.3 m.y.) should be taken as a minimum. The actual age perhaps is closer to that determined for the unnamed welded tuff.

In summary, a source for the late Miocene alluvial pumice exposed beneath the complex of table mountains near Friant has not been positively identified, but it must have come from east of the present Sierran drainage divide, and the welded tuff east of Mono Lake appears to be the most likely source. In addition, the abundant pumice and associated fine silt in the alluvial deposits suggest that the original stream gradient at the depositional site was low and that the site was near the margin of the late Miocene Central Valley. The coarser gravel also present would represent flood-stage deposits.

TRACHYANDESITE OF KENNEDY TABLE

COMPOSITION AND AGE

The trachyandesite of Kennedy Table was originally described as an olivine basalt (Macdonald, 1941), and subsequent references have followed this designation. Unfortunately, Macdonald's description was apparently the basis for a subsequent miscorrelation of the lava flow with an olivine-basalt plug at Sugarloaf Hill in Jose Basin, whose location is approximately on the upstream projection of the flow (Dalrymple, 1963). Macdonald (1941) mapped that part of the trachyandesite within the Clovis 15' quadrangle, and Bateman and Busacca (1980, in press) mapped that part within the Millerton Lake 15' quadrangle.

The trachyandesite is a dark-gray, finely porphyritic rock with intersertal texture. The dominant phenocrysts are 2- to 5-mm plagioclase laths with average composition about An_{65}. Microphenocrysts are of clinopyroxene and minor olivine. The groundmass includes plagioclase, clinopyroxene, opaque minerals, and dark-brown glass with dusty inclusions. Stained slabs show that potassium is confined to the matrix, probably chiefly in the glass.

The Kennedy Table lava flow is designated a trachyandesite on the basis of its chemical composition (table 2) using the classification of Rittmann (1952). Although there are other bodies of trachyandesite in the central Sierra Nevada, few have as high a silica content as the Kennedy Table flow, and only two other bodies are known in the upper San Joaquin drainage basin. One body occurs east of the Devils Postpile, but it is of Pleistocene age (Huber and Rinehart, 1967; Huber, 1977). The second occurrence is an intrusive volcanic neck near the community of Big Creek (Bateman and Lockwood, 1976). However, the latter volcanic rock differs significantly from the trachyandesite of Kennedy Table in the content of all other major oxides as well as in mineralogy, notably a high olivine content. Thus there are no known volcanic flow remnants or necks of composition and age similar to the trachyandesite of Kennedy Table upslope from the easternmost table mountain remnants at Bug Table and Squaw Leap.

The olivine-basalt plug in Jose Basin, previously correlated with the trachyandesite of Kennedy Table, has

TABLE 1.—*Potassium-argon age determinations*

[Potassium analyses were done on an I.L. flame photometer using a lithium internal standard. Argon analyses were made using standard techniques of isotope dilution. Ages were calculated using the following constants:

^{40}K decay constants: $\lambda_{\epsilon} = 0.572 \times 10^{-10} yr^{-1}$; $\lambda_{\epsilon}' = 8.78 \times 10^{-13} yr^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10} yr^{-1}$; abundance ratio: $^{40}K/K = 1.167 \times 10^{-4}$ atom percent.

Analysts: TM-10 through SNV-51, Paul Klock, Scott Morgan, B. Myers, and S.E. Sims; 69-M-11, M. Cremer and M.L. Silberman; KA-2755 and 2916, KAr lab., University of California, Berkeley (see sample notes)]

Sample no.	Sample	Material	K_2O (Percent)		$^{40}Ar_{rad}$ (moles/g $\times 10^{-11}$)	$\frac{^{40}Ar_{rad}}{^{40}Ar_{total}}$ (percent)	Calculated age (millions of years)
TM-10	Trachyandesite of Kennedy Table	Plagioclase	0.447 .452	0.4495	0.6161	15	9.5±0.2
		Whole rock	2.92 2.91 2.94 2.91	2.92	4.372	76	10.4±0.2
MLC-52	Trachyandesite of Kennedy Table	Plagioclase	.482 .484	.483	.7057	11	10.1±0.5
		Whole rock	2.88 2.89 2.90 2.88	2.888	4.196	66	10.1±0.2
A-7	Pumice pebble beneath trachyandesite of Kennedy Table	Plagioclase	.897 .883	.890	1.458	54	11.3±0.2
		Biotite	7.71 7.67	7.69	12.15	24	10.9±0.2
SNV-41	Basalt at Rancheria Creek	Whole rock	4.62 4.60 4.62 4.58	4.61	2.123	42	3.20±0.06
SNV-54	Basalt pebble from Kings River fan	Whole rock	2.248 2.248 2.248 2.239	2.246	1.218	75	3.76±0.08
SNV-51	Dacite pebble from Kings River fan	Biotite	8.38 8.34	8.36	4.854	11.5	4.03±0.12
69-M-11	Dacite from Windy Peak	Hornblende	1.289 1.295	1.292	.838	14	4.5±0.4
		Biotite	5.45 5.18	5.32	3.351	13	4.4±0.4
KA-2755	Basalt from Stony Flat	Whole rock	2.14		1.048	35	3.40±0.06
KA-2916	Rhyolite tuff from Alpers Canyon	Sanidine	8.125		16.58	98	11.7±0.1

Sample locations and notes:

TM-10	Millerton Lake 15' quadrangle, Calif., lat 37°06'N, long 199°36'W. (Huber, 1977).
MLC-52	Millerton Lake West 7½' quadrangle, Calif., lat 37°01'N, long 119°38'W. (Huber, 1977).
A-7	Friant 7½' quadrangle, Calif., lat 36°57'N, long 119°41'W. (Huber, 1977).
SNV-41	Tehipite Dome 15' quadrangle, Calif., lat 36°58'N, long 118°55'W.
SNV-54	Piedra 7½' quadrangle, Calif., lat 36°46'N, long 119°30'W.
SNV-51	Piedra 7½' quadrangle, Calif., lat 36°46'N, long 119°30'W.
69-M-11	Marion Peak 15' quadrangle, Calif., lat 36°59'N, long 118°37'W. Collected by J. G. Moore.
KA-2755	Miramonte 7½' quadrangle, Calif., lat 36°43'N, long 119°2'W. Age data courtesy of G. H. Curtis and R. E. Drake, Univ. California, Berkeley (Moore and others, 1979).
KA-2916	Cowtrack Mountain 15' quadrangle, Calif., lat 37°45'N, long 118°56'W. Collected by R. A. Bailey and E. W. Hildreth. Age data courtesy of G. H. Curtis and R. E. Drake, Univ. California, Berkeley (written commun., 1979).

a potassium-argon age of 9.8 m.y. (recalculated from Dalrymple, 1963), and this age has commonly been cited as the age of the trachyandesite flow. The correlation is no longer tenable because of compositional differences. New data indicate an age of approximately 10 m.y. for the trachyandesite (table 1). This new age in itself is not sufficiently different enough from the previously assumed age to compromise seriously the calculations regarding relief and uplift of the Sierra Nevada made by Dalrymple (1963) and Christensen (1966), in spite of the miscorrelation.

Late Cenozoic volcanic rocks in this part of the Sierra fall into two main age groups, 3-4 m.y. and 9-11 m.y.; the younger group is more abundant geographically if not in volume. The trachyandesite of Kennedy Table is the only dated lava flow within the older group. All other dated rocks within this group, of which there are only three in the San Joaquin drainage, are basaltic dikes or volcanic necks; erosion since their emplacement has removed any of their extrusive equivalents. To my knowledge these intrusive rocks and the trachyandesite of Kennedy Table are the southernmost dated rocks of the 9-11-m.y. age group in the Sierra Nevada. Other volcanic rocks in this age group occur from the Tuolumne drainage northward and include a latite, dated at 9.2 m.y. (recalculated from Dalrymple, 1964), which makes up another Table Mountain west of Sonora, also a classic example of topographic inversion.

The eruptive source of the trachyandesite is unknown. The composition of the trachyandesite, unique for this part of the Sierra, rules out as a source any of the known late Cenozoic volcanic necks and plugs in adjacent areas of the San Joaquin drainage (Huber, 1977). Inasmuch as the flow must have originally covered at least 95 km^2 to a depth of as much as 60 m, the source must have been significant. The entire area has now been mapped geologically in considerable detail (1:62,500), and it is unlikely that any major possible source has been overlooked. I believe that the lava flow ponded and covered its own source, which was most likely in the area of Kennedy Table.

TABLE 2.-*Chemical analyses of quartz-latite welded tuff, pumice, and trachyandesite of Kennedy Table*

[GM-41 and A-7: x-ray spectrographic analyses by L. F. Espos; chemical analyses of FeO, H_2O, and CO_2 by M. J. Cremer. MLc-52 and TM-10: X-ray spectrographic analysis by V. G. Mossotti and B. W King; chemical analyses of FeO, H_2O and CO_2 by J. H. Tillman]

Field no.[1] Lab. no.	Welded tuff GM-41 M-131678	Pumice A-7 M-131679	Welded tuff GM-41[2]	Pumice A-7[2]	Trachyandesite MLc-52 M131275	Trachyandesite TM-10 M131272
SiO_2	63.03	61.08	64.13	64.37	57.57	57.12
Al_2O_3	16.80	17.03	17.09	17.95	18.67	18.55
Fe_2O_3	3.08	2.47	3.13	2.60	2.20	2.44
FeO	1.30	1.67	1.32	1.76	3.47	3.24
MgO	1.10	1.09	1.12	1.15	2.36	2.35
CaO	2.46	2.79	2.50	2.94	6.29	6.31
Na_2O	3.93	2.75	4.00	2.90	4.12	4.02
K_2O	5.35	4.85	5.44	5.11	3.27	3.29
H_2O+	.41	4.21	--	--	.66	.79
H_2O-	.36	.99	--	--	.12	.70
TiO_2	.89	.81	.91	.85	1.08	1.06
P_2O_5	.25	.26	.25	.27	.47	.46
MnO	.066	.074	.067	.078	.10	.096
CO	.29	.06	--	--	.03	.03
Total S	027	.011	.027	.012	.005	.006
Total	99.34	100.15	99.98	99.99	100.4	100.44
Cr	39 ppm	36 ppm	--	--	--	--
Ni	14	15	--	--	16 ppm	16 ppm
Ba	1500	1300	--	--	1350	1450
	230	220	--	--	96	101
Sr	400	490	--	--	980	1000
V	40	40	--	--	174	165
Sc	10	11	--	--	16	15
Y	31	44	--	--	23	20

[1]GM-41: Welded tuff from sec. 36, T. 2 N., R. 29 E., Glass Mountain 15' quadrangle, California; A-7: Pumice pebble from steam gravel beneath trachyandesite of Kennedy Table, sec. 21, T. 11 S., R. 21 E., Friant 7½' quadrangle, California; MLc-52: Trachyandesite from sec. 35, T. 10 S., R. 21 E., Millerton Lake 15' quadrangle, California; TM-10: Trachyandesite from sec. 32, T. 9 S., R. 22 E., Millerton Lake 15' quadrangle, California.

[2]Recalculated less H_2O and CO_2.

RECONSTRUCTION OF THE LAVA-FLOW GEOMETRY

Similarities in texture and composition of rocks from each of the table mountain remnants, as well as their difference from other volcanic rocks in the region, indicate that together they make up a volcanic unit. Macdonald (1941) thought that he could recognize two flows on Table Mountain, apparently because of the presence of two zones of columnar jointing, one above the other. However, excellent exposures at the north

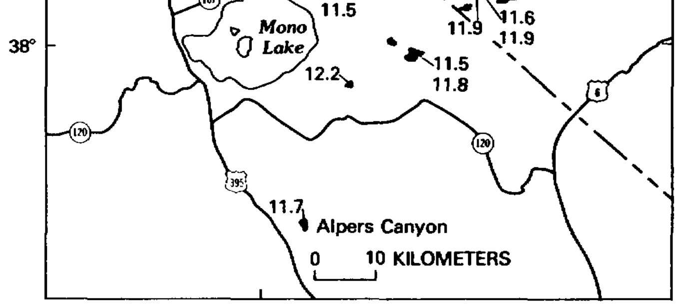

FIGURE 4.—Distribution and radiometric ages of quartz-latite welded tuff in "11-m.y." age group east of Mono Lake (Gilbert and others, 1968). Ages indicated have been recalculated using new decay constants. Alpers Canyon is location of rhyolite welded tuff (table 1).

end of Table Mountain and the south end of the adjacent unnamed table (both north of Macdonald's map area) make it clear that the trachyandesite is a single flow with individual columnar zones related to the upper and lower parts of the flow and grading inward to a blocky jointed center. Bateman and Busacca (1980, in press) also found no evidence for more than one flow either here, at Kennedy Table, or elsewhere in the Millerton Lake 15' quadrangle (P. C. Bateman, oral commun., 1977). Thus the trachyandesite of Kennedy Table is the result of a single eruption, and reconstruction of its original surface and distribution need not be complicated by the possibility of several flows with differing geometry.

The present attitude of a plane that closely approximates the original upper surface of the trachyandesite lava flow can be determined by contouring elevations on the least eroded parts of the table mountain remnants, a procedure that yields surprisingly uniform results. For a flow distance of 15 km the plane has a slope of about 24.3 m/km and a dip azimuth of S. 40° W. (fig. 5). This azimuth closely approximates the average trend of both the present and the late Miocene San Joaquin River; its projection 94 km northeastward from Friant Dam crosses the present drainage divide only 5 km south of Deadman Pass, the site of the late Miocene river crossing of the present divide. Because of this concidence I assume that this azimuth approximates the actual direction of tilt for this segment of the Sierra in the last 10 m.y., and in further reconstructions in this report all data points are projected onto a vertical plane with this azimuth. This azimuth differs by about 10° from one (S. 50° W.) obtained by drawing a line through Friant Dam perpendicular to elevation contours generalized for the Sierra Nevada by Smith (1964). Distances measured along one projection rather than the other would only differ by 1.5 percent, an amount probably of little significance considering the imprecision of the data.

The upper surface of the lava flow appears to define a rather uniform plane as far west as the last control point at Table Mountain. No faulting of the flow surface was recognized. Data points on the base of the flow, however, indicate a decreasing gradient westward from 27.1 m/km in the Bug Table-Squaw Leap area to 22.3 m/km for the exposures north of Little Dry Creek; this gradient change presumably reflects a westward decrease in the gradient of the pre-volcanic San Joaquin River (fig. 5). The stream profile represented by the base of the lava flow is a projection rather than a true longitudinal profile that follows the stream course, and the gradients determined from it are greater than actual ones. In an alluviated area, such a projected gradient might best be thought of as the gradient of the river flood plain rather than that of the active channel itself, and thus it represents the broader surface over which the lava flow was spread.

The lower gradient of 22.3 m/km at the west end of the trachyandesite exposures occurs where the prevolcanic alluvium reaches thicknesses greater than 40 m, consists in part of pumice and fine silt, and can reasonably be considered to be part of the flood plain of the late Miocene San Joaquin River where it was probably graded to the newly evolving Central Valley. I assume that the gradient at this locale 10 m.y. ago was about 1 m/km, similar to that of the present San Joaquin River where it is graded to the present Central Valley axis below Friant Dam (Marchand and Allwardt,

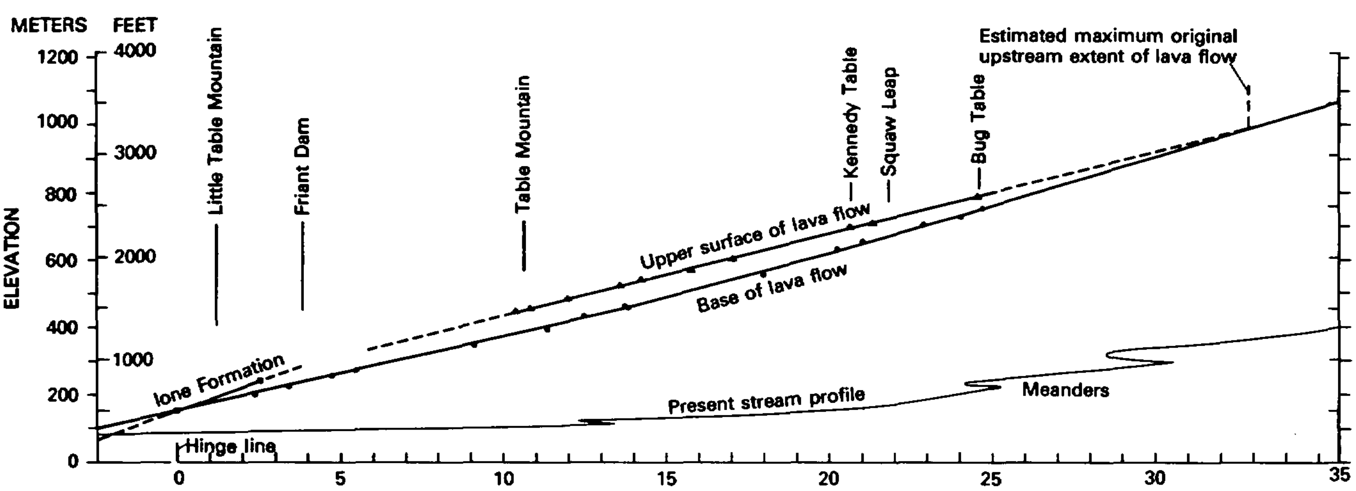

FIGURE 5.—Reconstruction of upper and lower surfaces of trachyandesite of Kennedy Table. Also shown is projection of conglomerate horizon in Ione Formation and present-day profile of San Joaquin River. All data are projected onto a vertical plane striking N. 40° E. Vertical exaggeration about 10 ×.

1980, in press). Control points from the base of the lava flow indicate that this assumed gradient increased to nearly 6 m/km some 23 km to the northeast in the vicinity of Squaw Leap (fig. 5). The change in gradient over this reach is not gradual but takes place rather abruptly near Table Mountain, on either side of which the gradient is relatively uniform. I interpret the Table Mountain area, therefore, as being the approximate point at which the 10-m.y.-old San Joaquin River became graded to the Central Valley area within a reentrant of that valley into low foothills existing at that time. That this abrupt change does not represent a superimposed flexure is demonstrated by the absence of a similar feature on the upper surface of the lava flow. Northeast of the gradient change, the prevolcanic alluvial deposits appear to be thinner, and locally the lava flow rests directly upon weathered granitic bedrock.

AREAL DISTRIBUTION

The trachyandesite of Kennedy Table is interpreted as a single lava flow. Reconstruction of the original extent of the flow requires fitting its remaining erosional remnants into a reasonable physiographic setting.

The arcuate shape of some of the table remnants, particularly Table Mountain and the unnamed table to the northeast, suggests that they might reflect meander patterns of the prevolcanic stream. Most previous workers appear to have adopted this hypothesis although it has not been explicitly stated, except perhaps by Wahrhaftig (1965a, p. 124): "the basalt [sic] apparently flowed down a winding former valley of the San Joaquin River." The overall distribution of the trachyandesite suggests, however, that the lava filled a much broader valley and that the fortuitous shapes of some of the table remnants is a result of erosion controlled instead by a meandering stream superimposed upon the newly erupted lava flow.

The presence of well-developed columnar joints indicates that the lava flow ponded and solidified in place, a circumstance that means the lava filled the preexisting stream valley to a relatively even level and developed a relatively flat upper surface. It also suggests that the stream gradient, at least at the west end of the flow, was low, reinforcing the conclusion drawn from the nature of the underlying alluvial deposits.

Ponding of the lava flow would provide a hydraulic head for driving lava from the eruptive source into the main river valley upstream and into tributaries, such as that at Squaw Leap, until hydrostatic equilibrium was reached. This situation makes possible a reasonable reconstruction of the possible original extent of the lava flow and of its upper surface.

The minimum original extent of the trachyandesite of Kennedy Table can be obtained by simply circumscribing the area of present outcrop, treating several outlying segments as the result of backflow into tributary valleys. Such an area as enclosed by the short-dash line on figure 6 includes about 95 km^2. If one envisions a wider, more mature, pre-volcanic valley, the areal extent of the lava flow could have been considerably greater. The area enclosed by the long-dash line on figure 6 includes the outcrops on Pincushion and Crook Mountains as part of the main-valley flow rather than tributary back-up, and allows for up-valley flow as far as consistent with the eastward projection of the upper flow surface, about to Redinger Dam. This area of about 250 km^2 does not include any westward extension beyond the water gap between the cuesta of Ione Formation south of Little Table Mountain and the ridge of metamorphic rock at Owens Mountain. The hachured line on figure 6 indicates areas higher than the plane of the present flow top and limits the location of the prevolcanic San Joaquin River, although it does not allow for erosion since 10 m.y. ago. The meander pattern of the present San Joaquin River east of Friant suggests that the lava did indeed flow into a fairly broad valley and that the larger original areal extent of the flow is more likely.

SIGNIFICANCE OF RIVER MEANDERS

The meanders of the San Joaquin River where it traverses the Sierra foothills from Redinger Dam to the Friant Dam are of large wavelength and amplitude (fig.6). The meanders also exhibit a complex sinuousity with northeastward downstream components, which exceed 1 km in three places, opposite to the mean slope direction. This pattern indicates that the meanders must have developed their present configuration on a low-gradient surface prior to subsequent uplift and tilting of the river channel, long before the present river gradient was established. The meanders were probably formed shortly after the river flowed out over the newly erupted trachyandesite of Kennedy Table, which provided a new low-gradient surface several kilometers wide within the preexisting late Miocene valley of the San Joaquin River.

The meanders are incised into bedrock for the entire length of the channel eastward from Friant Dam, but it is likely that their geometry was established in alluvial material spread out by the river as it flowed with a reduced gradient over the new surface for much of the length of the lava flow. Drawing on the experimental work of Gardner (1975), Schumm (1977) noted that one way incised meanders can form is by base-level lowering or nearly vertical uplift. In the case of the San Joaquin River, its bed would have been uplifted nearly vertically and instantaneously an amount equal to the thickness of the lava flow, resulting in what would be equivalent to a base-level lowering at the western distal end of the flow. Quoting Schumm (1977, p. 200-201):

> ***a lowering of base level causes headward incision up the meander pattern. Following rejuvenation, a nickpoint will migrate upstream and will follow the existing channel pattern to form incised meanders in the underlying bedrock. However, as headward erosion progresses along a given meander, the downstream limb of the meander encounters bedrock first, and is then locked in position. The upstream limb of the meander, still on alluvium, continues to shift downstream as part of a normal downvalley sweep of the meander pattern, and the meander loop is deformed. By the time the upstream limbs of the meanders became fixed in bedrock, a very deformed meander usually had developed.

This mechanism would explain the "deformed" meanders of the San Joaquin, which look very much like the incised meanders of the Goosenecks of the San Juan River on the Colorado Plateau, illustrated as examples by Schumm. This meander pattern also suggests that the original extent of the lava flow included most of the area occupied by the present meander belt, the larger of the two areas indicated in figure 6.

Lateral migration of the river within the highly resistant lava flow would be difficult, and the meander pattern once established was probably rapidly incised into the trachyandesite and subsequently into the underlying deeply weathered granitic rocks. That the granitic rocks were deeply weathered by post-Eocene time is shown by the abundance of quartz grains and feldspar-derived clay and the absence of granitic pebbles in the Eocene Ione Formation and the relative rar-

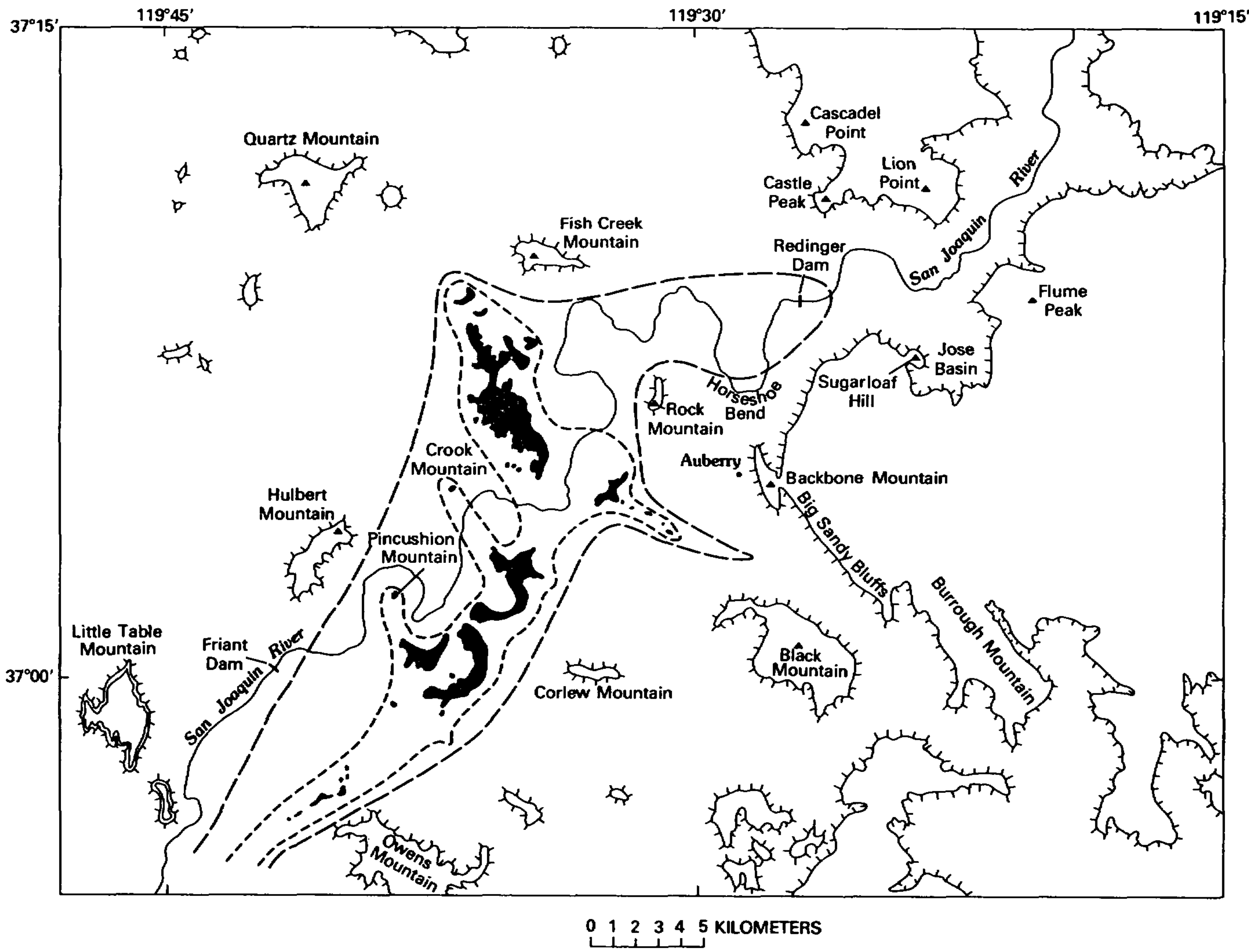

FIGURE 6.—Postulated original extent of trachyandesite of Kennedy Table. Dark areas show present outcrop; short-dash line indicates minimum extent; long-dash line probable extent. Hachured line indicates areas presently above plane defined by top of trachyandesite. Hachured double line indicates cuestas of Ione Formation, the east edges of which are above that plane. Millerton Lake and other reservoirs omitted to emphasize pre-reservoir meander pattern of San Joaquin River.

ity of granitic pebbles in the late Miocene gravels underlying the lava flow. The lava flow itself was eroded chiefly by undercutting and spalling of joint blocks as shown by continued existence of remnant surfaces nearly approximating the original surface of the flow.

With accelerated uplift of the Sierra Nevada, channel downcutting would also have been accelerated. There was, of course, some lateral cutting and meander migration, as shown by local asymmetry of the canyon walls at some meander bends, such as at Horseshoe Bend north of Auberry, but such migration appears to have been insufficient to greatly alter the original meander pattern, and the canyon as a whole has surprisingly symmetrical cross sections for a stream with meanders of such large wavelength.

"Meander length is empirically related to the square root of effective or dominant discharge" (Leopold and others, 1964, p. 296). Other factors remaining constant, discharge in turn is directly proportional to the area of the drainage basin. Between Friant Dam and Redinger Lake, a straight-line distance of about 30 km, meander wavelengths range from 4.2 to 5.6 km, with an average of 4.6 km. For the present San Joaquin drainage basin of 4340 km^2 this is an order of magnitude larger than that to be expected on the basis of data from alluvial channels (Leopold and others, 1964, fig. 7-48). Although the meanders under consideration are in bedrock rather than alluvium, Dury (1977) concluded that "meanders in bedrock, however great the distorting influence of structure, tend to be geometrically similar to alluvial meanders, in every respect except that of being ingrown." Direct comparison between alluvial- and bedrock-channel meanders is probably not without pitfalls, but it appears that the initial meanders developed upon the surface of the newly erupted lava flow were formed by a stream with a larger discharge and drainage basin than the present stream, which would be the case if the stream at that time headed east of the present Sierran drainage divide. In summary, the meander wavelength suggests that the stream discharge was higher than at present and their sinuosity suggests that the stream gradient was low.

UPLIFT AND TILTING OF THE CENTRAL SIERRA NEVADA

AMOUNT OF UPLIFT AT SIERRAN DIVIDE

Previous estimates of the amount of uplift of the Sierran divide mostly have been based upon the reconstruction of former stream profiles. This method has been useful; indeed, stream profiles will be used to help decipher uplift history in this report. However, I have used an additional method of estimating uplift that involves establishing a base-level plane independent of variable stream gradients within the interior of the range. Much of the foregoing discussion regarding the geometry and physiographic setting of the trachyandesite and the underlying alluvial deposits has been a preamble to the use of such a method.

POST-LATE MIOCENE UPLIFT

Several lines of evidence have been developed—the fine-grained and locally pumiceous nature of some of the alluvial deposits, the planar and broad lateral extent of the trachyandesite lava flow, and the post-volcanic stream-meander pattern—that collectively suggest that the late Miocene San Joaquin River had a very low gradient near the site of the westernmost exposures of the pre-volcanic alluvial deposits north of Little Dry Creek. I assume that this site was near the margin of the Central Valley 10 m.y. ago, as it is today, and that the river was essentially graded to the local base level of that valley, with a gradient possibly as low as 1 m/km.

If the original late Miocene "base-level" gradient is taken as 1 m/km and the present gradient of the contact between the alluvium and the overlying lava flow is 22.3 m/km at the same site, then the base-level plane has been rotated from its near-horizontal position through an angle that would increase its slope by 21.3 m/km (about 1.2°) (fig. 7). For purposes of calculation, the hinge line for the rotation is taken as the point at which the base-level plane intersects a plane defined by the upper conglomerate horizon of the Ione Formation on Little Table Mountain about 1.5 km west of the westernmost outcrop of the late Miocene alluvium. Such a rotation, based upon tilting of the Sierra *as a rigid block*, results in an uplift of the site of the present drainage divide at Deadman Pass, some 100 km from the hinge line, of about 2,150 m, regardless of what the stream profile might have been like in the interior part of the range.

Subtracting uplift of 2,150 m from the present elevation of Deadman Pass (3,040 m) yields an elevation about 10 m.y. ago of about 900 m at the present drain-

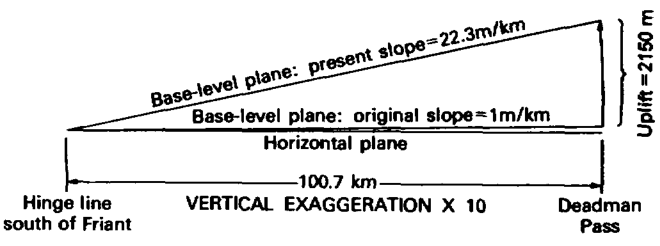

FIGURE 7.—Uplift of Sierran drainage divide at Deadman Pass calculated by rotation of late Miocene base-level plane, assuming tilting as a rigid block.

age divide. Mount Ritter, some 6 km to the west and the highest peak in the area, would have had an elevation of about 2,000 m, not allowing for post-10-m.y. erosion.

This calculated amount of uplift is considered to be a maximum for at least two reasons. Any increase allowed for the original gradient of the 10-m.y.-old base-level plane would lessen the amount of uplift necessary to rotate that plane into its present position (by about 100 m for each m/km increase in original gradient). Also, the concept of tilting the Sierra as a rigid block is, of course, only a first approximation. Any tendency for broad doming rather than simple tilt in the region of the Sierra crest would result in a convex-upward warping of the base-level plane in which the rotation measured at the hinge line would decrease eastward, resulting in less uplift at the crest than that calculated. Subtracting a lesser amount of uplift from the present elevation would mean the Deadman Pass region was at a correspondingly higher elevation 10 m.y. ago.

The amount of uplift calculated above does not depend upon reconstruction of the longitudinal profile of the 10-m.y.-old San Joaquin River within the interior of the range. However, such a reconstruction provides additional constraints on the amount of uplift and is particularly instructive because reconstruction of the trachyandesite lava-flow geometry in this study provides more realistic estimates of both original and present slopes of at least parts of the 10-m.y.-old profile than those used by Christensen (1966).

I started with the assumption discussed above that the gradient of the river 10 m.y. ago was about 1 m/km where it entered the Central Valley. Data from the base of the trachyandesite lava flow indicate that the gradient increased to about 6 m/km some 24 km to the east in the vicinity of Squaw Leap (fig. 5); this is the easternmost empirically determined value. Longitudinal stream profiles are normally concave upward and increase in gradient headward, except for reversals caused by anomalous streambed conditions or structural factors, and I would expect the San Joaquin River to do likewise, at least within the Sierran structural block. At a minimum, then, the profile would reach an elevation of 650 m at the site of Deadman Pass if projected eastward from Squaw Leap with no increase in gradient (fig. 8). When rotated to reflect the present gradient of the profile at Squaw Leap, the profile elevation at Deadman Pass, 2150 m higher, would be at 2800 m. This projection places the profile lower than the actual surface within which the inner canyon was incised in response to later uplift of the range and indicates that the 10-m.y.-old stream profile must have increased in gradient eastward from Squaw Leap.

The 10-m.y.-old profile should probably have a present elevation closer to 3,050 m at Deadman Pass if the channel south of Deadman Pass, filled with 3.2-m.y.-old basalt, mostly represents incision below the 10-m.y.-old profile (see fig. 14). I think that condition is reasonable because although uplift began before 10 m.y. ago, canyon incision would be accelerated by the increased rate of uplift after 10 m.y. ago. To reach 3,050 m would require the stream profile to climb an additional 225 m east of Squaw Leap beyond the level reached by a projection assuming no increase in gradient. This would amount to an increase in average gradient east of Squaw Leap of 2.9 m/km for an average original gradient of 8.6 m/km between Squaw Leap and Deadman Pass. The actual stream gradients measured along the stream channel would be appreciably less than these projected values that ignore additional stream length due to meanders. The average projected gradient for the entire reach between Friant and Deadman Pass would be about 7.4 m/km as compared with 14.6 m/km for the 3.2-m.y.-old profile and 22.9 m/km for the profile of the present San Joaquin River (see fig. 13).

I do not have a fully satisfactory method of testing the reasonableness of this reconstructed profile for 10 m.y. ago, particularly inasmuch as it totally ignores that part of the stream profile east of Deadman Pass, which, as I will suggest in a later section, may well have had a lower gradient. However, it does fit the general pre-uplift physiographic setting, in which case a post-10-m.y. uplift of about 2150 m (7050 ft) appears to be compatible with that setting, and I shall use this figure for further calculations.

If my interpretation of the present elevation of the 10-m.y.-old stream profile as being at about 3050 m at Deadman Pass is reasonable, it puts constraints on the

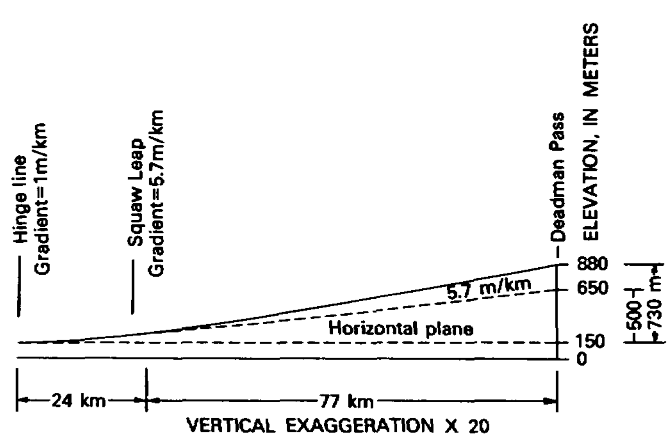

FIGURE 8.— Reconstruction of 10-m.y.-old profile of upper San Joaquin River projected to vertical plane striking N. 40° E. Elevation drop of 730 m between Deadman Pass and hinge line allows for increase in gradient east from Squaw Leap whereas 500-m drop does not.

model of tilting. The present position of the profile is the sum of pre-10-m.y. elevation and post-10-m.y. uplift. Uplift involving warping of the profile (and consequently the base-level plane) would require the profile to reach its present elevation at Deadman Pass from a greater original height, that is, with less uplift than that calculated for the rigid-block model (fig. 9). However, the higher original elevation for the profile at Deadman Pass would require a higher average stream gradient westward from there to the Central Valley 10 m.y. ago. For example, if the amount of post-10-m.y. uplift was two-thirds of that calculated for the rigid-block model, both the elevation at Deadman Pass and the average stream gradient 10 m.y. ago would be nearly double that calculated herein. In fact the gradient would be equal to that calculated for the 3.2-m.y.-old stream profile, and the amount of uplift would be only slightly greater than the amount of pre-10-m.y. uplift to be calculated in the next section. This example is undoubtedly too extreme and does not negate the possibility of some warping of the tilted block and consequently some reduction in the amount of uplift required. I believe such reduction, however, to be small relative to the total uplift calculated and will ignore it in further calculations realizing that my uplift calculations probably represent maximum values requiring some undetermined correction factor.

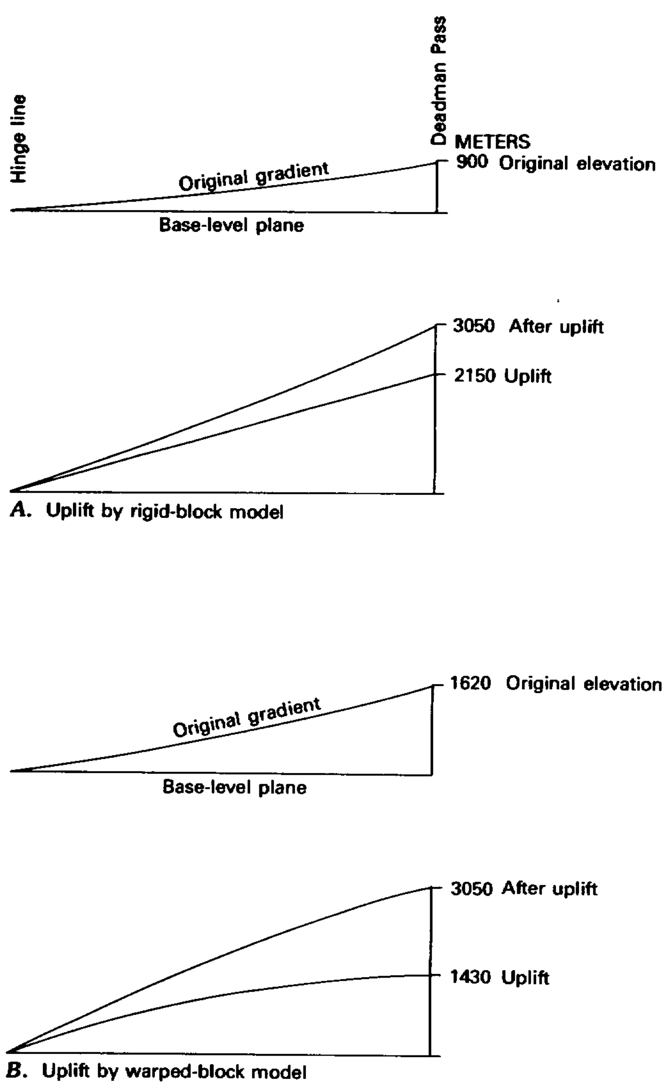

FIGURE 9.—Differences in uplift and tilt of central Sierra Nevada. Elevation of 10-m.y.-old stream profile is assumed to be 3050 m at Deadman Pass. Vertical scale and curvatures greatly exaggerated to emphasize differences. *A*, Rigid-block model. *B*, Warped-block model. Uplift for warped-block model arbitrarily reduced by one-third from that calculated for rigid-block model.

The 10-m.y.-old stream profile for the San Joaquin River as reconstructed in this report differs from that of Christensen (1966), particularly in its upper reach, a difference that highlights the problems in estimating uplift from profiles reconstructed without some control at the upper end. The westernmost segments of the two reconstructions have similar *average* gradients, and both profiles intersect the basalt knob at Sugarloaf Hill in Jose Basin, fortuitously in mine and by design in his, as he accepted Dalrymple's (1963) and Wahrhaftig's (1965a; 1965b) correlation of that basalt with the trachyandesite of Kennedy Table. For the segment east of Jose Basin, however, my reconstructed profile continues to increase in gradient while Christensen's decreases abruptly from an average of 26.5 m/km to an average 17 m/km, the latter gradient adopted from Matthes' (1960) "Pliocene" profile, even though he recognized that Matthes' profile in the western reach does not coincide with the 10-m.y.-old profile being reconstructed ("Pliocene" of Matthes would probably fall within the late Miocene of current usage). Christensen (1966, p. 169) then concluded that this change in gradient "may represent a warp along the western margin of the range, a departure from the rigid tilting to the north," a situation for which there is considerable evidence further south.

Christensen's gradient of 17 m/km is unrealistically low, however, as it produces a profile that intersects bedrock in the *present* streambed about 11 km (projected distance) west of Deadman Pass, an impossible situation if the 10-m.y.-old San Joaquin River headed east of Deadman Pass, as I believe I have adequately demonstrated. Any realistic profile reconstruction, therefore, must not only clear pre-volcanic bedrock at Deadman Pass, but also must allow for channel downcutting between 10 and 3+ m.y. ago, as I have attempted to show in my reconstruction. I do not imply that there was no warping of the 10-m.y.-old profile during uplift of the range, even though none is shown in my reconstruction, but only that the elevation of any reconstructed profile must be constrained by physiographic considerations, past and present, in the Deadman Pass area. As a matter of fact, a flattening of the profile in the Deadman Pass area would simplify relations between the Sierran block and the area to the east, as discussed elsewhere in this report, but I have not been able to devise a method to determine how much warping might be reasonable.

Christensen's use of an overly low gradient for the present position of the 10-m.y.-old profile would naturally result in a low uplift estimate by his method, but his concurrent use of unrealistically low initial gradients partially compensates. His minimum estimated initial gradient of an average 1.06 m/km for the entire reach from Friant to the crest (Christensen, 1966, table 1) is virtually identical to that used for the base-level plane in this study. Because the average gradient of his uplifted profile is nearly as great as the amount of base-level tilt in this study, his *maximum* uplift estimate of 2070 m (6800 ft) approaches that calculated herein.

PRE-LATE MIOCENE UPLIFT

Several lines of evidence point to considerable uplift of the central Sierra Nevada prior to 10 m.y. ago. The reconstructed San Joaquin River profile of 10 m.y. ago drops roughly 750 m in the 100 km between Deadman Pass and the Central Valley. As local relief was more than 1000 m within the proto-Sierra Nevada being traversed, appreciable incision of the stream is indicated by that time (see fig. 13). Similar relief characterizes the terrane over which the 9-m.y.-old Eureka Valley Tuff was deposited in the Tuolumne River drainage basin to the north (N. K. Huber, mapping in progress, 1979). It is difficult to imagine such a gradient and incision for a reach of stream graded to a local base level unless some sort of stream rejuvenation, such as uplift, had taken place. The fact that the Eocene Ione Formation west of Friant has a greater present dip than the trachyandesite lava flow also suggests appreciable uplift of the Sierra before 10 m.y. ago and provides a means of estimating the amount of that uplift.

Calculations in the previous section result in estimates of perhaps 2150 m of uplift at Deadman Pass on the Sierran divide since about 10 m.y. ago, utilizing a base-level plane derived from the trachyandesite of Kennedy Table and the underlying alluvial deposits. The westernmost exposure of these deposits is on strike with exposures of the Ione Formation of Eocene age. The Ione Formation, which forms the cuesta of Little Table Mountain(fig. 3), is armored by a resistant conglomerate horizon, and reconstruction from remnants of that horizon yields a plane dipping 35 m/km in a S. 40° W. direction, the same direction determined for the dip of the trachyandesite. This plane has a gradient 12.7 m/km greater than that of the late Miocene deposits and indicates a significant amount of tilting at the margin of the Central Valley between deposition of the two formations. The absolute age of the Ione Formation has not been established, but if a correlation with the Domengine Formation and the Ulatisian foraminifer stage is accepted (Repenning, 1960), then its age is probably about 50 m.y. (Brabb and others, 1977, fig. 2). The Ione Formation thus serves as a stratigraphic plane about five times as old as the trachyandesite. This age is not critical to determining the amount of pre-10-m.y. uplift, only the timing and rate.

The stratigraphic plane defined by the Ione Formation can only be reconstructed over a dip-distance of a little more than 3 km. Thus projection of this plane eastward into the Sierra is considerably more speculative than that for the trachyandesite. The difference in dip for the two planes suggests an uplift at Deadman Pass of about 1300 m during the 40 m.y. or so between deposition of the Ione Formation and eruption of the trachyandesite, again on the basis of tilting as a rigid block. The initial dip for the Ione Formation at this locality cannot easily be determined, and because of other uncertainties, this amount of uplift should be viewed as no more than a gross estimate. This amount probably should also be viewed as a maximum value inasmuch as there is some evidence for flexure along the east margin of the Central Valley farther north (D. E. Marchand, written commun., 1979). Therefore, dips on the Ione Formation near Friant and elsewhere should be viewed in that context, and projections of such dips toward the range crest could be considerably in error. Nevertheless, the data suggest that considerable uplift, perhaps an amount as much as half of the post-10-m.y. uplift, took place before 10 m.y. ago. The total post-Ione uplift would then be about 3450 m.

Marchand and Allwardt (1980, in press), in summarizing the Tertiary stratigraphy for the northeastern San Joaquin Valley, noted that the Ione, Valley Springs, Mehrten, and Laguna Formations dip southwest at successively lower gradients, and they concluded that this represents deformation closely related to tectonic events in the Sierra Nevada. The age of the trachyandesite of Kennedy Table is similar to that of the Table Mountain Latite near Sonora, about 9.2 m.y. (recalculated from Dalrymple, 1964); the latite is within the Mehrten Formation as here used. Thus, gradient data for the Valley Springs Formation, at about 20 to 23 m.y., would be useful. Unfortunately, reliable data do not seem to be readily available.

Marchand and Allwardt (1980, in press, table 1) give "gradients" of 17.7 m/km and 18.9 m/km for the Valley Springs and Mehrten Formations along the Merced River some 50 km northwest of Friant. The Mehrten slope is from Arkley (1962), who does not state how it was obtained, and the Valley Springs figure is for the reconstructed eroded surface of the Valley Springs Formation rather than on a stratigraphic horizon that might help reconstruct primary dip (D. E. Marchand, oral commun., 1979). If the present slope of the Valley Springs and Mehrten Formations even approached being similar, that fact would suggest that the Sierra Nevada was tectonically relatively quiet between 20 and 10 m.y. ago. Grant, McCleary, and Blum (1977, table 1) present data from the Mokelumne drainage, an additional 50 km farther northwest, indicating similar dips for the Valley Springs and Mehrten Formations in that locality, but as they do not indicate how the data were obtained or what parts of the formations are represented, the significance of their data is uncertain. In summary, although the statigraphic data are equivocal, they suggest not only that pre-late Miocene uplift of the Sierra Nevada was significant, but that the uplift resulting in the present elevation of the range began before 10 m.y. ago.

TIMING OF POST-LATE MIOCENE UPLIFT

The preceding sections developed the thesis that most of the present elevation of the central Sierra Nevada resulted from uplift that occurred later than 10 m.y. ago, although it began earlier. Dalrymple (1964) was the first to propose that a major part of the incision of the inner canyon of the San Joaquin River took place before about 3.6 m.y. ago; he based his conclusion on several K-Ar age determinations on basalt that cascaded into the canyon. Inasmuch as the canyon grew in response to accelerated uplift of the range in the late Cenozoic, it is clear that by 3.6 m.y. ago uplift had not only begun but was of sufficient magnitude to permit cutting the canyon to more than half of its present depth below the river's profile of 10 m.y. ago (see figs. 13 and 14). It should be kept in mind that present basalt outcrops are erosional remnants on the canyon walls and only provide a minimum figure for the depth of the canyon at the time of their eruption. Two of the basalts shown within the canyon and on the upland surface in figure 14 have been dated: 3.6 m.y. near Pine Flat and 3.4 m.y. near Snake Meadow (Dalrymple, 1964). All of these basalt flows (excluding that at Deadman Pass, discussed later) are assumed to be of approximately the same age; except for late Pleistocene basalt, such as at the Devils Postpile, all seven basalt flows that have been dated in the upper San Joaquin drainage basin have ages from 3.4-3.9 m.y., all have similar physiographic settings, and all probably are part of a discrete eruptive cycle.

Some additional control on the timing of uplift and tilting can be obtained from Pliocene gravel deposits in the Central Valley that occur both north and south of the San Joaquin River. The China Hat Gravel Member, a remnant of an alluvial fan deposit south of the Merced River, is considered by Marchand and Allwardt (1980, in press) to be "the uppermost member of the upper unit of the Laguna Formation." They believe the Laguna Formation to be of late Pliocene age from stratigraphic and paleontological data. It unconformably overlies the Mehrten Formation, is truncated by the North Merced pediment of latest Pliocene or earliest Pleistocene age, and contains a vertebrate fauna of latest Hemphillian age, possibly transitional into Blancan (Marchand and Allwardt, 1980, in press). South of the Merced River, the China Hat Gravel Member slopes southwest at about 10.5 m/km, half the gradient of the Mehrten at 18.9 m/km (Marchand and Allwardt, 1980, in press, table 1); this slope suggests appreciable tilting between deposition of the two units.

On the north side of the Kings River, where it enters the Central Valley, there are several erosional remnants that Macdonald (1941) mapped as a "high terrace" deposit. The deposit originally covered a broad area there, and perhaps it is more properly an alluvial fan than a terrace. Segments of the present surface of the largest remnant, on Kirkman Hill north of Centerville, appear to approximate the plane of the original surface, which slopes westward at about 13.2 m/km. This slope is only slightly greater than that for the China Hat Gravel Member south of the Merced River, and the two deposits may be correlative in age. The coarseness of the two gravels in comparison to all younger deposits is another basis for possible correlation (D. E. Marchand, written commun., 1979).

The surface of the fan north of the Kings River is mantled with abundant basalt and dacite pebbles and cobbles although they appear to be absent from stratigraphically lower parts of the deposit. In a count of all pebbles and cobbles 3 cm and larger on a surface of 10 m^2, more than 50 percent were of Cenozoic volcanic rock; basalt was somewhat more abundant than dacite and andesite combined. This result shows that during the final period of active deposition on the fan, before its tilting and incision, late Cenozoic volcanic rocks made up a large proportion of the stream bedload, presumably during and shortly after the eruption of these rocks somewhat more than 3 m.y. ago.

A dacite cobble collected from the surface of the fan has been dated at 4.0 m.y. (table 1) so the uppermost depositional surface of the fan could be no older than that. The dacite cobble is petrologically similar to dacite exposed at Windy Peak on the Middle Fork Kings River in the Marion Peak quadrangle (Moore, 1978), for which ages of 4.4 and 4.5 m.y. have been obtained (table 1). A slightly younger limit for the age of the active fan is derived from a basalt cobble collected from the fan surface and dated at 3.8 m.y. (table 1).

The only other age determinations for volcanic rocks in the Kings River drainage basin of which I am aware are 3.4 m.y. for an andesite at Stony Flat on Mill Creek (table 1; Moore and others, 1979) and 3.2 m.y. for a basalt at Rancheria Creek, tributary to the North Fork Kings River (table 1). The latter area is probably the site of what was the largest volume of 3- to 4-m.y.-old volcanic rocks in the Kings River drainage basin and could have been the major source area for most of the basalt cobbles on the fan at Kirkman Hill. If so, these dates provide a maximum age of about 3.2 m.y. for the active Kirkman Hill fan.

Arkley (1962) estimated an original gradient for the China Hat Gravel Member of 3.8 m/km. If a similar original gradient is assumed for the fan north of the Kings River, then this fan has been tilted by about 9.4 m/km to reach its present slope, presumably during the past 3 m.y. or so. Assuming that a similar amount of tilt during the same interval took place on the San Joaquin River some 27 km to the northwest, the calculated resultant uplift at Deadman Pass is about 950 m, or about 45 percent of the total post-10-m.y. uplift of 2150 m I have inferred above.

Along the Merced River, gradients of reconstructed depositional or erosional surfaces associated with late Tertiary and Quaternary deposits consistently decrease with decreasing age; such gradients suggest continuing uplift and tilt up to the present time (Marchand, 1977, p. 39 and table A; Marchand and Allwardt, 1980, in press, table 1).

Along the upper San Joaquin River, the 0.6-m.y.-old Friant Pumice Member of the Turlock Lake Formation provides the only radiometrically dated Pleistocene unit of stratigraphic usefulness (Janda, 1965, 1966). Reconstruction from scattered outcrops yields a "minimum average slope" of 2.75 m/km for this unit (Janda, 1966, p. 237) at the present time in the Friant area. The fine ash appears to have been deposited on a flood plain with a low gradient; for purposes of calculation I am assuming that the original gradient did not exceed 1 m/km, as I assumed for the 11-m.y.-old pumice deposit. This results in a post-depositional tilt of 1.75 m/km, which translates into 175 m of uplift at Deadman Pass in the last 600,000 years. This amount of uplift, which is roughly one-fifth of the 950 m of post-3-m.y. uplift calculated above, would have taken place during about one-fifth of the elapsed time and thus supports the concept of continued uplift at a fairly uniform rate.

SUMMARY OF UPLIFT HISTORY

The meager geologic control for reconstruction of Sierran uplift makes estimation of uplift amounts difficult, and calculation of uplift rates is of uncertain validity. Some of the conclusions derived in this study are based on assumptions that are difficult or impossible to verify, and I hope that I have qualified them accordingly. Though I have not attempted to place error estimates on my uplift data, I suggest that they probably represent maximum values that will decrease with departure from the rigid-block tilt model.

Slemmons, Van Wormer, Bell, and Silberman (1979) recently presented uplift estimates for the Carson Pass-Sonora Pass area of the north-central Sierra Nevada, centered about 55 km north of Deadman Pass. Although most of their estimates include a range of values, their data are difficult to evaluate as there is no indication as to how they were obtained or what the range signifies. In an earlier study Slemmons (1953) estimated various amounts of tilt determined largely from reconstructed stream profiles correlated with volcanic episodes, and these estimates probably form the basis for the more recent uplift estimates. Uplift estimates based on tilt depend, of course, on distance from an assumed hinge line, and thus they will vary from place to place within the mountain range. The estimates of uplift for the Carson Pass-Sonora Pass area, therefore, may not represent sequential events at a given site, a necessary requirement if sequential uplift rates are to be determined. Nevertheless, it is instructive to compare their data with that for Deadman Pass in an attempt to develop an overall uplift history.

Uplift estimates plotted against time produce strikingly similar curves for the Carson Pass-Sonora Pass area and the Deadman Pass area, differing chiefly in magnitude and rate of uplift (figs. 10 and 11). These "smooth" uplift curves should probably have perturbations in uplift that are reflected by various erosion stages or surfaces within the Sierra and pulses of sedimentation in the Central Valley, but these perturbations cannot be discerned with the available data. The curves indicate that uplift of the central Sierra Nevada was well underway 10 m.y. ago, having begun perhaps more than 25 m.y. ago. Uplift began slowly and has increased in rate more or less continuously to the present, although the sparseness of data may conceal fluctuations. Data from the Carson Pass-Sonora Pass area suggest an increase in average rate of uplift from about 0.02 mm/yr, 25 m.y. ago, to about 0.16 mm/yr at present. The data for the Deadman Pass area suggest that the average rate of uplift in that area underwent a greater increase from about 0.03 mm/yr, 25 m.y. ago, to about 0.35 mm/yr at present. The total amount of uplift increases from an estimated 2000 m in the Carson Pass-Sonora Pass region to perhaps as much as 3450 m in the Deadman Pass area. Uplift undoubtedly was even greater farther south in the Mount Whitney area, but late Cenozoic stratigraphic markers are not available for similar calculations in that area.

If the uplift curves in figures 10 and 11 have even qualitative validity, they indicate that the Sierra Nevada is still rising, and at a possibly increasing rate.

DIFFERENTIAL UPLIFT AND THE EASTERN ESCARPMENT

Matthes (1930b, 1960) was the first to conclude from his study of stream profiles and upland erosion surfaces that during the late Tertiary a major fork (perhaps the main channel) of the San Joaquin River had its source east of the present drainage divide, and he believed that it was beheaded by the formation of a fault escarpment on the east side of that divide. Pumice pebbles and cobbles that must have been derived from east of the present Sierran divide occur in 10-m.y.-old alluvial deposits at the margin of the Central Valley and confirm that the San Joaquin River flowed across the site of the present divide at that time. Erwin (1934) apparently accepted the concept of a throughgoing drainage in this locality, and he suggested that the basalt exposed locally on the San Joaquin Mountain ridge may have flowed down this ancient drainage and was later uplifted along the fault-bounded range front. Subsequent mapping has delineated the probable location of such a basalt-filled channel just south of Deadman Pass (Huber and Rinehart, 1965; 1967). This 3.2-m.y.-old basalt, slightly younger quartz latite, the 0.7-m.y.-old Bishop Tuff and related rocks, the rhyolite of the Mono Craters, and extensive alluvial and lacustrine deposits in the Mono Lake basin now cover much of the area that might have drained into the older San Joaquin River. If this drainage area found a new outlet, it most likely drained southward into Owens Valley.

The Long Valley and Mono Valley structural basins now interrupt the continuity of pre-existing volcanic strata, and the area between these basins and that to the east is broken by numerous faults and warps (Gilbert, 1941; Gilbert and others, 1968; Krauskopf and Bateman, 1977; Bailey and Koeppen, 1977) that document considerable deformation of the volcanic rocks. In spite of this deformation, segments of a surface 11 m.y. old or older can be reconstructed from scattered outcrops of welded tuff (fig. 4). The base of the westernmost outcrops of tuff of this age mapped east of Mono Lake lies at about 2135 to 2195 m (Gilbert and others, 1968). Ten kilometers to the south, similar tuff lies at about 2135 m in the northwest corner of the Glass Mountain quadrangle (Krauskopf and Bateman, 1977). Another 30 km to the southwest, Bailey and Koeppen (1977) mapped a small area of welded tuff (welded tuff of Alpers Canyon) at about 2195 m elevation on the north side of Long Valley caldera; this tuff was recently dated at 11 m.y. (table 1). The latter tuff is rhyolite whereas the tuffs to the northeast are quartz latite; thus these tuffs are not all parts of a single eruptive sheet. Nevertheless, the tuffs collectively define parts of a surface of moderate relief that existed about 11 m.y. ago, and although this surface has since been badly faulted and disrupted, the area east of this part of the Sierran escarpment appears to have acted independently of the Sierran block and in particular has not been a part of the westward tilting of that block.

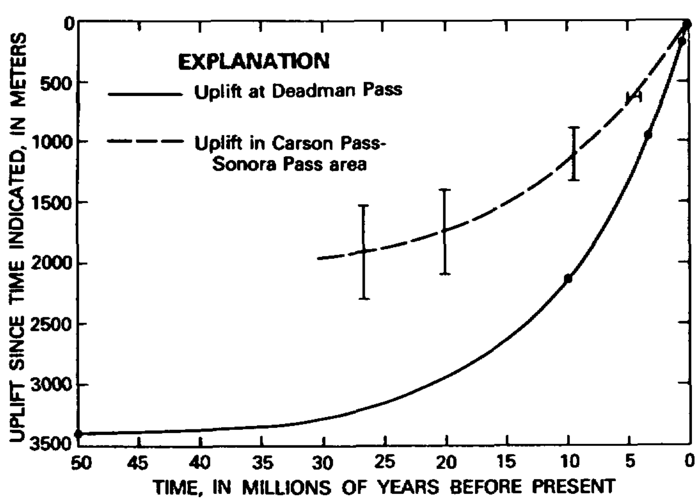

FIGURE 10.—Uplift of crest of central Sierra Nevada at Deadman Pass and in Carson Pass-Sonora Pass area. Data for Carson Pass-Sonora Pass area were presented as a range in uplift or time (Slemmons and other, 1979); dashed line represents an arbitrary average.

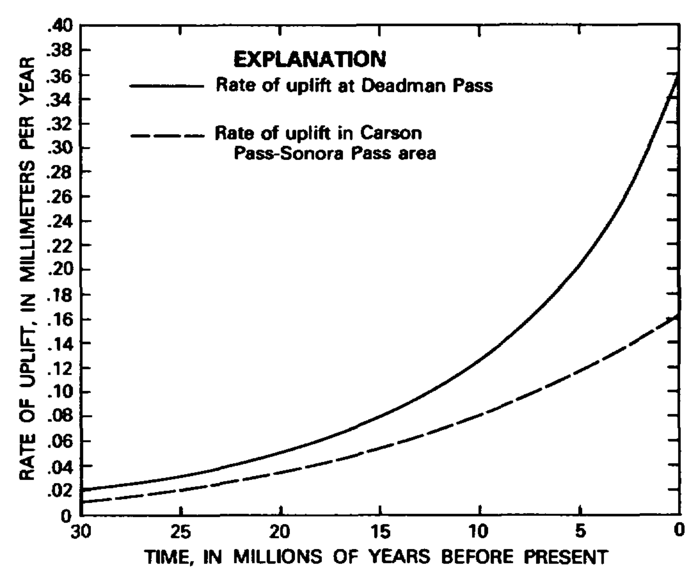

FIGURE 11.—Rate of uplift of crest of central Sierra Nevada at Deadman Pass and in Carson Pass-Sonora Pass area. Curves based on graphic differentiation of uplift curves in figure 10.

Displacement along the east boundary of the Sierran block is commonly distributed over a series of subparallel faults. In the Deadman Pass area, the two most important of these are the Hartley Springs fault and an unnamed fault about 2 km east of Deadman Pass (fig. 12). The Hartley Springs fault, the best documented, displaces 3.2-m.y.-old basalt down to the east by 450 m and the 0.7-m.y.-old Bishop Tuff by about 300 m (Bailey and others, 1976). However, for the speculative calculations that follow, I shall assume that the westernmost of these two faults marks the boundary of the Sierran block and that all the cumulative displacement occurred on it.

Using methods described above, I have calculated the total post-10-m.y. uplift of the range at the site of the unnamed fault east of Deadman Pass at about 2200 m. Projection of the 10-m.y. elevation of the stream profile at Deadman Pass (900 m) 2 km farther northeast yields a pre-uplift elevation of about 920 m at this site. Projected 13 km farther northeast, the profile 10 m.y. ago would have an elevation of about 1100 m at the location of the welded tuff of Alpers Canyon north of Long Valley caldera, and the tuff itself would have been at a similar elevation or higher, depending on its topographic setting relative to the San Joaquin River. Subtracting a minimum value of 1100 m from the present elevation of 2200 m for the tuff results in a maximum value of 1100 m for post-10-m.y. uplift of the tuff. Over the past 10 m.y., then, the Sierran block has been uplifted 2200 m at the site of the frontal fault east of Deadman Pass, the area immediately to the east has been uplifted a maximum of 1100 m, and displacement on the fault(s) is a minimum of 1100 m. This conclusion has only local validity, if any, because much of the area east of the Sierra Nevada has reacted to tectonism as a maze of independent blocks.

When did displacement on the frontal faults in the Deadman Pass area begin? If I extrapolate already speculative calculations, I can come up with some bounding limits. If I assume that 55 percent of the total post-10-m.y. uplift occurred before 3 m.y. ago, then the San Joaquin River profile at the site of the frontal fault would have an elevation of 2100 m at about 3 m.y. ago, nearly as high as the present elevation of the welded tuff of Alpers Canyon some 13 km to the east and upstream. The tuff would therefore have been near or above its present elevation 3 m.y. ago. As the Sierran block was subsequently uplifted an additional 1000 m at the site of the frontal fault, while the tuff remained at approximately the same elevation it was 3 m.y. ago, displacement on the frontal fault system must have begun sometime about 3 m.y. ago. That displacement on this system began before 0.7 m.y. ago is indicated by greater displacement of 3.2-m.y.-old basalt than of the Bishop Tuff on the Hartley Springs fault strand.

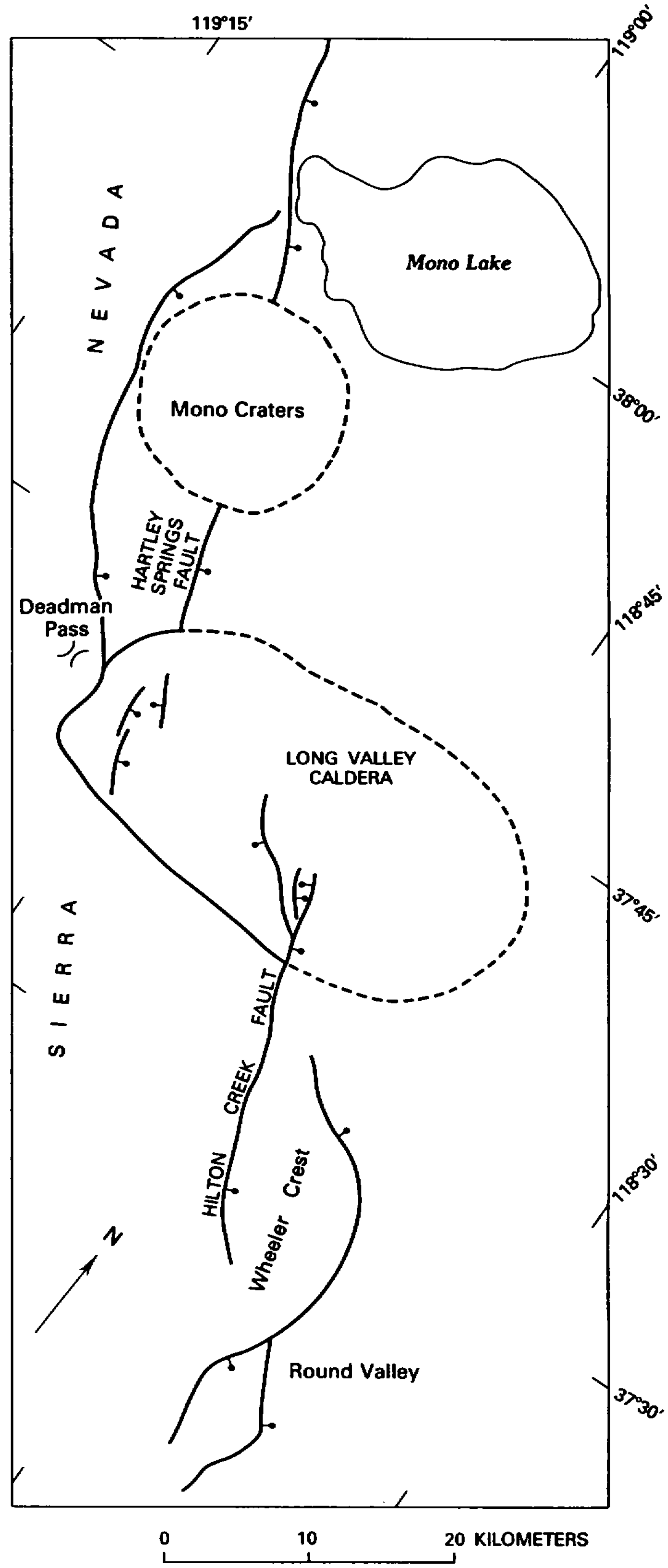

FIGURE 12.— Major faults east of Deadman Pass in Long Valley-Mono basin area. Bar and ball on downthrown side of fault. Dotted lines represent extent of Mono Craters ring structure and Long Valley caldera. After Bailey and others (1976).

The 1100 m calculated as if all displacement took place at the frontal fault just east of Deadman Pass is a minimum value tied to uplift calculations, and it is undoubtedly less than the cumulative displacement on faults in the frontal system. Nevertheless, 300 m of post-Bishop Tuff displacement on the Hartley Springs strand in less than the last 0.7 m.y., a significant part of the total, suggests that the rate of fault displacement is being maintained or even increased. Caution must be used in attempting to tie all of this to continued rates of Sierran uplift, however, as the area east of Deadman Pass may be undergoing some downward adjustment in the absolute sense.

If these speculations are approximately correct, they suggest that the area immediately east of Deadman Pass was uplifted as part of the Sierran block until about 3 m.y. ago, after which it broke free and remained behind as the Sierran block continued to rise. It is possible that the eastern area followed, but at a lower rate, and then underwent some later downward displacement in the absolute sense. Matthes (1930a, p. 29) noted these possibilities when he stated that "Owens Valley and the other desert regions adjoining the range on the east and south dropped back or else suffered but slight uplifts as compared with the mountain block."

The Deadman Pass area is atypical of much of the eastern Sierran escarpment, located as it is in an embayment within the Sierran block with a relatively broad area of moderate relief to the northeast, and my calculations cannot readily be extended to other parts of the escarpment. To the southeast in Owens Valley, for example, displacement on the frontal fault system is much greater, is concentrated in a narrower zone, and probably began earlier than at Deadman Pass. Indeed, new radiometric data indicate that the southern Owens Valley basin was forming at least 6 m. y. ago (Bacon and others, 1979; Giovannetti, 1979), although its development probably also lagged behind initial uplift of the Sierran block. Downfaulting of the Owens Valley graben in the absolute sense also was more important, inasmuch as buried bedrock surfaces are in places below sea level (von Huene and others, 1963; Bateman, 1965).

INCISION OF THE SAN JOAQUIN CANYON

In its course down the west slope of the Sierra Nevada, the San Joaquin River flows in a canyon that has been deeply incised into a gentler upland erosion surface (figs. 13 and 14). Incision of the canyon was

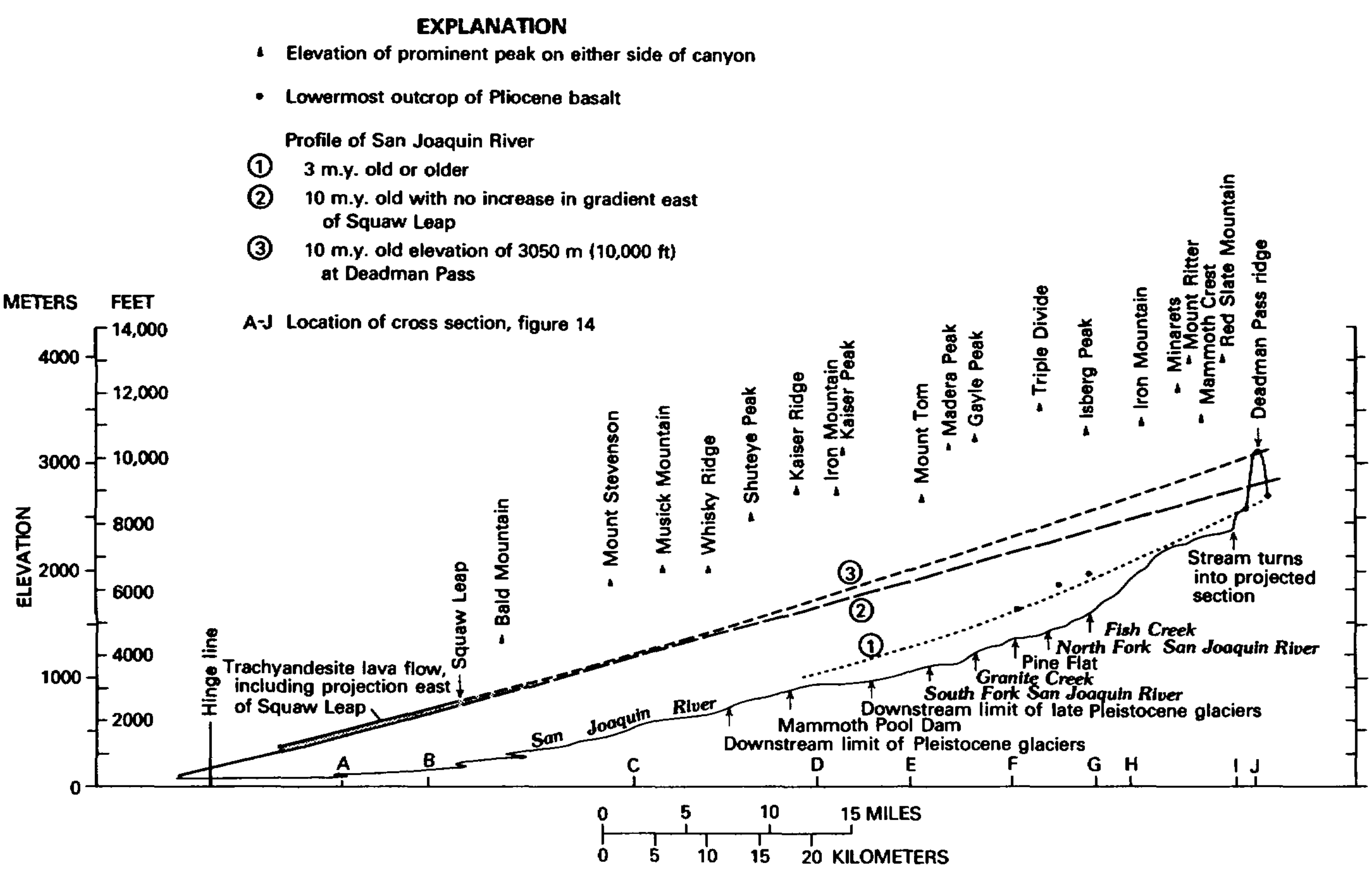

FIGURE 13.—Longitudinal profile of San Joaquin River in Sierra Nevada, projected onto vertical plane striking N. 40° E. Reconstructed profiles for late Miocene and Pliocene channels also shown.

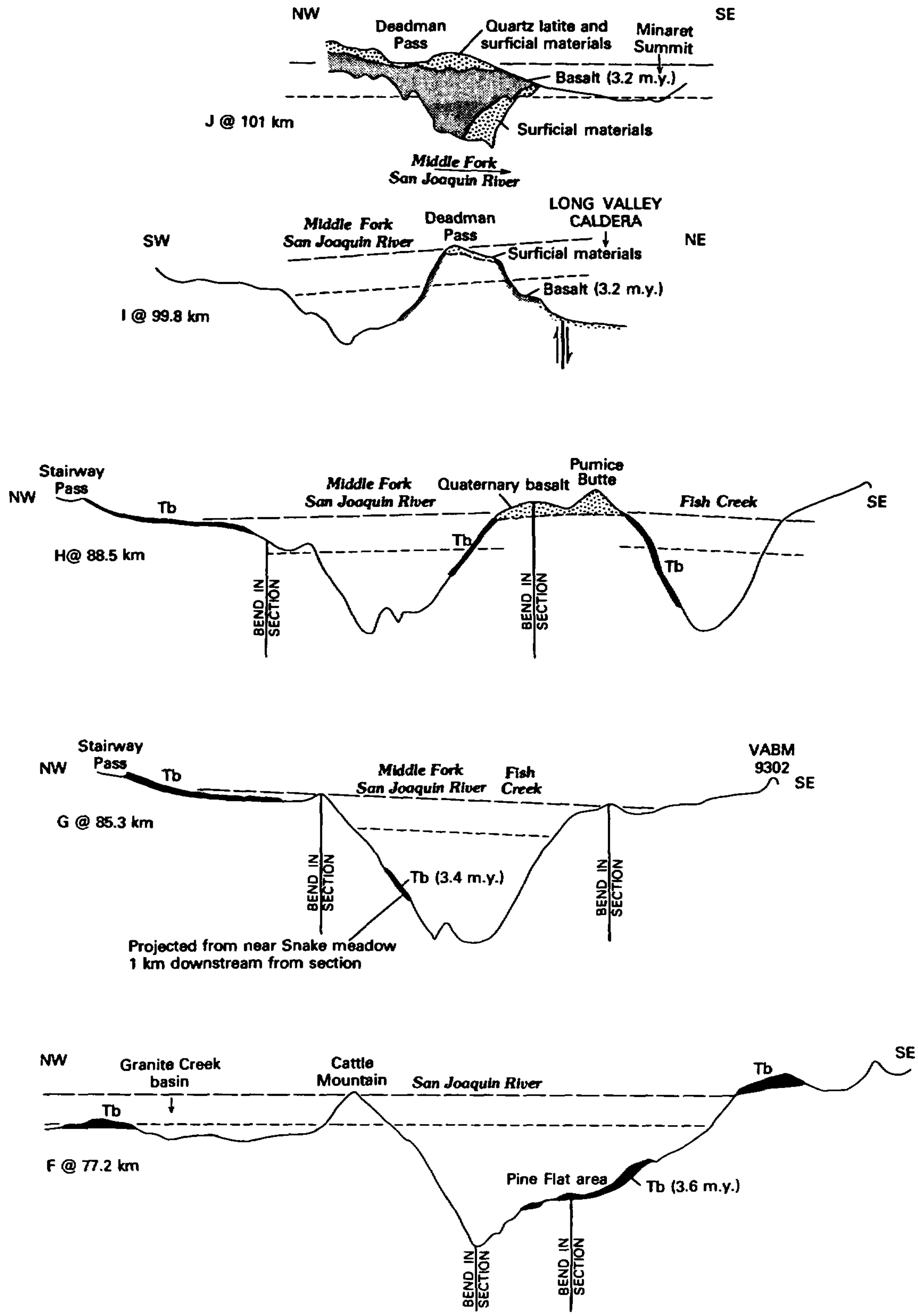

FIGURE 14.—See description on opposite page.

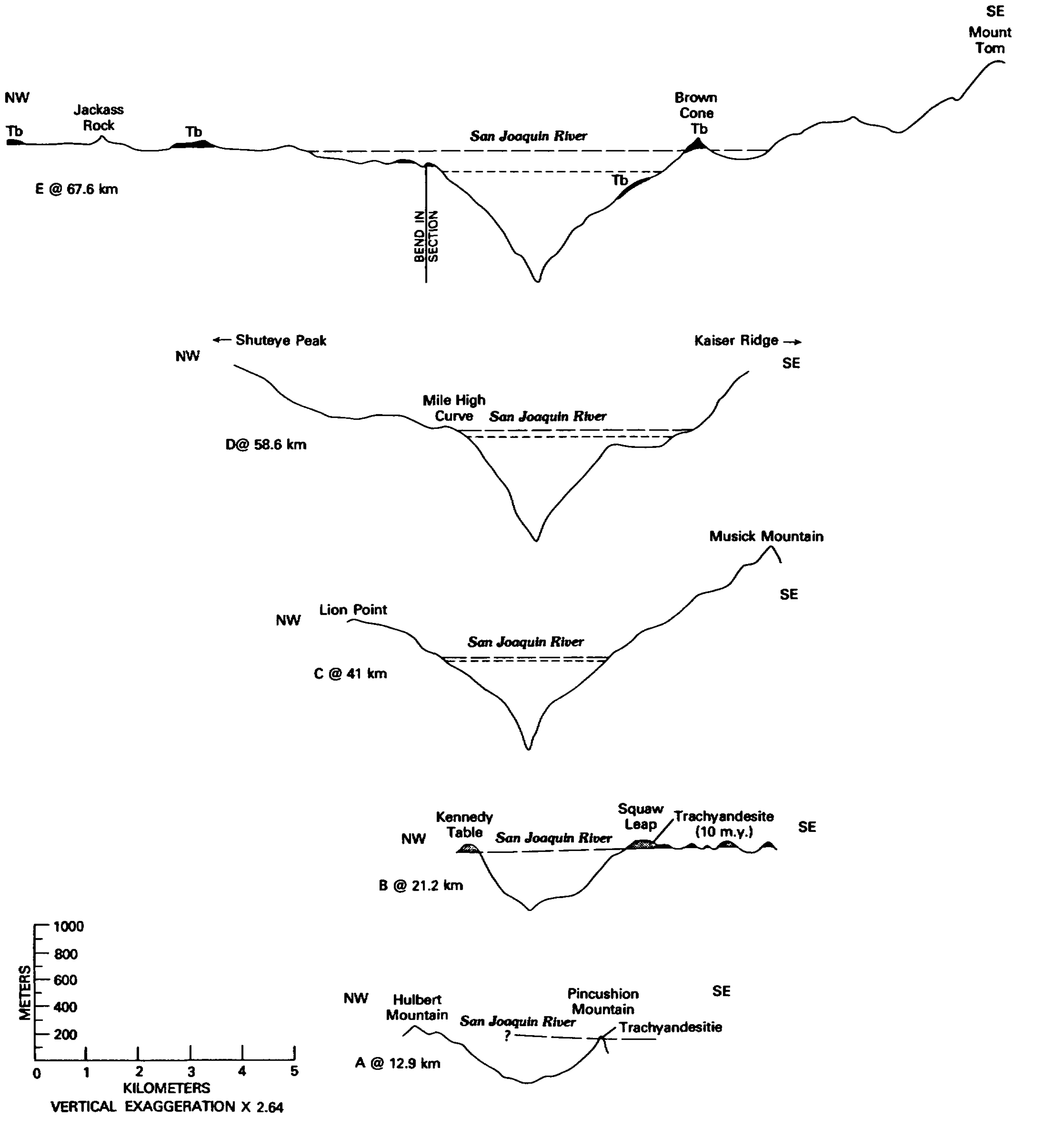

FIGURE 14.—Cross sections of San Joaquin River canyon in Sierra Nevada. Projected distances from hinge line indicated for each section (see fig. 13 for location). Section J is view of west face of Deadman Pass ridge and shows basalt-filled Pliocene channel crossing present divide south of Deadman Pass. On sections C through J, short-dash line indicates 10-m.y.-old Miocene stream profile reconstructed with no increase in gradient east of Squaw Leap; long-dash line profile with elevation of 3050 m (10,000 ft) at Deadman Pass. Actual profile assumed to lie between these lines. Section I shows fault with arrows showing direction of relative movement. Tb, Pliocene basalt.

presumably initiated by late Cenozoic uplift and westward tilting of the range, which significantly increased the gradient and rejuvenated the river. The 3.6-m.y.-old basalt that cascaded into the canyon near Pine Flat at the junction of the North and Middle Forks of the river indicates that a major part of the uplift and incision took place before its eruption. The amount of pre- and post-basalt uplift at this location can be estimated in a manner similar to that used at Deadman Pass assuming that 55 percent of the post-10-m.y. uplift occurred before about 3 m.y. ago when the Kings River fan was abandoned; the results are shown in table 3.

The basalt near Pine Flat also can be used to estimate the relative amount of channel downcutting during approximately the same time intervals (table 3). Such estimates utilize the 10-m.y.-old stream profile as reconstructed above. Because the lowest preserved outcrop of basalt in the canyon may not represent the lowest original extent, the 10- to -3.6-m.y. estimate of downcutting should be considered a minimum value and the post-3.6-m.y. estimate a maximum. Whereas the post-3.6-m.y. estimate results from a direct measurement between the basalt elevation and the present canyon bottom, the pre-3.6-m.y. estimate depends upon the accuracy of the reconstruction of the 10-m.y.-old stream profile.

Schumm (1963), in his study of rates of orogeny and denudation, pointed out that denudation following uplift takes place by two processes, channel incision and hillslope erosion. The first process may be rapid enough to keep up with uplift, but the second is much less likely to lower interfluvial areas at the same pace. Slow uplift may allow landforms to remain in an equilibrium state, but a range of faster uplift rates in relation to denudation will allow channel cutting to dominate the erosional regime. In particular, "when rocks are very resistant, channel incision will be relatively much greater than hillslope erosion and a narrow canyon is formed" (Schumm, 1963, p. 12). Incision of the San Joaquin canyon appears to follow this pattern, as broad, slightly eroded upland surfaces still remain.

After rejuvenation of a drainage basin by increase in overall gradient, the zone of maximum erosion migrates toward the head of the basin. As this occurs, stream profiles, gradients, and sediment yields will change accordingly, with increasing concavity of the profile migrating upstream (Schumm, 1977, p. 69-71). The results of this process are evident in the canyon of the San Joaquin River, as the 10-m.y.-old, 3-m.y.-old, and present stream profiles show successively greater concavity. For the interval 10–3 m.y., this change is reflected by differences in the ratio of downcutting to uplift as determined near Pine Flat and Deadman Pass (table 3). At Pine Flat the amount of downcutting is more than three-quarters that of uplift whereas at Deadman Pass it drops to less than half. The ratio of downcutting to uplift during this time interval continues to increase downstream from Pine Flat, but the reach with the maximum amount of downcutting or incision of the canyon probably is about 16 km west of Pine Flat below the junction of the South Fork; there an additional 1165 km^2 is added to the drainage basin.

Both the amount of downcutting and the downcutting-uplift ratio decrease eastward from Pine Flat, but the pre-basalt channel near Deadman Pass still represents a significant incision below the pre-uplift surface, and the upstream end of the increase in gradient due to uplift must be to the east of Deadman Pass. As the 10- and 3-m.y. profiles are thus converging, simple eastward projection would cause them to intersect about 30 km east of Deadman Pass. However, I believe that both the 10-m.y. and 3-m.y. profiles should both decrease in slope east of Deadman Pass and merge into the gentler headwater drainage basin that once fed the river from beyond the area of appreciable tilt.

The beheading of the San Joaquin River about 3.2 m.y. ago by the eruption of basalt into the river channel near Deadman Pass resulted in an abrupt and drastic change in stream dynamics downstream in the re-

TABLE 3.–*Comparison of uplift, downcutting, and ratio of downcutting to uplift near Pine Flat and Deadman Pass*

Time span	Near Pine Flat (78 km from hinge line)					Near Deadman Pass (100 km from hinge line)				
	Uplift		Downcutting		Ratio of D/U	Uplift		Downcutting		Ratio of D/U
	(m)	(percent)	(m)	(percent)	(percent)	(m)	(percent)	(m)	(percent)	(percent)
10 m.y. to about 3 m.y. ago	900	55	700	73	77	1200	55	490	73	40
About 3 m.y. ago to present	750	45	260	27	35	950	45	180	27	19
Total	1650	100	960	100	--	2150	100	670	100	--

NOTES. – Assumptions for calculations:
For uplift: Total post-10-m.y. uplift is about 2150 m (7050 ft) at Deadman Pass and post-3-m.y. uplift is 45% of total.
For downcutting: 10-m.y.-old stream profile now at about 3050 m (10,000 ft) at Deadman Pass.
Age differences between 3-m.y.-old fan, 3.6-m.y. basalt at Pine Flat, and 3.2-m.y. basalt at Deadman Pass are ignored.
Downcutting is of pre-Cenozoic bedrock and does not consider necessary removal of Pliocene and Pleistocene volcanic rock from canyon.

maining part of the San Joaquin as well as a forced change in outlet for the drainage system remaining to the east. I think it likely that the headwater system soon breached what was probably a low divide on its southern side and was diverted into the Owens Valley drainage where it possibly was a factor in initiating increased discharge about this time into the Owens-China-Searles Lakes system (Smith, 1977; 1978a; 1978b; Smith and others, 1980, in press).

An outlet from Mono Lake through Adobe Valley to Owens Valley existed during the Tahoe Glaciation (Putnam, 1950), and it is likely that such overflow occurred earlier whenever a lake of sufficient size existed in the Mono basin. Hubbs and Miller (1948, p. 79) concluded that the distribution of a distinctive fish fauna "calls for a former connection between the Lahontan and Death Valley fluvial-pluvial systems, and the most plausible route for such a connection is through the Mono basin" sometime in the past. Lake sediments near the east margin of Mono basin were deposited between 3 and 4 m.y. ago, according to radiometric dates on associated volcanic materials (Gilbert and others, 1968, p. 290). Freshwater mollusks and fish collected from these sediments indicate external drainage for the basin at that time.

The present San Joaquin drainage basin upstream from Friant Dam has an area of 4340 km^2. The size of the area to the east that formerly contributed to the total San Joaquin discharge is unknown, but it could easily have been of equivalent size or larger. With the loss of this eastern area, the discharge at Friant was significantly reduced even though the eastern area may not have received as much precipitation as the Sierra block.

For the reach of the San Joaquin that we have been examining in some detail, however, the loss in discharge was even greater, as the drainage area upstream from Pine Flat was reduced from perhaps 4000 km^2 or more to about 455 km^2. The drainage area upstream from the location on the San Joaquin River west of Deadman Pass used for the downcutting estimate in table 3 would have been reduced to a mere 65 km^2.

The reduced erosive power of the stream resulting from reduced discharge should be reflected in reduced downcutting and a reduction in the ratio of downcutting to continued uplift, as indicated in table 3 for the past 3 m.y. period. However, the differences in pre- and post-3-m.y. data only partly reflect reduced stream discharge because other complicating factors are of considerable importance. The Pliocene basalt that disrupted the drainage must itself be removed from the pre-existing channel before downcutting into basement rock (which is what table 3 estimates) can continue. At Pine Flat the reach involved is not long and a great volume of basalt may not have been present, but a considerable volume of basalt must have filled the Middle Fork valley west of Deadman Pass. With the available discharge, roughly equivalent to that of today, removal of the basalt by stream erosion alone would have been slow and it is likely that it was only accomplished through glaciation. After the Sherwin Glaciation, somewhat more than 0.7 m.y. ago, downcutting was again interrupted when the Middle Fork valley was blocked by the eruption of the tuff of Reds Meadow and basalt of the Devils Postpile (Huber and Rinehart, 1967; Bailey and Koeppen, 1977). These volcanic rocks were largely removed by subsequent glaciation, but locally the stream still flows over basalt, as at Rainbow Falls, and, at this locality, bedrock downcutting by the stream itself appears to be almost negligible at the present time.

With the competence of the beheaded San Joaquin River greatly reduced, glacial erosion thus must have been responsible both for removal of late Pliocene and Pleistocene volcanic rocks erupted into the river canyon and for most of the further downcutting of the canyon into pre-Cenozoic bedrock in the upper reaches of the drainage basin, including both the Pine Flat and Deadman Pass localities in table 3. The dominance of glacial over fluvial erosion is reflected in the greater tendency toward U-shaped valleys in the upper reaches and in the present stream profile. The present profile consists of two concave-upward segments interrupted by a convex segment in the vicinity of Mammoth Pool Dam (fig. 13). The convex segment marks the approximate downstream limit of glaciers in the main canyon during the Pleistocene, and I interpret the upstream concavity in the profile as reflecting glacial erosion superimposed upon fluvial erosion.

UPLIFT AND GLACIATION—SOME TIME CONSTRAINTS

Three major episodes of glaciation in the Sierra Nevada are recognized at the general latitude of Deadman Pass. In addition to the well-documented multiple sequence of late Pleistocene advances, these include the Sherwin, whose deposits are overlain by the 0.7-m.y.-old Bishop Tuff, and the McGee, which overlies 2.7-m.y.-old basalt (Dalrymple, 1963; Dalrymple and others, 1965). A fourth and older episode, represented by the so-called Deadman Pass Till, which lies between volcanic units dated at 3.2 and 2.8 m.y. ago, has been proposed by Curry (1966, 1971). (All ages cited have been recalculated.)

Most workers have accepted a glacial origin for the lag deposit on McGee Mountain, about 24 km southeast of Deadman Pass, and for many years the McGee

Till was widely regarded as the oldest known till in the eastern Sierra Nevada (Putnam, 1962) although an absolute age for it still is far from established.

C. D. Rinehart and I mapped a lag deposit of unsorted debris in the saddle at Deadman Pass and referred to it as a glacial deposit (Huber and Rinehart, 1965). We did not assign this deposit to any specific glaciation, but considered it to be pre-Wisconsin because of its physiographic position above the probable limits of glaciers in the San Joaquin drainage basin considered to be of Wisconsin age. We initially thought the lag deposit to be a till on the basis of a superficial examination of varied clasts, some of which we thought to have been derived from the topographically higher Ritter Range to the west, a likely source direction if they were transported by a glacier that filled the valley of the Middle Fork of the San Joaquin River. Curry (1966, 1971) also thought that he recognized clasts derived from the west. The lag deposit overlies basalt dated at about 3.2 m.y. (Dalrymple, 1964), and it in turn was shown by Curry to be overlain by a quartz-latite flow dated at about 2.8 m.y. ago, and on this basis he concluded that there had been a glaciation in this part of the Sierra Nevada about 3 m.y. ago.

On a revisit to the Deadman Pass locality in 1978, I recognized that large clasts that I had previously thought to be of metavolcanic crystal tuff from the Ritter Range instead were of a distinctive hypabyssal intrusive rock with quartz and feldspar phenocrysts that crops out north of Deadman Pass on the east side of the San Joaquin Mountain ridge; Rinehart and I had included this intrusive rock with the quartz monzonite of Lee Vining Canyon on the geologic map of the Devils Postpile quadrangle (Huber and Rinehart, 1965). Other clasts on Deadman Pass and along the east side of the San Joaquin Mountain ridge, including vesicular basalt and Paleozoic metamorphic rocks, could be derived locally a short distance north of Deadman Pass; granitic clasts did not appear to be definitive and no Ritter Range rocks were positively identified. Patches of "Deadman Pass Till" mapped by Curry (1971) above the dated basalt on both the east and west flanks of the ridge south of Deadman Pass contain clasts similar to those at Deadman Pass; I could find no Ritter Range lithologies. Derivation of the clasts from the north rather than from the west would not appear to be compatible with a glacial origin for the lag deposit but perhaps would be compatible with some sort of a debris-flow origin; indeed Curry (1971) has described volcanic mudflow deposits (lahars) north of Deadman Pass. The origin of the lag deposit is thus uncertain.

A glacial deposit that Rinehart and I (Huber and Rinehart, 1965) mapped at the north end of the San Joaquin Mountain ridge subsequently was included by Curry (1971) in his "Deadman Pass Till." I revisited this locality in 1980 and recognized abundant clasts of metavolcanic breccia from the Ritter Range and granodiorite from the Thousand Island Lake basin; these clasts indicate derivation from the west. However, there is no evidence to suggest that this glacial deposit is older than the quartz latite and I consider it to be much younger, perhaps as young as Tahoe in age. If I am correct, then this glacial deposit has no bearing on the problem of the origin of the Deadman Pass deposit and need not be considered further in that context.

The uplift calculations in this report provide additional constraints for possible glacial episodes. Particularly significant is the conclusion that 3 m.y. ago the Sierra Nevada in the vicinity of Deadman Pass was about 950 m lower than now, leaving the site of Deadman Pass at about 2075 m and Mount Ritter at 3100 m. Is this elevation high enough to permit glaciation at that time?

Wahrhaftig and Birman (1965) reconstructed the extent of the mountain icecap during the Tahoe Glaciation and contoured the climatic firn limit, based on summit altitudes of lowest peaks to have had glaciers on their south-facing sides, which they place at about 3350 m in the Deadman Pass-Ritter Range area. Under those conditions, Mount Ritter would not have been high enough to sustain glaciers 3 m.y. ago. Using a different parameter, the climatic snow line, the lower limit of perennial snow on fully exposed flat surfaces, now estimated to be at 4,500 m, was probably only about 750 m lower during the Wisconsin glacial maximum (Wahrhaftig and Birman, 1965), an amount less than the 950 m lower elevation of the range 3 m.y. ago. Thus even if climatic conditions were somewhat more severe 3 m.y. ago than during the Wisconsin Glaciation, elevations in the summit areas west of the Deadman Pass region were probably too low to produce other than marginal cirque glaciers, and a glaciation of the extent of the proposed Deadman Pass Glaciation appears unlikely. This conclusion is based on an uplift value near the maximum calculated. However, even using an uplift value 300 m less, about the minimum permitted by calculations based on stream profile reconstructions at Deadman Pass, or some value in between, elevations in the Deadman Pass area might still have been only marginal for glaciation 3 m.y. ago.

The deep-sea temperature record indicates global cold cycles centered around 2.5 and 1.5 m.y. ago (Beard, 1969), and a number of workers have suggested that perhaps the McGee Glaciation occurred during the cycle 1.5 m.y. ago (Cox, 1968; Birkeland and others, 1971). If the rate of post-3-m.y. uplift was reasonably uniform, the Sierra Nevada might still not have been high enough to sustain major glaciation 2.5 m.y. ago, but probably it would have been high enough 1.5 m.y. ago, at least in the north-facing cirque area feeding into McGee Creek. Thus although my uplift calculations could preclude glaciation in the present vicinity of Deadman Pass 3 m.y. ago, they would not preclude the McGee Glaciation if it occurred 1.5 m.y. ago.

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