Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California

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ABSTRACT

Upper Quaternary terraces of the Ventura River, California, are uplifted, tilted, and folded over the Ventura Avenue anticline. Rates of uplift and tilting have decreased since inception of the structure over the past 200 ka. Assuming that the chronology, based on amino-acid racemization, ^{14}C dates, and soils correlation, is approximately correct, then the minimum possible average rate of uplift in the axial region of the fold has decreased from ~14 mm/yr to 2 mm/yr during the past 200 ka. Interval rates of uplift for the periods 200 ka to 80 or 105 ka, 80 or 105 ka to 30 ka, and 30 ka to present are, respectively, about 20 mm/yr, 9 mm/yr, and 5 mm/yr. The rate of tilting shows a similar trend, decreasing from ~5.8 urad/yr, 2.5 urad/yr, and 1.2 urad/yr for the same time intervals, respectively. Based on the mechanics of flexural slip folds in stratified sedimentary rocks, these data suggest that the rootless Ventura Avenue anticline is a fold that has been shortening at a relatively constant rate of about 9 mm/yr since its inception.

VENTURA AVENUE ANTICLINE AND ASSOCIATED RIVER TERRACES

The Ventura Avenue anticline is an east-west-trending fold located south of the Red Mountain fault and Sulphur Mountain anticline in the western Transverse Ranges of southern California (Fig. 1). At the surface, upper Pliocene through Pleistocene sedimentary strata (Fernando Formation and Saugus Formation) dip as steeply as 45° on the south flank of the fold, with no apparent unconformity between or within them. The geochronology of these units, based on isotopically dated volcanic ash, tephrachronological correlation, and amino-acid racemization, is well established (Lajoie and others, 1982) and can be used to help determine the rates of folding (Fig. 2).

The age of the uppermost Saugus Formation has been estimated by amino-acid racemization on bivalve shells at about 200 ka (Wehmiller and others, 1978). The well-stratified nature of the section and the lack of angular unconformities within it suggest that folding began after this time (Lajoie and others, 1979, 1982). A marine terrace and a flight of fluvial terraces that range in age from 80 or 105 ka to 16 ka (Fig. 3) have been cut across these folded strata. Age control of these terraces (Table 1) is based on ^{14}C dates and soils correlation (Keller and others, 1980; Dembroff, 1982; Rockwell, 1983; Rockwell and others, 1983) and amino acid racemization (Lajoie and others, 1982). Unusually good age control on the terraces and underlying deformed Pleistocene strata greatly assists the interpretation of the tectonic geomorphology.

In the Ventura River valley, both tectonic uplift and climatic variations have probably contributed to the formation or preservation of upper Pleistocene through Holocene strath river terraces. High sea-level stands (interglacials or interstadials) may be associated with some of the late Pleistocene fluvial terraces (Fig. 3, terraces A, E, F, and H), but terraces B, C, D, and G are apparently associated with falling or low sea-level stands (glacial periods). Rapid uplift has resulted in the preservation of several discrete terrace levels, in part by elevating them to a position above burial from subsequent pulses of alluviation.

TECTONIC GEOMORPHOLOGY

Putnam (1942) first noted that marine and fluvial terraces are deformed on the flanks of the Ventura Avenue anticline. Near the city of Ventura, a marine terrace with an amino-acid racemization age of 80 ka or 105 ka (middle to late stage 5, oxygen-isotope numbering system of Shackleton and Opdyke, 1973) has been tilted ~10° (Lajoie and others, 1979, 1982), and late Pleistocene Ventura River terraces, the oldest of which grades to the marine platform, are warped over the crest of the Ventura Avenue anticline (Fig. 4).

The chronology and location of the upper Pleistocene river terraces allow rates of uplift and tilting produced by active folding of the Ventura Avenue anticline to be calculated (Table 2). Elevations for the uppermost layers or top of the 200-ka-old Saugus Formation and the 80-ka-old or 105-ka-old fluvial and marine terrace at the crest of the fold were derived by graphically projecting the surfaces to the hingeline of the anticline, using the surface radius of curvature of 1,375 m (Yeats, 1982, 1983) (Fig. 4). Other terrace surfaces are close enough to the hingeline to directly measure their elevation. Rates of uplift for the younger terraces (B, D, E, and F; Fig. 4 and Table 2) have a large potential range of error because of the uncertainty as to how much the Ventura River adjusted to lower sea levels during the past 50–60 ka.

Sea level was about 120 m below present at 17 ka, the lowest level during the late Pleistocene (Shackleton and Opdyke, 1973). As sea level rose to its present level after 17 ka, the 16-ka-old terrace is preserved because uplift associated with the fold must have been greater than the rate of rise in the river bed due to sea-level transgression in the vicinity of the anticline. This important inference, in conjunction with the observation that bedrock is exposed in the river bed in the hinge region, suggests that sea-level rise did not produce a large fill event near the hinge of the fold. Therefore, there may have been little incision of the Ventura River bed associated with late Pleistocene sea-level changes, perhaps due in part to the similar gradients of the Ventura River longitudinal profile and the offshore marine platform. This is supported by the presence of terraces that

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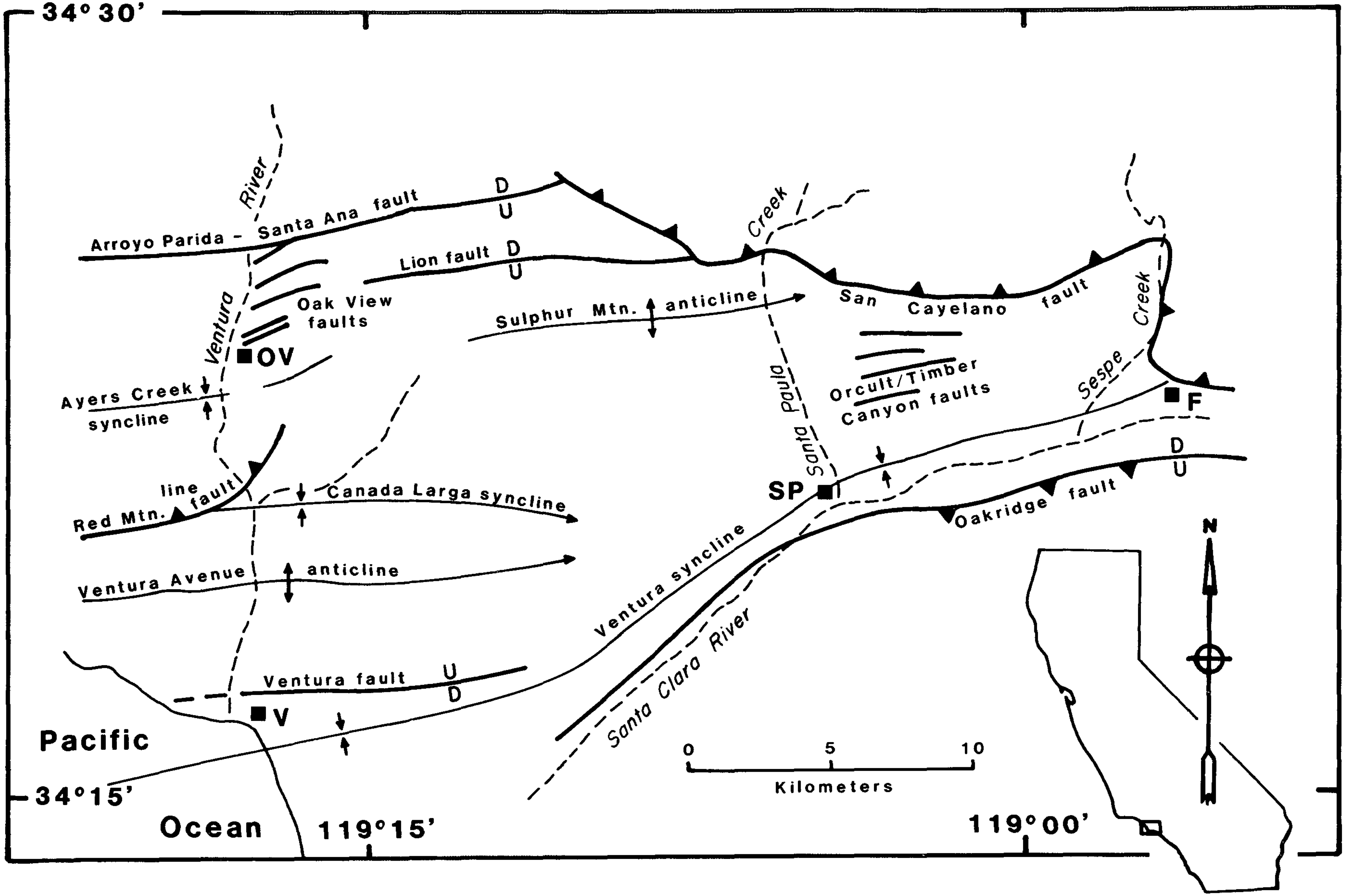

Figure 1. Map of the central Ventura Basin showing major geologic structures that deform upper Pleistocene and/or Holocene materials. V = Ventura, OV = Oak View, SP = Santa Paula, and F = Fillmore.

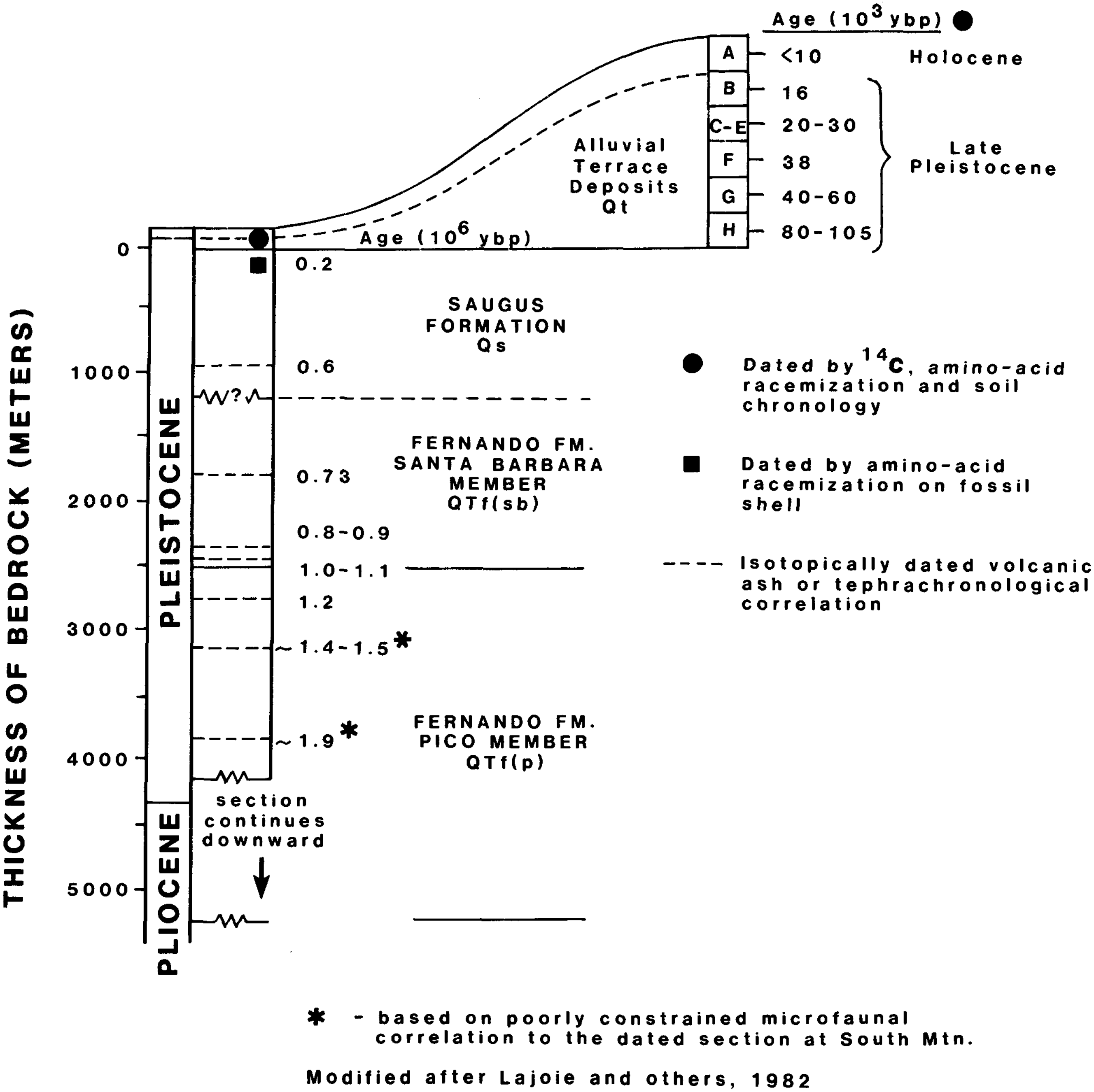

Figure 2. Pleistocene to Holocene chronostratigraphy of bedrock and terraces at the Ventura Avenue anticline.

correspond in age to periods of high, low, and changing sea level, which suggests that tectonics and minor climatically induced incision were more important in terrace formation than were sea-level fluctuations. Alternatively, the river may have incised, but the rate of uplift simply was more rapid than the rate of sedimentation, thereby allowing for the terraces to be preserved. This is supported by the depth of the fluvial fill at the mouth of the Ventura River, where uplift rates are considerably lower. At the river's mouth, about 20 m of fill (Gardner, 1978) suggests a minimum of that amount of incision, and the value at the fold hinge should not be much less than this. Thus, for the assessment of the minimum amount of uplift, the Ventura River is assumed to have not incised its course during the late Pleistocene; however, a more realistic minimum assessment uses a min-

TABLE 1. RADIOCARBON (^{14}C) DATES FOR SOILS AND TERRACE DEPOSITS ALONG THE VENTURA RIVER

Site*	River terraces in Figure 3	Geomorphic surface†	Sample number§	Age (yr B.P.)**
Getty-1	B	Qt_{5a1}	UW-721	15,880 ± 210
Shell-3	D	Qt_{5a2}	UW-741	20,040 ± 590
Shell-1	E	Qt_{5b}	UW-710	29,700 ± 1,250
Oak View	F	Qt_{6a}	UW-570	39,360 ± 2,610
Oak View	F	Qt_{6a}	ISGS-799	36,600 ± 1,100

*These site names are referenced in Dembroff (1982) and Rockwell (1983).
†Qt numbers refer to Rockwell (1983).
§UW numbers are samples analyzed in the laboratory of A. W. Fairhall at the University of Washington. ISGS samples were analyzed in the laboratory of D. D. Coleman at the Illinois State Geological Survey.
**These ages are radiocarbon years before present and are not dendrochronologically corrected.

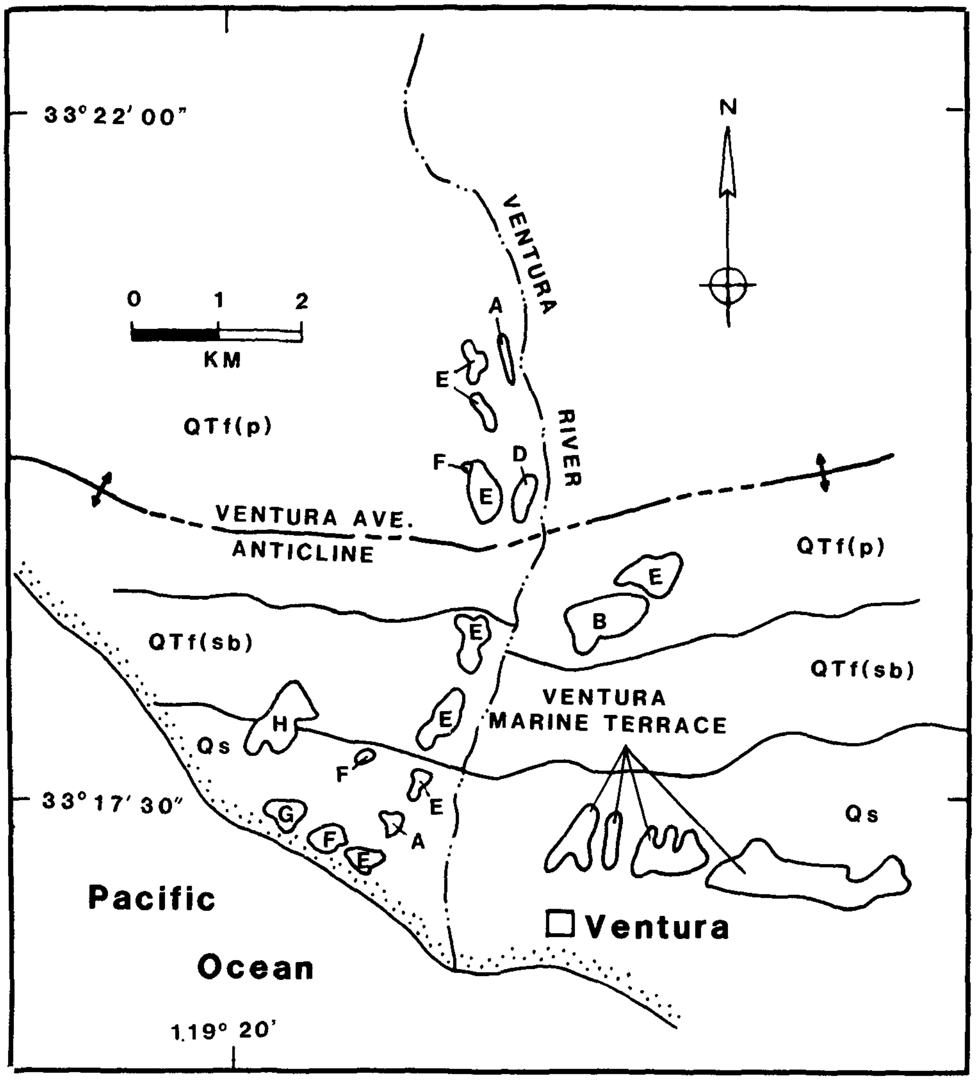

Figure 3. Generalized location map for the Ventura marine terrace and prominent Ventura River fluvial terraces. Formation terminology used is from Figure 2.

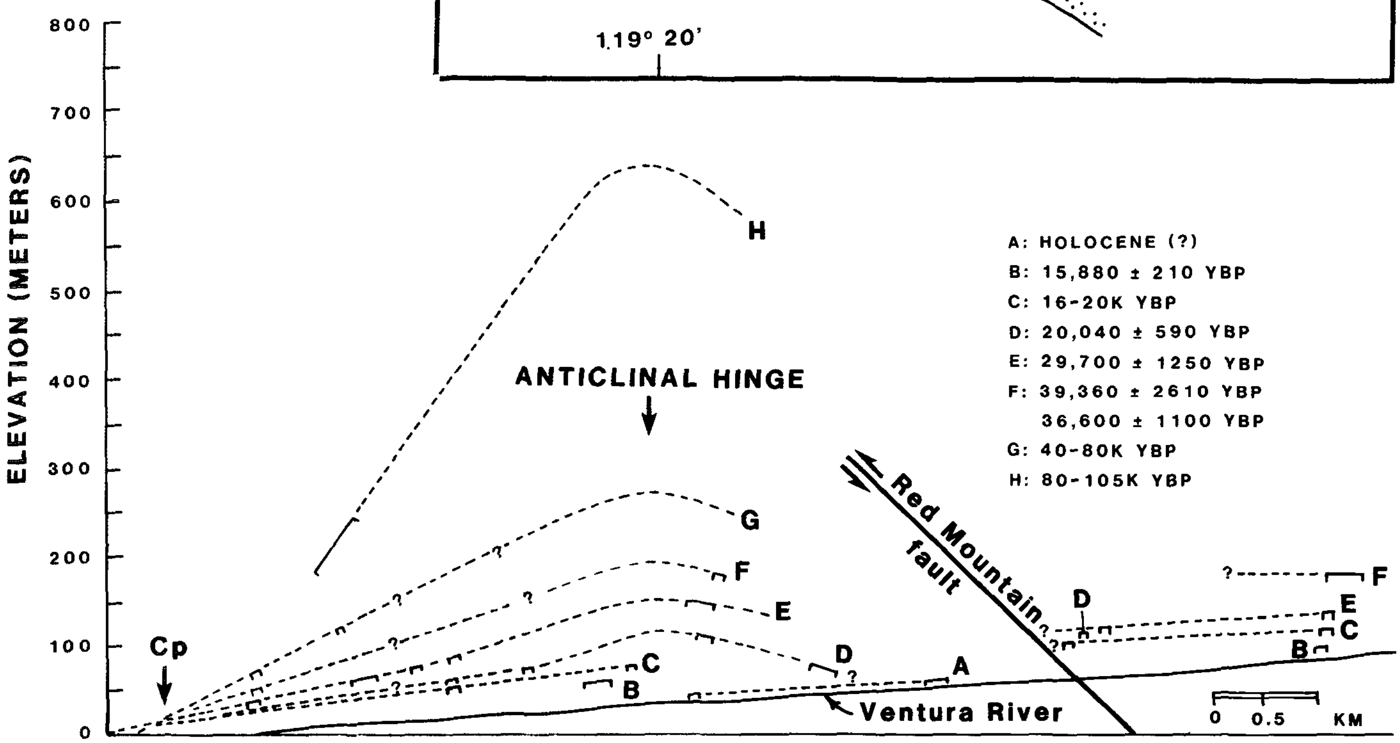

Figure 4. Ventura River terrace profiles over the Ventura Avenue anticline and Red Mountain fault. Age control is from ^{14}C dates (terraces B, D, E, F) (Rockwell and others, 1983) and correlation to a marine terrace east of the Ventura River (terrace H) dated by amino-acid racemization (Lajoie and others, 1982).

TABLE 2. UPLIFT AND TILTING OF BEDROCK AND RIVER TERRACE DEPOSITS OVER THE VENTURA AVENUE ANTICLINE

Geomorphic surface designation	Age*	Sea level (m)†	Present height above Ventura River (m)§	Potential uplift rate range to the present (mm/yr)**	Min. possible uplift rate to the present (mm/yr)††	Best estimated amount of incision (m)§§	Best estimated uplift rate (mm/yr)***	Tilt rate (urad/yr)
B	15,880 ± 210	–120	30.5 ± 10	5.4 ± 4.2	1.9 ± 0.7	37	4.25 ± 0.7	..
D	20,040 ± 590	–90	85.3 ± 10	6.6 ± 0.5	4.3 ± 0.5	28	5.65 ± 0.65	..
E	29,700 ± 1,250	–41	120 ± 10	4.7 ± 1.0	4.1 ± 0.5	13	4.50 ± 0.5	1.2
F	38,000 ± 1,900	–38	175 ± 10	5.1 ± 0.8	4.7 ± 0.4	12	4.95 ± 0.5	..
H	80,000 or 105,000	–13	625 ± 100	7.0 ± 1.3	7.1 ± 2.0	4	7.10 ± 2.0	1.7–2
Bedrock	200,000	< present	2,720 ± 200	13.6 ± 1.0	13.6 ± 1.0	n.d.	13.6 ± 1.0	3.9

*Based on ^{14}C and amino-acid racemization chronology (Table 1 and Lajoie and others, 1982).
†After Bloom and others (1974) and Lajoie and others (1979).
§Projected to the hinge of the anticline (Fig. 4).
**Assumes complete range of possible adjustment of the Ventura River to lower sea level.
††Assumes no adjustment of the Ventura River to lower sea level.
§§Best estimated amount of incision during respective time periods based upon the depth of alluvial fill near the mouth of the river.
***Uplift rate determined using the best estimated depths of incision of the Ventura River.

imum late Pleistocene incision value of about 20 m, based on the existing depth of fill near the river's mouth. Because the area around the mouth is being uplifted at a rate of about 1 mm/yr (20% of crestal rate based on interpolation of the first approximation of the late Pleistocene to present crestal uplift rate and zero uplift rate south of the projected convergence of all of the terraces; Fig. 4), a best estimate of the depth of incision during the lowest sea stand at 17 ka is 20 m plus 17 m (1 mm/yr for 17,000 yr) or about 37 m.

Assuming that the amino-acid age assessment of ~200 ka for the uppermost strata of the Saugus Formation is correct, then the minimum average rate of uplift near the axis of the fold decreased from about 14 mm/yr to 2 mm/yr during the past 200 ka. The best estimated average uplift rate also decreases from about 14 mm/yr to 4 mm/yr, and the interval rates of 200 ka to 80–105 ka, 80–105 ka to 38 ka, 38 ka to 29.7 ka, 29.7 ka to 15.9 ka, and 15.9 ka to the present are, respectively, 20 +5.25 or –4.15 mm/yr, 8.1 +5.6 or –3.3 mm/yr, 6.5 +7.85 or –3.5 mm/yr, 4.75 +2.15 or –1.75 mm/yr, and 4.25 ± 0.7 mm/yr (Table 3). The rate of tilting shows a similar trend based on the present bedrock dip and gradients of the Ventura River and the late Pleistocene terraces, decreasing from an average rate of 3.9 urad/yr for the period of 200 ka to the present to 1.7–2.2 urad/yr for the period of 80–105 ka to the present, and 1.2 urad/yr for 30 ka to present. The interval rates between 200 ka and 80–105 ka, 80–105 ka to 30 ka, and 30 ka to the present are 5.8 ± 0.7 urad/yr, 2.2 ± 0.5 urad/yr, and 1.2 urad/yr, respectively, clearly indicating decreasing rates of tilting with time. Unlike uplift, this rate is not influenced by the river's response to sea-level fluctuations.

MECHANICS OF FLEXURAL SLIP FOLDS AND THE VENTURA AVENUE ANTICLINE

The sedimentary section may be represented ideally as a series of individual layers of rock which are assumed to have been flat lying before deformation and in which each rock layer has homogeneous strength properties (Currie and others, 1962). For the purposes of this discussion, individual sedimentary layers comprising the folded section of the Ventura Avenue anticline are assumed to maintain a constant thickness and length, and folding is dominantly parallel (concentric) in type. This probably requires, then, that flexural slip occur between some bedding surfaces during folding.

The concept of flexural slip is well documented. Chapple and Spang (1964) studied strain of the Greenport Center syncline and determined that most of the strain was accompanied by bending and flexural slip. Similarly, the Hunterville arch west of Marlington, West Virginia, has accommodated flexural slip as evidenced by continuous slickensided surfaces bounding the dominant members (Curie and others, 1962). Strata of the Ventura Avenue anticline also have slickensided bedding surfaces (Dembroff, 1982; Rockwell, 1983). Rockwell and others (1984) documented bedding-plane faulting in the Oakview area, a few kilometres north of the Ventura Avenue anticline. In modeling studies, Ghosh (1968) also concluded that flexural slip plays an important role in parallel folding. What layer-parallel shortening that does occur in folding of sedimentary strata apparently occurs only in the early stages of deformation; beyond a 15° dip, folding progresses to high amplitude at constant arc length (Sherwin and Chapple, 1968; Huddleston, 1973).

Folded geologic strata approximate sine curves in form (Currie and others, 1962; Chapple and Spang, 1964) and may thus be analyzed mathematically. For the Ventura Avenue anticline, two methods are used. First, because the radius of curvature of the fold is fairly large at the surface (1,375 m) (Yeats, 1982, 1983), deformation during folding is modeled as an open sinusoidal curve. The second method is to model the deformation of the terraces as resulting from chevron folding where the radius of curvature is fairly small. The second approach is done because deformation of the terraces (Fig. 4) appears to more or less follow a chevron form with relatively straight flanks and a small radius of curvature near the crest. This may be due, however, to their scanty preservation.

For the type of fold conditions for method 1, Adams (1984) and Rockwell (1983) used elliptic integrals to solve mathematically for percent shortening versus flank dip (θ) and present horizontal fold extent or size (D). The length (L) along a sine curve or geologic stratum folded sinusoidally from a maximum or minimum to the nearest point of inflection (one-quarter of the complete sine curve or any multiple thereof) is

$$L = \frac{2D}{\pi}\frac{E(\theta)}{\cos\theta} \quad (1)$$

where θ is the slope of the curve at the point of inflection (flank dip of strata), $E(\theta)$ is the elliptic integral of the second kind, and D is the horizontal distance from inflection point to crest or trough (Fig. 5) (after Adams, 1984). The shortening (S) is represented by the original length (L) minus the present length (D) or

$$S = \frac{2DE(\theta)}{\pi\cos\theta} - D. \quad (2)$$

The percent shortening (X) is then defined as

$$S = 100\,\frac{S}{L}\,\% = \frac{100\,\dfrac{2DE(\theta)}{\pi\cos\theta} - D}{\dfrac{2D}{\pi}\dfrac{E(\theta)}{\cos\theta}}\,\% = 100\,\frac{1-\pi\cos\theta}{2\,E(\theta)}. \quad (3)$$

Notice that in calculating the percent shortening, the scale factor or hori-

TABLE 3. INTERVAL RATES OF UPLIFT AND TILTING OF BEDROCK AND RIVER TERRACE DEPOSITS OVER THE VENTURA AVENUE ANTICLINE

Geomorphic surface interval*	Age interval (ka)†	Time length (ka)†	Interval uplift amount (m)§	Interval uplift rate (mm/yr)	Interval tilt amount (degrees)	Interval tilt rate (urad/yr)
Bedrock - H	200 to 105 or 80	107.5 ± 12.5	2,145 ± 250	19.95 + 5.25 − 4.15	35	5.8 ± 0.7
H - F	105 or 80 to 38	54.5 ± 14.4	440 ± 110	8.1 + 5.6 − 3.3		
F - E	38 to 29.7	8.3 ± 3.15	54 ± 20	6.5 + 7.85 − 3.5		
H - E	105 or 80 to 29.7	64 ± 12.8			8	2.2 ± 0.5**
E - B	29.7 to 15.9	13.8 ± 1.45	65.5 ± 20	4.75 + 2.15 − 1.75		
E - present	29.7 to 0	29.7 ± 1.25			2	1.2**
B - present	15.9 to 0	15.9 ± 0.2	67.5 ± 10	4.25 ± 0.7		

*These surfaces are from Figures 3 and 4 and correspond to those in Table 2.
†Based on Tables 1 and 2 and Figure 2. The time range presented is the maximum length of time between surfaces and includes the error associated with each dated unit.
§Based on the maximum range for the best estimate of the amount of uplift in Table 2. This value includes the best estimate of sea level at the time of terrace formation.
**These tilt rate values may be slightly low because they represent the present average gradient of the terraces and do not take into account bedding-plane faulting.

zontal distance drops out and percent shortening simply reflects, and is a function of, the flank dip. Note also that the amount of tilting (Fig. 6) increases rapidly at first for small amounts of shortening followed by smaller changes in tilt in well-developed folds which have already accommodated significant shortening. This translates into decreasing tilt rates as folding proceeds if the rate of shortening remains constant.

Similarly, the amount of uplift (fold amplitude) may be evaluated as a function of flank dip. Uplift (U) or subsidence of the apices of a fold with respect to the inflection points is defined as

$$U = \frac{2D}{\pi} \tan \theta \tag{4}$$

where D and θ are again the horizontal distance and flank dip, respectively (Fig. 5) (modified from Currie and others, 1962). Combined with equation 1 when $L = 1$ km, the uplift may be graphed as a function of D and θ (Fig. 7). If shortening rates remain constant, time may be substituted for D on the horizontal axis, and it can be seen that both the rate of uplift and tilting should decrease with time as shortening proceeds. Uplift may also be defined as a function of θ and L where

$$U = \frac{L \sin \theta}{E(\theta)} \tag{5}$$

as shown diagrammatically in Figure 6.

For a discrete shortening interval ΔD where d_1 is shortened to D_2 and flank dip θ_1 is rotated to θ_2, the uplift for that interval (ΔU) is defined by

$$\Delta U = \frac{2}{\pi} D_2 \tan \theta_2 - D_1 \tan \theta_1, \tag{6}$$

which, when evaluated over time, yields the uplift rate as a function of the change in flank dip (or tilt of a terrace cut across the fold at the inflection point) and the amount of shortening. From this, the rate of shortening (dD/dt) may be determined, given the rate of tilting ($d\theta/dt$) and the flank dip (θ):

$$\frac{dD}{dt} = \frac{-\pi L}{2} \frac{\cos \theta}{E(\theta)} \frac{E'(\theta)}{E(\theta)} + \tan \theta \frac{d}{dt} \text{ (radians).} \tag{7}$$

In this case, however, L is taken to be the length of the fold from flexure point to flexure point as measured along a geologic stratum or as defined by equation 1.

Finally, the age of initiation of folding may be tested, assuming a constant shortening rate. D and θ may be taken from cross sections, and after $d\theta/dt$ is determined, dD/dt may be calculated. Then divide dD/dt into dD to ascertain the time folding began. The constant shortening-rate

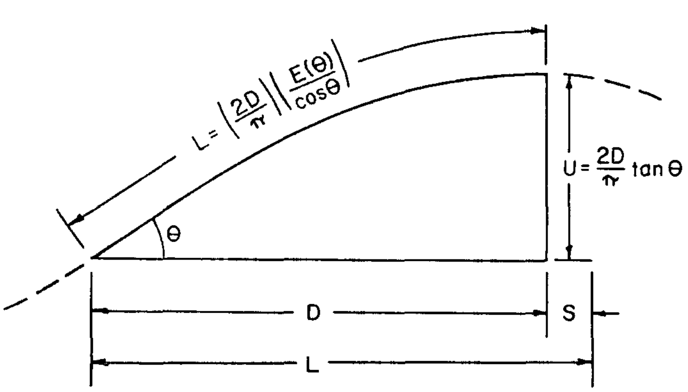

Figure 5. Relationship between L, D, U, and θ for a sinusoidal fold.

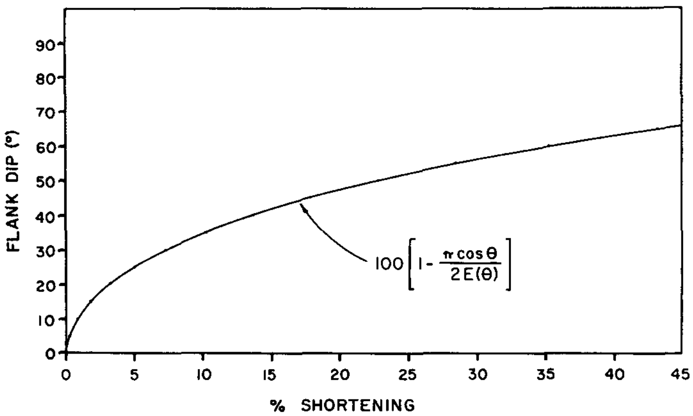

Figure 6. Flank dip as a function of percent shortening for a sinusoidal fold.

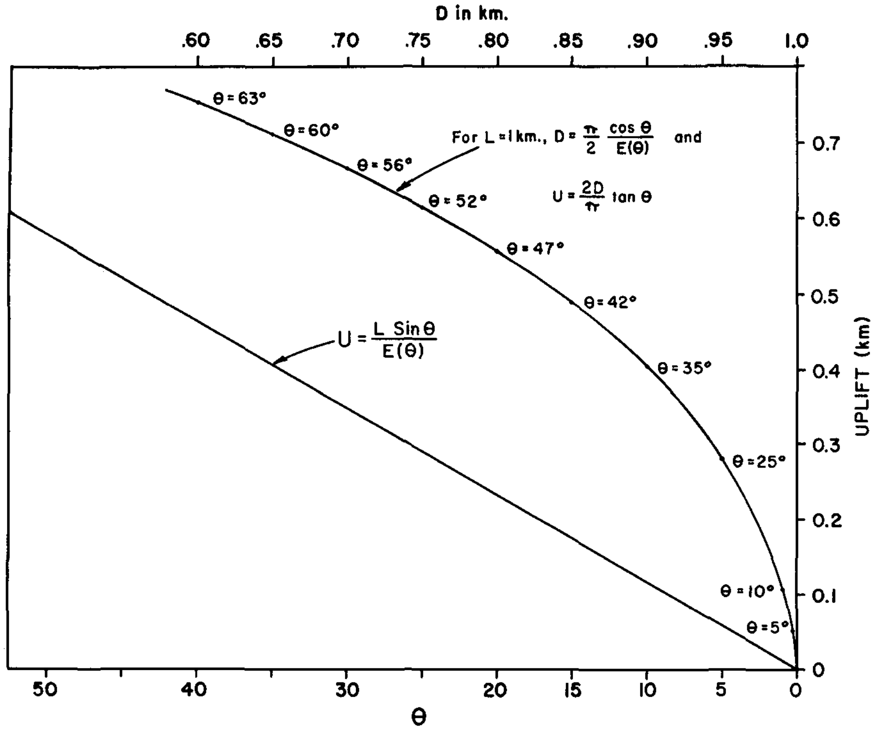

Figure 7. Uplift as a function of D and θ (upper curve) and L and θ (lower curve).

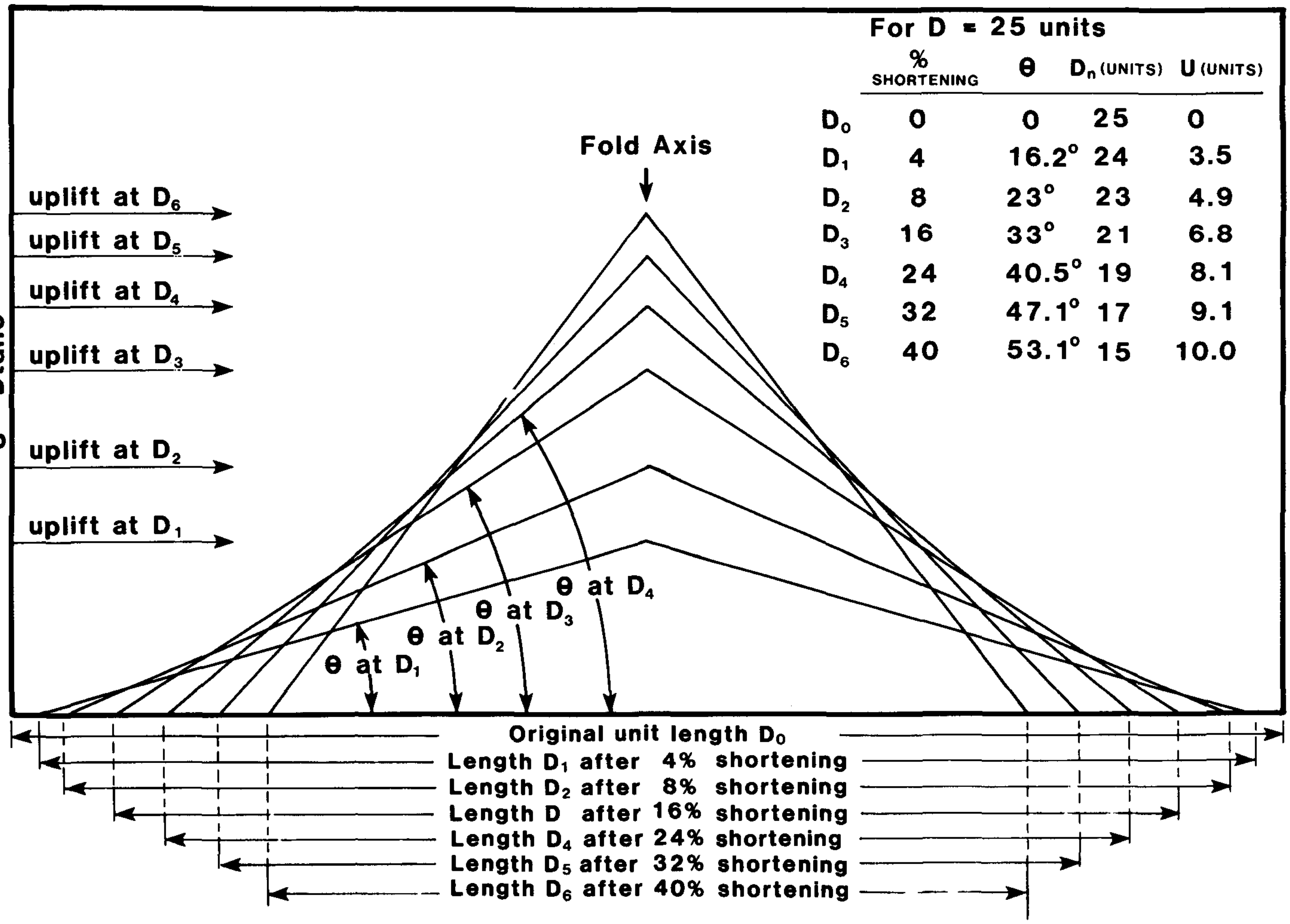

Figure 8. Changes in uplift and tilting as a function of percent shortening for a chevron fold.

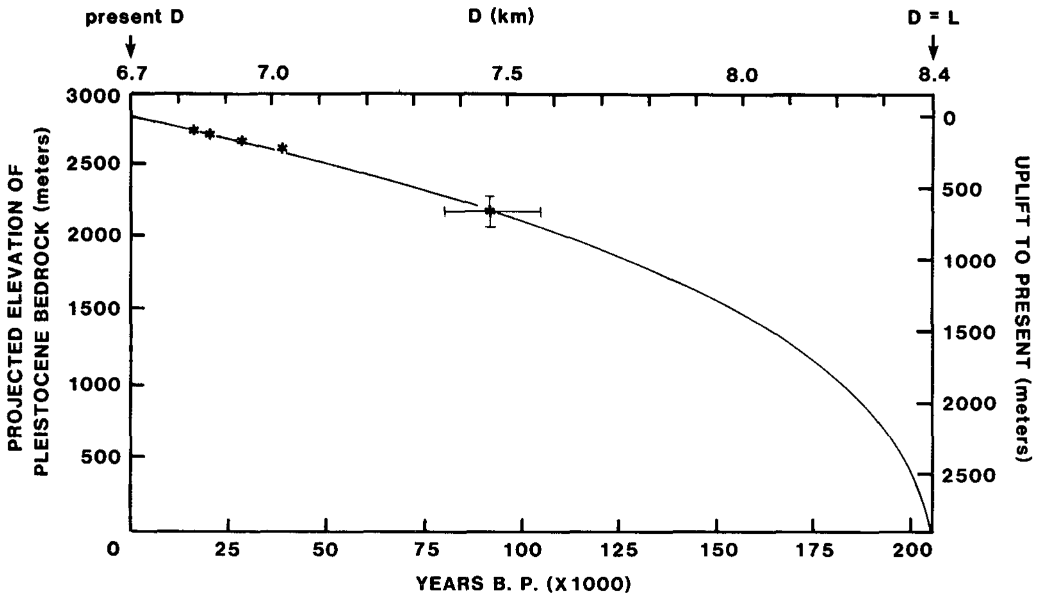

Figure 9. Terrace data and the theoretical uplift curve for the Ventura Avenue anticline. The temporal error reflects error in the ^{14}C and amino-acid dating techniques; the vertical error reflects measurement error as well as the uncertainty of the level of Ventura River at that time.

assumption may be tested if $d\theta/dt$ is determined for more than one time interval (that is, interval tilt rates for deformed terraces of different ages).

The Ventura Avenue anticline provides an excellent test for the mathematical model outlined above, at least to a first approximation, because the approximate timing of initiation of folding is known, and therefore, an independent shortening rate across this structure may be determined graphically (see Rockwell, 1983, cross section B–B′). For the Ventura Avenue anticline, $D = 6.7$ km, $\theta = 45°$, and $L = 8.4$ km (determined graphically) and $L = 8.2$ km (determined mathematically). The tilt rate is taken to be 10° in 80–105 ka based on tilting of the middle to late stage 5 marine terrace that now slopes 12° (an assumed 2° primary slope), yielding a rate of 1.7 to 2.2 urad/yr. The shortening rate based on equation 7 is 7.7 to 10.1 mm/yr. Graphically, the amount of shortening, or $L - D$, is 1.7 km in ~200 ka for an average shortening rate of 8.5 mm/yr, in close agreement with the shorter-term mathematically determined rate. These data suggest a relatively constant shortening rate over two time intervals.

Method 2 for chevron folding is considerably simpler mathematically. For any given present fold extent or size (D), bed length (L), and flank dip (θ), uplift (U) = $D \tan \theta$, and $L = D/\cos \theta$. Figure 8 shows graphically the relative uplift as shortening proceeds and results again in decreasing rates of both uplift and tilting with progressive folding. This method would predict about 3,250 m of uplift at the Ventura Avenue anticline fold crest, which is probably too high, because it does not take into account the radius of curvature of the fold.

The theoretical uplift curve derived from the above equations using the elliptic integrals, defines a section of an ellipse (Fig. 9). Uplift to present (right side of diagram) represents the uplift of a point on the apex of the fold from a given time to the present. When age and amount of uplift of the five river terraces (derived independently) are plotted, they fall on the upper part of the curve. This suggests that the decreasing rates of uplift and tilting determined for the terraces result from relatively constant rates of shortening of the upper several kilometres of bedrock. This interpretation is supported by the close correlation in shortening rates as determined graphically and mathematically.

DISCUSSION

The Ventura Avenue anticline is not as simple a structure as is depicted by the above models. Drilling of the anticline in search for oil has revealed a complex subsurface structure with numerous faults (Yeats, 1982). Our work supports Yeats' hypothesis that the anticline is rootless with a radius of curvature decreasing downward from 1,375 m at the surface to 30 m at 3,350 m below sea level and low variable dips in the shaley Miocene Monterey Formation. Yeats suggested a décollement in the Miocene strata with the shale accommodating north-south shortening by ductile flow. Our simple model adequately demonstrates the surface behavior of the folded Pleistocene bedrock and terrace deposits in a compressional regime. Further, it suggests that a low-angle fault, which may comprise the décollement, is accumulating slip at a rate of about 7.7 to 10.1 mm/yr based on both graphical and mathematical determinations of the rate of shortening (Rockwell, 1983).

Evaluation of the recent tectonic history of the Ventura Avenue anticline suggests that rates of tectonic deformation may vary in time and space. Furthermore, the changes are systematic and are due to geologic constraints and mechanics of folding. There is a direct relationship between rate of uplift and magnitude of the regional tectonic stress, but this can be evaluated only when the geology associated with a structure or group of structures and their respective rates has been fully considered; a constant rate of shortening can produce systematic change of the rate of uplift and tilting over time. As another example, rates of flexural-slip faulting near Oak View, California, vary from about 0.3 to 1.1 mm/yr as a function of fault location in a synclinal structure and/or mechanics of folding (Rockwell and others, 1984). The above discussion suggests that rates of uplift and faulting must be evaluated in terms of the regional and local tectonic framework. High rates of uplift and faulting are not necessarily more significant than lower rates in evaluating active tectonics. Rather high (or low) rates may be the result of local time-dependent mechanics of deformation in a regional setting of tectonic stress that produces a relatively constant rate of shortening.

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