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Geomorphological analysis of neotectonic deformation, northern Owens Valley, California

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Abstract At the western edge of the Basin and Range Province, the Owens Valley is the site of active seismicity and deformation. Morphometric analyses of three geomorphological features are used to determine the patterns and rates of neotectonic deformation: (1) a network of Pleistocene channels cut on top of the Bishop Tuff; (2) uplifted terraces of the Owens River; and (3) alluvial fans of the White Mountain front.

In the Owens Valley, the three analyses are consistent with the same solution: net eastward tilt of the Owens Valley block at a rate of between 3.5 and 6.1°/Ma. Given the dip on the basement determined from geophysical data and extrapolating the rate of tilt in the Owens Valley back in time, it is inferred that the break-up of the Sierra Nevada and the northern Owens Valley occurred in the Pliocene, between around 2 and 4 Ma ago. The pattern of deformation in the northern Owens Valley matches anticlinal flexure on the Coyote warp, near the front of the Sierra Nevada, and faulting across the Volcanic Tableland is consistent with flexural extension. It is proposed that the Coyote warp is an expression of the tectonic hinge between westward rotation of the Sierra Nevada and eastward rotation of the Owens Valley since the Pliocene.

Key words neotectonics · morphometric analysis · crustal deformation · Basin and Range · Owens Valley

Introduction

Setting

The Owens Valley is a deep structural depression between the Sierra Nevada to the west and the write Mountains to the east (Fig. 1); it is the westernmost down-dropped block of the Basin and Range Province. The western wall of Owens Valley is a precipitous escarpment up to 2 600 m high and has been called the tallest mountain-front in the USA (Hinds, 1952). The earliest geomorphologists to visit this area were struck by its rugged topography; J. D. Whitney, visiting the valley in 1872, wrote:

> Both sides of the valley are bordered by extremely steep and elevated mountains, by which it is closed in, as if by two gigantic walls. On the west is the Sierra Nevada, with no pass across it of less than 12,000 feet [≈ 3 700 m] in elevation; the crest of the range broken into a thousand pinnacles and battlements... The Inyo and White Mountain range ... is one narrow crest, almost unique in its narrowness and steepness... Dark, sombre, destitute of trees and water, and rarely whitened with snow, even for a short period, it presents a most striking contrast to the Sierra side of the valley. (Whitney, 1872)

Active faulting

Active differential motion between the Sierra Nevada and the Owens Valley is expressed on the Owens Valley Fault Zone (OVFZ), which was the site in 1872 of one of the largest earthquakes recorded in the USA, of magnitude $M_w = 7.5-7.7$ or larger (Beanland and Clark, 1993). The 1872 earthquake is generally interpreted to have been an oblique slip, with both normal and right-lateral components. Eyewitness and historical reports (e.g. Whitney, 1972; Gilbert, 1884) support dominantly normal offsets of up to 7 m and a subsidiary, ambiguous pattern of strike-slip offsets. Recent research suggests the opposite – up to 10 m of right slip in 1872 and much smaller normal offsets averaging only 1 ± 0.5 m (Beanland and Clark, 1993).

Differential motion between the Owens Valley and the White Mountains is less well constrained than between the valley and the Sierra Nevada. In the vicinity of the town of Big Pine, a discrete White Mountain fault zone is identified, with right-normal oblique offset (Ramelli and

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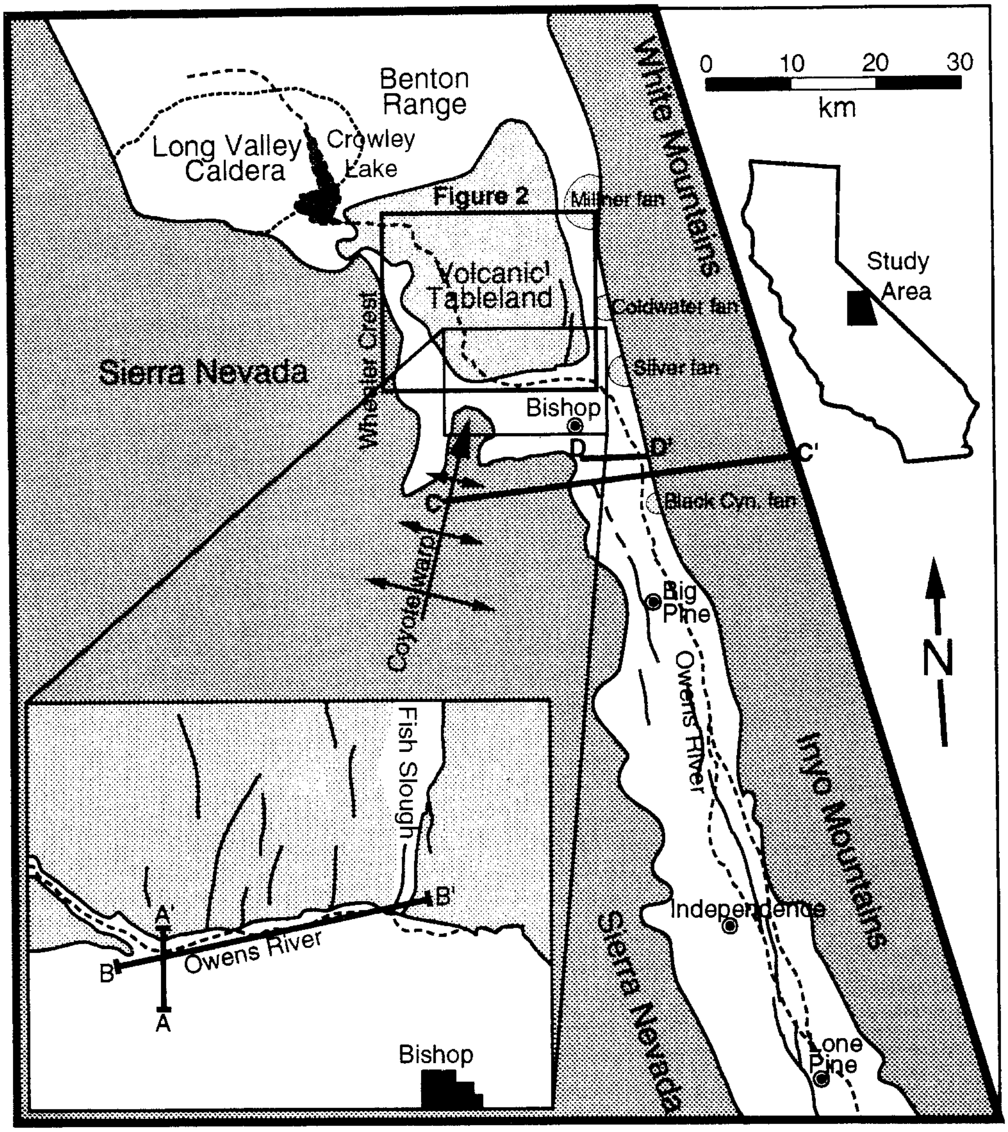


Fig. 1. Location map of major physiographic features of the Owens Valley. The boxed area shows area illustrated in Fig. 2, and the inset at the lower left shows the cross sections illustrated in Fig. 4 and Fig. 12. The locations of profiles A – A′, B – B′, C – C′ and D – D′ are shown. Note that the Coyote warp is defined only imprecisely and its position as shown is approximate

Depolo, 1987). Further north, the fault is said to merge with the eastern escarpment of the Owens Valley. Gravimetric measurements suggest that the frontal fault of the White Mountains is much more uniform, linear and roughly coincident with the topographic scarp of the range than is the boundary fault of the Sierra Nevada (Pakiser et al., 1964).

Bishop Tuff

A single event approximately 738,000 years ago 738 ka; Izett et al., 1988) fundamentally altered the physiography of the northern Owens Valley – the cataclysmic unroofing of Long Valley caldera ejected an estimated 600 km^3 of volcanic material (Bailey et al., 1976). Ash from that eruption is found in Quaternary deposits across much of the USA. In the northern Owens Valley, ash occurs both as airfall deposits widespread across the valley and adjacent ranges and as the Bishop Tuff, a thick, welded ignimbrite sheet north of the town of Bishop (Fig. 2).

The Bishop Tuff crops out over an area of more than 1 000 km^2, with an average thickness of 150 m (Dalrymple et al., 1965). The surface of the Bishop Tuff – known as the Volcanic Tableland – slopes broadly down to the south and west away from Long Valley and is characterized by (1) pervasive joints formed by contraction during cooling of the sheet; (2) fault scarps reflecting ongoing rupture in the 738 ka since emplacement of the sheet; and (3) an ancestral drainage network, particulary well developed in the higher elevations near Long Valley.

Other geomorphological features of the Volcanic Tableland include ridges and mounds, elevated from a few meters to a few tens of meters (Fig. 3), which have been interpreted as relict fumaroles, vents to gases escaping the sheet during cooling. The Fish Slough fault (Fig. 2) is the largest of the many fault scarps across the Volcanic Tableland, with a total throw of up to 120 m. The Fish Slough fault forms the abrupt eastern boundary of Fish Slough, a spring-fed wetland which is home to a number of unique species. Another characteristic of the Tableland

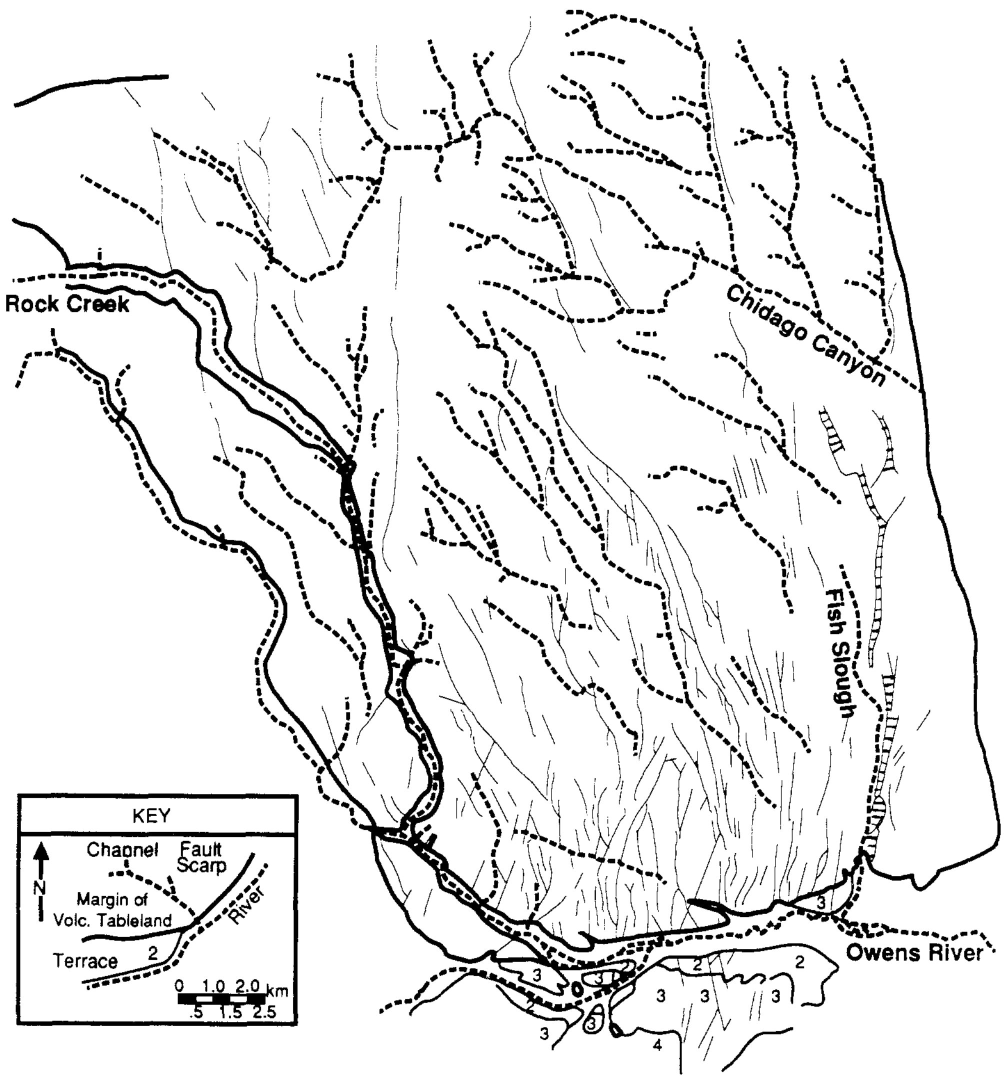


Fig. 2. Geomorphological features of the Volcanic Tableland, including terraces of the Owens River. The area represented here is shown in Fig. 1

is the gorges cut by the Owens River and Rock Creek (Fig. 3) – deeply entrenched meanders cut to depths of 150 m, or more.

River terraces

At the southern margin of the Volcanic Tableland, the Owens River leaves its gorge and takes an abrupt left turn, flowing west to east, perpendicular to the structural grain of the valley (Fig. 2). Along this stretch of the river, the fluvial system has cut and preserved three uplifted terrace surfaces (Q 2, Q 3 and Q 4) between the modern floodplain of the Owens River (Q 1) and the surface of the Bishop Tuff (Q 5) (Fig. 4). The Q 2 terrace is a sharp surface preserved up to 20 m above the modern floodplain, consisting of fluvial sand and gravel overlying pre-Bishop Tuff sediments. Terraces Q 3 and Q 4 are constructed of several meters of river gravel overlying a platform cut onto Bishop Tuff. The different levels converge downstream, to the east. By the time that the Owens River turns south, all of the terraces, as well as the top of the Bishop Tuff, merge with the active floodplain.

The Owens River is fed by a number of streams which drain the Sierra Nevada. Several of these leave canyons that were extensively glaciated in the Late Pleistocene. Many researchers have worked on the timing of glacial events in the Sierra Nevada, and the numerical ages of these glaciations are still the subject of continued discussion (Dorn et al., 1987; Gillespie, 1988; Phillips et al., 1990). The published age control is summarized in Table 1. The three terraces of the Owens River have been correlated with three Late Pleistocene glacial stages of the Sierra Nevada (Pinter et al., in press). The Q 2 level dates to the end of the Tioga glaciation. The Q 3 level dates to the end of the Tahoe glaciation. The small Q 4 surface is tentatively correlated to the end of the 'pre-Tahoe' glaciation, but may also record the Mono Basin stage (see Table 1).

The formation of the three terraces of the Owens River also coincides with three Late Pleistocene aggradation events in the Mojave Desert and elsewhere in southern California and southern Nevada (Bull, 1991) at roughly 125 000, 55 000 and 10 000 years. Although the terraces of

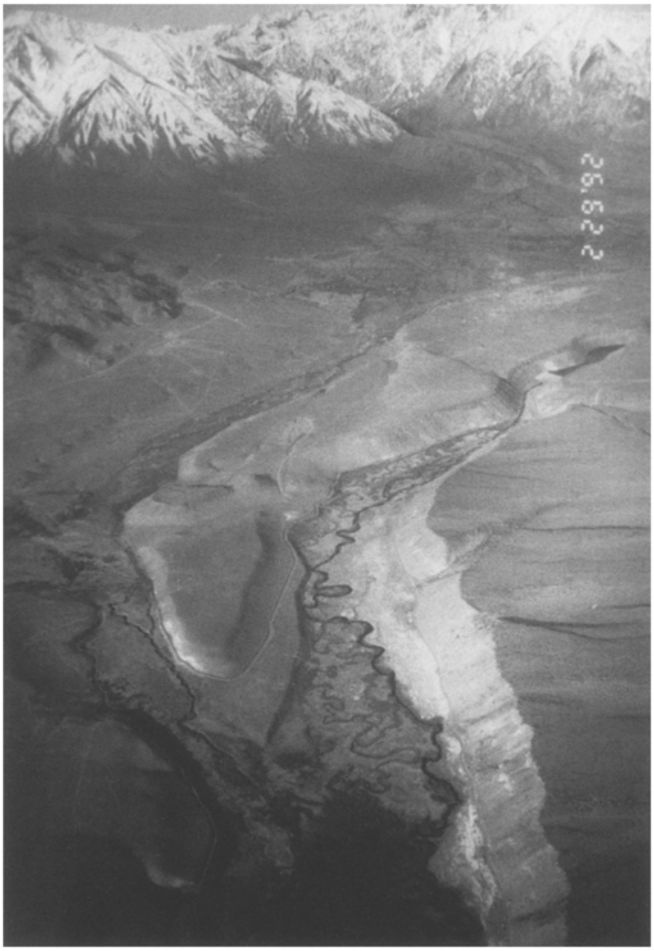


Fig. 3. The northern Owens Valley looking west, with the Sierra Nevada in the background. The Volcanic Tableland, a 738 000 year old ignimbrite sheet, is visible on the right side of the photograph, including some of the fault scarps that cut its surface. The Owens River flows across the Volcanic Tableland through the Owens Gorge and along the southern margin of the Tableland. Two uplifted fluvial terraces of the Owens River are visible south of the River and a third is found still further to the south

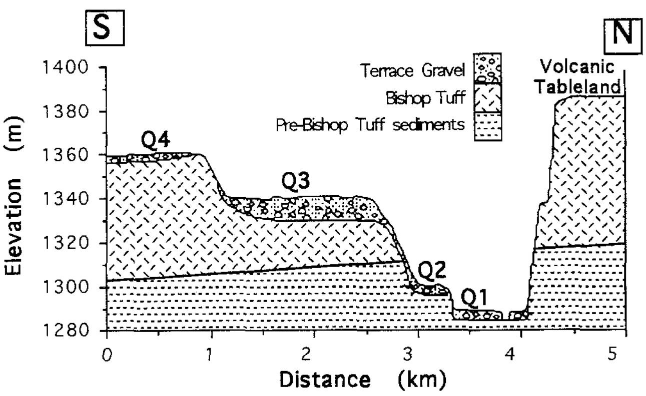


Fig. 4. Diagrammatic cross-section across terraces of the Owens River along the line A – A' (see Fig. 1). Terrace elevations are from topographic maps; gravel thicknesses are approximate. Vertical exaggeration approximately is 20 times

Table 1. Late Pleistocene glacial stages of the Sierra Nevada and available age control

Glacial stage	Radiometric age control	Surface exposure age estimates	
		Dorn et al. (1990)	Phillips et al. (1990)
Tioga	$>13.2,^{1,a}$ $<26^{2}$	–	$20.4-23.1^{c}$
Tenaya	–	–	$23.3-25.5^{c}$
Tahoe	$>53\pm44^{3}$, $<119\pm7^{4}$ $>100^{2}$	$61-79^{b}$	$55.9-65.8^{c}$
Mono Basin	–	–	$79-119^{c}$
Pre-Tahoe	$>131\pm10$, $<463\pm40^{4}$	$135-152$, $177-206^{b}$	$133-218^{c}$
Casa Diablo	$>62\pm13$, $<126\pm25^{5}$	–	–
Sherwin	$>738^{6}$	–	–

(1) Dorn et al. (1987); (2) Atwater et al. (1986); (3) Dalrymple et al. (1982); (4) Gillespie (1988); (5) Bailey et al. (1976); and (6) Izett et al. (1988).

methods: (a) AMS Radiocarbon from varnish; (b) cation ratio; and (c) chlorine-36.

the Owens River are more directly controlled by glacial events, climate oscillations of the Late Pleistocene seem to drive geomorphological history throughout the region.

Coyote warp

Preserved across the broad interfluves along the eastern base of the Sierra Nevada from Big Pine Creek northward across the Tungsten Hills is an erosional surface, inferred to be of Pliocene age, and warped into a NNE-trending anticline (Bateman, 1965). The surface is dissected, mantled by a thick soil and locally buried by subsequent glacial deposits, but its two flanks – east-facing and west- to NW-facing, respectively – are preserved. The eastern flank (which dips at 11°) and the summit of the warp are extensively cut by north-south-trending normal faults, in subparallel an en echelon segments, with both eastward and westward displacement. In contrast, the NW-facing flank of the Coyote warp is predominantly unfaulted, and those few scarps that are found strike east, northwest and northeast (Bateman, 1965).

Asymmetry of the northern Owens Valley

The topography across the northern Owens Valley is broadly symmetrical – the valley floor is flanked on either side by alluvial aprons and tall mountainous spines. Fine-grained fluvial and lacustrine sediments form a nearly level depositional surface across most of the valley floor south of the Volcanic Tableland. However, in contrast with the symmetry of the surface, geophysical and geomorphological evidence suggests that the geological structure of the valley is profoundly asymmetrical. Gravity and seismic reflection surveys conducted by the US Geological Survey in the 1950s and 1960s (Pakiser

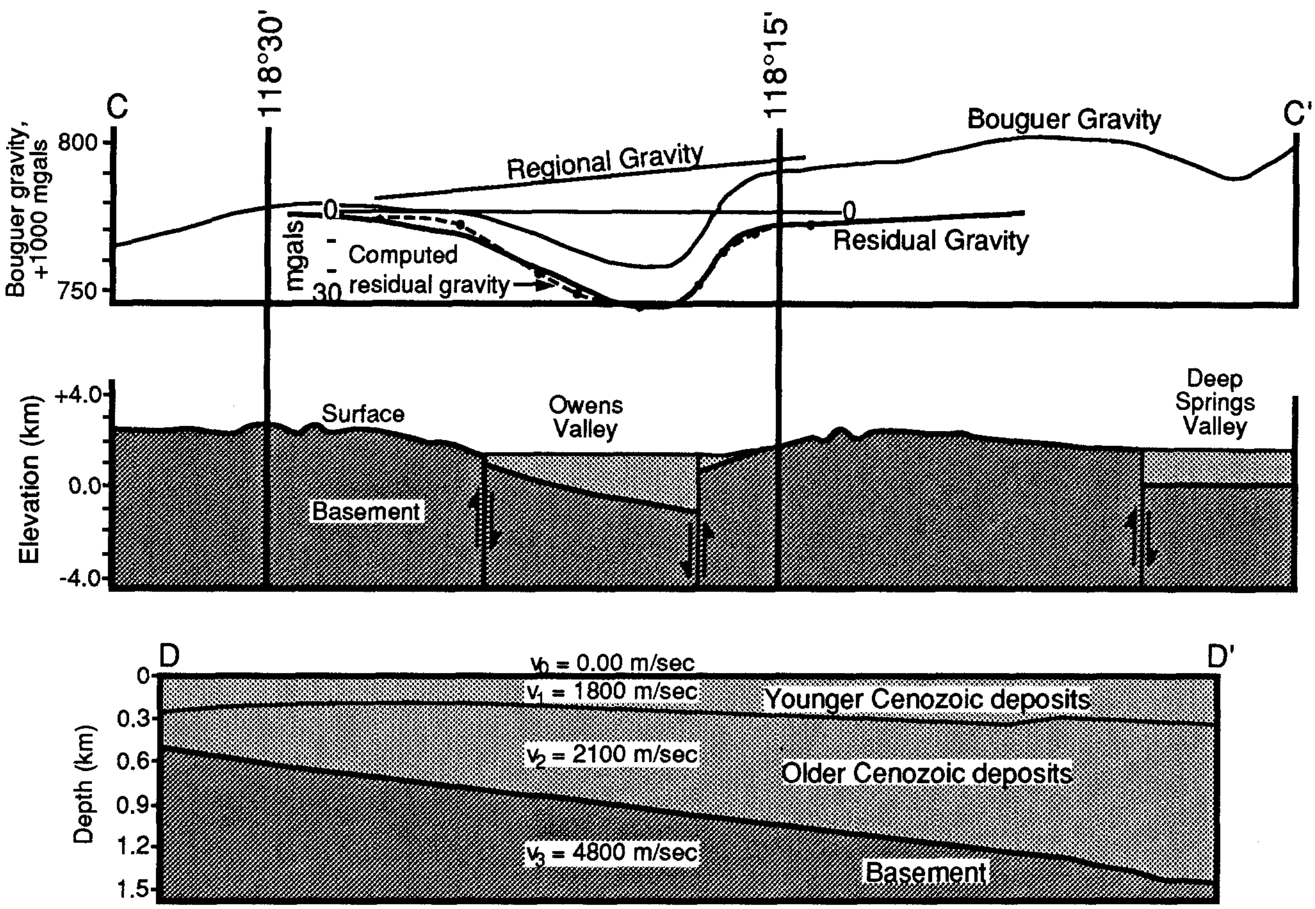


Fig. 5. Gravity and seismic reflection profiles across the northern Owens Valley along the lines C–C' and D–D', respectively (after Pakiser et al., 1964)

and Kane, 1956; 1962; Pakiser et al., 1964) reveal that the crystalline basement beneath the floor of the Owens Valley dips down to the east (Fig. 5). This dip is evident at least as far south as Lone Pine, but is especially pronounced in the vicinity of Bishop. Estimates of the depth of sedimentary fill atop basement calculated from gravity and seismic reflection data differ: 2440 and 1950 m, respectively. The angle of dip on the basement is calculated to be 11.0° from seismic reflection and 13.7° from gravity (from data in Pakiser et al., 1964).

Asymmetry of the northern Owens Valley is also indicated by the position of the Owens River within the valley. Along most of the length of the valley, the river does not run in the center of the valley, but rather at the very eastern margin, near the base of the alluvial fans of the White Mountain front. This geometry is consistent with models of drainage in active half-graben basins (Leeder and Gawthorpe, 1987) and provides the first hint that not only is the structure of the northern Owens Valley asymmetrical, but the mechanism which caused the asymmetry remains active in shaping the modern geomorphological systems.

Geomorphological tools

Three morphometric analyses are utilized here to quantify the mode and rate of deformation in the northern Owens Valley: (1) Channels cut a top of the Bishop Tuff preserve a downslope vector that does not match the modern topography; (2) The shape of alluvial fans along the front of the White Mountains, at the eastern margin of the Owens Valley, reflect on-going deformation; and (3) Terraces of the Owens River have been systematically tilted.

Using terraces to measure deformation of the land surface is a familiar technique. Measuring channel reorientation is an application of simple techniques in structural geology. The alluvial fan analysis is a quantitative solution that is outlined here for the first time.

Drainage reorientation

Method

The surface of the Volcanic Tableland has developed a complex network of fluvial channels (see Fig. 2). This network is ancestral and not active. Several channels are abruptly offset by faults (Fig. 6) and others are locally covered by eolian deposits. Where several of the channels reach the southern margin of the Tableland, where the

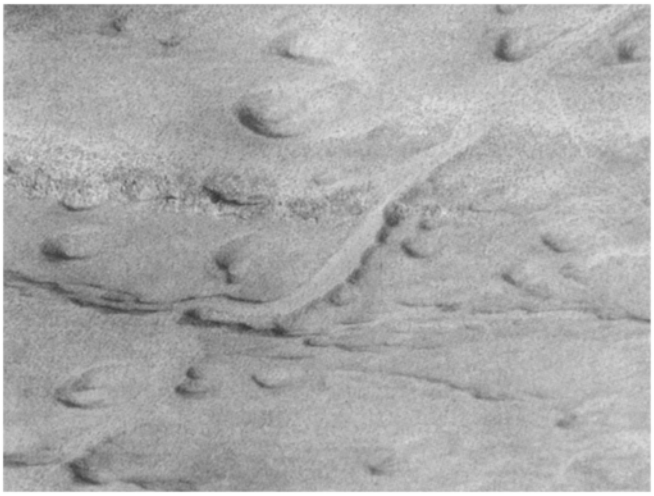


Fig. 6. Faulted paleochannel cut atop the Volcanic Tableland, looking to the SW. The former direction of flow of the channel was to the SE, from left to right across the photograph. Note that the channel crosses and is offset by a number of west-facing fault scarps

Owens River has cut a tall bluff, they grade to the high, Q 3 terrace level, as much as 50 m or more above the modern base level. Where modern streams flow across the Volcanic Tableland, in the Owens River and Rock Creek, they flow through deeply incised gorges. Modern drainage on the Tableland appears to be dominantly through the subsurface (Pinter and Keller, 1991).

The fluvial network developed some time after the emplacement of the Bishop Tuff. The geometry of the network shows that many of the faults on the Volcanic Tableland were already in place when the network formed. The network was active when the Q 3 surface was active, but not afterwards. The glacial deposits of the northern Owens Valley generally consist of three major post-Bishop Tuff moraine systems, recording extensive glaciation within the last 200 ka (Gillespie, 1988; Dorn et. al., 1990; Phillips et al., 1990). Earlier glacial episodes may have occurred, but must have been relatively small, so that their records were erased by the subsequent advances. Available evidence in the Sierra Nevada suggests that the first occurrence of conditions favorable to the formation of the paleochannels was the pre-Tahoe glaciation, between 206 and 131 ka (see Table 1). The channels were subsequently reoccupied during the Tahoe glaciation (56 – 79 ka).

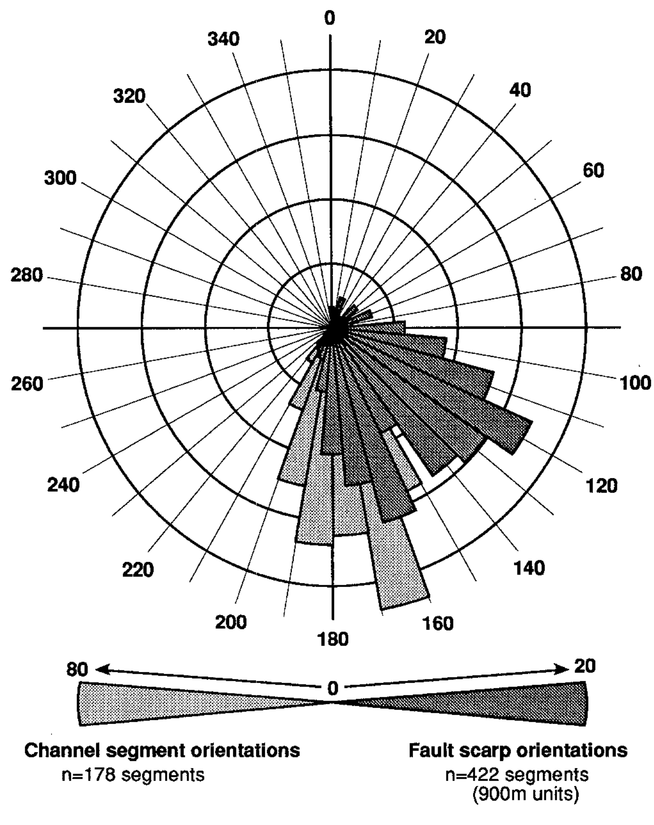
The channel network was mapped from 1 : 40 000 scale air photographs and rectified to a 1 : 64 500 base map (see Fig. 2). The stream-order (*S*) of each segment in the network was determined as outlined by Strahler (1952), and the orientation (from endpoint to endpoint) of each segment $S \geqq 2$ was measured. The first-order tributaries were excluded because they varied much more than the higher-order segments, and because the great number of first-order channels tended to overwhelm the analyses.

Results

We measured the orientations of 178 channel segments and the results are plotted in Fig. 7. The distribution of orientations is distinctly bimodal, at 121 – 125° and 161 – 165° azimuth. Furthermore, we note that most of the channels associated with the second, more southerly mode occur at the bases of large west-facing fault scarps (see Fig. 2). Analysis of the orientations of fault scarps across the Volcanic Tableland reveals that the 161 – 165° direction also coincides with the mean orientation (160 – 169°) of the faults (Fig. 7).

The first glacial event after the emplacement of the Bishop Tuff recorded in the northern Owens Valley is the pre-Tahoe glacial stage. The orientations of the channels support the hypothesis that the network formed at that time – increased precipitation during the glacial period incised channels into the sloping surface of the Tableland. However, that surface was already extensively faulted and the downslope flow (oriented 121 – 125° on average) was blocked by a number of west-facing fault scarps (oriented 161 – 165° on average) and redirectered along the bases of the scarps. During the preceding and subsequent non-glacial times, flow across the porous and fractured Bishop Tuff has been predominantly in the subsurface.

Fig. 7. Rose diagram of channel-segment and fault-scarp orientations on the Volcanic Tableland. Angle about the center of the circle represents the compass azimuth, and distance from the center represents relative frequency. Note that the frequency scale is different for the channels and the faults – each concentric ring denotes 5 fault-scarp segments in that interval or 20 channel segments



The mode of channel orientations at 121 – 125° is close to, but not equal to, the modern slope of the Volcanic Tableland, which averages 113° azimuth (N 23° E strike) and 2.8° dip to the SE. Apparently, since the time that the channels were cut into the surface in pre-Tahoe glacial time, the average slope of the Tableland has been reoriented. This change in strike of 8 – 12° to a more easterly slope is consistent with tilting of a few degrees down to the east about a north-south axis. Tilting down to the east has the effect of steepening dips in that direction and reorienting them to more easterly configurations. We assume that this rotation occured about an axis parallel with the average strike of faults on the Tableland, oriented 165 – 169°. Using this information, we calculate tectonic tilt of 0.6 – 0.8° down to the east, which has occurred since 131 – 206 ka.

Summary of technique

Tectonic tilt can be calculated from measurement of a drainage network, given the appropriate setting and a few assumptions:

1. Setting – where a drainage network on a broad, regular surface was cut some time in the past and the area subjected regional deformation;
2. Measurements – the orientations of a statistically significant number of channels, preferably excluding first-order tributaries
   – the modern slope of the surface on which the drainage network in found;
3. Assumptions – that the network is either now inactive or that it is incised and the orientation of channels no longer changes
   – that deformation is sufficiently regional to affect the network uniformly.
   As with all of the analyses described in this paper, an estimate of the age of the landform is necessary to the calculate the rate of deformation.

Deformation of alluvial fans

Background

The modern-day geomorphology of the White Mountain front is dominated by a number of large, well-formed alluvial fans which are located at the outlets of canyons draining the mountain block. It has been recognized that alluvial fans, the distinctive landforms of arid to semiarid mountain fronts, have cross-sectional profiles (from the head of the fan to its base) which are smooth and broadly concave-upward (Troeh, 1965). However, in most instances, the concavity is small and the profile nearly linear. As a result, the fans are approximately conical in shape under geometrically-simple and tectonically-stable conditions. Topographic contours across a cone-shaped fan approximate segments of evenly spaced concentric circles.

It also has been recognized that if a conical fan is tilted (Fig. 8), contours across it become segments of ellipses (Wahrhaftig, 1970). The changes in the shape of a conical alluvial fan subjected to tilt have been worked out in detail by West (1991). The elongation of contours into ellipses is sensitive only to the horizontal component of rotation. In the extreme opposite case, rotation about a vertical axis (such as 'rotations' in the paleomagnetic sense) will pivot a fan without altering the shape of the contours. For the sake of brevity, the word 'tilt' will be used here to denote the purely horizontal component of rotation. Deformation caused by tilting is most clearly preserved where the fan, or segments of it, have been rendered depositionally inactive. If deposition on the fan exceeds the tectonic deformation, it will tend to anneal the fan and return it to the conical shape.

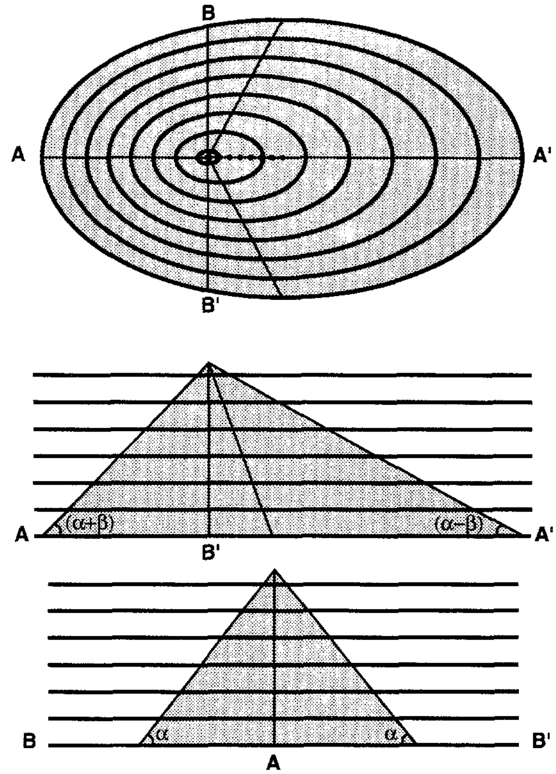


Fig. 8. Geometric model of a tilted cone, viewed from above and along the profiles indicated. Heavy lines represent lines of equal elevation across the surface of the cone (contour lines). Each ellipse shares one common focus, but the center of each ellipse of descending elevation is progressively offset away from the direction of downward tilt. The major axes of all ellipses are colinear; the minor axes are parallel but offset

Two types of information can be gained from the morphometry of tilted fans. Where a fan or large segment of a fan has been inactive, both the orientation of the tilt axis and the magnitude of the tilt can be determined by the method outlined below. Where subsequent deposition has partially annealed the fan, only the orientation of tilt may be preserved.

Method

Analysis of fan morphology for tilt requires two steps: (1) the use of a quantitative model of a tilted cone – we provide here an algebraic solution to the geometrical model of a tilted cone described by West (1991) – and (2)

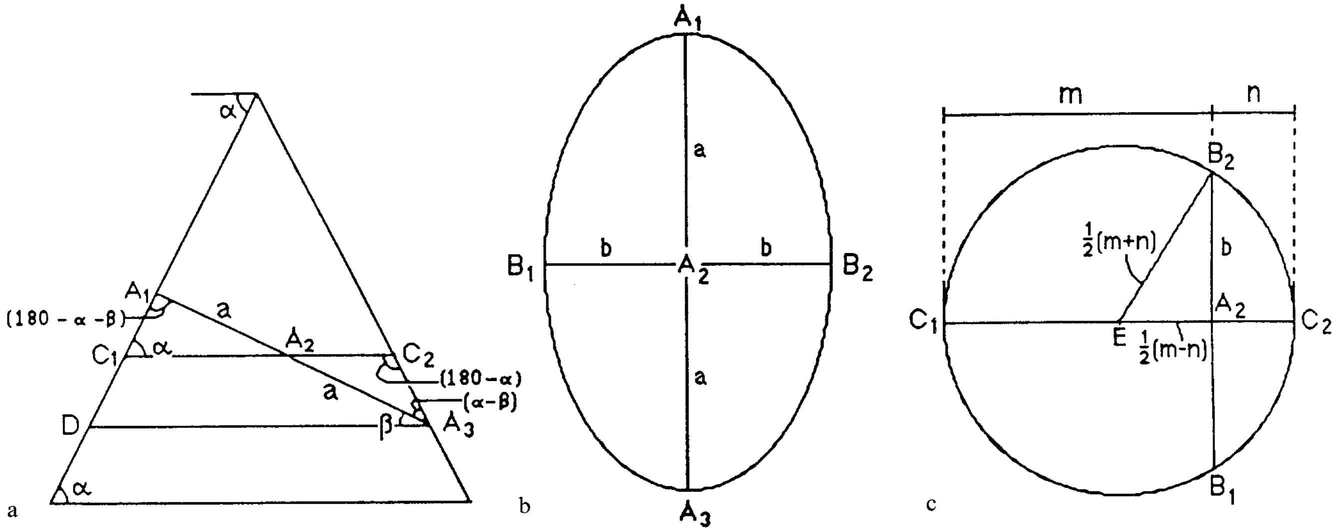


Fig. 9 a–c. Oblique intersection of a cone and a plane. Different views of the feature: (a) $x-z$ section of the cone; (b) in the plane of the intersecting plane; and (c) $x-y$ section of the cone

a method for fitting geometrically-correct ellipses to the topographic contours of a real-world alluvial fan. Both the algebraic solution of a tilted cone and a straightforward method of fitting the model to contour lines are outlined in the following.

Solution of a tilted cone

The intersection of a cone with slope α away from its apex and a plane oblique to it by an angle β (Fig. 8, Fig. 9a) produces an ellipse. The major axis of this ellipse (Fig. 9b), running from A_1 to A_3, is of length $2a$; and the minor axis, running from B_1 to B_2, is of length $2b$ and intersects the major axis at A_2. A cross-section through the cone parallel to the line, D_1 A_3, produces a circular section (Fig. 9c), where E is the center of the circle and m and n are the lengths indicated. Looking at the triangle $E-B_2-A_2$, application of Pythagoras's Theorem results in

$$b^2 + [0.5\,(m-n)]^2 = [0.5\,(m+n)]^2 \qquad (1)$$

Simplifying and solving for m

$$m = b^2/n \qquad (2)$$

Looking at triangles $A_1-C_1-A_2$ and $A_2-A_3-C_2$ (Fig. 9a), the Law of Sines gives

$$\frac{\sin\alpha}{a} = \frac{\sin(180-\alpha-\beta)}{m} \qquad (3)$$

Combining Equation (2) and (3) and solving for n

$$n = \frac{b^2 \sin\alpha}{a \sin(180-\alpha-\beta)} \qquad (4)$$

Again by the Law of Sines (Fig. 9a) and solving for n

$$n = \frac{a \sin(\alpha-\beta)}{\sin(180-\alpha)} \qquad (5)$$

Combining Equations (4) and (5) and simplifying

$$b^2/a^2\,(\sin\alpha)\,[\sin(180-\alpha)] = [\sin\alpha\cos(-\beta) + \cos\alpha\sin(-\beta)] * [\sin(180-\alpha)\cos(-\beta) + \cos(180-\alpha)\sin(-\beta)] \qquad (6)$$

Because it is predetermined that $0 \leqq \alpha \leqq 90°$ and $0 \leqq \beta \leqq 90°$

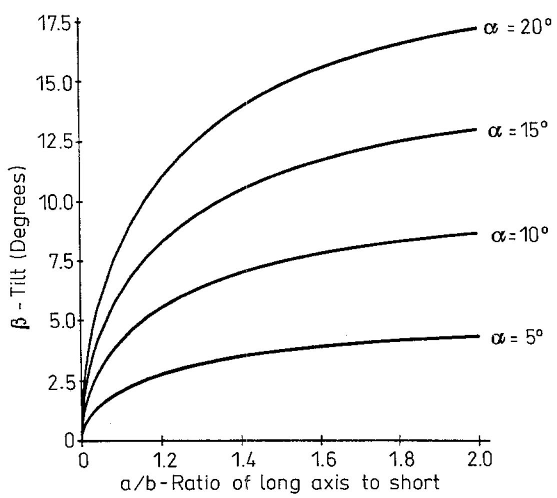
$$b^2/a^2 \sin^2\alpha = [\sin\alpha\cos\beta - \cos\alpha\sin\beta]\,[\sin\alpha\cos\beta + \cos\alpha\sin\beta] = b^2/a^2 \sin^2\alpha = [\sin^2\alpha\cos^2\beta - \cos^2\alpha\sin^2\beta] \qquad (7)$$

Solving for β, the angle of tilt of the cone

$$\beta = \arccos\{[(b/a)^2 \sin^2\alpha + \cos^2\alpha]^{0.5}\} \qquad (8)$$

In summary, the angle of tilt of the cone, β, can be calculated knowing α, the slope of the untilted cone, and

Fig. 10. Relationship between the magnitude of tilt of the cone (β) and the elongation of elliptical cross sections (a/b) for a few values of α, which is the lateral (also original) slope of the cone



a/b, the ratio of the lengths of the long axis to the short, of the resulting elliptical cross-section (Fig. 10). The values of a and b can be measured directly from the ellipse. The value of α, although not immediately obvious, can also be measured directly from the modern, tilted fan. The angle α is equivalent to the slope of any tilted cone parallel to the tilt axis (perpendicular to the line of steepest descent down the fan).

Fitting of ideal ellipses to topographic contours

If all tilted alluvial fans were completely unconfined and uneroded, then all parameters for measuring tilt could be measured directly from topographic maps and all we would need to calculate tilt would be a ruler, Equation (8) and a calculator. In the field, however, fans will cover a limited radial arc, forming only a segment of the complete ellipse, and be eroded, so that the contours only approximate that segment.

The second step in this procedure is to fit a true, complete ellipse to one or more contours around the tilted fan. What makes this possible is the mathematical axiom that for any segment of an ellipse, no matter how small, there exists a unique full ellipse that can be fitted to it. The limiting factor to geological applications is the degree to which the contours in question deviate from the mathematically perfect form.

Different ellipses differ in their size, orientation and eccentricity. Fitting an ideal ellipse to a single contour line can be accomplished either digitally or graphically. To fit ideal ellipses to more than one contour line on the same tilted fan, each fit must be geometrically consistent with all others. Contours on an ideal tilted cone will consist of a series of concentric ellipses, their centers progressively offset in the direction of downward tilt (see Fig. 8). To adhere to this ideal model, all ellipses must: (1) be of the same shape (identical a/b ratios); (2) have parallel minor axes; (3) have colinear major axes; and (4) be offset such that the up-tilted, minimum slope equals $(\alpha - \beta)$ and the down-tilted, maximum slope is $(\alpha + \beta)$. We have found that this process can be most easily accomplished by scanning the desired portions of topographic maps into a computer and using a commercial computer graphics package (we use *Adobe* or *Canvas* on the Macintosh) to draw, scale, rotate and fit the ellipses.

Results

We have analysed several of the most prominent alluvial fans of the White Mountains front, at Millner, Silver, Poleta and Black Canyons, for fit to the tilted cone model in order to calculate the magnitude and direction of tilt (Fig. 11). The fit of the actual alluvial fans to the models varies from moderate to excellent. Deviations from the ideal fall into one of three categories: (1) poor fit at the lateral margins of the fans, where material is shed directly onto the fans; (2) upslope 'vee-ing' of the contours at incised channels; and (3) localized downslope bulging of the contours, which probably reflects lobes of recent deposition and aggradation.

Topographic contours across one of the four alluvial fans studied, the Millner fan, are circular and indicate no tilt. The Millner fan is much larger than the others analysed here and is the only one for which active deposition is recorded – a large debris flow in 1952 (Beaty, 1963). However, the solutions for the three other fans all point to down-to-the-east tilt about axes nearly north–south.

Because all of these fans are, to some degree, depositionally active, the magnitudes of tilt calculated here (0.8, 1.5 and 4.3° on the Silver, Coldwater and Black canyon fans, respectively) are not meaningful. Among the four fans, including the Millner, greater tilts are derived for the smaller fans, suggesting that there is indeed a dynamic balance between deformation and restoration. The greatest utility of this morphometric analysis is in settings where inactive fan segments are preserved and the absolute magnitude of tilt can be calculated (West, 1991).

Summary of technique

Tectonic tilt can be calculated from the morphology of alluvial fans, given the appropriate setting and a few basic assumptions:

1. Setting – where an alluvial fan has been subjected to tectonic tilt
   – If the process of deformation has dominated over the process of deposition, then it is possible to determine the *character* of tilting
   – If a fan or a portion of a fan has been depositionally inactive over a period of time, then it is possible to calculate the *amount* of tilt
   – If the age of the fan or inactive fan segment is known, then the *rate* of tilt can be calculated
2. Measurements – topographic contours on an alluvial fan are fit to a series of ellipses to find the best possible match between the fan and a geometrically-correct model of a tilted cone
   – The slope of the alluvial fan parallel to the short axes of the ellipses (α)
   – The lengths of the long axis (a) and the short axis (b) of the ellipse are measured; where $a \neq b$, there has been tilt, and the amount (β) can be calculated using Equation (8)
3. Assumptions – that the alluvial fan is nearly conical in shape; i.e. that a cross-sectional profile from the head of the fan to its toe is close to a straight line
   – That the alluvial fan covers an adequate radial area. At best, a fan along a linear mountain front will span 180°of arc; at worst, a fan within a narrow embayment or coalesced with adjacent fans (for example, on a bajada) will not be useful.
   – That erosion has not altered the surface of the fan significantly. Minor gullying is to be expected and is largely eliminated by the best-fit process, but large-scale erosion renders this analysis invalid.

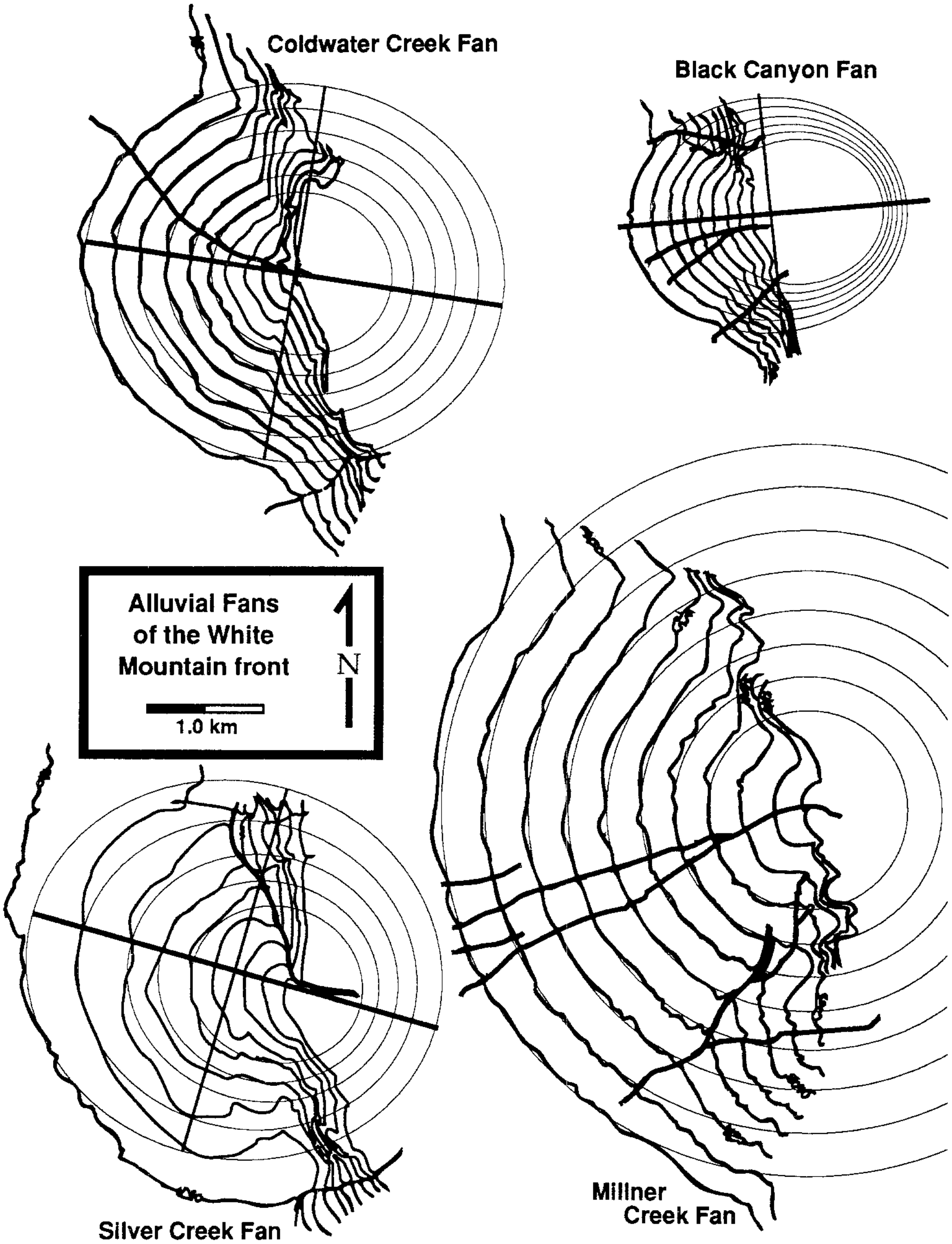


Fig. 11. Fit of tilted cone models to topographic contours across the alluvial fans along the White Mountains front of the northern Owens Valley. The contour interval shown for the Silver, Coldwater and Black Canyon fans is 10 m; the interval for the Millner Canyon fan is 80 ft.

Tilting of terraces

Method

Where the Owens River leaves its gorge through the Tableland and runs west to east, perpendicular to the structural trend of the Owens Valley, the four terraces of the river as well as the Tableland surface converge dramatically in the downstream direction. The terrace fronts of Q 2 and Q 3, which are tall scarps to the west, gradually decrease in height to the east until they merge entirely with the modern floodplain in the vicinity of Fish Slough. The surface of the Bishop Tuff also dives down and is covered by recent alluvium at the base of the Fish Slough fault.

We measured several transit profiles across the terraces to determine the geometry of the terrace sequence (Fig. 12). The floodplain of the Owens River is a smoothly-sloping surface, and its elevation can be determined from topographic maps. We assume that the modern slope of the Owens River is similar to its slope in the Late Pleistocene. The magnitude of deformation is measured as the average slope of each terrace (over a distance of 7.0 km from near the outlet of the gorge to the Fish Slough fault), minus the slope of the modern river.

Results

Divergence or convergence of river terraces is typically the result of either tectonic or climatic processes. Long-term climatic changes may slowly alter the dynamics of

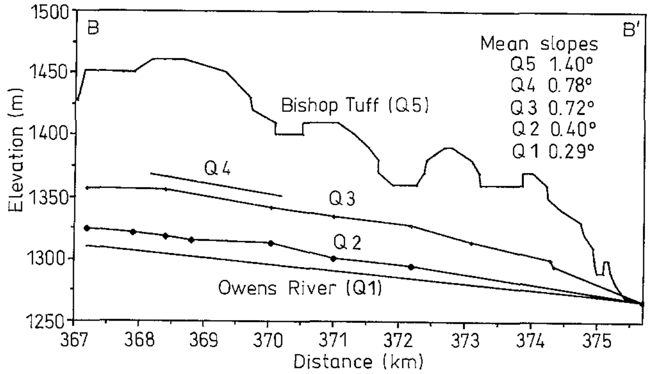


Fig. 12. Terrace elevations along the line B–B' (see Fig. 1) measured relative to the modern floodplain of the Owens River, the elevation of which was determined from topographic maps. The elevations of Q4 and Q5 also were taken from topographic maps

the fluvial system, increasing or decreasing the gradient of the river and producing terraces. However, in the Owens Valley and adjacent Sierra Nevada, Late Quaternary climate is known to be characterized by waxing and waning glaciers, not be any steady, long-term shift. Instead, the downstream convergence of the terraces of the Owens River is consistent with systematic rotation down to the east during Late Pleistocene time.

The southern Volcanic Tableland forms a broad topographic arch, the highest elevation of which coincides with the greatest vertical spacing of the terraces on Fig. 12. To the west, the surface of the Tableland declines and is buried by alluvium near the foot of the Sierra Nevada. Taken as a whole, eastward-tilting observed across the terraces and most of the Volcanic Tableland may reflect hinging about an axis that projects northward from the Coyote warp. Hinging consists of both broad flexure and offsets on discrete faults. Much of the recent deformation is concentrated near Fish Slough, which has been the locus of deformation late in the history of the Tableland (Pinter and Keller, 1990).

Summary of technique

Tectonic tilt can be calculated from the spacing of a series of fluvial terraces, given the approporiate setting and a few basic assumptions:

1. Setting – where a river has cut terrace surfaces and episodically incised through and abandoned them, and where ongoing deformation has tilted the abandoned terraces such that the oldest ones are the steepest and the younger ones closest to the modern gradient of the river
2. Measurements – vertical spacing of the terraces at a number of locations along the river, and the modern gradient of the river
3. Assumptions – that divergence or convergence of the terraces reflects tectonic, rather than climatic, processes
   – that given a number of terraces with a number of age estimates, calculating the rate of tilt becomes much simpler by assuming a uniform rate through time

Summary of results

Geophysical evidence, the asymmetry of the Owens River and the results of the three geomorphological analyses discussed here (channel reorientation, alluvial fan morphology and terrace rotation) reveal the long-term deformation in the northern Owens Valley. During at least the last 738 000 years, the region has undergone net displacement and tilting down to the east. The coincidence of independent lines of evidence adds strength to the conclusion.

Discussion

The northern Owens Valley has been a fruitful study area because it has allowed us to quantify the amount of deformation on a variety of landforms. However, equally importantly, the area provides a detailed chronology, both volcanic and glacial, that allows us to calculate the rate of deformation. Deformation data and available age control are summarized in Table 2. Because of the uncertainty of the absolute ages of the glacial stages, these ages are expressed as ranges, using the maximum and minimum controls published elsewhere. Rates of tilting are calculated from the magnitude of tilt and the age of the feature and are quoted as the broadest possible range given the data. All of the available evidence is consistent with eastward rotation at a rate of between 3.5 and 6.1°/Ma (degrees per million years).

Rate of tilt is itself a powerful tool. Extrapolating the rotation measured during the last 738 ka to the 11.0–13.7° dip of the northern Owens Valley basement suggests that the onset of sedimentation in the valley occurred between 1.8 and 3.9 Ma. The break-up of the Sierra Nevada and Owens Valley blocks must pre-date the

Table 2. Summary of age and deformation data for landforms of the northern Owens Valley. The range of rates shown is calculated as the maximum and minimum values, given maxima and minima in the age and deformation data

Analytical technique	Age range (ka)	Rotation (°)	Rate (°/Ma)
Alluvial fan morphology	NA	0–4.3	NA
Tilting of terraces			
Q2 (Tioga age)	13–26	0.11	4.2–8.5
Q3 (Tahoe age)	53–119	0.42	3.5–7.9
Q4 /pre-Tahoe or possibly Mono Basin	79–218	0.52	2.4–6.6
Paleochannel network (pre-Tahoe age)	131–218	0.6–0.8	2.9–6.1
Basement of Owens Valley			
Gravity measurments	See discussion	13.7	See discussion
Seismic reflection		11.0	

onset of sedimentation. Although the extrapolation may be unwarranted, this age is consistent with other estimates of the onset of motion between the Sierra Nevada and the Owens Valley. Tilting of the Sierra Nevada (in the opposite direction, down to the west) began around 5 Ma (Unruh, 1991). In addition, deposition of the Coso Formation – the oldest dated basin fill within the southern Owens Valley – began around 6.0 Ma (Giovanetti, 1979). Assuming that both age estimates are valid, the break-up of the Sierra Nevada and Owens Valley may have progressed northward during the Pliocene, much as the volcanic activity associated with Long Valley caldera has migrated northward during the Pleistocene and Holocene (Bailey et al., 1976).

We also must consider the regional significance of deformation in the northern Owens Valley. The pattern of faulting across the Volcanic Tableland – north-trending, subparallel, en echelon fault segments – is identical to the pattern observed across the summit and eastern flank of the Coyote warp (Bateman, 1965). Similary, the 11° of eastward dip on the flank of the Coyote warp is consistent with the mode and the rate of tilting measured across the Volcanic Tableland and is coincident with the dip of the inferred Pliocene-age basement beneath the northern Owens Valley. In contrast, the structural style across the NW flank of the warp is far more consistent with the adjacent Sierra Nevada block – dipping a few degress to the west and, where faulted at all, cut by complex, cross-trending structures. Eastward tilting of the Owens Valley and westward tilting of the adjacent Sierra Nevada must be accommodated. We propose that the anticlinal trend of the Coyote warp has acted as the tectonic hinge between the Sierra Nevada and the Owens Valley blocks.

Fault displacements across the surface of the Volcanic Tableland are both down to the east and the west. A transect was measured 14 km across the width of the densely faulted southern Tableland to precisely measure the net contribution to down-to-the-east displacement across the valley. Including the Fish Slough fault, there is essentially zero net eastward displacement on faults. Flexure of a rigid medium will necessarily cause extension across the upper surface. The widely distributed normal faulting across the northern Owens Valley may reflect extension necessarily associated with hinging between the Sierra Nevada and Owens Valley.

Conclusions

In summary, several techniques have been developed and used to infer the amount of deformation in the northern Owens Valley from the morphometry of the landforms. The result show down-to-the-east rotation during at least the last 738 000 years at a rate of 3.5 – 6.1°/Ma. If this rate can be projected back in time, the dip on basement suggests that the break-up of the Sierra Nevada and the Owens Valley and the onset of sedimentation in the valley occurred in the Pliocene, between around 2 and 4 Ma ago. The character of deformation in the northern Owens Valley, both eastward rotation and faulting on the Volcanic Tableland, is consistent with deformation of the Coyote warp anticlinal trend. We suggest that flexure, tilting and faulting in the northern Owens Valley reflect hinging between the westward-tilting Sierra Nevada and eastward-tilting of the Owens Valley block.

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