Quaternary low-angle slip on detachment faults in Death Valley, California

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ABSTRACT

Detachment faults on the west flank of the Black Mountains (Nevada and California) dip 29°–36° and cut subhorizontal layers of the 0.77 Ma Bishop ash. Steeply dipping normal faults confined to the hanging walls of the detachments offset layers of the 0.64 Ma Lava Creek B tephra and the base of 0.12–0.18 Ma Lake Manly gravel. These faults sole into and do not cut the low-angle detachments. Therefore the detachments accrued any measurable slip across the kinematically linked hanging-wall faults. An analysis of the orientations of hundreds of the hanging-wall faults shows that extension occurred at modest slip rates (<1 mm/yr) under a steep to vertically oriented maximum principal stress. The Black Mountain detachments are appropriately described as the basal detachments of near-critical Coulomb wedges. We infer that the formation of late Pleistocene and Holocene range-front fault scarps accompanied seismogenic slip on the detachments.

Keywords: detachment, Death Valley, Quaternary, extension, tephrochronology.

INTRODUCTION

Low-angle normal, or detachment, faults are recognized in extended regions worldwide. Detachment faulting is a controversial process that seemingly defies a mechanical explanation despite its prevalence and its possible role in accommodating large-magnitude extension and denudation (Wernicke, 1985). Two general questions are currently debated: (1) can slip occur on normal faults that dip 30° or less (Buck, 1988; Wills and Buck, 1997)?, and (2) is slip on detachments seismogenic (Wernicke, 1995; Jackson and White, 1989)? One reason that these questions remain is that there are few documented examples of detachment faults that have been active in the Quaternary Period (Wernicke, 1995).

The literature contains arguments for and against low-angle, normal-sense slip on detachments. For example, the rolling-hinge model for extension hypothesizes that detachments originated as steeply dipping normal faults that were tilted and became deactivated as the footwalls isostatically responded to exhumation (Buck, 1988; Wernicke and Axen, 1988). In contrast, geologic and geophysical evidence from some extended regions indicates that slip occurred on normal faults dipping ≤30° (Axen, 1999; Axen et al., 1999; Abbott et al., 2001). We report geologic evidence from Death Valley that strongly supports the argument that seismogenic slip occurred on low-angle normal faults in Quaternary time.

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BLACK MOUNTAIN DETACHMENTS

Death Valley is in the southwestern part of the Basin and Range Province, an exemplar of intracontinental extensional tectonics. Since late Miocene–early Pliocene time, the Death Valley pull-apart basin between the Black Mountains and Panamint Mountains extended between the Northern Death Valley and Southern Death Valley dextral strike-slip fault systems (Fig. 1) (Burchfiel and Stewart, 1966). The extension has been accommodated on the eastern margin of Death Valley along the Black Mountains fault zone, which comprises gently (range 19°–36°, average 25°) and steeply (~60°) dipping normal faults with local oblique-to-strike-slip components (Keener et al., 1993). We studied three localities in the Black Mountains fault zone where the detachments and hanging walls are exposed above the basin floor: Badwater, Mormon Point, and South Mormon Point (Fig. 1). We investigated the stratigraphy and structure of the hanging walls and the relationship of faults in the hanging walls to the detachments.

In a typical exposure of a detachment fault at these localities, a well-defined principal slip plane separates the hanging wall from a 0–7-m-thick zone of gouge and breccia (Miller, 1996). Above the detachments, hundreds of steeply dipping and listric faults cut the hanging-wall sediments (Fig. 2). In exposures, these faults sole into or are cut by the principal slip plane, and hanging-wall sediment is locally present within the pervasively deformed fault rocks. These observations collectively indicate that slip on the detachments and on the hanging-wall faults occurred during the same interval of geologic time.

HANGING-WALL TEPHROCHRONOLOGY

Sediments constituting the hanging walls at Badwater and Mormon Point were deposited in playa lake and alluvial fan environments that are similar to those of today. The most continuous exposures of hanging-wall sediments are at Mormon Point, where the section contains several pronounced tephra layers (Fig. 2). The central tephra is 100–200 cm thick and is correlated with 0.77 Ma Bishop ash on the basis of glass composition[1] and the nature of biotite phenocrysts. The Bishop ash is also intercalated with alluvial-fan breccias at Badwater.

There are prominent tephra layers stratigraphically above and below the Bishop ash exposed at Mormon Point. The younger tephra correlates with the 0.64 Ma Lava Creek B tephra (Lanphere et al., 2002) and the older with 0.8–1.2 Ma upper Glass Mountain tephra (Knott et al., 1999). These lower to middle Pleistocene sediments are overlain by 0.18–0.12 Ma (oxygen isotope stage [OIS] 6) Lake Manly gravel (Ku et al., 1998). At a few localities the Bishop ash is cut by gently dipping detachment faults. Most of the section above and below the Bishop ash is only slightly tilted from its depositional orientation. This evidence demonstrates that some slip on the detachments is younger than 0.77 Ma.

[1]GSA Data Repository item 2003041, electron microprobe analysis of volcanic glass shards from middle Pleistocene tephra layers, Death Valley, California, and comparative compositions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

HANGING-WALL FAULTS

We measured the strikes and dips of 267 hanging-wall faults above the Badwater, Mormon Point, and South Mormon Point detachments. Fault dips have a bimodal distribution (Fig. 1). West-dipping faults that are synthetic to the detachments have a mode of 55° and mean of 65°, and the east-dipping, antithetic set has a less-well-defined mode near 70° and a mean of 65°. Coulomb materials with an angle of internal friction of 30° fail along conjugate pairs of normal faults wherein the maximum principal compressive stress, σ_1, bisects an acute angle of intersection of 60°. The modes of the fault-population data are compatible with a steep to vertically oriented σ_1. This conclusion is consistent with Andersonian mechanics, which predicts that σ_1 is normal to Earth's surface (Anderson, 1951). Above the detachments, the surfaces of the hanging walls have a 0°–6° slope (Fig. 2). We argue that the near-vertical σ_1 indicates that neither the strata in the hanging walls nor the populations of normal faults have been tilted more than a few degrees.

The hanging-wall faults are kinematically coupled with the detachments: the general directions and amounts of slip observed on the hanging-wall faults have been equivalently resolved on the detachments, and the detachments and the hanging walls have not independently tilted. The evidence for kinematic coupling of the two fault systems includes the following: (1) We note that none of the observed hanging-wall faults cuts completely across a principal slip plane and related fault rocks (Fig. 3). Moreover, many hanging-wall faults are listric and curve to join the principal slip plane. (2) The mode of the strikes of the hanging-wall fault populations at each locality is parallel to the local strike of the related detachment (Fig. 1). (3) There is a normal sense of separation of strata across exposed faults, and a net down-to-the-west or -northwest throw across the population of faults. The presence of a conjugate set in the bulk population is consistent with dip slip on the hanging-wall fault system. (4) Striae on the principal slip planes of the detachments are parallel to the modal dip direction of the hanging-wall faults and the direction of net extension across the hanging-wall fault system.

We note that there are striae and other kinematic indicators recording lateral and oblique slip on parts of the Black Mountain fault system (Keener et al., 1993). Local deviations from pure dip slip on the faults that we studied are spatially coincident with the hinges of the lower-plate antiforms (Wright et al., 1974; Holm et al., 1994), unmapped irregularities in the detachment surface (Nemser, 2001), or the influence of dextral slip on the

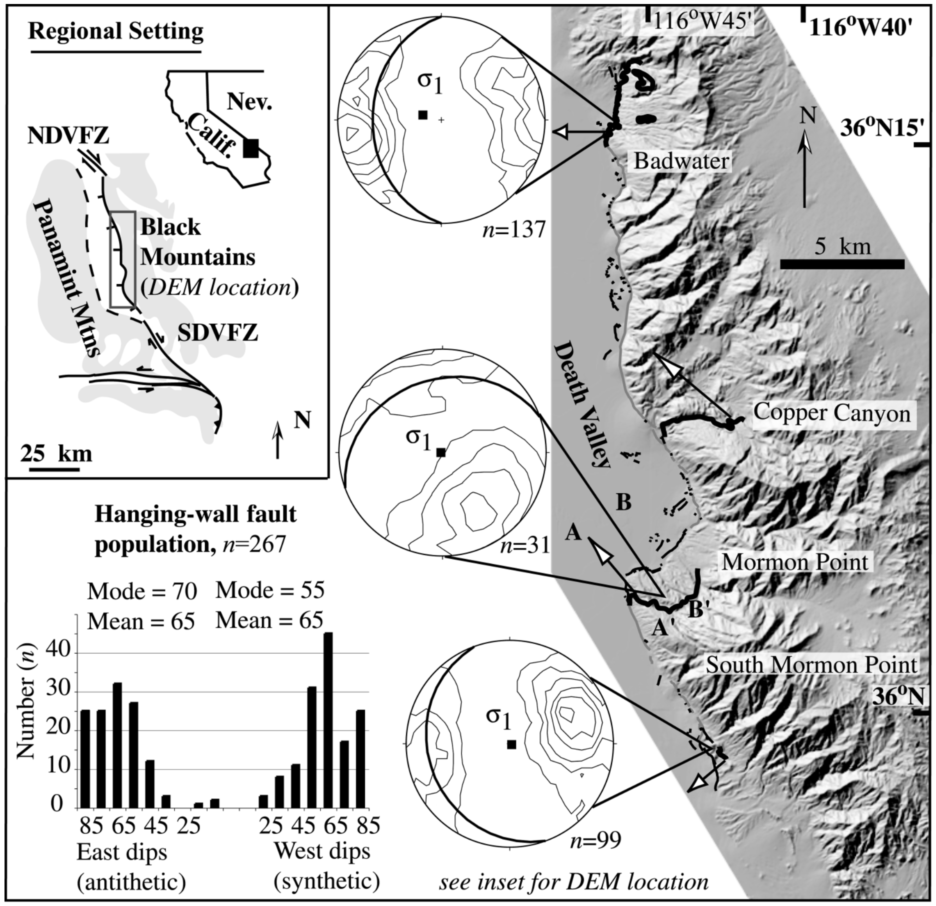

Figure 1. Death Valley, pull-apart basin between Northern and Southern Death Valley fault zones (NDVFZ and SDVFZ, respectively). Black Mountains (shown in compiled 30 m U.S. Geological Survey digital elevation model [DEM]) are bound by fault system that consists of scarps on valley floor (traces from Brogan et al., 1991) and low-angle detachments (traces from Drewes, 1963; Miller, 1991). Hanging walls, to west of and above traces of detachments, consist of Pliocene to Holocene sediments. These sediments are cut by steeply dipping faults (histogram) that do not cut detachments. Stereographic projections (plotted with Stereonet by R. Allmendinger) of 2σ contours of poles to hanging-wall fault planes at each locality define modes that are synthetic (Mormon Point and South Mormon Point) and antithetic (Badwater) to detachment plane (continuous great circles). Striae on detachments (arrows) are parallel to slip direction on hanging-wall fault populations and overall slip direction of two fault systems is normal to range front. Orientation of maximum principal stress, σ_1, is inferred to be steep to vertical and to bisect acute angle between modes of hanging-wall fault population (histogram and square symbols on stereonet). Cross sections A–A′ and B–B′ are shown in Figure 2.

Northern and Southern Death Valley fault zones (Keener et al., 1993).

DISCUSSION

Age of Slip and Original Orientation of the Detachments

At Mormon Point and Badwater, the Bishop tephra (0.77 Ma) is directly cut by the detachment, and the youngest sediment in the overlying strata is the 0.18–0.1 Ma (OIS 6) gravel. These Quaternary strata are relatively flat lying except in a rollover anticline (Fig. 2), where a significant listric hanging-wall fault places the Quaternary section against Pliocene sediment. The high-angle fault system that cuts the entire Quaternary section is kinematically coupled with the detachment. Moreover, the modes of the fault populations are most compatible with a σ_1 that is normal to the surfaces of the hanging walls. Collectively, these observations are evidence that the detachments have not tilted from an initial dip of 19°–36°. Any kinematic model for detachment tilt without corresponding hanging-wall tilt would conflict with these observations and would require structures that are not observed (e.g., young breakaway basins or extensional duplexes).

The field relationships only require that the detachment and hanging-wall fault system slipped since 0.18–0.1 Ma. However, slip restricted to the last 0.18 m.y. would be incompatible with the observed extension across the fault system. We estimate ~600 m net horizontal extension, or ~14% elongation along the 5 km NW-SE section across the high-angle faults in the Quaternary sediments at Mormon Point. This estimate is derived from hundreds

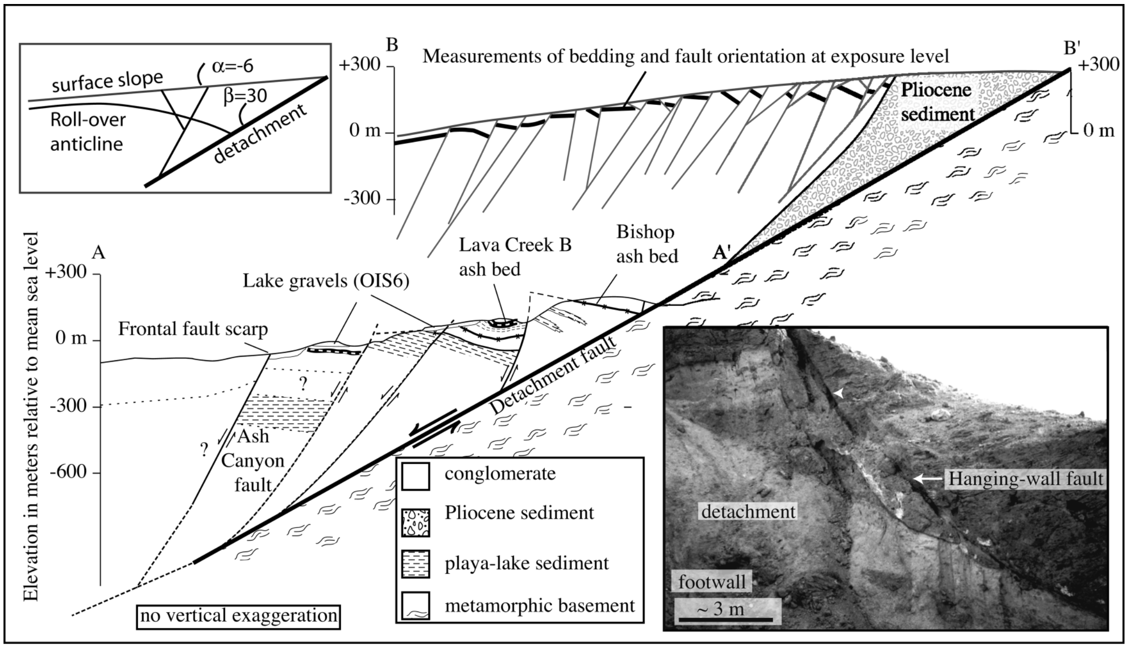

Figure 2. Cross section A–A′ across Mormon Point illustrating (1) sedimentary horizons of known or inferred ages and (2) amounts of slip on more significant normal faults. Intersections between hanging-wall faults are inferred where not exposed, such as depth trace of frontal fault scarp. Projected above section A–A′ is adjacent cross section, B–B′, depicting hanging-wall rollover anticline, density of significant faults, and presence of Pliocene sediments at updip, easternmost part of section. For locations of cross sections, see Figure 1. Photograph is south-facing view of hanging-wall fault, in Quaternary sediment, soling into detachment at Mormon Point. OIS is oxygen isotope stage.

of small-displacement ($<$1 m) normal faults and several large-displacement ($>$10–100 m) faults (Fig. 2) and is a minimum because it does not include translation on the detachments that was unaccompanied by hanging-wall deformation. We adopt a value for slip rates of $<$1 mm/yr, supported by geodesy and paleoseismology of the Basin and Range (Wernicke et al., 2000). For example, 600 m of extension since the deposition of the 1.2 Ma upper Glass Mountain tephra would have proceeded at an average slip rate of 0.5 mm/yr.

The Pliocene sediments above the Copper Canyon detachment, and correlative sediments at Mormon Point and Badwater, contain a similar hanging-wall fault system (Holm et al., 1994). The kinematics in these older sections are more complicated to reconstruct than in the Quaternary section yet are compatible with coupled slip on low-angle detachments and hanging-wall faults in Pliocene time.

Application of the Extensional Coulomb Wedge Model

Our observations and inferences concerning Quaternary slip on detachment faults are at odds with most models for detachment faulting. For example, a strict application of the rolling-hinge model predicts that low-angle detachments are inactive in the shallow crust (Buck, 1988; Wernicke and Axen, 1988). Other models for the initiation of, and slip on, low-angle normal faults involve rapid extension rates, the rotation of the stress field relative to the fault plane, or the elevation of fluid pressure (Wills and Buck, 1997). To provide an alternative explanation for active slip on this fault system we propose that the wedge-shaped sedimentary sections along the Black Mountains are extensional Coulomb wedges (Fig. 3) (Xiao et al., 1991). This model predicts that a critically or subcritically tapered wedge is stable and therefore can slide on a detachment without undergoing internal deformation. Hanging-wall wedges that have tapers greater than critical, however, will fail and extend by normal faulting in the hanging wall; slip on each fault is resolved onto the detachment.

One control on the maintenance of the critical taper is the effective basal friction of the detachment (μ_{eff}). When μ_{eff} is lowered from typical values of 0.6–0.85 [$\phi = 30°$, $\mu = \tan(\phi)$] the detachment is weakened. One mechanism for weakening could be the development of fault rocks with unusually low static friction (μ). Alternatively, if the ratio of fluid pressure to lithostatic pressure along the detachment (λ_b) is higher than that within the wedge (λ), then $\mu_{eff} = \mu[(1 - \lambda_b)/(1 - \lambda)]$ and $\mu_{eff} < \mu$. We use the observed taper at Mormon Point with a surface slope (α) of $-6°$ and a basal dip (β) of 30° (Fig. 2), and we assume that the sediment is cohesionless, that λ does not deviate from hydrostatic throughout the wedge, and that $\phi = 30°$ for the wedge materials. The extensional solution to the Coulomb wedge problem (Fig. 3) (Dahlen, 1984; Xiao et al., 1991) predicts that when $\mu_{eff} > 0.4$ or $\phi_b > 21°$, the observed taper is supercritical. If the detachment were to be weakened such that $\phi_b \leq 21°$, the wedge would be stable or critically stable. If $\mu = 0.6–0.85$ for the fault rocks within the detachment, then the fluid pressure is the dominant control on detachment weakening, requiring that $\lambda_b = 0.7$ for $\lambda = 0.5$; the latter is a nominal value for the hydrostatic fluid pressure. Such an elevation of fluid pressure within a fault zone is within the range of measured fluid pressures within faults (Xiao et al., 1991). Regardless of the assumptions used to apply the model or the mechanism for the modest weakening of the detachment, the extensional Coulomb wedge model adequately describes the behavior on the Black Mountain fault zone.

Seismic Slip on the Detachments

The Black Mountains fault zone includes range-front fault scarps in upper Pleistocene or Holocene alluvial fan and playa sediments (Fig. 1) (Brogan et al., 1991). The scarps are the surface expression of steeply dipping faults that in central Death Valley accrue dominantly normal slip (Brogan et al., 1991). The intersections of the frontal faults and the detachments are buried beneath the valley floor (Fig. 2). It has been argued that either the frontal faults resolve themselves on the detachments (Hamilton, 1988; Burchfiel et al., 1995) or, alternatively, cut the detachments at depth (Miller, 1991; Keener et al., 1993; Chichanski, 2000). In the latter case, Holocene and possibly older slip on the frontal faults would have superseded any slip on the detachments and necessarily deactivated them.

We propose that the steep frontal faults belong to the larger population of hanging-wall faults that resulted from extension of the hanging-wall wedges. It is probable that some of the members of the population that are now situated above the floor of the valley once defined the mountain front, just as the youngest

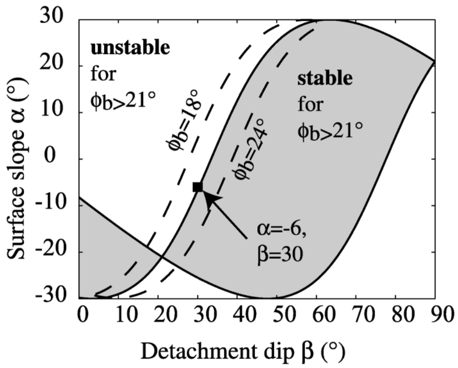

Figure 3. Solution to extensional critical Coulomb wedge problem described by Xiao et al. (1991): $\alpha + \beta = \psi_1 - \psi_0$, where α is surface slope, β is detachment dip, ψ_0 is stress angle, and ψ_1 is function of friction, ϕ, basal friction, ϕ_b, and α. As explained by Dahlen (1984), ψ_1 is periodic function with two minima and extensional solution is for $-\pi/2 < \psi_0 < 0$. Thus, any given α and β have two critically stable solutions that we solved for numerically and plot here as curves bounding shaded region. Any α and β that plot on this curve or within shaded region, are either critically stable or stable, respectively, and can translate down detachment dip without internal faulting. Any α and β that plot within unshaded region are unstable and hanging-wall faulting is required for wedge to accommodate tectonic extension. Mechanisms for maintaining criticality vary in nature, but we consider ϕ_b to be controlling parameter; wedge at Mormon Point ($\alpha = -6$, $\beta = 30$) is critically stable for $\phi_b = 21$. However, if $\phi_b > 21$, boundary for stability field would shift to right (dashed line for $\phi_b = 24$) and wedge would become unstable. Alternatively, if $\phi_b < 21$, boundary would shift to left (dashed line for $\phi_b = 18$) and wedge would become stable. Mechanism for changes in friction of detachment could be either presence of fault rocks with anomalously low friction, or elevated fluid pressure.

scarps do today. According to our hypothesis, the frontal faults do not cut the buried downdip continuations of the detachments; rather, slip on them is kinematically coupled to slip on the buried detachments. If our hypothesis is true, then the seismic ruptures thought to be responsible for the young scarps in Death Valley (Brogan et al., 1991) must have propagated up the detachment faults. Our proposal that at least some slip on the detachments was seismogenic agrees with recent interpretations made elsewhere in the Basin and Range Province (Axen, 1999; Axen et al., 1999; Abbott et al., 2001).

CONCLUSIONS

Structural and stratigraphic data from the hanging wall of the Black Mountain detachments require that the detachments accrued low-angle, normal-sense slip in the Quaternary, likely since the Pliocene and into Holocene time. The detachment slip was coupled with slip on a system of high-angle faults in the hanging wall. A modest slip rate, a steep to vertically oriented principal stress, and the angular relationship between the surface of the hanging walls and the detachments support the best mechanical explanation for detachment faulting in this setting: the sediment overlying the detachment forms an extensional Coulomb wedge. Our conclusions lead to the interpretation that the seismic slip that created the high-angle fault scarps on the valley floor originated on the detachments at depth.

ACKNOWLEDGMENTS

Hayman, Nemser, and Cowan received support from the donors to the Petroleum Research Fund, administered by the American Chemical Society. Knott and Sarna-Wojcicki received support from National Science Foundation grant EAR 94-06029 and the U.S. Geological Survey. We thank John Bartley, John Dewey, Martin Miller, and Brian Wernicke for valuable reviews.

REFERENCES CITED

Abbott, R.E., Louie, J.N., Caskey, S.J., and Pullammanappallil, S., 2001, Geophysical confirmation of low-angle normal slip on the historically active Dixie Valley fault, Nevada: Journal of Geophysical Research, v. 106, p. 4169–4181.

Anderson, E.M., 1951, The dynamics of faulting: London, Oliver and Boyd, 206 p.

Axen, G.J., 1999, Low angle normal fault earthquakes and triggering: Geophysical Research Letters, v. 26, p. 3693–3696.

Axen, G.J., Fletcher, J.M., Cowgill, E., Murphy, M., Kapp, P., MacMillan, I., Ramos, V.E., and Aranda, G.J., 1999, Range-front fault scarps of the Sierra El Mayor, Baja California: Formed above an active low-angle normal fault?: Geology, v. 27, p. 247–250.

Brogan, G.E., Kellogg, K.S., Slemmons, D.B., and Terhune, C.L., 1991, Late Quaternary faulting along the Death Valley–Furnace Creek fault system, California and Nevada: U.S. Geological Survey Bulletin 1991, 23 p.

Buck, R.W., 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959–973.

Burchfiel, B.C., and Stewart, J.H., 1966, ''Pull-apart'' origin of the central segment of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439–441.

Burchfiel, B.C., Molnar, P., Zhang, P., Deng, Q., and Wang, Y., 1995, Example of a supradetachment basin within a pull-apart tectonic setting: Mormon Point, Death Valley, California: Basin Research, v. 7, p. 199–214.

Chichanski, M., 2000, Low-angle, range-flank faults in the Panamint, Inyo, and Slate Ranges, California: Implications for recent tectonics of the Death Valley region: Geological Society of America Bulletin, v. 112, p. 871–883.

Dahlen, F.A., 1984, Noncohesive critical Coulomb wedges: An exact solution: Journal of Geophysical Research, v. 89, p. 10,125–10,133.

Drewes, H., 1963, Geology of the Funeral Peak Quadrangle, California, on the eastern flank of Death Valley: U.S. Geological Survey Professional Paper 413, 78 p.

Hamilton, W.B., 1988, Detachment faulting in the Death Valley region, California and Nevada: U.S. Geological Survey Bulletin 1790, p. 51–85.

Holm, D.K., Fleck, R.J., and Lux, D.R., 1994, The Death Valley Turtlebacks reinterpreted as Miocene–Pliocene folds of a major detachment surface: Journal of Geology, v. 102, p. 718–727.

Jackson, J.A., and White, N.J., 1989, Normal faulting in the upper continental crust: Observations from regions of active extension: Journal of Structural Geology, v. 11, p. 15–36.

Keener, C., Serpa, L.F., and Pavlis, T.L., 1993, Faulting at Mormon Point, Death Valley, California: A low-angle normal fault cut by high-angle faults: Geology, v. 21, p. 327–330.

Knott, J.R., Sarna-Wojcicki, A.M., Meyer, C.E., Tinsley, J.C., III, Wells, S.G., and Wan, E., 1999, Late Cenozoic stratigraphy and tephrochronology of the western Black Mountains piedmont, Death Valley, California: Implications for the tectonic development of Death Valley, *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic basins of the Death Valley region: Geological Society of America Special Paper 333, p. 345–366.

Ku, T.H., Luo, S., Lowenstein, T.K., Li, J., and Spencer, R.J., 1998, U-series chronology of lacustrine deposits in Death Valley, California: Quaternary Research, v. 50, p. 261–275.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovick, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field: Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: Geological Society of America Bulletin, v. 114, p. 559–568.

Miller, M.G., 1991, High-angle origin of the currently low-angle Badwater Turtleback fault, Death Valley, California: Geology, v. 19, p. 372–375.

Miller, M.G., 1996, Ductility in fault gouge from a normal fault system, Death Valley, California: A mechanism for fault-zone strengthening and relevance to paleoseismicity: Geology, v. 24, p. 603–606.

Nemser, E.S., 2001, Kinematic development of upper plate faults above low-angle normal faults in Death Valley, California [M.S. thesis]: Seattle, University of Washington, 102 p.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Science, v. 22, p. 108–125.

Wernicke, B., 1995, Low-angle normal faults and seismicity: A review: Journal of Geophysical Research, v. 100, p. 20,159–20,164.

Wernicke, B., and Axen, G.J., 1988, On the role of isostacy in the evolution of normal fault systems: Geology, v. 16, p. 848–851.

Wernicke, B., Friedrich, A.M., Niemi, N.A., Bennett, R.A., and Davis, J.L., 2000, Dynamics of plate boundary fault systems from Basin and Range Geodetic Network (BARGEN) and geologic data: GSA Today, v. 10, no. 11, p. 1–6.

Wills, S., and Buck, R.W., 1997, Stress-field rotation and rooted detachment faults: A Coulomb failure analysis: Journal of Geophysical Research, v. 102, p. 20,503–20,514.

Wright, L.A., Otton, J.K., and Troxel, B.W., 1974, Turtleback surfaces of Death Valley viewed as phenomena of extensional tectonics: Geology, v. 2, p. 53–54.

Xiao, H.B., Dahlen, F.A., and Suppe, J., 1991, Mechanics of extensional wedges: Journal of Geophysical Research, v. 96, p. 10,301–10,318.

Manuscript received 6 August 2002
Revised manuscript received 21 November 2002
Manuscript accepted 3 December 2002

Printed in USA