Late Cenozoic extensional transfer in the Walker Lane strike-slip belt, Nevada

John S. Oldow
Gretchen Kohler
Raymond A. Donelick
Department of Geology and Geophysics, Rice University, Houston, Texas 77251

ABSTRACT

Mid-Miocene to Pliocene (11 to 6 Ma) displacement on the shallowly northwest-dipping Silver Peak–Lone Mountain detachment system transferred 30 to 40 km of right slip from the Furnace Creek transcurrent fault 85 km east-northeast to the central Walker Lane strike-slip faults. Top-to-the-northwest slip on the detachment was accompanied by upper-plate extension on steeply dipping faults and large-scale exhumation of midcrustal rocks of the lower-plate complex. Doubly plunging, northwest-trending folds (turtleback structures) control the outcrop distribution of the extensional complex and formed in response to simple shear of the footwall complex. Activity on the detachment ceased as Miocene-Pliocene (6–4.8 Ma) volcanic rocks were erupted and deformed during the final stage of northwest-trending folding. Late Pliocene to Holocene displacement transfer shifted north to a curved array of steeply dipping faults that may be underlain by a shallowly northwest-dipping detachment.

INTRODUCTION

The association of dip-slip and strike-slip faults is well established within extensional and transcurrent tectonic regimes. Typically, one set of faults is subordinate and serves as a displacement transfer mechanism, such as extensional faults within releasing bends of transcurrent systems or as strike-slip transfer faults within or between extensional complexes. Within wrench systems, extensional faults link dilational jogs or steps in strike-slip faults and result in pull-apart basins (Crowell, 1974) or extensional duplex systems (Woodcock and Fischer, 1986). In the near surface, extensional structures are viewed as high-angle faults, but subsurface geometries are poorly understood. As proposed by K. Arbenz (Manspeizer, 1985) and imaged in seismic-reflection profiles of the Ridge basin in California (May et al., 1993) and the Dead Sea basin (ten Brink and Ben-Avraham, 1989), pull-apart basins ostensibly are underlain by shallowly dipping detachments linking strike-slip faults.

In this context, areally restricted extensional complexes such as the Death Valley system of California (Wright et al., 1974), the Rhodope complex of northwestern Greece (Dinter and Royden, 1993), and extensional windows in the Alps (Selverstone, 1988) may have formed in tectonic settings similar to those responsible for the exhumation of lower-plate rocks exposed in the Silver Peak–Lone Mountain extensional complex of the central Walker Lane area. There, displacement transfer between stepped transcurrent faults occurred on a shallowly dipping decollement resulting in large-scale extension in the area between the strike-slip faults.

TRANSCURRENT FAULTS IN THE WESTERN GREAT BASIN

The late Cenozoic Walker Lane belt (Stewart, 1988) marks the boundary between the Great Basin province and the Sierra Nevada (Fig. 1) and is characterized by northwest-striking transcurrent faults and coeval dip-slip faults formed in response to spatially segregated components of a partitioned displacement field (Oldow, 1992). Within the central Walker Lane belt, faulting began between 15 and 10 Ma (Hardyman and Oldow, 1991) and resulted in cumulative right slip of 60 to 75 km and coeval extension of 20 to 45 km (Oldow, 1992). The faults commonly have surface breaks in Qua-

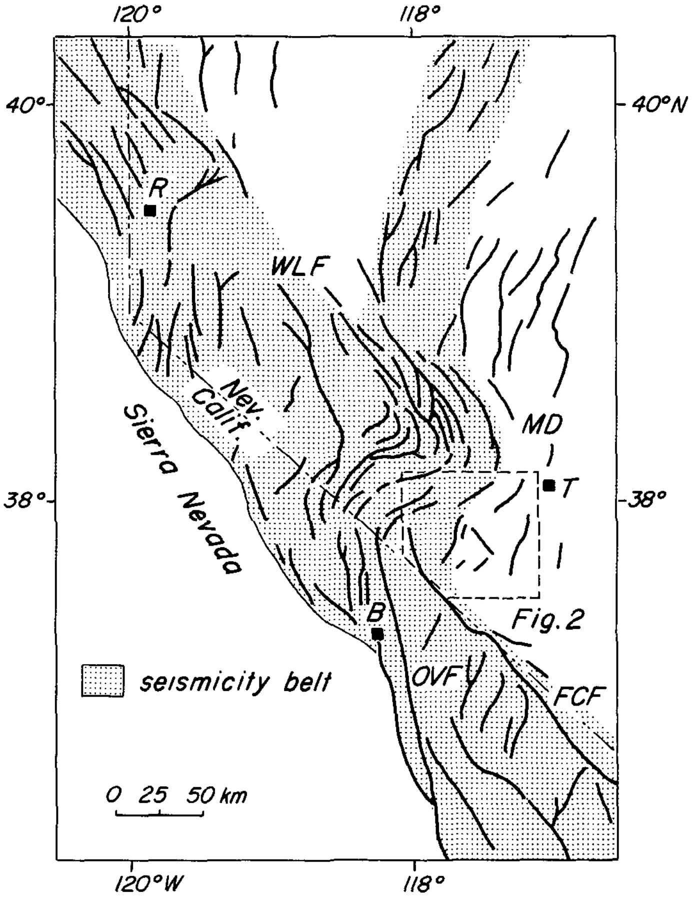


Figure 1. Late Cenozoic faults of western Great Basin and generalized geologic map of Mina deflection region of west-central Nevada. FCF—Furnace Creek fault, OVF—Owens Valley fault, WLF—Walker Lane faults, MD—Mina deflection, R—Reno, B—Bishop, T—Tonopah.

ternary deposits, and the Walker Lane belt is one of the most seismically active parts of the western Great Basin (Rogers et al., 1991).

Within the Walker Lane belt, recent fault activity does not continue southeast of Tonopah (Fig. 1) but steps west and is concentrated along the Furnace Creek and Owens Valley fault systems of eastern California. In Owens Valley, numerous recent surface breaks define a fault zone ~300 km long that is composed of north-northwest-striking faults with different components of dip-slip and strike-slip motion. Net strike-slip across the Owens Valley fault zone is only a few kilometres (Stewart, 1988), possibly because of the relative youth of the system, which formed between 3 and 5 Ma (Bachman, 1978). Farther east, cumulative right slip of 40 to 50 km (Stewart, 1988; Reheis, 1992) occurs along the Furnace Creek fault (Fig. 1), which began activity between 12 and 8 Ma (Reheis and McKee, 1991). The northwest-striking Furnace Creek fault stretches 250 km from southeast California to a northern terminus in western Nevada (Reheis, 1992; Oldow, 1992).

MINA DEFLECTION

Northwest-trending faults of the Walker Lane belt are joined by the Mina deflection (Wetterauer, 1977), which is a 120-km-long and 75-km-wide belt of east-northeast-striking late Cenozoic faults and corresponding diffuse swath of seismicity (Ryall and Priestly, 1975). High-angle faulting within the Mina deflection postdates late Miocene to Pliocene volcanic rocks (e.g., Stewart et al., 1982) but may have begun earlier. The bend in late Cenozoic structures and seismicity is attributed to pre-Cenozoic crustal structure (Wetterauer, 1977; Cogbill, 1979) and follows the isotopically located boundary between continental and noncontinental crust (Kistler, 1991).

East-northeast-striking faults of the Mina deflection kinematically link transcurrent faults of the central Walker Lane with those of the Furnace Creek and Owens Valley fault systems (Oldow, 1992). At their northern ends, the eastern strand of the Owens Valley fault and the Furnace Creek fault bend to the east and merge with the east-northeast-striking faults (Fig. 1). A comparable change in fault orientation is observed at the southern end of the central Walker Lane, where north-northwest and northwest strikes prevail. Individual strands of mapped faults change orientation through nearly 90°, forming curves with radii of between 10 and 20 km. Slip on the faults changes systematically from right oblique on north-northwest-striking fault segments to left oblique on east-northeast-striking fault segments. Downdip displacement is recorded on faults at the apexes of the curves (Fig. 1), where extension is expressed as deep Pliocene to Quaternary alluvial basins (Oldow, 1992). Regional gravity analysis (Saltus, 1988) indicates that the basins have steep boundaries and, where analyzed by detailed gravity studies (Cogbill, 1979), are ~1.5 to 3.0 km deep.

South of the Mina deflection (Fig. 2), northwest-trending turtleback structures (Kirsch, 1971) of the Silver Peak–Lone Mountain extensional complex (Oldow, 1992) are exposed. Late Miocene to Pliocene extension on a shallowly dipping detachment (Stewart and Diamond, 1990) juxtaposed an upper-plate assemblage of moderately to steeply dipping upper Miocene clastic and relatively unmetamorphosed lower Paleozoic rocks and a lower plate composed of amphibolite-facies metamorphic tectonites. The upper-plate rocks exhibit bedding-cutoff angles with the underlying detachment indicating top-to-the-northwest displacement (Stewart and Diamond, 1990). Lower-plate tectonites are Lower Cambrian to Precambrian

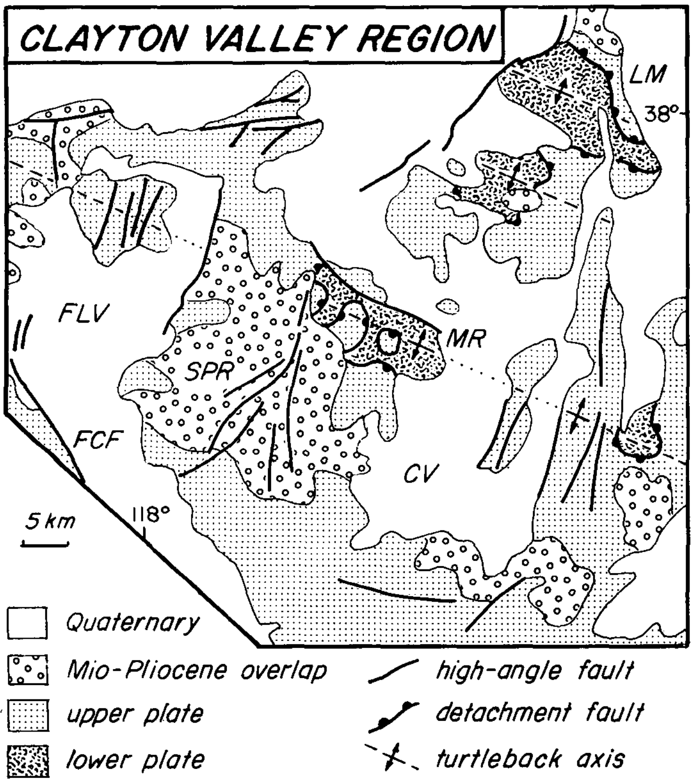
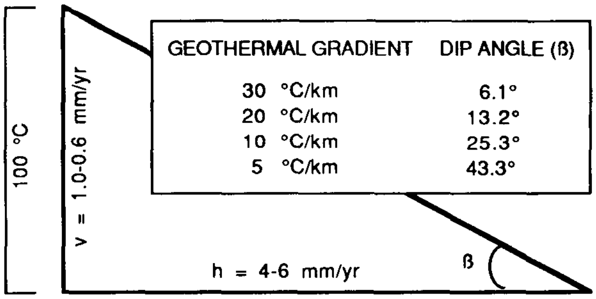


Figure 2. Generalized geologic map of Silver Peak–Lone Mountain extensional complex. FCF—Furnace Creek fault, FLV—Fish Lake Valley, SPR—Silver Peak Range, LM—Lone Mountain, CV—Clayton Valley, MR—Mineral Ridge.

#	LAT., LONG.	ELEV. (FT.)	MIN.	AGE (MA)
1	37.81° 117.70°	5900	Ap.	4.7 ±0.7
2	37.77° 117.70°	6000	Ap. Zr.	7.8 ±1.2 10.8 ±0.9
3	37.77° 117.71°	6200	Ap. Zr.	5.4 ±1.1 11.2 ±1.0
4	37.76° 117.66°	5600	Ap.	6.9 ±1.4
5	37.75° 117.67°	5400	Ap.	7.0 ±1.2



GEOTHERMAL GRADIENT	DIP ANGLE (ß)
30 °C/km	6.1°
20 °C/km	13.2°
10 °C/km	25.3°
5 °C/km	43.3°

Figure 3. Apatite and zircon fission-track ages from lower plate exposed at Mineral Ridge. Analyses by R. A. Donelick using standard techniques. Initial dip estimate for Silver Peak–Lone Mountain detachment determined by using exhumation rate of lower-plate rocks calculated for a range of geothermal gradients and horizontal displacement rate of Furnace Creek fault.

carbonate and clastic rocks that were intruded by synmetamorphic felsic plutons. Metamorphism occurred prior to Miocene-Pliocene extension (Stewart and Diamond, 1990), during late Mesozoic or early Cenozoic tectonism that carried lower-plate rocks to mid-crustal levels and temperatures of ~350 °C (Kohler et al., 1993).

Displacement on the detachment ceased during the extrusion of 6 to 4.8 Ma volcanic rocks, which unconformably overlie both upper- and lower-plate assemblages (Stewart and Diamond, 1990). Both the detachment surface and overlying volcanic rocks are warped in broad, northwest-trending folds with doubly plunging axes. The folds have half-wavelengths of ~15 km and control bedrock exposure across the Silver Peak and Lone Mountain region (Fig. 2). The folds define the long axis of the turtlebacks and are parallel to the direction of upper-plate transport.

The cooling history of lower-plate rocks was determined by fission-track analysis of apatite and zircon separates from the felsic intrusions exposed at Mineral Ridge in the Silver Peak Range (Fig. 3). Apatite samples indicate that lower-plate rocks passed through ~100 °C at about 5.8 ±0.5 Ma, and zircon separates from the same samples cooled through ~200 °C at 11.0 ±0.7 Ma. The cooling ages of the lower-plate assemblage correspond to the timing of major activity on the northern Furnace Creek fault (Reheis and McKee, 1991) and with exhumation ages of the Death Valley turtlebacks at the southern end of the Furnace Creek fault system (Holm and Dokka, 1993).

DISPLACEMENT TRANSFER SYSTEM

The curved high-angle faults of the Mina deflection behave as a displacement relay between the Owens Valley and Furnace Creek faults and the central Walker Lane transcurrent faults. The amount of displacement transferred by these faults is gauged by the geometry of basins formed at the apexes of the curved faults. Given the 75 km width of the Mina deflection and reasonable estimates of basin depths, <10 km of right-lateral displacement can have been transferred between bounding transcurrent systems (Oldow, 1992). For the limited right slip on the Owens Valley fault system, displacement transfer by high-angle faults in the Mina deflection does not pose a problem. In contrast, transfer of 40 to 50 km of right slip from the Furnace Creek fault to the Walker Lane belt cannot be accommodated by the high-angle faults and presents a displacement deficit of more than 30 to 40 km.

Expanding on the work of Reheis (1992), we propose that earlier displacement transfer was accommodated by northwest-directed slip on the Silver Peak–Lone Mountain extensional fault system. Given the present-day deformed state of the detachment, it is important to estimate the initial dip of the fault. To this end, we use the thermal history of lower-plate rocks and coeval slip rates on the northern Furnace Creek fault. By using geothermal gradients calculated by Lachenbruch and Sass (1978) for stable craton (20 °C/km) and the Basin and Range (30 °C/km), conversion of the cooling history of the lower-plate assemblage to a vertical component of exhumation yields values of between 1.0 and 0.6 mm/yr. Post–late Miocene slip rates for the northern and central Furnace Creek fault, determined from offset plutons and layered rocks, are 4–6 mm/yr (Reheis and McKee, 1991; Oakes, 1987). Assuming displacement compatibility between the transcurrent and detachment fault systems, the slip components are combined (Fig. 3) to yield an initial detachment dip of <15°.

Perturbations of the thermal structure of this tectonically active region are expected and may affect depth-conversion calculations. Deviations from equilibrium thermal conditions caused by tectonic displacements, coeval magmatism, and fluid migration predictably would increase the apparent geothermal gradient. As pointed out by Dokka (1993) in similar calculations for a detachment fault in the Mojave desert, increased fault dip can be attained only if anomalously low geothermal gradients prevailed. To increase the dip of the Silver Peak–Lone Mountain detachment to 30° requires a geothermal gradient of ~10 °C/km, which may be possible if the thermal

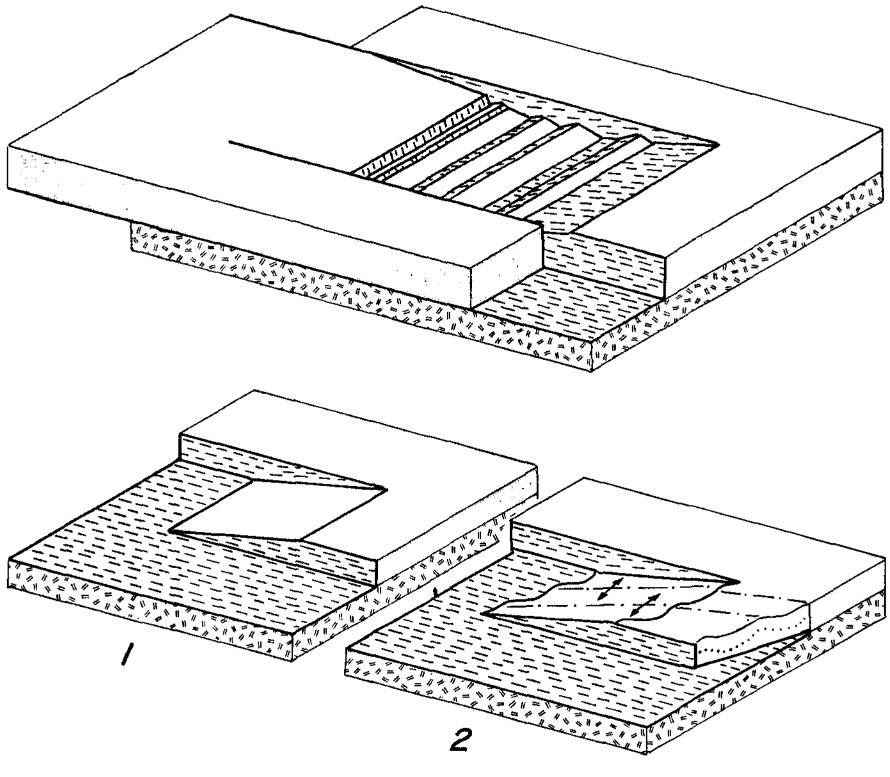


Figure 4. Models of low-angle displacement transfer system between Furnace Creek and Walker Lane transcurrent faults (upper diagram) and of simple-shear deformation and formation of northwest folds of footwall assemblage of displacement transfer system (lower diagrams 1 and 2). Lower layer of model is undeformed for displacement reference frame.

structure of the nearby Sierra Nevada is cool (Lachenbruch and Sass, 1978). Dips of 45° and greater, however, are unlikely because they require geothermal gradients of <5 °C/km.

We argue that the Silver Peak–Lone Mountain detachment was a shallow northwest-dipping structure linking the Furnace Creek and Walker Lane fault systems. This geometry is shown in the simplified scheme of Figure 4, where strike-slip and shallowly dipping detachment faults emanate from a common basal decollement probably located at midcrustal depths. Right slip on the bounding transcurrent faults resulted in displacement of the upper plate to the northwest. Subsidiary synthetic and antithetic faults in the upper plate merged with the shallowly dipping detachment and formed tilted blocks as the lower plate was drawn from beneath the overlying cover.

Northwest-trending folds of the detachment system are part of progressive deformation associated with displacement transfer and are not due to later superposed deformation nor crustal constriction (e.g., Holm et al., 1993). Some component of continuum deformation was transferred from the bounding transcurrent faults and distorted the upper and lower plates of the low-angle detachment system. Northwest folds are related to simple shear–induced shortening of the transfer-zone footwall (Fig. 4).

Fold growth apparently locked the detachment, resulting in northern migration of the site of active displacement transfer. Curved late Pliocene to Holocene high-angle faults of the Mina deflection accommodate displacement transfer and may be the surface expression of a shallowly northwest-dipping transfer system.

ACKNOWLEDGMENTS

Partially supported by the Geological Society of America (Kohler) and the Kennecott Exploration Company (Oldow). We thank M. Gordon, M. Quinn, V. Sisson, S. Wyld, J. Bartley, and M. Miller for helpful reviews.

REFERENCES CITED

Bachman, S. B., 1978, Pliocene-Pleistocene break-up of the Sierra Nevada–White–Inyo Mountains block and formation of Owens Valley: Geology, v. 6, p. 461–463.

Cogbill, A. H., Jr., 1979, The relationship between seismicity and crustal structure in the western Great Basin [Ph.D. thesis]: Evanston, Illinois, Northwestern University, 290 p.

Crowell, J. C., 1974, Origin of late Cenozoic basins in southern California, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 190–204.

Dinter, D. A., and Royden, L., 1993, Late Cenozoic extension in northeastern Greece: Strymon Valley detachment system and Rhodope metamorphic core complex: Geology, v. 21, p. 45–48.

Dokka, R. K., 1993, Original dip and subsequent modification of a Cordilleran detachment fault, Mojave extensional belt, California: Geology, v. 21, p. 711–714.

Hardyman, R. F., and Oldow, J. S., 1991, Tertiary tectonic framework and Cenozoic history of the central Walker Lane, Nevada, *in* Raines, G. L., et al., eds., Geology and ore deposits of the Great Basin: Reno, Geological Society of Nevada, p. 279–302.

Holm, D. K., and Dokka, R. K., 1993, Interpretation and tectonic implications of cooling histories: An example from the Black Mountains, Death Valley extended terrane, California: Earth and Planetary Science Letters, v. 116, p. 63–80.

Holm, D. K., Geissman, J. W., and Wernicke, B. P., 1993, Tilt and rotation of the footwall of a major normal fault system: Paleomagnetism of the Black Mountains, Death Valley extended terrane, California: Geological Society of America Bulletin, v. 105, p. 1373–1387.

Kirsch, S. A., 1971, Chaos structure and turtleback dome, Mineral Ridge, Esmeralda County, Nevada: Geological Society of America Bulletin, v. 82, p. 3169–3176.

Kistler, R. W., 1991, Chemical and isotopic characteristics of plutons in the Great Basin, *in* Raines, G. L., et al., eds., Geology and ore deposits of the Great Basin: Reno, Geological Society of Nevada, p. 107–110.

Kohler, G., Oldow, J. S., Sisson, V. B., and Donelick, R. A., 1993, Displacement transfer system linking the Furnace Creek and Walker Lane fault systems, west-central Nevada: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 63.

Lachenbruch, A. H., and Sass, J. H., 1978, Models of an extending lithosphere and heat flow in the Basin and Range province, *in* Smith, R. B., and Eaton, G., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 209–250.

Manspeizer, W., 1985, The Dead Sea rift: Impact of climate and tectonism on Pleistocene and Holocene sedimentation, *in* Biddle, K. T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 143–158.

May, S. R., Ehman, K. D., Gray, G. G., and Crowell, J. C., 1993, A new angle on the tectonic evolution of the Ridge basin, a "strike-slip" basin in southern California: Geological Society of America Bulletin, v. 105, p. 1357–1372.

Oakes, E. H., 1987, Age and rates of displacement along the Furnace Creek fault zone, northern Death Valley, California: Geological Society of America Abstracts with Programs, v. 19, p. 437.

Oldow, J. S., 1992, Late Cenozoic displacement partitioning in the northwestern Great Basin, *in* Craig, S. D., ed., Structure, tectonics, and mineralization of the Walker Lane: Reno, Geological Society of Nevada, p. 17–52.

Reheis, M. C., 1992, Late Cenozoic extension in the Silver Peak Range, west-central Nevada, related to strike-slip motion on the Furnace Creek fault zone: Geological Society of America Abstracts with Programs, v. 24, no. 5, p. 77.

Reheis, M. C., and McKee, E. H., 1991, Late Cenozoic history of slip on the Fish Lake Valley fault zone, Nevada and California: U.S. Geological Survey Open-File Report 91-290, p. 26–45.

Rogers, A. M., Harmsen, S. C., Corbett, E. J., Priestley, K., and de Palo, D., 1991, The seismicity of Nevada and some adjacent parts of the Great Basin, *in* Slemmons, D. B., et al., eds., Neotectonics of North America: Boulder, Colorado, Geological Society of America, Geology of North America Decade Map Volume, p. 153–184.

Ryall, A. S., and Priestly, K., 1975, Seismicity, secular strain, and maximum magnitude in the Excelsior Mountains area, western Nevada and eastern California: Geological Society of America Bulletin, v. 86, p. 1585–1592.

Saltus, R. W., 1988, Regional, residual, and derivative gravity maps of Nevada: Nevada Bureau of Mines and Geology Map 94B, scale 1:1,000,000.

Selverstone, J., 1988, Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing of the Tauern Window: Tectonics, v. 7, p. 87–105.

Stewart, J. H., 1988, Tectonics of the Walker Lane belt, western Great Basin: Mesozoic and Cenozoic deformation in a shear zone, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States: Englewood Cliffs, New Jersey, Prentice-Hall, p. 681–713.

Stewart, J. H., and Diamond, D. S., 1990, Changing patterns of extensional tectonics: Overprinting the basin of the middle and upper Miocene Esmeralda Formation in western Nevada by younger structural basins, *in* Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 447–476.

Stewart, J. H., Carlson, J. E., and Johannesen, D. C., 1982, Geologic map of the Walker Lake 1° by 2° quadrangle, California and Nevada: U.S. Geological Survey Miscellaneous Field Study Map MF-1382-A; scale 1:250,000.

ten Brink, U. S., and Ben-Avraham, Z., 1989, The anatomy of a pull-apart basin: Seismic reflection observations of the Dead Sea basin: Tectonics, v. 8, p. 333–350.

Wetterauer, R. H., 1977, The Mina deflection—A new interpretation based on the history of the Lower Jurassic Dunlap Formation, western Nevada [Ph.D. thesis]: Evanston, Illinois, Northwestern University, 155 p.

Woodcock, N. H., and Fischer, M., 1986, Strike-slip duplexes: Journal of Structural Geology, v. 8, p. 725–735.

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.

Manuscript received December 23, 1993
Revised manuscript received April 4, 1994
Manuscript accepted April 7, 1994