Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific–North American plate boundary

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ABSTRACT

In the western Great Basin of North America, a system of dextral faults accommodates 15%–25% of the Pacific–North American plate motion. The northern Walker Lane in northwest Nevada and northeast California occupies the northern terminus of this system. This young evolving part of the plate boundary offers insight into how strike-slip fault systems develop and may reflect the birth of a transform fault. A belt of overlapping, left-stepping dextral faults dominates the northern Walker Lane. Offset segments of a W-trending Oligocene paleovalley suggest ~20–30 km of cumulative dextral slip beginning ca. 9–3 Ma. The inferred long-term slip rate of ~2–10 mm/yr is compatible with global positioning system observations of the current strain field. We interpret the left-stepping faults as macroscopic Riedel shears developing above a nascent lithospheric-scale transform fault. The strike-slip faults end in arrays of ~N-striking normal faults, suggesting that dextral shear diffuses into extension in the Great Basin. Coeval extension and dextral shear have induced slight counterclockwise fault-block rotations, which may ultimately rotate Riedel shears toward the main shear zone at depth, thus facilitating development of a throughgoing strike-slip fault.

Keywords: Walker Lane, Nevada, transform fault, Riedel shear, paleovalley.

INTRODUCTION

The western margin of North America contains a broad zone of distributed shear extending from the San Andreas fault system to the Basin and Range province (Fig. 1; Wernicke, 1992; Atwater and Stock, 1998). Global positioning system (GPS) geodetic data indicate that a system of dextral faults in the western Great Basin, known as the Walker Lane in the north (Stewart, 1988) and the eastern California shear zone in the south (Dokka and Travis, 1990), accommodates 15%–25% of the dextral motion between the North American and Pacific plates (Thatcher et al., 1999; Bennett et al., 2003). This fault system merges southward with the San Andreas fault in southern California and terminates northward near the south end of the Cascade arc. The Walker Lane essentially accommodates dextral motion of the Sierra Nevada block relative to the central Great Basin.

Because the Walker Lane accommodates a significant fraction of Pacific–North American plate motion and the San Andreas fault system has been growing northward (Atwater and Stock, 1998), it follows that the Walker Lane may also be propagating northwestward. Estimates of cumulative dextral offset across the eastern California shear zone and Walker Lane since Miocene time are ~50–100 km in southern California (Dokka and Travis, 1990), 60–75 km in west-central Nevada (Oldow, 1992), and essentially zero at its northwest terminus. Thus, the northern Walker Lane in northwest Nevada and northeast California is possibly the least developed and youngest part of the transform boundary.

In this paper we utilize the youthfulness of the northern Walker Lane to assess how strike-slip fault systems develop. Our new geologic mapping, structural analysis, and geochronology (Faulds et al., 2002; Henry et al., 2003, 2004) define the geometry and kinematics of the northern Walker Lane and provide the first detailed constraints on the timing and magnitude of dextral displacement across this region. We develop a kinematic model for this youthful system, which applies previously published clay models to a macroscopic scale. This kinematic model may have implications for incipient intracontinental strike-slip faults in many tectonic settings.

GEOLOGIC SETTING

As western North America has evolved from a convergent to a transform margin in the past 30 m.y., the northern Walker Lane has undergone widespread volcanism and tectonism. Tertiary volcanic strata include 31–23 Ma ash-flow tuffs associated with the southward-migrating ''ignimbrite flare up,'' 22–5 Ma calc-alkaline intermediate-composition rocks related to the ancestral Cascade arc, and 13 Ma to present bimodal rocks linked to Basin and Range extension (Stewart, 1988; Best et al., 1989; Christiansen and Yeats, 1992). In the past 13–3 m.y., coincident with the northward migration of the Mendocino triple junction and associated termination of subduction, arc volcanism retreated northwestward, Basin and Range normal faulting advanced westward (Dilles and Gans, 1995; Henry and Perkins, 2001; Surpless et al., 2002), and strike-slip faulting began in the northern Walker Lane.

The ignimbrite flare up is important to unraveling northern Walker Lane evolution because thick sequences of ash-flow tuffs, erupted from calderas in central Nevada (Best et al., 1989; John, 1995), were deposited in paleovalleys that extended across western Nevada and California (Lindgren, 1911; Henry et al., 2003). Our work has shown that the paleovalleys contain distinctive 31–23 Ma tuff sections (Fig. 2) that reflect the southward progression of magmatism and provide piercing lines with which to gauge dextral offset. The southward migration of volcanism is critical, because ash-flow tuffs that fill paleoval-

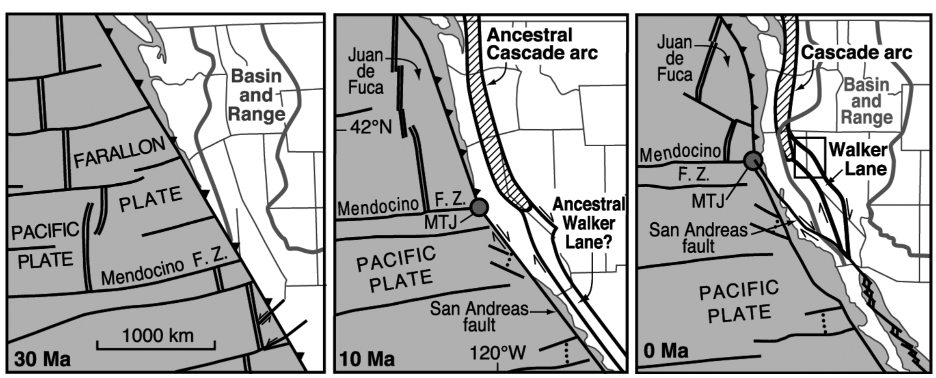

Figure 1. Cenozoic tectonic setting, western North America (after Atwater and Stock, 1998). San Andreas fault system has progressively lengthened in past 30 m.y., as more of Pacific plate has come into contact with North America. MTJ—Mendocino triple junction; F.Z.—fracture zone. In map on right, box surrounds study area.

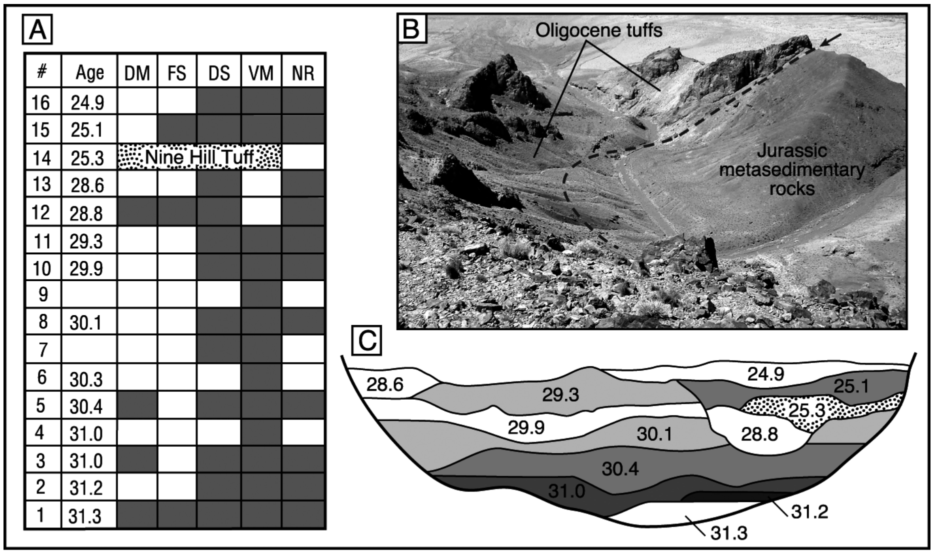

Figure 2. A: Shaded boxes indicate presence of tuff in paleovalley segment (see Fig. 3B for locations and abbreviation definitions; ages are in millions of years). B: Northern margin (dashed line) of paleovalley, Nightingale Range (looking west). C: Schematic paleovalley fill at Dogskin Mountain, with ages corresponding to individual tuffs.

leys in the northern Walker Lane are distinct from generally younger sections farther south. Thin gravels are commonly sandwiched between tuffs and indicate deposition in a fluvial system flowing from volcanic highlands in central Nevada westward to the Pacific Ocean. Uplift of the Sierra Nevada relative to the Great Basin had not yet occurred. In western Nevada and northeast California, ignimbrite volcanism terminated by 22 Ma, prior to Walker Lane development. Thus, offset Oligocene paleovalleys record cumulative displacement across the northern Walker Lane.

The northern Walker Lane consists of kinematically linked systems of NW-striking, left-stepping dextral faults, N-striking normal faults, and subordinate ENE-striking sinistral faults. From east to west, major dextral faults are the Pyramid Lake, Warm Springs Valley, Honey Lake, and Mohawk Valley faults (Fig. 3B). In the west, major dextral faults merge southward with a system of E-dipping normal faults, which coalesce southward to form the

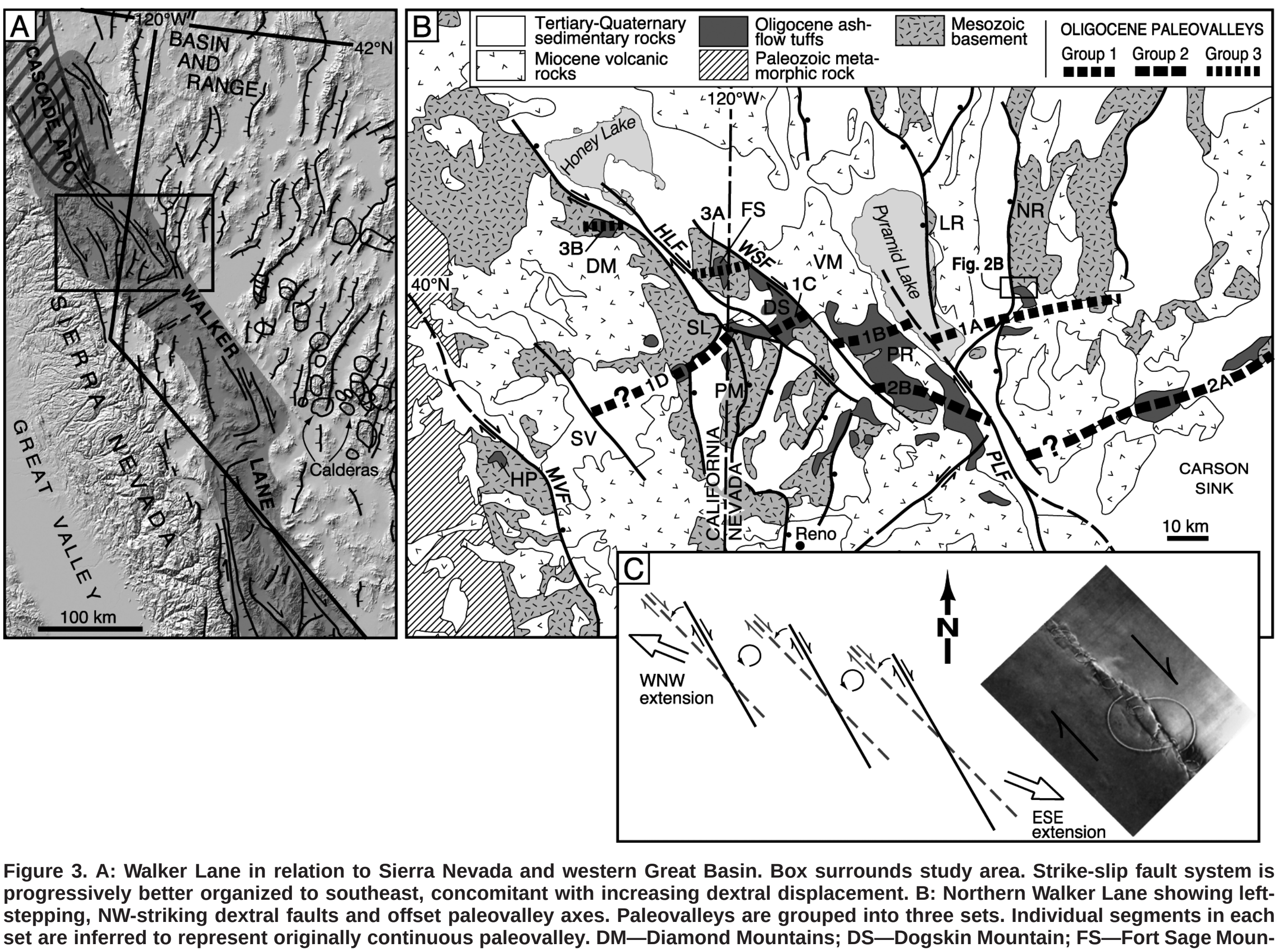

Figure 3. A: Walker Lane in relation to Sierra Nevada and western Great Basin. Box surrounds study area. Strike-slip fault system is progressively better organized to southeast, concomitant with increasing dextral displacement. B: Northern Walker Lane showing left-stepping, NW-striking dextral faults and offset paleovalley axes. Paleovalleys are grouped into three sets. Individual segments in each set are inferred to represent originally continuous paleovalley. DM—Diamond Mountains; DS—Dogskin Mountain; FS—Fort Sage Mountains; HLF—Honey Lake fault; HP—Haskell Peak; LR—Lake Range; MVF—Mohawk Valley fault; NR—Nightingale Range; PLF—Pyramid Lake fault; PM—Peterson Mountain; PR—Pah Rah Range; SL—Seven Lakes Mountain; SV—Sierra Valley; VM—Virginia Mountains; WSF—Warm Springs Valley fault. C: Riedel shear model for northern Walker Lane and analogous clay model from Wilcox et al. (1973). Coeval northwest-directed dextral shear and west-northwest extension may account for slight counterclockwise rotation of fault blocks that collapse in domino-like fashion to accommodate extension.

Sierra Nevada frontal fault system. To the east, the Pyramid Lake fault splays northward into the W-dipping Lake and Nightingale Range normal faults. This discrete belt of dextral faults gives way northwestward to a diffuse zone of widely spaced NW-striking dextral faults and lineaments that extends to the southern Cascade arc (Fig. 3A; Grose, 2000). Paleomagnetic data indicate slight (~15°) counterclockwise rotation in much of the northern Walker Lane in contrast to 35°–44° of clockwise rotation farther south near the Carson Sink (Cashman and Fontaine, 2000).

CONSTRAINTS ON STRIKE-SLIP FAULTING

Well-defined axes and/or margins of Oligocene paleovalleys, extending from the Nightingale Range in Nevada to the Diamond Mountains in California, provide piercing lines with which to estimate dextral offset (Fig. 3B). Petrography and $^{40}Ar/^{39}Ar$ geochronology demonstrate that all segments of this paleovalley system contain a similar, westward-thinning sequence of 31.3–23.5 Ma ash-flow tuffs (Fig. 2A and Data Repository Appendix DR1[1], which includes analytical data and sample locations). This sequence includes the widespread 25.3 Ma Nine Hill Tuff (Deino, 1985). The westward thinning of tuffs reflects greater distance from source calderas (Fig. 3A), not relative uplift and erosion of the Sierra Nevada and related blocks, because Miocene volcanic rocks, which predate uplift at these latitudes (Trexler et al., 2000; Henry and Perkins, 2001), generally cap the Oligocene tuffs.

East of the Pyramid Lake fault, the Nightingale Range contains a WSW-trending, ~10-km-wide paleovalley with an abrupt northern margin, where the entire >700-m-thick sequence of 11 tuffs pinches out (Figs. 2B and 3B; segment 1A). The southern Lake Range, however, contains only a thin veneer (<30 m thick) of Oligocene tuff, indicating that the westward continuation of the paleovalley projects south of the range. West of the Pyramid Lake fault in the Virginia Mountains, the northern part of a WSW-trending paleovalley contains an ~600-m-thick sequence of 15 ash-flow tuffs (Fig. 3B; segment 1B). Nearly identical tuff sequences in the Nightingale Range and Virginia Mountains indicate correlation of the respective paleovalley segments. On the basis of the westerly trend, this paleovalley has been offset 5–10 km across the Pyramid Lake fault.

Similar relationships indicate ~10–15 km of dextral offset across the Warm Springs Valley fault. On the northwest flank of Dogskin Mountain (Fig. 3B; segment 1C), >500 m of 31.3–24.9 Ma ash-flow tuffs (16 units) pinch out against the southeast margin of a WSW-trending paleovalley. Also, a distinctive rock-avalanche megabreccia derived from nearby rhyolite domes overlies a 25.1 Ma tuff in both the Virginia Mountains and at Dogskin Mountain.

Oligocene ash-flow tuffs are distributed over a 20 km north-south width between the Pyramid Lake and Warm Springs Valley faults (Fig. 3B; segments 1B, 2B). Mesozoic paleoridges in the Pah Rah Range suggest that this greater width, relative to the Nightingale Range and Dogskin Mountain, results from the confluence of two major tributaries in the paleovalley system.

Because of thick Neogene basin fill in the Honey Lake basin, displacement on the Honey Lake fault is more difficult to constrain. However, the southern margin of a paleovalley at Peterson Mountain correlates with that at Dogskin Mountain, indicating 3–6 km of dextral offset along the southeastern Honey Lake fault. A northern branch of the paleovalley system is marked by similar 200–250-m-thick sections of ash-flow tuff in the Fort Sage and north-central Diamond Mountains (Fig. 3B; segments 3A and 3B). Although the Honey Lake basin may obscure additional tuff deposits, the lack of other significant tuff outcrops in the Diamond Mountains suggests a correlation between these paleovalley segments. If correct, the central part of the Honey Lake fault accommodated 10–15 km of dextral offset of a W-trending paleovalley. As the Honey Lake fault zone dies out to the southeast, part of the displacement may be taken up by folding in a restraining bend at Seven Lakes Mountain and major E-dipping normal faults (Fig. 3B). The westward continuation of the main-stem paleovalley may underlie Sierra Valley (Fig. 3B; segment 1D), as suggested by a 300-m-thick sequence of correlative tuff west of Sierra Valley at Haskell Peak (Brooks et al., 2003).

The westernmost strand of the northern Walker Lane, the Mohawk Valley fault, has accommodated little dextral offset. Here, paleovalleys are obscure owing to scant exposure of Oligocene tuff. However, a contact between Cretaceous granite and Paleozoic metamorphic rock shows little (<1 km) dextral offset across the fault (Fig. 3B; Saucedo and Wagner, 1992).

Several features suggest a relatively recent onset of strike-slip faulting in the northern Walker Lane. For example, Oligocene tuffs and Miocene volcanic rocks are equally tilted, suggesting little deformation during the ignimbrite flare up and arc volcanism. Although approximately east-west extension initiated basin development at 13 Ma (Trexler et al., 2000), evidence is lacking for strike-slip faulting during early stages of extension. Moreover, 3.5 Ma sedimentary rocks along the Warm Springs Valley fault are as highly deformed as Oligocene tuffs. Also, clockwise vertical-axis rotation just west of the Carson Sink began ca. 9–5 Ma (Cashman and Fontaine, 2000). Considering these relationships, we infer that the onset of strike-slip faulting propagated northwestward in the northern Walker Lane, beginning as early as 9 Ma in the southeast and as late as 3 Ma in the northwest. Subsequent movement on strike-slip and normal faults has been broadly coeval, as evidenced by Quaternary fault scarps and seismicity (Ichinose et al., 1998).

In summary, inferred offsets of an Oligocene paleovalley system indicate ~20–30 km of cumulative dextral displacement, as measured orthogonal to the northern Walker Lane (Fig. 3B). The inferred magnitude and timing of deformation suggest long-term slip rates of ~2–10 mm/yr, which is compatible with GPS data from the northern Walker Lane (e.g., Bennett et al., 2003).

DISCUSSION

The en echelon dextral-fault pattern, minimal offset (5–15 km) on individual faults, and relatively small cumulative displacement indicate that the northern Walker Lane is an incipient strike-slip fault system. Although small left steps on individual faults have induced local shortening, the broad left steps between major faults accommodate little, if any, shortening and are unlike typical restraining bends. The left-stepping, en echelon geometry instead resembles patterns of primary Riedel shears (Petit, 1987) developed above strike-slip faults in clay models (Fig. 3C; e.g., Wilcox et al., 1973). The macroscopic Riedel shears in the Walker Lane terminate in ~N-striking normal fault systems, thereby transferring dextral shear to west-northwest extension in the northern Great Basin. The diffuse zone of faulting at the northwest terminus of the Walker Lane in northeast California mimics clay models (e.g., An and Sammis, 1996) involving broadly distributed shear with no throughgoing fault at depth. In this early stage, the minor NW-striking faults are also primary Riedel shears, but shear strain has not exceeded a threshold necessary to induce a continuous fault at depth. Evidence for this earlier stage abounds in northwest Nevada, as blocks between major strike-slip faults commonly contain minor inactive NW-striking dextral faults (Faulds et al., 2002). We therefore conclude that the northern Walker Lane records two early stages in the evolution of an intracontinental strike-slip fault system. Stage

[1]GSA Data Repository item 2005093, Appendix DR1, ages and ash-flow tuff correlation, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

one comprises a broad zone of widely spaced Riedel shears in northeast California. Stage two, in northwest Nevada, consists of a narrower belt of overlapping Riedel shears, which may indicate a throughgoing dextral shear zone in the upper mantle and/or lower crust. This stepwise development may characterize other incipient strike-slip fault systems (e.g., Taymaz et al., 1991; Jackson et al., 1995; Bayasgalan et al., 1999), including those at transform, oblique, and convergent plate boundaries.

The slight counterclockwise rotation in the northern Walker Lane is opposite the typical clockwise rotation in dextral shear zones. In the transtensional setting of the northern Walker Lane, coeval dextral shear in the left-stepping fault system and west-northwest regional extension may account for the counter-intuitive counterclockwise rotation (Fig. 3C). This sense of rotation would ultimately rotate Riedel shears toward the orientation of the main shear zone at depth, thus facilitating development of a throughgoing upper-crustal strike-slip fault. As such a fault develops and the strike-slip fault system matures, the sense of vertical-axis rotation may reverse and become compatible with the overall shear strain. The apparent change from counterclockwise to clockwise rotations southeastward in the northern Walker Lane (Cashman and Fontaine, 2000) may reflect such a progression. Such complex kinematics may characterize the early evolution of strike-slip fault systems in both transtensional and transpressional settings.

With the eventual northward migration of the Mendocino triple junction to the Oregon coast, the Walker Lane may ultimately afford a more stable configuration for the Pacific–North American plate boundary. Notably, the San Andreas fault has a history of stepping inland (Atwater and Stock, 1998). The Walker Lane may therefore reflect the birth of a lithospheric-scale transform fault and presage a significant eastward jump in the plate boundary.

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REFERENCES CITED

An, L.-J., and Sammis, C.G., 1996, Development of strike-slip faults: Shear experiments in granular materials and clay using a new technique: Journal of Structural Geology, v. 18, p. 1061–1078.

Atwater, T., and Stock, J., 1998, Pacific–North America plate tectonics of the Neogene southwestern United States: An update: International Geology Review, v. 40, p. 375–402.

Bayasgalan, A., Jackson, J., Ritz, J.-F., and Carretier, S., 1999, Field examples of strike-slip fault terminations in Mongolia and their tectonic significance: Tectonics, v. 18, p. 394–411.

Bennett, R.A., Wernicke, B.P., Niemi, N.A., Friedrich, A.M., and Davis, J.L., 2003, Contemporary strain rates in the northern Basin and Range province from GPS data: Tectonics, v. 22, doi: 10.1029/2001TC001355.

Best, M.G., Christiansen, E.H., Deino, A.L., Grommé, C.S., McKee, E.H., and Noble, D.C., 1989, Eocene through Miocene volcanism in the Great Basin of the western United States: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91–133.

Brooks, E.R., Wood, M.M., Boehme, D.R., Potter, K.L., and Marcus, B.I., 2003, Geologic map of the Haskell Peak area, Sierra County, California: California Geological Survey Map Sheet 55, scale 1:12,000.

Cashman, P.H., and Fontaine, S.A., 2000, Strain partitioning in the northern Walker Lane, western Nevada and northeastern California: Tectonophysics, v. 326, p. 111–130.

Christiansen, R.L., and Yeats, R.S., 1992, Post Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., et al., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 261–406.

Deino, A.L., 1985, Stratigraphy, chemistry, K-Ar dating, and paleomagnetism of the Nine Hill Tuff, California–Nevada: Miocene/Oligocene ash-flow tuffs of Seven Lakes Mountain, California–Nevada: Improved calibration methods and error estimates for potassium-40–argon-40 dating of young rocks [Ph.D. thesis]: Berkeley, University of California, 457 p.

Dilles, J.H., and Gans, P.B., 1995, The chronology of Cenozoic volcanism and deformation in the Yerington area, western Basin and Range and Walker Lane: Geological Society of America Bulletin, v. 107, p. 474–486.

Dokka, R.K., and Travis, C.J., 1990, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, p. 311–340.

Faulds, J.E., dePolo, C.M., and Henry, C.D., 2002, Preliminary geologic map of the Sutcliffe Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 03-17, scale 1:24,000.

Grose, T.L.T., 2000, Volcanoes in the Susanville region, Lassen, Modoc, Plumas Counties, northeastern California: California Geology, v. 53, p. 4–23.

Henry, C.D., and Perkins, M.E., 2001, Sierra Nevada–Basin and Range transition near Reno, Nevada: Two-stage development at 12 and 3 Ma: Geology, v. 29, p. 719–722.

Henry, C.D., Faulds, J.E., Garside, L.J., and Hinz, N.H., 2003, Tectonic implications of ash-flow tuffs and paleovalleys in the western US: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 346.

Henry, C.D., Faulds, J.E., and dePolo, C.M., 2004, Geologic map of the Dogskin Mountain Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 148, scale 1:24,000.

Ichinose, G.A., Smith, K.D., and Anderson, J.G., 1998, Moment tensor solutions of the 1994 to 1996 Double Spring Flat, Nevada, earthquake sequence and implications for local tectonic models: Seismological Society of America Bulletin, v. 88, p. 1363–1378.

Jackson, J., Haines, J., and Holt, W., 1995, The accommodation of Arabia-Eurasia plate convergence in Iran: Journal of Geophysical Research, v. 100, p. 15,205–15,219.

John, D.A., 1995, Tilted middle Tertiary ash-flow calderas and subjacent granitic plutons, southern Stillwater Range, Nevada: Cross sections of an Oligocene igneous center: Geological Society of America Bulletin, v. 107, p. 180–200.

Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada of California: U.S. Geological Survey Professional Paper 73, 226 p.

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

Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: Journal of Structural Geology, v. 9, p. 597–608.

Saucedo, G.J., and Wagner, S.L., 1992, Geologic map of the Chico quadrangle: California Division of Mines and Geology, Regional Geologic Map Series, map no. 7A, scale 1:250,000.

Stewart, J.H., 1988, Tectonics of the Walker Lane belt, western Great Basin: Mesozoic and Cenozoic deformation in a zone of shear, *in* Ernst, W.G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 683–713.

Surpless, B.E., Stockli, D.F., Dumitru, T.A., and Miller, E.L., 2002, Two-phase westward encroachment of Basin and Range extension into the northern Sierra Nevada: Tectonics, v. 21, doi: 10.1029/2000TC001257.

Taymaz, T.J., Jackson, J., and McKenzie, D., 1991, Active tectonics of the north and central Aegean Sea: International Geophysical Journal, v. 106, p. 433–490.

Thatcher, W., Foulger, G.R., Julian, B.R., Svarc, J., Quilty, E., and Bawden, G.W., 1999, Present-day deformation across the Basin and Range province, western United States: Science, v. 283, p. 1714–1718.

Trexler, J.H., Cashman, P.H., Henry, C.D., Muntean, T., Schwartz, K., TenBrink, A., Faulds, J.E., Perkins, M., and Kelly, T., 2000, Neogene basins in western Nevada document the tectonic history of the Sierra Nevada–Basin and Range transition zone for the last 12 Ma, *in* Lageson, D.R., et al., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 97–116.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., et al., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 553–581.

Wilcox, R.E., Harding, T.P., and Seely, D.R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74–96.

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