Influence of the Late Cenozoic Strain Field and Tectonic Setting on Geothermal Activity and Mineralization in the Northwestern Great Basin

James E. Faulds[1], Christopher D. Henry[1], Mark F. Coolbaugh[2], and Larry J. Garside[1]

[1]Nevada Bureau of Mines and Geology, MS 178, University of Nevada, Reno, NV 89557
[2]Great Basin Center for Geothermal Energy, University of Nevada, Reno, NV 89557

Keywords

Walker Lane, Great Basin, geothermal, epithermal, transtension, and extension

ABSTRACT

In the northwestern Great Basin, relatively high rates of recent (<10 Ma) west-northwest extension have absorbed a northwestward decrease in dextral motion along the Walker Lane. Abundant geothermal fields and a number of young (< ~7 Ma) epithermal mineral deposits in this region are most commonly situated along north- to northeast-striking structures. This hydrothermal activity may result from a transfer of northwest-trending dextral shear in the Walker Lane to west-northwest extension in the northern Great Basin. Enhanced extension favors dilation and deep circulation of aqueous solutions along north- to northeast-striking structures oriented perpendicular to the extension direction. The individual belts of geothermal fields probably reflect loci of strain transfer.

Introduction

A broad zone of distributed dextral shear stretches across western North America from the San Andreas fault system to the Basin and Range province (Figure 1). In the western Great Basin, the Walker Lane belt is the principal system of northwest-striking, right-lateral faults (Stewart, 1988). As evidenced by GPS geodetic data, it accommodates 10-25% of the Pacific-North American plate motion (Bennett et al., 2003; Hammond and Thatcher, 2004). To the south, the Walker Lane merges with the eastern California shear zone (Dokka and Travis, 1990). To the northwest, the Walker Lane terminates in northeast California near the southern end of the Cascade arc (Figure 1). Today, the northwestern Great Basin lies within a transtensional setting, characterized by both northwest-directed dextral shear and west-northwest-trending extension.

Abundant geothermal fields (Coolbaugh et al., 2002) and a number of late Cenozoic epithermal mineral deposits (John, 2001) reside in the northwestern Great Basin (Figures 2 and 3, overleaf). However, volcanic activity in most of this region ceased 3 to 10 Ma, with significant magmatism ending in most areas by ~7 Ma. And yet, many of the mineral deposits are younger than 7 Ma (Table 1, overleaf) and geothermal activity is prolific today. This suggests that much of the recent mineralization and most of the ongoing geothermal activity are not linked to magmatism, or that significant young magmatism has gone unrecognized in the region. If magmatism is not a factor (which seems probable based on available data), why then is recent (< 7 Ma) hydrothermal and geothermal activity relatively widespread in this region?

In this paper, we evaluate the tectonic setting, broad structural controls on geothermal systems, and preferred orientation of mineralized structures in young (< ~7 Ma) epithermal mineral deposits of the northwestern Great Basin. We conclude that the transtensional setting of this region facilitates geothermal and hydrothermal activity along north- to north-northeast-striking structures, which are favorably oriented within the regional strain field.

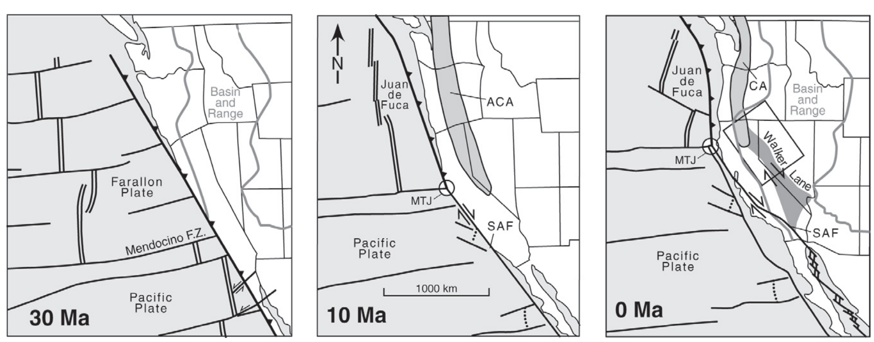

Figure 1. Cenozoic tectonic evolution, western North America. A. 30 Ma. B. 10 Ma. C. 0 Ma. The box in (C) surrounds the locus of geothermal activity and several young (< 7 Ma) epithermal Au-Ag deposits in the northwestern Great Basin. ACA, ancestral Cascade arc; CA, Cascade arc; MTJ, Mendocino triple junction; SAF, San Andreas fault.

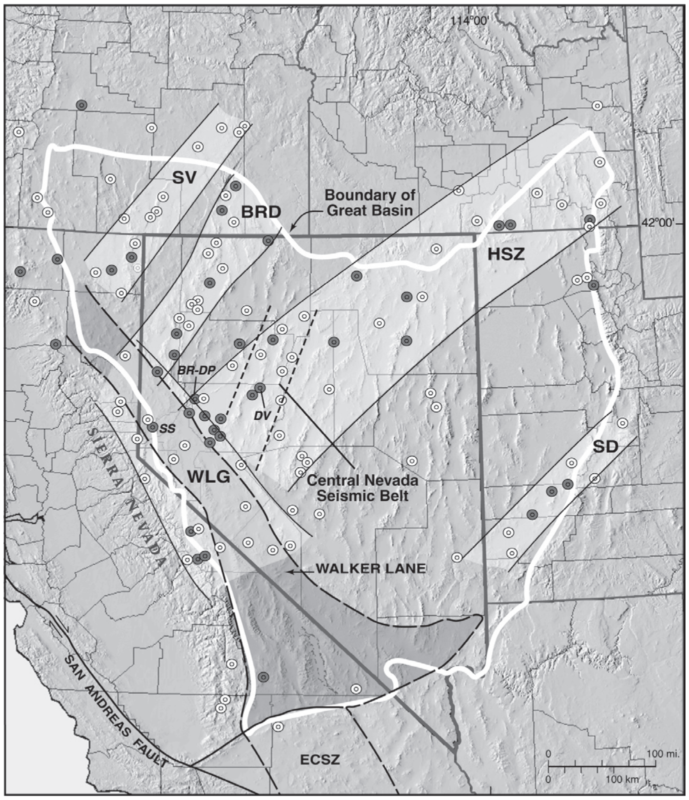

Figure 2. Geothermal belts in the Great Basin (from Faulds et al., 2004). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. White circles are geothermal systems with maximum temperatures of 100-160°C; grey circles have maximum temperatures >160°C. ECSZ, eastern California shear zone. Dashed lines (short dashes) bound the central Nevada seismic belt. Abbreviations for individual geothermal fields: BR-DP, Brady's and Desert Peak; DV, Dixie Valley; SS, Steamboat.

Geologic Setting

As the western margin of North America evolved from a convergent to a transform plate boundary during Cenozoic time (Figure 1; Atwater and Stock, 1998), the northwestern Great Basin experienced widespread volcanism that coincided in part with regional extension and strike-slip faulting. This includes 1) 31 to 23 Ma rhyolitic ash-flow tuffs associated with the "ignimbrite flare-up", which swept southwestward across the Great Basin in Eocene to middle Miocene time; 2) 22 to 5 Ma intermediate volcanism associated with an ancestral Cascades arc, which retreated northwestward as the Mendocino triple junction migrated northward; and 3) 13 Ma to present bimodal volcanism related to ~east-west Basin and Range extension (Best et al., 1989; Christiansen and Yeats, 1992; Henry et al., 2004a; John, 2001). However, volcanism waned rapidly in the late Miocene, with only local outpourings in most of the Great Basin after ~7 Ma (Henry and Faulds, 2004). Only widely spaced, relatively small volcanic centers have erupted in the Quaternary.

A complex three-dimensional strain field characterizes the northern Walker Lane and northwestern Great Basin (Figure 4). Major structural elements in and adjacent to the northern Walker Lane include: (1) northwest-striking right-lateral faults, (2) east-northeast-striking left-lateral faults, (3) north- to north-northeast-striking normal faults and associated tilted fault blocks and half grabens, and (4) localized east-trending fold belts. Available data suggest that movement on all three sets of faults and the folding have been broadly coeval, with activity continuing through the Quaternary. Accordingly, strike-slip faults within the Walker Lane are intimately linked with major normal fault systems within the Great Basin (e.g., Oldow et al., 1994; Faulds et al., 2005). However, geodetic data (Bennett et al., 2003; Hammond and Thatcher, 2004), historical seismicity (dePolo et al., 1997), and present physiography indicate that northwest-trending dextral shear dominates the contemporary strain field of the Walker Lane belt, whereas west-northwest extension prevails farther east within the Great Basin. The localized east-trending fold belts probably reflect minor approximately north-south shortening induced by northwest-directed dextral shear. Bulk constrictional strain, involving a component of horizontal shortening, probably characterizes most transtensional terranes (Dewey, 2000). Thus, northwest-directed dextral shear, west-northwest-trending extension, and a minor component of north-south shortening all contribute to the three-dimensional strain field within the northwestern Great Basin (Figure 4).

Major extension and strike-slip faulting within the northwestern Great Basin is relatively young. Early basin development, tilt fanning in half grabens, and thermochro-

Figure 3. Young (< ~7 Ma) epithermal Au-Ag deposits in the northwestern Great Basin. Long axes of crosses represent average strike of veins or mineralized structures (Table 1). Squares denote deposits of known or possible magmatic origin; circles represent deposits that are not linked to magmatism. Abbreviations are defined in Table 1.

Table I. Young (< ~7 Ma) Epithermal Mineral Deposits, Northwestern Great Basin.

Symbol	Deposit Name	Age	Average Trend	Trend Range	Source
BM	Blue Mountain	3.9 Ma	N0°E		Parr and Percival, 1991; Garside et al., 1993
CL	Crofoot/Lewis	3.9 Ma	N5°E		Ebert and Rye, 1997; Ebert et al., 1996
Sc	Scossa	6.5 Ma	N0°E		Noble et al., 1987
HH	Humboldt House	Quaternary	N16°E		Coolbaugh et al., 2005
FC	Florida Canyon	2.0 Ma	N0°E		Hastings et al., 1988; Coolbaugh et al., 2005
WM	Wind Mountain	Pliocene-Quaternary	N12°E		Wood, 1991
Wi	Willard	6.1 Ma			Noble et al., 1987
RC	Relief Canyon	Pliocene-Quaternary	N18°W		Wallace, 1989
DC	Dixie Comstock	<1 Ma	N5°E	N0-10°E	Vikre, 1994
MH	McGiness Hills	ca. 2.7 Ma	N10°E		Casaceli et al., 1986
GD*	Golden Dome-Antelope Neck	7.1 Ma	N10°E		Young and Cluer, 1992; Garside et al., 1993
SS*	Steamboat	0 to 3 Ma	N12°W		Silberman et al., 1979
Cm*	Como	6.8 Ma	N56°E		Vikre and McKee, 1994
MM*	Monitor-Mogul	4.9 Ma	N23°E	N0°E to N45°E	Prenn and Merrick, 1991
SP*	16 to 1 Mine, Silver Peak area	<6 Ma	N55°E		Keith, 1977
LV*	Long Valley, CA	0.4 Ma	~N-S		Prenn and Muerhoff, 2003

*Known or possible magmatic systems.

nology indicate that extension began 10 to 15 Ma (Henry and Perkins, 2001; Surpless et al., 2002; Colgan et al., 2004). Early extension in this region (ca. 20-10 Ma) was probably characterized by a west-southwest-trending least principal stress (Zoback et al., 1981) in contrast to the present west-northwest-trending extension direction. Strike-slip faulting probably began 9 to 3 Ma. For example, ~3 Ma strata are as highly deformed as middle Tertiary rocks along major strike-slip faults in the northern Walker Lane (Henry et al., 2004b, 2005). In addition, the onset of vertical-axis rotation of fault blocks within the northern Walker Lane, as inferred from paleomagnetic data, is bracketed between ~9 and 5 Ma just west of the Carson Sink (Cashman and Fontaine, 2000). These relations suggest that strike-slip faulting in the northern Walker Lane initiated 9 to 3 Ma, with possibly a later onset to the northwest. Thus, it would appear that the current strain field (Figure 4) in the northwestern Great Basin is no older than 9 Ma and possibly younger than 3 Ma in some areas.

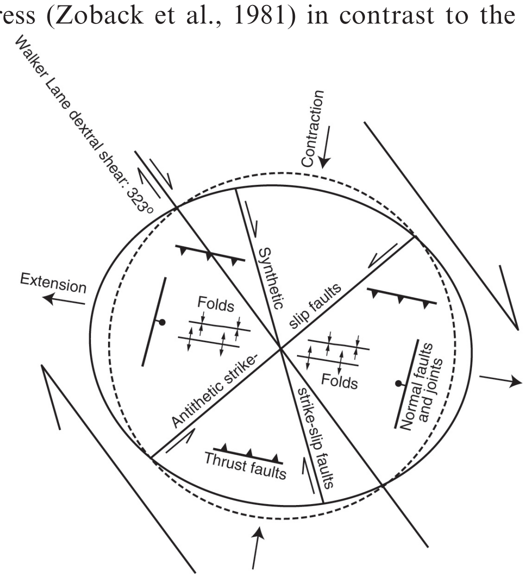

Figure 4. Diagrammatic strain ellipse for northwest-directed dextral shear within the Walker Lane and expected orientations of major structures (adapted from Sylvester, 1988).

Dextral offset appears to decrease significantly toward the northwest within the Walker Lane. In west-central Nevada, central parts of the Walker Lane accommodated 48-75 km of dextral offset (Ekren and Byers, 1984; Oldow, 1992). Farther north, offset west-trending Oligocene paleovalleys, which are filled with 31-23 Ma ash-flow tuffs, indicate only 20-30 km of cumulative displacement (Faulds et al., 2005). In northeast California and southern Oregon, cumulative slip decreases to essentially zero across a diffuse zone of discontinuous, widely-spaced, northwest-trending faults (Grose, 2000). The decrease in cumulative strain is compatible with a decline in present-day slip rates from approximately 12 mm/yr to 4-8 mm/yr between west-central Nevada and northeast California, as inferred from GPS geodetic data (Bennett et al., 2003; Hammond and Thatcher, 2004).

As the Walker Lane loses displacement to the northwest, dextral shear progressively bleeds off into belts of west-northwest extension in the northern Great Basin, including the central Nevada seismic belt, Black Rock Desert region, and Surprise Valley area (Figure 2; Faulds et al., 2004). Individual strike-slip faults terminate in arrays of northerly striking normal faults. Loci of strain transfer appear to correspond to prominent belts of geothermal systems, which partially overlap with areas containing abundant young (< ~7 Ma) epithermal mineral deposits.

Geothermal Fields

Geothermal fields within the Great Basin are most abundant in the northwestern part (Figure 2). Known geothermal systems within and adjacent to the Great Basin can be grouped into four northeast-trending belts and one northwest-trending belt (Faulds et al., 2004). Only one belt lies entirely outside of the northwestern Great Basin. Moreover, most of the high-temperature (>160°C) amagmatic systems reside within the northwestern Great Basin. This locus of geothermal activity is situated directly northeast of the central and northern parts of the Walker Lane, where dextral shear associated with plate boundary motions dies out to the northwest (Figures 1 and 2).

From southeast to northwest, the northeast-trending belts have been referred to as the Sevier Desert, Humboldt, Black Rock Desert, and Surprise Valley geothermal belts. The Sevier Desert belt trends ~N40°E and extends through southwest Utah. The Humboldt belt is a broad zone of geothermal systems that trends ~N50°E and extends through much of western and northern Nevada into southeast Idaho. The Humboldt belt includes a broad zone of east-northeast- to northeast-striking sinistral-normal faults that has been referred to as the Humboldt structural zone (Rowan and Wetlaufer, 1981).

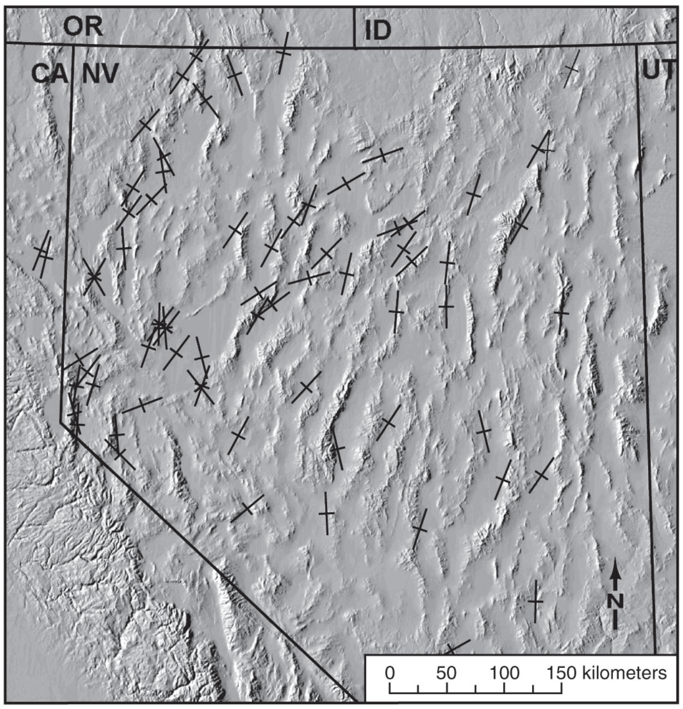

Figure 5. Structural controls on known geothermal systems in Nevada and adjacent areas (from Faulds et al., 2004). Long axes of crosses represent inferred strike of controlling fault for individual geothermal systems.

Farther northwest, the Black Rock Desert and Surprise Valley geothermal belts trend ~N25-30°E.

The Walker Lane geothermal belt is a northwest-trending zone of geothermal systems that follows the western margin of the Great Basin along the east front of the Sierra Nevada. It is not as conspicuous as the northeast-trending belts. Geothermal systems in the northern part of the Walker Lane belt could be included in the Humboldt and Black Rock Desert belts.

Detailed investigations and reconnaissance studies (e.g., Blackwell et al., 1999; Johnson and Hulen, 2002; Faulds et al., 2003; Wannamaker, 2003) show that north- to northeast-striking faults (N0°E-N60°E) control about 75% of the geothermal fields in Nevada and northeast California (Figure 5; Faulds et al., 2004). This control is strongest for high temperature systems (> 160°C; Coolbaugh et al., 2002). In the northwestern Great Basin, where the extension direction trends west-northwest, most of the controlling faults strike north-northeast approximately orthogonal to the extension direction.

Late Cenozoic Mineralization

Late Tertiary to Quaternary epithermal Au-Ag deposits are relatively common in the northwestern Great Basin. Considering the spatial and temporal distribution of volcanism in this region, many of the young (<7 Ma) epithermal deposits may not be related to magmatism. Similar to dikes, mineralized structures typically develop along dilational fractures oriented orthogonal to the extension direction (Rehrig and Heidrick, 1976; Drier, 1984). In the case of the northwestern Great Basin, it is important to note that the extension direction shifted from west-southwest to west-northwest in late Miocene-early Pliocene time (Zoback et al., 1981) concomitant with development of northwest-directed dextral shear associated with Pacific-North American plate boundary motion.

The approximate ages and general trends of mineralized structures in late Miocene to Quaternary epithermal deposits in the northwestern Great Basin are compiled in Table 1. Hydrothermal alteration and/or mineralization at some districts may span more than one age. The table includes deposits that are closely tied to synchronous igneous activity (e.g., Golden Dome and Steamboat), as well as those that are spatially associated with recent geothermal systems. These young (< ~7 Ma) Au-Ag mineral deposits formed at shallow depths, as evidenced by synsedimentary mineralization, sinter, and synsedimentary hydrothermal breccias. Several low-sulfidation epithermal and hot-spring-type deposits have fine-grained chalcedonic veins, silica replacement bodies, or indications of boiling. At some deposits, mineralization occurs along Quaternary faults that bound or parallel the present mountain range.

Whether of known magmatic or possible amagmatic origin, veins and mineralized structures within these young (< ~7 Ma) epithermal mineral deposits have relatively consistent strikes, with a mean of N11°E and range from N18°W to N56°E (Table 1 and Figure 3). The average trend of mineralized structures reflects a predominant west-northwest-trending extension direction, which is compatible with the current strain field (Figure 4). Examples of north- to northeast-striking mineralized structures that parallel range-front normal faults include the Dixie Comstock, Wind Mountain, and Crofoot/Lewis Mines.

Discussion

Most geothermal fields (e.g., Desert Peak, Brady's, Dixie Valley) and young (< ~7 Ma) hydrothermal systems related to epithermal Au-Ag deposits (e.g., Dixie Comstock and Crofoot-Lewis) in the northwestern Great Basin occur along north- to northeast-striking normal fault zones or mineralized structures (Figures 3 and 5), where dilation is favored by northwest-directed dextral shear and west-northwest-trending extension. Known magmatism generally ceased by ~7 Ma and may therefore not account for much of the geothermal activity and mineralization. We suggest that the transtensional setting of the northwestern Great Basin has induced deep circulation of meteoric fluids, which has in turn has facilitated widespread geothermal activity and epithermal mineralization in the region.

The distribution of shear- and dilational-strain magnitudes within the Great Basin (Blewitt et al., 2003), as derived from GPS geodetic data, show that 1) shear strain is focused in the western part of the Great Basin along the Walker Lane belt; 2) shear strain terminates northwestward within the northern Walker Lane, and 3) a broad area of high dilational strain lies directly northeast of the central and northern parts of the Walker Lane. In the northern Walker Lane, major strike-slip faults terminate in arrays of normal faults both within the Great Basin and along the eastern front of the Sierra Nevada (Faulds et al., 2005). It therefore appears that the northwestward decrease in displacement along the Walker Lane is accommodated by a transfer of dextral shear to extensional strain. North- to north-northeast-striking normal faults absorb the northwestward decrease in dextral motion within the Walker Lane, diffusing that motion into the Basin and Range province. The bleeding off of dextral shear from the Walker Lane has probably accentuated rates of recent (<10 Ma) west-northwest extension within the northwestern Great Basin (Figure 1c).

Abundant geothermal fields and several young epithermal mineral deposits occur within the active transtensional setting in the northwestern Great Basin, beginning in the southeast where dextral shear starts to decrease and ending to the northwest where dextral shear essentially terminates (Figures 2 and 3). Steeply dipping, north-northeast-striking structures host most geothermal systems and many of the epithermal deposits (Figures 3 and 5). This probably results from dilation and deep circulation of aqueous fluids along fractures oriented perpendicular to the west-northwest-trending extension direction. The north- to northeast-trending geothermal belts and mineralized structures are also oriented orthogonal to the extension direction and may therefore reflect loci of strain transfer from the Walker Lane into the Great Basin.

Acknowledgments

This research was supported by the U.S. Department of Energy (DE-FG36-02ID14311 and DE-FG07-02ID14311) and National Science Foundation (grant EAR-0124869). We thank Bill Pickles for reviewing this manuscript.

References

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.

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, p. 3-1–3-31.

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.

Blackwell, D., Wisian, K., Benoit, D., Gollan, B., 1999, Structure of the Dixie Valley geothermal system: A "typical" Basin and Range geothermal system from thermal and gravity data: Geothermal Resource Council Transactions, v. 23, p. 525-531.

Blewitt, G., Coolbaugh, M.F., Sawatzky, D.L., Holt, W., Davis, J.L., and Bennett, R.A., 2003, Targeting of potential geothermal resources in the Great Basin from regional to basin-scale relationships between geodetic strain and geological structures: Geothermal Resource Council Transactions, v. 27, p. 3-7.

Casaceli, R.J., Wendell, D.E., and Hoisington, W.D., 1986, Geology and mineralization of the McGinness Hills, Lander County, Nevada in Tingley, J.V., and Bonham, H.F., Jr., eds., Precious metal mineralization in hot springs systems, Nevada-California: Nevada Bureau of Mines and Geology Report 41, p. 93-102.

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., Lipman, P.W. and Zoback, M.L., eds., The Cordilleran orogen: conterminous U.S.: Boulder, Geological Society of America, The Geology of North America, v. G-3, p. 261-406.

Colgan, J.P., Dumitru, T.A., and Miller, E.L., 2004, Diachroneity of Basin and Range extension and Yellowstone hotspot volcanism in northwestern Nevada: Geology, v. 32, p. 121-124.

Coolbaugh, M.F., Taranik, J.V., Raines, G.L., Shevenell, L.A., Sawatzky, D.L., Minor, T.B., and Bedell, R., 2002, A geothermal GIS for Nevada: defining regional controls and favorable exploration terrains for extensional geothermal systems: Geothermal Resources Council Transactions, v. 26, p. 485-490.

dePolo, C.M., Anderson, J.G., dePolo, D.M., and Price, J.G., 1997, Earthquake occurrence in the Reno-Carson City urban corridor: Seismological Research Letters, v. 68, p. 386-397.

Dewey, J.F., 2000, Transtension in arcs and orogens: International Geology Review, v. 44, p. 402-439.

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

Drier, J., 1984, Regional tectonic controls of epithermal veins in the western U. S. and Mexico: Arizona Geological Society Digest, v. 15, p. 28-52.

Ebert, S.W., Groves, D.I., and Jones, J.K., 1996, Geology, alteration, and ore controls of the Crofoot/Lewis Mine, Sulphur, Nevada: A well-preserved hot spring gold-silver deposit, in Coyner, A.R., and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, p. 209-234.

Ebert, S.W., and Rye, R.O., 1997, Secondary precious metal enrichment by steam-heated fluids in the Crofoot-Lewis hot spring gold-silver deposit and relation to paleoclimate: Economic Geology, v. 92, p. 578-600.

Ekren, E.B. and Byers, F.M., Jr., 1984,The Gabbs Valley Range - a well-exposed segment of the Walker Lane in west-central Nevada *in* Lintz, J., Jr., ed., Western Geologic Excursions, v.4, Geological Society of America Guidebook, p. 204-215.

Faulds, J.E., Garside, L.J., and Oppliger, G.L., 2003, Structural analysis of the Desert Peak-Brady geothermal fields, northwestern Nevada: Implications for understanding linkages between northeast-trending structures and geothermal reservoirs in the Humboldt structural zone: Geothermal Resources Council Transactions, v. 27, p. 859-864.

Faulds, J.E., Coolbaugh, M., Blewitt, G., and Henry, C.D., 2004, Why is Nevada in hot water? Structural controls and tectonic model of geothermal systems in the northwestern Great Basin: Geothermal Resources Council Transactions, v. 28, p. 649-654.

Faulds, J.E., Henry, C.D., and Hinz, N.H., 2005, Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific – North American plate boundary: Geology, v. 33, p. 505-508.

Garside, L.J., Bonham, H.F., Tingley, J.V., and McKee, E.H., 1993, Potassium-argon ages of igneous rocks and alteration minerals associated with mineral deposits, western and southern Nevada and eastern California: Isochron/West, no. 59, p. 17-23.

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

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the Global Positioning System: Journal of Geophysical Research, v. 109, B08403, DOI: 10.1029/2003JB002746.

Hastings, J.S., Burkhart, T.H., and Richardson, R.E., 1988, Geology of the Florida Canyon gold deposit, Pershing County, Nevada, in Schafer, R.W, Cooper, J.J, and Vikre, P.G., eds., Bulk mineable precious metal deposits of the western United States symposium proceedings, Geological Society of Nevada, p. 433-452.

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., Cousens, B.L., Castor, S.B., Faulds, J.E., Garside, L.J., and Timmermans, A., 2004a, The ancestral Cascades arc, northern California/western Nevada: Spatial and temporal variations in volcanism and geochemistry: EOS, American Geophysical Union, v. 85, no. 47, Abstract V13B-1478.

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

Henry, C.D., and Faulds, J.E., 2004, Paired magmatic-tectonic evolution of the northern Walker Lane (NWL), northwestern Nevada and northeastern California: Earthscope/NSF Great Basin Symposium, Lake Tahoe, California, June 21-23.

Henry, C.D., Faulds, J.E., and dePolo, C.M., 2005, Geometry and timing of strike-slip and normal faults of the northern Walker Lane, northwestern Nevada and northeastern California: Strain partitioning, sequential extensional and strike-slip deformation, or both? Geological Society of America Special Paper, in press.

John, D.A., 2001, Miocene and early Pliocene epithermal gold-silver deposits in the northern Great Basin, western United States: Characteristics, distribution, and relationship to magmatism: Economic Geology, v. 96, p. 1827-1853.

Johnson, S.D., and Hulen, J.B., 2002, Subsurface stratigraphy, structure, and alteration in the Senator thermal area, northern Dixie Valley geothermal field, Nevada: Transactions Geothermal Resource Council, v. 26, p. 533-542.

Keith, W.J., 1977, Geology of the Red Mountain mining district, Esmeralda County, Nevada: U.S. Geological Survey Bulletin 1423, 45 p., 1:12,000.

Noble, D.C., McKee, E.H., and Larson, L.T., 1987, Late Miocene hydrothermal activity at the Willard and Scossa mining districts, Pershing County, Nevada: Isochron West, no. 48, p. 9-10.

Oldow, J. S., 1992, Late Cenozoic displacement partitioning in the northwestern Great Basin, *in* Structure, Tectonics and Mineralization of the Walker Lane, Stewart, J., ed., Walker Lane Symposium Proceedings Volume, Geological Society of Nevada, p. 17-52.

Oldow, J.S., Kohler, G., and Donelik, R.A., 1994, Late Cenozoic extensional transfer in the Walker Lane strike-slip belt, Nevada: Geology, v. 22, no. 7, p. 637-640.

Parr, A.J., and Percival, T.J., 1991, Epithermal Gold Mineralization and a Geothermal Resource at Blue Mountain, Humboldt Co., Nevada: Geothermal Resources Council Transactions, v. 15, p. 35-39.

Prenn, N., and Merrick, P., 1991, The Monitor-Mogul mining district, Alpine County, California: The Mineralogical Record, v. 22, no. 1, p. 29-40.

Prenn, N. and Muerhoff, C.V., 2003, Technical report, Long Valley project, Mono County, USA: prepared by Mine Development Associates on behalf of Vista Gold, Corp., 75 p.

Rehrig, W. A., and T. L. Heidrick, 1976, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range province, Arizona: Arizona Geology Digest, v. 10, p. 205-228.

Rowan, L.C., and Wetlaufer, P.H., 1981, Relation between regional lineament systems and structural zones in Nevada: American Association of Petroleum Geology Bulletin, v. 65, p. 1414-1452.

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.

Silberman, M.L., White, D.E., Keith, T.E.C., and Dockter, R.D., 1979, Duration of hydrothermal activity at Steamboat Springs, Nevada, from ages of spatially associated volcanic rocks: U. S. Geological Survey Professional Paper 458-D, 14 p.

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: Prentice Hall, Englewood Cliffs, New Jersey, p. 7186.*

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, p. 2-1 to 2-13.

Sylvester, A.G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666-1703.

Vikre, P., 1994, Gold mineralization and fault evolution at the Dixie Comstock Mine, Churchill County, Nevada: Economic Geology, v. 89, p. 707-719.

Vikre, P.G., and McKee, E.H., 1994, Geology, alteration, and geochronology of the Como district, Lyon County, Nevada: Economic Geology, v. 89, p. 639-646.

Wallace, A.R., 1989, The Relief Canyon gold deposit, Nevada: A mineralized solution breccia: Economic Geology, v. 84, p. 279-290.

Wannamaker, P.E., 2003, Initial results of magnetotelluric array surveying at the Dixie Valley geothermal area, with implications for structural controls and hydrothermal alteration: Geothermal Resources Council Transactions, v. 27, p. 37-40.

Wood, J.D., 1991, Geology of the Wind Mountain gold deposit, Washoe County, Nevada, in Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and ore deposits of the Great Basin: Symposium proceedings: Geological Society of Nevada, p. 1051-1061.

Young, T.H., and Cluer, J.K., 1992, The Antelope Valley precious metal deposits, a Tertiary acid sulfate system in Sierra County, California, *in* Craig, Steve, ed., Walker Lane Symposium, 1992 spring field trip #2 guidebook, Reno area - northern Walker Lane mineralization and structure: Geological Society of Nevada Special Publication no. 15, p. 33-42.

Zoback, M.L., Anderson, R.E., and Thompson, G.A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: Philosophical Transactions of the Royal Society of London, v. 300A, p. 407-434.