WHY IS NEVADA IN HOT WATER? STRUCTURAL CONTROLS AND TECTONIC MODEL OF GEOTHERMAL SYSTEMS IN THE NORTHWESTERN GREAT BASIN

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Keywords: Walker Lane, Great Basin, tectonics, structural controls, geothermal systems, Nevada, strike-slip faults, normal faults, strain transfer

ABSTRACT

In the western Great Basin, the Walker Lane is a system of right-lateral strike-slip faults accommodating ~15-25% of relative motion between the Pacific and North American plates. Relatively high rates of recent (<10 Ma) west-northwest extension absorb northwestward declining dextral motion in the Walker Lane, diffusing that motion into the Basin-Range. Abundant geothermal fields cluster in several northeast-trending belts in the northern Great Basin (e.g. Humboldt structural zone and Black Rock Desert region) and collectively define a broad, northeast-trending zone of high heat flow. Individual fields are largely controlled by north-northeast-striking normal faults. The Walker Lane begins losing displacement to the northwest in west-central Nevada near the southeast margin of the high heat-flow region. The abundant geothermal fields may therefore 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-northeast-striking faults. The individual belts of geothermal fields probably reflect loci of strain transfer.

INTRODUCTION

Within the Great Basin of the western US, geothermal fields are in greatest abundance in northern Nevada and neighboring parts of northeast California and southernmost Oregon (Fig. 1). This clustering of geothermal fields lies within a broad region of high heat flow that trends northeastward across the northern Great Basin (e.g. Lachenbruch and Sass, 1977). The geothermal systems cluster in discrete northeast-trending belts, including the Humboldt structural zone and Black Rock Desert region. Volcanic activity in most of this region ceased ~3 to 10 Ma. Thus, magmatism is not a likely source of the high heat flow and geothermal activity within the bulk of the northwestern Great Basin.

Why then is this region characterized by such widespread geothermal activity? In this paper, we evaluate both the tectonic setting and structural controls on individual systems as a means of developing a tectonic model for geothermal activity in the Great Basin. Our findings may have implications for geothermal *hotspots* in relatively amagmatic extensional or transtensional settings in other parts of the world.

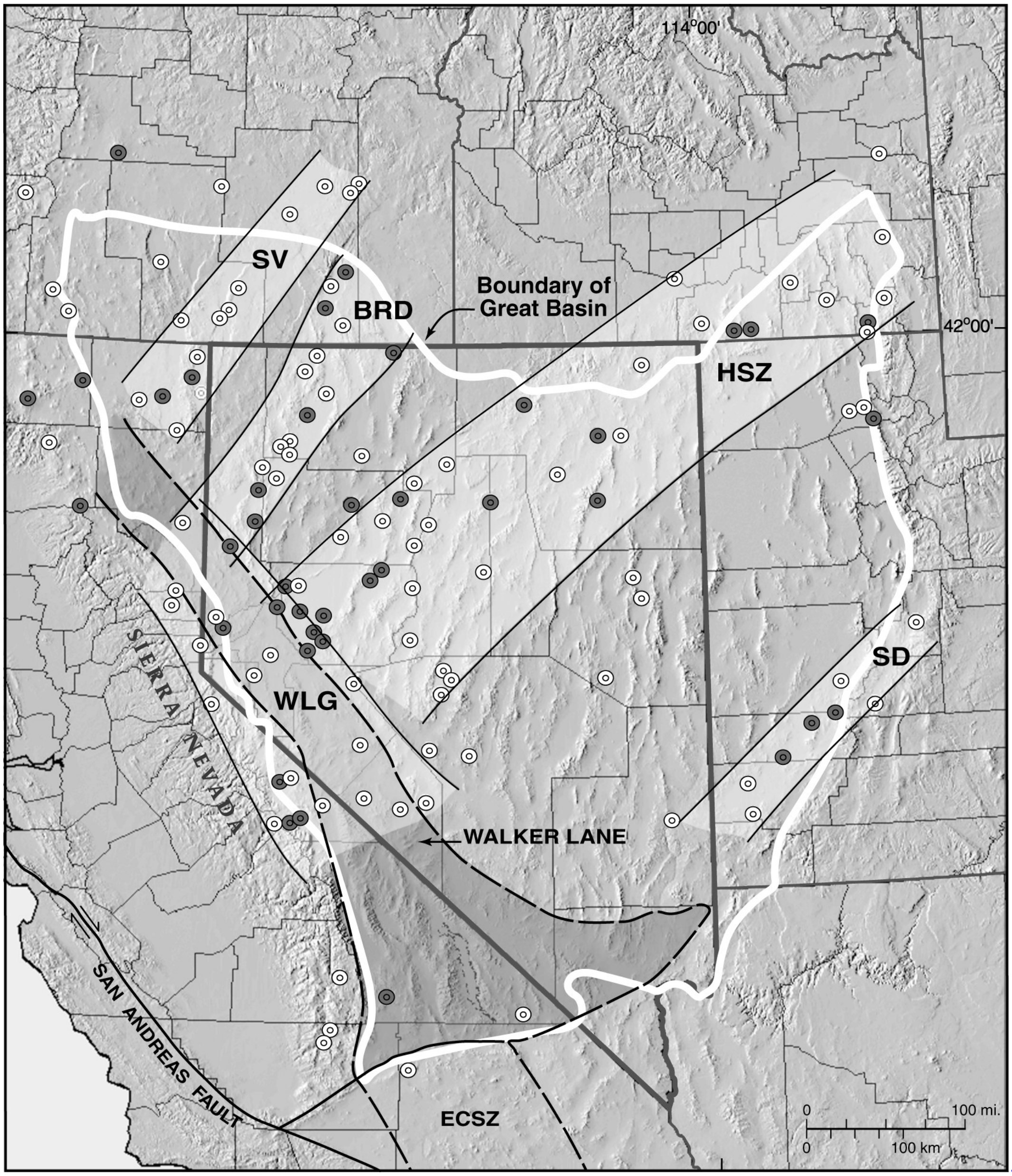


Figure 1. Geothermal fields in the Great Basin. Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. The northwestern Great Basin, directly northeast of the northwest terminus of the Walker Lane, contains the greatest concentration of fields. White circles are geothermal systems with maximum temperatures of 100-160ºC; grey circles have maximum temperatures >160ºC. ECSZ, eastern California shear zone.

TECTONIC SETTING

The San Andreas fault system was born ~30 Ma as the Pacific plate came into contact with the western margin of North American in response to subduction of the last vestiges of the Farallon plate (Fig. 2; Atwater and Stock, 1998). As remnants of the Farallon plate (e.g. Juan de Fuca plate) progressively disappeared into the subduction zone, bringing more of the Pacific plate into contact with North America, the San Andreas fault lengthened both to the northwest and southeast. Thus, the triple junction at the north end of the San Andreas, which defines the contact between the North American, Pacific, and Juan de Fuca plates, has progressively migrated northward in the past 30 million years. It now lies off the coast of Mendocino, California, and is referred to as the Mendocino triple junction. The northern part of the San Andreas fault system is therefore significantly younger than segments farther south in central and southern California. As the San Andreas fault system has grown through time, it has periodically stepped inland, effectively transferring parts of North America to the Pacific plate (e.g. Powell et al., 1993). The most significant recent jump in the San Andreas occurred ~6 Ma when the southern part of the system shifted eastward into the Gulf of California (Oskin et al., 2001).

Today, a broad zone of distributed dextral shear stretches across western North America from the San Andreas fault system to the Basin and Range province (Fig. 2c; Wernicke, 1992). GPS geodetic results indicate that strike-slip fault systems in the western and northwestern parts of the Great Basin accommodate as much as 15-25% of dextral motion between the North American and Pacific plates (e.g. Thatcher et al., 1999; Bennett et al., 2003). The Walker Lane is the principal system of northwest-striking, right-lateral faults in the western Great Basin (Stewart, 1988) and accommodates 4 to 12 mm/yr of dextral motion between the Sierra Nevada block and central parts of the Great Basin. To the south, the Walker Lane merges with the eastern California shear zone that, in turn, connects with the San Andreas fault system in southern California (Dokka and Travis, 1990). To the northwest, the Walker Lane terminates in northeast California near the southern end of the Cascade arc (Figs. 1 and 2).

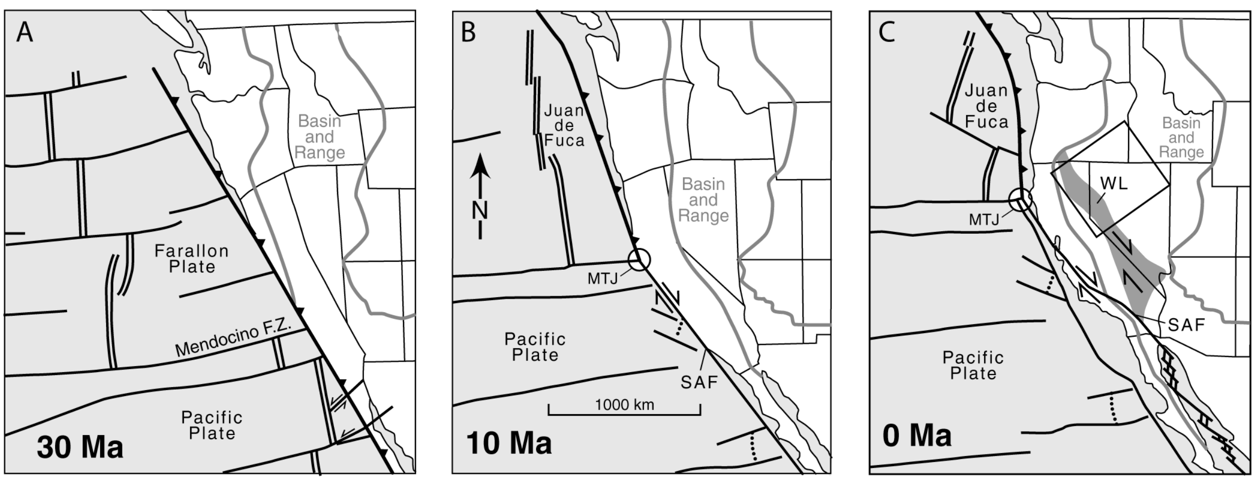


Figure 2. Cenozoic tectonic evolution, western North America. The San Andreas fault system has progressively lengthened over the past 30 million years, as more of the Pacific plate has come into contact with North America. GPS geodetic data indicate that the Walker Lane currently accommodates ~15-25% of the Pacific-North American plate motion. The box surrounds the locus of geothermal activity in the northwestern Great Basin. MTJ, Mendocino triple junction; SAF, San Andreas fault; WL, Walker Lane.

GPS geodetic data and the northwest termination of the Walker Lane in northern California near the present latitude of the Mendocino triple junction suggest a genetic link between the San

Andreas fault system and Walker Lane. Because the Mendocino triple junction has only recently passed by the region offshore to the west (Fig. 2; Atwater and Stock, 1998), the northern Walker Lane is one of the youngest parts of the evolving transform boundary between the North American and Pacific plates. North of about the latitude of Carson City, strike-slip deformation began between 3 and 9 Ma (Cashman and Fontaine, 2000; Henry et al., 2002). Geodetic data (Thatcher et al., 1999; Bennett et al., 2003), historical seismicity (dePolo et al., 1997), and present physiography demonstrate that strike-slip faulting dominates the contemporary strain field of the Walker Lane. This contrasts with predominant west-northwest extension in the western Great Basin and ~east-west extension in the eastern Great Basin.

Throughout the Walker Lane, strike-slip faults are kinematically linked with major normal faults in the Great Basin (e.g. Oldow, 1992; Oldow et al., 1994; Cashman and Fontaine, 2000; Faulds et al., 2003b). Thus, the northwestern Great Basin contains a complex system of kinematically related and broadly coeval northwest-striking dextral faults and north-striking normal faults, as well as east-northeast-striking sinistral-normal faults. It is noteworthy that major extension in the northwestern Great Basin and northern Sierra Nevada is relatively young, having begun in the past 10-15 Ma (e.g. Henry and Perkins, 2001; Surpless et al., 2002; Colgan et al., 2004) apparently just prior to the onset of strike-slip faulting in many areas.

Cumulative slip across the Walker Lane appears to decrease from 48-75 km to 30-40 km between west-central (Ekren and Byers, 1984; Hardyman and Oldow, 1991) and northwest Nevada (Faulds et al., 2003b) concomitant with a decline in slip rates from ~12 mm/yr to 4-8 mm/yr (Oldow et al., 2001; Thatcher et al., 1999; Bennett et al., 2003). In northwest Nevada, the Walker Lane consists of a discrete belt of overlapping, northwest-striking dextral faults, which gives way in northeast California to a diffuse zone of discontinuous, widely-spaced, northwest-trending faults and lineaments. Accordingly, dextral motion across the Walker Lane essentially terminates in northern California. These relations suggest that the Sierra Nevada block and northwesternmost Great Basin are essentially one micro-plate and that the Sierra Nevada has been progressively decoupling from the Great Basin as the Walker Lane has evolved (Fig. 3).

GEOTHERMAL FIELDS

Regional Trends. Figure 1 shows the location of major geothermal systems with respect to major tectonic features and provinces within and directly adjacent to the Great Basin. The fields can be grouped into four northeast-trending belts and one northwest-trending belt. From southeast to northwest, the northeast-trending belts are here referred to as the Sevier Desert, Humboldt, Black Rock Desert, and Surprise Valley geothermal belts. The Sevier Desert belt trends ~N40ºE and extends through southwest Utah. It includes geothermal systems near the western margin of the Colorado Plateau along the Hurricane fault zone, as well as fields in the Sevier Desert region. Three of these systems (Roosevelt, Cove Fort, and Thermo Hot Springs) have maximum subsurface temperatures in excess of 160ºC, but Roosevelt and Cove Fort probably have magmatic heat sources (Koenig and McNitt, 1983). The structural framework of southwest Utah is complex and includes northerly striking normal faults and east-northeast-striking left lateral faults (e.g. Hudson et al., 1998).

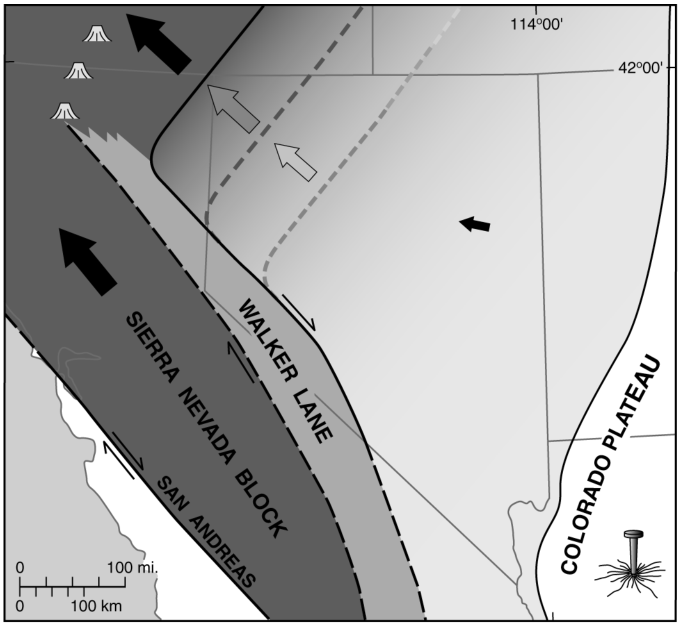


Figure 3. General kinematics of the northwestern Great Basin. Dextral motion within the Walker Lane, which accommodates northwestward translation of the Sierra Nevada block relative to the central and eastern Great Basin, is probably progressively transferred to systems of north-northeast-striking normal faults in the northern Great Basin.

The Humboldt geothermal belt is a broad zone of geothermal systems that trends ~N50ºE and extends through much of western and northern Nevada into southeast Idaho, where it follows the southeast margin of the Snake River Plain. It includes several high-temperature (>160ºC) amagmatic geothermal systems (e.g. Desert Peak, Dixie Valley, Beowawe, Hot Sulphur Springs, and others). The Humboldt belt includes a broad zone of east-northeast- to northeast-striking sinistral-normal faults extending from near Reno to Elko (Fig. 1). This zone of faulting and high heat flow has been referred to as the Humboldt structural zone (Rowan and Wetlaufer, 1981).

Farther northwest, the Black Rock Desert and Surprise Valley geothermal belts trend ~N25-30ºE and, similar to the Humboldt belt, include several high-temperature systems (e.g. Needle Rock Hot Springs (Pyramid Lake), Pinto Hot Spring, and Borax Lake Hot Springs). The Black Rock Desert belt extends through the Black Rock Desert region of northwest Nevada northward into the Alvord Desert area of southern Oregon. The Surprise Valley belt lies within the Surprise Valley area of northeasternmost California and extends northward into the Warner Valley region of southern Oregon.

The Walker Lane geothermal belt is a northwest-trending zone of geothermal systems, including several high-temperature fields, that follows the western margin of the Great Basin along the east front of the Sierra Nevada in the central to northern parts of the Walker Lane. 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. Many high-temperature systems within the Walker Lane geothermal belt may have a magmatic origin (e.g. Coso, Mammoth, and possibly Steamboat; Koenig and McNitt, 1983; Arehart et al., 2003).

Although geothermal fields are found throughout the Great Basin, the greatest concentration and higher temperatures occur within the northwestern part, primarily in west-central to northwest Nevada and southernmost Oregon. This region includes three of the aforementioned northeast-trending belts. This locus of geothermal activity lies within the region of high heat flow and is situated directly northeast of the central and northern parts of the Walker Lane, where dextral shear associated with plate boundary motions terminates northwestward.

Structural Controls on Individual Systems. The structural controls of most geothermal systems in the Great Basin have not been thoroughly analyzed. However, detailed investigations have been conducted on several systems, including Desert Peak, Brady's, Steamboat, and Dixie Valley (e.g. Blackwell et al., 1999; Caskey and Wesnousky, 2000; Johnson and Hulen, 2002; Faulds et al., 2003a; Wannamaker, 2003; Henry, unpublished mapping). These studies and other available data, including our reconnaissance efforts, were incorporated into a compilation of the orientation of apparent controlling structures for geothermal fields in Nevada (Fig. 4).

This compilation shows that north to northeast-striking faults (N0ºE-N60ºE) are the primary controlling structure for approximately 75% of the geothermal fields in Nevada, and this control is strongest for higher temperature systems (Coolbaugh et al., 2002). In the northwestern Great Basin, where the extension direction trends west-northwest, north-northeast-striking controlling faults oriented approximately orthogonal to the extension direction dominate. Controlling faults trend more northerly, however, in both eastern Nevada and along the east front of the Sierra Nevada, where the extension direction is ~east-west. Other important structural trends include northwest-striking faults in the Walker Lane and Black Rock Desert geothermal belts and east-northeast-striking faults in the Humboldt belt.

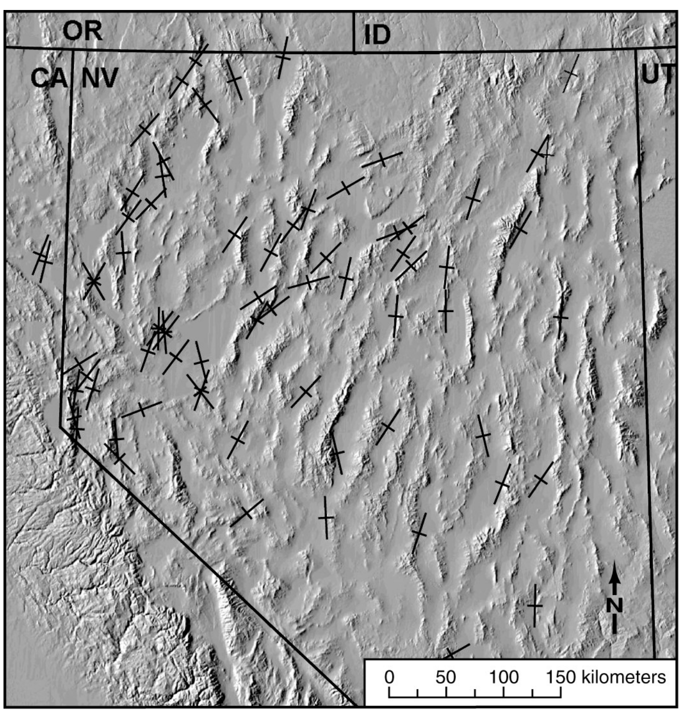


Figure 4. Structural controls on geothermal systems. Long axes of crosses represent inferred strike of controlling fault on individual geothermal systems. Most systems lie along north-northeast-striking faults, but important subsets occur along northwest- and east-northeast-striking faults.

A closer look at individual fields reveals that the controlling north-northeast-striking structures are typically moderately to steeply dipping normal fault zones, as exemplified at the Dixie Valley (Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003), Brady's, and Desert Peak fields (Faulds et al., 2003a). The Brady's, Desert Peak, and Salt Wells fields occupy discrete left steps in overlapping en echelon, north-northeast-striking normal fault zones in association with significant displacement gradients. In other geothermal fields, such as Steamboat, Kyle Hot Springs, Leach Hot Springs, Jersey Valley Hot Springs, and Rye Patch, geothermal reservoirs are focused near the intersections of two major fault zones. For example, the Steamboat field occurs near the intersection of an east-northeast-striking fault zone and a broadly distributed zone of northerly striking normal faults. In the Black Rock Desert region, faults that control geothermal activity have a bimodal strike distribution, with modes at N30-40ºE and N20-40ºW: these faults appear to link in an en echelon manner to form the north-northeast trending Black Rock Desert geothermal belt.

DISCUSSION

The distribution of shear- and dilational-strain magnitudes (Blewitt et al., 2003; Fig.5), as derived from GPS geodetic data, show that 1) shear strain terminates northwestward within the northern Walker Lane, and 2) 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., 2003b). It therefore appears that the northwestward decrease in slip rates along the Walker Lane is accommodated by a transfer of dextral shear to extensional strain, both within the Great Basin and along the east front of the Sierra Nevada. North-northeast-striking normal faults within the northwestern Great Basin essentially 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 accounts for the relatively high rates of recent (<10 Ma) west-northwest-directed extension within the northwestern Great Basin. Thus, the northwestern Great Basin is situated in a youthful transtensional setting that accommodates a northward decrease in dextral shear in the evolving transform boundary between the North American and Pacific plates.

The clustering of geothermal fields in the northwestern Great Basin coincides with this active transtensional setting, beginning in the southeast where dextral shear starts to decrease and ending to the northwest where dextral shear essentially terminates (Fig. 1). The north-northeast-trending geothermal belts are oriented approximately orthogonal to the west-northwest-trending extension direction and may therefore reflect loci of strain transfer from the Walker Lane into the Great Basin. Moderately to steeply dipping, north-northeast-striking normal fault zones host most geothermal systems, because dilation and deep circulation of thermal waters are favored perpendicular to the west-northwest-trending extension direction. Mild left-lateral shear within the Humboldt structural zone may also serve to enhance west-northwest-directed extension, thus accounting for the particularly high density of geothermal systems in this region.

Although the tectonic setting favors geothermal systems along north-northeast-striking normal faults and dilational fractures, the specific locations of individual fields are likely controlled by local features that enhance fracture density. For example, the detailed studies suggest that individual geothermal systems commonly reside either within stepovers in north-northeast-striking normal fault systems or near the intersection of major normal faults with northwest-striking dextral or east-northeast-striking sinistral faults. Subvertical conduits of high fracture density in such areas may enhance fluid flow and facilitate the rise of deep-seated thermal plumes.

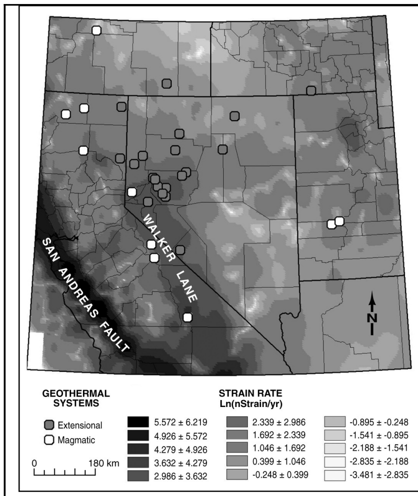
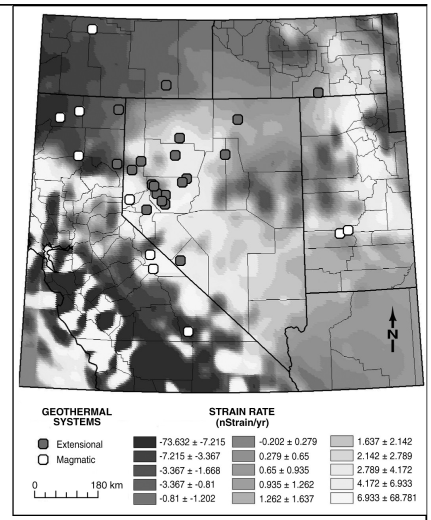


Figure 5. (a) Shear component of maximum extensive strain rate in the Great Basin, derived from GPS velocities. (b) Dilational component of maximum extensive strain rate in the Great Basin, derived from GPS velocities. The strain rates are based on a world-wide compilation of GPS velocities in 2003 (see Blewitt et al., 2003). Squares represent economic or sub-economic geothermal systems, based on current power production or expectations of possible production in the future. Definitive and possible magmatic systems are shown in white. nStrain (10^{-9}) is a unit-less parameter.



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In summary, the clustering of geothermal fields in the northwestern part of the Great Basin and their affinity for north-northeast-striking normal fault zones probably results from three major factors: 1) west-northwest-directed regional extension; 2) a transfer of northwest-trending dextral shear in the Walker Lane to west-northwest-directed extension in the northern Great Basin concomitant with the northwestward termination of the Walker Lane; and 3) mild left-lateral shear within the east-northeast-trending Humboldt structural zone. The latter two factors accentuate west-northwest-directed regional extension within the northwestern Great Basin.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy under instrument number DE-FG36-02ID14311 (changed from DE-FG07-02ID14311 in June, 2003). We thank Frank Monastero and Lisa Shevenell for reviews of the manuscript.

REFERENCES CITED

Arehart, G.B., Coolbaugh, M.F., and Poulson, S.R., 2003, Evidence for a magmatic source of heat for the Steamboat Springs geothermal system using trace elements and gas geochemistry: Geothermal Resources Council Transactions, v. 27, p.269-274.

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, no. 2, p. 3-1 – 3-31.

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.

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.

Caskey, S.J., and Wesnousky, S.G., 2000, Active faulting and stress redistributions in Dixie Valley, Beowawe, and Bradys geothermal fields: Implications for geothermal exploration in the Basin and Range: 25th workshop on Geothermal Reservoir Engineering, Stanford University.

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; Proceedings, Annual Meeting, Reno, NV., Sept. 22-25, 2002, 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.

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

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, Annual Meeting, Reno, Nevada, p. 204-215.

Faulds, J.E., Garside, L.J., and Oppliger, G.L., 2003a, 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., Henry, C.D., and Hinz, N.H., 2003b, Kinematics and cumulative displacement across the northern Walker Lane, an incipient transform fault, northwest Nevada and northeast California: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 305.

Hardyman, R.F., and Oldow, J.S., 1991, Tertiary tectonic framework and Cenozoic history of the central Walker Lane, Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and ore deposits of the Great Basin: Geological Society of Nevada Symposium Proceedings, p. 279-301.

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., and dePolo, C.M., 2002, Structure and evolution of the Warm Springs Valley fault, northern Walker Lane, Nevada: Post-3-Ma initiation: Geological Society of America Abstracts with Programs, v. 34, no. 5, p. 84.

Hudson, M.R., Rosenbaum, J.G., Gromme, C.S., Scott, R.B., and Rowley, P.D., 1998, Paleomagnetic evidence for counterclockwise rotation in a broad sinistral shear zone, Basin and Range province, southeastern Nevada and southwestern Utah: Geological Society of American Special Paper 323, p. 149-180.

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.

Koenig, J.B. and McNitt, J.R., 1983, Controls on the location and intensity of magmatic and non-magmatic geothermal systems in the Basin and Range province: Geothermal Resources Council, Special Report No. 13, p. 93.

Lachenbruch, A.H., and Sass, J.H., 1977, Heat flow in the United States and the thermal regime of the crust, *in* Heacock, J.G., ed., The Earth's crust: Its nature and physical properties: American Geophysical Union Monograph 20, p. 626-675.

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, Reno, NV, 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.

Oldow, J.S., Aiken, C.L.V., Hare, J.L., Ferguson, J.F., and Hardyman, R.F., 2001, Active displacement transfer and differential block motion within the central Walker Lane, western Great Basin: Geology, v. 29, no. 1, p. 19-22.

Oskin, M., Stock, J., and Martin-Barajas, A., 2001, Rapid localization of Pacific-North America plate motion in the Gulf of California: Geology, v. 29, p. 459-462.

Powell, R.E., Weldon, R.J., and Matti, J.C., eds., 1993, The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, 332 p.

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

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. 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, no. 1, p. 2-1 to 2-13.

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.

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.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *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. 553-581.