# Regional Patterns of Geothermal Activity in the Great Basin Region, Western USA: Correlation With Strain Rates

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***Keywords***

*Great Basin, Walker Lane, tectonics, strain rates, strain transfer, geothermal potential, Nevada, strike-slip faults, normal faults*

## ABSTRACT

The regional patterns of geothermal activity in the western USA correlate directly with strain rates derived from GPS geodetic data. In the Great Basin region, geothermal fields are concentrated in discrete belts along the eastern margin of the Basin and Range (Wasatch Front) in western Utah and southeastern Idaho and in western to north-central Nevada within and directly northeast of the Walker Lane, which is a system of right-lateral faults accommodating ~20% of relative motion between the Pacific and North American plates. These two regions have higher current strain rates than other parts of the Basin and Range province. Enhanced extension in western to north-central Nevada probably results from the northwestward termination of the Walker Lane and the concomitant transfer of dextral shear into west-northwest directed extension, thus producing a broad transtensional region. High-temperature systems cluster within the zones of highest strain rate directly northeast of the Walker Lane, in areas of recent magmatism, or in particularly high-strain transtensional pull-apart basins along the Walker Lane or San Andreas fault system. The capacity of geothermal power plants also correlates with strain rates, with the largest (hundreds of megawatts) along the Walker Lane or San Andreas fault system, where strain rates range from 10-100 nanostrain/yr to 1,000 nanostrain/yr, respectively. Lesser systems (tens of megawatts) reside in the Basin and Range (outside the Walker Lane), where local strain rates are typically < 10 nanostrain/yr. These results may have implications for assessing and quantifying geothermal potential in other tectonically active regions.

## Introduction

In the western USA, geothermal fields and geothermal power plants are in greatest abundance in the Basin and Range province of northern Nevada and neighboring parts of northeast California and southernmost Oregon (Fig. 1). This clustering of geothermal fields lies within a much broader region of high heat flow that covers much of the western USA (Blackwell and Richards, 2004). Geothermal power plants in the Basin and Range generally produce between ~2 and 200 MW. Although the density of geothermal fields is greatest

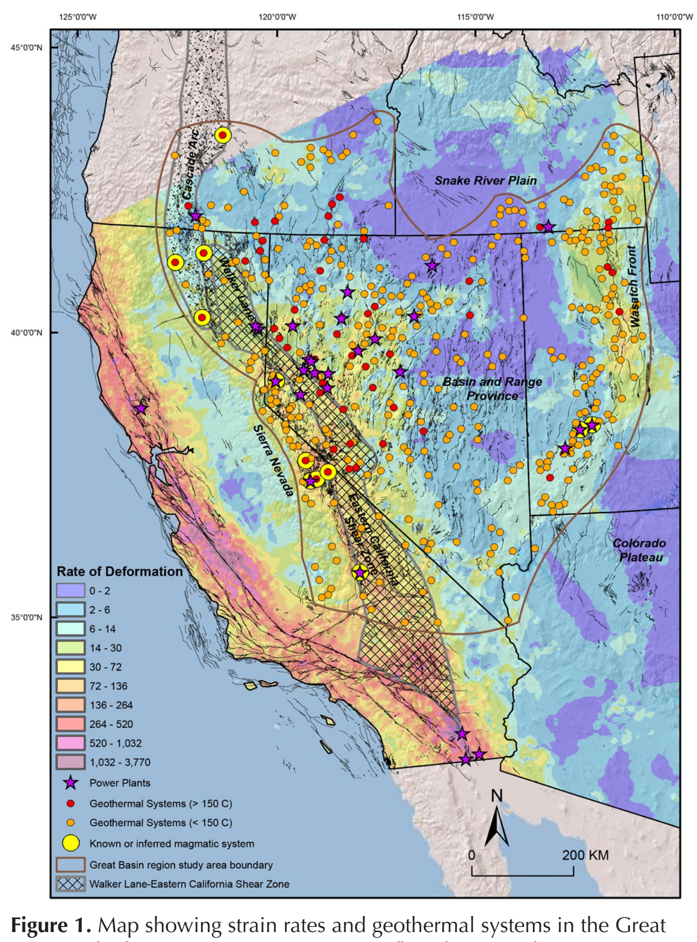


**Figure 1.** Map showing strain rates and geothermal systems in the Great Basin and adjacent regions. Strain rates reflect the second invariant strain rate tensor ($10^{-9}$/yr; from Kreemer et al., 2012).

in the northwestern Basin and Range, geothermal fields with the greatest electrical output in the western USA occur along the San Andreas fault system, including the Geysers in northern California and fields in the Salton Trough in southern California. Electrical output in these areas ranges from 200 to ~1,000 MW.

In this paper, we explore the regional patterns of geothermal activity in the context of tectonic settings and strain rates. Strain rate is the relative velocity between two points divided by distance. This work essentially supersedes an earlier analysis by Faulds et al. (2004) and also builds on an earlier recognition of the correlation between transtensional strain rates and the occurrence of geothermal resources (e.g., Blewitt et al., 2005, Kreemer et al., 2006). We conclude that there is a direct correlation between strain rates and geothermal potential, with the presence or absence of recent (<0.5 Ma) magmatism also playing a major role. Our findings may have implications for geothermal assessments in other parts of the world.

## Tectonic Setting

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. 1; Wernicke, 1992). GPS geodetic results indicate that strike-slip fault systems in the western and northwestern parts of the Basin and Range accommodate as much as ~20% of dextral motion between the North American and Pacific plates (e.g. Bennett et al., 2003; Hammond and Thatcher, 2004; Kreemer et al., 2009). The Walker Lane and eastern California shear zone are the principal systems of northwest-striking, right-lateral faults in the western Great Basin (Stewart, 1988; Faulds and Henry, 2008) and accommodate ~1 cm/yr of dextral motion between the Sierra Nevada block and central parts of the Great Basin, as evidenced by geodetic data (Hammond and Thatcher, 2004; Kreemer et al., 2009). To the south, the eastern California shear zone 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 (Faulds and Henry, 2008; Fig. 1).

The northern Walker Lane is one of the youngest parts of the evolving transform boundary between the North American and Pacific plates (Faulds et al., 2005). North of about the latitude of Carson City, strike-slip deformation began between 3 and 9 Ma (Cashman and Fontaine, 2000; Faulds et al., 2005; Faulds and Henry, 2008). Geodetic data (Bennett et al., 2003; Kreemer et al., 2009), 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; Faulds et al., 2005). Thus, the northwestern Great Basin contains a complex system of kinematically related and broadly coeval northwest-striking dextral faults and north- to north-northeast-striking normal faults.

Cumulative slip across the Walker Lane appears to decrease from 48-75 km in west-central Nevada (Ekren and Byers, 1984; Hardyman and Oldow, 1991), to 20-30 km in northwest Nevada (Faulds et al., 2005), to negligible in northeastern California (Faulds and Henry, 2008). These relations suggest that the Sierra Nevada block and northwestern-most Basin and Range are essentially one micro-plate and that the Sierra Nevada has been progressively decoupling from the Great Basin as the Walker Lane has progressively grown northwestward in concert with the lengthening San Andreas fault (Fig. 1).

The distribution of shear- and dilational-strain magnitudes (Blewitt et al., 2003; Kreemer et al., 2012; Fig. 1), 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., 2005). It therefore appears that the northwestward decrease in cumulative slip along the Walker Lane, as well as the overall termination of the Walker Lane, are accommodated by a transfer of dextral shear to transtensional and extensional strain, both within the Great Basin and along the eastern 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.

## Distribution of Geothermal Fields

Figure 1 shows the locations of major geothermal systems and power plants with respect to major tectonic features and strain rates within and adjacent to the Great Basin. The parameters of the geothermal database utilized in our plots were described by Coolbaugh et al. (2002) and Faulds et al. (2011). Figure 2 illustrates the density of known geothermal systems.

The known geothermal systems cluster in several discrete belts.

- **Wasatch geothermal belt**: A prominent belt extends along the Wasatch Front in Utah following the eastern margin of the Basin and Range province, with an arm extending westward directly southeast of the Snake River Plain (Fig. 2). It is here referred to as the Wasatch geothermal belt (formerly the Sevier Desert belt of Faulds et al., 2004). The Wasatch belt trends ~NNE to N. It includes fields in the Sevier Desert region (Roosevelt, Cove Fort, and Thermo Hot Springs) that have maximum subsurface temperatures in excess of 160°C. Roosevelt and Cove Fort probably have magmatic heat sources (Koenig and McNitt, 1983).
- A second larger composite cluster occupies western to north-central Nevada and extends into extreme southern Oregon and northeastern-most California (Fig. 2). This large cluster is actually composed of several smaller belts, including:

- **Walker Lane geothermal belt**: A NW-trending cluster along the central to northern Walker Lane extending westward through the Sierra Nevada-Basin and Range transition zone is here referred to as the Walker Lane geothermal belt. Many high-temperature systems within the Walker Lane geothermal belt may have a magmatic origin, including Coso, Casa Diablo, and possibly Steamboat (Koenig and McNitt, 1983; Arehart et al., 2003).
- **Humboldt geothermal belt**: A NE-trending zone extending from western to north-central and northeastern Nevada is termed the Humboldt geothermal belt. The Humboldt belt essentially forms a bridge between the Walker Lane and Wasatch geothermal belts, suggesting that the corresponding enigmatic Humboldt structural zone (cf., Rowan and Wetlaufer, 1981) plays an important role in facilitating geothermal activity. The Humboldt structural zone is a broad zone of ENE- to NE-striking sinistral-normal faults stretching across northern Nevada from near Reno to Elko. This belt includes several high-temperature (>150°C) amagmatic geothermal systems and associated power plants, such as Bradys, Desert Peak, Dixie Valley, Beowawe, Tuscarora, and others.
- **Black Rock Desert geothermal belt**: A NNE-trending belt that extends through the Black Rock Desert region of northwest Nevada northward into the Alvord basin of southern Oregon is referred to as the Black Rock Desert belt. This belt includes several high-temperature systems, such as Needle Rocks at Pyramid Lake, San Emidio, Gerlach, Pinto Hot Spring, and Borax Lake.
- **Surprise Valley geothermal belt**: A small area in the northeastern corner of California is termed the Surprise Valley belt. This belt includes the Surprise Valley area of northeastern-most California and extends northward into the Warner Valley region of southern Oregon (e.g., Crump Geyser).

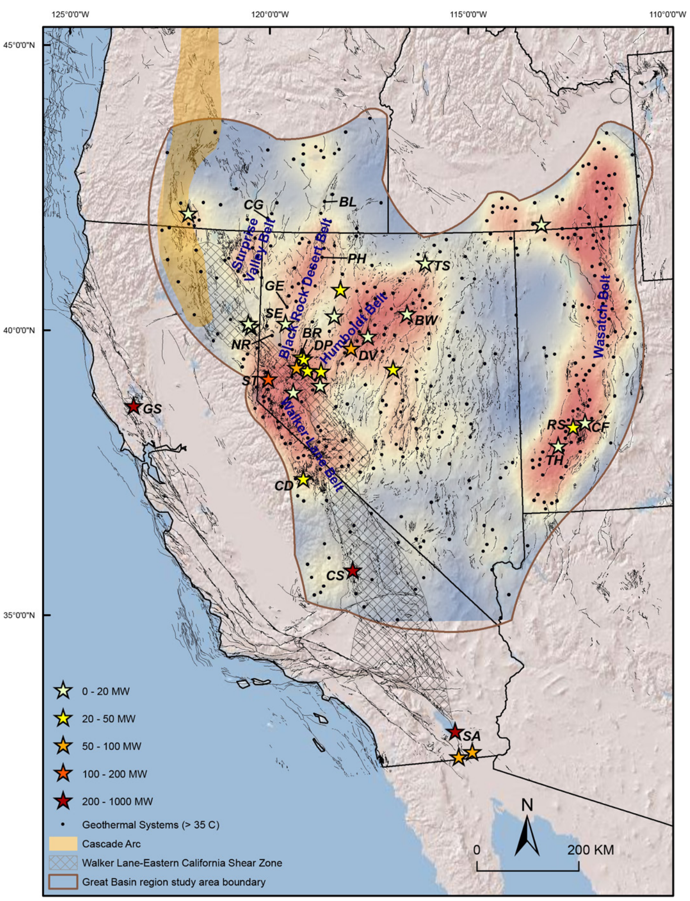


**Figure 2.** Density of known geothermal systems (≥37°C) in the Great Basin region. Density values were calculated using a kernel density plot in which the number of geothermal systems with temperatures ≥37°C within a radius of ~30 km was calculated for each 3 km cell in a grid. Warmer colors represent progressively greater geothermal system densities. Power plants and relative capacities are shown by stars. Geothermal systems: BL, Borax Lake; BR, Bradys; BW, Beowawe; CD, Casa Diablo; CF, Cove Fort; DP, Desert Peak; DV, Dixie Valley; CG, Crump Geyser; CS, Coso; GE, Gerlach; GS, The Geysers; NR, Needle Rocks, Pyramid Lake; PH, Pinto Hot Springs; RS, Roosevelt; SA, Salton Trough; SE, San Emidio; ST, Steamboat; TS, Tuscarora; TH, Thermo.

The distribution of geothermal systems with respect to Quaternary faults is notable. The relatively sharp declines in geothermal activity to the south in south-central Nevada and northward near the Oregon-Nevada border appear to correspond to significant decreases in the density of Quaternary faults (Fig. 2). Similarly, the western margin of the Wasatch geothermal belt follows a significant westward decline in the density of Quaternary faulting associated with proximity to active fault zones along the Wasatch Front. These findings are compatible with observations that most geothermal fields are associated with Quaternary faults (Bell and Ramelli, 2007).

High-temperature (>150ºC) systems are an important subgroup of geothermal fields, because they help to define areas with the greatest potential for producing electricity. The distribution of high-temperature systems is broadly similar to that of all systems (i.e., both low and high temperature), but with some critical differences (Figs. 2 and 3). For example, the extensive Wasatch geothermal belt breaks down into two discrete high-temperature lobes, with one in southwestern Utah and a second near the Utah-Idaho border. The southwestern lobe includes the Roosevelt and Cove Fort systems, which probably have magmatic heat sources (Koenig and McNitt, 1983). In western to north-central Nevada, the distribution of high-temperature systems is more condensed than that for all systems, with most of the systems lying within or directly northeast of the Walker Lane. Discrete nodes of high-temperature systems reside in the Mina deflection of the Walker Lane and in northwestern Nevada. The Black Rock geothermal belt loses some definition in the plot of high-temperature systems but has a prominent locus in the Alvord basin of southern Oregon. The locus of high-temperature systems in the Surprise Valley belt shifts slightly northward relative to the distribution of all systems. However, it should be noted that many low- to moderate-temperature systems have not been adequately studied or explored to determine their maximum temperatures. Thus, the plot of high-temperature systems should be considered conservative, with the distribution subject to change with subsequent exploration and additional studies. Nonetheless, most of the existing power plants occur within loci of known high-temperature systems (Fig. 3), suggesting that the known distribution of such systems can indeed serve as a proxy for geothermal potential.

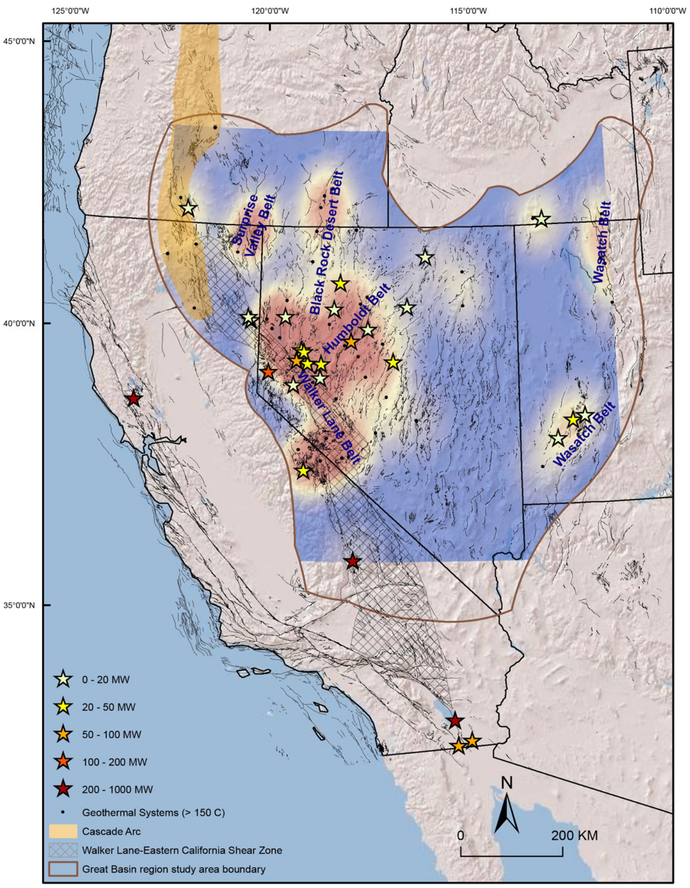


**Figure 3.** Density of known high-temperature (≥150ºC) geothermal systems in the Great Basin region  Density values were calculated using a kernel density plot in which the number of geothermal systems with temperatures ≥150°C within a radius of ~30 km was calculated for each 3 km cell in a grid. Warmer colors represent progressively greater geothermal system densities. Power plants and relative capacities are shown by stars.

There is also a direct correlation between strain rates and the distribution of geothermal systems, especially high-temperature fields (Blewitt et al., 2003; Coolbaugh et al., 2002).  For example, geothermal fields within the Great Basin region clearly cluster in the broad transtensional setting directly northeast of the Walker Lane and along the Wasatch Front.  Strain rates in both of these areas are significantly higher compared to other parts of the Basin and Range (Fig. 1).

The electrical-generating capacity of individual power plants or groups of plants within a geothermal field is also proportional to strain rate (Figs. 1 and 2).  All fields with capacities of 200-1,000 MW lie within large transtensional pull-apart basins along the San Andreas fault (Salton Trough), on strands of the San Andreas system (The Geysers), or in pull-apart basins within the Walker Lane-eastern California shear zone (Coso).  Strain rates in these areas range from ~100 nanostrain/yr at Coso to ~1000 nanostrain/yr in the Salton Trough.  It should be noted that all of these systems also have a magmatic component contributing to the heat source.

## Discussion

Regional tectonism appears to be the primary driving force for geothermal activity in the western USA, as evidenced by the striking correlations between strain rates and the distribution of geothermal fields (Figs. 1 and 2). Volcanic activity ceased ~10 to 3 Ma in most of the Great Basin region.  Thus, upper crustal magmatism is not a likely source of the high heat flow and geothermal activity within the bulk of this region.  Although geothermal fields are found throughout the Great Basin, the greatest concentrations occur in western to north-central Nevada (Walker Lane and Humboldt geothermal belts) and in western Utah to southeastern Idaho (Wasatch geothermal belt), where strain rates are generally higher than other parts of the region. Furthermore, the majority of high-temperature systems occur in western to north-central Nevada, which has the highest strain rates in the region east of the Walker Lane.

The locus of geothermal activity in western to north-central Nevada corresponds to the active transtensional setting situated directly northeast of the central and northern parts of the Walker Lane, where dextral shear associated with plate boundary motions decreases northwestward and is transferred to west-northwest-directed extension in the Basin and Range.  The NNE to NE trends of the major geothermal belts in this region (e.g., Humboldt and Black Rock Desert 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.  Enhanced extension in this active transtensional setting promotes both high heat flow and dilation on normal faults, thus inducing deep circulation of meteoric waters and up-flow along fault zones. As the Walker Lane dies out completely farther northwest, along with the presumed strain transfer, geothermal activity decreases considerably.  Mild left-lateral shear within the Humboldt structural zone may further enhance west-northwest-directed extension, thus accounting for the particularly high density of geothermal systems in this region.

The correlation between strain rates and capacity of existing geothermal power plants in the western USA suggests that it may be possible to develop empirical relationships relating strain to geothermal potential, which could ultimately guide resource assessments and exploration strategies.  However, higher strain rates alone do not equate with resource potential.  For example, higher strain rates along the San Andreas fault system and Walker Lane-eastern California shear zone would seemingly favor geothermal activity, but strike-slip faulting includes a component of shortening, which tends to restrict fluid flow.  Accordingly, robust geothermal systems in these zones of dextral shear only occur in transtensional pull-apart basins and/or in areas of recent volcanism (e.g., Salton Trough, The Geysers, and Coso).  It would appear that without recent magmatism, extensional or transtensional deformation is a necessary ingredient in generating most viable geothermal systems.  Earlier analyses between the spatial distribution of strain rates and geothermal resources also indicated transtensional strain rates as the main factor in the geothermal potential (Blewitt et al., 2002, 2005; Faulds et al., 2004; Kreemer et al., 2006, Hammond et al., 2007)

We should also stress that lower strain rates and the associated lower power-plant capacities in the Basin and Range should not deter exploration and development.  Although systems with hundreds to thousands of megawatts seem unlikely in the Basin and Range, the distribution of the known systems indicates strong potential for development of many additional systems in the tens of megawatts range. Furthermore, relatively closely-spaced fault zones can host separate exploitable geothermal systems, whose combined capacity can rival that of regions with higher strain rates. The northern Hot Springs Mountains in western Nevada exemplify this potential, as each major normal fault zone in this area hosts a high-temperature geothermal system (e.g., Bradys, Desert Peak, and Desert Queen systems; Faulds et al., 2010).

In addition to enhancing our understanding of the geothermal resources in the western USA, this work has implications for assessing the geothermal potential of other geothermally-endowed regions around the world, including Iceland, the East African rift system, New Zealand, and western Turkey. Tectonism clearly facilitates geothermal activity. Multidisciplinary studies incorporating geologic and geodetic studies into geodynamic models are probably critical for evaluating and potentially quantifying geothermal potential.

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