Late Cenozoic strain field and tectonic setting of the northwestern Great Basin, western USA: Implications for geothermal activity and mineralization

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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 (< about 7 Ma) epithermal mineral deposits occur in this region and 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 within this rapidly evolving region.

Key Words: Nevada, Walker Lane, Great Basin, geothermal, epithermal, transtension, magmatism, extension.

INTRODUCTION

The San Andreas fault system began developing about 30 Ma as the Pacific plate came into contact with the western margin of North America in response to subduction of the last vestiges of the Farallon plate (Fig. 1; Atwater and Stock, 1998). Since 30 Ma, the San Andreas fault has progressively lengthened both to the northwest and southeast as more of the Pacific plate has come into contact with North America. 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 about 6 Ma when the southern part of the system shifted eastward into the Gulf of California (Oskin et al., 2001).

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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. 1; Wernicke, 1992). 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 4 to 12 mm/yr of dextral motion between the Sierra Nevada block and central parts of the Great Basin, which amounts to 10–25% of the Pacific-North American plate motion (e.g., Oldow et al., 2001; Bennett et al., 2003; Hammond and Thatcher, 2004). 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 and southern Oregon near the southern end of the Cascade arc (Fig. 1c). 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; Faulds et al., 2004a) and a number of late Cenozoic epithermal

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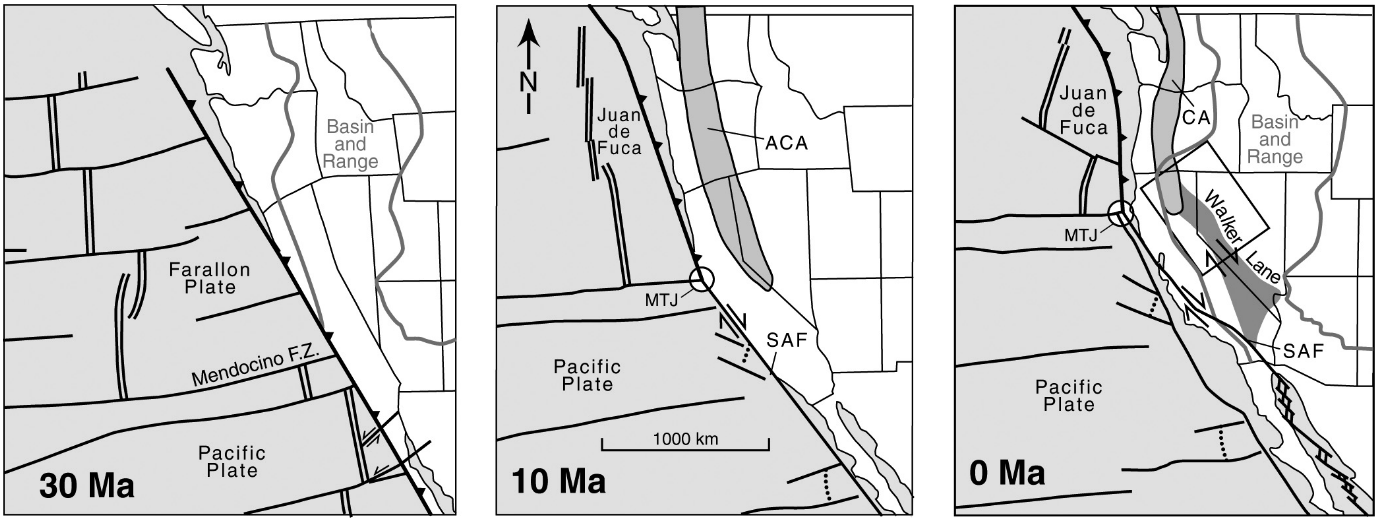

Figure 1. Cenozoic tectonic evolution, western North America. A. 30 Ma. B. 10 Ma. C. 0 Ma. The San Andreas fault has progressively lengthened over the past 30 Ma, as more of the Pacific plate has come into contact with North America. The Walker Lane currently accommodates 10–25% of the Pacific-North American plate motion. 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.

mineral deposits (John, 2001) occur in northern Nevada and neighboring parts of northeast California and southernmost Oregon (Figs. 2 and 3). This clustering lies within a broad region of high heat flow that includes much of the Great Basin (e.g., Lachenbruch and Sass, 1977; Blackwell and Richards, 2004) and spatially corresponds with at least two magmatic assemblages (John, 2001). However, volcanic activity in most of this region ceased 3 to 10 Ma, with significant magmatism ending in most areas by about 7 Ma. However, many of the mineral deposits are younger than 7 Ma (Table 1; see also Coolbaugh et al., this volume) and geothermal activity is prolific today. This suggests that either much of the recent mineralization and most of the ongoing geothermal activity are not linked to magmatism, or significant younger magmatism has not been recognized in the region. If young 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 regional 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. For the purposes of this paper, the northwestern Great Basin includes approximately the northwestern third of Nevada and adjoining parts of northeastern California and southern Oregon. We incorporate recent findings on the timing of deformation in the northwestern Great Basin, particularly within the Walker Lane belt (e.g., Henry et al., 2003, 2004a; Faulds et al., 2003b, 2005; Colgan et al., 2004). 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 a complex regional strain field, regardless of whether the activity is or is not related to magmatism. It is important to note, however, that the current strain field in this rapidly evolving region developed in only the past 3 to 9 m.y. Thus, many early to late Miocene epithermal mineral deposits probably reflect older magmatic and tectonic events, such as the ancestral Cascade arc.

GEOLOGIC SETTING

Cenozoic Magmatism

As the western margin of North America evolved from a convergent to a transform plate boundary during Cenozoic time (Fig. 1; Severinghaus and Atwater, 1990; Atwater and Stock, 1998), the northwestern Great Basin experienced widespread and protracted volcanism that coincided in part with regional extension and strike-slip faulting. This includes three distinct but partly gradational episodes (Silberman et al., 1979; Deino, 1985; Saucedo and Wagner, 1992; Stewart et al., 1994; Garside et al., 2000; Henry and Perkins, 2001): 1) 31 to 23 Ma rhyolitic ash-flow tuffs associated with calc-alkaline magmatism of the "ignimbrite flareup" (Best et al., 1989), which swept southwestward across the Great Basin in Eocene to middle Miocene time (Seedorff, 1991; Christiansen and Yeats, 1992; Wernicke, 1992; Humphreys, 1995; Henry and Ressel, 2000; Henry et al., 2004b); 2) 22 to 5 Ma dominantly andesitic to dacitic, mostly effusive calc-alkaline volcanism associated with an ancestral Cascades arc (Christiansen and Yeats, 1992; Stewart, 1998; Garside et al., 2000); and 3) 13 Ma to present bimodal volcanism related to approximately east-west Basin and Range exten-

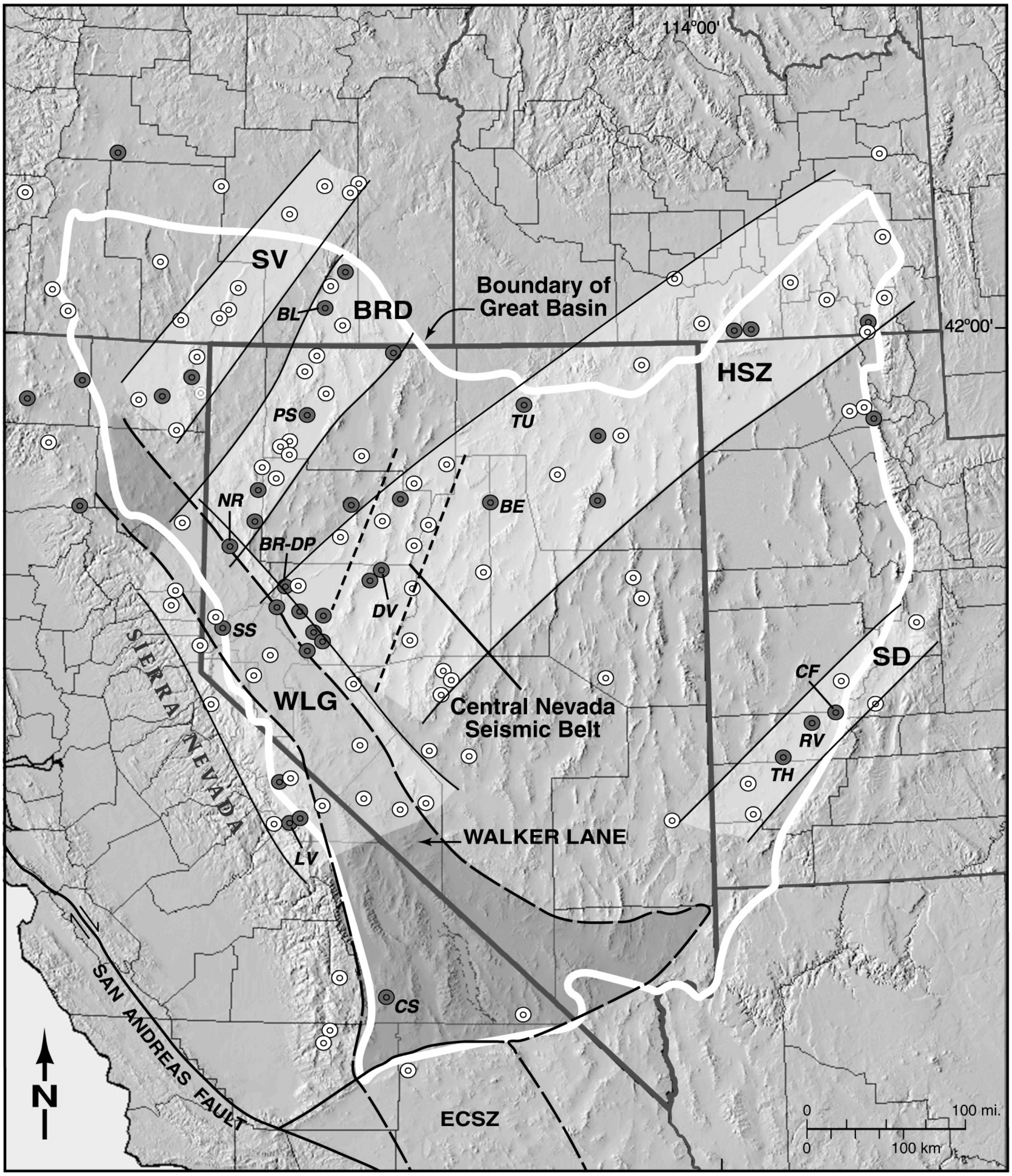

Figure 2. Geothermal belts in the Great Basin (modified from Faulds et al., 2004a). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. The northwestern Great Basin contains the greatest concentration of fields. White circles are geothermal systems with maximum temperatures of 100–160°C; grey circles have maximum temperatures >160°C. ECSZ, eastern California shear zone. The boundary of the Great Basin is indicated by a closed white polygon. Dashed lines (short dashes) bound the central Nevada seismic belt. Abbreviations for individual geothermal fields: BL, Borax Lake Hot Springs; BE, Beowawe; BR-DP, Brady's and Desert Peak; CF, Cove Fort; CS, Coso; DV, Dixie Valley; LV, Long Valley-Mammoth; NR, Needle Rocks; PS, Pinto Hot Springs; RV, Roosevelt; SS, Steamboat; TH, Thermo Hot Springs; TU, Tuscarora.

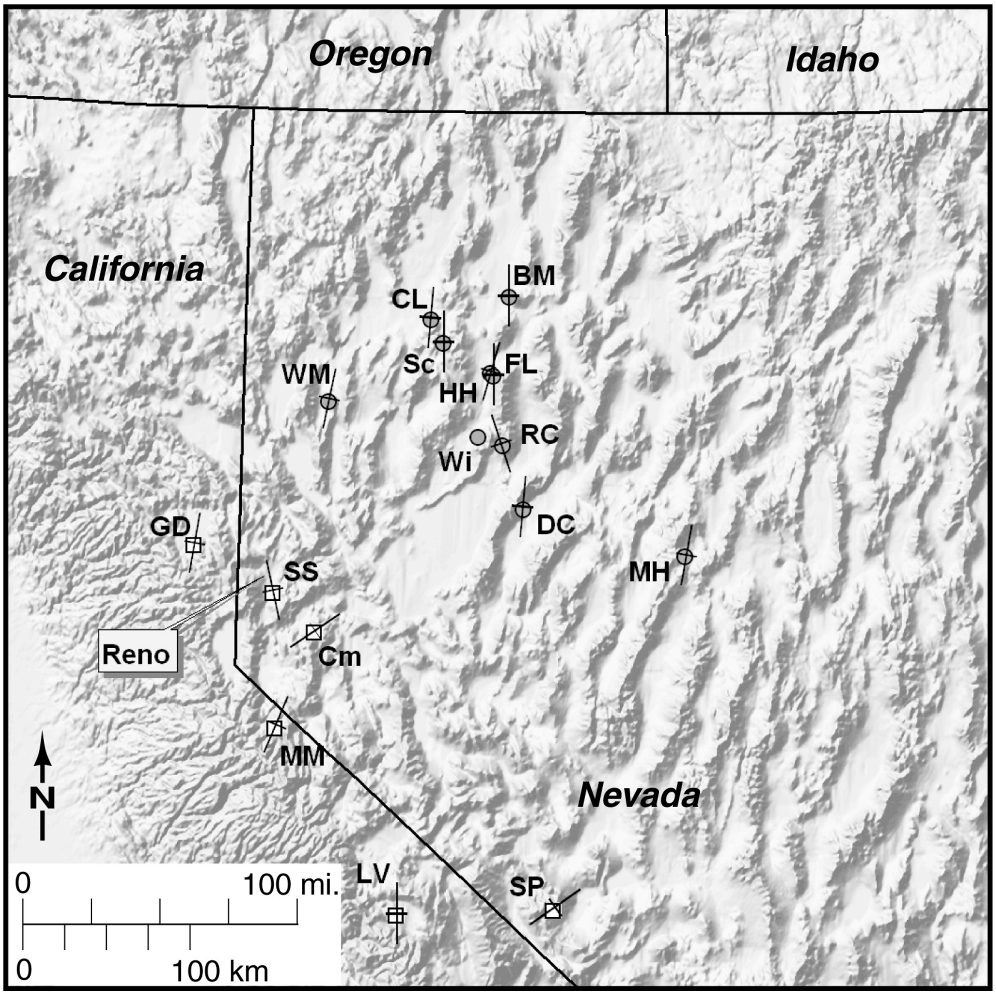

Figure 3. Young (< ca. 7 Ma) epithermal Au-Ag deposits in the northwestern Great Basin. Long axes of crosses represent average strike of veins or mineralized structures (Table 1). Squares denote deposits of known or possible magmatic origin; circles represent deposits that are not clearly linked to magmatism.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

sion (e.g., John, 2001). In addition, east-west extension produced north-trending basins, within which accumulated thick sections of alluvial fan, fluvial, and lacustrine sedimentary rocks commonly interbedded with thin pyroclastic flows, ash-fall tephras, and mafic lavas (e.g., Trexler et al., 2000; Henry and Perkins, 2001). Thus, the northwestern Great Basin contains a relatively complete late Oligocene to recent stratigraphic section, which records development of the northern Walker Lane, Sierra Nevada, and Basin and Range. The Tertiary sections rest nonconformably on Mesozoic granitic and metamorphic basement.

Although it predates development of the major strike-slip fault systems, the ignimbrite flareup is particularly relevant to unraveling the evolution of the northern Walker Lane. In central Nevada, a northwest-trending belt of southward-younging calderas developed from late Eocene through middle Miocene time (Best et al., 1989; John, 1995; Henry et al., 1997). Caldera magmatism skirted the eventual Walker Lane to the northeast. In western Nevada and northern California, however, multiple Oligocene to earliest Miocene ash-flow tuffs accumulated in west-trending paleovalleys (e.g., Lindgren, 1911; Henry et al., 2003; Garside et al., this volume), which serve as regional structural and stratigraphic markers. The paleovalleys provide piercing lines with which to gauge right-lateral offset across the northern Walker Lane (Faulds et al., 2003b, 2005).

In contrast to the ignimbrite flareup, the axis of ancestral Cascade arc volcanism essentially paralleled the Walker Lane (Henry et al., 2004a). Intermediate to mafic volcanism related to the ancestral Cascade arc first appeared as early as about 30 Ma (Dilles and Gans, 1995; Henry and Faulds, 2004; Garside et al., this volume), replaced rhyolitic activity in the early Miocene, peaked between 15 and 12 Ma, and continued into the early Pliocene (e.g., Garside et al., 2000; Saucedo and Wagner, 1992; Grose, 2000; Henry et al., 2004a). Andesitic to dacitic

TABLE I. YOUNG (<~7 MA) EPITHERMAL MINERAL DEPOSITS

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	Crowfoot/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., this volume
FC	Florida Canyon	2.0 Ma	N0°E		Hastings et al., 1988; Coolbaugh et al., this volume
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	N55°E		Keith, 1977
LV*	Long Valley, CA	0.4 Ma	~N-S		Prenn and Muerhoff, 2003

*Known or possible magmatic systems.

lavas, breccias, and related intrusions typical of stratovolcanoes in the contemporary Cascade arc were erupted from several centers in the region (e.g., Virginia City area; Castor et al., 2002; Hudson et al., 2003; Vikre et al., 2003; Castor et al., this volume). As in the present-day Cascade arc, however, mafic volcanism, including voluminous outpourings of basaltic andesite lavas from large shield volcanoes, dominated much of the ancestral Cascade arc in the northwestern Great Basin (e.g., Faulds and Henry, 2002). With progressive northward migration of the Mendocino triple junction (Atwater and Stock, 1998), arc magmatism has slowly retreated to the northwest since the late Miocene (Fig. 1). Plate reconstructions suggest that the southern edge of the subducted Farallon slab (or Gorda plate) presently lies just to the north of Reno (Wilson, 1989).

As extension developed in middle to late Miocene time, bimodal (basalt-rhyolite) volcanism became progressively more dominant. However, bimodal volcanism waned rapidly in the late Miocene, with only local outpourings in most of the Great Basin after approximately 7 Ma (Henry and Faulds, 2004). Only widely spaced, relatively small volcanic centers have erupted in the Quaternary.

Structural Framework

A complex three-dimensional strain field characterizes the northern Walker Lane and northwestern Great Basin (Fig. 4). Major structural elements in and adjacent to the northern Walker Lane include: 1) a left-stepping system of 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 belts of east-trending folds (Fig. 5). Available data suggest that movement on all three sets of faults and the folding have been broadly coeval, with activity continuing through the Quaternary (e.g., Ichinose et al., 1998; Briggs and Wesnousky, 2004). Accordingly, strike-slip faults within the Walker Lane are intimately linked with major normal fault systems within the Great Basin (e.g., Oldow, 1992; Oldow et al., 1994; Cashman and Fontaine, 2000; Faulds et al., 2003b). 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 (Fig. 4). 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 (Fig. 4).

Major extension and strike-slip faulting within the northwestern Great Basin is relatively young, having begun in most areas since the late Miocene. Early basin development, angular

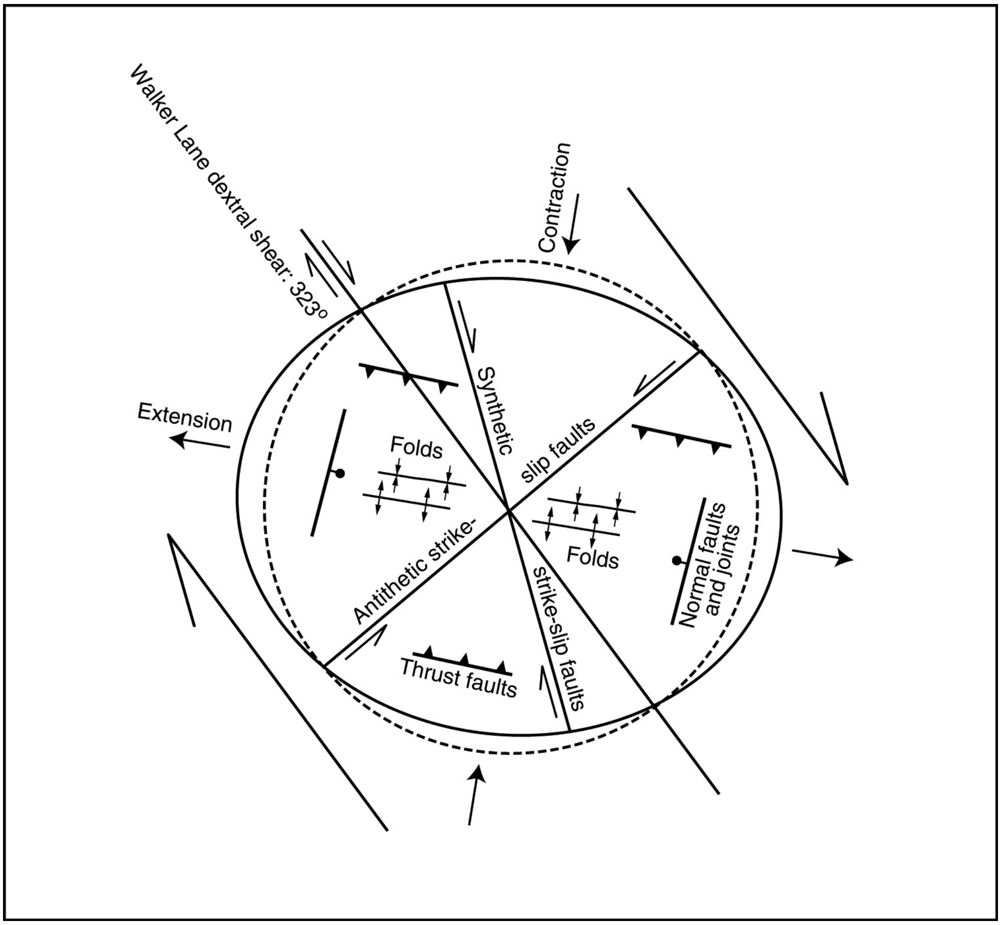

Figure 4. Diagrammatic strain ellipse for northwest-directed dextral shear within the Walker Lane and expected orientations of major structures, including north-northeast-striking normal faults, northeast-striking sinistral faults, east-west-trending folds, and east-striking thrust or reverse faults (adapted from Sylvester, 1988).

unconformities and tilt fanning in half grabens, and thermochronology of uplifted basement blocks indicate that extension began 10 to 15 Ma (e.g., Trexler et al., 2000; 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-east-northeast least principal stress (Zoback et al., 1981) in contrast to the present-day west-northwest-trending extension direction. There is no evidence that major strike-slip faulting accompanied the onset of extension within the northern Walker Lane. Instead, accumulating evidence suggests that strike-slip faulting initiated somewhat later, roughly between 9 and 3 Ma. For example, approximately 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 about 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 (Fig. 4) in the northwestern Great Basin is no older than 9 Ma and possibly younger than 3 Ma in some areas.

The en echelon, left-stepping pattern of northwest-striking right-lateral faults within the northern Walker Lane is also suggestive of an incipient strike-slip fault system. As mimicked in clay-model experiments (Wilcox et al., 1973; An and Sammis, 1996), such faults may be primary Riedel shears (cf., Petit, 1987) developing above a more through-going shear zone at depth (Faulds et al., 2003b; 2005). In contrast to the San Andreas fault, cumulative strain within the Walker Lane has not been sufficient to initiate a through-going, upper-crustal strike-slip fault.

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, Faulds et al. (2003b, 2005) estimated only 20–30 km of

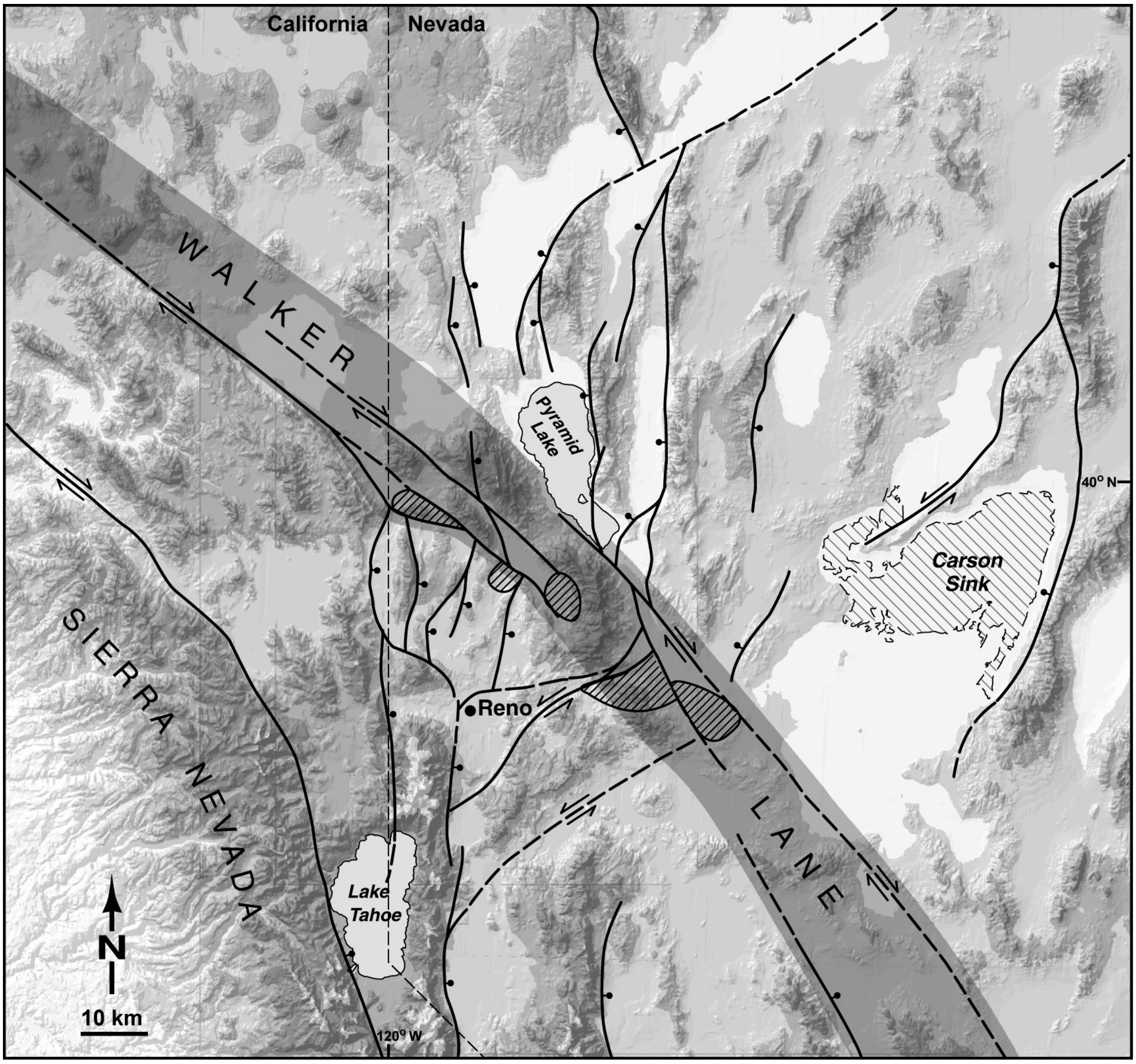

Figure 5. Structural framework of part of the northwestern Great Basin. The northwestern Great Basin in western Nevada and northeast California includes northwest-striking right-lateral faults, east-northeast-striking left-lateral faults, and northerly striking normal faults. All fault sets are active in the modern strain field, which is dominated by dextral shear in the vicinity of the Walker Lane and west-northwest-directed extension within the Great Basin.

cumulative displacement on the basis of offset approximately west-trending Oligocene paleovalleys that are filled with 31–23 Ma ash-flow tuffs. In northeast California and southern Oregon, cumulative slip decreases to essentially zero across a diffuse zone of discontinuous, widely-spaced, northwest-trending faults and lineaments (e.g., 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 (Oldow et al., 2001; 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-north-west-directed extension in the northern Great Basin, including the central Nevada seismic belt, Black Rock Desert region, and Warner Mountains-Surprise Valley area (Figs. 2 and 6; Oldow et al., 2001; Faulds et al., 2004a). Individual strike-slip faults terminate in arrays of northerly striking normal faults. Loci of strain transfer appear to correspond to the prominent belts of active geothermal systems, which partially overlap with areas containing abundant young (< about 7 Ma) epithermal mineral deposits.

GEOTHERMAL FIELDS

Geothermal fields within the Great Basin are most abundant in the northwestern part of the region (Fig. 2). As reported by Faulds et al. (2004a), known geothermal systems within and

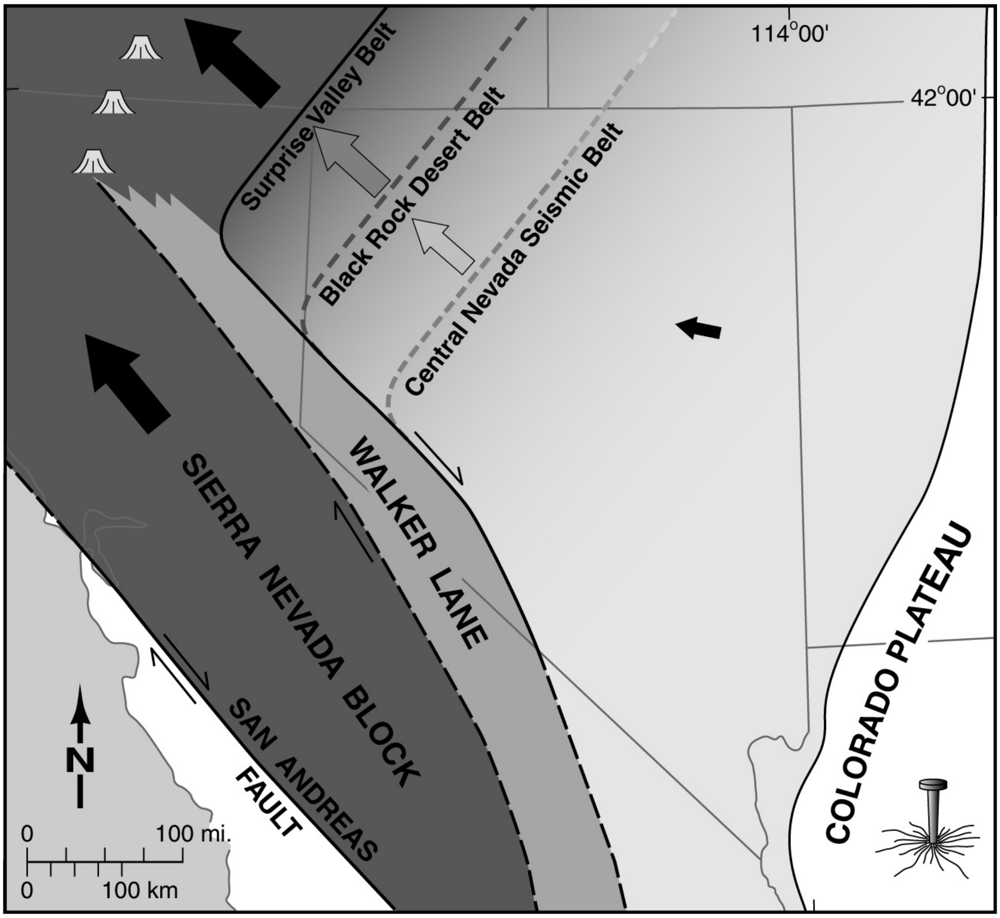

Figure 6. General kinematics of the northwestern Great Basin. Dextral motion within the Walker Lane, which accommodates northwestward translation of the Sierra Nevada block relative to the central and eastern Great Basin, is probably progressively transferred to systems of north-northeast-striking normal faults in the northwestern Great Basin. As the Walker Lane terminates northwestward in northeast California, dextral motion is diffused into northwest-directed extension within the northern Great Basin. Greater extension in this region favors increased dilation along north-northeast-striking faults and fractures, which in turn facilitates deep circulation of fluids, mineralization, and geothermal activity.

directly adjacent to the Great Basin can be grouped into four northeast-trending belts and one northwest-trending belt. Only one of these belts 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 (Figs. 1c 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 (Faulds et al., 2004a). The Sevier Desert belt trends about N40°E 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 160°C, but Roosevelt and Cove Fort probably have magmatic heat sources (Koenig and McNitt, 1983).

The Humboldt geothermal belt is a broad zone of geothermal systems that trends about N50°E 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 (>160°C) geothermal systems in areas where no young magmatism is known (e.g., Brady's-Desert Peak, Dixie Valley, Beowawe, Tuscarora, and others). The Humboldt belt includes a broad zone of eastnortheast- to northeast-striking sinistral-normal faults extending from near Reno to Elko. This zone of faulting 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 about N25-30°E and, similar to the Humboldt belt, include several high-temperature systems (e.g., Needle Rocks 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, Long Valley-Mammoth, and possibly Steamboat; Koenig and McNitt, 1983; Arehart et al., 2003).

Although most geothermal systems in the Great Basin have not been thoroughly analyzed, detailed investigations and reconnaissance efforts (e.g., Blackwell et al., 1999; Caskey and Wesnousky, 2000; Johnson and Hulen, 2002; Faulds et al., 2003a; Wannamaker, 2003; C. Henry, unpublished mapping) show that north- to northeast-striking faults (N0°E–N60°E) control about 75% of the geothermal fields in Nevada and neighboring parts of northeast California (Fig. 7; Faulds et al., 2004a). 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. Controlling faults strike more northerly, however, in eastern Nevada, where the extension direction is approximately 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.

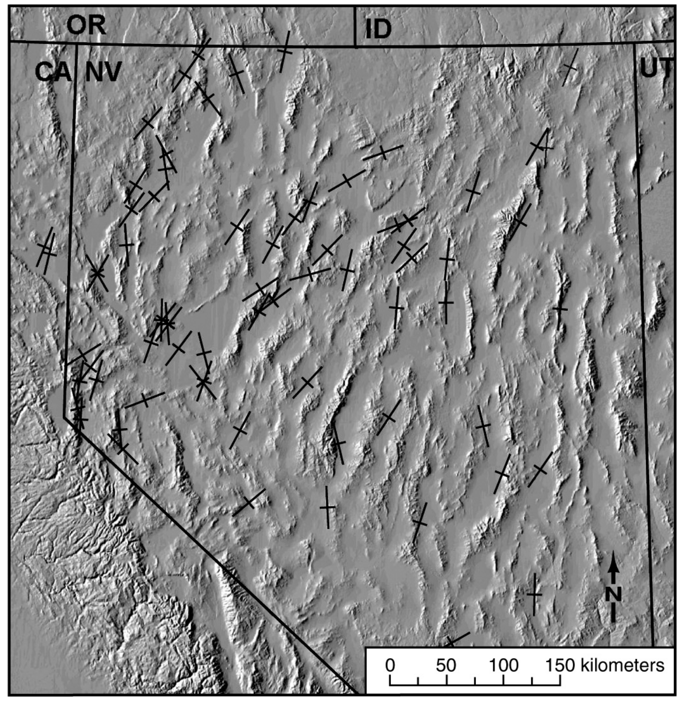

Figure 7. Structural controls on known geothermal systems in Nevada and adjacent areas (from Faulds et al., 2004a). Long axes of crosses represent inferred strike of controlling fault for individual geothermal systems. Most of the systems denoted here correlate with those shown on Figure 2.

LATE CENOZOIC MINERALIZATION

The northern Great Basin has been an important source of precious metals since the discovery of the Comstock Lode in 1859. Late Tertiary to Quaternary epithermal Au-Ag deposits are an important source of these metals. Although most of these deposits are hosted by igneous rocks associated with the ancestral Cascade arc (Hudson, 2003; Berger et al., 2003) or bimodal extension-related volcanism (e.g., John et al., 2003), the links between magmatism and many of the low sulfidation deposits are commonly equivocal (e.g., John, 2001). Considering the spatial and temporal distribution of volcanism in this region, it is possible that many of the young (<7 Ma) epithermal deposits are not related to magmatism.

Similar to dikes, mineralized structures typically develop along dilational fractures oriented orthogonal to the extension direction, which typically corresponds to the least principal stress (Rehrig and Heidrick, 1976; Drier, 1984; Price and Henry, 1984; Price et al., 1988; Henry et al., 1991). Thus, mineralized structures within the Great Basin can be used to infer the orientation of the extension direction, which can then be related to the general tectonic setting. 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 (e.g., Zoback et al., 1981) concomitant with development of northwest-directed dextral shear associated with Pacific-North American plate boundary motion.

We have therefore compiled the approximate ages and general trends of mineralized structures in late Miocene to Quaternary epithermal deposits in the northwestern Great Basin (Table 1). The table includes deposits that are rather closely tied to synchronous igneous activity (e.g., the high-sulfidation Golden Dome deposit and the low-sulfidation 1.1 Ma Steamboat mineralization) as well as those that are spatially associated with recent geothermal systems. For completeness, we include data of varied certainty, with the hope of stimulating more research on this important group of deposits. These young (< ca. 7 Ma) Au-Ag mineral deposits exhibit many features indicative of formation at shallow depths, such as synsedimentary mineralization, sinter, or synsedimentary hydrothermal breccias. A number of low-sulfidation epithermal and hot-spring-type deposits have fine-grained chalcedonic veins, silica replacement bodies, or indications of boiling (e.g., two-phase fluid inclusions, silica replacement of lamellar calcite, hydrothermal breccias, etc.). Calcite makes up a significant portion of some veins. At some deposits, synfaulting mineralization occurs along Quaternary faults that bound or parallel the present mountain range. Opaline sinter (e.g., McGinness, Table 1) also suggests a youthful deposit, as opal converts to chalcedony with increased time or temperature. Fine-grained mineralization commonly includes silica, gold, and sulfides of iron, silver, antimony, and mercury; native sulfur may be present as well. It is possible that hydrothermal alteration and/or mineralization at some districts span more than one age. In addition, dated mineral phases (commonly adularia or alunite) may, in some cases, postdate the Au-Ag mineralization or be supergene.

Whether of known magmatic or possible amagmatic origin, veins and mineralized structures within these young (< ca. 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 Fig. 3). Although significant scatter does exist, the average trend of mineralized structures appears to reflect a predominant west-northwest-trending extension direction, which is compatible with the current strain field (Fig. 4). Examples of districts with N- to NE-striking mineralized structures that parallel range-front normal faults include the Dixie Comstock Mine in Dixie Valley, the Wind Mountain Mine in the San Emidio Desert, and the Crofoot/Lewis Mine in the Black Rock Desert.

Several late Tertiary mining districts in the northwestern Great Basin are characterized, however, by northwest- or approximately east-west-striking mineralized structures, which are incompatible with the current strain field. Mineralization in these districts appears to predate the onset of strike-slip faulting and/or major extension in the region. For example, although situated between two strands of the Walker Lane, the Pyramid district in the Pah Rah Range contains west-northwest- to northwest-striking, 23 Ma subvertical veins and dikes (Wallace, 1975; Garside et al., 2000, 2003) that predate the onset of both major extension in western Nevada and strike-slip faulting in the Walker Lane. These structures may reflect an earlier episode of mild northeast-southwest extension (e.g., Zoback et al., 1981). Farther southeast in the Virginia Range, the Talapoosa, Ramsay, and Gooseberry districts form an east-southeast-trending belt (Albino, 1991) and contain east- to east-southeast-striking veins, which have yielded approximately 9–11 Ma K-Ar and $^{40}Ar/^{39}Ar$ ages (Morton et al., 1977; Garside et al., 1993, 2000) and thus predate the onset of dextral shear and transtension. Mineralization in all four districts was contemporaneous with ancestral Cascade arc volcanism (Garside et al., 2000, 2003).

It is important to note, however, that vertical-axis rotations (e.g., Hudson et al., 1998; Cashman and Fontaine, 2000; Faulds et al., 2004b) may have affected some of the mineral districts in the northwestern Great Basin. Thus, some of the mineralized structures may have originally formed in different orientations. Ongoing paleomagnetic studies in the region (Faulds et al., 2004b) will elucidate the distribution and magnitude of such rotations.

DISCUSSION

Most geothermal fields (e.g., Desert Peak, Brady's, Dixie Valley) and young (< ca. 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 (Figs. 3 and 7), where dilation is favored by northwest-directed dextral shear and west-northwest-trending extension. Known magmatism generally ceased prior to 7 Ma in the region and therefore appears unable to account for much of the geothermal activity and at least some of the mineralization. We therefore suggest that the transtensional setting of the northwestern Great Basin has induced high heat flow and especially deep circulation of meteoric fluids, which has in turn produced the widespread geothermal activity and a number of epithermal mineral deposits in the region.

Recent compilations depicting the distribution of shear- and dilational-strain magnitudes within the Great Basin (Blewitt et al., 2003), as derived from GPS geodetic data, are very relevant to this premise. These maps show that: 1) shear strain is focused along the western margin 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 (Fig. 5; Faulds et al., 2003b, 2005). It therefore appears that the northwestward decrease in cumulative displacement and slip rates along the Walker Lane is accommodated by a transfer of dextral shear to extensional strain (Fig. 6), both within the Great Basin and along the east front of the Sierra Nevada. North- to 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 has probably accentuated rates of recent (<10 Ma) west-northwest-directed extension within the northwestern Great Basin. The northwestern Great Basin is clearly 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 (Figs. 1c and 6).

The abundant geothermal fields and some young epithermal mineral deposits in the northwestern Great Basin coincide 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 (Figs. 2, 3, and 6). The north- to northeast-trending geothermal belts and mineralized structures 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 structures host most geothermal systems and many of the epithermal deposits (Figs. 3 and 7). This probably results from dilation and deep circulation of thermal waters along fractures oriented 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 relatively high density of geothermal systems and epithermal deposits in this region (Faulds et al., 2003a). Coolbaugh et al. (this volume) suggest that geothermal activity in this region may be linked to present-day development of epithermal mineral deposits.

Transtensional settings in other parts of the world may be analogous to the northwestern Great Basin. Examples include parts of East Africa (e.g., Scott et al., 1992; Chorowicz and Sorlien, 1992), western Turkey and southern Greece (e.g., Eyidogan and Jackson, 1985; Taymaz et al., 1991; King et al., 1993), and other parts of the Alpine-Himalayan orogenic belt. Characterizing the links between the structural controls and tectonic setting of young epithermal deposits in the Great Basin may also be useful in developing exploration strategies for older transtensional terranes within which deformation has ceased or changed in style.

CONCLUSIONS

Abundant geothermal fields and a number of young epithermal mineral deposits reside in the northwestern Great Basin and are most commonly found along north- to northeast-striking structures. Such relations probably result 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) possibly 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. Magmatism generally has not played a major role in the recent geothermal and hydrothermal activity.

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