Active Geothermal Systems and Associated Gold Deposits in the Great Basin

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Keywords

Great Basin, geothermal, gold deposits, Quaternary

ABSTRACT

In western North America, a number of geothermal systems derive their heat from magmas or cooling intrusions. The interior of the Great Basin however, is characterized by widespread amagmatic geothermal activity that owes its existence to high crustal heat flow and active extensional tectonics. Both the magmatically heated and extensional fluid types in the Great Basin have recently, or are currently, depositing gold. Quaternary to Pliocene-aged gold deposits with adjacent high-temperature (≥ 150°C) active geothermal systems occur at Long Valley, California, and Florida Canyon, Wind Mountain, Dixie Valley, and other locations in Nevada. Prolonged uplift of mineralized zones along range-front faults suggests that these geothermal systems, although possibly episodic, have lifetimes measured in millions of years. The total known gold inventory in deposits younger than 7 Ma in the Great Basin exceeds 12 million ounces.

Many Great Basin geothermal systems are aligned along northeast-trending belts hundreds of kilometers long that are likely related to ongoing northwest-directed crustal extension. However, the highest-temperature extensional systems and the most productive young gold deposits are aligned along northwest trends sub-parallel to the dextral Walker Lane shear zone. A transitional transtensional setting in which right-lateral fault motion along the Walker Lane splays into extensional northeast-striking normal fault systems may promote deep fracturing and the circulation and heating of meteoric fluids to form hydrothermal systems and gold deposits.

Introduction

Evidence suggests that many active geothermal systems in the Great Basin are either forming gold deposits now or have done so in the recent past (ie, Quaternary). By studying these young gold-producing geothermal systems, we can gain insights into the roles that magmas or deeply circulating meteoric fluids play in providing heat and metals to hydrothermal systems. The tectonic settings and structural controls of modern geothermal systems offer examples of how mineral belts form and the structural conditions necessary for mineral deposition.

Great Basin Geothermal Systems

Two types of geothermal systems in the Great Basin have temperatures and fluid flows sufficient to support power plants. As described by Koenig and McNitt (1983) and Wisian et al.

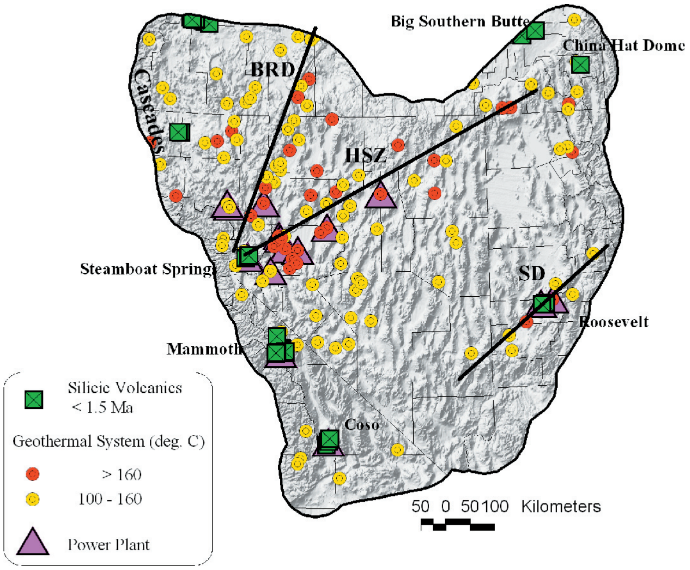

Figure 1. Active geothermal systems of the Great Basin. Magma-heated geothermal systems are those occurring adjacent to young silicic volcanic rocks < 1.5 Ma. Extensional geothermal systems occur elsewhere. BRD = Black Rock Desert trend, SD = Sevier Desert trend. HSZ = Humboldt structural zone.

(1999), magma-heated systems are those geothermal systems closely associated with young (≤ 1.5 Ma) silicic volcanic rocks along the margins of the Great Basin, whereas extensional-type systems occur throughout the Great Basin (Figure 1) and are not associated with volumetrically significant young volcanic rocks that could have provided a source of heat.

In most places of the world, convective geothermal systems do not attain temperatures of 200°C or higher without an upper crustal magmatic heat source (Arehart et al., 2003). The Great Basin appears to be an exception; 6 known extensional-type geothermal systems with no known magmatic affinity have measured or estimated temperatures exceeding 200°C and 17 known systems have measured or geochemical temperatures exceeding 180°C. Active extensional tectonics and high crustal heat flow (Koenig and McNitt, 1983; Wisian et al., 1999) may allow meteoric fluids to penetrate along permeable fractures to greater-than-normal depths into hotter-than-normal crust to reach these anomalous high temperatures.

High heat flow alone does not appear sufficient to explain the unusual concentration of relatively high-temperature geothermal systems in the Great Basin because similarly high heat flow is found inboard of the western continental margin throughout western North and Central America, from Alaska to Costa Rica (Blackwell and Richards, 2004). It is believed that active extensional tectonics play a key supporting role in providing the fracturing and permeability necessary for deep fluid circulation.

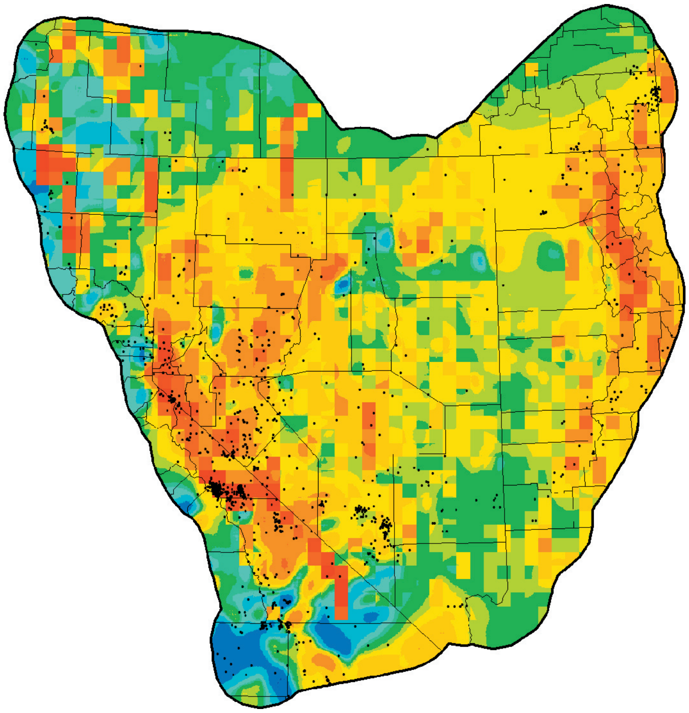

Figure 2. Crustal extension and earthquakes are focused along the margins of the Great Basin. Warmer shades of color indicate relatively greater amounts of crustal dilation, as determined from GPS measurements of crustal velocity and estimates of slip rates along Quaternary faults (Coolbaugh et al., this volume). All earthquakes of magnitude 4.0 and higher are shown as small black dots.

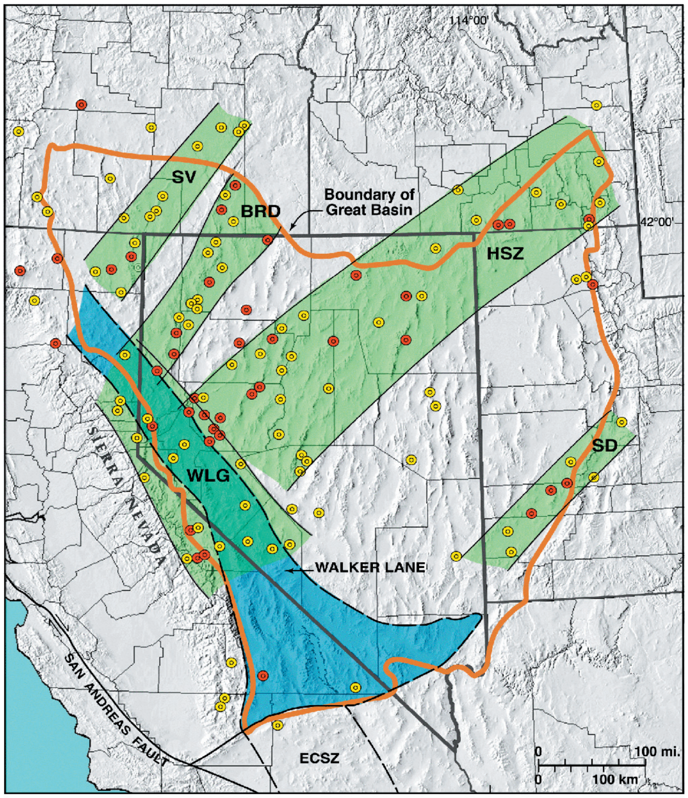

Figure 3. Dextral strike-slip motion from the Walker Lane is transferred into a series of northeast-striking normal faults in the northern and northwestern Great Basin. Those normal faults are concentrated in the Humboldt structural zone (HSZ) and the Black Rock Desert (BRD) and Surprise Valley (SV) belts. Yellow circles are geothermal systems with maximum temperatures of 100 – 160°C; red circles have maximum temperatures > 160°C. ECSZ = eastern California shear zone. SD = Sevier Desert belt. Figure taken from Faulds et al. (2004).

Structural Environment of Great Basin Geothermal Systems

Regional Structure: From a plate tectonics perspective, crustal strain is currently focused on the margins of the Great Basin, as evidenced by global positioning system (GPS)-based geodetic velocity measurements (Kreemer et al., 2004) and earthquake activity (Figure 2). Quaternary silicic volcanic activity and magma-heated geothermal systems are restricted to these same margins (Figure 1). A broader and more diffuse zone of extension characterizes the interior of the Great Basin, as evidenced by basin and range-style deformation. The origin of extension in the Great Basin remains somewhat controversial; possible causative mechanisms include back-arc spreading behind Cenozoic volcanic arcs (e.g. Karig, 1971), gravitational collapse of thickened crust into regions of thinner crust (e.g. Coney and Harms, 1984), and mantle upwelling beneath the Great Basin (Gans et al., 1989).

Crustal deformation in the Great Basin acquires a transtensional character near its western and northwestern margins, due to the influence of dextral strike-slip faulting along the Walker Lane (Figure 3). Recent findings summarized by Faulds et al. (2004) suggest that the amount of strike-slip motion along the Walker Lane decreases northward, as strike-slip motion is transferred into a broad zone of north-northeast-trending normal faults in the Humboldt structural zone, the central Nevada seismic belt, and other structures in northwestern Nevada, northeastern California, and southeastern Oregon (Faulds et al., 2004; Figure 3).

Geothermal Patterns: The greatest concentration of high-temperature geothermal systems occurs in the northwestern quarter of the Great Basin (Figure 4), broadly coincident with the transition from Walker Lane-style transtension to the more regional west-northwest-directed extension (Figures 2, 3). Some Great Basin geothermal systems are aligned along northeast-trending belts hundreds of kilometers long that are likely related to regional west-northwest-directed crustal extension (Rowan and Wetlaufer, 1981; Koenig and McNitt, 1983; Figure 1). However, the highest-temperature geothermal systems fall along crude northwest-trending zones subparallel to the Walker Lane (Figure 4) that cut across the more regional northeast-trending belts.

Active Geothermal Systems and Gold Deposits

Arehart et al. (2002; 2003) reviewed trace-element concentrations in geothermal fluids and found that magma-heated fluids have higher concentrations of arsenic, lithium, boron, and cesium than their amagmatic extensional counterparts at similar temperatures and chloride contents. This lends support to arguments (e.g., Hedenquist, 1991; Hedenquist and Lowenstern, 1994; Giggenbach, 1995; Simmons, 1995; among others) that magmas provide important contributions of metals to epithermal ore deposits. Nevertheless, as described below, there is clear evidence that both magma-heated and extensional-type geothermal systems in the Great Basin have recently, or are currently, producing mineral deposits, particularly gold.

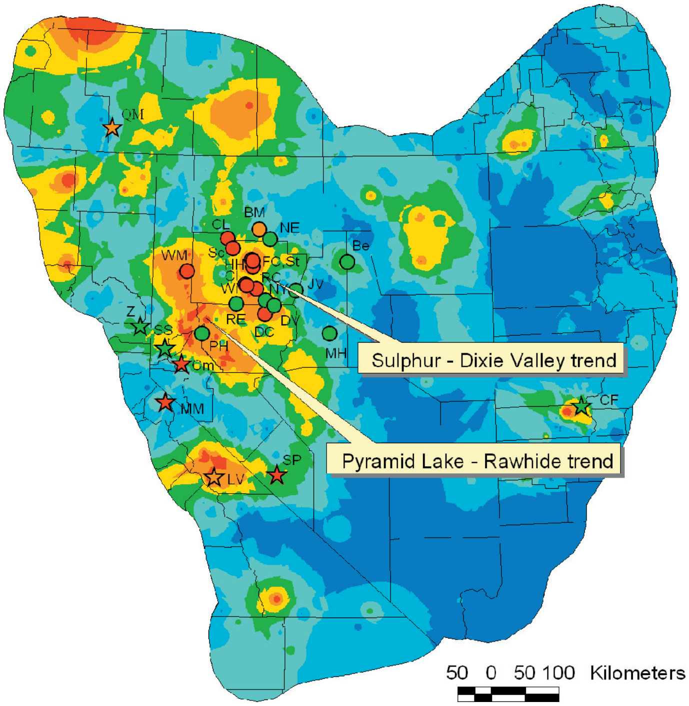

Figure 4. High-temperature geothermal systems and 7-0 Ma gold deposits occur along northwest trends in the northwestern portion of the Great Basin. Circles denote young gold deposits without known magmatic heat sources; stars indicate deposits believed to have a magmatic heat source. Red symbols indicate young gold deposits with past mine production or reserves, orange symbols indicate deposits for which an approximate gold inventory has been calculated, and green symbols indicate prospects where at least some samples assayed > 100 ppb gold. Abbreviations correspond to descriptions in Table 1 of this paper and Appendix A of Coolbaugh et al. (2005). Warmer background colors represent progressively higher maximum temperatures of active geothermal systems in the Great Basin (Figure 5, Coolbaugh et al., 2005).

Gold deposits formed by magma-heated geothermal systems in the Great Basin are exemplified by the 1.2 million ounce Long Valley gold deposit in Mono County, California (Prenn and Muerhoff, 2003). The Long Valley deposit is hosted by the 730 Ka Bishop Tuff in the Long Valley caldera, and silicified breccia and chalcedonic silica veins adjacent to the deposit have yielded ages ranging from 210 to 310 Ka (Sorey et al., 1991). At least one hot spring in Little Hot Creek on the north end of the deposit is currently precipitating black sulfide-rich coatings containing several percent or more of arsenic and antimony. However, evidence suggests that gold mineralization and most hydrothermal alteration may have formed from a slightly older and somewhat higher-temperature Quaternary hydrothermal system that was active during a period of rhyolite dome extrusion (Smith and Suemnicht, 1991; Flexser, 1991). Modern-day geothermal waters adjacent to this gold deposit have an estimated geothermal reservoir temperature in the range of 214 to 248°C based on fluid geothermometers (Sorey et al., 1991). These geothermal fluids feed the Casa Diablo geothermal power plant a few kilometers away.

A growing body of evidence indicates that extensional geothermal systems in the Great Basin are also actively forming gold deposits, even though some of these young deposits are not as well studied as their 17-10 Ma hydrothermal equivalents. Wallace et al. (in press) describe several of these "hot spring" deposits, to which they attribute a late Miocene to Quaternary age. In some cases, uplift along range-front faults has exposed gold mineralization that may have formed earlier in the history of presently active geothermal systems. Possible examples include the Humboldt House geothermal system (Florida Canyon Mine), the Rye Patch geothermal system (Standard Mine), Colado (Willard Mine), Empire-San Emidio (Wind Mountain Mine), and Dixie Meadows-Central Dixie Valley (Dixie Comstock Mine). Based on geothermometers, each of the geothermal systems associated with these epithermal gold deposits, with the exception of Colado, has maximum reservoir temperatures estimated to approach or exceed 200°C (Benoit and Butler, 1983; Mariner et al., 1983; Edmiston and Benoit, 1984; Waibel et al., 2003; Blackwell and Richards, 2005). The hottest temperature reported from Colado is 155°C (Mariner et al., 1983).

At the Humboldt House geothermal system, in Pershing County, Nevada, gold grades as high as 3.4 – 5.1 ppm (0.10-0.15 oz/ t), averaged over 4.6 m (15 ft), were encountered during shallow drilling of silicified Quaternary gravels, and a rough, unconstrained inventory of 70,000 + oz was identified before hot water and shallow steam pockets forced suspension of exploration drilling (Ron Parratt, personal communication, 2004). Gold grades in iron-oxide-rich fractures in surface travertines at the same locality range up to 10 ppm (0.3 oz/t Au; Andy Wallace, personal communication, 2004). The Humboldt House geothermal system occurs in the downthrown, hanging wall side of an active range-front fault, and the adjacent Florida Canyon Mine lies in the upthrown footwall side on the flanks of the Humboldt Range. Florida Canyon has produced 2 million oz of gold from a resource of nearly 5 million ounces (Thomason, 2002). Hypogene alunite from the deposit yielded an age of 2.0 ± 0.6 Ma (K/Ar; Vikre, 2000; Peter Vikre, personal communication, 2004).

At Colado, in Pershing County, Nevada, grades of up to "several hundred ppb" Au and 20 oz/t Ag were encountered in silicified and feldspathized alluvium during drilling of the Colado geothermal resource (Jeff Hulen, personal communication, 2004). An inventory of approximately 300,000 to 400,000 oz Au was defined by drilling in bedrock below alluvium within the confines of the geothermal system, and mineralization included native sulfur and marcasite (John Wood, Ron Parratt, personal communications, 2004). The nearby Willard gold mine, with production of roughly 25,000 ounces Au (Struhsacker et al., 1996), occurs on the upthrown footwall side of an active range-front fault. The exact relationship between the Willard mine and the Colado geothermal system remains unclear, but a 6.1 ± 0.3 Ma mineralization age (K/Ar on adularia; Noble et al., 1987) indicates Willard is younger than most epithermal gold deposits in the Great Basin.

Anomalous gold values were encountered during the shallow drilling of other geothermal systems. Drilling near the Senator fumaroles in the Dixie Valley geothermal system in Churchill County, Nevada encountered ore-grade gold (Stuart Johnson, personal communication, 2004), and pyrite concentrates gathered from collecting ponds at geothermal wells at Rye Patch in Pershing County assayed 8.5 ppm (0.25 oz/t) Au (Andy Wallace, personal communication, 2004). A total of 19 young (≤ 7.0 Ma) gold occurrences presumed to have formed from extensional-type geothermal systems have been identified in the Great Basin (Table 1). Of these, eight have an aggregate production or reserves of over 4 million ounces of gold. Minerals commonly reported in these deposits (Crofoot/Lewis, Florida Canyon, Wind Mountain, Colado, for example) include sulfur, alunite, pyrite, marcasite, cinnabar, and kaolinite. These are minerals typical of "hot spring gold deposits" (Berger, 1985) and are characteristically found in the uppermost levels of geothermal systems. Other deposits listed in Table 1, including the Dixie Comstock and many of the deposits associated with magma-heated geothermal systems, show a slightly deeper style of alteration and mineralization more characteristic of volcanic-hosted epithermal deposits (Heald et al., 1987).

Table 1. Gold-bearing deposits in the Great Basin with evidence of a 7 – 0 Ma age of formation. For references and descriptions, see Coolbaugh et al., 2005.

Symbol	Name	County and State	Est. Age	Age Method	Production Reserves (x 1000 oz)	Inventory (x 1000 oz) P=prospect
	Gold Deposits without coeval vocanics (Extensional)					
Be	Beowawe - White Canyon	Eureka, NV	Quaternary	geologic		P
BM	Blue Mountain	Humboldt, NV	3.9 Ma	K/Ar, alunite		590
Cl	Colado	Pershing, NV	Quaternary	geologic		350
CL	Crofoot/Lewis (Sulphur)	Humboldt, NV	2 - 4 Ma	K/Ar, Ar/Ar	1,100	888
DC	Dixie Comstock	Churchill, NV	Quaternary	geologic, U-series calcite	5	100
DV	Dixie Valley - Senator	Churchill, NV	Quaternary	geologic		P
FC	Florida Canyon	Pershing, NV	2.0 Ma	K/Ar, hypogene alunite	2,000	2,755
HH	Humboldt House	Pershing, NV	Quaternary	geologic		70
JV	Jersey Valley	Pershing, NV	Quaternary	geologic		P
MH	McGinnis Hills	Lander, NV	2.2 - 3.2 Ma	K/Ar, adularia		P
NE	Northern East Range	Humboldt, NV	Quaternary?	geologic		P
NY	New York Canyon	Pershing, NV	Quaternary?	geologic		P
PH	Patua Hot Springs (Hazen)	Lyon, NV	Quaternary?	geologic		P
RC	Relief Canyon	Pershing, NV	late Mio to Quat	geologic	270	
RE	Red Edge	Pershing, NV	Quaternary?	geologic		P
Sc	Scossa	Pershing, NV	6.5 Ma	K/Ar, hypogene alunite	1	
St	Standard Mine	Pershing, NV	late Mio to Quat	geologic	404	
Wi	Willard	Pershing, NV	6.1 Ma	K/Ar, adularia	25	
WM	Wind Mountain	Washoe, NV	? Pliocene	geologic	300	
				Total Extensional:	**4,105**	**4,753**
	Gold Deposits associated with coeval volcanics (Magma-heated)					
CF	Cove Fort	Beaver, UT	Quaternary?	geologic		P
Cm	Como	Lyon, NV	6.8 Ma	K/Ar	20?	
LV	Long Valley	Mono, CA	0.30 Ma	K/Ar, geologic		1,210
MM	Monitor-Mogul	Alpine, CA	4.86 Ma	K/Ar, sericite	80	
SS	Steamboat Springs	Reno, NV	0 - 3 Ma	K/Ar		P
QM	Quartz Mountain	Lake, OR	5.5 Ma	K/Ar, adularia		2,730
SV	Silver Peak, 16-1 Mine	Esmeralda, NV	< 6 Ma	K/Ar, geologic	40	
Z	Zule	Sierra, CA	4.4 Ma	K/Ar, hypogene alunite		P
				Total Magmatic Heated:	**140**	**3,940**
				Grand Total Gold:	**4,245**	**8,693**

Longevity of Extensional Geothermal Systems: Extensional geothermal systems, although possibly episodic, may have overall lifetimes measured in millions of years. Long life spans are required to explain the large amount of vertical offset of hydrothermally mineralized zones across range front-faults. The minimum time required to offset mineralization at Florida Canyon ranges from 0.68 to 4.6 m.y. This minimum time depends on whether: a) the 0.100 mm/yr slip rate of Adams and Sawyer (1999) or the 0.312 mm/yr slip rate rate of dePolo (1998) is used, and b) the maximum elevation of kaolinite-rich hot-spring-style mineralization at Florida Canyon or the maximum elevation of replacement-style mineralization is used (Richard Larson, personal communication). In any case, the 0.68 to 4.6 m.y. inferred minimum time span of mineralization coincides reasonably well with the 2.0 ± 0.6 Ma hypogene alunite date.

Using similar criteria, minimum time spans at the Empire geothermal system (and adjacent Wind Mountain Mine) and the Dixie Meadows geothermal system (and adjacent Dixie Comstock Mine; Vikre, 1994) are estimated at 0.44 and 0.33 m.y., respectively. No independent age determinations on mineralization at Wind Mountain are available at this time, but at the Dixie Comstock mine, a minimum age of 0.35 Ma for vein calcite (Vikre, 1984) is in approximate agreement with the minimum fault displacement time.

Spatial Distribution of Young Gold Deposits in the Great Basin: Young volcanic-hosted epithermal gold deposits (with ages estimated at between 7 and 0 Ma), with evidence of having formed from magma-heated geothermal systems are largely restricted to the western margin of the Great Basin. Some but not all of these deposits are associated with the ancestral Cascades volcanic arc. Gold deposits without demonstrated volcanic/magmatic affinities are clustered in the northwestern interior of the Great Basin, and have a spatial distribution similar to that of higher-temperature extensional-type geothermal systems (Figure 4).

In greater detail, larger or higher-grade gold deposits (e.g., gold mines; see red circles, Figure 4) of the extensional-type form a northwest trend (Sulphur-Dixie Valley trend) in west-central Nevada that matches a similar trend in the geothermometer temperatures of active geothermal systems. This spatial correlation supports the hypothesis of a cause and effect relationship between active extensional geothermal activity and these young epithermal gold deposits. This correlation begs the question "Why aren't young gold deposits associated with a similar subparallel trend of high geothermometer temperatures west of the Sulphur-Dixie Valley trend?" (Figure 4, Pyramid Lake-Rawhide trend). A probable answer lies in the contrasting styles of range-front faulting found in the two trends. In the Sulphur-Dixie Valley trend, many high-temperature geothermal systems occur along classic range-front faults with large vertical offsets and high slip rates that unroofed the young gold deposits in the uplifted footwall block. The Pyramid Lake-Rawhide trend lacks development of this classic range-front fault style and its associated large offsets. Most high-temperature geothermal systems (≥ 150°C), including those at Needle Rocks, Bradys Hot Springs, Desert Peak, Soda Lake, and Stillwater, are not associated with abrupt range fronts. Erosion in such areas has been insufficient to strip away rocks overlying possible gold mineralization. The Pyramid Lake-Rawhide trend lies on the northeast margin of the Walker Lane, where strike-slip faulting may play an important role in developing the deep-level permeability necessary for high-temperature geothermal systems to form.

Discussion

The fact that extensional-type geothermal systems in the Great Basin appear to be producing gold deposits suggests that upper crustal magmas are not a prerequisite for the formation of all types of hydrothermal gold deposits. In the Great Basin, a regional transtensional environment appears to provide the fracturing and permeability needed at sufficient depths to form high-temperature (> 150°C) geothermal systems without magmatic heat. Presumably, sufficient gold can be and has been leached along fluid pathways without the need to acquire gold from magmas. Additionally, a suitable chemical and/or physical trap for precipitating those metals appears to be provided by the rapidly changing chemical and physical parameters characteristic of the near-surface hot-spring environment.

Nevertheless, all young extensional-type gold deposits in the Great Basin discovered to date are either of low-grade or low-tonnage, although at least two deposits, at Florida Canyon and Crofoot/Lewis, have reserves and/or production of over 1 million ounces (Table 1). Based on the observations of Arehart et al. (2003) of higher concentrations of some trace elements (As, Li, B, Cs) in magma-heated geothermal fluids compared to their extensional counterparts, it might be argued that magma-heated fluids would be better able to produce larger and richer metallic ore deposits. A definitive test of that hypothesis must await more detailed geological and geochemical studies that would likely include analyzing many geothermal fluids and mineral deposit fluids for their precious-metal contents. In any case, regions of the Great Basin containing high-temperature geothermal activity have the potential for hosting undiscovered young gold deposits, especially where range-front faults have not exposed underlying hydrothermally altered rocks. Similarly, the presence of young gold mineralization could provide clues to the presence of a possible nearby active geothermal system.

Pronounced uplift of mineralized and hydrothermally altered zones along range-front faults suggests that extensional geothermal systems, although possibly episodic, can have overall lifetimes measured in millions of years. In this respect, extensional systems may be similar to magma-heated systems, since magma-heated systems can be reinvigorated with each intrusive pulse. Hydrothermal waters will flow as long as weak areas in the upper crust are favorably oriented and able to focus crustal strain. Thermal modeling by McKenna and Blackwell (2003) showed that steady-state reservoir temperatures approaching or exceeding 200°C can be maintained for millions of years (depending on bulk conductivity, fault penetration, and other factors), although peak temperatures will be episodic. In any case, significant periodicity in temperatures and flow rates can be expected in extensional systems because of a) long earthquake recurrence intervals along some basin and range faults, and b) possible cycling of strain among multiple subparallel fault strands.

The highest-temperature extensional geothermal systems in the Great Basin occur along NW-trending belts oriented roughly parallel to, but outside of, the Walker Lane. This suggests that a combination of both shear and extension (transtension) may be ideal for the formation of extensional geothermal systems. The transtensional character of strain would likely be at a maximum where the dextral strike-slip Walker Lane meets the NE-trending Humboldt structural zone, and this is where the Pyramid Lake-Rawhide trend of high-temperature geothermal systems occurs.

The existence of a second sub-parallel, northwest-trending zone of higher geothermal temperatures with associated gold deposits (the Sulphur-Dixie Valley trend), suggests that a component of shear and transtension may extend eastward well into west-central Nevada. At several geothermal systems in west-central Nevada, including Rye Patch (Waibel et al., 2003), Kyle Hot Springs (Garside and Schilling, 1979), and Leach Hot Springs (Garside and Schilling, 1979), geothermal flow appears to be focused along northeast-striking faults that intersect major north- to northwest-striking range-front faults at a large angle. A small component of dextral shear parallel to the Walker Lane would help open northeast-striking faults in these areas, in a manner analogous to mild pull-apart blocks. Interestingly, some of the north- to north-northeast-striking faults have accommodated a component of right slip in historical ruptures (Caskey et al., 2004).

Acknowledgments

We gratefully acknowledge the sharing of information and insights on young gold deposits of the Great Basin, without which this report could not have been completed. Contributers include Alan Wallace, Ron Parratt, Peter Vikre, John Wood, Chris Henry, Andy Wallace, Richard Larsen, Richard Smith, Jeff Hulen, Eric Struhsacker, Roger Steininger, Rick Zehner, Dave John, Jim Rytuba, Joe Moore, Stuart Johnson, Jerry Fairley, Don Hudson, Virginia Gillerman, Mark Ferns, John McCormack, Tommy Thompson, Tim Percival, and Bob Blackett. This research was made possible by support from the U.S. Department of Energy under instrument number DE-FG07-02ID14311.

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