# Heat Flow in Railroad Valley, Nevada and Implications for Geothermal Resources in the South-Central Great Basin

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***Keywords***

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## ABSTRACT

The Great Basin is a province of high average heat flow (approximately 90 mW m $^{-2}$), with higher values characteristic of some areas and relatively low heat flow (<60 mW m $^{-2}$) characteristic of an area in south-central Nevada known as the Eureka Low. There is hydrologic and thermal evidence that the Eureka Low results from a relatively shallow, hydrologically controlled heat sink associated with interbasin water flow in the Paleozoic carbonate aquifers. Evaluating this hypothesis and investigating the thermal state of the Eureka Low at depth is a high priority for the US Geological Survey as it prepares a new national geothermal resource assessment. Part of this investigation is focused on Railroad Valley, the site of the largest petroleum reservoirs in Nevada and one of the few locations within the Eureka Low with a known geothermal system. Temperature and thermal conductivity data have been acquired from wells in Railroad Valley in order to determine heat flow in the basin. The results reveal a complex interaction of cooling due to shallow ground-water flow, relatively low (49 to 76 mW m $^{-2}$) conductive heat flow at depth in most of the basin, and high (up to 234 mW m $^{-2}$) heat flow associated with the 125°C geothermal system that encompasses the Bacon Flat and Grant Canyon oil fields. The presence of the Railroad Valley geothermal resource within the Eureka Low may be reflect the absence of deep ground-water flow sweeping heat out of the basin. If true, this suggests that other areas in the carbonate aquifer province may contain deep geothermal resources that are masked by ground-water flow.

## Introduction

The Great Basin is a province of high average heat flow (approximately 90 mW m $^{-2}$), and it contains sub-provinces of both higher and lower heat flow. Higher heat flow (> 100 mW m$^{-2}$) is characteristic of the north-central Great Basin (the Battle Mountain High of Sass et al., 1971a) and several smaller areas, mostly along its margins. Most geothermal power plants in the Great Basin are located within or near these high heat-flow zones. There is also a large area of relatively low heat flow (< 60 mW m$^{-2}$, the Eureka Low) in the south-central portion of the province. This area of low heat flow was first delineated by Sass et al., (1971a), and subsequent heat flow measurement programs in the Great Basin (e.g., Sass et al., 2005) and recent compilations of all published heat flow measurements (e.g., Blackwell and Richards, 2004) confirm the existence of the Eureka Low, although there are varied interpretations regarding its areal extent.

There is both hydrologic and thermal evidence that the Eureka Low is a relatively shallow (up to 3 km) hydrologically controlled heat sink associated with the well-documented interbasin water flow in the Paleozoic carbonate aquifers (Sass *et al.*, 1971a; Prudic *et al.*, 1995). For example, the temperature profile from a 3.7 km deep hole at Pahute Mesa in the Eureka Low indicates low heat flow in the upper 1.5 km and characteristic Great Basin heat flow in the lowermost kilometer (Sass *et al.*, 2005). In addition, the relatively sharp transition from lower to higher heat flow around the margins of the Eureka Low is consistent with a shallow thermal anomaly (Sass *et al.*, 1971a). On the other hand, some seismic and magnetic studies suggest that the heat sink in the Eureka Low extends to at least mid-crustal depths (e.g., Blakely, 1988).

Understanding the deep crustal thermal conditions in the Eureka Low is a critical problem for geothermal resource and exploration studies. If, as suggested by both heat flow and hydrologic studies (e.g., Lachenbruch and Sass, 1977; Winograd and Thordarson, 1975), the Eureka Low is a manifestation of the extraction of heat and the southward lateral transfer of heat from the sedimentary basins by inter-basin flow, there should be recognizable outflow zones both within and to the south of the feature. In fact, Lachenbruch and Sass (1977) note that if 40 mW m$^{-2}$ is being removed, the heat sink represented by the Eureka Low is comparable to the absolute magnitude of the heat source at Yellowstone.

Almost all of the know high-temperature geothermal systems in the Great Basin are located outside of the region underlain by the carbonate aquifers (Coolbaugh *et al.*, 2005). If the Eureka Low reflects relatively low thermal gradients through the upper crust, then the region is unlikely to host significant geothermal resources. By contrast, if the groundwater flow in the carbonate aquifers masks thermal conditions at depth that are consistent with other parts of the Great Basin, then the potential exists for the formation and maintenance of geothermal systems, albeit at depths greater than typically encountered outside of the aquifer region. The U.S. Geological Survey has embarked on a 3-year program to conduct a new national geothermal resource assessment (Williams and Reed, 2005), and understanding the thermal state of the Eureka Low is an important part of the effort to assess the spatial extent and magnitude of undiscovered resources.

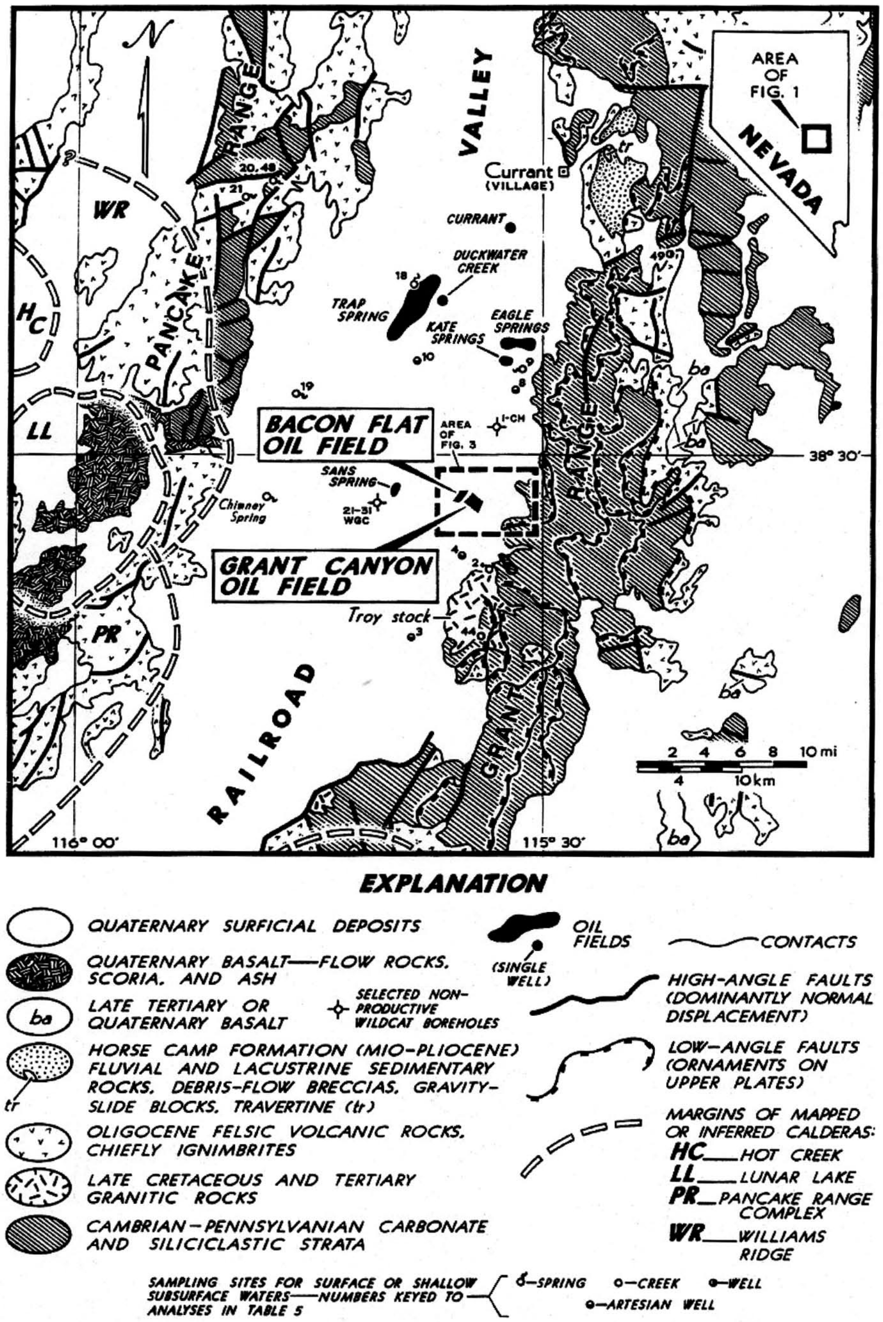

**Figure 1.** Location map for Railroad Valley and its associated oil fields, after Hulen *et al.*, 1995.

## Railroad Valley

Paradoxically, temperature-gradients as high as 100 °C km-$^{1}$ and an underlying hydrothermal system with temperatures in excess of 120°C are found within the Eureka Low in Railroad Valley, which contains the most productive oil-fields in the Great Basin (Figure 1; Hulen et al., 1994). Railroad Valley is a large asymmetric basin that started forming in the early Miocene (Hulen et al., 1994). Petroleum reservoirs are found within faulted blocks of Paleozoic carbonates that underlie Cenozoic sediments and volcanics (Figure 2), although the relative roles of high-angle normal faulting and low-angle detachment faulting in the formation of the present-day structures is a matter of unresolved debate in the literature (e.g., Lund et al., 1993; Hulen et al., 1994, Francis and Walker, 2001).

Hulen *et al.* (1994) have suggested that the Railroad Valley hydrothermal system has enhanced hydrocarbon transport and has accelerated maturation, but a number of fundamental questions remain. What is the spatial extent of the hydrothermal system, and how does it compare to the distribution of petroleum reservoirs? Is the collocation of unusually high temperatures and highly productive petroleum reservoirs coincidental or are the two linked in some process? What is the reason for the presence of the Railroad Valley hydrothermal system in the Eureka Low, and what does it tells us about the potential for other systems in the region?

In order to address these issues, the US Geological Survey initiated a heat flow study and measured temperatures and thermal conductivities within the reservoir rocks and the overlying formations for four oil wells in Railroad Valley. These measurements were combined with commercial temperature logs from additional wells to provide the basis for mapping the lateral and vertical variation of heat flow within the basin.

## Data

The USGS temperature measurements were acquired from four idle wells at or near thermal equilibrium: Eagle Springs 1-35 (ES35), Grant Canyon 3 (GTCN), Bacon Flat 1 (BF01), and Zuspann 24-3 (ZU24). The locations of these wells are shown in Figure 3 and the resulting profiles are plotted in Figure 4, along with USGS temperature profiles from two shallow wells to the northeast: Currant Creek Summit

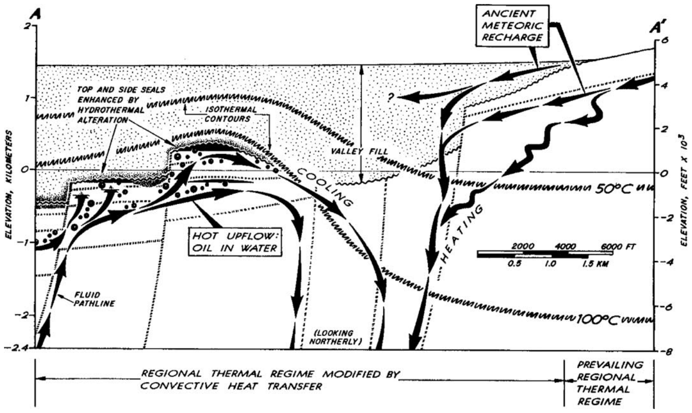

**Figure 2.** East-west cross-section through the Bacon Flat and Grant Canyon oil fields of Railroad Valley, after Hulen *et al.* (1995). Note the inferred migration of hot water up high-angle faults and within the carbonate rocks that form the principal oil reservoirs. Location of section indicated by box in Figure 1.

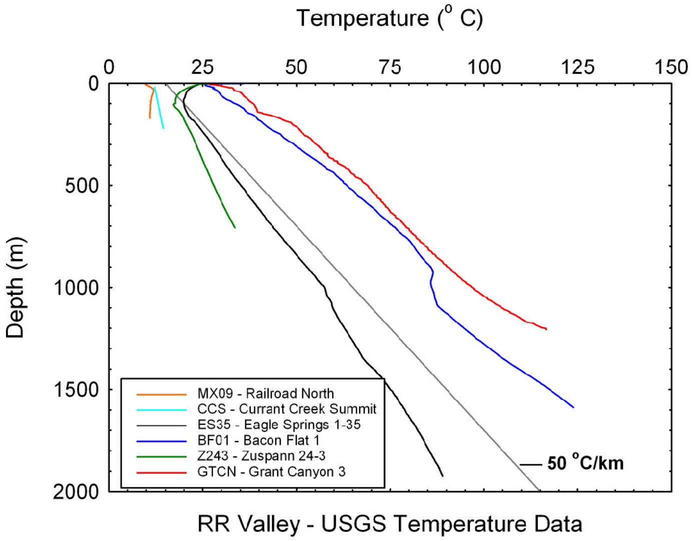

**Figure 4.** Temperature profiles from idle oil wells logged by the USGS.

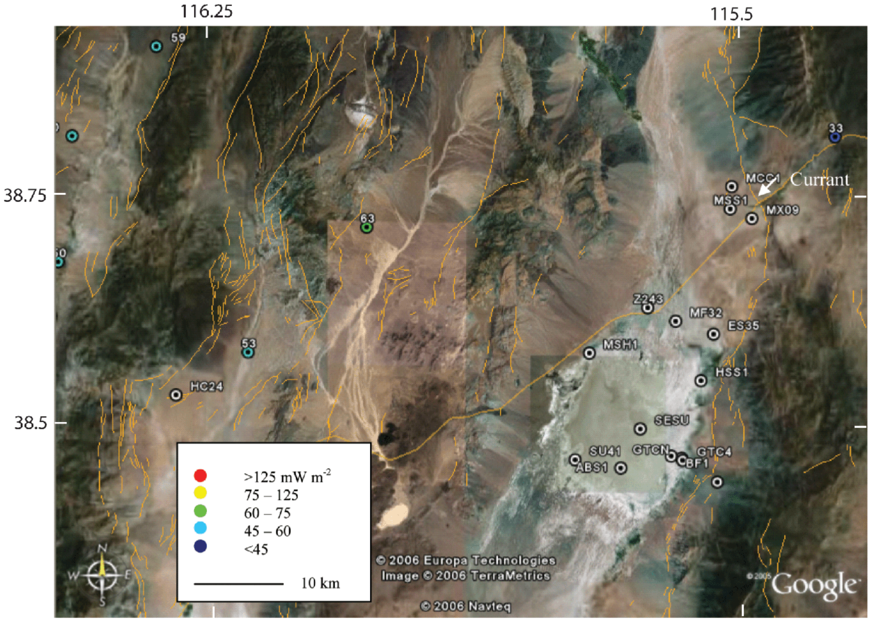

**Figure 3.** Satellite image of the Railroad Valley area, showing Quaternary faulting (orange), the location of existing heat flow measurements (Sass *et al.*, 1971 and Sass *et al.*, 2005; numbers are heat flow in mW m$^{-2}$), and the location of wells investigated for this study.

(CCS; Sass *et al.*, 2005) and MX09. Commercial temperature logs were acquired from nine additional wells: Marathon Currant Creek 1 (MCC1), Meridian Federal 32-29 (MF32), Marathon Silver Springs 1 (MSS1), Husky Soda Springs 1 (HSS1), Marathon Shoreline (MSH1), Shell ESU2 (SESU), Bullwhacker Springs 1 (ABS1), Shell USA 41-24 (SU41), and Grant Canyon 4 (GTC4). The locations of these wells are also shown in Figure 3, and the temperatures are plotted in Figure 5, overleaf. Although the commercial temperature logs were acquired from wells at varying non-equilibrium conditions, analysis of the available information on well histories indicates that the average geothermal gradients are within 10% of equilibrium values.

The combined Railroad Valley temperature dataset reveals three characteristic thermal features. In the northeastern portion of the valley near the town of Currant, temperature gradients in CCS, MX09, and MSS1 are low, varying from isothermal conditions to less than 20 °C km$^{-1}$. These low gradients appear to reflect the cooling effects of shallow ground-water flow. With the exception of the high values in MCC1, gradients in the northern portion of the valley (above 38.5° N), gradients range between 25 and 45 °C km$^{-1}$. Finally, in the vicinity of the Grant Canyon and Bacon Flat fields in the central portion of the valley, gradients increase to values ranging between 60 and 120 °C km$^{-1}$, with the highest gradients occurring at depths below 1 km. This dramatic change in temperature gradient is magnified in terms of heat flow through a significant increase in the thermal conductivity of the sediment below 700 m in the Grant Canyon and Bacon Flat fields (Figure 6, overleaf).

Thermal conductivities were measured on cores and cuttings from wells in the Eagle Springs, Trap Springs and Bacon Flat fields using a divided-bar apparatus similar to the one described by Sass et al. (1971a,b). Matrix thermal conductivities were corrected to bulk thermal conductivity using porosity data from well logs, and the results are shown in Figure 6. Bulk thermal conductivity follows a clear trend of increasing values from an average of approximately 1.2 W m$^{-1}$ K$^{-1}$ in the near surface to approximately 2.2 W m$^{-1}$ K$^{-1}$ between 1.5 and 2.0 km depth. This increase in thermal conductivity with increasing depth results from the corresponding decrease in porosity of the valley fill due to compaction and alteration. Within the deeper sedimentary units that form the permeability trap and the petroleum reservoirs for the Bacon Flat and Grant Canyon fields, thermal conductivity is relatively constant at a value of approximately 2.4 W m$^{-1}$ K$^{-1}$ (Figure 6).

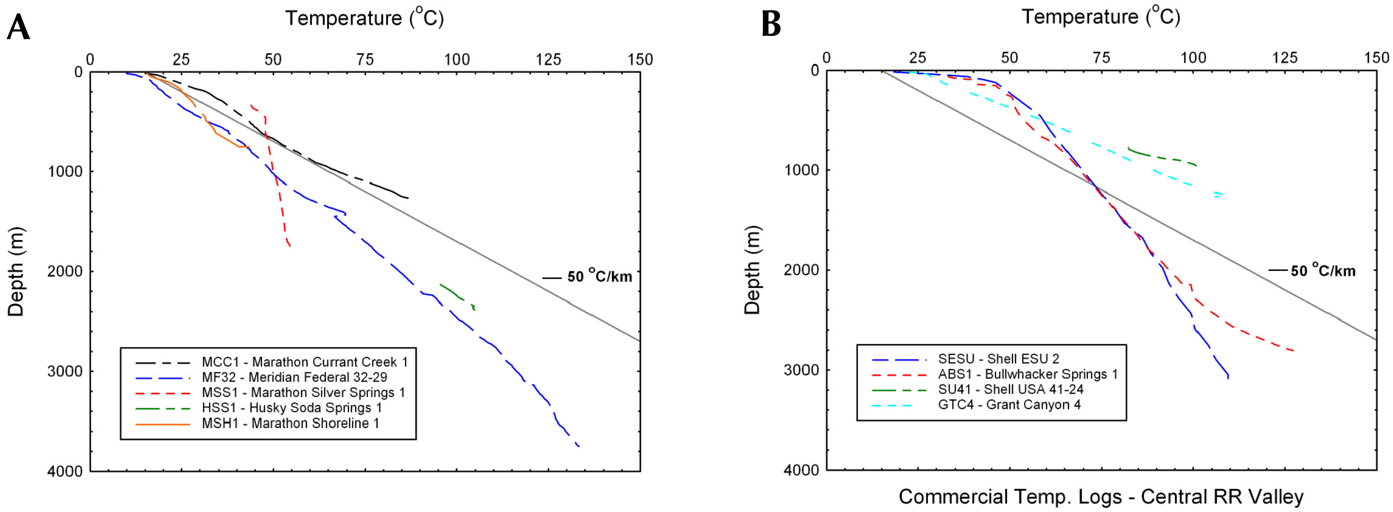

**Figure 5.** Temperature profiles from oil wells logged by commercial logging companies (a) north of the Bacon Flat and Grant Canyon fields (38.5° N) and (b) within and west of the Bacon Flat and Grant Canyon fields.

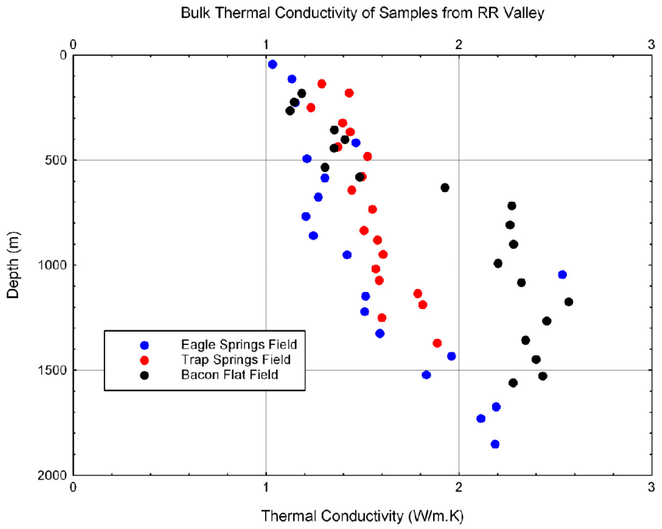

**Figure 6.** Profile of thermal conductivity measurements from wells in Railroad Valley.

## Analysis and Interpretation

Heat flow was determined for the study wells by combining the measured temperature gradients with thermal conductivity measurements from the same or nearby wells. For the wells with USGS equilibrium temperature profiles (Figure 4), the resulting heat flow values are accurate to within approximately ±10%, reflecting the uncertainty associated with estimating bulk rock thermal conductivity from measurements on cuttings samples (e.g., Sass *et al.,* 1971b). For the wells with non-equilibrium commercial temperature profiles, the corresponding uncertainty in heat flow is approximately ±20%, due to the combined uncertainties in both conductivity and temperature gradient. As indicated by the contrasts in temperature gradient, a map of the deepest heat flow value from each well reveals substantial lateral variations in heat transport within Railroad Valley (Figure 7). To the northwest of Currant, high heat flow (115 mW m$^{-2}$) is found in the MCC1 well. In the vicinity of Currant (CCS, MSS1, MX9) low heat flow (0 to 33 mW m$^{-2}$) reflects the advective effects of groundwater recharge from the Grant Range into the valley. To the south of Currant (Z243, MF32, ES35, MSH1, HSS1, ESU2) moderate heat flow (49 to 76 mW m$^{-2}$) is on average slightly higher than other measurements in the Eureka Low. Near the Grant Canyon and Bacon Flat fields (GTCN, GTC4, BF1, ABS1, SU41) high heat flow (80 to 234 mW m$^{-2}$) is direct evidence for the active hydrothermal system discussed by Hulen *et al.* (1994).

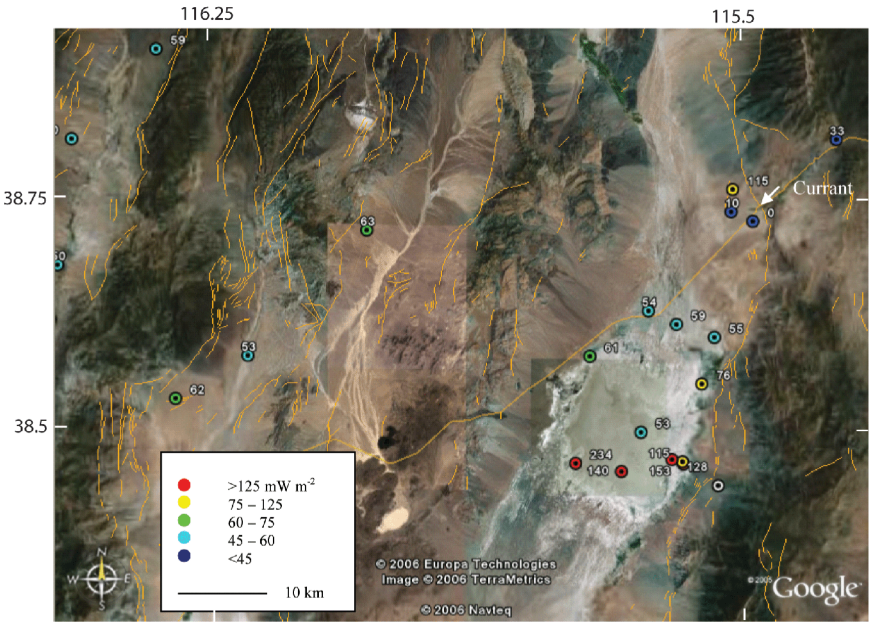

**Figure 7.** Satellite image from Figure 3 with new heat flow values substituted for well names.

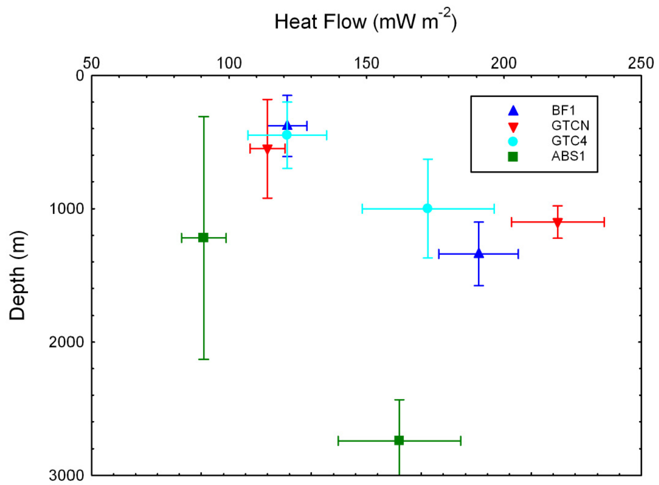

**Figure 8.** Vertical profiles of heat flow for those four wells (BF1, GTCN, GTC4, ABS1) that show significant changes with depth.

An important feature of the Grant Canyon/Bacon Flat region and the area to the west is that heat flow is not uniform with depth. With the exception of ABS1 (in which the transition is deeper), heat flow is typically 80 to 90 mW m$^{-2}$ above 1 km depth and greater than 140 mW m$^{-2}$ below 1 km (Figure 8). This vertical variation in heat flow could reflect the thermal transient from initiation of a very young (<50 ka) hydrothermal system or the cooling action of lateral groundwater flow within the shallow sediments. Hulen *et al.* (1994) note that chemical analyses indicate that the geothermal waters of the Bacon Flat and Grant Canyon fields may be no older than 10,000 years.

Bottom-hole temperature (BHT) data and the measurements presented in this paper constrain the extent of the high heat flow associated with the Bacon Flat and Grant Canyon fields to an area of 50 to 100 km$^2$ extending from the base of the Grant Range just east of the Grant Canyon field to the western end of Railroad Valley (Figures 1 and 7). This is in contrast to the standard conceptual model for Basin and Range geothermal systems, such as Dixie Valley, in which hot water circulation is focused along the strike of the major range-bounding faults. Based on the deep heat flow measurements from just above the reservoirs, the total heat flux through the area of anomalously high heat flow in Railroad Valley may be estimated to lie in the range of 5 to 10 MW.

A number of thermal springs are located in Railroad Valley (Garside and Schilling, 1979; Reed *et al.*, 1983). The hottest of these, Chimney Hot Springs, is located at the western end of the high heat flow trend and is characterized by an outflow of approximately 1440 l/min and a temperature of between 60 and 71 °C (Reed *et al.*, 1983). The thermal output of Chimney Hot Springs relative to an average ground surface temperature of 20 °C is approximately 4 MW. If the water flowing from Chimney Hot Springs cooled from a reservoir temperature of 125 °C, the heat loss along the flow path would be another 6 MW, which is approximately the same as the conductive heat loss from the hydrothermal system into the overlying sediments. Alternatively, if the Chimney Hot Springs surface temperature reflects significant mixing with cooler ground-water, than the actual conductive heat loss along the outflow path will be much lower.

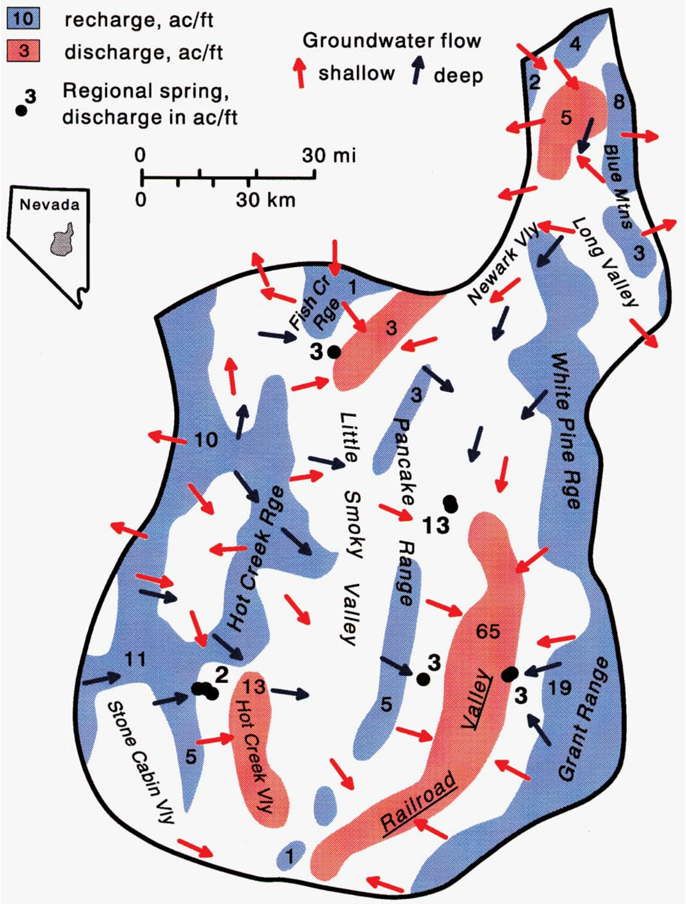

**Figure 9.** Map showing principal patterns of ground-water flow in the carbonate aquifers in the vicinity of Railroad Valley (after Prudic *et al.*, 1995).

## Implications

The measurements described above suggest that cool water flow through the valley fill and hot water flow through the underlying carbonates and along faults within the shales, granites and volcanics (Hulen et al., 1994) dramatically alters the pattern of conductive heat flow in Railroad Valley. If there is pervasive regional ground-water flow within the carbonates, it does not have the consistent reducing effect on heat flow found in the rest of the Eureka Low. Prudic *et al.* (1995) note that although Railroad Valley receives substantial interbasin flow from Hot Creek Valley and Little Smoky Valley, outflow is restricted to evapotranspiration and stream discharge (Figure 9). The high temperatures found within the Grant Canyon and Bacon Flat fields may reflect deep (~5 km) circulation of water below the carbonate aquifer or advective heat output from recent, as yet undetected, magmatic activity. In either case, high heat flow from depth is manifest in Railroad Valley because there are local restrictions to regional flow in the carbonate aquifer system. Substantial interbasin flow through Railroad Valley would not only remove the thermal evidence for a heat source at depth but also carry away any excess heat necessary for maturation of hydrocarbons. Consequently, the formation of both geothermal and hydrocarbon reservoirs in the Eureka Low may be favored in those basins where regional-scale ground-water flow in the carbonate aquifer is not removing heat from the basins.

The full implications of this study for the potential for undiscovered geothermal resources elsewhere in the Eureka Low await a more complete understanding of Railroad Valley geothermal system, particularly the nature of the Railroad Valley heat source and the spatial and temporal variation of ground-water flow within the basin. At present the available information indicates that the Railroad Valley-type systems may be found elsewhere in the region covered by the carbonate aquifers, although perhaps at greater depth. Hulen *et al.* (1994) argue that Railroad Valley is a deep circulation system unrelated to any magmatic heat source, which implies that the background heat flow is sufficient to drive geothermal systems given the presence of a favorable permeability structure. By contrast, if the Railroad Valley system is driven by a magmatic heat source, then the favorable conditions required for the formation of equivalent systems are uncommon in the south-central Great Basin..

Another important constraint on the potential for undiscovered systems of this type is the spatial extent of the Railroad Valley thermal anomaly. Hundreds of exploratory oil wells have been drilled in eastern Nevada, and the chances of those wells missing hidden geothermal reservoirs are small if those reservoirs are likely to have thermal anomalies that cover large areas. In the case of Railroad Valley, the thermal anomaly associated with the geothermal system is relatively small (Figure 7), and wells drilled to depths greater than 2 km just north and south of the Bacon Flat-Grant Canyon trend show no anomalous thermal conditions. This observation is consistent with models for the conductive thermal effects of hot springs (e.g., Lister, 1996) and with the possibly young (less than 50 ka) age of the Railroad Valley geothermal system. Consequently, in other basins within the carbonate aquifer system, shallow ground-water flow may mask the underlying thermal regime from shallow temperature-gradient hole exploration programs, and relatively deep (>1 km) exploratory drilling may not intersect a geothermal system unless other geological, geochemical or geophysical evidence is available to pinpoint an exploration target. Systematic mapping of the deep thermal regime under the carbonate aquifers may be necessary to resolve the question of geothermal potential.

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