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HEAT FLOW IN THE WESTERN UNITED STATES AND EXTENSIONAL GEOTHERMAL SYSTEMS

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ABSTRACT

This paper presents the latest surface heat flow map of the continental United States and analyzes the distribution of known extensional geothermal systems in the western US with respect to background heat flow (heat flow outside the area of disturbance associated with a convecting system).

The heat flow map is an updated version of the DNAG Geothermal Map of North America (Blackwell and Steele, 1992). The update adds a number heat flow measurements to the original map for the central and western US. The overall heat flow picture has not changed from the 1992 map, but the additional data have improved contour detail in some areas (particularly the southwest US) as well as increased confidence in the contouring in other areas. The map is sufficiently detailed and accurate to be used as a basic data source for further studies.

The density of high temperature (>150°C), extensional geothermal systems, increases rapidly with heat flow. While not unexpected, the fit of the curve suggests that sampling of known geothermal systems is unbiased to any significant degree in all but the highest heat flow regions. Reservoir temperatures of known geothermal systems fall off rapidly in areas with heat flow less than $80 mW/m^2$. For typical thermal conductivity and assuming reservoir temperature equals geochemical system temperature, the depth of circulation of most Basin and Range systems is less than 5 km. Taken together, the data suggest that there is little value to exploration for extensional geothermal systems in areas with less then $80 mW/m^2$ background heat flow.

INTRODUCTION

Geothermal systems that are not driven by a cooling magma (or solidified intrusive) body are very sensitive to the amount of background heat flow present. While this concept is intuitively obvious, the relation has not been well quantified. Many studies of geothermal systems have been published, but until recently, published heat flow maps have either covered limited regions, or larger areas in less detail. The availability of a heat flow map of the US, based on the most comprehensive heat flow database published, makes it possible to establish some initial quantitative relations between heat flow and extensional geothermal systems.

HEAT FLOW MAP

Blackwell (1971, 1978), Roy et al. (1972), Lachenbruch and Sass (1978, 1980, 1992), Morgan and Gosnold (1989), Reiter et al. (1991) and Blackwell et al. (1991) have given general summaries of the heat flow in the western United States. Because of these and many other area specific papers, most of the larger scale thermal features are relatively well known. Recently, extensive new heat flow data have been presented by Sass et al. (1994) for the Arizona and southern California area. Much proprietary data has also been made available in recent years.

In contrast to the relatively simple Eastern United States heat flow (Blackwell et al, 1994, 1995) the factors that affect the heat flow in the western United States are varying, complex, and overlap. In the western United States both high and low heat flow anomalies are associated with tectonic activity. Because of its complexity, regional heat flow patterns have been extensively studied. Close to 2000 site values, many representing more than one hole (not counting the multiple hole studies in geothermal systems) were used in compiling the map in Figure 1.

The heat flow map for the conterminous US is shown in Figure 1. Figure 2 shows the western half of the heat flow map, without the data points for clarity. The heat flow contours are similar to the DNAG Geothermal Map of North America (Blackwell and Steele, 1992) with modifications to reflect new data. The data shown on the map are the heat flow sites (with coded heat flow values), and heat flow contours in mW/m^2. Over some areas of the map there are insufficient data to constrain fully the contouring at the 10mW/m^2 interval. However, a coarser interval would lose detail in the areas of high data density and not be fine enough to show some significant features. Therefore, for consistency, the 10mW/m^2 interval was used between 10 and 100 mW/m^2 for the whole map. In some cases contours follow known or presumed tectonic/physiographic/thermal trends in the absence of constraining heat flow data.

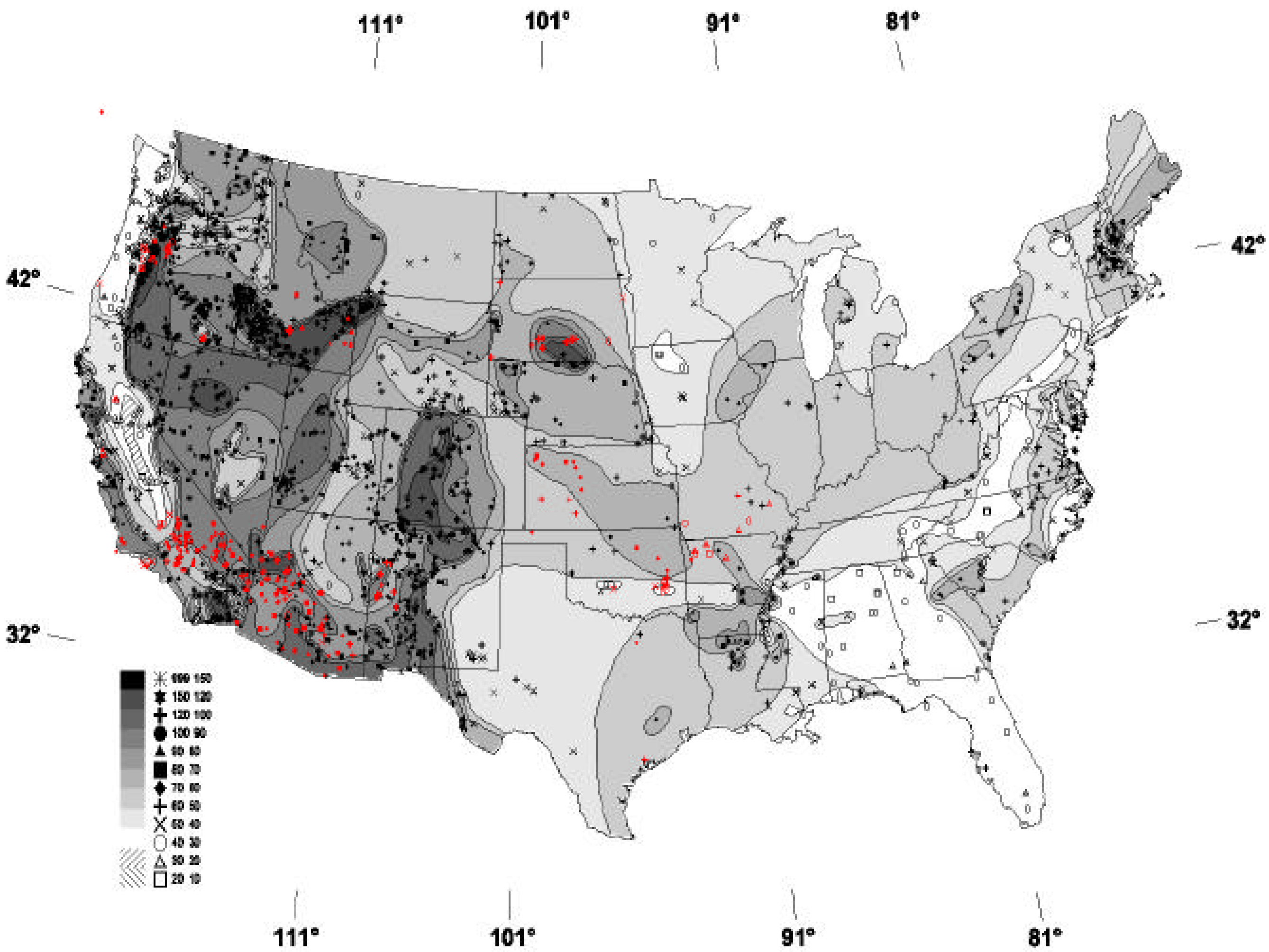

Figure 1. Heat flow map of the conterminous United States along with the data points, contour intervals in mW/m^2.

The basic heat flow and ancillary data are available from the authors, as are color image files. The SMU geothermal web site (www.smu.edu/~geothermal) has a downloadable heat flow point database, heat flow and temperature maps of the US, and an extensive reference list. An early version of the basic heat flow data was included in the Geophysics of North America CD-ROM (Blackwell et al., 1989). The data included in the compilation for the United States are quite inclusive for individual heat flow sites including some data not in the original publications. Pollack and others (1990) also contain a subset of the information for each site in a worldwide heat flow compilation. A summary of references to temperature-depth data from geothermal areas is included in Blackwell and others (1989).

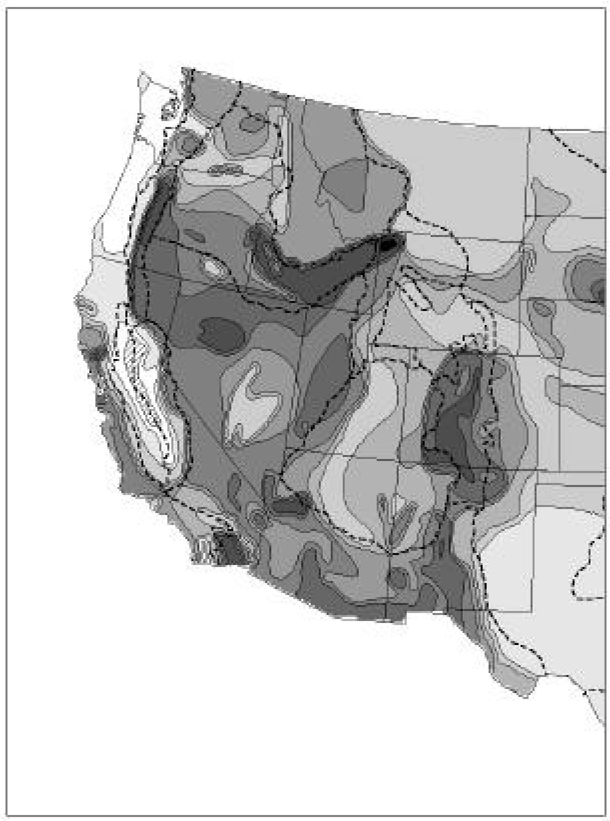

Figure 2. Detail of the western half of the heat flow map shown in Figure 1 (minus data points). Dashed lines are physiographic province boundaries. Contour values are the same as in Figure 1.

The contoured areas within the western US range between 20 and 30mW/m^2 in the Sierra Nevada Mountains (the lowest heat flow in North America) to greater than 120 mW/m^2 in Yellowstone and the Salton Trough. The cause of the variations is generally volcanic/tectonic disturbances in the lithosphere and variations in the radioactive heat generation of the crust. In a few areas, more surficial factors (most commonly rapid groundwater flow) affect the heat flow from the crust and mantle. Blackwell and Wisian (1996) discuss the tectonic aspects of the updated heat flow map in more detail.

The areal distribution of heat flow for both the conterminous US as a whole and the US west of the Great Plains is shown in Figure 3. Most of the US is in the 40-60mW/m^2 range typical for a stable craton. However, there are two heat flow modes in the map. The Rocky Mountains / Great Plains province boundary forms a demarcation between the tectonically “active” western US and the “quiet” eastern US. The vast majority of geothermal systems occur in the “active”, western US, and all the high temperature (>150°C) geothermal systems are in the west.

Looking at the heat flow distribution for the western US alone changes the picture considerably. For the western US, heat flow by area peaks at 70-79mW/m^2, but not very sharply. Eighty percent of the western US has a background heat flow of 60mW/m^2 or greater.

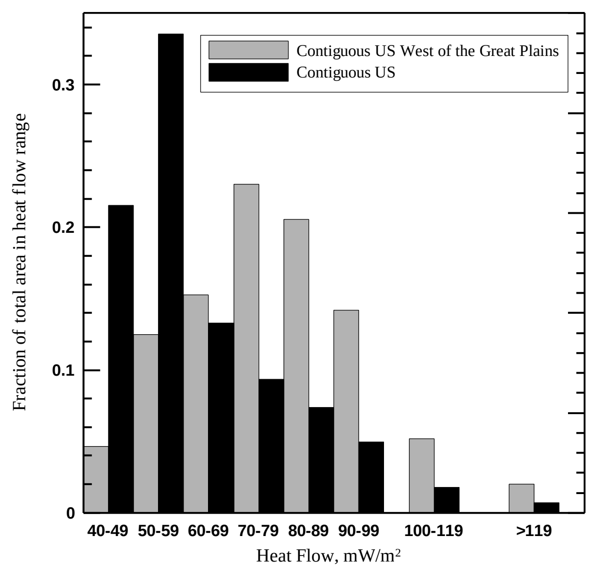

Figure 3. Fraction of total area versus heat flow for the conterminous US as a whole and for the area west of the Great Plains. The US as a whole has an average heat flow of around 55mW/m^2. The more tectonically active western US has an average near 75mW/m^2. The interval is stretched out on the high heat flow end.

CORRELATION OF HEAT FLOW AND EXTENSIONAL GEOTHERMAL SYSTEMS

Heat flow obviously is a primary factor in the development of an extensional geothermal system. Heat flow is here taken to be the background value absent of any fluid flow effects or extremes caused by any shallow crustal intrusive bodies. An extensional geothermal system is defined as a system that relies on deep circulation of water to achieve elevated temperatures (i.e. not a nearby magma body). Deep circulation systems rely on the existence of faults to provide a rapid up-flow conduit for the water, otherwise heat would be lost by conduction and no geothermal system would exist. This faulting is often provided by extensional tectonics – hence the name.

To study the correlation of heat flow with the occurrence of extensional geothermal systems, two approaches were used. The first approach used the high temperature (>150°C) springs and geothermal systems from the DNAG heat Flow map (Blackwell and Steele, 1992). The second approach used only geochemical reservoir temperatures from open literature (Mariner et al., 1983, Garside and Schilling, 1979 [and too many others to mention here]) as well as proprietary sources, as a database. In both cases systems thought to be driven by intrusive bodies (e.g. Long Valley and the Geysers) were excluded. Both data sets are very similar and can largely be interchanged (they are the outgrowth of two separate projects). Both data sets also focus on systems in the Basin and Range province because systems in this province have been intensively studied and developed in the US. No claim is made as to the comprehensiveness of either data set.

Background heat flow values were determined for the high temperature systems of Blackwell and Steele (1992) based on the revised heat flow map shown in Figures 1 and 2. Figure 4 shows the number of high temperature systems per heat flow bin. These raw numbers show a peak at 90-99mW/m^2. Almost no systems are found in region with less than 60mW/m^2 of heat flow. The number of systems in a given heat flow range is strongly affected by the amount of area with that heat flow. Thus even though heat flow above 100mW/m^2 is a stronger drive than 90-99mW/m^2, there are fewer systems in that range because there is relatively little land in the US with such a high heat flow.

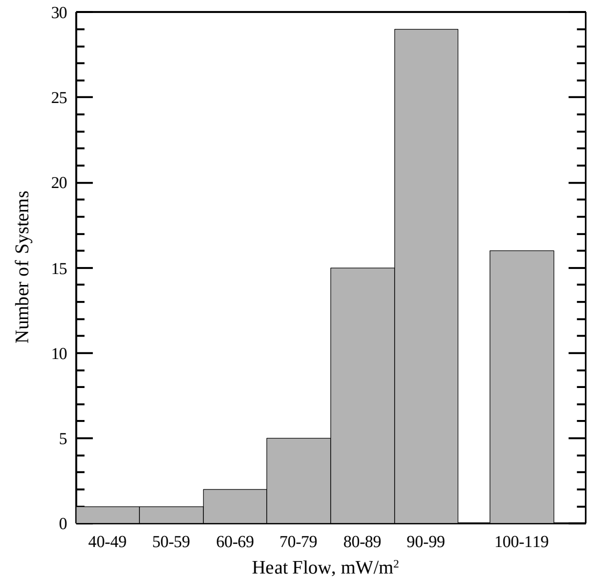

Figure 4. Raw numbers of high temperature (150°C or higher) extensional geothermal systems versus heat flow range. The high temperature systems are from Blackwell and Steele, (1992).

The density of geothermal systems versus heat flow is shown in Figure 5. The density is determined by dividing the number of systems in a bin by the area of the bin (area in km^2 with a given heat flow). In Figure 5, as compared to Figure 4, the increase of systems with heat flow follows a more exponential shape. The upper bin, at 100-119mW/m^2, is below an exponential trend (this bin is twice the size of the others). This divergence from an exponential trend is probably due to the relatively small area (represented by the 100-119mW/m^2 bin) becoming statistically significant, and due to the presence of magma bodies in these regions.

The low end of the heat flow scale, where there is a reasonable area, but very few high temperature systems, is also statistically less reliable. Figure 5 shows two sets of data, the entire conterminous US, and just the western section. Since all the higher heat flow areas are in the western section, the densities are the same for the 90-119mW/m^2 bins. As heat flow decreases, more of the respective bin falls in the eastern US, thus the differences in density between the data sets.

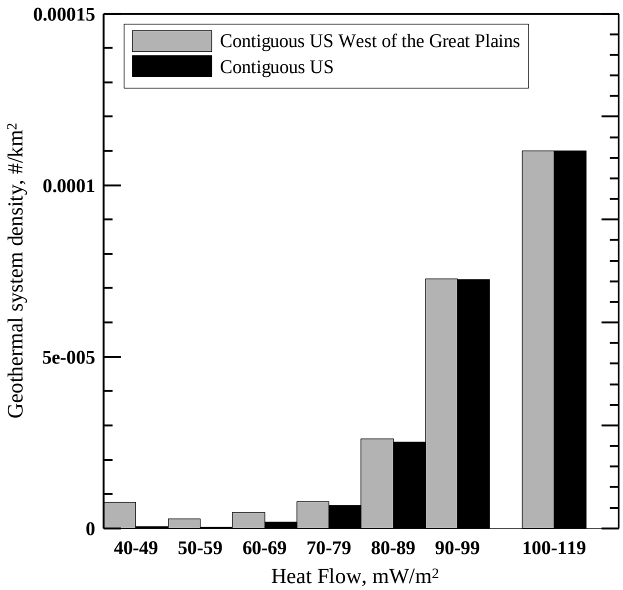

Figure 5. Areal density of high temperature, extensional geothermal systems versus heat flow. The density of systems increases rapidly with heat flow in the 50-100mW/m^2 range (where there is good sampling).

In an idealized system, the reservoir temperature of a geothermal system will be approximately equal to the temperature at the minimum depth of circulation. Temperature at depth can be predicted based on heat flow, rock thermal conductivity and surface temperature.

$$T = T_{Surface} + \left(\frac{HeatFlow}{ThermalConductivity} * Depth \right)$$

Setting T equal to reservoir temperature, and assuming a reasonable thermal conductivity, an effective depth of circulation can be determined. [This linear relation is a simplification of a complex system, but is a reasonable first order approximation.]

Figure 6 shows the best available reservoir temperatures of extensional geothermal systems versus background heat flow. Statistically, the sampling of geothermal systems falls off each side of the central region of the graph. The large decreases in maximum temperatures in the 70-79mW/m^2 range and again below 70mW/m^2 appear too rapid to be due entirely to the smaller number of systems in terrain of that heat flow (thus less statistical significance). Less heat flow could push more potential geothermal systems below the critical Rayleigh number (Ra_{crit}) for the onset of natural convection. Alternatively, the tectonics associated with lower heat flow regions might not favor the development of the deep faulting needed for geothermal systems. Whatever the cause, there is an obvious, sharp decline in reservoir temperatures in regions with less than 80mW/m^2 heat flow.

There is also obvious bias in the sampling at lower temperatures. There should be a steady rise in the frequency of systems with decreasing temperature at all heat flow values, but in reality low temperature systems are not looked for and are therefore underrepresented.

Keeping the above limitations in mind, the region from 80 to 95mW/m^2, and 150 to 250°C is well represented by the known systems. In Figure 6, shaded lines are plotted showing the expected reservoir temperatures at 4, 5 and 6km depths of circulation, for a rock thermal conductivity of 2.0W/m/K (and a 0°C surface temperature). The dashed lines are for a thermal conductivity of 1.5W/m/K. Valley fill clastic, sediments typically have conductivities in the 1-2W/m/K range while basement/range rocks, though varying widely, are often in the 2-4W/m/K range. Modeling shows that in a typical Basin and Range setting, the valley fill sediment caries about a 1/3 weight factor for determining a representative thermal conductivity (Wisian, 1999). The 2.0W/m/K value is a “best guess” whole system value.

Comparing the depth of circulation projections with the geochemical reservoir temperatures shows that, depending on overall thermal conductivity, geothermal systems in the western US, effectively circulate to depths of 4-6 km at most.

A 5km maximum flow depth is well above the projected brittle-ductile transition of ~15km in the Great Basin, where most extensional geothermal systems are located (Rodgers et al, 1991). In general, water is expected to be present and at least somewhat mobile throughout the brittle crust. For almost any permeability and above average heat flow, the critical Rayleigh number (Ra_{crit}) for the onset of natural convection is exceeded (Straus and Schubert, 1977). So why are reservoir temperatures not higher? Fluid systems would not be expected to work well above the critical point (~375°C), which is somewhat of a natural limit. Critical point temperature is still much higher than the reservoir temperatures seen here. There are many factors that could be limiting most fluid flow to the upper third of the brittle crust (e.g. loss of porosity and/or permeability due to pressure, or diagenesis could stop circulation). Perhaps the geochemical temperatures represent an intermediate stage reservoir or partial re-equilibration between maximum depth and the surface. There are also well known, significant variations in geochemical thermometer results depending on how they are used and interpreted (Fournier, 1990, Nicholson, 1993).

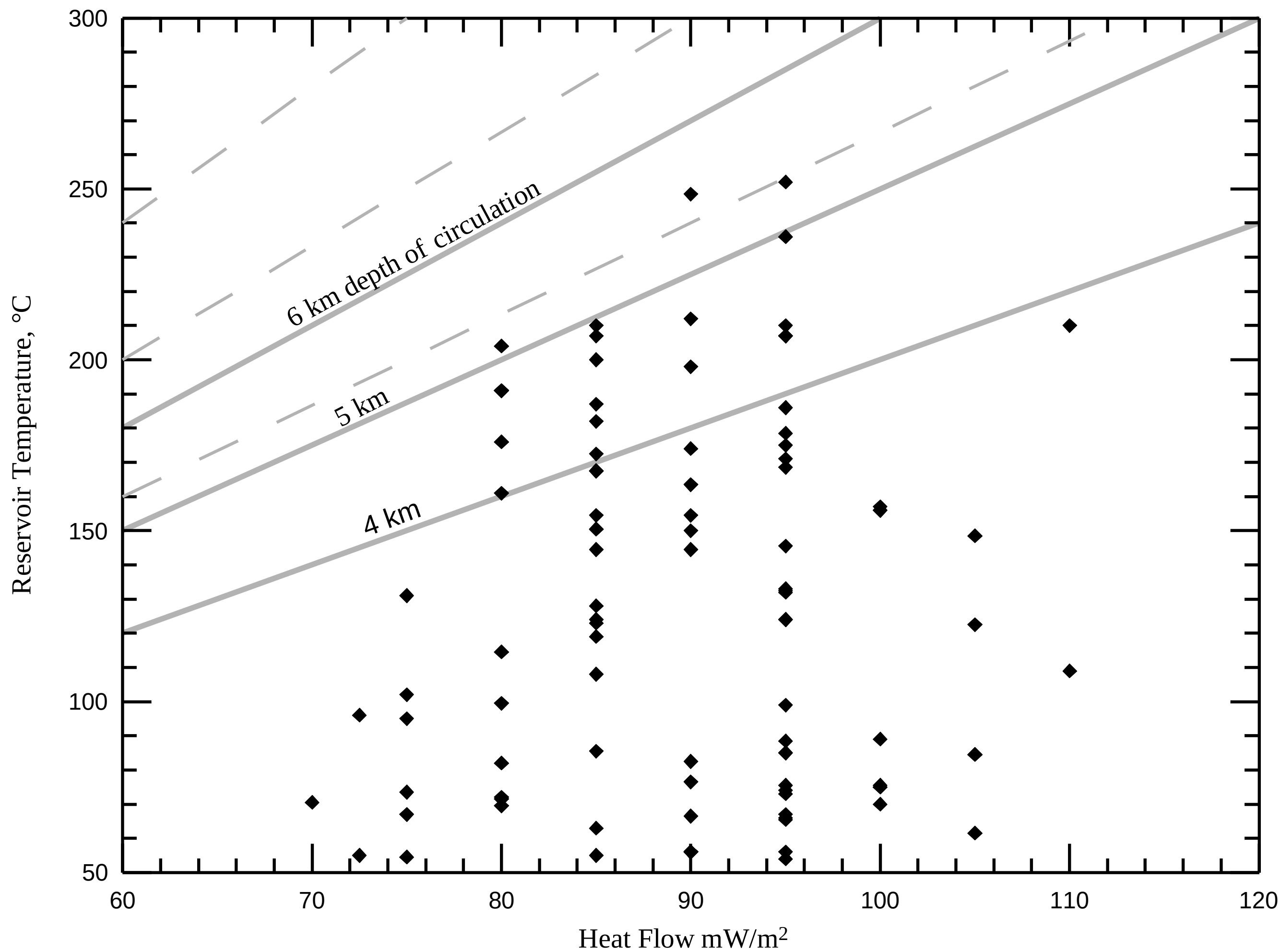

Figure 6. Reservoir temperatures versus heat flow for extensional geothermal systems in the western US. Reservoir temperatures are from a variety of open and proprietary sources. Note this is a different (though overlapping) data set from that used in the other figures. The number of available samples falls off rapidly above 95mW/m^2 and below 80mW/m^2. Gray shaded lines represent the temperatures for a geothermal system of labeled depth in a rock matrix with a thermal conductivity of 2.0 W/m/K. The dashed lines are the same as the gray lines except for a rock conductivity of 1.5W/m/K. Effective depth of circulation for the hottest extensional systems in the western US is about 5 km.

CONCLUSION

The updated heat flow map of the United States is sufficiently detailed and accurate to be used as a basic data source for further studies. Both the density of high temperature geothermal systems and the geochemical reservoir temperature fall off rapidly for heat flow below $80mW/m^2$. Taken together, the data suggest that there is little value to exploration for extensional geothermal systems in areas with less then $80mW/m^2$ background heat flow.

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