Evaluation of Approaches and Associated Uncertainties in the Estimation of Temperatures in the Upper Crust of the Western United States

Colin F. Williams and Jacob DeAngelo

U.S. Geological Survey, Menlo Park CA

Keywords

Heat flow, temperature, thermal conductivity, heat production, resource assessment, enhanced geothermal systems

ABSTRACT

The United States Geological Survey (USGS) has been conducting a series of geothermal resource assessments of the United States, and an important component of the ongoing work is evaluating the resource potential associated with the application of Enhanced Geothermal Systems (EGS) technologies, which involve the creation of productive geothermal reservoirs in low permeability rock units. Whereas conventional geothermal resources are formed due to hydrothermal fluid circulation that results from the convergence of high temperatures and high permeability, typically fracture permeability produced as a result of recent or active faulting, the exploitation of EGS resources involves the augmentation or creation of permeability *in situ*. Consequently the presence of elevated temperatures at drillable depths is the dominant factor controlling the quality of the resource, provided stimulation of the host rock is technically viable. For the 2008 provisional USGS assessment of EGS potential in the western United States, we calculated EGS resource values for those portions of the crust where estimated temperatures exceed 150 °C at depths less than or equal to 6 km. In this report we summarize the series of thermal modeling studies that formed the basis for the EGS assessment, studies which included evaluation of existing models, acquisition and interpretation of new data, development of alternative models for the distribution of temperature at depth in the crust, and formal analysis of the uncertainties associated with models for temperature at depth.

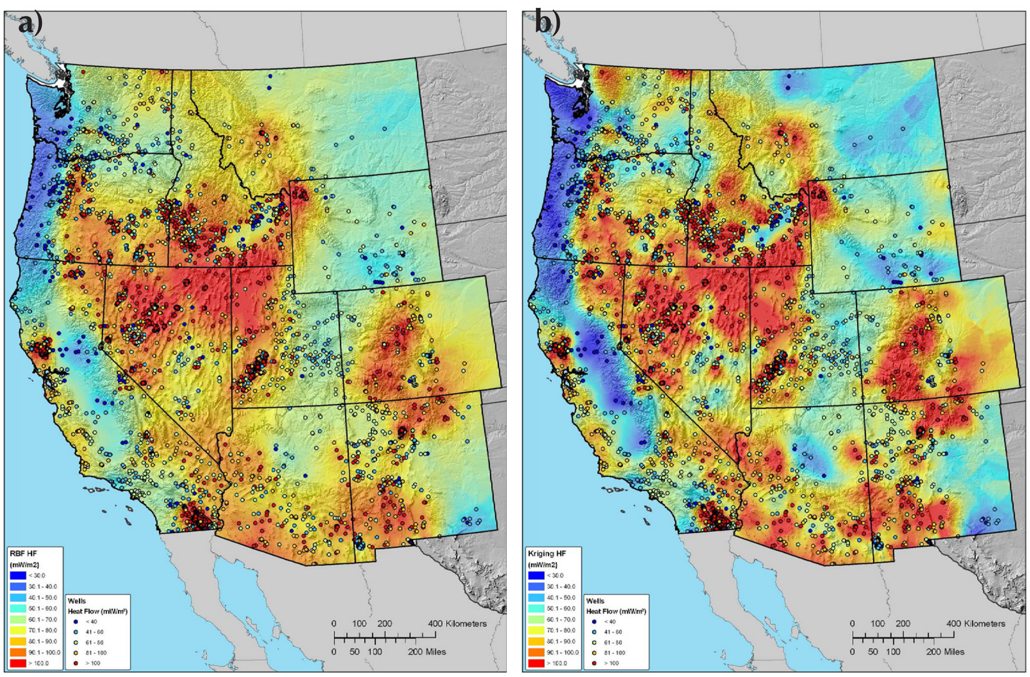

Figure 1. Maps showing heat flow surfaces in the Western United States derived from (a) smoothed regularized splines and (b) ordinary kriging.

Introduction

Under the mandate of the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, the United States Geological Survey (USGS) has been conducting a series of geothermal resource assessments of the United States. An important component of the 2008 assessment (Williams et al., 2008) as well as a focus of ongoing work is the power production potential of Enhanced Geothermal Systems (EGS) techniques, which involve the creation of producing geothermal reservoirs in low permeability rock units. Conventional geothermal resources depend upon hydrothermal fluid circulation that arises only with the convergence of high temperatures (due either to magmatism or other tectonic processes that elevate crustal temperature gradients) and permeability, typically fracture permeability produced as a result of active faulting. Because exploitation of EGS resources incorporates the augmentation or creation of permeability *in situ*, the presence of elevated temperatures at drillable depths is the dominant factor controlling the quality of the resource.

Under the assumption of successful implementation of EGS technology, provisional estimates of EGS electric power resource potential in the western United States, where high crustal heat flow is most favorable for EGS development (Figure 1), were included in the recent USGS geothermal resource assessment (Williams, et al., 2008). In this assessment, models for the extension of geothermal thermal energy recovery techniques into regions of hot but low-permeability crust down to a depth of 6 km yield an estimated mean electric power resource on private and accessible public land of approximately 520,000 MWe, which is similar to the resource estimate reported by an DOE-sponsored panel convened by the Massachusetts Institute of Technology (MIT) (Tester et al., 2006). This is nearly half of the current installed electric power generating capacity in the United States and an order of magnitude larger than the conventional geothermal resource. As part of the ongoing assessment efforts, the USGS has been investigating the factors that influence the potential development of EGS technology, and a critical element in EGS resource assessment is quantifying the distribution of temperature at exploitable depths. In this report we summarize analyses of heat flow measurements in the western United States applied in the 2008 assessment, describe models for estimating temperature at depth from heat flow, and discuss uncertainties associated with the estimates.

Heat Flow

With the lower temperature bound of 150 °C applied in both the 2008 USGS and 2006 MIT assessments, the depths of interest for EGS development outside of the shallow, high-temperature margins of geothermal systems are generally greater than 3 km. Except for those portions of sedimentary basins exploited for petroleum production, there are few boreholes reaching depths greater than 3 km, with essentially none as deep as 6 km, the maximum depth for the EGS resource in the 2008 USGS assessment. As a result of these limited opportunities for direct measurement of temperature at depth, evaluation of the thermal resource base in the western United States requires downward continuation of shallow conductive heat flow measurements. In this section we outline the approach employed in the 2008 assessment to quantify conductive heat flow in the western United States.

Heat flow measurements in the western United States are characterized by irregular spacing and variable accuracy. Uncertainties are reported for some measurements (e.g., Sass et al., 2005) but not for others (e.g., Lachenbruch and Sass, 1980), and the methods employed in the uncertainty calculations are not always consistent. At the most basic level, the vertical component of crustal heat flow (q) is simply the product of the vertical temperature gradient and the thermal conductivity of the rock (λ) in which the temperature gradient is measured, expressed as

$$q = \lambda \frac{\partial T}{\partial z} \tag{1}$$

The thermal conductivity of rocks can be measured in the laboratory to an accuracy of better than 5% (e.g., Sass et al., 1971), and the uncertainty in the measured temperature gradient can be significantly less than 1%, which suggests that individual heat flow measurements uncertainties can be reduced to less than ±5%. However, these uncertainties reflect the performance of the laboratory and borehole logging equipment, not the epistemic uncertainty associated with the question of whether these measurements accurately represent background crustal heat flow and can be used to estimate temperature at depth. Even in the best of circumstances, with high precision equilibrium temperature logs and numerous samples for thermal conductivity measurements, heat flow determinations have to account for a large number of potential disturbances, such as thermal refraction, topography, sedimentation or erosion, conductive transients, and shallow groundwater flow. Although accurate corrections can be applied when these effects are recognized and quantifiable, in many cases the relevant information is unavailable or only sufficient to place approximate bounds on the magnitude of the disturbances.

The uncertainties associated with estimates of heat flow at significant distances away from measurements are more difficult to constrain, in part because of variable uncertainty in the measurements themselves, in part because of the irregular spatial distribution of the measurements, in part because of the incompletely characterized role of geologic processes and rock properties in controlling the spatial variation of heat flow, and in part because of potential variations in results due to contrasting choices in approaches to interpolating and contouring the data. For example, Blackwell and Richards (2004) applied a mixture of automated and manual contouring to their selected heat flow dataset, having contour lines follow physiographic boundaries in areas of limited data coverage and removing measurements that conflicted with their preferred interpretations regarding the deeper crustal thermal regime.

In order to provide a more comprehensive examination of uncertainties associated with crustal temperature estimates we developed alternate estimates of the distribution of heat flow in the western United States, augmenting the dataset used by Blackwell and Richards (2004) with more recently published heat flow measurements (e.g., Sass et al., 2005; Williams and Sass, 2006). Two representative heat flow surfaces are shown in Figure 1, along with the associated measurements. Figure 1a shows the map resulting from a radial basis function fit of smoothed regularized splines to the data. Figure 1b shows the surface derived from the same data set using ordinary kriging. In both mapping approaches values below 30 mW/m^2 located outside of the Sierra Nevada Mountains of California, which are characterized by unusually low conductive heat flow (Lachenbruch, 1968), were filtered out of the dataset to eliminate values depressed by shallow groundwater flow. Similarly, high heat flow values were limited to 120 mW/m^2 in order to minimize the influence of anomalously high heat flow associated with hydrothermal systems. The smoothed radial basis function surface is representative of a class of surface interpolation techniques that highlight regional averages (~100 km in wavelength) rather than local patterns whereas the kriging surface is more responsive to local variability. Differences between the two surfaces exceed 10 mW/m^2 in places, but the average heat flow over the entire region encompassed by the 11 western states is essentially the same for the two, 74.9 mW/m^2 for the radial basis function surface and 73.4 mW/m^2 for the kriging surface.

With the exception of the imposed upper and lower limits on the heat flow measurements described above, the surfaces shown in Figure 1 are entirely data-driven rather than modified to align contour lines with the boundaries of physiographic provinces as done by Blackwell and Richards (2004). At this time it is not clear which approach provides the best overall representation of the true pattern of conductive heat flow in the western United States. The mapping techniques described in this report and applied in the 2008 assessment were adopted primarily to explore alternative interpretations and better quantify the uncertainties associated with estimated temperatures at depth in the crust. As a geostatistical approach to surface analysis, the kriging analysis includes a spatial estimate of the standard error, which serves as a measure of uncertainty relative to the mean data value (Lloyd and Atkinson, 2001). A map of this standard error surface (Figure 2) indicates that in regions lacking heat flow measurements the standard error increases by values ranging from 10 to 15 mW/m^2, approximately 15 to 20% of the mean value for the selected heat flow dataset of 73.4 mW/m^2.

In one large region, the eastern portion of the Snake River Plain in Idaho, there is some evidence (Brott et al., 1981) that low to moderate values of measured heat flow reflect the thermal influence of large-scale groundwater flow rather than background conductive thermal conditions. Although the magnitude of the cooling effect of the regional groundwater flow is uncertain, the USGS heat flow and subsurface temperature analysis applied in the assessment incorporated both the high heat flow interpretation for the Snake River Plain (Figure 3) and the data-driven interpretation shown in Figure 1, with equal weight assigned to each.

Models for Temperature at Depth

Assuming conductive thermal equilibrium in the upper crust and predominantly vertical conductive heat flow, the relationship between temperature and heat flow for a temperature-dependent thermal conductivity can be expressed as

$$\frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right] = -A(z) + \rho C\frac{\partial T}{\partial z} \tag{2}$$

where ρ is density, C heat capacity, and A is the radiogenic heat production. The solution of Equation 2 for the variation of temperature with depth depends on the distribution of heat production and thermal conductivity with depth, as well as the dependence of thermal conductivity with temperature. Many models apply a constant thermal conductivity in the basement with an exponential decrease of radiogenic heat production with depth (e.g., Blackwell et al., 2007; Diment et al., 1975), which is derived from an observed linear relationship between heat flow and near-surface heat production. This results in a variation of temperature with depth given by

$$T(z) = [q_r z + D^2 A_0 (1 - e^{-z/D})] / \lambda \tag{3}$$

where q_r is the reduced (or "mantle") heat flow, A_0 is the surface radiogenic heat production, and D is the scaling depth for the exponential decrease in radiogenic heat production with depth. However, systematic analyses of heat flow measurements in the western United States have only established the validity of this relationship in the Sierra Nevada batholith (Lachenbruch, 1968; Lachenbruch and Sass, 1977) and part of the Rocky Mountains (Decker et al., 1988). The heterogeneous composition of the upper crust in the western United States is more consistent with a constant value for A in the upper 6 km of the crust as a more reasonable approximation, provided variations in this average value are incorporated in the uncertainty analysis. In either case, as discussed below, the differences between the two models are small unless extreme values of A are introduced.

A more significant source of variation in Equation (2) is the sensitivity of thermal conductivity to temperature. As noted by Birch and Clark (1940), the thermal conductivity of quartz-rich rocks decreases with increasing temperature, with a model fit to thermal conductivity measurements on a variety of

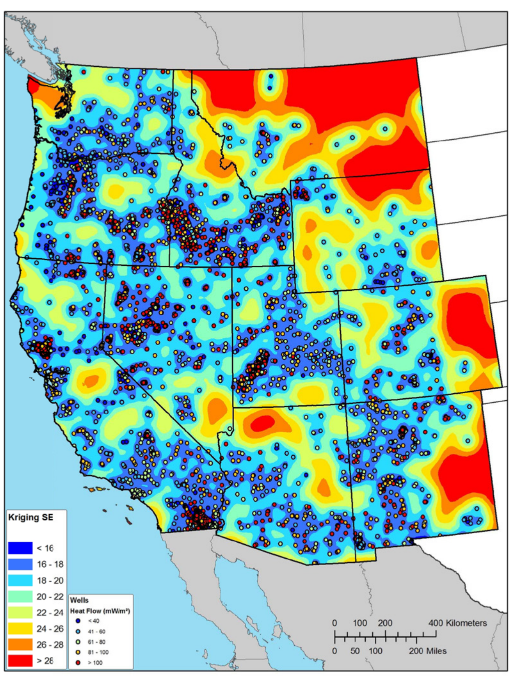

Figure 2. Map showing the variation in the kriging standard error distribution for the model shown in Figure 1a.

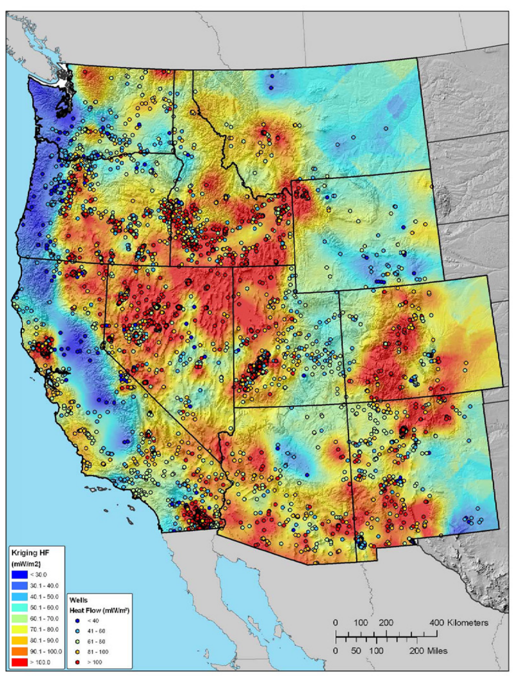

Figure 3. Map showing impact assumption of high heat flow in the Snake River Plain region on the heat flow map of the western United States.

igneous, metamorphic, and low-porosity sedimentary rocks giving the relationship

$$\lambda(T) = \frac{\lambda_0}{a + bT} \tag{4}$$

where λ_0 is the thermal conductivity at a temperature of 0 °C, a and b are constants (a=1.0 and b=0.0024-0.0052/ λ_0), and T is the temperature in °C. According to Williams (1996), for conductive heat flow in a crustal layer of constant heat production A, surface heat flow q_s, and thermal conductivity given by Equation (3), temperature varies with depth z according to

$$T(z) = \frac{1}{b} \cdot [\exp(c_1 z - c_2 z^2 + c_3) - a] \tag{5}$$

where $c_1 = bq_s/\lambda_0$, $c_2 = bA/2\lambda_0$, and $c_3 = \ln(a + bT_s)$. Implementation of these equations for T(z) requires estimates of thermal properties, which are discussed in the next section.

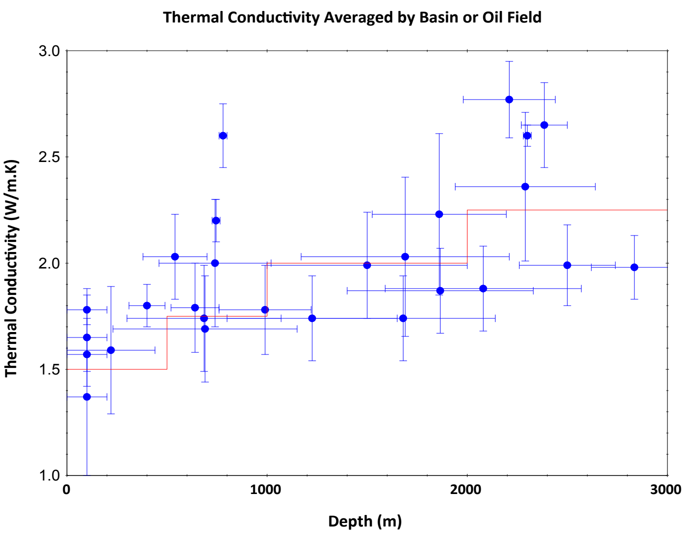

Figure 4. Plot showing distribution of thermal conductivity with depth from sedimentary basins in California and Nevada.

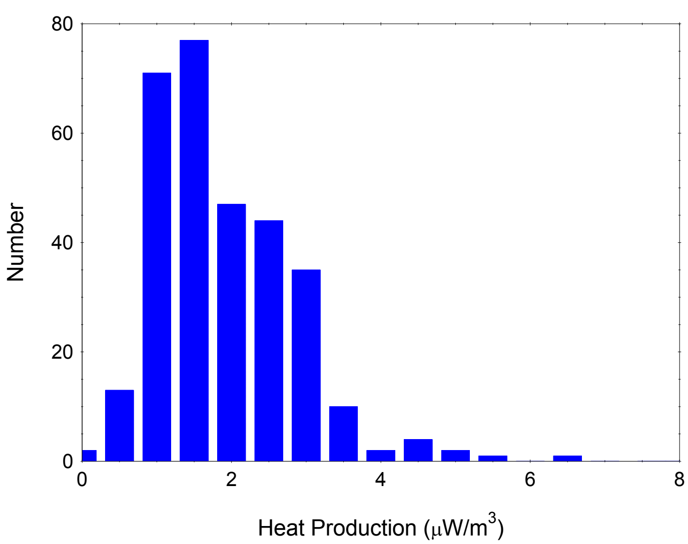

Figure 5. Histogram of radiogenic heat production measurements in California, Nevada and Oregon (Munroe and Sass, 1974).

Thermal Conductivity and Radiogenic Heat Production

Provided near-surface heat flow measurements are accurate and representative of thermal conditions at the depth of interest, the major source of uncertainty in any model for temperature at depth is the thermal conductivity, which can span a wide range of values due to variations in both mineralogy and porosity (e.g., Clauser, 2006). Representative averages for the room temperature thermal conductivity of common basement rock types found in the western United States are approximately 2.9 W/m.K (Clauser, 2006; Munroe and Sass, 1974). Crustal radiogenic heat production has been measured at a number of sites in the western United States, and Figure 5 shows the results of a compilation of measurements from Munroe and Sass (1974). The mean value for heat production from this set of measurements is 1.89 μW/m², with a standard deviation of 0.95. In the application of the Equation 3 temperature model by Blackwell et al. (2007), the western United States is divided in regions of q_r equal to either 30 or 60 mW/m². Some local variations of surface heat flow mapped by Blackwell et al. (2007) (1) exceed 70 mW/m² in regions where q_r is assumed to be 30 mW/m² and (2) fall near or below 60 mW/m² in regions where q_r is assumed to be 60 mW/m². In case (1) A is required to be either on the order of 4 μW/m³, and unusually high value, and in case (2) A is required to be either near or below zero. Such extremes are avoided by incorporating a constant mean value of A with associated uncertainties.

The thermal conductivity of sedimentary rocks in the western United States is significantly lower. Figure 4 shows a compilation of conductivity measurements from basins in California and Nevada along with a corresponding model for the variation in thermal conductivity with depth that is derived from grouping the measurements by basin (Munroe and Sass, 1974; DeRito et al., 1989; Williams et al., 1994; Sass et al., 2005). The general increase in thermal conductivity with depth is primarily a function of decreasing porosity with in some cases secondary effects due to changes in mineralogy with increasing temperature (e.g.,

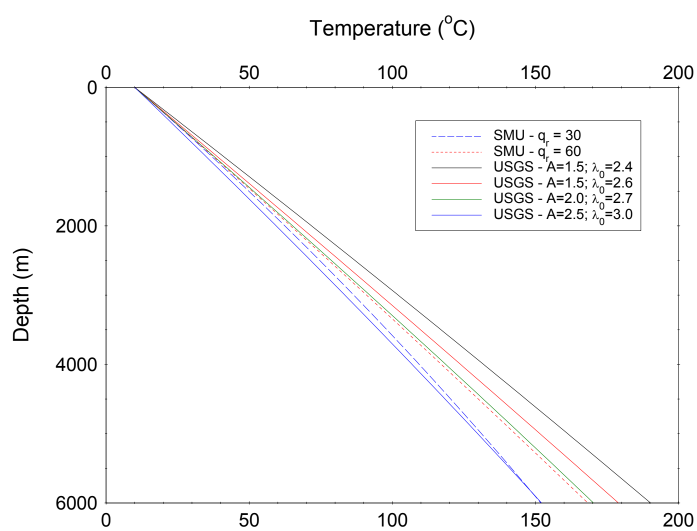

Figure 6. Comparison of USGS temperature-depth models derived from Equation 5 with models presented by Blackwell et al. (2007), for a near-surface heat flow of 75 mW/m².

Williams et al., 1994). The challenge in incorporating the thermal influence of sedimentary basins is that the spatial variation of basin depths is poorly characterized. Based on recent digital compilations of regional geologic mapping (Garrity and Soller, 2009; Soller et al., 2009), Quaternary and Tertiary sediments comprise more than 50% of the surface cover in the 11 states included in this study. Frezon et al. (1983) developed a regional compilation of sediment thickness for the major basins of the western United States relying primarily on information from oil and gas drilling, and we incorporated the thermal effects of these basins into the model using the layered conductivity structure shown in Figure 4. This compilation (as well as the equivalent AAPG study used by Blackwell et al., 2007) is relatively limited in resolution and does not cover the smaller basins of the Great Basin or the Mojave-Sonoran Desert.

Temperature Maps and Uncertainties

Based on the general observations described above regarding thermal conductivity and radiogenic heat production, we prepared a series of temperature maps for the western United States at 1 km depth intervals from 3 km to 6 km using Equation 5. The results incorporate 4 basic sets of model parameters: Model 1 with A=2.5 $\mu W/m^3$ and λ_0 = 3.0 W/m.K, Model 2 with A=1.5 $\mu W/m^3$ and λ_0 = 2.4 W/m.K, Model 3 with A=2.0 $\mu W/m^3$ and λ_0 = 2.7 W/m.K, and Model 4 with A=1.5 $\mu W/m^3$ and λ_0 = 2.6 W/m.K. Models 1, 2 and 3 reflect the likely range of average thermal conductivity and heat production values in the upper crust of the western United States, with Model 4 developed to cover those circumstances in which shallow cover by sediments outside of major basins or low conductivity basalt flows add an insulating effect to the temperatures in the upper crust. Temperature profiles derived from these models for a near-surface heat flow of 75 mW/m^2 are shown in Figure 6, along with equivalent curves from Blackwell et al. (2007) for the two cases studied in their paper of q_r = 30 and 60 mW/m^2. The USGS temperature models span a range of approximately ±12% relative to the predicted value from Model 3 of 170 °C. Maps of the estimated temperatures at a depth of 6 km in the western United States are shown in Figure 7 for smoothed regularized spline interpolation examples in which the heat flow from the Snake River Plain is left uncorrected. The maps illustrate the resulting spatial range of variation in the resulting temperature estimates from these four models.

In order to further evaluate the uncertainties associated with these models, we estimated uncertainties in temperature as a function of the variables A, λ_0, and q_s using the error analysis relationship

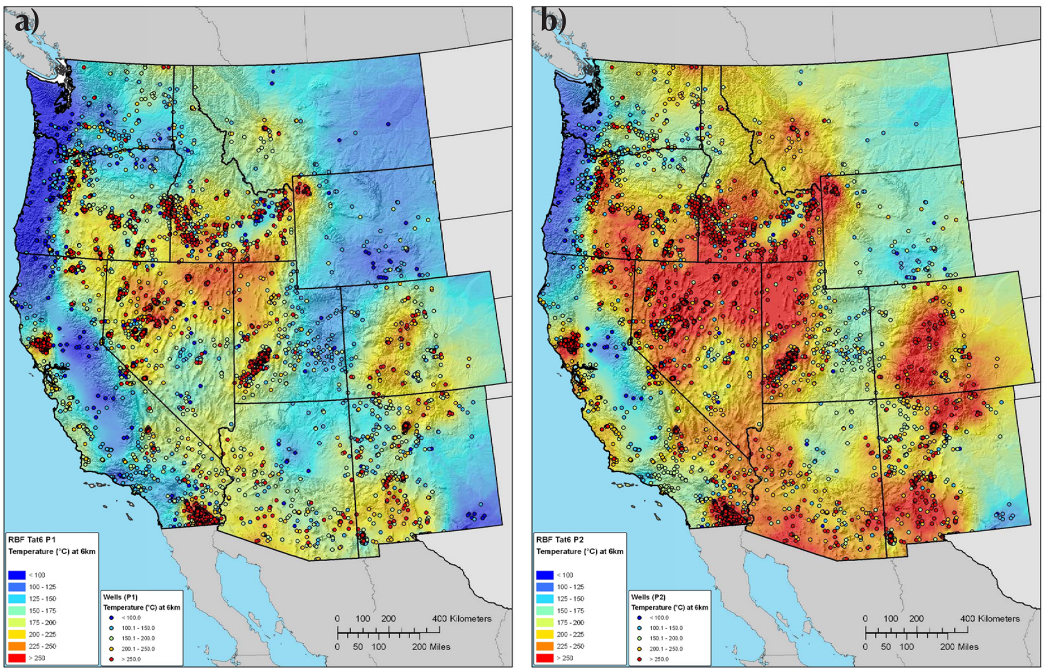

Figure 7. Maps showing distribution of estimated temperatures at a depth of 6 km for each of the four models presented in the text, with (a) through (d) corresponding to Models 1 through 4.

$$\delta T = \sqrt{\left(\frac{\partial T}{\partial q_s}\delta q_s\right)^2 + \left(\frac{\partial T}{\partial \lambda_0}\delta\lambda_0\right)^2 + \left(\frac{\partial T}{\partial A}\delta A\right)^2} \tag{6}$$

where δT, δq_s, $\delta\lambda_0$, and δA represent the uncertainties in the each of the respective quantities. Of the various factors, the influence of uncertainty in surface heat flow is by far the largest, and Figure 8 shows the results of Equation 6 evaluated for surface heat flow uncertainties ranging from 5% (essentially the best possible case) to 20% (representative of regions with sparse and/or highly uncertain measurements) for models with a mean λ_0 of 2.7 W/m.K and an uncertainty of ±0.3 W/m.K, and with a mean A of 2.0 μW/m^3 and an uncertainty of ±0.5 μW/m^3. The associated uncertainty in the temperature at 6 km ranges from approximately 12% to approximately 24%, with some modest variation depending on the mean value of heat flow. For most of the western US, uncertainties in heat flow are probably on the order of 10 to 15% (see Figure 2), which in turn indicates that uncertainties for the temperature at 6 km are on the order of 15 to 20%, significantly larger than the 10% estimated by Blackwell et al. (2007).

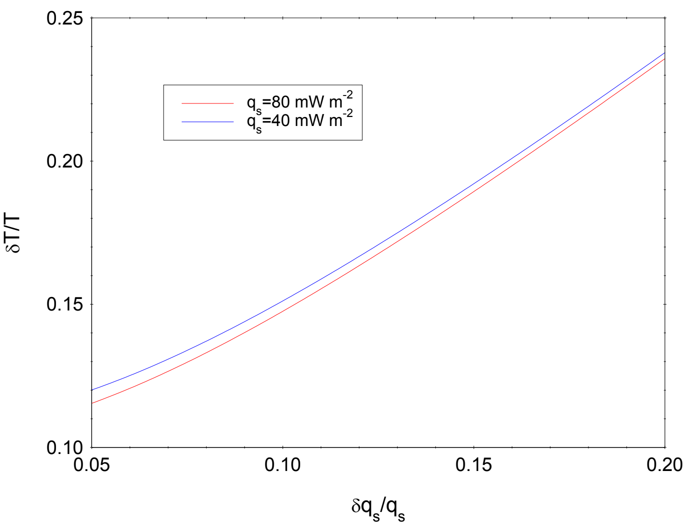

Figure 8. Results of analysis of potential uncertainties associated with estimates of temperature at a depth of 6 km due to variations in the uncertainty in surface heat flow.

Summary

In this report we summarize the series of thermal modeling studies that formed the basis for the 2008 provisional USGS assessment of EGS potential in the western United States, studies which included evaluation of existing models, acquisition and interpretation of new data, development of alternative models for the distribution of temperature at depth in the crust, and formal analysis of the uncertainties associated with models for temperature at depth. As noted by Williams et al. (2008), the basic results indicate that broad regions of western United States are favorable for EGS development, although significant uncertainties remain. The resource estimates incorporated both USGS models for temperature at depth and those presented by Blackwell et al. (2007). Although these models incorporate different assumptions regarding the spatial variation of heat flow and the thermal properties of the upper crust, the results are similar, with the USGS models spanning a larger range of potential temperatures. We believe this larger range of temperatures better reflects the uncertainties in estimating temperature at depth, which are generally on the order of 15 to 20% and could be higher if there are crust is not purely conductive or in thermal equilibrium with temperatures at the surface.

Acknowledgements

We acknowledge the helpful and insightful reviews provided by J. Glen, J.O. Kaven, J. Palguta, and J. Pritchett. The work described in this paper was supported by the USGS Energy Resources Program and the DOE Geothermal Technologies Program under Interagency Agreement DE-EE0001501.

References

Birch, A.F., and H. Clark, 1940, The thermal conductivity of rock and its dependence on temperature and composition, American Journal of Science, v. 238, p. 529-558.

Blackwell, D.D., and M.C. Richards, 2004, Geothermal Map of North America, American Association of Petroleum Geologists.

Blackwell, D.D., P.T. Negraru, and M.C. Richards, 2007, Assessment of the Enhanced Geothermal System resource base of the United States, Natural Resources Research, v. 15, n. 4, p. 283-308.

Brott, C.A., D.D. Blackwell, and J.P. Ziagos, 1981, Thermal and tectonic implications of heat flow in the eastern Snake River Plain, Idaho, Journal of Geophysical Research, v. 86, n. 12, p. 11709-11734.

Clauser, C., 2006, Geothermal energy, in Heinloth, K., ed., Renewable Energies, Subvol. C, Vol. 3, Group VIII, Advanced Materials and Technologies, Landolt-Bornstein, Springer Verlag, Berlin, p. 480-595.

Decker, E.R., H.P. Heasler, K.L. Buelow, K.H. Baker, and J.S. Hallin, 1988, Significance of past and recent heat flow and radioactivity studies in the southern Rocky Mountains region, Geological Society of America Bulletin, v. 100, n. 12, p. 1851-1885.

De Rito, R., A. H. Lachenbruch, T.H. Moses Jr., and R.J. Munroe , 1989, Heat flow and thermotectonic problems of the central Ventura Basin, southern California, Journal of Geophysical Research, v. 94, n. B1, p. 681-699.

Diment, W.H., T.C. Urban, J.H. Sass, B.V. Marshall, R.J. Munroe, and A.H. Lachenbruch, 1975, Temperatures and heat contents based on conductive transport of heat, in White, D.F., and D.L. Williams, eds., Assessment of Geothermal Resources of the United States – 1975, U.S. Geological Survey Circular 726, p. 84-103.

Frezon, S.E., T.M. Finn, and J.H. Lister, 1983, Total thickness of sedimentary rocks in the conterminous United States, U.S. Geological Survey Open-File Report 83-920.

Garrity, C.P., and D.R. Soller, 2009, Database of the Geologic Map of North America, U.S. Geological Survey Data Series 424 [http://pubs.usgs.gov/ds/424/].

Lachenbruch, A.H., 1968, Preliminary geothermal model for the Sierra Nevada, Journal of Geophysical Research, v. 73, n. 22, p. 6977-6989.

Lachenbruch, A. H., and J.H. Sass, 1977, Heat flow in the United States and the thermal regime of the crust, *in*, Heacock, J.G., ed., The nature and physical properties of the earth's crust: Am. Geophys. Union Geophys. Mon. 20.

Lachenbruch, A.H., and J.H. Sass, 1980, Heat flow and energetics of the San Andreas fault zone, Journal of Geophysical Research, v. 76, n. 26, p. 6376-6413.

Lloyd, C.D., and P.M. Atkinson, 2001, Assessing uncertainty in estimates with ordinary and indicator kriging, Computers and Geosciences, v. 27, p. 929-937.

Munroe, R.J., and J.H. Sass, 1974, Basic heat-flow data from the United States, U.S. Geological Survey Open-File Report 74-9, 456p.

Sass, J.H., A.H. Lachenbruch, R.J. Munroe, G.W. Greene, and T.H. Moses, Jr., 1971, Heat flow in the western United States, Journal of Geophysical Research, v. 76, n. 26, p. 6376-6413.

Sass, J.H., S.S. Priest, A.H. Lachenbruch, S.P. Galanis, Jr., T.H. Moses, Jr., J.P. Kennelly, Jr., R.J. Munroe, E.P. Smith, F.V. Grubb, R.H. Husk, Jr., and C.W. Mase, 2005, Summary of supporting data for USGS regional heat-flow studies of the Great Basin, 1970-1990, U.S. Geological Survey Open-File Report 2005-1207, [http://pubs.usgs.gov/of/2005/1207]

Soller, D.R., M.C. Reheis, C.P. Garrity, and D.R. Van Sistine, 2009, Map database for surficial materials in the conterminous United States, U.S. Geological Survey Data Series 425 [http://pubs.usgs.gov/ds/425/].

Tester, J. and others, 2006, The Future of Geothermal Energy, Massachusetts Institute of Technology, Cambridge, Massachusetts, 374p.

Williams, C.F., 1996, Temperature and the seismic-aseismic transition: observations from the 1992 Landers earthquake, Geophysical Research Letters, v. 23, n. 16, p.2029-2032.

Williams, C.F., S.P. Galanis, Jr., F.V. Grubb, and T.H. Moses, Jr., 1994, The thermal regime of the Santa Maria Province, California, U.S. Geological Survey Bulletin 1995-f,g, p. F1-25.

Williams, C.F. and J.H. Sass, 2006, Heat flow in Railroad Valley, Nevada, and implications for geothermal resources in the south-central Great Basin, Transactions, Geothermal Resources Council, v. 30, p.111-116.

Williams, C.F., M.J. Reed, R.H. Mariner, J. DeAngelo, and S.P. Galanis, Jr., 2008, Assessment of moderate- and high-temperature geothermal resources of the United States, U.S. Geological Survey Fact Sheet 2009-3082, 4p.