Proposed Reliability Code for Heat Flow Sites

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Keywords

Heat flow, thermal conductivity, quality, reliability, bottom-hole temperature, well logging

ABSTRACT

Heat flow is one of the primary variables used to assess the geothermal resource of a region or a site specific project. Various standards for quality codes used since the 1970s, primarily focused on conventional heat flow sites with equilibrium temperature logs, thermal conductivity measurements from samples in or near the well, and appropriate data corrections. Bottom-hole temperature data from oil/gas wells have been in existence for decades, but are rapidly increasing in use for geothermal resource assessments. Today's geothermal maps produced by various groups, such as the SMU Geothermal Laboratory, have more sites from oil/gas wells than from traditional heat flow sites. New standards for a quality/reliability code are proposed incorporating the past systems with increased parameter definition. These standards for use in the new National Geothermal Data System will be capable of being applied consistently to both traditional and bottom-hole temperature sites. A method encompassing weighted values for each of the primary parameters used to determine heat flow are concatenated to rank the site reliability using an automated tool. The proposed new reliability tool allows the user to compare heat flows from different data types and calculation methods to determine data reliability for each heat flow site with a consistent system.

Introduction

Heat flow is simply the amount of thermal energy (heat) transferred through a medium (rock). The primary inputs for calculating heat flow include temperature gradient and thermal conductivity of the rock formations. Heat flow is important in assessing a region's geothermal resource; however, the heat flow calculation is not trivial. A number of authors have published site quality rating systems using a similar set of codes (Table 1) (Lachenbruch and Sass, 1977; Pollack and Chapman, 1977; Balling et al., 1981; Blackwell et al., 1991). During the 1970s and 80s the collection of well data from oil and gas wells made it possible to work with larger sets of data and quality codes were devised for bottom-hole data (Vacquier, 1984; Eggleston and Reiter, 1984; AAPG, 1994; Rollin, 1995). Recently the use of bottom-hole temperature data from oil/gas wells as a research tool has exponentially increased in developing regional-scale geothermal resource assessments (Blackwell et al., 2011; Crowell and Gosnold, 2011; Dingwall and Blackwell, 2011; Williams and Blackwell, 2011). There are now more heat flow sites from oil/gas wells than all the conventional (or equilibrium) heat flow sites (sites with equilibrium temperature logs, core and/or cuttings samples and appropriate corrections such as for terrain effects) collected in the United States over the past 50 years. Changing data types, calculation methods, and user

Table 1. Examples of Existing Quality Ranking of Heat Flow Determinations.

Global Heat Flow Database classification (Jessop et al., 1976)	A = >10% heat flow error with two or more gradient measurements B = 10 to 19.9% heat flow error with one gradient measurement and/or large uncertainty in conductivity C = 20%+ heat flow error and/or only one temperature measurement
Commission of the European Communities (Balling et al., 1981) Note: the quality included the depth interval, the number of values to calculate heat flow (gradients) and the variation in heat flow over a small area. The conductivity values received a separate quality ranking.	A = heat flow measurement variation >10% B = heat flow measurement variation between 10 and 19.9% C = heat flow measurement variation from 20 to 30%.
SMU Heat Flow Quality Criteria (Blackwell et al., 1991) Note: Original codes used for Geothermal Map of North America published as part of the DNAG Map set.	A = High Quality: >100 meters with > 50 meter linear gradient B = Medium Quality: >50 meters; some problems C = Poor Quality: Shallow; Isothermal D = Check Again, not used in resource assessment X = No Hope, not used in resource assessment G = Geothermal System, not used in regional mapping

understanding necessitate reexamination and updating of the quality codes.

The quality codes in Table 1 represent the focus on error estimation for each site. For a specific conventional heat flow site the error is based on both absolute error (the degree of accuracy of the measurement tools) and the relative error (the estimation of the systematic errors including the absolute error and applied corrections). With the BHT data, determining a constraint on systematic errors is not possible because of the multiple variables, including drilling method, temperature collection method, temperature correction method, thermal conductivity determination method, etc. Because of this the emphasis is now on both error and repeatability of a site heat flow value, thereby determining the site reliability. In order for BHT data to be given a quality code based on absolute error, as done in the past, a conventional heat flow site is necessary within the geologically relevant area. It is rare to have such a combination within a sedimentary basin producing oil/gas resources; just as it is rare to have numerous BHT sites in the vicinity of conventional heat flow sites, since they are typically in basement rock settings.

Table 2. The proposed parameter weighting system for *conventional* heat flow sites to be used in conjunction with the National Geothermal Database System.

Parameter	Qualification	Max Value	Site Reliability	
Temperature				
Total depth of temperature measurements to 1000 m *.01	≤1000	**10**	yes =	10
Thermal equilibrium established or Shut-in time of well ≥ 48 hours	if yes = 1 if no = 0	**1**	yes =	1
Temperature reading spacing or # of measurements	# of temps ≤4	**4**	yes =	4
			Sub Total	**15**
Gradient of Temperature				
Length of conductive gradient (depth start to end with max value of 100 m to count)*.1	≤100	**10**	yes =	10
example gradient based on depth between 75m - 150 m = 75 (reliability = 7.5)				
example gradient based on depth between 75m - 250 m = 175 (still a reliability of 10)			Sub Total	**10**
Thermal Conductivity/Lithology				
Conductivity measurements on core/cutting (same well)		**7**	yes =	7
# of conductivities per well site * 1	# of measurements ≤3	**3**	yes =	3
Well log data from site of lithology and/or gamma ray, etc.	if yes = 6	**6**	yes =	
Same formation in geologic area	if yes = 5	**5**	yes =	
Similar rock type	if yes = 3	**3**	yes =	
			Sub Total	**10**
Heat Flow Value				
Correction: Terrain/Climate/Refraction/Drilling disturbances/ Ground changes	if considered = yes	**6**	yes =	6
≤ 5% Error percentage of heat flows within well site		**6**	yes =	6
≤10% Error percentage of heat flows within well site		**4**	yes =	
< 5% of HF STDev of area wells within geologic relevant distance		**3**	yes =	3
≤ 20% of HF STDev of area wells within geologic relevant distance		**2**	yes =	
≤ 30% of HF STDev of area wells within geologic relevant distance		**1**	yes =	
			Sub Total	**15**
			Site Total	**50**

Parameters Considered

The previous quality codes used by the SMU Geothermal Laboratory (Blackwell and Steele, 1992) emphasized well depth, gradient interval, terrain correction, and percent of error in heat flow based on thermal conductivity and gradient (Table 1). The quality ranking mixed both evaluation of the site data quality, for broad scale mapping (A – C), along with the type of setting (G for temperature logs with overturns or extremely high gradients) and internal information related to the SMU Field Notes (D). With internet access, users from all educational backgrounds are using the heat flow data for a variety of purposes, often with little understanding of the nuances between the data quality rankings as described. When the new National Geothermal Data System (NGDS) comes online in 2013, even more users are expected to use heat flow for site evaluation. Realizing that users of the heat flow research community find the existing quality criteria somewhat confusing, it was clear that a more detailed, step-by-step (or parameter-by-parameter) rating would give increased understanding and value to the data.

In addition to increasing the level of detail for the specific parameters, the new reliability criteria must be capable of application for large datasets. Because the NGDS is being populated with data from many different agencies and projects, criteria easily applied to any dataset (past and future) will assist users in comparing all sites for quality and reliability. The quality rankings from the past are still included in the NGDS and are valuable, but the proposed new system is capable of calculating the reliability of site data automatically, adding a new additional code based on a weighting of given parameters for ease of comparison between conventional heat flow and BHT data heat flow sites.

The proposed method considers each of the key input parameters and provides a means to discriminate between high quality data from those with lower confidence and reliability. The process uses a weighting system for each of the variables used to determine the heat flow: gradient and thermal conductivity, as well as a weighting for applied corrections and site error calculations. Many factors are evaluated in the new heat flow reliability code as shown in Tables 2 and 3. The primary parameters are discussed in the following sections.

Temperature and Gradient

Temperature is usually the first parameter captured. How it was obtained directly effects the reliability attached to this parameter.

Table 3. The proposed parameter weighting system for *bottom-hole temperature* heat flow sites to be used in conjunction with the National Geothermal Database System.

Parameter	Qualifi-cation	Max Reliability Value	Site Reliability	
Temperature				
BHT Depth* .0025 up to 2000 m	≤2000	**5**	yes =	5
BHT Correction analyzed/applied (Type specified)		**4**	yes =	4
# of BHT intervals ≥ 4		**1**	yes =	1
			Sub Total	**10**
Thermal Conductivity/Lithology				
Measurements on core/cutting (same well)		**5**	yes =	5
Same formation		**4**	yes =	
Similar rock type		**2**	yes =	
Well log data (lithology, gamma, etc.)		**5**	yes =	5
Basin Cross-Section		**4**	yes =	
COSUNA		**3**	yes =	
Generalized Model		**1**	yes =	
			Sub Total	**10**
Heat Flow Value				
Correction for Terrain/Climate/Refraction analyzed	Reviewed?	**3**	yes =	3
# of Wells within ±0.080° (up to a value of 10)	# of wells * .2	**2**	yes =	2
< 5% HF Standard Deviation from Neighbors		**10**	yes =	10
≤10% HF Standard Deviation from Neighbors		**5**	yes =	
≤15% HF Standard Deviation from Neighbors		**2**	yes =	
>20% HF Standard Deviation from Neighbors		**-5**	yes =	
			Sub Total	**15**
			Site Total	**35**

a) The best case scenario is when temperature is acquired through high precision temperature logging of a well at equilibrium. There are wireline and slickline temperature probes, as well as fiber-optic cable techniques, for collecting distributed-temperature data. These tools are considered equally high quality for data collection (Wisian et al., 1998).

b) Temperature data may also be bottom-hole temperatures (BHTs) extracted from well log headers, primarily from the oil/gas industry. These BHT data are generally maximum reading thermometer measurements made during the course of collecting a suite of geophysical logs at the current drilled-to depth, so with each additional drilled section of a well there is a new "bottom-hole" temperature. For a specific well site, BHT measurements range from one to a few. However, during the life of that well, other logging may be completed that includes temperature, e.g., pressure-temperature logs run many times at multiple depth intervals and therefore have improved reliability for understanding the temperature in that well.

The well gradient (rate of temperature change over specified depth) often changes throughout a borehole, thus a shallow well may not have enough depth to overcome being effected by near surface conditions and therefore not accurately characterize the true site gradient. Consequently, the depth of the temperature reading is an important parameter. Regardless of the temperature measurement type, deeper measurements better constrain the mean geothermal gradient for the site. For temperatures from equilibrium logs, with no fluid flow up or down the borehole, the minimum depth for "normal" gradient conditions (20 to 30°C/km) is approximately 200 m. This is because of the difficulty in correcting shallower data for transient and steady state shallow conditions (Jessop et al., 1975). Wells with a depth of <200 m can be used but should be considered less reliable and even removed from mapping if there is not a consistent gradient of at least 50 meters and no terrain and/or climate correction (Roy et al., 1972; Gosnold et al., 2011). The deeper the temperature measurement the more reliable the heat flow value, especially when wells have multiple long gradient intervals. Although temperatures deeper than 1,000 m are possible and important for climate change variations, the majority of heat flow sites from equilibrium wells are less than 1,000 m deep (Chapman et al., 1984; Blackwell et al., 2011), so 1000 m is used as the depth which quality is maximized and deeper depths do not improve reliability.

Wells with a consistent gradient interval of >100 m have limited improvement in reliability; rather this reflects a consistency in the lithology influencing the thermal conductivity values. Multiple gradient intervals with related assigned/measured thermal conductivity values, do give additional improvement to the overall site heat flow value, with a calculated weighted average from the intervals. This improves the determined site heat flow value (Rollin, 1995).

BHT are currently very common in heat flow studies, yet they have been used in specific areas since the 1980s (Reiter and Tovar, 1982; Vacquier, 1984; Morgan, 2009; etc). With the only two parameters being the BHT and surface temperature to determine a gradient, accuracy of these temperatures is of prime importance. The thickness of each sedimentary basin is different as well as the depth to the oil and/or gas resource allowing for large variations in depth, temperatures and thermal conductivity. If possible, each basin needs to be reviewed separately for the reliability of the parameters. For example, Reiter and Tovar (1982) found BHT data in the Colorado Plateau have improved temperatures if deeper than 900 m, and in other basins where drilling into basement rock had heat flow values reliable at shallower depths (> 650 m). The amount of data scatter in the deeper wells diminishes around 2,000 m (Rollin, 1995; Crowell and Gosnold, 2011; Gosnold et al., 2011).

As mentioned above, the surface temperature is the common second variable for determining gradient with BHT data. Typically surface temperatures for the continental US fall between approximately 10 and 20°C (Gass, 1982). At depths below 3 km it was found temperature measurements in one oil/gas well could vary by up to 18°C over the life of a well because of production changes and tools used (Blackwell et al., 2010). Using the possible range in surface temperature of 10°C and the possible range in downhole temperature of 18°C as the maximum variability for determining a gradient, the depth where the fluctuation in gradient diminishes to approximately 1% based on the max/min changes is between 1,700 and 2,300 m depth (SMU Geothermal Laboratory Data, (Blackwell et al., 2011). Therefore, based on minimal gradient impact and reduced data scatter a depth of 2,000 m is assigned the maximum value for the reliability.

Temperature Corrections

Temperature corrections include drilling impact and circulation of fluids, paleoclimate changes, steepness of terrain, lake measurements, and temperature refraction induced by high conductivity contrast. These can all have impact on the value used for site temperature at depth. This becomes especially true at shallow depths of less than 200 m (Gosnold et al., 2011; Blackwell et al., 1980; Jessop et al., 1975) because of the increased percentage effect on gradient. Corrections may need to be made on both equilibrium temperature logs and BHT measurements. Temperatures from well log headers of oil/gas wells are expected to be especially impacted by the circulation of drilling fluids. There are numerous methods for correcting the temperature (Blackwell et al., 2011; Förster et al., 1997; Morgan, 2009). From the point of view of the reliability of a site, it is more important for the individual researcher to understand the geologic setting they are working in and apply an appropriate temperature correction than for a consistent correction to be applied across all data sets. Although the proposed code does not differentiate between the different correction types and/or methods, it does increase the site reliability if a correction was either applied or determined not applicable by the researcher.

Number of Temperature Measurements

It was determined that the amount of variability of heat flow from BHTs within one well is similar to the overall variability of the surrounding wells. Where data are scarce, a well that has multiple depth readings increases in reliability because of the ability to review the multiple gradients. Four intervals is the maximum number of intervals needed for the full reliability weighting in the proposed reliability code since equilibrium logs will have 100s of points, and BHTs will normally have 1 or 3 points. Thus, if four or more intervals are achieved, then the well can be reviewed for quality using the intervals of BHT, similarly to the many temperatures of an equilibrium log.

The speed of the temperature logging is more significant for "continuous" temperature logs rather than the temperature reading intervals (every 1 m, 5 m, 10 m) (Wisian et al., 1998). Ideally the log should be run downhole rather than uphole and at a speed slow enough that the temperature probe is near equilibrium. The rate and direction of logging, however, is not a parameter typically collected; therefore, the number of heat flow intervals is the criteria used to determine the reliability of the site.

A gradient that has no associated fluid movement within the borehole is considered useful. Therefore, a well that has a gradient interval considered isothermal, very low or negative would be noted and receive a lower quality and reliability code weighting.

Another factor that increases reliability is the length of time since circulation (TSC) of drilling fluid. Yet, an empirical relationship has not been made to correct a single point for a given time since drilling, therefore, at this time the reliability code does not include a weighting for TSC.

Lithology and Thermal Conductivity

For a conventional heat flow site, there is typically an equilibrium temperature log and either core or cuttings collected for thermal conductivity. Measured conductivity within one well normally differs with changes in the formations. Even within the same formation conductivity can vary up to 15% depending on the internal lithologic variations (Walsh and Decker, 1966; Beardsmore and Cull, 2001). Thermal conductivity will increase as a function of depth due to decrease in porosity and mineral changes; as temperatures rise, it will decrease (Birch and Clark, 1940; Beardsmore and Cull, 2001). Thus, with the possible variations in thermal conductivity samples within the same formation at various depths, the highest reliability is when samples are from the specific well site (Rollin, 1995; Walsh and Decker, 1966). If this is not possible, thermal conductivity measurements on the same formation at a different location are the next best sample source.

For many heat flow sites no direct measurement of the rock is possible for thermal conductivity; therefore, the only available value is derived from values for similar formations or rock types. Equilibrium sites usually have detailed lithology information, i.e., the rock type is determined from the well core/cuttings/logs. For BHT sites the lithology data are available from a detailed mud log or gamma log. If these are not available local or regional cross-sections are used for determining the formation/rock type for correlating the temperature and depth with thermal conductivity in the well. If the above options are not possible large-scale cross section such as the Correlation of Stratigraphic Units of North America (COSUNA) (AAPG, 1985; Blackwell et al., 2010) may be used.

Heat Flow

The percentage of heat flow error at a site builds from the absolute and systematic errors from the gradient and thermal conductivity parameters, to include heat flow methods and data density. The basic method of calculating heat flow is to use the thermal gradient of the well multiplied by the thermal conductivity of the rock formation. An example of a more detailed method is the Bullard plot, which compares rock resistance versus temperature. If thermal resistances (inverse of thermal conductivity) are correctly determined, data points should plot along a straight line. The slope of the line represents the heat flow and the intercept is the related surface temperature (Blackwell et al., 2010). When determining the site heat flow error percentage, other factors that need to be included are the corrections for the site variability. This comes from related information on the surface topography, geologic structure, and fluid movement.

Data Density

In comparing the heat flow of a well with neighboring wells, it is helpful if the surface and geologic conditions are considered, yet for application of the reliability code to changing data sets, this is not possible. In examining a basic, non-geologic standard radius that could be applied across the U.S. data, different data densities were analyzed. A comparison of radii of 0.20°, .08°, and 0.025° of latitude and longitude (approximately 300 km^2, 50 km^2 and 5 km^2 respectively) was done to determine how many sites were averaged and the significance of the standard deviation of those sites (Table 4). The standard deviation is for individual sites in comparison to the average for each group (cluster of neighboring sites) of wells within the different designated radius. The difference between the "Total Sites Averaged" and the initial number of sites (33,861) is the number of individual sites that did not have a neighbor close enough to be included in a group for the different radius dimensions.

Table 4. Comparison of radius sizes and the resulting data density of 33,861 sites.

Radius (decimal degrees)	**0.20°**	**0.08°**	**0.025°**
Total Sites Averaged	32,587	30,617	22,588
% of Total Sites	96%	90%	67%
# of Sites Density 2 to 5 pts	4,190 or 12%	15,038 or 44%	16,118 or 47%
# of Sites with STDev.s of ≤4 mW/m^2	20,598 or 61%	20,690 or 61%	16,680 or 49%

Typically, it is expected that the more sites averaged within the designated radius, the more accurate the comparison of the site heat flow to the group averaged heat flow value. Although there tend to be fewer sites averaged in a smaller area (i.e., ± 0.025° has 47% of the clusters with 2 – 5 wells averaged) the wells should have increased similarity in thermal conductivity and thus have similar heat flow values (Table 4; Figures 1-4). Whereas the largest radius area (i.e., ±0.20°) has more sites averaged per cluster (typically between 5 to 15, Figure 1). Between radii of 0.20° and 0.08° the data densities are different within the clustering, yet the overall individual site comparison within the grouped average has the same 61% of the sites had a standard deviation error of ≤4 *m*W/m^2, which for this data set is approximately 8 - 12% difference of the individual site values to the group average. Thus, although it is desirable to determine outliers with as many sites as possible, having at least one other site to check the heat flow against increases the reliability of the individual heat flow. This is shown by the decrease in sites (49%) having a low STDev from the averaged heat flow for the smallest radius of 0.025°, even though the majority of clusters were averages of 2 – 3 sites (Figure 3).

For the reliability code, if the STDev of a site is <5% of its cluster averaged heat flow it is considered highly reliable for heat flow (Figures 2-4). A comparison of site standard deviation (*m*W/m^2) to its group of neighbors, using two radii for size of latitude and longitude areas of 0.20° and 0.025°, shows that even as the number of sites averaged within an area increases the overall deviation is relatively the same for both radii (Figure 4).

When the percent of standard deviation is between 5 and 20% it is considered average in reliability. When the percent of standard deviation of the site heat flow is greater than 20%, the heat flow value is not plotted on regional-scale heat flow maps, and if it is greater than 30% it should be considered poor data quality and discarded or marked as anomalous heat flow. Sites with outliers need to be reviewed for data accuracy to determine if the temperature and/or thermal conductivity are wrong or if the site is truly an anomaly. Higher than expected heat flow sites may be related to real structural or lithological reasons for the anomalous values and therefore, with more research, could become possible geothermal exploration targets.

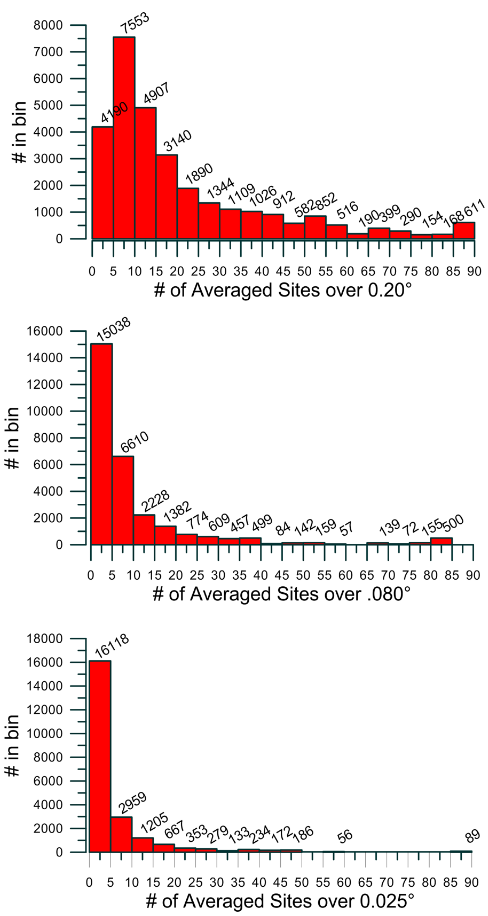

Figure 1. Histogram of number of sites used to generate group (neighboring clusters) averages for the different radii about a well.

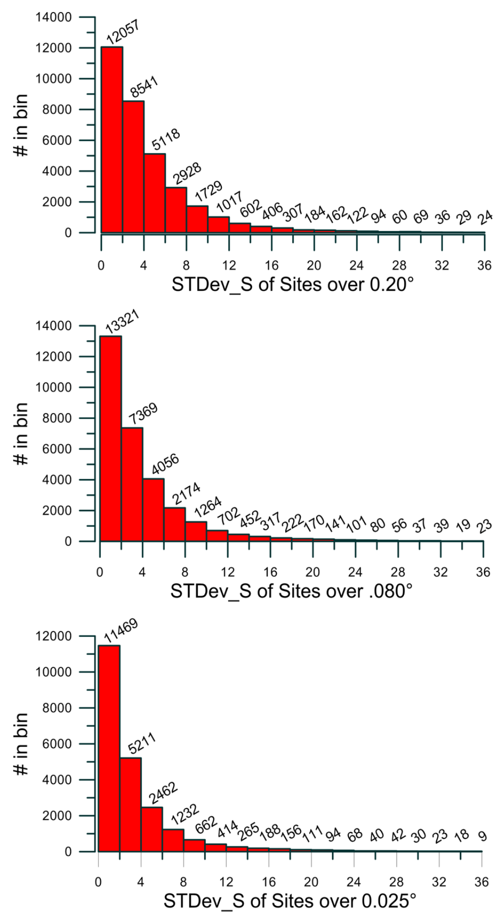

Figure 2. Histogram comparing the standard deviations (*m*W/m^2) of individual sites from the group average for the different radii about a well.

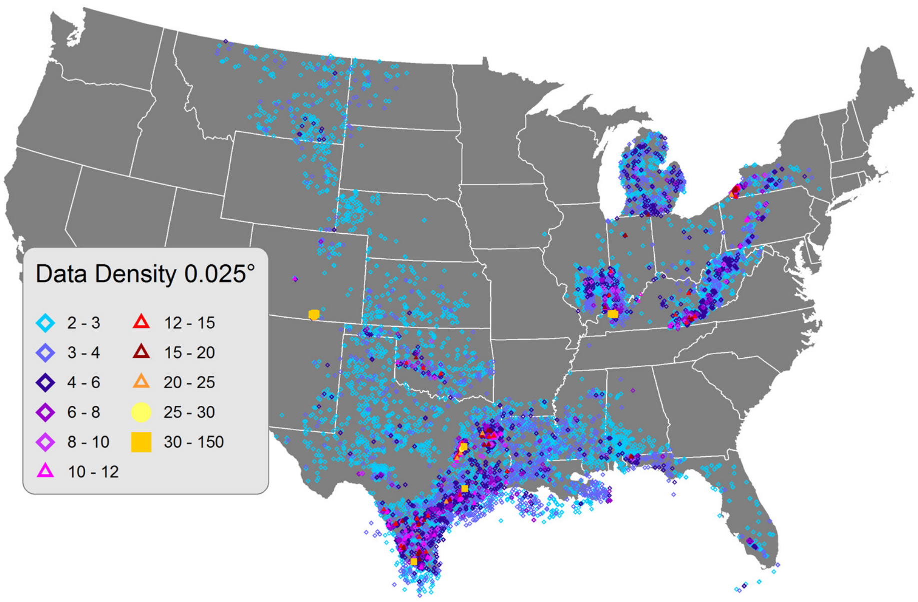

Figure 3. BHT site locations used for comparison of data density of averaged sites over a latitude and longitude radius of 0.025°. The single well sites are not shown on this map.

Conclusions

It is exciting to have so many new heat flow sites to work with on resource assessments. When evaluating the data it is of utmost importance to understand the level of accuracy for each parameter. Using this proposed new reliability code with weighted values offers the user a visual list of items to review and questions to ask about the data. For any heat flow site there will be assumptions made and biases induced through the methods and corrections applied to the raw data. Even the raw data have inherent flaws according to the method of collection. The ability to review large data sets and compare the existing heat flow sites with this new proposed system will allow future users a foundation to build their knowledge and increase the overall use of the heat flow data. The proposed reliability code is a work in progress and will undoubtedly continue to change and expand with new data being collected.

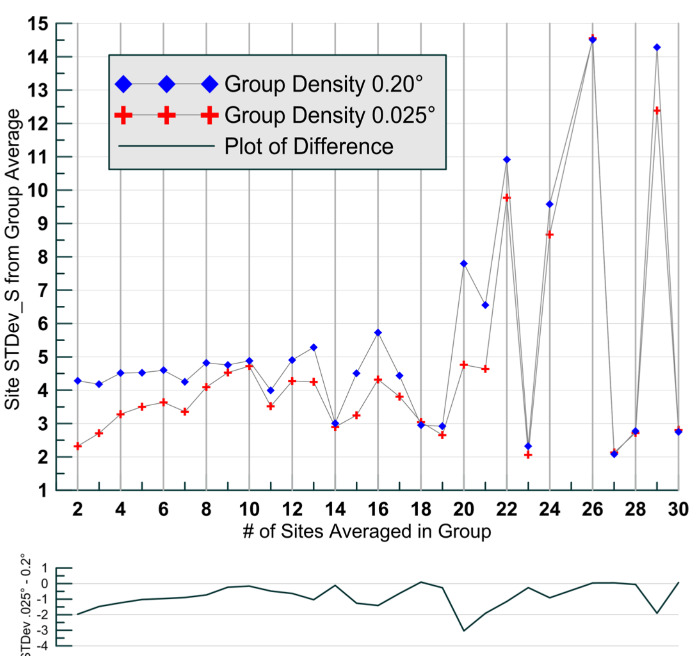

Figure 4. Comparison of site standard deviation (*m*W/m^2) to its grouped average using two radii for area size based on latitude and longitude areas of 0.20° (blue diamonds) and 0.025° (red crosses). The bottom line tracks the difference between the standard deviation of the group densities, showing that the overall differences are minimal, even though the scatter increases as the group size increases.

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