Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Updated Heat Flow Map of Alaska: Developing a Regional Scale Map for Exploration from Limited Data

Joseph Batir, David Blackwell, Maria Richards

SMU Geothermal Laboratory, Huffington Department of Earth Sciences, Dallas, TX 57275

jbatir@smu.edu

Keywords: heat flow, geothermal gradient, temperature logging, map contouring

ABSTRACT

The 2015 update to the Heat Flow Map of Alaska (HFMAK) is described, focusing on the methodology of regional scale interpretation where direct geothermal measurements are sparse. The 2013 HFMAK had only 120 direct subsurface temperature measurements for gridding heat flow for the 1.718 million square kilometers of Alaska; furthermore, data were clustered in areas of petroleum exploration producing a data location bias. This methodology was constructed to combine geological and geophysical understanding and thermal data to interpolate heat flow between data points to define locations best suited for future research. Heat flow resolution is relatively high where there is sufficient data coverage (e.g. Copper River Basin and the Aleutian Volcanic Arc), whereas, map areas lacking detailed data coverage show the interpreted regional average heat flow. Heat flow is proposed to vary locally in map sections that are lacking data based on previous research in analogous geologic settings. The methodology presented here is best suited for constructing regional thermal maps for areas containing variable thermal data density with supplementary research in basement lithology, geophysics, and tectonic history.

1. INTRODUCTION

The Heat Flow Map of Alaska (HFMAK) was revised in 2013 as part of a grant from the Alaska Energy Authority. The new revision implemented techniques developed at Southern Methodist University including methodology for new data collection, processing and gridding of data, and integration of Geology and Geophysics to support heat flow contouring. The previous version of the Geothermal Map of Alaska was published in 2004 with the Geothermal Map of North America by the SMU Geothermal Laboratory (Figure 1) (Blackwell and Richards, 2004). The 2004 map had sparse data primarily located on the North Slope and in selective areas known to have anomalously high heat flow. This sampling bias towards higher heat flow produced a high heat flow band over much of Alaska that supported the back-arc heat flow theory suggested for interior Alaska (Blackwell, Personal Communication). Between 2004 and 2007 research was focused on specific locations, such as Chena Hot Springs, to assess site specific geothermal potential. For the 2013 revision, 91 new sites were reviewed, of which 55 met the criteria to be included on the HFMAK. Since the 2013HFMAK, supplemental data has been collected to verify previous heat flow values and more gridding and cross checking techniques have been attempted to better refine areas lacking sufficient data coverage. Volcanoes, hot springs, and earthquake locations were overlaid on the map to assist in geologically constraining the heat flow contouring. Earthquake locations are overlaid to examine "activity" associated with hot spring and volcano locations as a geophysical check to geothermal favorability. Additionally, a two tone color scheme is used to emphasize sections of the map that are considered more reliable. The two tone color scheme is based on data density, data quality, and if data points exhibit a plausible heat flow trend. These additional steps in production yield a map that is less prone to misinterpretation because areas where heat flow is not directly measured are evident.

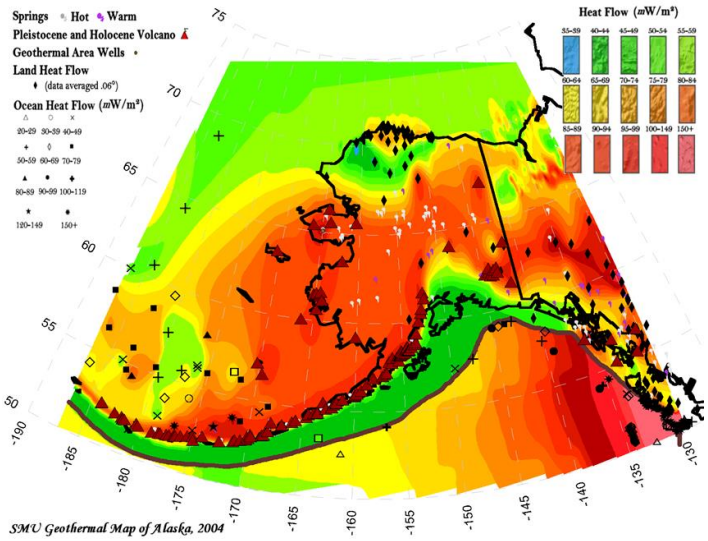

Figure 1. The 2004 Heat Flow Map of Alaska (Blackwell and Richards, 2004). Sparse data and the presence of the Central Alaska Hot Spring Belt produced a band of high heat flow across much of Alaska. The high heat flow band, however, was only an interpretation of regional above average heat flow and was never intended to indicate the presence of a potential geothermal resource across the majority of interior Alaska.

Similarly, a gravity-magnetic map has been produced following Blackwell et al. (2010) to infer basement lithology as a secondary geological heat flow constraint. There is a poor data distribution to effectively examine Alaska for geothermal prospects solely based on heat flow data. Gridding procedures that combine gravity and magnetics to estimate basement lithology have been developed in the SMU Geothermal Laboratory to qualitatively estimate areas expected to have higher or lower regional heat flow. This qualitative estimation is used to force gridding contours in areas where data are sparse. This qualitative Geophysical method has been shown to work in the Eastern United States (Batir er al., 2010).

Surface heat flow is one of the required data to determine the favorability of a site for geothermal energy production, but it is not all that is required. Heat flow can be used to determine the amount of heat in place that can be extracted from the Earth, but does not give a good indication of presence of fluid or pathways to move the fluid for a given location. When these additional factors are taken into account, a heat flow map can be considered a favorability map for geothermal system potential: areas with a higher heat flow are suggested to have the heat-in-place and therefore have better potential to host a geothermal system as opposed to areas of lower heat flow.

2. METHODOLOGY

Data collection and heat flow calculation methodology are straight forward when there are abundant data for use. Much of the data for the HFMAK are Bottom Hole Temperature (BHT) measurements that are lacking thermal conductivity measurements. This complicates heat flow calculation, making more steps and assumptions necessary. Likewise, gridding procedures are straight forward when there are abundant data points evenly distributed throughout the gridded region. Figure 2 shows that the data distribution is uneven, focusing on areas of hydrocarbon production. Uneven data distribution means large areas of the grid are based on no data or that are not representative of the region they are contouring. Instead of leaving these regions blank, Geology is taken into account to control gridding in a geologically relevant manner.

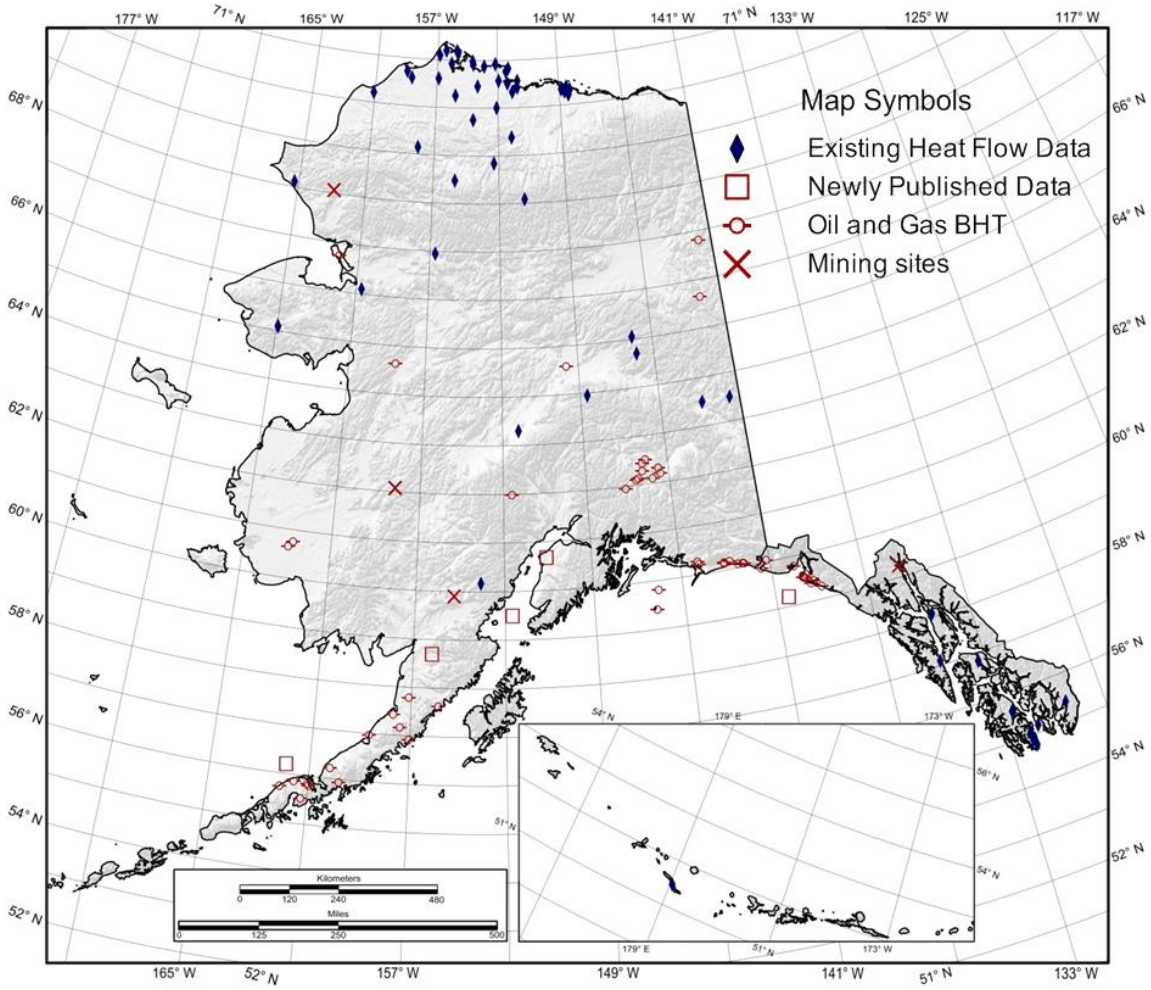

Figure 2. Data points and locations used for the 2013 Heat Flow Map of Alaska. Large areas are contoured based on one or no points creating a potential for erroneous heat flow contour patterns.

2.1 Heat Flow Data Collection and Calculation

The Heat Flow Map of Alaska (HFMAK) illustrates the amount of heat flowing from the Earth's interior to the atmosphere. Heat is produced within the earth through release of remnant heat of formation and radiogenic heat production. To calculate a heat flow value, the heat diffusion equation is simplified to only the vertical component (as shown in Equation 1), i.e., the geothermal gradient of a rock formation multiplied by the formation's thermal conductivity. This is possible because temperature logs measured in the near subsurface are thought to be above depths where radiogenic heat production occurs; therefore, near surface

measurements take into account both types of heat production (Carslaw and Jaeger, 1959; Beardsmore and Cull, 2001; Batir et al., 2013). In areas where heat flow is not measured, it can be estimated by the presence of geothermal activity, or the composition basement rock if it is known. Blackwell et al., (2010) demonstrated that basement lithology can be used as an indicator of relatively high or low heat flow because mafic rocks have less radioactive elements than felsic rocks. The use of geothermal activity and basement rock mapping is discussed in more detail in the gridding section.

$$Q = {}^{\Delta T}/_{\Delta z} * k \quad (1)$$

Where: Q = heat flow, mW/m^2

${}^{\Delta T}/_{\Delta z}$ = geothermal gradient, °C/km

K = thermal conductivity, W/m*K

2.1.1 Geothermal Gradient, $\Delta T/\Delta z$

The geothermal gradient is the rate of change in temperature with respect to depth within Earth. Temperature measurements are collected from well bores. The most accurate source of a thermal gradient is from an equilibrium temperature log (ETL). An ETL is a temperature log collected within a well that is at equilibrium with the surrounding rock after the thermal effects of drilling have dissipated. The depth intervals with a conductive gradient that are at equilibrium with the surrounding rock are the sections that represent the background geothermal gradient of the formation. The conductive gradient sections represent the background geothermal gradient because conduction is the primary method of heat transfer within the crust. Even when a temperature log is at equilibrium with the surrounding rock, the background geothermal gradient may be masked because of seasonal climatic effects, fluid flowing within the formation(s), thermal refraction, and/or topographic effects. Ideal ETL measurements are collected deeper than 100 m to remove seasonal climatic effects (Majorowicz et al., 2004). New temperature logs were found to have no major fluid flow disturbances. No corrections for thermal refraction were made as the geological data in general are not detailed enough, or the probable corrections are within the error of the sites. The topographic effect on temperature disturbs the gradient to a depth roughly equal to the total topographic relief for a ridge-valley topographic profile (Blackwell et al., 1980). A topographic correction has been applied for data points in this study where the correction was thought to be significant. Those wells identified for topographic

effect correction had changes in geothermal gradient totaling less than 3%, so a conservative estimate of error for wells not corrected for topography would be ±3%.

Bottom Hole Temperature (BHT) and Logging While Drilling (LWD) measurements were also utilized for gradient calculations. An average gradient is calculated from the mean annual surface temperature to a BHT measurement. A mean annual surface temperature of 0 °C was used for all BHT sites because of the low resolution of available surface temperature data. The 0 °C value is within the ±20% of the maximum/minimum possible value, based on the mean annual surface temperature map (National Climatic Data Center, 2011). Several different empirical temperature corrections have been developed to correct for this disturbance when using oil and gas industry BHT (Lachenbruch and Brewer, 1959; Förster et al., 1998; Harrison et al., 1983). The SMU Geothermal Laboratory determined that the Harrison correction yields the most consistent results when applied broadly to oil and gas wells deeper than 600 m where there is no basin-specific BHT correction for drilling disturbances (Blackwell et al., 2011). If there is not an ETL in the vicinity to test the accuracy of the correction applied, empirical evidence shows that BHT measurements are typically within ±20% of equilibrium temperatures.

Similar to BHT measurements, LWD is a process of collecting down-hole logs during the drilling process. Some deviation measurement tools have temperature probes, which are the primary source of LWD temperature data from the mining industry. It was hypothesized that LWD data would preserve the thermal gradient because temperature disturbances were equal at the respective depths when measurements took place. However, in this project the LWD did not provide interpretable data, and therefore LWD measurements were treated as 'uncorrected' BHT. Lee and Han (2001) concluded the smaller the hole, the quicker thermal equilibrium is reached, which implies applying a correction intended for large diameter oil and gas wells to the smaller diameter wells used for mineral exploration (the same wells LWD data came from) would overestimate the equilibrium temperature. Instead, mineral exploration well temperatures were conservatively estimated to be at equilibrium with an error of ±10%. There are now sites in the data set that include an ETL to test this model in a real world setting, but a correction for small diameters holes has yet to be developed through this study.

2.1.2 Thermal Conductivity, *k*

After determining thermal gradient, the thermal conductivity of the rock layers is required to calculate the heat flow. The thermal conductivity of a rock is the rate at which heat will conduct through the rock. The devices used in the SMU Geothermal Laboratory are a divided-bar thermal conductivity measurement apparatus and a needle probe measurement device, both shown in Figure 3. The divided bar apparatus creates a temperature gradient within the sample; the heat that travels across the sample is measured when the sample has reached steady state, and the heat flux can then be used to calculate a relative thermal conductivity of the rock sample that is compared to a standard sample of known conductivity to calculate an absolute thermal conductivity. The needle probe is similar to the divided-bar apparatus in that it sends heat into a rock sample and measures the rate at which heat travels through the rock to calculate a relative thermal conductivity in comparison to standards (Sass et al., 1984; Blackwell and Spafford, 1987).

Ideally, thermal conductivity and thermal gradient are collected from the same site. The ideal raw material is full core, but conductivity can also be measured from half core or cuttings (Goss and Combs, 1976; Blackwell and Spafford, 1987). If rock samples were not available, published values from the same formation were used as an analogous sample. If an analogous rock could not be found, thermal conductivity values for sedimentary rocks from a study in the Anadarko Basin in Oklahoma (Gallardo and Blackwell, 1999) were used and modified for permafrost within the pore space where applicable. These published values were

used because the technique of conductivity measurement has shown to be robust and repeatable; however, these rocks may not be suitable proxies because of age and location differences but were the best values found. A lithology model combined with published thermal conductivity values were used to estimate thermal conductivity. The ideal lithology model for a heat flow site would use a detailed lithology log from the well. When unavailable, a basin or regional cross-sectional model was used; if even this information was not accessible, the area was given a generalized volcanic or non-volcanic locality determination.

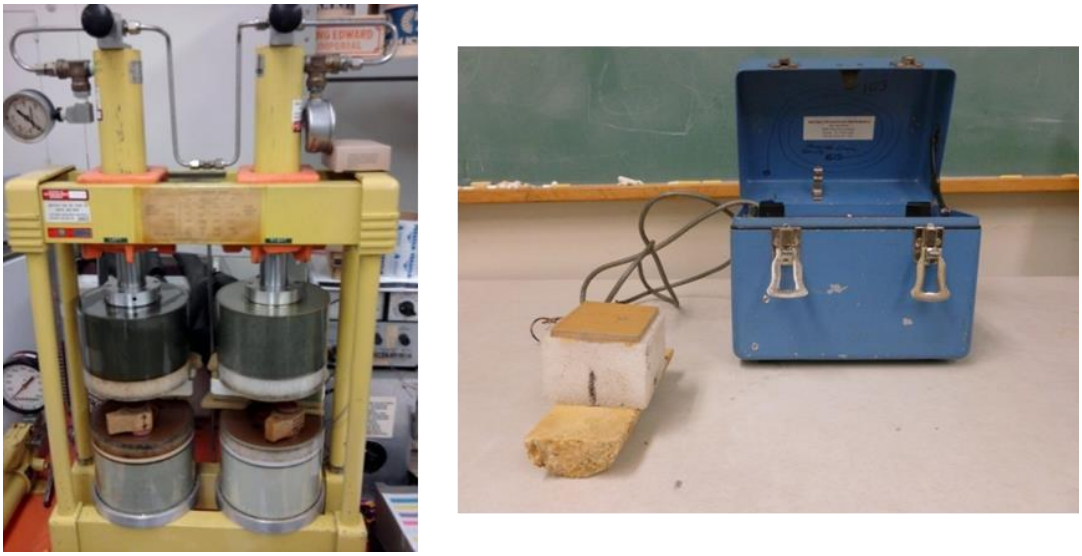

Figure 3. (Left) The divided-bar thermal conductivity measurement apparatus. Samples are placed in between the press where the wooden blocks are located in the picture. (Right) The needle probe measuring device. The tool shown here has an insulating surface glued to one side (with a piece of wood on top) so that the needle probe will send heat into a rock slab sample. The needle probe has a heater wire running the length of the white insulating foam at the base of the black line; the tan half cylinder under the foam is a half core rock sample.

2.2 Gridding Procedure

Data were contoured using the Kriging method with a search ellipse elongated in an east-west direction, thus mimicking the same directional trend seen in the orientation of Alaska's geologic features. When contouring the 2013 HFMAK, the first step was to generate a grid based on the available data. As shown in Figure 2, data are sparse and unevenly distributed. Contouring data without adjustment or geological controls yields erroneous high heat flow sections (Figure 4). Pseudo heat flow points were added to the gridding to guide contouring to follow predictable trends where no data exist. The additional points worked well to control contours and limit unexpected results not supported by data.

The next step was to adjust the contours in consideration of the regional geology in areas of no or inadequate heat flow control. That is, the contouring is complimentary to geologic features. For example, the Denali fault is a large tectonic feature running through Alaska that acts as a boundary between the Alaska Range and Coastal Alaska. A geologic feature of this magnitude might act as a thermal boundary similar to other fault systems such as the San Andres fault in California (Blackwell et al., 1991; Morgan and Gosnold, 1989). While these hypotheses are based on Geology and analogous structures, research has not been done to test these hypotheses in Alaska. In areas without well data but with high concentrations of surface geothermal manifestations, heat flow values were assigned to these manifestations for gridding purposes. Young volcanoes and hot springs were given a variable heat flow value (74-100 mW/m^2) in relation to proximity to other surface manifestations, heat flow measurements, and recent activity. For example, the Aleutian Volcanic Arc sites were given higher heat flow values because of the frequency of eruptions along the arc. Earthquakes and age were also considered for interior geothermal manifestations.

As a secondary check to Geological hypotheses, a gravity-magnetic map was made for Alaska to infer basement lithology. As described in Blackwell et al. (2010), the gravity-magnetic map is made based on a logic chart (Figure 5) that attempts to differentiate mafic versus felsic basement. If there is an area that has a negative magnetic anomaly and also a negative gravity anomaly, the geophysical data suggests this area described could be granite or similar felsic basement lithology. Granite, being higher in radioactive elements, would yield a higher heat flow. Likewise, an area with a high gravity anomaly and high magnetic anomaly suggests a mafic basement lithology, and a lower radiogenic heat production in the area. Specific examples of this technique being verified in the Eastern United States are shown in Batir et al. (2010). Gravity-magnetic mapping worked well in the Eastern United States because of the stable intercontinental setting. Alaska has continuous tectonic activity complicating basement lithology and surface geology. The creating of a gravity-magnetic map as a tool to constrain heat flow was not as successful in Alaska as previous attempts because of the complex geologic setting; consequently, the gravity-magnetic map of Alaska was not used to control any contouring of heat flow data.

In order to emphasize locations with collected heat flow data versus assigned values based on geologic constraints, the 2013 HFMAK has a two layer color density scheme. Two tone contouring is used here as a qualitative approach to visually show confidence of the map. It is an attempt to add a visual "error bar" while keeping the aesthetics of the map. Bold colors are used where contouring is supported by data, whereas the faded colors are areas that are interpolated or driven by Geology. There is one caveat to this color scheme. Anywhere on the map where there is active geothermal activity is still contoured as a low confidence

area because no measured heat flow data exist, but geothermal activity such as volcanoes and hot springs requires a high heat flow which is often significantly higher than what is contoured on the map. One will notice the distance from the data point where the transition from bold to faded colors is variable. The variation in distance is a semi quantitative way to express more or less confidence for specific data points. In general, if the data point has a higher reliability, than it is given a larger circle; likewise, if the data point has a lower reliability, the circle around the data point is smaller. A complete flow chart explaining size of confidence circles is given in Figure 6 (from Batir et al., 2013).

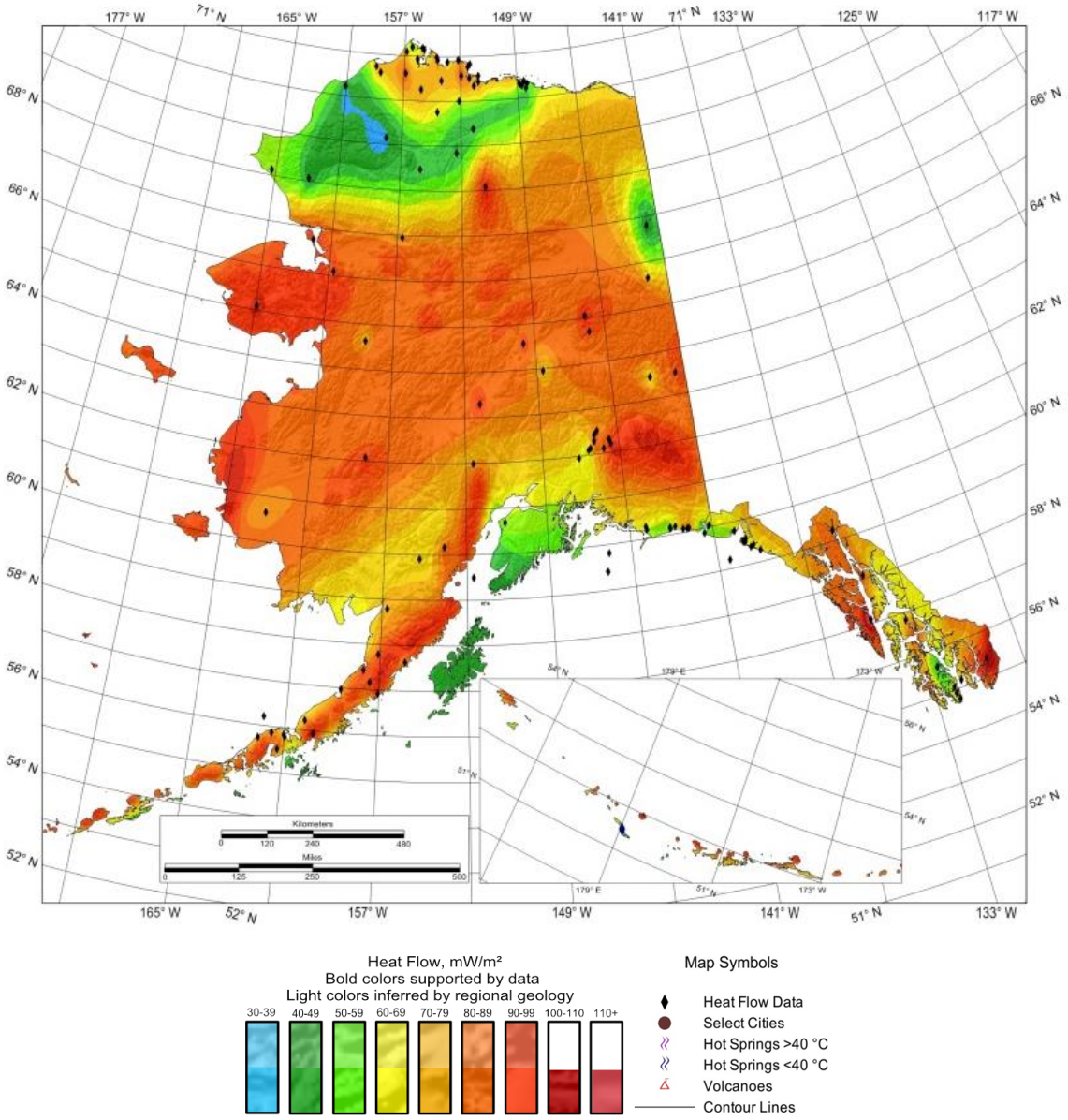

Figure 4. Heat flow map of Alaska prior to manual grid forcing. Erroneous high heat flow values can be seen within Central Alaska and potentially in the Northeast. A map legend is located below.

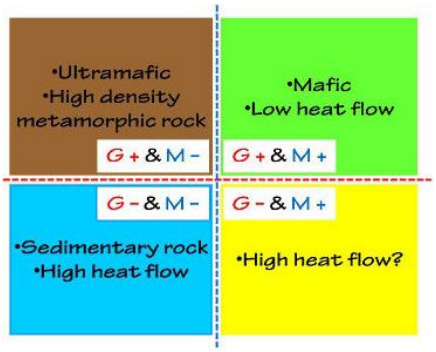

Figure 5. Logic argument for inference of basement lithology to derive heat flow. From Blackwell et al. (2010).

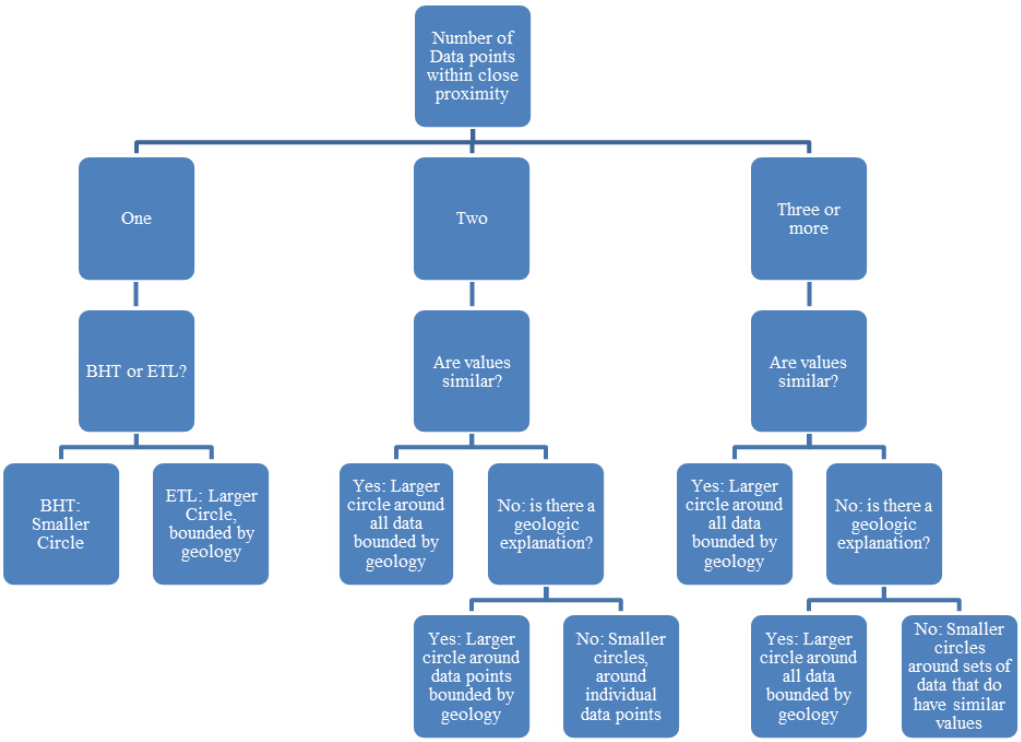

Figure 6. Flow chart establishing circle of confidence for mapping the brighter color layer of the 2013 HFMAK. There is a semi-quantitative measure to the circle size (larger circles around more reliable data, and smaller around less reliable data), but it is not directly related to total error within each data point. Any previously published values for the purpose of this flow chart were treated as equilibrium temperature logs (ETL). From Batir et al., 2013.

This semi qualitative method of contouring is one attempt to show reliability of mapped areas that incorporates both Geology and contoured data. Another way to test contour reliability is statistical analysis of data compared to near neighbor data points. Heat flow from the Wrangell Volcanic Range (Figure 7) is one example why a direct statistical approach will not always work. As data move away from the mountain range, heat flow drops. Heat flow is expected to drop moving away from a volcanic mountain range; however, if a statistical analysis of the data surrounding the Wrangell Mountains were to be done, it would suggest some of the data are wrong and should not be trusted. The ideal scenario is a statistical analysis of data to suggest areas where there is potentially erroneous data which can then be checked by the mapper.

3. AVAILABLE DATA

Available data are split into two categories, geophysical data and heat flow data. The geophysical data are used to infer basement lithology and tectonics throughout Alaska. Inferences of basement lithology are important because the majority of radiogenic heat production is from the basement rocks within the upper crust (Beardsmore and Cull, 2001). Tectonics are used to infer two things: 1) potential for fluid flow evidenced by active faults, and 2) large-scale tectonic structures (e.g. the Denali fault) that may act as regional thermal boundaries. Integration of these data sets are a primary role in the revised mapping techniques.

3.1 Geophysical Data

Geophysical data include gravity and magnetic anomaly maps, and earthquake location data. All data are obtained from the United States Geological Survey as open access data and are then gridded and contoured for specific use. While these data are not necessary for generating a heat flow map, results support these additional steps as beneficial to map production.

3.1.1 Gravity Map

Gravity data are available through the United States Geological Survey (USGS) as a compilation of all gravity measurements collected during the past 50 years (Saltus et al., 2008). Gravity data were examined to compare to heat flow because of the relationship of mafic and felsic basement lithology to heat flow. Felsic rocks have higher concentrations of radioactive elements and a lower density than mafic rocks. This basic inverse relationship between radioactivity and density is used when examining gravity anomalies because gravity lows are associated with low density rocks, i.e., felsic rocks. This relationship does not always hold, but in geologically stable regions this relationship has been empirically supported (Batir et al., 2010). Gravity data in Alaska provide sufficient coverage to examine regional trends and identify low and high gravity anomalies. Several regional trends are visible within the gravity data that are geologically relevant such as the Brooks and Alaska ranges, and the Aleutian Volcanic Arc. These trends, unfortunately, are more related to active tectonics and cannot be tied to basement structures in a way to increase confidence of heat flow contouring.

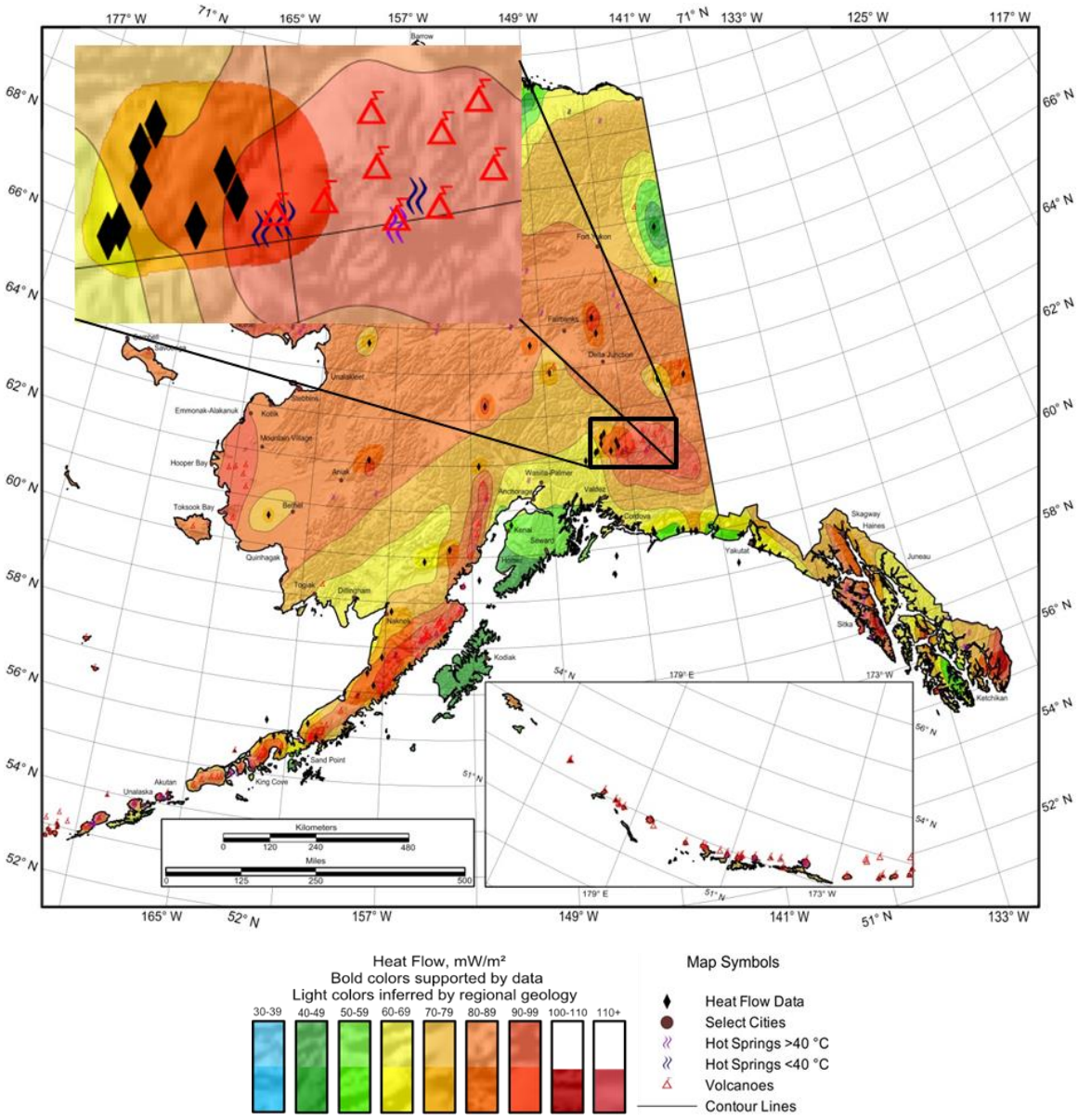

Figure 7. Detailed image of the Wrangell Mountains. The Wrangell Mountains are volcanic in origin and have associated hot springs. It is a logical progression for heat flow to drop as data move away from the volcanoes as seen on the map. A confidence circle is drawn around the data because even though values change, the data follow the geological expectation.

3.1.2 Aeromagnetic Map

The USGS has produced a compiled and merged aeromagnetic map for the state of Alaska that was examined for increasing resolution of the heat flow mapping (Saltus et al., 1999). Magnetic susceptibility is variable within the Earth through variations in the abundance of iron rich minerals. Mafic and ultramafic rocks have greater magnetic susceptibility while also having less radioactive minerals implying a general inverse relationship between magnetic susceptibility and heat flow (Blackwell et al., 2010). The hypothesis is that a magnetic map would represent changes in basement lithology and be useful for constraining heat flow contouring. The aeromagnetic map of Alaska is complex because of tectonic activity. A pseudogravity and 10 km upward continuation model provided by the USGS were both examined to remove high frequency variation in the magnetic anomaly map (Saltus, personal communication). While the pseudogravity and upward continuation models show regional trends, the visible anomalies still could not be confidently interpreted as basement lithology variations. Therefore, aeromagnetic data were not used for constraining heat flow contouring.

3.1.3 Earthquake Locations

Recent earthquake locations (Figure 8) are used here to compare areas of recent seismic activity to heat flow. Regional faults have been shown to act as thermal boundaries. A map of earthquake location aids in mapping regional scale faults and shows which faults are still active. Earthquake locations displayed on Figure 8 are from 1973 to 2012 implying that any lineaments on the map are presumed to be active faults (U.S. Geological Survey, 2013). Areas with active faults are also thought to have potential for better fluid pathways and higher permeability because they are still active and not sealed. This is important for interpretation and use of any heat flow map to search for potential geothermal systems. The Denali fault is clearly visible as well as subduction

underneath the Aleutian Volcanic Arc. Specific areas within interior Alaska with seismic activity suggests these areas are candidates for open fractures and fluid flow pathways that would be necessary for a geothermal system. These lineaments in interior Alaska are not associated with major faults, but do coincide with clusters of hot springs (Waring, 1917). These earthquakes align with geothermal manifestations, giving them a higher confidence to having potential for a geothermal system.

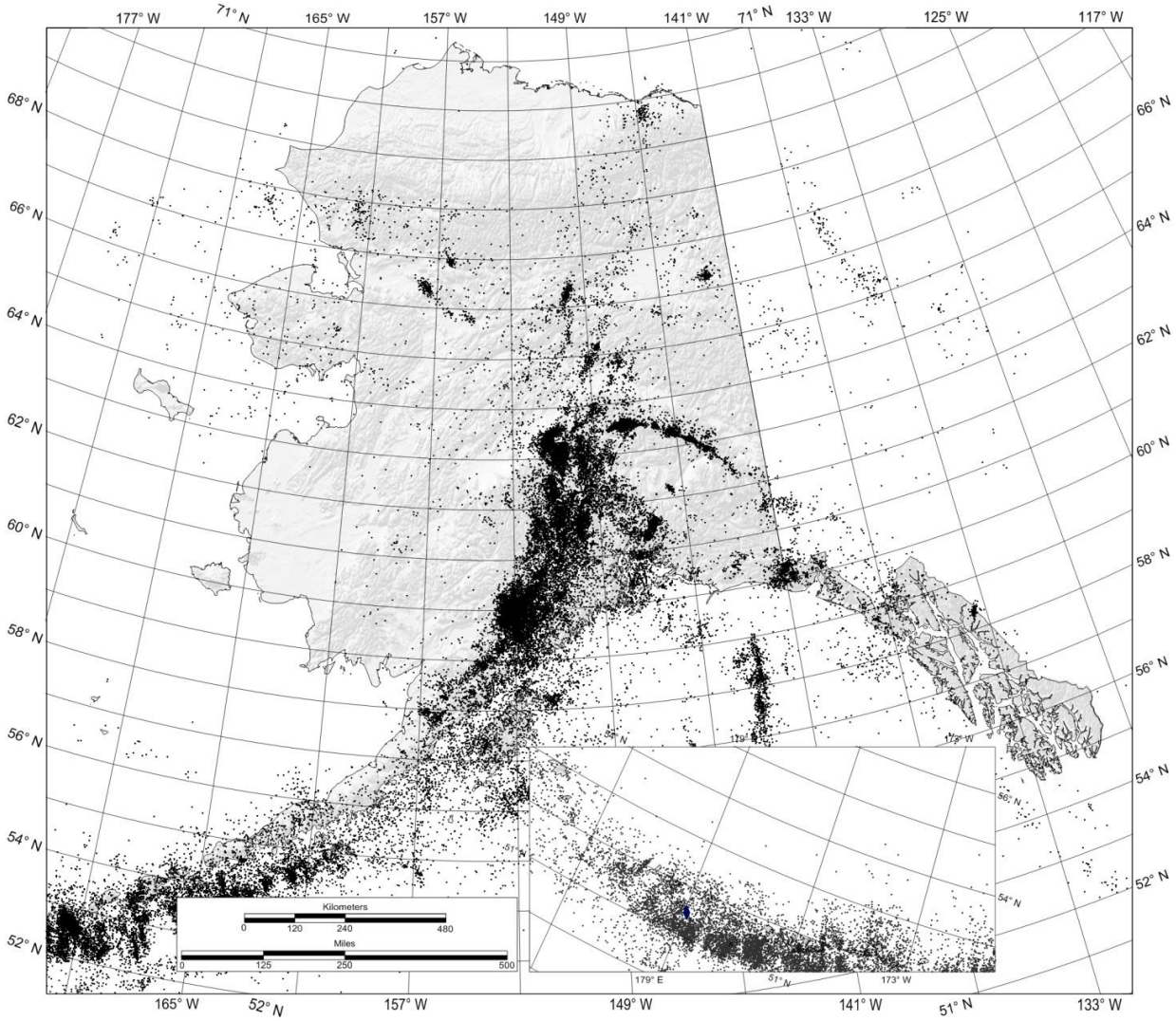

Figure 8. Earthquake location map of Alaska. Shown in the map are all detectable earthquakes that occurred between 1973 through 2012. Earthquakes displayed are variable magnitude and depth and were used to search for seismically active lineaments but not particular modes or magnitudes of slip motion.

3.2 Heat Flow Data

Heat flow data used for contouring include the new data that have been collected since 2007, legacy data collected by the USGS in the early 1960's, 70's, and 80's, and integration of geothermal manifestations mapped by the Alaska Volcano Observatory. A full list of data used for gridding can be found in Batir et al. (2013). Several data points were suspected to be unreliable because at the time of logging the wellbore was still disturbed from drilling, or erroneous thermal conductivity measurements were collected and used for heat flow calculations. An attempt was made to examine legacy data to assure values are good quality. Several legacy holes had fluid flow evident within the wellbore, or abnormally high gradients that were difficult to explain, therefore were not used for mapping purposes. Figure 2 shows location of all measured heat flow data separated by data type. There is still a large swath of Alaska with no measured heat flow.

4. DISCUSSION

Gridding and contouring techniques are often a glossed over topic. Data are the most important part of any mapping project, but when data are sparse, gridding technique becomes just as important. Any tools that can aid in the gridding process should be used to better define and refine maps. Here, Geology and Geophysics have become key data sources to interpolate between data points as a check for geologic plausibility and reliability of individual points. Figure 9 shows the updated Heat Flow Map of Alaska (HFMAK). The integration of geothermal manifestations and earthquakes has improved the map beyond what new heat flow data was able to do. While gravity and magnetic data were examined, the resulting gravity-magnetic map did not change confidence in the current HFMAK contouring.

The updated HFMAK shows that more data are still needed to continue improving the map. For example, interior Alaska has a high variability of heat flow values (61-106 mW/m^2), similar to the Basin and Range Province. As new data are added throughout the interior, it is likely that the average of ~84 mW/m^2 will stay the constant, but localized anomalies will become visible. This new edition of the HFMAK highlights areas of interest for geothermal exploration such as the George Parks Highway between Denali National Park and Anchorage, Wasilla/Palmer, Delta Junction, Glenallen/Gakona Junction, the Sitka vicinity, the Seward Peninsula, Kotzebue, and the Purcell Mountain vicinity. Sitka and Purcell Mountain are interesting because these areas map to suggest geothermal potential. The other areas of interest are in data gaps that would directly test one or several of the Geologic hypotheses implemented for gridding of this map.

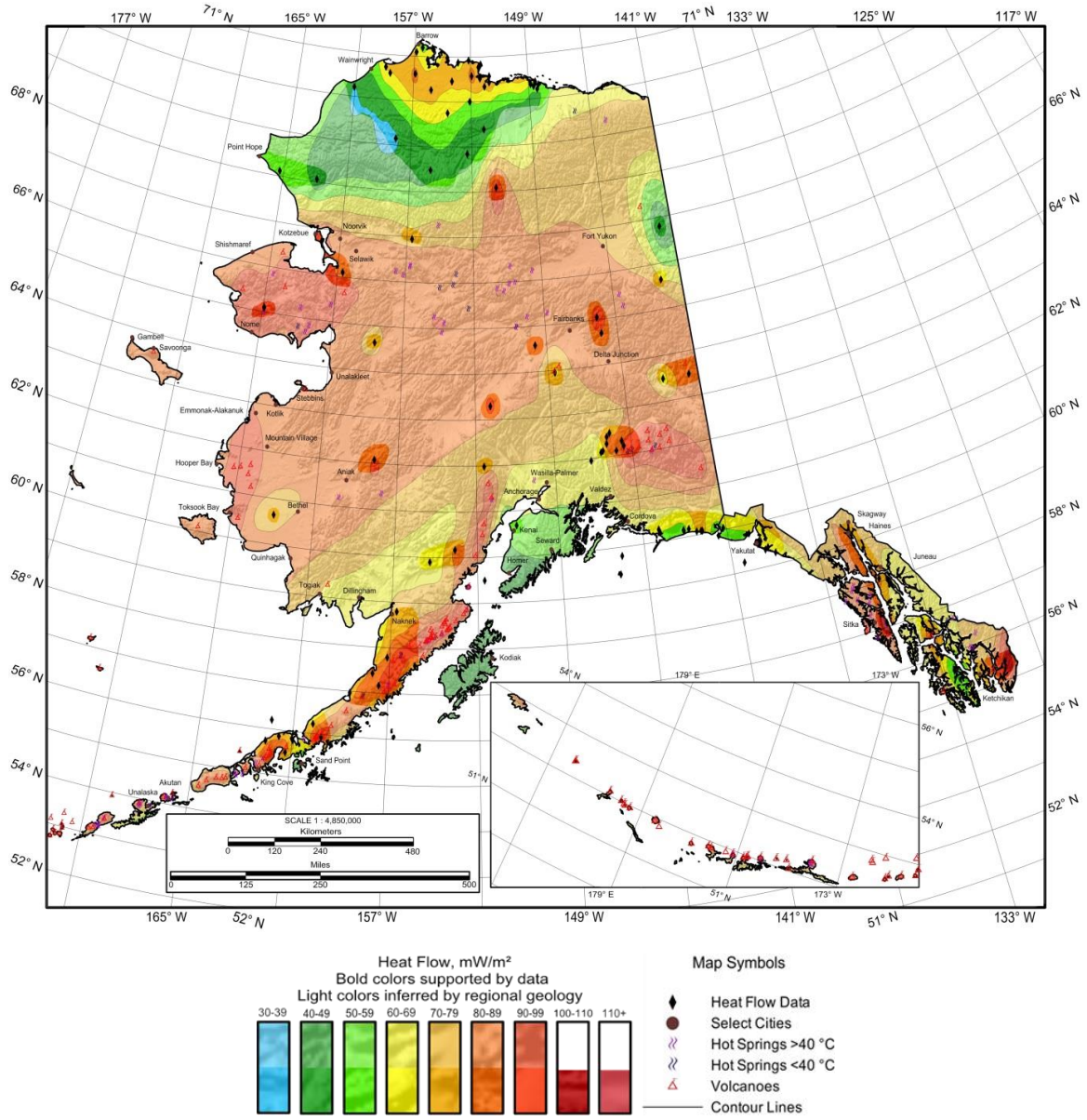

Figure 9. Updated Heat Flow Map of Alaska. The map has been improved upon by the integration of Geology and Geophysics into the gridding procedure.

5. CONCLUSIONS

Through new gridding and cross referencing techniques, the Heat Flow Map of Alaska has been improved and is now more geologically accurate. The ability to infer basement lithology through the combination of gravity and magnetics was not as useful as expected. It did show large trends that may be related to regional heat flow, but more work is needed to implement these data into heat flow. Use of earthquake locations has also been a useful tool for defining active faults to display as thermal boundaries and for secondary analysis to examine the level of geothermal activity at various sites. These techniques are applicable anywhere with variable basement and a near complete gravity and magnetic data set, although tectonically active regions like Alaska are more difficult to interpret.

Examination of the Heat Flow Map of Alaska yields several interesting observations. Overall, heat flow throughout Alaska is more locally variable than this statewide map suggests. Bottom Hole Temperatures and Equilibrium Temperature logs have shown variability even where there are multiple data points clustered together. This amount of variation is important to keep in mind when

conducting reconnaissance studies using this map. While a general trend of high heat flow is still present, the heat flow is not definitively assessed outside the bold colored sections. The variability of heat flow has been tested against independent data sources, and the new heat flow patterns interpreted agree with regional geology and earthquake locations. The new data show variable heat flow throughout Alaska ranging from high values above 120 mW/m^2 to values below 40 mW/m^2. This variability indicates that the geothermal energy potential is not uniform and emphasizes the natural heterogeneity of heat flow. As more data are added to the map, it is likely more variability will be displayed, yet the regional trends we have presented here.

Map making is not as simple as gridding and contouring available data. Contours need to be checked for Geologic relevance and erroneous measurements. Use of multiple Geophysical data sources has improved the quality of the HFMAK by doing this Geologic check of the heat flow data. As new ideas and ways to cross check heat flow become available, these new techniques will be implemented to continue improvement of the HFMAK.

ACKNOWLEDGEMENTS

The authors would like to thank the companies and organizations that have supplied data, including: Alaska Oil and Gas Conservation Commission, Chena Hot Springs Resort, United States Geological Survey, Constantine Metal Resources, Ltd., Donlin Gold, LLC., Kinross Gold Corporation, Kiska Metals Corporation, The Pebble Limited Partnership, Teck Alaska, Inc., and Usibelli Coal Mine, Inc. Groups that have provided research funding and field assistance for this map include the Alaska Energy Authority, the Alaska Center for Energy and Power, Chena Hot Springs Resort, and the American Association of Petroleum Geologists. Thanks go to Patrick Stepp for making initial contacts with several of the mining companies, collecting data early on in this project, and help with construction of the gravity-magnetic map.

REFERENCES

Batir, J.F., Blackwell, D.D., Richards, M.C., and Park, J. (2010), "Evaluation of EGS Resources in the Eastern United States: Illinois, Michigan, Indiana, Western Ohio, and Western Kentucky," *GRC Transactions*, **34**.

Batir, J.F., Blackwell, D.D., and Richards, M.C. (2013), "Updated Heat Flow of Alaska: New Insights into the Thermal Regime", Final Report to the *Alaska Energy Authority* and *Alaska Center for Energy and Power at University of Alaska – Fairbanks*, pp. 26.

Beardsmore, G.R. and Cull, J.P., 2001. Crustal Heat Flow, Cambridge, *Cambridge University Press*, pp. 324.

Blackwell, D.D., 2014, *Personal Communication*.

Blackwell, D.D., and Richards, M., 2004. "Geothermal Map of North America", *Am. Assoc. of Pet. Geol*. 1 sheet, scale 1:6,500,000.

Blackwell, D.D. and Spafford, R.E, 1987. " Experimental methods in continental heat flow", *in* Sammis, C.G., and Henyey, T.L., eds., Experimental Methods in Physics, Part B - Field Measurements, **24**, *Geophysics*: Academic Press, 189-226.

Blackwell, D.D., Richards, M., Batir, J.F., Frone, Z., Park, Z. (2010), "New Geothermal Resource Map of the Northeastern US and Technique for Mapping Temperature at Depth," *GRC Transactions*, **34**.

Blackwell, D.D., Richards, M., Frone, Z., Batir, J.F., Ruzo, A., Dingwall, R., Williams, M. 2011. "Temperature-at-Depth Maps for the Conterminous United States and Geothermal Resource Estimates", *Geothermal Resources Council Transactions*, **35**, 1545-1550.

Blackwell, D.D., Steele, J.L., and Brott, C.A., 1980. "The Terrain Effect on Terrestrial Heat Flow", *Journal of Geophysical Research*, **85**, no. B9, 4757-4772.

Blackwell, D.D., Steele, J.L., and Carter, L.C., 1991. "Heat flow patterns of the North American Continent: A discussion of the DNAG Geothermal Map of North America", *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D. eds., Neotectonics of North America: Boulder, Colorado, *Geological Society of America*, Decade Map **1**.

Carslaw, H.S., and Jaeger, J.C. 1959. Conduction of heat in Solids. Oxford, *Oxford University Press*, pp. 510.

Förster, A.; Merriam, D.F.; and Hoth, Peer., 1998. "Geohistory and Thermal Maturation in the Cherokee Basin (Mid-Continent, U.S.A.): Results from Modeling", *Am. Assoc. of Pet. Geol. Bulletin*, **82**, 9.

Gallardo, J., and Blackwell, D.D., 1999. "Thermal Structure of the Anadarko Basin", *Am. Assoc. of Pet. Geol. Bulletin*, **82**, 2, 333-361.

Goss, R. and Combs, J., 1976. "Thermal conductivity measurement and prediction from geophysical well log parameters with borehole application", *in* Second U.N. Symposium on the Dev. And Use of Geothermal Resources, *U.S. Govt. Printing Office*, 1019-1027.

Harrison, W.E., Luza, K.V., Prater, M.L, and Chueng, P.K., 1983. "Geothermal resource assessment of Oklahoma", *Oklahoma Geological Survey*, Special Publication 83-1.

Lachenbruch, A.H. and Brewer, M.C., 1959. "Dissipation of the temperature effect in drilling a well in Arctic Alaska", *U.S. Geological Survey Bulletin*, **1083-C**, 73-109.

Lee, C., and Han, U, 2001. "Estimation of borehole temperature disturbed by drilling", *Geosciences Journal*, **5**, 4, 313-318.

Majorowicz, J.A., Skinner, W.R., and Safanda, J., 2004. "Large ground warming in the Canadian Arctic inferred from inversions of temperature logs", Earth and Planetary Science Letters, 7042, 1-11.

Morgan, P., and Gosnold, W.D., 1989. “Heat flow and thermal regimes in the continental United States”, in Pakiser, L.C., and Mooney, W.D., Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America, Memoir 172, 493-522.

National Climatic Data Center, 2011. “Climatological Data Annual Summary: Alaska”, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 87, no.13, pp.36.

Saltus, R.W., Brown, P.J. II, Morin, R.L., and Hill, P.L., 2008, “2006 compilation of Alaska gravity data and historical reports”, *U.S. Geological Survey* Digital Series 264, CD-ROM.

Saltus, R.W., Hill, P.L., Connard, G.G., Hudson, T.L., and Barnett, A., 1999, “Building a Magnetic View of Alaska”, *U.S. Geological Survey*, Open-File Report 99-0418.

Saltus, R.W., 2014, *Personal Communication*.

Sass, J.H., Kennelly Jr., J.P., Smith, E.P., Wendt, W.E., 1984. “Laboratory line-source methods for the measurement of thermal conductivity of rocker near room temperature”, *U.S. Geological Survey*, Open-File Report 84-91, pp. 21.

U.S. Geological Survey, “Earthquake Archive Search & URL Builder”, *U.S. Geological Survey Earthquake Hazards Program*, 7 January 2013 < http://earthquake.usgs.gov/earthquakes/search/>. 15 January 2013.

Waring, G.A., 1917. “Mineral Springs of Alaska”, *U.S. Geological Survey*, Water-Supply Paper 418, pp. 114.