Updated Heat Flow Map of Alaska: Developing a regional scale map for exploration from limited data

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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. The methodology presented here 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.

DATA SOURCE AND LOCATION

Heat flow data points have more than doubled since the 2004 Geothermal Map of Alaska, but are still bias to petroleum exploration (Blackwell and Richards, 2004). The data bias introduces a methodology problem for choosing the most appropriate gridding method to interpolate contour intervals between distant data points. Geologic data has been introduced as indirect heat flow to aid contouring.

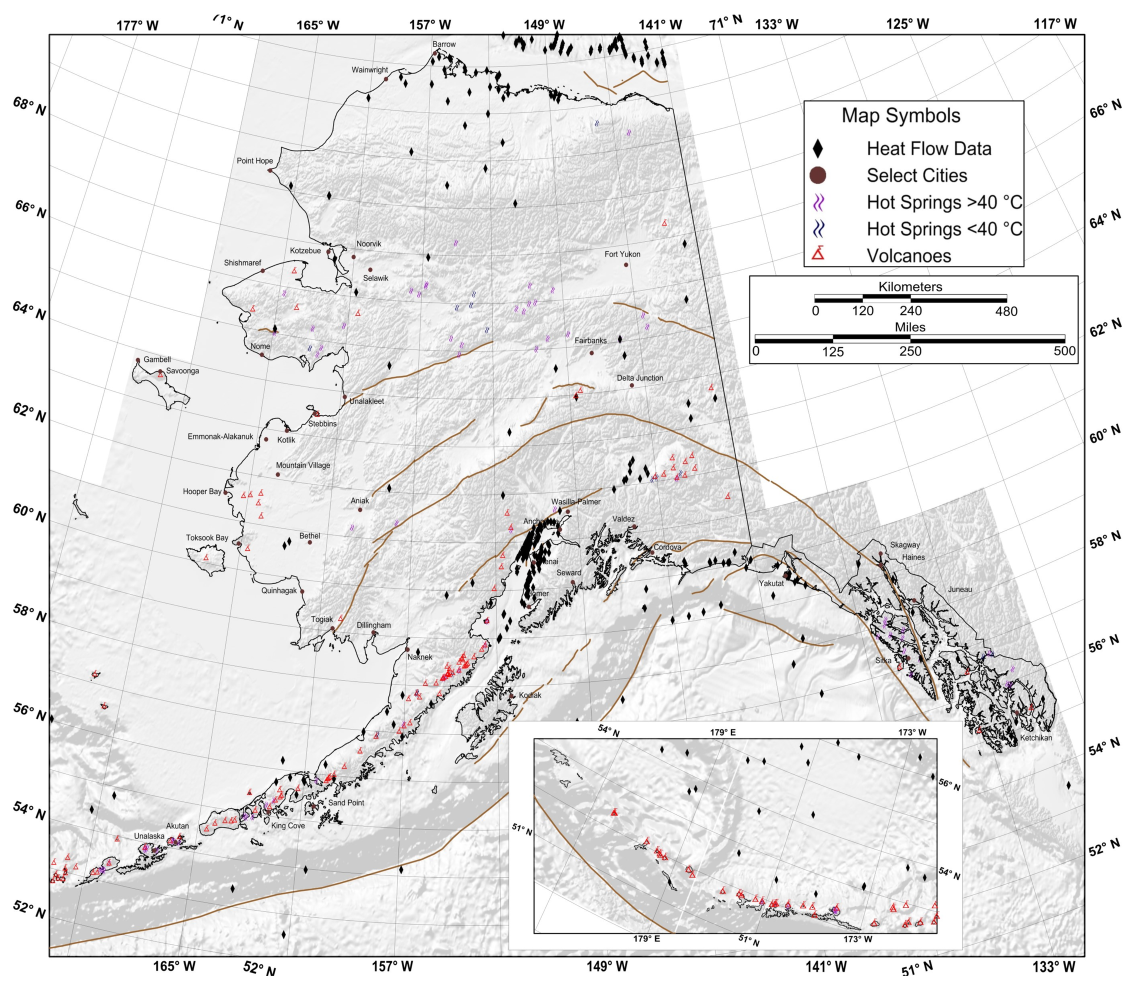

Figure 1. Map of data location. Data are biasedly distributed throughout Alaska with the majority of temperature data coming from oil and gas industry exploration. Temperature from mining sites are evenly, but sparsely, distributed throughout Alaska. Hot springs and volcanoes are given heat flow values as an indirect heat flow measurement to aid in interpolation between measured heat flow data points.

BACKGROUND

Heat flow is the heat moving through the earth for a given location. Heat flow is calculated by multiplying the geothermal gradient through a rock layer by the thermal conductivity of that layer at a given site (Carslaw and Jaeger, 1959). Heat flow varies spatially because changes in geology causes changes in these thermal properties. Table 1 shows how changes in geothermal gradient or thermal conductivity effect heat flow. Geothermal gradient data are collected as temperature data, either temperature logs that are in equilibrium with the background geothermal temperatures or Bottom Hole Temperature (BHT) data that roughly estimates background temperature (Blackwell et al., 2011). BHT data are used in conjunction with ground surface temperature to calculate a geothermal gradient. Thermal conductivity is measured on rock samples using the SMU Geothermal Laboratory's divided-bar device. Size and geology of samples determines the length of time required to measure thermal conductivity (Blackwell and Spafford, 1987). These samples are used to represent thermal conductivity at hundreds of meters to kilometer scale regions both vertically and laterally. Heat flow data are then contoured to make a heat flow contour map to examine regional heat flow trends and relate visible trends to the regional geology.

Calculated Heat Flow						
Gradient	Conductivity W/m*K					
	1.5	2	2.5	3	3.5	4
15	22.5	30	37.5	45	52.5	60
20	30	40	50	60	70	80
25	37.5	50	62.5	75	87.5	100
30	45	60	75	90	105	120
35	52.5	70	87.5	105	122.5	140
40	60	80	100	120	140	160
45	67.5	90	112.5	135	157.5	180
50	75	100	125	150	175	200

Table 1. Possible heat flow values for a combination of different geothermal gradients and thermal conductivities. Any one geothermal gradient can produce a wide range of heat flow values depending on the conductivity value.

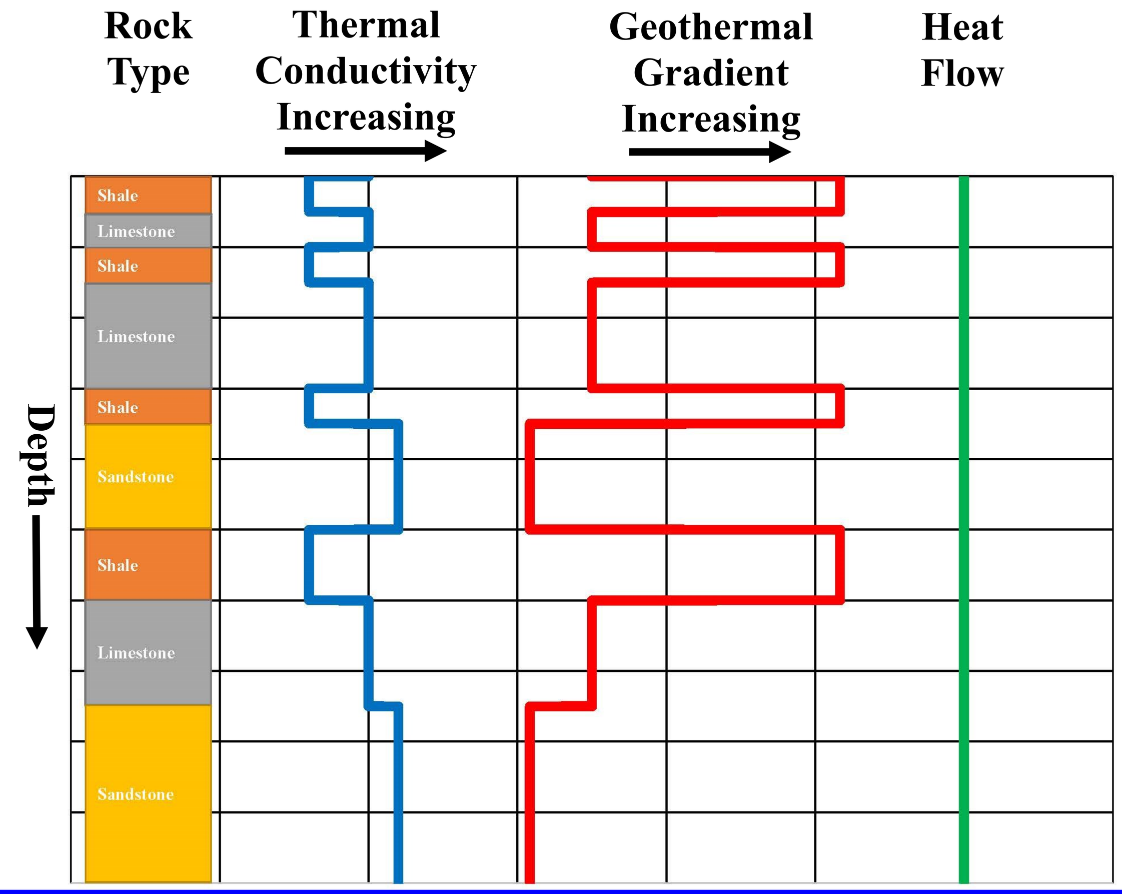

Figure 2. Schematic diagram of heat flow with depth versus changing lithology. The heat flow is constant in the upper portions of the crust. Because heat flow is directly related to geology, changes in heat flow can be used in conjunction with geology to refine mapping techniques where there are sparse data. This key relationship can be used for finding areas of interest for future geothermal development. Note: there is an inverse relationship between thermal conductivity and geothermal gradient, where low thermal conductivity is associated with high gradient and vice versa.

GRIDDING AND MULTI-DATA METHODOLOGY

Sparse and uneven data distribution cause erroneous contouring between data points when traditional heat flow data points were the only input. Additional geologic and geophysical inputs examined to combine with traditional data include geothermal manifestations, gravity, magnetic, quaternary faults, and earthquake locations. Table 2 summarizes the usefulness of each of the data sets examined as it is related to Alaska. In addition, various gridding algorithms were tested to find which would allow the most geologic input to drive contouring. The Kriging gridding method was the algorithm of choice for the 2013 HFMAK. Minimum Curvature was used for the 2015 HFMAK because Minimum Curvature allows faults to input as breaks to data communication. Treating faults as breaks in gridding follows the use of faults in the 2013HFMAK as thermal boundaries, however, now the break is driven by known faults as opposed to added control points to make gridding follow geology. Gridding was still produced using an East-West search ellipse to mimic geologic trends. The addition of faults directly into the gridding procedure has reduced the impact of single data points so the data can still be used without creating a significant area of influence from potentially suspect data.

Dataset	Hypothesis	Result	Used for gridding?
Geothermal manifestations (volcanoes and hot springs)	Surface manifestations indicate higher heat flow	Heat flow measurements near hot spring/volcano is higher than background	Yes
Combined Gravity and Magnetics anomaly map	Predict basement lithology to estimate radiogenic heat production	Tectonics complicate basement lithology and no direct lithology-heat flow relationship exists in Alaska	No
Quaternary fault traces	Quaternary (active) faults act as thermal boundaries	There is not enough data across a major fault in Alaska to test this theory	Yes
Earthquake locations	Locations indicate active tectonics	Earthquake locations match well to Quaternary fault traces	Yes
Earthquake depth	Maximum depth represents brittle-ductle, thermal transition	Data from California indicate this use, but not tested for Alaska	No

Table 2. Data sets examined as additional inputs to heat flow contour gridding. The goal of additional inputs is to infer indirect heat flow values. An inference of heat flow lets us compare the additional data to the regional measured values to aid interpolation between data points. More datasets could be examined in the future to supplement traditional heat flow data.

HEAT FLOW MAP OF ALASKA

The 2013 HFMAK versus the 2015 HFMAK are shown below as Figure 3 and Figure 4, respectively. The 2013 HFMAK used the Kriging gridding method with control points to drive contouring to follow geology where there were insufficient data. The 2015 HFMAK uses Minimum Curvature contouring with the addition of quaternary faults as break lines for gridding. The other primary difference is the use of two toned coloring. In the 2013 HFMAK, the two tone coloring emphasizes locations of heat flow data. The addition of fault traces in the 2015 HFMAK make deciding confidence intervals difficult because, while faults are theoretically thermal boundaries on regional heat flow, this theory has been tested in few locations (Blackwell et al., 1991; Morgan and Gosnold, 1989). New data was also added in the Beaufort Sea, along the Aleutian Trench, and within the Cook Inlet; the majority of these data would have been removed by following the procedures used in 2013 because they are offshore. Instead, onshore Alaska is represented by bold colors, and offshore and Canadian portions of the map are represented by the lighter colors.

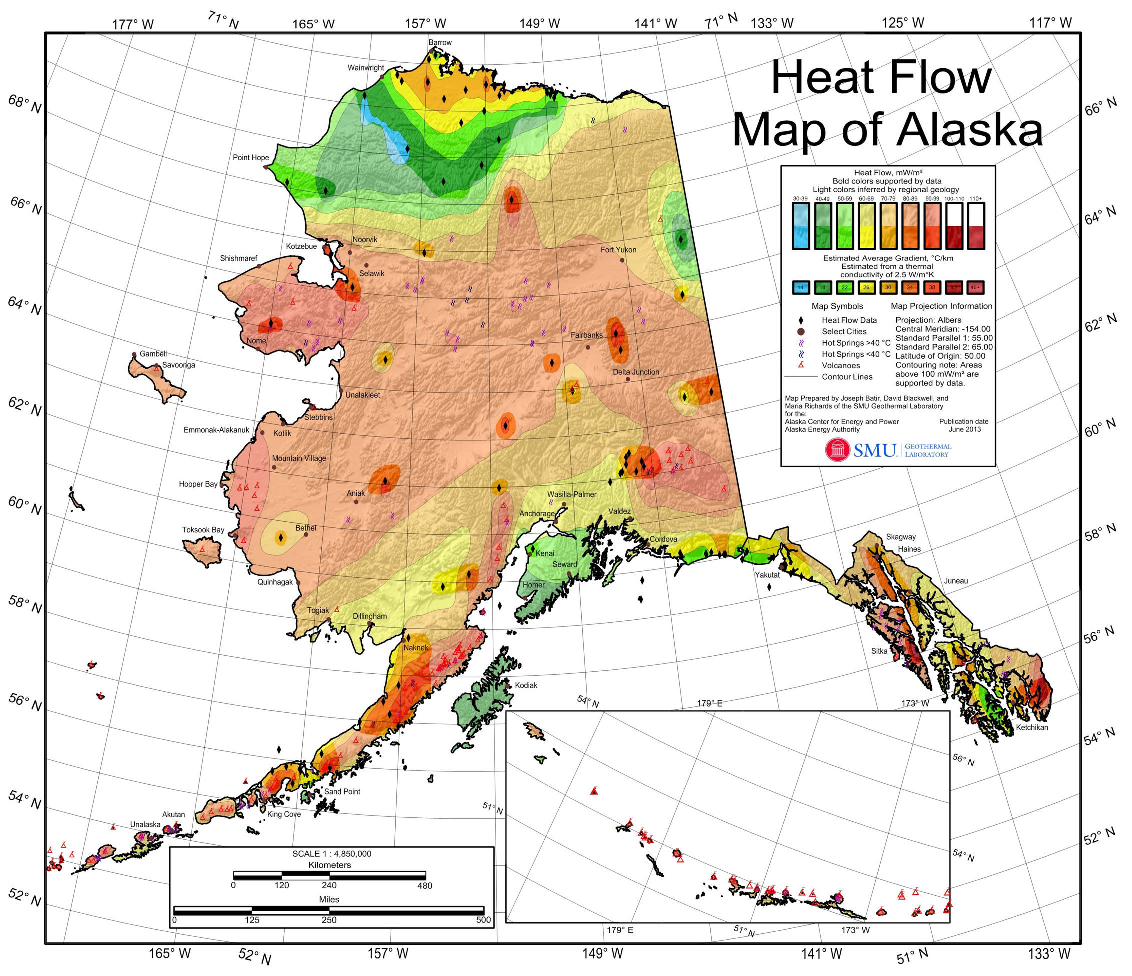

Figure 3. The 2013 Heat Flow Map of Alaska. Areas with collected temperature data to support contouring have bolder colors; whereas areas without temperature measurements to support the contouring are displayed with lighter colors and are contoured based on regional geology. This map edition included control points to add the effect of major faults through Alaska such as the Denali Fault.

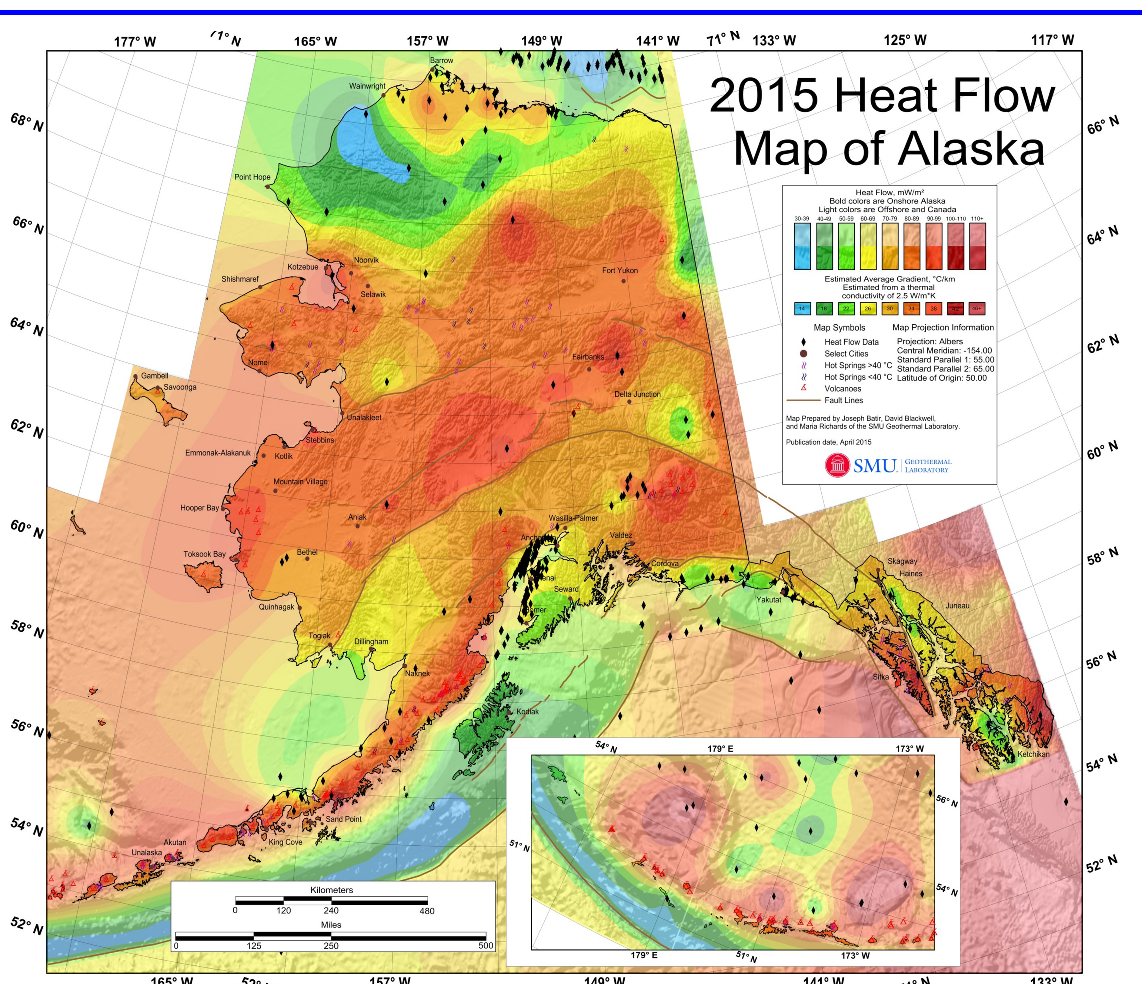

Figure 4. The 2015 Heat Flow Map of Alaska. Onshore Alaska is represented by bold coloring, whereas off-shore and Canadian portions of the map are lighter colors. The map versions have a similar overall appearance implying there was not an increase in statewide data density. The primary difference in the contouring patterns can be attributed to additional data along the Aleutian Trench, the Beaufort Sea, and a simplified quaternary fault layer used as break lines within the gridding algorithm.

DISCUSSION

- New data show more local variation than previously on the map with both higher and lower heat flow regions. Regional trends, however, are unchanged
- Gridding methods produce similar contouring where data density is sufficient, but where data is lacking, minimum curvature is superior because of the addition of quaternary fault traces
- Gravity and Magnetic were not applicable in Alaska to map basement structure for correlation to relatively high or low heat flow because of the complicated tectonics making a complicated basement

CONCLUSIONS

- The newest Heat Flow map of Alaska is more conclusive because of the addition of fault traces within the gridding process
  - More research is required to understand how large fault systems effect the regional thermal regime in Alaska
- Additional data in areas of interest have given the authors the opportunity to reexamine previous regional trends that were based on geology that can now be supported by data
- Continued heat flow collection and effort to add more geologic data sets to the mapping process will further refine our understanding of the thermal regime of Alaska

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*A full list of applicable references available in:

Batir, J.F., Blackwell, D.D., and Richards, M.C. (2015), "Updated heat flow of Alaska: Developing a regional scale map for exploration from limited data", *WGC 2015*, Melbourne, Australia.