Updated Surface Heat Flow Map of Alaska

Joseph F. Batir, David D. Blackwell, and Maria C. Richards

SMU Geothermal Laboratory

Keywords

Alaska, heat flow, conductivity, thermal gradient

ABSTRACT

The 2013 update to the Geothermal Map of Alaska (GMAK) is described, including the methodology for heat flow calculation, contouring of the heat flow, and conclusions drawn from the expanded dataset. The previous version of the Geothermal Map of Alaska was published in 2004 with the Geothermal Map of North America by the Southern Methodist University Geothermal Laboratory. 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 led to faulty interpretations. Between 2004 and 2007 research was focused on specific locations to assess site geothermal potential. In 2012, the Alaska Center for Energy and Power (ACEP) and Alaska Energy Authority (AEA) commissioned the SMU Geothermal Laboratory to collect new data to update the GMAK. 91 new sites were reviewed, of which 56 were considered of high enough confidence to be included in this version of the GMAK. Results from this edition of the GMAK suggest heat flow throughout Alaska is locally variable, even within a geologic regime. The new data show variable heat flow ranging from high values above 120 mW/m^2 to values below 40 mW/m^2.

Generalized Geology of Alaska for New Heat Flow Sites

The geology of Alaska is complex and challenging because of an intricate history of extension, subduction, deformation, sediment deposition, and volcanism. Therefore, the geology was simplified into volcanic and non-volcanic localities where lithology logs and/or thermal conductivity measurements were unavailable. Volcanic localities are classed as areas associated with recent (Quaternary) volcanism. Recent volcanism implies a significant amount of volcanic glass within the upper portion of any stratigraphic section, giving an overall lower thermal conductivity to the section. The Alaska Peninsula is classified as a volcanic locality for the purposes of this study because it is formed by Quaternary mafic volcanism (Plafker and Berg, 1994). Non-volcanic localities are defined as areas where there is a significant source of sediment that does not include major contributions of recent mafic volcanism. Stratigraphic sections of sediment are fundamentally different than stratigraphic sections dominated by recent mafic volcanism because any volcanic glass that was in the section will have likely been buried and devitrified. Thick sedimentary sections compared to basaltic rocks will have more quartz which increases the thermal conductivity of the units.

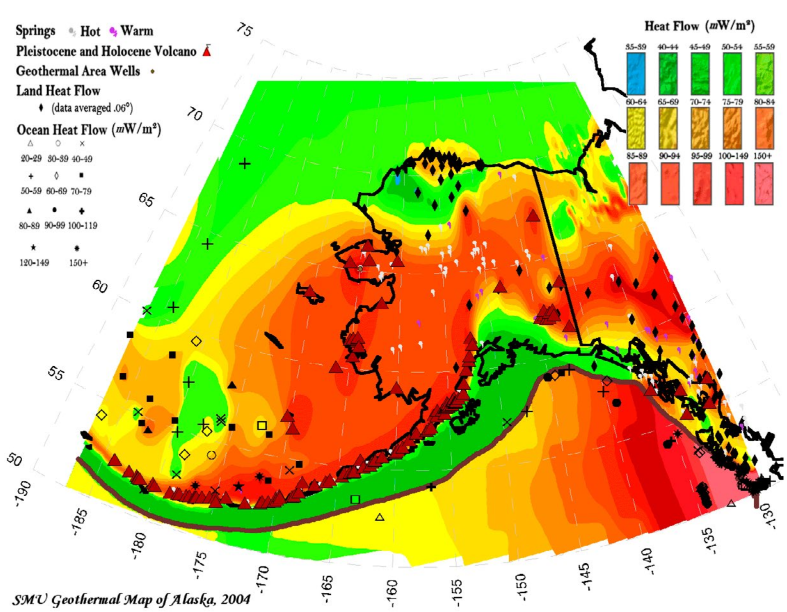

Figure 1. 2004 Geothermal Map of Alaska. Data on land are labeled with diamonds and hot springs are shown with white symbols. Note that data within Alaska are focused on the North Slope, with low data density elsewhere to constrain the contouring of heat flow through the interior part of the state (Blackwell and Richards, 2004).

Previous Data Collected in Alaska

The majority of heat flow data collected for the Alaskan portion of the 2004 Geothermal Map of North America (Figure 1) were along the North Slope in conjunction with the oil and gas industry in the latter half of the 20th century (Blackwell and Richards, 2004). Many of these sites were chosen with the goal of quantifying permafrost thickness and the thermal conditions, processes and sensitivity of the area. An auxiliary product of the permafrost studies was characterization of the thermal regime (Lachenbruch and Marshall, 1969; Deming et al., 1996). These studies were followed by attempts to fill data gaps, logging wells of opportunity within the interior of Alaska and southeast Alaska (Lawver et al., 1981; Sass et al., 1985). Since these major studies, there have been site specific studies associated with surface geothermal manifestations (Forbes et al., 1979; Erkan et al., 2008; Martini et al., 2011; Kolker et al., 2012; Miller et al., 2013). Presented in Figure 2 are locations of all data, new and old.

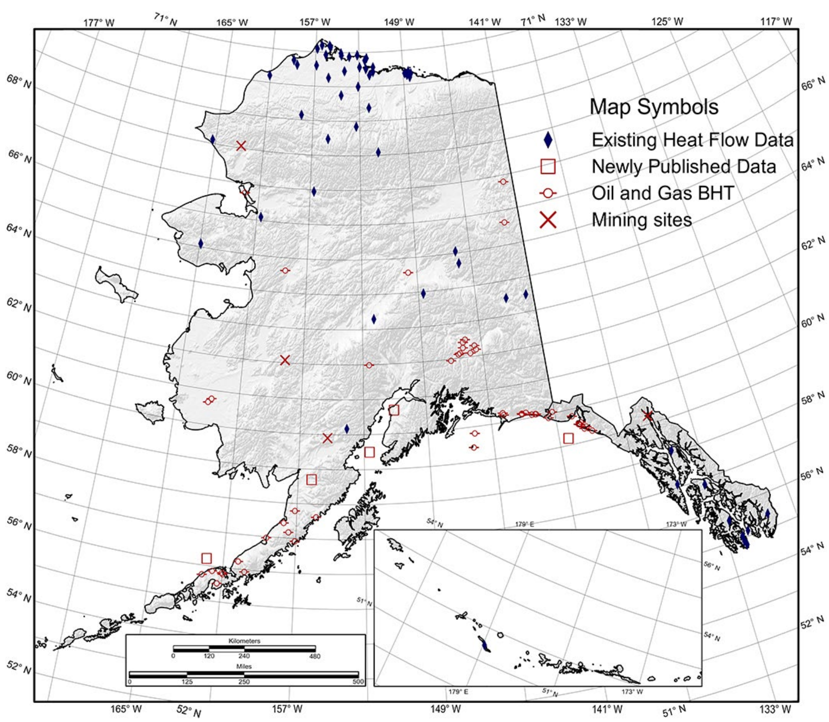

Figure 2. Data location map for all heat flow points used to contour the 2013 Geothermal Map of Alaska. Notice the sparse data within interior Alaska.

Methodology

Heat Flow Data Collection and Calculation

The Geothermal Map of Alaska illustrates the amount of heat flowing from the Earth's interior to the atmosphere. To calculate a heat flow value, the heat diffusion equation is simplified to only the vertical component, i.e., the geothermal gradient of a rock formation multiplied by the formation's thermal conductivity, as shown in Equation (1) (Carslaw and Jaeger, 1959; Beardsmore and Cull, 2001; Batir et al., 2013).

$$Q = \frac{\Delta T}{\Delta z} * k \tag{1}$$

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

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

K = thermal conductivity, W/m*K

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

The geothermal gradient is the rate of change in temperature with respect to depth within the 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 if 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%.

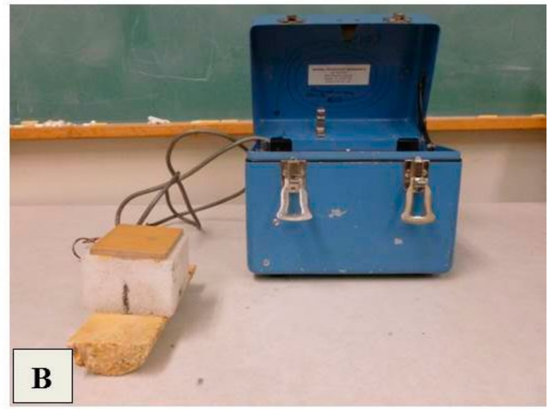

Figure 3. (A) The divided-bar thermal conductivity measurement apparatus. Samples are placed in between the press where the wooden blocks are located in the picture. (B) The needle probe measuring device. The tool shown here has an insulating surface glued to one side (with a piece of wood on top) so 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.

Thermal Conductivity, k

After determining geothermal 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 to compare 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 be a detailed lithology log from the well being examined. When unavailable, a basin or regional cross-sectional model was used; if even this information was not accessible, the area was given a volcanic or non-volcanic locality determination.

Gridding Procedure

Data were contoured using the Kriging method with a search ellipse elongated in a longitudinal direction, thus mimicking the same directional trend seen in the orientation of Alaska's geologic features. When contouring the 2013 GMAK, the first step was to generate a grid based on the available data. The next step was to adjust the contours in consideration of the regional geology in areas of no or inadequate site 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). In areas without well data, locations with high concentrations of surface geothermal manifestations were assigned heat flow values 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 and heat flow measurements. In order to emphasize locations with collected heat flow data, versus assigned values based on geologic constraints, the 2013 GMAK has a two layer color density scheme. A full list of assumptions and limitations to gridding of the sparse data within Alaska is discussed within the final report associated with the 2013 GMAK (Batir et al., 2013).

New Data Collected

Since 2007, a combination of rock samples and/or temperature logs were collected from 8 mineral exploration locations in

Table 1. New data added to the 2013 Geothermal Map of Alaska. Data is split into sources. All DC points were collected at Donlin Creek and averaged for a site heat flow. All RDM points are from Red Dog Mine, and were averaged for a site heat flow.

Published Values

Longitude	Latitude	Name	Depth (m)	Gradient (°C/km)	Gradient Interval (m)	Conductivity (W/m*K)	Heat Flow (mW/m2)	Quality
-161.950	56.200	COST 1	5090	31.0	1378-4975	1.8	56	A
-140.450	59.200	YAKUTAT 1	-	32.0	-	-	54	A
-156.195	58.701	NAKNEK	3195	49.1	0-1097	1.5	74	C
-152.674	59.498	COST 1-CI	3776	22.8	0-3775	2.5	57	C
-151.069	60.679	SWANSON	-	23.7	-	2.5	59	C

Mining Sites

Longitude	Latitude	Name	Depth (m)	Gradient (°C/km)	Gradient Interval (m)	Conductivity (W/m*K)	Heat Flow (mW/m2)	Quality
-158.197	62.079	DC_MW05-22	183	29.1	90-175	3.6	106	B
-158.197	62.079	DC_MW05-23a	178	24.9	120-140	3.8	95	B
-158.197	62.079	DC_MW05-23b	178	29.7	142.5-170	3.5	104	B
-158.197	62.079	DC_MW07-11	160	21.0	90-150	3.6	77	B
-162.861	68.071	RDM_T96-012	150	20.5	90-150	2.4	49	C
-162.861	68.071	RDM_T96-013	150	16.6	90-150	1.9	31	C
-155.279	59.901	PEBBLE PRS	1000	27.8	0-1000	2.5	70	BHT-C
-135.445	59.236	PALMER PRJ	600	23.5	0-600	3.4	81	BHT-C
-152.599	61.985	WHISTLER PRJ	875	25.0	0-875	2.8	71	BHT-C

Oil and Gas BHT

Longitude	Latitude	Name	Depth (m)	Gradient (°C/km)	Gradient Interval (m)	Conductivity (W/m*K)	Heat Flow (mW/m2)	Quality
-162.959	60.648	NAPATUK CK 1	4544	30.9	0-4544	2.5	77	BHT-C
-162.122	55.734	CATHEDRAL RIV UNIT 1	4359	33.6	0-4359	2.0	67	BHT-C
-162.114	66.740	NIMIUK PT 1	1925	40.3	0-1925	2.5	101	BHT-C
-161.569	55.863	DAVID RIV USA 1-A	4198	38.1	0-4198	2.0	76	BHT-C
-161.247	55.523	CANOE BAY UNIT 1	2025	40.5	0-2025	2.0	81	BHT-C
-161.022	55.843	HOODOO LK UNIT USA 1	2454	29.4	0-2454	2.0	59	BHT-C
-160.972	55.809	HOODOO LK UNIT USA 2	3427	36.5	0-3427	2.0	73	BHT-C
-160.173	56.215	SANDY RIV FED 1	3818	39.4	0-3818	2.0	79	BHT-C
-159.782	55.936	BIG RIV A-01	3466	64.3	0-3466	2.0	129	BHT-C
-158.685	56.967	PORT HEIDEN UNIT 1	4579	32.9	0-4579	2.0	66	BHT-C
-158.567	64.633	NULATO UNIT 1	3663	24.4	0-3663	2.5	61	BHT-C
-157.738	57.426	UGASHIK 1	2890	46.7	0-2890	2.0	93	BHT-C
-157.433	57.163	PAINTER CK 1	2412	43.3	0-2412	2.0	87	BHT-C
-157.110	57.784	BECHAROF 1	2751	40.4	0-2751	2.0	81	BHT-C
-157.046	56.916	KONIAG CHEVRON USA 1	3330	47.2	0-3330	2.0	94	BHT-C
-155.862	57.628	BEAR CK UNIT 1	3849	35.7	0-3849	2.0	71	BHT-C
-149.638	64.581	NENANA 1	934	38.7	0-934	2.5	97	BHT-C
-146.493	62.138	TAZLINA 1	1616	41.4	0-1616	2.5	103	BHT-C
-146.265	62.282	SALMONBERRY LK UNIT 1	1585	29.4	0-1585	2.5	73	BHT-C
-146.260	59.409	MIDDLETON IS ST 1	2522	24.1	0-2522	2.5	60	BHT-C
-146.234	62.431	RAINBOW FED 1	2412	47.1	0-2412	2.5	118	BHT-C
-146.071	62.509	RAINBOW FED 2	3663	29.6	0-3663	2.0	59	BHT-C
-145.811	62.106	MOOSE CK UNIT 1	915	31.0	0-915	2.5	77	BHT-C
-145.492	62.300	AHTNA INC 1	1574	34.4	0-1574	2.0	69	BHT-C
-145.411	62.190	AHTNA INC A-01	852	31.3	0-852	2.5	78	BHT-C
-144.210	60.264	BERING RIV UNIT 1	2397	31.8	0-2397	2.5	79	BHT-C
-144.165	60.210	BERING RIV UNIT 2	2421	32.3	0-2421	2.5	81	BHT-C
-143.039	60.157	KALIAKH RIV UNIT 2/RD	1700	41.9	0-1700	2.5	105	BHT-C
-143.024	60.136	KALIAKH RIV UNIT 1	1883	31.6	0-1883	2.0	63	BHT-C
-142.778	60.165	DUKTOTH RIV UNIT 1	1835	29.2	0-1835	2.0	58	BHT-C
-142.421	60.080	WHITE RIV UNIT 1	3699	28.8	0-3699	2.0	57	BHT-C
-142.210	60.073	WHITE RIV UNIT 3	4481	26.7	0-4481	2.0	53	BHT-C
-142.147	60.073	WHITE RIV UNIT 2	3168	31.1	0-3168	2.0	62	BHT-C
-142.141	65.649	DOYON LTD 1	2433	35.6	0-2433	2.0	71	BHT-C
-141.717	66.805	DOYON LTD 3	2078	44.5	0-2078	2.0	89	BHT-C
-141.425	59.897	RIOU BAY 1	3561	38.6	0-3561	2.0	77	BHT-C
-141.152	60.037	CHAIX HILLS 1/A	3365	38.2	0-3365	2.5	95	BHT-C
-139.991	59.797	MALASPINA UNIT 1-A	4125	15.1	0-4125	2.5	38	BHT-C
-139.674	59.526	YAKUTAT 1	3361	21.4	0-3361	2.0	43	BHT-C
-139.625	59.520	YAKUTAT 3	3054	30.2	0-3054	2.0	60	BHT-C
-139.587	59.514	YAKUTAT 2	3683	29.4	0-3683	2.0	59	BHT-C
-139.523	59.571	CORE HOLE 1	2812	33.1	0-2812	2.0	66	BHT-C
-139.373	59.371	CORE HOLE 2	3204	27.8	0-3204	2.0	56	BHT-C
-139.237	59.407	DANGEROUS RIV UNIT 1	3586	27.9	0-3586	2.0	56	BHT-C
-138.939	59.257	CORE HOLE 3	982	34.0	0-982	2.0	68	BHT-C
-162.760	60.753	NAPATUK CK CORE 2-A	652	17.1	0-652	2.5	17	BHT-D
-147.142	61.952	EUREKA 2	1735	28.4	0-1735	2.0	57	BHT-D
-146.607	62.109	TAWAWE LK UNIT 1	2632	31.7	0-2632	2.0	63	BHT-D
-146.105	59.805	C.O.S.T. ALASKA 1 DST-01	1670	33.1	0-1670	2.0	66	BHT-D
		SULLIVAN 2	3675	27.5	0-3675	2.0	55	BHT-D
		SULLIVAN PHILLIPS 1	2259	34.0	0-2259	2.0	68	BHT-D

Alaska for heat flow measurements, 5 of which were included in the gridding for the 2013 GMAK. Sites include the Red Dog Mine, Donlin Creek, Pebble Prospect, Whistler Project, Palmer Project, Usibelli Coal Mine, Ft. Knox Gold Mine, and True North Mine. A full list of new data, and data used to grid the 2013 GMAK are available within the final report (Batir et al., 2013). Additionally, published values were discovered in the literature that have now been included (Bergman et al., 1993; Bergman et al., 2008; Magoon, 1986; Vukich and Friedmann, 2011), and 78 oil and gas wells were examined for usable temperature data. 46 of the 78 examined have heat flows that were used for the gridding of the 2013 GMAK. Listed in Table 1 is all new data added in Alaska, separated by the source of data.

Discussion

The 2013 Geothermal Map of Alaska (GMAK) has a total of 56 new data points (Figure 4). The new data collected increased variability of the GMAK. Earthquake locations from 1973-2011 were overlain onto the 2013 GMAK (Figure 5) to examine seismically active zones versus the geologic contouring of heat flow method. This seismicity test was to validate using major faults as tectonic boundaries that may also act as thermal boundaries. Several linear earthquake trends appear that are not associated with major faults, but do coincide with hot spring groups (Waring, 1917). The general earthquake trends are in agreement with the constrained contouring based on specific geologic constraints.

Several interesting results came from the 2013 GMAK. The Copper River Basin has a higher heat flow in the volcanic gap between the Aleutian Volcanic Arc and the Wrangell Mountains than previously thought. New data added along the Alaska Peninsula show more variability than the 2004 Map. A priori knowledge suggested the entire Alaska Peninsula to have high heat flow and be viable for geothermal power generation. The new data suggest the high heat flow associated with the volcanic arc does not extend far into Bristol Bay; however, data are limited so that the contouring is relatively unconstrained. Data within interior Alaska also exhibit a high amount of variability (61-106 mW/m^2) that resembles a range of heat flows similar to

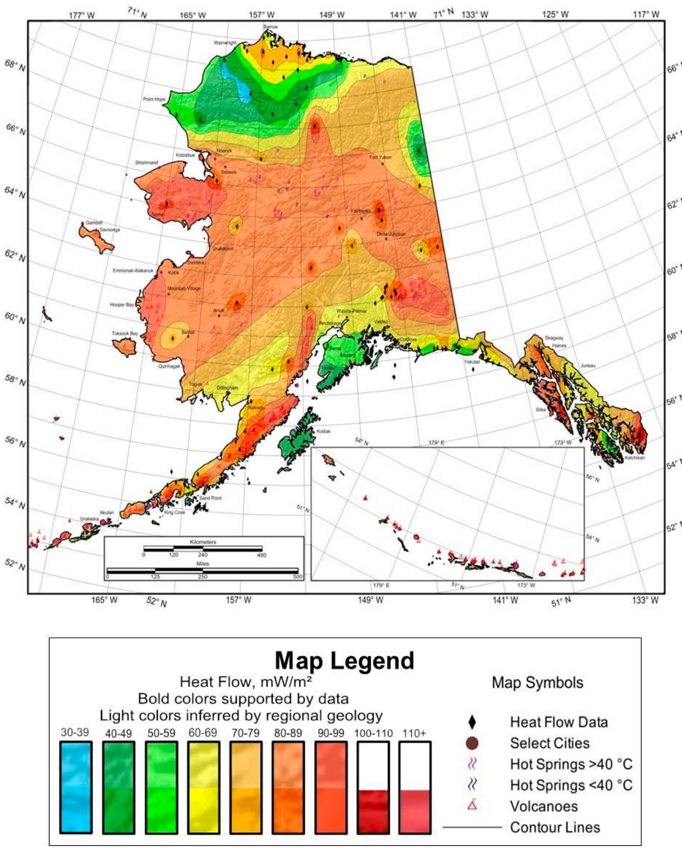

Figure 4. Geothermal Map of Alaska, 2013. Areas with collected temperature data to support contouring have bold colors; areas without discrete temperature measurements to support the contouring are displayed with light colors and are contoured based on regional geology. The color differences are shown in the legend. The legend also applies to Figure 4.

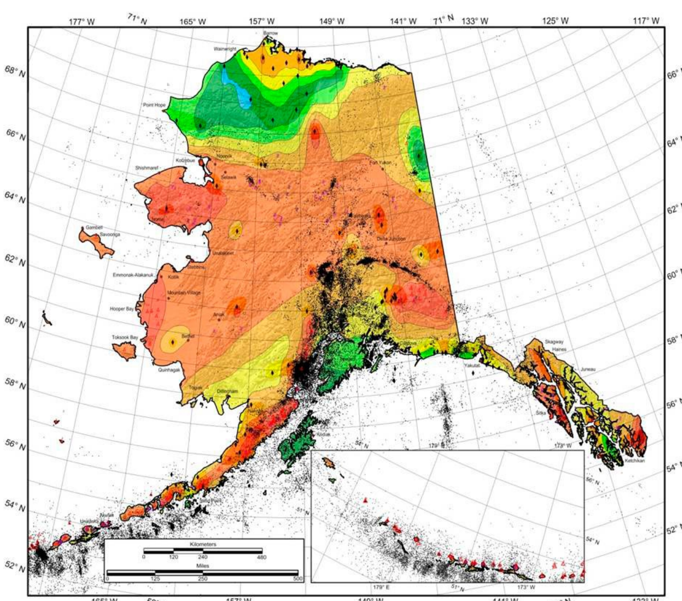

Figure 5. 2013 Geothermal Map of Alaska with earthquakes plotted as small black dots. Contouring of the data matches the active seismicity along the Denali fault well; however, there is high seismicity between Anchorage and the Denali fault that cannot be explained by the thermal regime because there is limited heat flow data in the area. The map legend can be found with Figure 4.

the Basin and Range in the conterminous United States (Blackwell and Richards, 2004).

This project increases our understanding of the regional thermal regime of Alaska but there is still much to be learned through more data collection. The future of geothermal energy exploration will need to include funding for drilling projects where data have shown potential for geothermal resources. Drilling is an expensive endeavor, but new locations are necessary to fill data gaps. This new edition of the Geothermal Map of Alaska 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 (Batir et al., 2013).

Conclusions

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 areas of the calculated sites. 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 throughout is not uniform and emphasizes the natural heterogeneity of heat flow, compounded by the complex geology of Alaska. More data need to be collected in specific areas of interest for site specific geothermal energy viability to be assessed. For this to occur, wide-spread data collection through collaboration with public and private agencies should be ongoing to identify the most productive areas for exploration of geothermal resources within Alaska.

Acknowledgements

The authors thank the companies and organizations that have supplied data, including: Alaska Oil and Gas Conservation Commission, Chena Hot Springs Resort, 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 and collecting data early on in this project.

References

Batir, J.F., Blackwell, D.D., and Richards, M.C., 2013. “Surface heat flow of Alaska: new insights into the thermal regime”, *Alaska Center for Energy and Power,* final report, pp. 44.

Beardsmore, G.R., and Cull, J.P., 2001. *Crustal Heat Flow: A Guide to Measurement and Modeling*, Cambridge, *Cambridge University Press*, pp. 324.

Bergman, S., Corrigan, J., Swenson, R., Talbot, J., Watts, A., and Van Kooten, G., 1993. "Fission Track, ^{40}Ar-^{39}Ar, and K-Ar Geochronology and Petrology of Cenozoic and Upper Mesozoic Rocks from the Gulf of Alaska Area and Yakutat #1 Well (OCS-Y-0211), 1992 Field Study Results", *ARCO Exploration and Production Technology, Exploration Research and Technical Services,* Final Report, pp. 199.

Bergman, S.C., Murphy, J., and Kelley, S. 2008. "Fission Track Geochronology of the North Aleutian COST #1 Well (OCS-8218), Bristol Bay Basin, Alaska", *Bristol Bay-Alaska Peninsula region, overview of 2004-2007 geologic research*, RI 2008-1J, 177-206.

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., Richards, M., Frone, Z., Batir, J.F., Ruzo, A., Dingwall, R., and 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., 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., 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.

Deming, D., Sass, J.H., and Lachenbruch, A.H., 1996. "Heat Flow and Subsurface Temperature, North Slope of Alaska", *in,* Johnsson, M.J. and Howell, eds., *Thermal Evolution of Sedimentary Basins in Alaska*, Washington, *U.S. Geological Survey Bulletin* 2142, 21-44.

Erkan, K., Holdmann, G., Benoit, W., and Blackwell, D. 2008. "Understanding the Chena Hot Springs, Alaska, Geothermal System Using Temperature and Pressure Data from Exploration Boreholes", *Geothermics,* 37, 6, 565-585.

Forbes, R.B., Wescott, E.M., Turner, D.L., Kienle, J., Osterkamp, T., Hawkins, D.B., Kline, J.T., Swanson, S., Reger, R.D., and Harrison, W., 1979. "A Geological and Geophysical Assessment of the Geothermal Potential of Pilgrim Springs, Alaska", *Geophysical Institute, UAF and Alaska D.G.G.S.*, preliminary report, pp. 39.

Förster, A., Merriam, D.F., and Hoth, P., 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, 1673-1693.

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 Development and Use of Geothermal Resources*, *U.S. Government 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.

Kolker, A.M., Stelling, P., Cumming, W., and Rohrs, D. 2012. "Exploration of the Akutan Geothermal Resource Area", *Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering,* 37, SGP-TR-194.

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.

Lachenbruch, A.H., and Marshall, B.V., 1969. "Heat flow in the Arctic", *ARCTIC*, 22, 300-311.

Lawver, L.A., Lachenbruch, A.H., and Munroe, R.J., 1981. "Heat Flow in Alaska", *in* Youloukian, Y.S., Judd, W.R., and Roy, R.F., *Physical Properties of Rocks and Minerals*, *Purdue Research Foundation*, II-2, 539-540.

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

Magoon, L.B., 1986. "Geologic Studies of the Lower Cook Inlet COST No. 1 Well, Alaska Outer Continental Shelf", *U.S. Geological Survey Bulletin* 1596, pp. 99.

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.

Martini, B.A., Lide, C., Owen, L., Walsh, P., Delwiche, B., and Payne, A., 2011. "Geothermal Resource Definition at Mt. Spurr, Alaska", *Geothermal Resources Council Transactions*, 35, 897-904.

Miller, J.K., Prakash, A., Daanen, R., Haselwimmer, C., Whalen, M., Benoit, D., Cumming, W., Clark, A.C., Mager, M., and Holdmann, G., 2013. "Geologic Model of the Geothermal Anomaly at Pilgrim Hot Springs, Seward Peninsula, Alaska", *Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering,* 38, SGP-TR-198.

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.

Plafker, G., and Berg, H.G., 1994. "Overview of the geology and tectonic evolution of Alaska", *in* Plafker, G. and Berg, H.C. eds., The Geology of Alaska, Boulder, CO., *Geological Society of America*, The Geology of North America, G-1, 989-1021.

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

Sass, J.H., Lawver, L.A., and Munroe, R.J., 1985. "A heat-flow reconnaissance of southeastern Alaska", *Canada Journal of Ear. Sci.*, 22, 416-421.

Vukich, D., and Friedmann, G., 2011. "Southwest Alaska Regional Geothermal Energy Project", *Naknek Electric Association*, DOE Geothermal Technologies Program 2011 Peer Review Presentation, pp. 15.

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