ERDC/CRREL TR-23-14

Cold Regions Research and Engineering Laboratory

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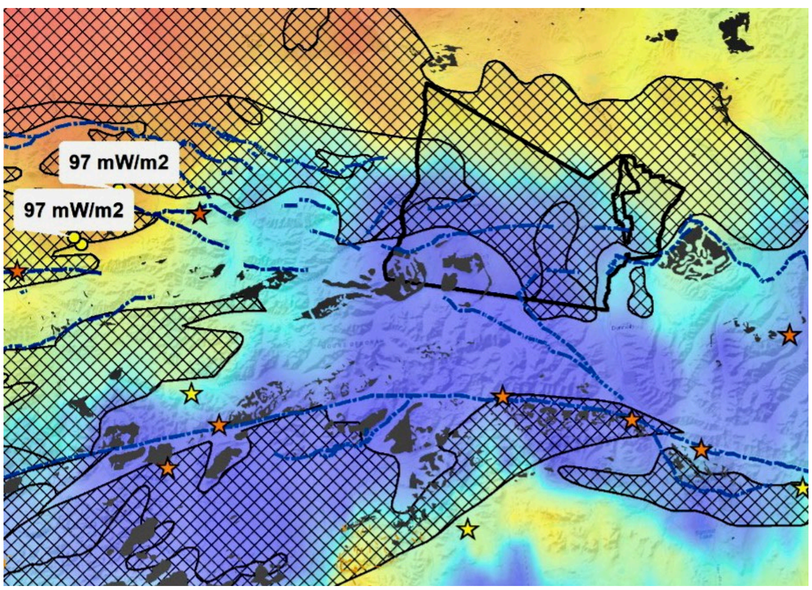
Phase I Geothermal Opportunities Assessment of the Delta Junction Area, Alaska

Viktoria R. Gisladottir, Amanda Kolker, Zachary J. Zody, and Ian Warren

September 2023



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Phase I Geothermal Opportunities Assessment of the Delta Junction Area, Alaska

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Abstract

To enhance energy resilience at military installations in Interior Alaska, we are exploring geothermal energy, which harvests Earth's heat to provide thermal energy, electricity, or both. Parts of Interior Alaska have high subsurface heat flow, likely related to high-heat-producing granites. While electric load is usually the focus of energy resilience; in cold regions, the thermal load dominates energy demand, and operations can be sensitive to it. A local geothermal energy source enhances energy resilience by providing baseload energy and lessening supply chain demand. Geothermal energy technology is mature and often economical, but resource location and assessment remain challenging.

We present exploration methods for a geothermal feasibility study for Interior Alaska and Phase I prefeasibility study results assessing opportunities to develop geothermal at Fort Greely, Alaska. We present possible geothermal resource types, their potential uses, likelihood of existence, and development risk. We also present custom methodology for locating the resources, associated uncertainty, and the impact of finding each resource. Phase I shows geothermal at Fort Greely survives the elimination test. Investment into a Phase II field study to address knowledge gaps should consider the higher risk in comparison to other geothermal plays due to new methodology and sparse existing data.

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Preface

This study was conducted for Headquarters, US Army Corps of Engineers, under PE 0603734A, Project T15. The technical monitor was Dr. Thomas A Douglas, US Army Engineer Research and Development Center, Cold Regions Research Laboratory (ERDC-CRREL).

The work was performed by the Terrestrial and Cryospheric Science Branch of the Research and Engineering Division, ERDC-CRREL. At the time of publication, Dr. John Weatherly was branch chief and acting division chief. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

Portions of Section 2.2.1 have been modified and reprinted with permission from A. Kolker, "Geologic Setting of the Central Alaskan Hot Springs Belt: Implications for Geothermal Resource Capacity and Sustainable Energy Production" (PhD thesis, University of Alaska Fairbanks, 2008). Portions of that section have also been modified and reprinted from A. Kolker, K. Young, A. Badgett, and J. Bednarek, *GeoRePORT Case Study Examples: Reporting Using the Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT)* (Golden, CO: National Renewable Energy Laboratory, 2019). Public domain.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

The US Army Corps of Engineers (USACE) is looking for resilient renewable energy solutions. Operations at installations in cold region are highly sensitive to the resilience of the thermal load, as system failure represents life-threating conditions. Additionally, in cold regions, heating represents a majority of the annual energy consumption. At Fort Greely this thermal load is largely met using electricity.

Geothermal energy is a local sustainable energy source that harvests the earth's heat to provide thermal energy and electricity. Geothermal energy can function as a baseload resilient energy source independent of external power or be incorporated into heating systems via direct use. Because of the nature of geothermal technology, being a thermal load, the economic upside is often stronger in cold regions. Combining that with the remoteness of installations such as Fort Greely makes geothermal even more competitive against other energy sources that need to be brought in through the supply chain.

We are interested in exploring the possibility of harnessing geothermal energy to enhance energy resilience at military installations in Interior Alaska. Interior Alaska has high subsurface heat flow, likely due to the presence of high-heat-producing (HHP) granites. To tap into this extensive energy potential in Interior Alaska would require establishing geological region-specific systematic resource location methods in parallel with data collection and analysis. A systematic approach to locate geothermal resources from radiogenic heating from HHP granites currently does not exist. Identifying previously unknown geothermal resources would advance Alaska toward the goal of providing baseline heating and electrical load from a sustainable source that is independent of external power. This could support mission readiness by increasing the resiliency of installation power supply and decreasing cost in a reasonable period at installations.

The US Army Cold Regions Research and Engineering Laboratory (CRREL) and the National Renewable Energy Laboratory (NREL) have a shared interest in exploring the feasibility of geothermal energy applications in Alaska. USACE recently published a *Resilience Initiative*

Roadmap in which *resilience* is defined as “the ability to anticipate, prepare for and adapt to changing conditions and withstand and recover from disruptions” (USACE 2016, 1). The *Roadmap* develops principles for resiliency and a framework for action, including “resilience considerations for military installations” (8). Under this framework, each service is tasked with determining “the range of actions to be taken to increase installation resilience and readiness in conjunction with strategic goals” (8).

Geothermal energy encompasses a large source of untapped potential energy for electricity generation and heating. In its most recent report, the US Department of Energy states that up to 60 GW* of US energy needs can come from untapped geothermal resources by 2050 (Augustine et al. 2019). Moreover, not only are geothermal resources substantial but they are also unique among sustainable energy sources in their ability to provide constant power when developed and not wax or wane with load amount.

Geothermal energy production involves using the earth’s heat to provide thermal energy (e.g., space heating or domestic water) or electricity. The two prongs of geothermal is shallow geothermal and deep geothermal. *Shallow geothermal* is when ground-source heat pumps use the earth’s top subsurface as a heat source (winter) or sink (summer) for central heating and cooling systems. *Deep geothermal* is when heat from deep within the subsurface is brought to the surface to produce electricity or thermal load. Deep geothermal can be used in geographic regions where suitable hydrothermal sources are located, and these sources are sometimes referred to as *high-temperature fields*. For electric production to be feasible in a high-temperature field, the field must have regions where fractures, fluid, and high temperature intersect. Those intersections can be targeted for production where the thermal energy is carried by geothermal fluid from wells to the surface. The fluid from the geothermal well is then funneled into a power plant where the liquid goes through a high-pressure steam separator. The steam runs the turbine for electric production, and the liquid (brine) is reinjected into the field. Many plants additionally have a heat exchanger to recapture waste heat from the brine to harvest thermal energy (e.g., utilization in space heating and domestic water systems) before reinjecting it into the reservoir. The brine reinjection into the field is

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: U.S Government Publishing Office, 2016), 248–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

critical both to enhance the sustainability and economics of the production site and for environmental protection.

Energy resilience often focuses on the resilience of the electric load; but in some regions, such as Interior Alaska, operations are highly sensitive to the resilience of the thermal load. At an installation in Interior Alaska in the deep of winter, a failure event of the thermal load would result in temperature drops low enough to be a threat to life, mission, and infrastructure. In addition to the thermal load being a critical component to operations, it is also the majority of the annual energy consumption, at approximately 80%. Therefore, not only is the thermal load a key component of energy resilience, but it is also a key component of the cost and the installation's dependence on the fuel's supply chain. That is why geothermal energy, a natural thermal load, lends itself as a distinctly useful resilient energy resource in the cold.

Geothermal energy is particularly suited for use in cold regions, both in regard to resilience (i.e., on-site baseload sustainable energy) and economic benefit. If the production and use is in a remote cold region, then eliminating the supply chain for the fuel source can increase resilience and reduce cost. Even in scenarios where geothermal does not become the sole energy source, it increases resilience by diversifying the fuel sources. The high thermal demand in cold regions also increases the value of geothermal, as harvesting otherwise untapped heat byproduct compared to cooling dominant environments increases the economic upside of the production. Additionally, cold ambient temperatures provide a greater temperature differential (ΔT) between a heat source and a heat sink, making lower-temperature geothermal resources more economically feasible than in locations with warmer climates and allowing use of a wider temperature range. Chena Hot Springs is an example of this, located in Interior Alaska, where a geothermal power plant is operated using approximately 74°C discharge water (Erkan et al. 2008). Additionally, the geothermal industry has started to produce plug-and-play production units for those high-temperature geothermal fields on the lower end of the temperature range, which in some cases can bring costs down. Historically, the focus has been on the higher range of high-temperature fields, but as technology advances and the awareness of the increased resilience of local sustainable fuel sources provided by low-temperature fields increases, these fields become increasingly of interest, especially in cold regions. Early work in Yukon targeting those lower-range high-temperature fields has been initiated (Fraser et al. 2018; Witter et al. 2018). Because of Yukon's geological similarities to Interior Alaska, each region could feed into the knowledge and method building of the other's.

Supply-chain disruptions can be a risk factor in energy supply for remote facilities in cold regions like those in Alaska, as isolation and harsh environments increase the negative effects of sudden change events such as power disruption. On-site energy production with sustainable sources produced locally would mitigate that risk and possibly reduce cost. With the energy being produced on-site, any supply-line disruption would not alter the base load available from the geothermal resource. This falls in line with the overall USACE goals of increasing community resiliency and sustainability.

The challenge and risk with geothermal energy harvesting is not the technology or necessarily the economic feasibility of the production but locating the geothermal resource. The production technology is well established and economically competitive globally. Geothermal heat and power is utilized particularly in cold regions, such as Iceland and Northern Europe, where there is a high demand for a thermal load. For a resource to be utilized for conventional geothermal heat and power, it requires heat, fluid, and fractures. Such resources are often located hundreds if not thousands of feet below the subsurface. The difficulty of locating a resource also varies based on geography, and many areas of geothermal interest do not have fully prospected substructures and often exist in remote locations (Hervey et al. 2014). Areas where there is history of geothermal harvesting often have more available data and a well-established geological region-specific systematic methodology. This applies to both "blind" systems and systems with surface manifestations.

Locating a natural resource deep in the subsurface has a set of challenges and associated risk that are enhanced in Alaska due to data sparsity and lack of precedence and methodology. When there is robust data and methodology for the geographic setting, the risk becomes lower. Regions such as northern California, New Zealand, and Iceland that have passed the initial challenge of establishing a methodology and data sets have an advantage when analyzing where to go after a resource and have lower risk involved in pursuing the target. In addition to the lack of precedence of robust geothermal harvesting, Alaska often has sparser data sets than other regions where geothermal prospecting is done but has numerous regions of geothermal potential. Many of these are related to magmatic heat sources, but Interior Alaska is unique in that it has isolated geothermal systems with potential for heat harvesting related to nonmagmatic origins. Successful development has occurred at the Chena Hot Springs northeast of Fairbanks (Erkan et al. 2008) by using a low-temperature radiogenic geothermal resource for heat and power. With the increased interest in use of low-temperature fields in cold climate regions such as Yukon, resources are being invested in developing methods and data collection (Fraser et al. 2018).

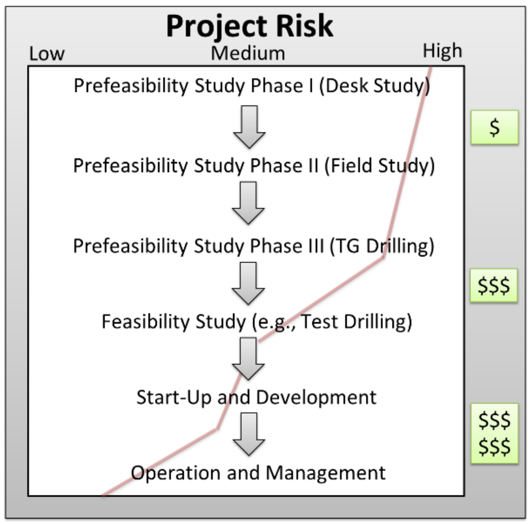
1.2 Objective

The purpose of this technical report is (1) to begin developing a systematic approach for locating geothermal resources near military installations in Interior Alaska (e.g., Fort Greely); (2) to provide a preliminary assessment of the opportunities to develop geothermal technologies at the Donnelly Training Area near US Army Fort Greely Army Base (combined sites henceforth called Fort Greely) to increase resiliency and reduction of electricity and fuel use; and (3) to guide exploration efforts that will be a part of a prefeasibility study for geothermal energy development at Fort Greely looking at the likelihood of a resource existing and its developmental risk.

1.3 Approach

For geothermal prospecting, the World Bank advises the use of a phased approach, a practice widely used in industry (Hervey et al. 2014). This strategy focuses on retiring risk at a pace that exceeds the increase in investment as each phase is systematically completed. Each step looks at the likelihood of success and filters out dead prospects. As in other phased elimination trials (e.g., multiphase pharmaceutical drug trails), each phase can only eliminate a prospect, and therefore it does not validate the prospective area. Rather than starting with a full feasibility study in subsurface exploration that requires a significant capital investment, geothermal exploration focuses on a phased narrowing down of the prospective geographic area, minimizing the economic risk. This prefeasibility study has two phases: (1) a regional-scale desk study and data analysis phase, resulting in a narrowing of the prospective area, and (2) one or more field-study phases of targeted areas. The completion of these two successive phases lays the foundation for risk-responsible decision-making in subsequent phases. We propose the addition of a third phase in some regions of Interior Alaska where thermal-gradient drilling would take place. Figure 1 shows an overview of the full development process made from a synthesis of the methods presented by the World Bank and United Nations University (Hervey et al. 2014; Arnason and Gislason 2009) with the addition of the third prefeasibility study phase.

Figure 1. Phased risk-reduction development process for geothermal prospecting. (Image adapted from Hervey et al. 2014 and Arnason and Gislason 2009.)



Phase I involves collecting and analyzing all relevant known information about the geology and geophysics of the region of interest. This includes all peer-reviewed literature and data from previous surveys. The goal of Phase I is to collect and analyze existing data, identify knowledge gaps, and design field studies to address them. Successful completion of Phase I and the subsequent field studies is integral to project success, as the cost of subsequent phases (e.g., feasibility study) rises exponentially.

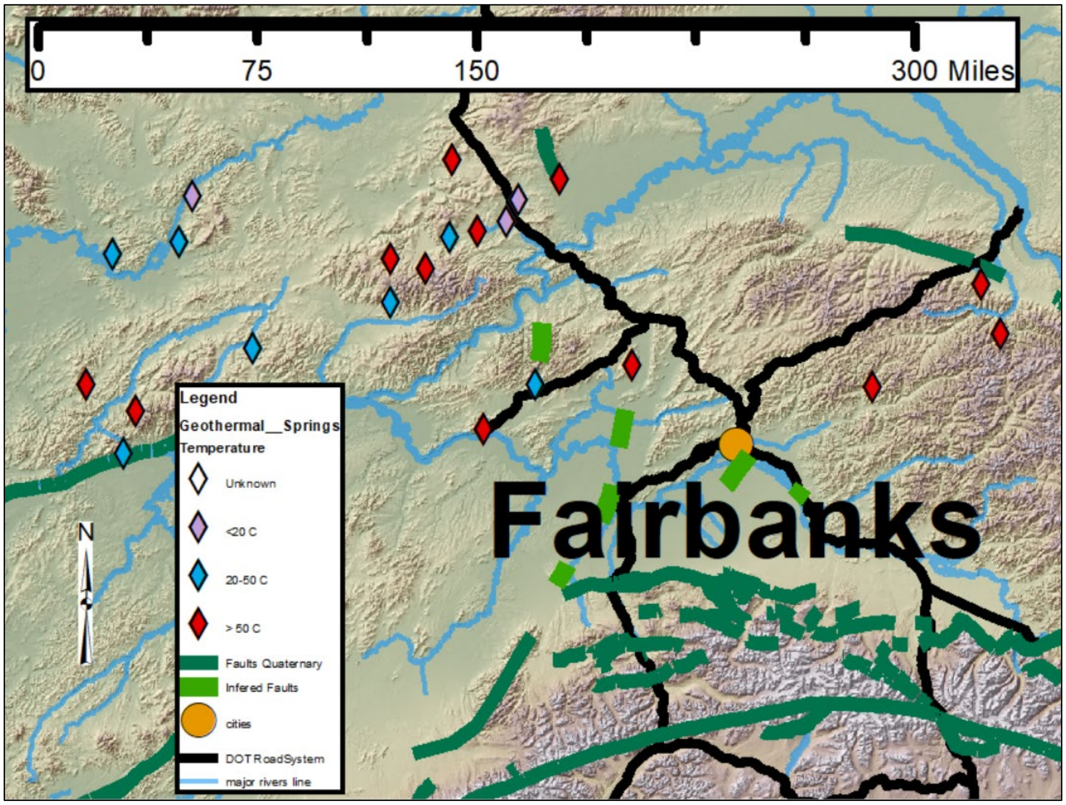
Following this phased approach for risk mitigation, the results from Phase I are presented here, including a review of existing data, identification of data gaps, and recommendations for the methodology for geological and geophysical exploration work planned to complete the full prefeasibility study. Phase II will perform the necessary geological and geophysical exploration to address the knowledge and data gaps identified in Phase I. The completion of Phase I and the design of a methodology for Phase II will provide information to assess the prospective value of geothermal at Fort Greely.

Section 2 discusses geothermal energy in Interior Alaska. Section 3 provides an overview of the relevant data for Phase I of geothermal prospecting in the Fort Greely area. From those findings, in Section 4 we identify potential geothermal resources, or *plays*; the likelihood of their presence; and the associated exploration and development risk. For each of those plays, we inventoried predrilling exploration methods, considering both existing methods and custom approaches adapted to the particular geological setting of Interior Alaska. Additionally, we review a small number of methods selected to be used as part of Phase II of the prefeasibility study. Section 5 provides an overview of a geothermal exploration in a geographically complimentary area: Yukon, Canada. Finally, Section 6 presents the conclusion and our recommendations.

2 Geothermal Energy in Interior Alaska

For the purposes of this report, *Interior Alaska* is loosely defined as the band across the state bounded by the Alaska Range and Brooks Range. Heat-flow estimates of Alaska indicate a vast geothermal resource beneath the surface (Batir et al. 2016), and prior statistical analysis by the US Geological Survey (USGS) estimates that the state has thousands of megawatts electric (MWe) in undiscovered geothermal resources (Williams et al. 2008). Undiscovered geothermal resources for heating and direct use were not included in this estimate, meaning the total potential is likely even higher (Augustine et al. 2019). Known geothermal surface manifestations in Interior Alaska form the Central Alaskan Hot Springs Belt (CAHSB). The CAHSB spreads across the full Interior and contains multiple non-communicating natural hot spring systems, including in the Fairbanks area (see Laney and Brizzee 2003 for a geothermal feature map of Alaska and Figure 2 for hot springs near Fairbanks). The systems are not derived from magmatic sources or active volcanism, and Kolker et al. (2008) believe that the origin of heat for these systems is related to crustal intrusions of granitic plutons. This region could potentially host isolated pockets of harvestable heat due to such intrusions without surface manifestation (i.e., hot springs), known as "blind" or concealed deep geothermal resources. Indicators for systems analogous to known hot springs in the region are of focus here given that no other known geothermal activity is present.

Figure 2. Fairbanks-area hot springs. (Data sources: Motyka et al. 1983; Koehler 2013.)



2.1 Geologic setting of Interior Alaska

2.1.1 Rock types

As summarized by Goldfarb et al. (2007), the eastern part of Interior Alaska is primarily underlain by metamorphic formations with some sedimentary and magmatic units. Cretaceous-aged rocks have widely intruded on country rocks. More detailed information on the geology is available in Goldfarb et al. (2007) and Foster et al. (1994). Some Cretaceous-age batholiths (which at the rock scale are called plutons or intrusives) in Interior Alaska have high concentrations of radioelements uranium (U), thorium (Th), and potassium (K) and therefore generate heat at anomalous levels (Kolker 2008).

2.1.2 Structure

Much of Interior Alaska lies between two major crustal strike-slip fault systems. This zone is a boundary between the metamorphic rocks of interest here and the greater North American craton (Gabrielse et al. 2006). Saltus (2007) presents further details and information on the use of magnetic anomalies to derive fault zones.

The two fault systems contain zones of broadly distributed seismicity that trend northeast (Ratchkovski and Hansen 2002). Epicenters are not well located, and no studies have identified a single fault as the source of any seismic zones. For further reference, see Newberry et al. (1996), who mapped the seismic zones in detail. Additionally, Page and Plafker (1995) suggested a block-rotation model for crustal activity in the region.

2.1.3 Ore deposits and mineralization

The Tintina Gold Province overlaps the study area. Gough and Day (2007) provide information on the major ore deposits, characterization of the distribution of pathfinder elements arsenic (As) and antimony (Sb) associated with mineralizing systems, and more. Of note is the effectiveness of the mentioned elements specifically to understanding geochemical controls on mobility and deposition of minerals in the province (Gough and Day 2007).

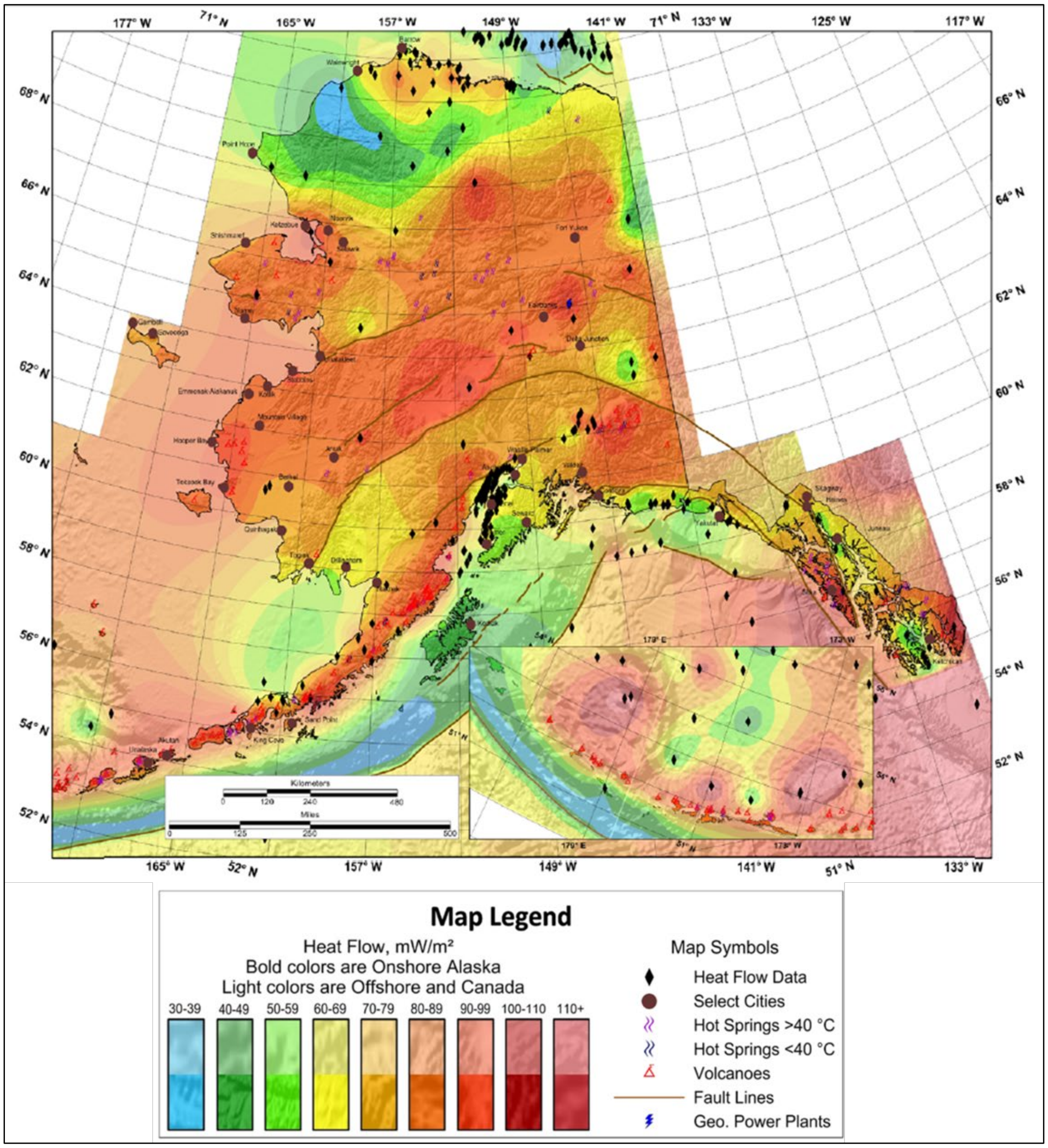
2.1.4 Heat flow

Batir et al. (2013) created an updated heat-flow map for Alaska from 310 deep wells in Alaska, most from the North Slope, in the Cook Inlet, and along the Aleutian Volcanic Arc (Figure 3). However, they caution against use of this heat-flow map for geothermal prospecting:

> 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 (Batir et al. 2013, 9–10).

The updated heat-flow map of Alaska indicates a vast geothermal resource beneath the surface. Interior Alaska has generally high heat flow but also highly variable heat-flow values, which range from 61 to 106 mW/m^2, excluding areas of known geothermal activity (Batir et al. 2016). The mean heat flow over the continental crust is 65 mW/m^2.

Figure 3. Updated heat flow map of Alaska (reprinted from Batir et al. 2016, 374, by permission of Oxford University Press), showing higher-than-average heat flow (65 mW/m² for continental crust) for most of Interior Alaska.



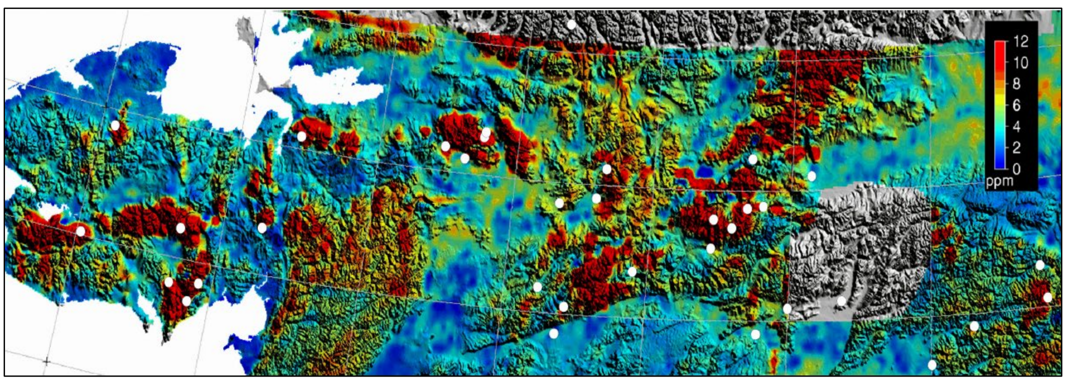
2.2 Central Alaska Hot Springs Belt (CAHSB)

A geothermal feasibility study in Interior Alaska would rely on a detailed analysis of the characteristics of the CAHSB. Kolker (2008) presents a comprehensive review of the CAHSB, and Section 2.2.1 includes excerpts containing relevant information.

2.2.1 Characteristics of the CAHSB

The CAHSB is a vast low-temperature geothermal regime that stretches east–west from the Seward Peninsula in the west to Yukon, Canada. Interior Alaska contains many rocks of intrusive origin, or *plutonic* rocks. Some intrusive bodies are of multiple ages, spanning up to 35 million years (Jones and Forbes 1976; Wallace 1979; Kolker et al. 2007). The bulk of the intrusive rocks are granitoids (Miller and Bunker 1975), and some contain anomalously high concentrations of radioactive elements U and Th, as shown in Figure 4 (Eakins et al. 1977; Miller and Johnson 1978; Reed and Miller 1980; Newberry 2000).

Figure 4. Hot springs (*white circles*) and surface-equivalent Thorium (Th) concentrations (from Saltus et al. 1999), draped over a shaded Alaskan digital elevated model. Colors represent equivalent Th in parts per million averaged over the upper meter of the land surface, data from airborne gamma surveys. (Image and caption reproduced with permission from Kolker 2008.)

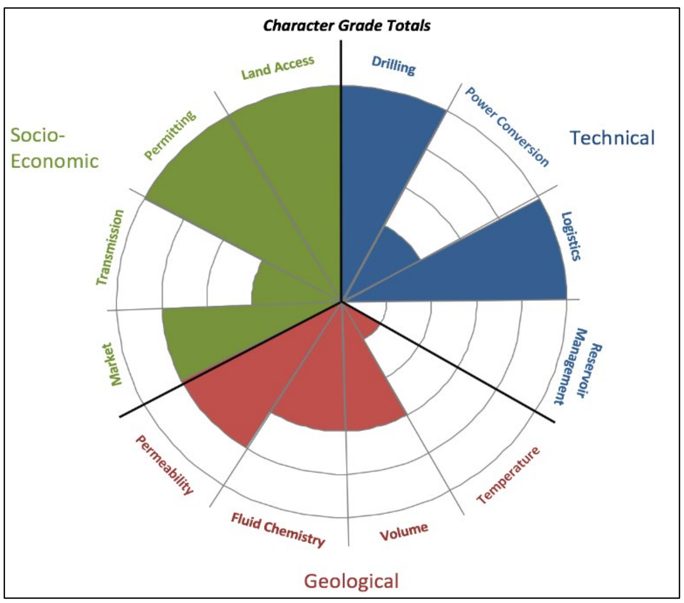


The 2,000-mile-long CAHSB contains approximately 30 low- to moderate-temperature hot springs, including Chena Hot Springs, and is associated with granitoid plutons of Cretaceous to Tertiary age (Kolker 2008). Thermal springs in the CAHSB all have alkali chloride–type waters at temperatures between 30°C and 88°C (average about 55°C). The bulk of the springs are dilute (total dissolved solids less than 1500 ppm), neutral pH, alkali chloride–type waters (Miller et al. 1973).

Chena Hot Springs Resort operates the only geothermal power plant in Alaska, with an installed capacity of 0.4 MW, utilizing a 73°C hot-water resource (Erkan et al. 2008). The Chena geothermal area is located approximately 100 km north of the Fort Greely study area and is also bound by the large-scale Denali and Tintina Faults.

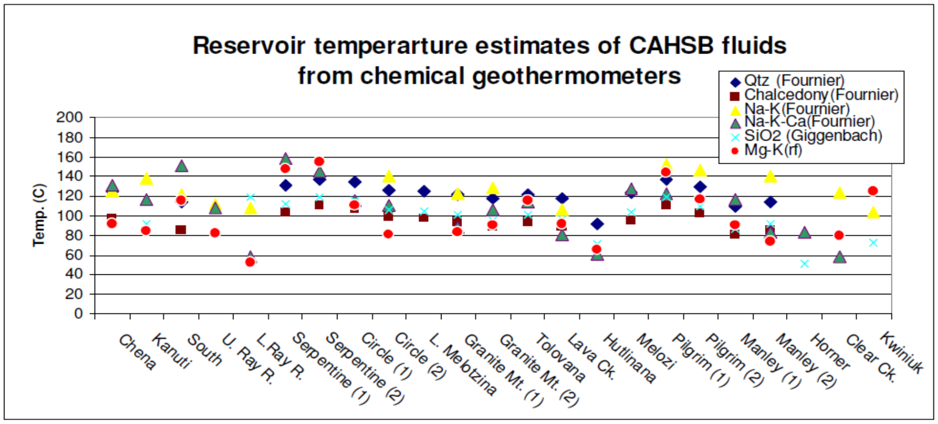
Installed in 2006, the organic rankine cycle plant successfully operates despite extremely low thermal efficiency due to the low-temperature geothermal resource (Holdmann 2007). Figure 5 shows the resource "grade" for the Chena geothermal using NREL's GeoRePORT tool (Kolker et al. 2019). Chena is a high-permeability, shallow geothermal system with a low overall temperature. These unique attributes can be seen in three of the character grades: temperature, drilling (the high drilling grade is driven largely by the system's shallow depth and low temperature), and low power conversion grade. Though the deeper reservoir is thought to have higher temperatures as estimated from geothermometry (Kolker 2008; Erkan et al. 2008), the fluids used for power production come from relatively shallow wells and do not attain these predicted reservoir temperatures.

Figure 5. GeoRePORT grades for Chena Hot Springs attributes, highlighting that many attributes are unconventional for a geothermal power project (low temperature, inefficient power conversion, and no transmission). (Image reproduced from Kolker et al. 2019. Public domain.)



Unlike the more common hydrothermal reservoirs (i.e., magmatic or deep crustal source heat), CAHSB "reservoirs" are likely to be low to moderate temperature (Kolker 2008). This is corroborated by the modest reservoir temperatures predicted by chemical geothermometry, ranging from 59°C to 150°C (Figure 6).

Figure 6. Reservoir temperatures for hot springs in the Central Alaskan Hot Springs Belt (CAHSB), as estimated by six chemical geothermometers. The chalcedony geothermometer method is likely the most accurate for CAHSB type fluids. (Image reprinted with permission from Kolker 2008.)



2.2.2 Occurrence model for CAHSB hydrothermal resources

The low-temperature geothermal resource of the CAHSB is poorly understood. One explanation for the resource could be deep circulation of meteoric water along faults and fractures. Kolker (2008) proposed and tested an alternative heat source model that radiogenic heating from HHP granites is the driver of geothermal activity in the CAHSB. According to this model, hot spring occurrence in the CAHSB correlates to intrusive bodies (granites, granodiorites, and monzogranites) with elevated U, Th, K concentrations. At Chena Hot Springs, older (Cretaceous age) granodiorite overlays and conceals younger HHP Tertiary granite, which mineral evidence suggests is likely to be voluminous at depth. This model may apply to the entire belt of more than 30 hot springs in the CAHSB system as well as to at least 10 hot springs in Yukon, Canada (Figure 4).

3 Resource Location Data for Fort Greely

The quantitative and qualitative data needed for the prefeasibility study fall under four categories—preliminary survey, geological and surface studies, geochemical surveys, and geophysical surveys. The prefeasibility study is the first step in iteratively working through the geothermal development process as a whole. As prescribed by the geothermal exploration best practices, once this data has been collected, the important step can be made to move onto test drilling. Risk retirement is a key factor in any resource exploration because of the inherent costs and limited volume of geospatial data. The results of drilling are a key go/no-go point in many exploration operations and feed directly into the feasibility study phase. Figure 1 illustrates the risk-cost trade-off at each stage of prospecting and development.

As Figure 1 shows, a successful completion of the test drilling phase significantly retires risk and allows for full feasibility planning to occur. The ultimate goal of the process, then, is to collect, interpret, and communicate all the literature and public data available on these topics so that a test plan can be developed to fill in knowledge gaps and subsequently design a drilling plan or put the project in stasis.

In the initial phase, information is gathered by conducting a comprehensive desk study of the peer reviewed literature and querying public data sets for previously archived field data. Since Alaska has long been relevant for both scientific and mineral prospecting reasons, various institutions have been collecting geological and environmental data in the Delta Junction area for decades. This allows us to leverage the results of previous efforts toward identifying geothermal indicators. We used ArcGIS software to centralize and manage the developed database. Important insights from the literature review are discussed in our report, and literature is also archived with the database for future reference.

This study used several existing and custom geographic information system (GIS) models. CRREL and NREL constructed models from the ground up by using relevant available raw data and preconstructed GIS models. Custom models all point to versions of the data transformed into ArcGIS geodatabases for simplicity and process streamlining. Publicly available models from data curators such as USGS and the National Geothermal

Data System (NGDS) were siloed away from custom models. The customized project databases are kept separate from the original source data and premade models. The customized models contain the data most pertinent to geothermal prospecting at Fort Greely.

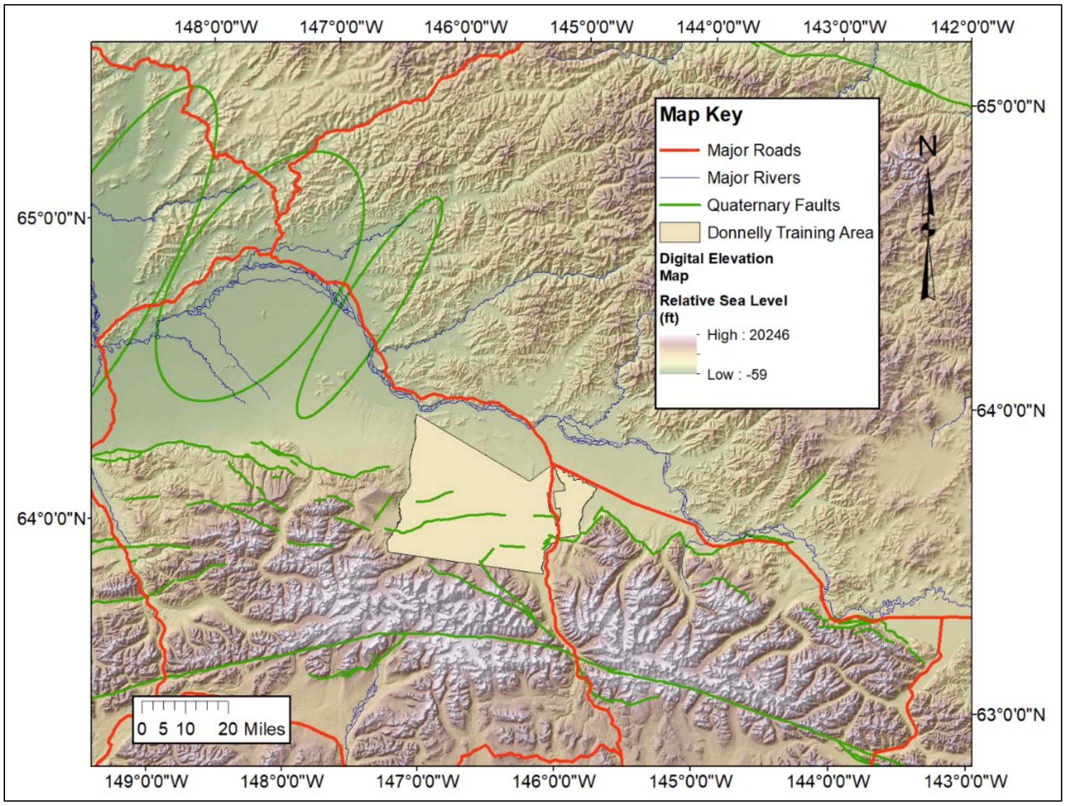
The end goal of data aggregation, cleaning, and management is to synthesize all quantitative and some qualitative data in ArcGIS so that a comprehensive, dynamic prospecting model for Fort Greely exists, can be maintained, and can be updated with the addition of collected field data. Preliminary analysis of this data is an important part of Phase I. Combining the desk study with data analysis allows for geothermal indicators and field-study targets to be identified. Once relevant insight is gleaned from the available data and literature, knowledge gaps can be identified, and any field studies can be designed in a more targeted manner.

3.1 Geology of Fort Greely

3.1.1 Geographic setting

Fort Greely is located in the Tanana Basin, just north of the Alaska Range and the Denali Fault. Several smaller-scale Quaternary faults cut across the study area and have important displacement histories that include normal movement (Figure 7).

Figure 7. Map showing the Fort Greely study area (labelled as "Donnelly Training Area") and nearby roads overlaid on a digital elevation map. Major rivers and Quaternary faults are shown in *blue* and *green*, respectively (*green circles* in *upper left corner* mark seismically active areas with no known faults).



3.1.2 Rock types

Fort Greely is on a large alluvial-fan-like feature in the Tanana Basin, immediately north of the Alaska Range. The majority of the subsurface at Fort Greely is made up of unconsolidated surficial deposits of both glacial and alluvial origin. The thickness of the alluvial deposits in the study area is approximately 500 m deep, according to the USGS sedimentary basin map. Glacial moraines are present along the Delta River valley. The only rock exposures in the study area are granodiorites and quartz monzonites, with minor metamorphic rocks of Paleozoic age. Those exposures occur as part of the Alaska Range foothills complex, located in the southwestern corner of the study area. Further details on the surficial deposits and unconsolidated materials in the Big Delta area are in Wilcox (1980) and Nelson (1995). Figure 8 and Figure 9 show the surface geology of the Donnelly Training Area and generalized geologic setting of the study area, respectively.

Figure 8. Geologic map of the study area, also called Donnelly Training Area. (Data source: USGS 2015.)

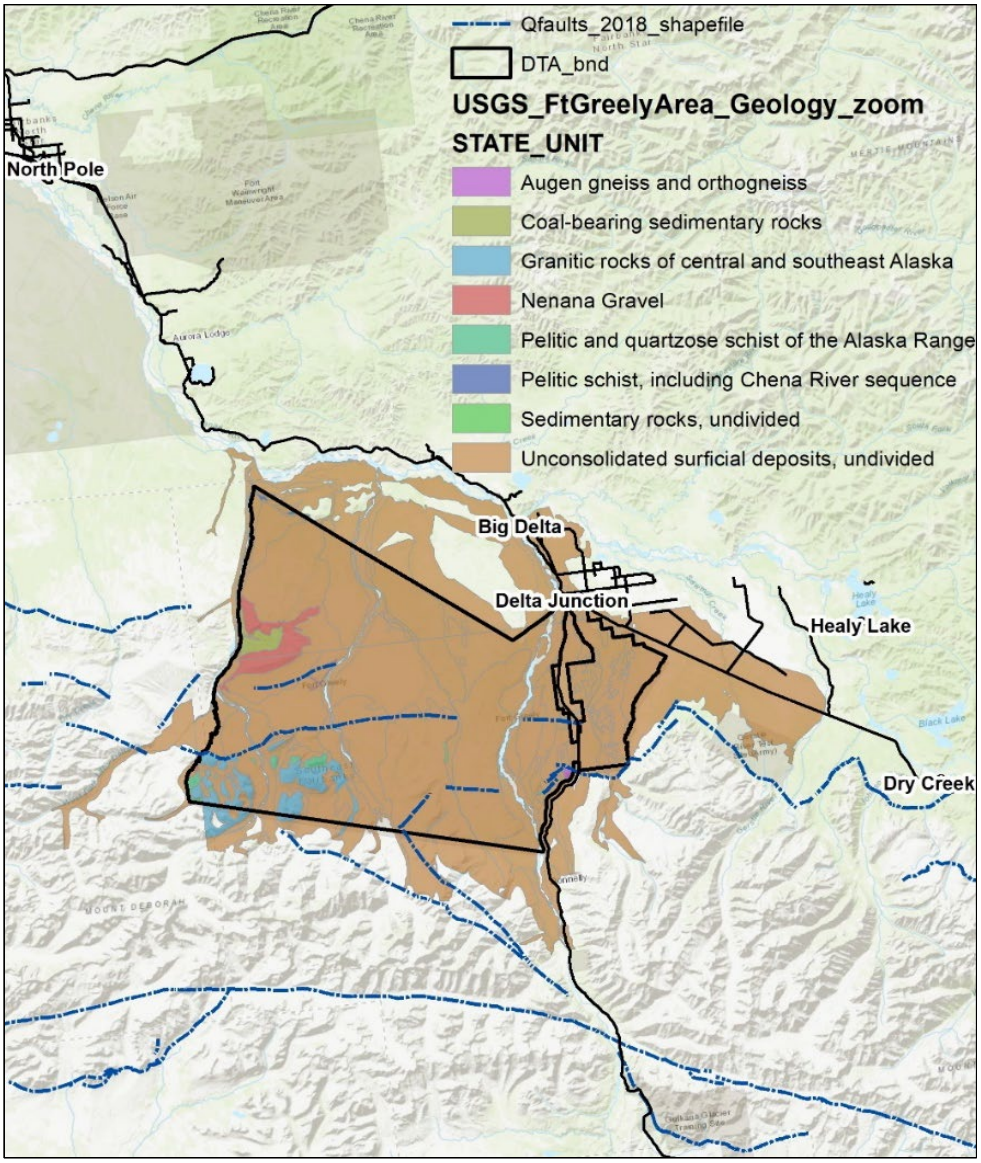
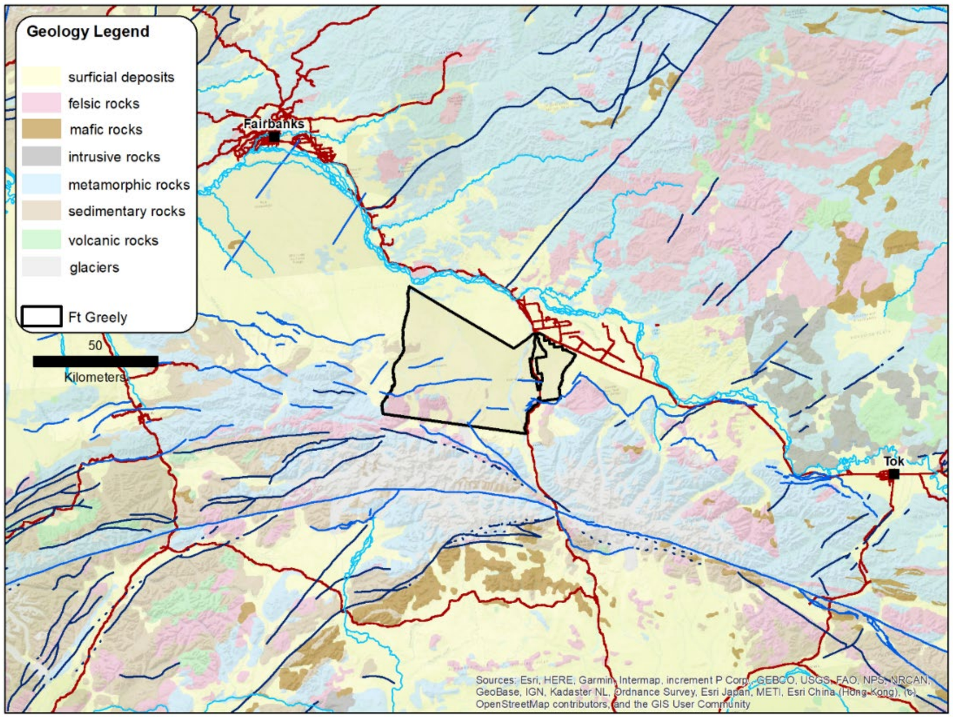


Figure 9. Generalized geologic setting of the study area, with major roads in *red* and major rivers in *light blue*. Quaternary faults are in *blue* and pre-Quaternary faults in *dark blue*. Aeromagnetic data was obtained for surveys conducted by the US Geological Survey (USGS) in 2008 and 2012. (Data source: USGS 2015.)



3.1.3 Structure

The Delta Junction area lies in the Tanana Basin, a structural basin bounded by the Alaska Range to the south (20 km from Delta Junction) and the Yukon-Tanana Upland to the north (35 km from Delta Junction). The area is also bounded by two major crustal-scale fault systems: the Denali and Tintina strike-slip faults and associated plays. Between these two major fault systems are smaller shear zones and faults associated with seismic activity (Figure 10).

Regional-scale magnetic data highlight large-scale crustal features, most notably the Denali Fault (Figure 11). Other anomalies are likely representative of buried volcanic rocks and mafic-rock-related mineralization. Likewise, regional gravity data similarly highlight large-scale crustal features (Figure 11). The gravity data also show interesting relative highs where bedrock geology is hidden beneath surficial deposits. Such anomalies might be indicators of radiogenic intrusive rocks with significant heat flow buried beneath sediments, and aforementioned high-heat-flow wells occur in these areas. The collection of denser ground magnetics and gravity data can aid in identifying finer-scale, local structures.

Figure 10. Map showing aeromagnetic data, highlighting contrasts across the regional-scale Denali Fault. (Data source: USGS 2002.)

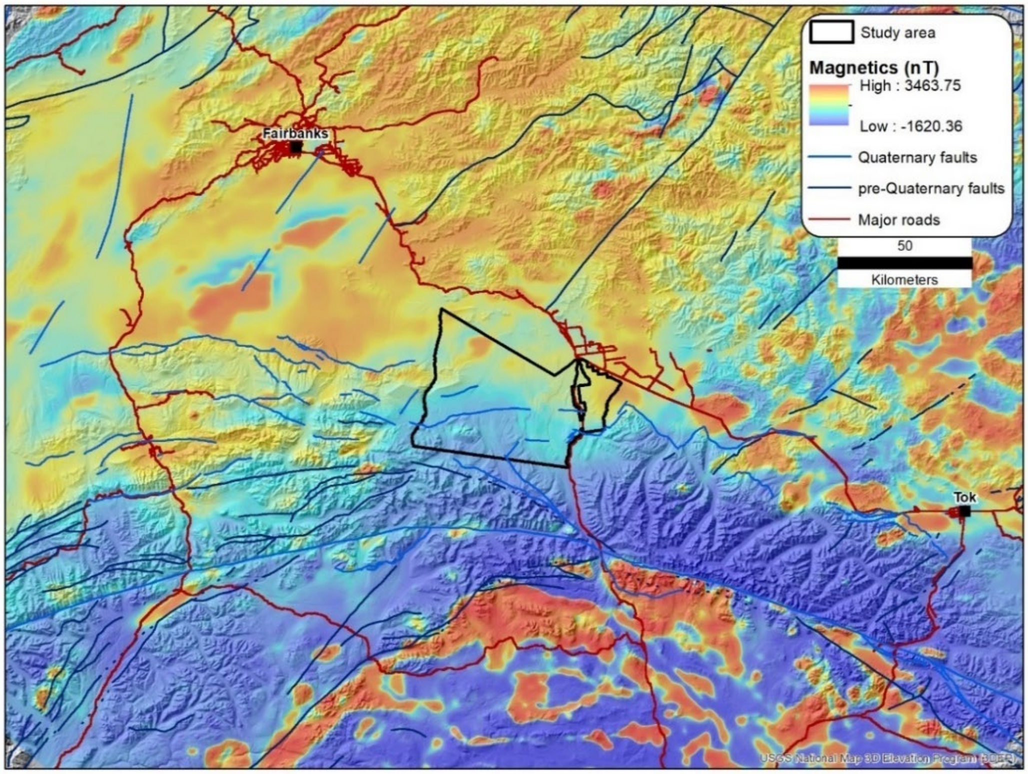
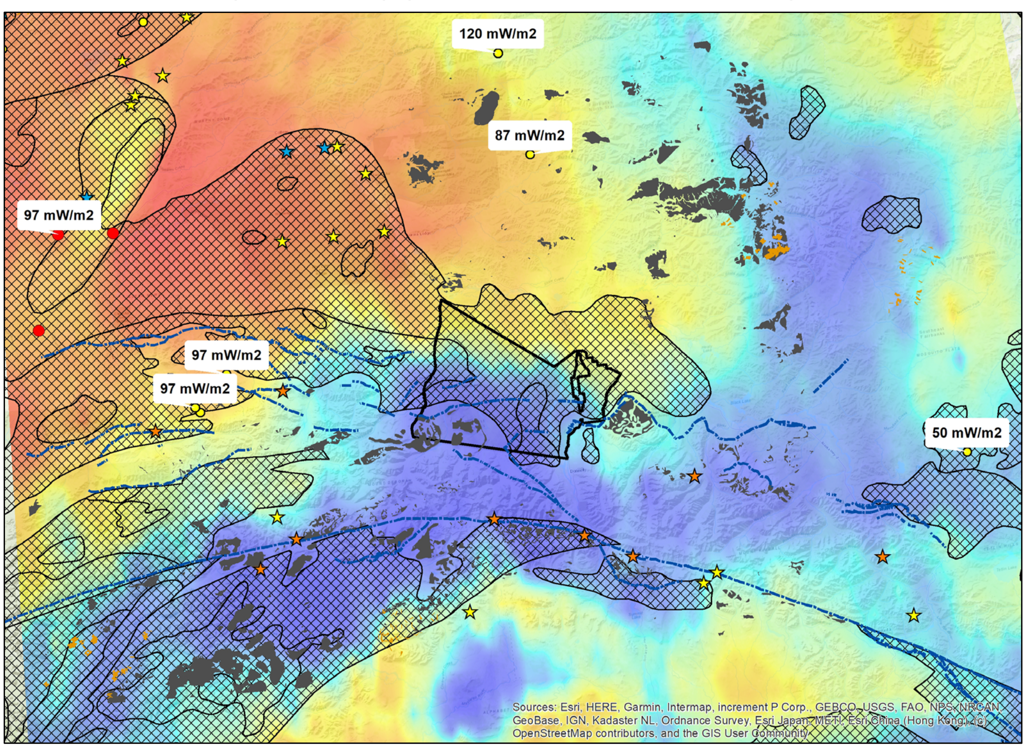


Figure 11. Gravity data from east-central Alaska overlain on a USGS sedimentary basins map (*crosshatched*). Map also shows Quaternary faults (*blue lines*) and the study area (*black outline*). (Data sources: USGS 2003, 2006.)



To the northeast of the study area lies the Black Mountain tectonic zone. O'Neill et al. (2007) provides a detailed description of its northeast-trending structural corridor and concluded that "the tectonic zone coincides with fundamental geophysical crustal anomalies, suggesting that the zone is related to deep-seated crustal discontinuities" (D8).

Active faults in the area besides the Denali Fault system include

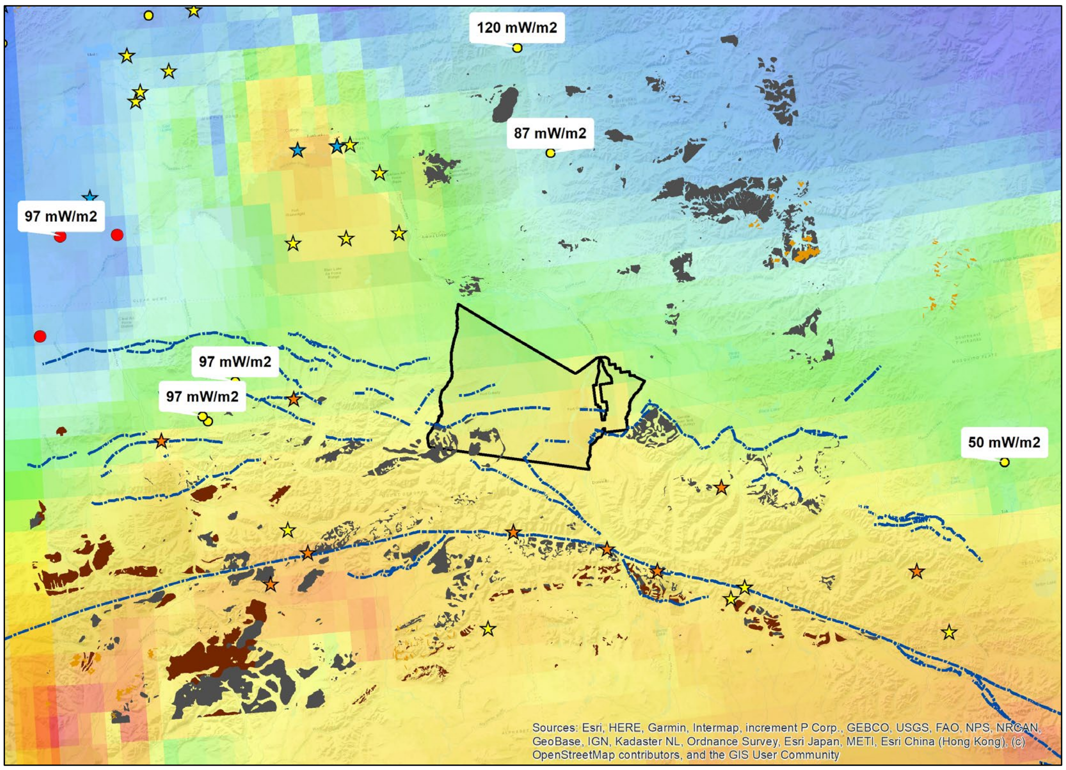
> the Donnelly Dome Fault, the Granite Mountain Fault, and the Healy Creek Fault. The north front of the Alaska Range west of Donnelly Dome is a monocline with few associated surface faults. The Clearwater Lake Fault, located along the Tanana River east of Delta Junction, appears to be active, although an origin of landforms due to faulting cannot be proven. Active faults in the Tanana-Kuskokwim Lowland and Yukon-Tanana Upland include the Minto, Shaw Creek, Champion Creek, and Tintina Faults (Brogen et al. 1975, 73).

The Hines Creek Fault, splays of which cut across the study area, is considered inactive.

While data is sparse for the Tanana Basin, oil companies have investigated the nearby Nenana Basin in detail due to the presence of hydrocarbon resources. The Nenana Basin is a transtensional deformation zone. Transtensional pull-apart basins, including the Nenana Basin, allow "tectonic subsidence by oblique-extension along major basin-bounding strike-slip faults" (Dixit et al. 2017, 99–100). This type of situation could also be occurring in the eastern Tanana Basin near the study area, but detailed investigations involving seismic data or other geophysical data would be necessary to validate this hypothesis.

Figure 12 shows data from the global strain rate map (Kreemer et al. 2014) along with earthquake locations and sense of slip. Additionally, it shows the occurrence of volcanic and intrusive rocks in relation to wells with measured heat flow. Thrust and strike-slip faults (displacements) dominate; however, there are normal fault displacements northwest of the Donnelly Training Area that coincide with a strain rate anomaly and are surrounded by high-heat-flow wells. At a regional scale, the coincidence of these anomalies identifies an area of geothermal potential.

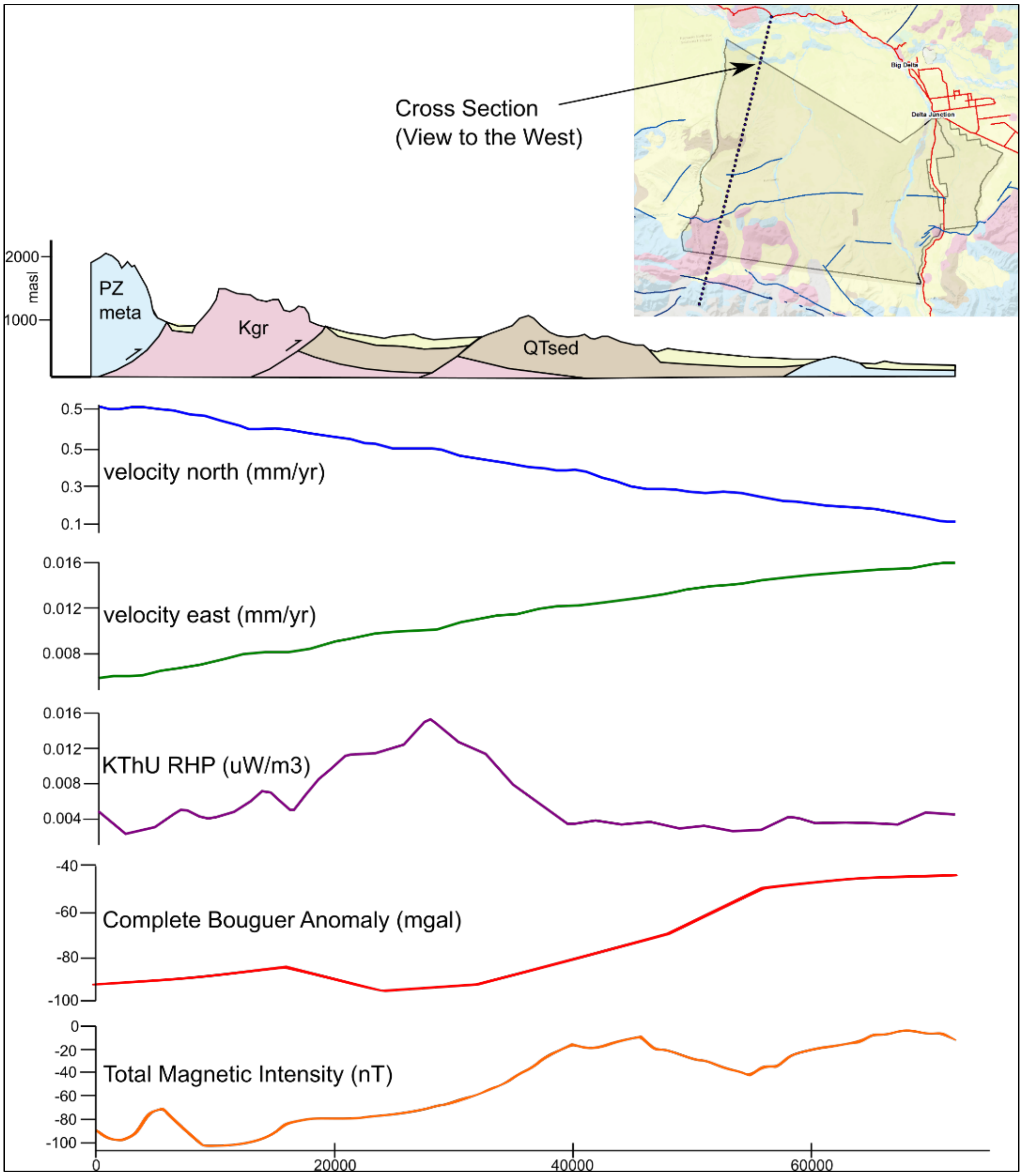
Figure 12. Strain rate and heat-flow measurements in the Tanana Basin. *Stars* show earthquake locations, and colors show the sense of slip: *yellow* = strike-slip, *orange* = thrust, and *blue* = normal. *Circles* are well locations with heat-flow values. *Cool* to *warm colors* indicate low to high relative strain rate (data from Kreemer et al. 2014). *Blue lines* are Quaternary faults.



3.1.4 Interpretive geologic cross section for the study area

Figure 13 shows an interpretive geological cross section and the geophysical data sets used to create the cross section. The confluence of high calculated radiogenic heat production (RHP), relatively low gravity, and sediments overlying felsic intrusions in the interpreted cross section show the potential for development of a hot sedimentary basin. This is only a first-pass conceptual approach and must be refined with better data from field campaigns before being used for site-specific tasks such as well targeting.

Figure 13. Cross section through part of the study area, comparing geology, strain rate velocities (Kreemer et al. 2014), and radiogenic heat production (using the equation from Rybach 1988).



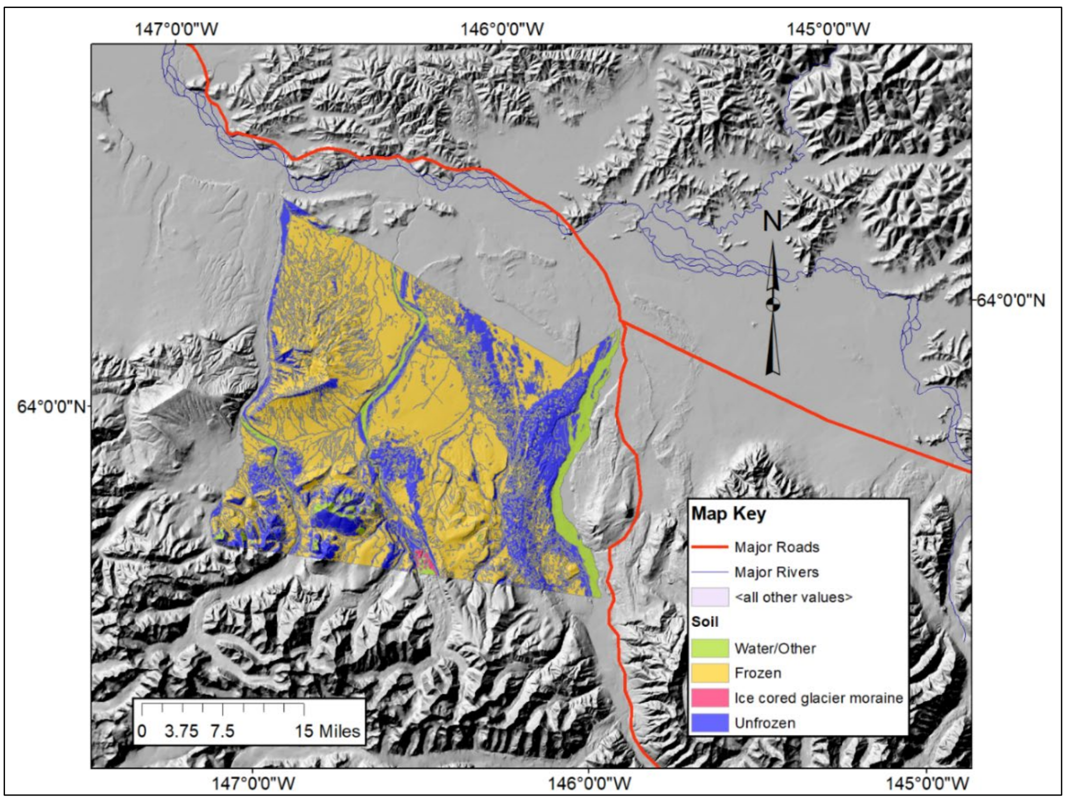
3.1.5 Shallow subsurface and local groundwater

The study area is located in the Tanana-Kuskokwim Lowlands ecoregion (Nowacki et al. 2002). The Delta River and Jarvis Creek are both glacier-fed braided channels that flow over permeable alluvium with large, broad floodplains. The permeability of the alluvium allows for high penetration of surface water into the subsurface, meaning that groundwater near those streams generally flows in a downstream direction, following streamflow.

The large-scale groundwater aquifers are bounded by the Alaska Range (20 km south) and the Yukon-Tanana Upland (35 km north).

This area lies within a zone of discontinuous permafrost (Figure 14). Nelson (1995) looked at 14 wells near Fort Greely; of those, 5 intersected permafrost. According to Wilcox (1980) the range of the depth of the permafrost was from right below seasonally frozen ground to 66 m below surface and was absent near rivers.

Figure 14. Soil map for the study area, showing permanently frozen soil (permafrost). Note that there is a substantial amount of permafrost within the study area; however, the region close to the Delta River is generally unfrozen. Permafrost is also notably absent in areas where granitic rocks outcrop in the southwest of the study area. (Data sources: USACE, unpublished data; Jorgenson et al. 2001.)

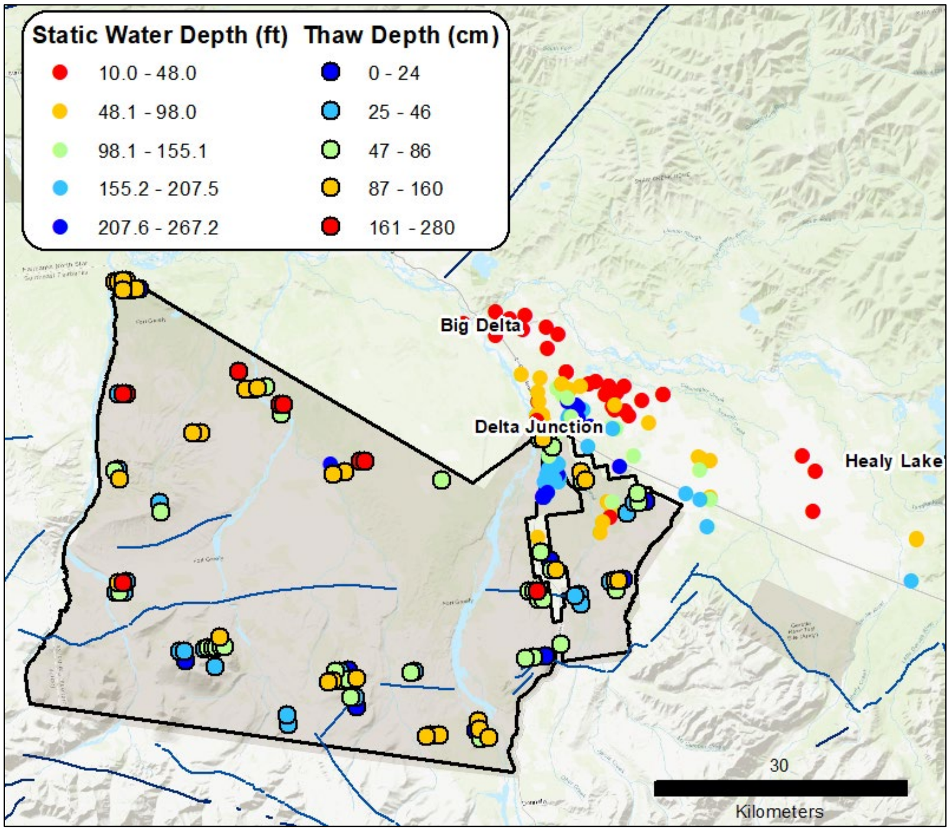


Compiled water well data in the vicinity of the study area comes from wells drilled from 30 to 590 ft below surface.* Based on simple drill logs, none of the wells appear to have intersected bedrock, though a few intersected granite boulders and one finished drilling in "granite." Figure 15 shows

* Units in this report are presented as reported in the field. There is inconsistency between metric and customary reporting as a result, but this is done to preserve the original data sources.

nearby wells and the depth to the water table and thaw depth (i.e., the level down to which the permafrost soil will normally thaw each summer).

Figure 15. Depth to the water table from compiled well data and thaw depth from prior ecological studies based on compiled well data. (Data sources: multiple logs; see log references in Table 1; Jorgensen et al. 2001.)



Subsurface data in the Fort Greely area are scarce. Waller and Tolen (1962) provide water chemistry data from wells along the Alaska Highway. The chemistry of those fluids is not indicative of contributions from geothermal fluids, with silicon dioxide (SiO_2) concentrations between 16 and 22 ppm; magnesium (Mg) concentrations between 11 and 29 ppm; and chlorine (Cl) concentrations between 1 and 18 ppm.

Table 1 summarizes data for water wells drilled in or near Fort Greely. The lithologic logs from the historic wells provide insight into the permafrost conditions and depth to bedrock in the area, though only a single well reports intersecting schist at 183 ft below surface (W1, Table 1). "Frozen muck" and sand were encountered in the Scotty Creek Lodge well, and the well terminated in bedrock (water-saturated schist) at a 183 ft depth. The

Eblen Camp well penetrated unfrozen sand to a 127 ft depth. The US Army Canol Pipeline well #4 was also unfrozen.

Table 1. Water well data for the study area as recorded in the log.

Well No.	Depth (ft)	Static Water Level (ft)	Year Drilled	Lithologies	Data Source	Owner
2980	230	194	1983	None given	ADNR (Alaska Department of Natural Resources) (2021)	DoD / Fort Greely
6621	230	196	1959	None given	ADNR (2021)	DoD / Fort Greely
11317	30		1985	Sand and clay	ADNR (2021)	Alaska Div. Parks and Rec.
11540	395	390	1974	"unconsol."	ADNR (2021)	Alyeska
23915	200	160	1994	Brown sands, gravels, and clays to 140 ft and 160–200 ft, gray to 140–160 ft	ADNR (2021)	Deltana
25097	520	390	1976	Unconsolidated to depth with occasional boulders	ADNR (2021)	Alyeska
25098	300	No water	1991	Unconsolidated to depth with gravel, sand, silt, boulders; possible frozen zone 180–195 ft	ADNR (2021)	Alyeska
28887	140	97	1987	Gravels and sands to depth	ADNR (2021)	DoD / Fort Greely
29273	300	240	1994	Gravels, silts, boulders, and sands to depth	ADNR (2021)	Individual (Mooneyham?)
33311	460	359	2008	Gravelly / cobbly sands to depth	ADNR (2021)	DoD / Fort Greely
33461	340	282	2008	Gravel, cobbles, boulder, and sands to depth	ADNR (2021)	DoD / Fort Greely
36432	300	175	2013	Gravel, clay, silt, and sand; saturated ~200–300 ft	ADNR (2021)	DoD / Fort Greely
40294	300	175	2013	Gravel, clay, silt, and sand; saturated ~200-300 ft [repeat of 36432]	ADNR (2021)	DoD / Fort Greely
46914	No info		No info	No info—missing log	ADNR (2021)	Delta Convenience Store
W1			<1962	Bedrock = water-sat schist at 183 ft	Waller and Tolen (1962)	Scotty Creek Lodge
W5			<1962	No bedrock or chemistry reported	Waller and Tolen (1962)	Eblen Camp

Well No.	Depth (ft)	Static Water Level (ft)	Year Drilled	Lithologies	Data Source	Owner
W6			<1962	No bedrock or chemistry reported	Waller and Tolen (1962)	US Army Canol Pipeline #4

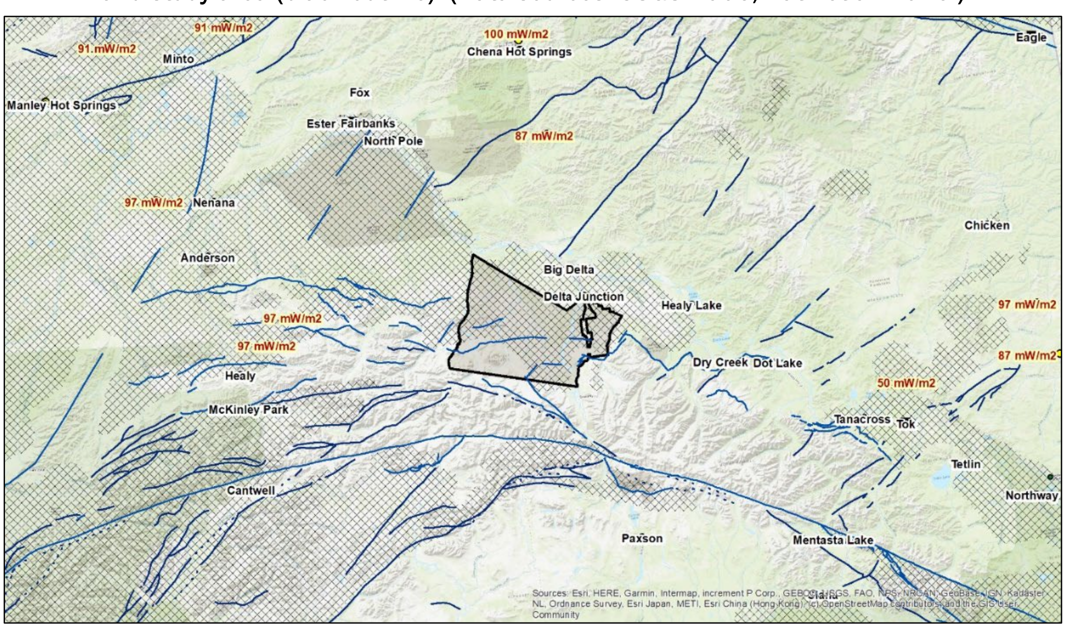
Jorgenson et al. (2001) recorded soil properties at Fort Greely as part of an ecological study conducted by CRREL. The average soil pH was 5.78, with a large range between 4.1 and 9.1. The thaw depth also had a large range of values—from 19 to 280 cm—with an average of 69 cm (Figure 15; Nelson 1995).

3.1.6 Heat flow

Heat-flow data come from measurements of oil and gas wells. Bottom hole temperature data was obtained from the Alaska Oil and Gas Conservation Commission (AOGCC 2019). However, the current compiled data do not include true vertical depth, temperature, and rock conductivity; so heat flow cannot be reliably calculated.

There are 10 measured heat-flow values within 175 km of Fort Greely (Batir et al. 2016). Nine of these measured values are well above average, ranging from 87 to 100 mW/m² (Figure 16). One value of 50 mW/m² was measured near Tok.

Figure 16. Heat-flow measurements from downhole data from east-central Alaska, overlain on USGS Sedimentary Basins map (*crosshatched*). Map also shows Quaternary faults (*blue lines*) and study area (*black outline*). (Data sources: USGS 2006; Batir et al. 2016.)



Where measurements are not available, heat flow can also be extrapolated from rock properties: heat generation and conductivity. Heat generation or RHP can be calculated from the following equation (Rybach 1988):

$$RHP = \rho\,(9.52\ U_c + 2.56\ Th_c + 3.48\ K_c) \times 10^{-5}, \qquad (1)$$

where ρ is rock density and U_c, Th_c, and K_c are radioelement concentrations (uranium and thorium in ppm and potassium in percent).

Figure 17 shows the estimated Th concentrations for Interior Alaska, derived from gamma-ray measurements from aerial radiometric surveys (USGS 2009), and Figure 18 shows the study area's RHP derived from aeromagnetic U, Th, and K data. RHP values range up to 277 µW/m3. Notable anomalies coincide with mapped exposed granitic rocks and beneath surficial deposits and sedimentary basin extents. Buried and insulated radiogenic rocks potentially lead to development of high-temperature sedimentary basins. We selected USGS rock geochemistry data locations where they occur within 1 km of mapped intrusive rocks, filtered for valid K, Th, and U values and RHP calculated. The highest RHP value from rocks nearest the study area is 62 µW/m3; it is likely representative of felsic intrusive rocks exposed in the southwest part of the study area.

Figure 17. Estimated thorium concentration for Interior Alaska, derived from gamma-ray measurements from aerial radiometric surveys. Equivalent data for Uranium and Potassium concentrations also exist. (Data source: USGS 2009.)

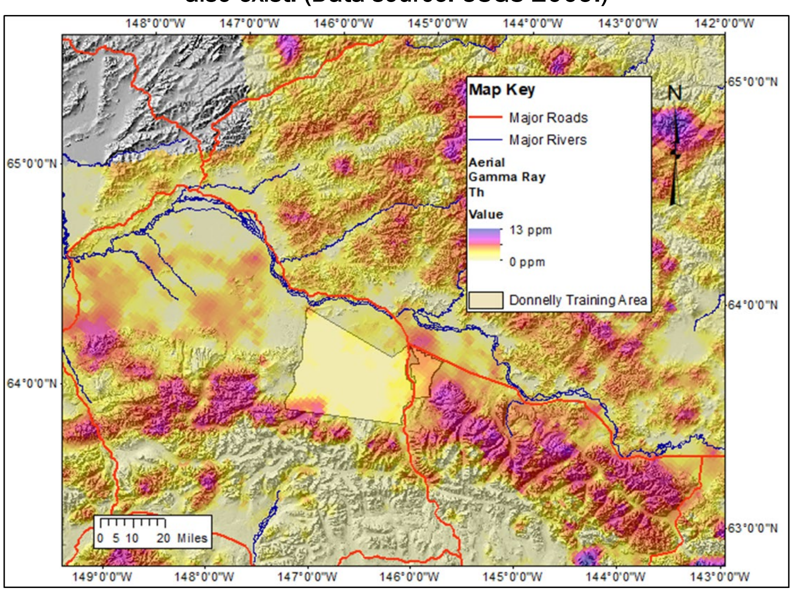
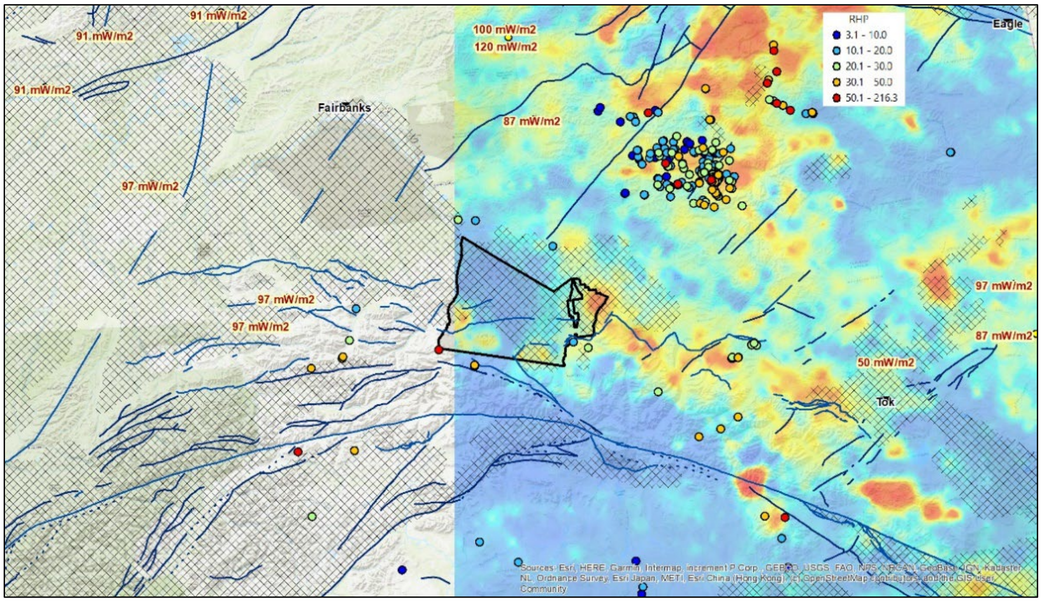


Figure 18. Airborne radiometric surveys (for potassium, Th, and uranium) were transformed into radiogenic heat-production values using Equation (1) and assuming a density of 2.7 g/cm^3. Radiogenic heat production (RHP) values (in microwatts per meter cubed) are represented by *colored circles* and were calculated where analyzed USGS rock samples overlap with mapped intrusive rocks with a 1 km buffer. Mapped sedimentary basins are shown *crosshatched*. (Data sources: USGS 2006, 2009, 2013.)



3.1.7 Minerals

Near Delta Junction are numerous mineral deposits, such as gold, molybdenum, and coal (Wahraftig and Hickcox 1953; Harun and Hendricks 2018). The same elements used for targeting hydrothermal metal deposits can be used to explore for geothermal potential; however, with widely occurring hydrothermal mineralization occurrences, it is challenging to interpret element anomalies (rock or stream sediment) for geothermal prospecting. To be reliably used for assessing geothermal potential, the elemental anomalies need to be collocated with temperature anomalies. The dearth of temperature data in the study area makes the elemental data difficult to interpret. Figure 19 shows the number of gold-mineralization-related entries in the USGS Mineral Resource Data System; many of these occurrences should have rocks anomalous in elements that are used to explore for geothermal occurrences (USGS 2013). Elemental anomalies need to be considered with respect to identified mineral occurrences, including some beyond the gold-related occurrences shown in Figure 20 (e.g., As, Sb, copper, and others).

Figure 19. Simplified geology and major faults overlain by gold-related Mineral Resource Data System entries (*dark gray circles*). (Data sources: Koehler 2013; USGS 2006, 2013.)

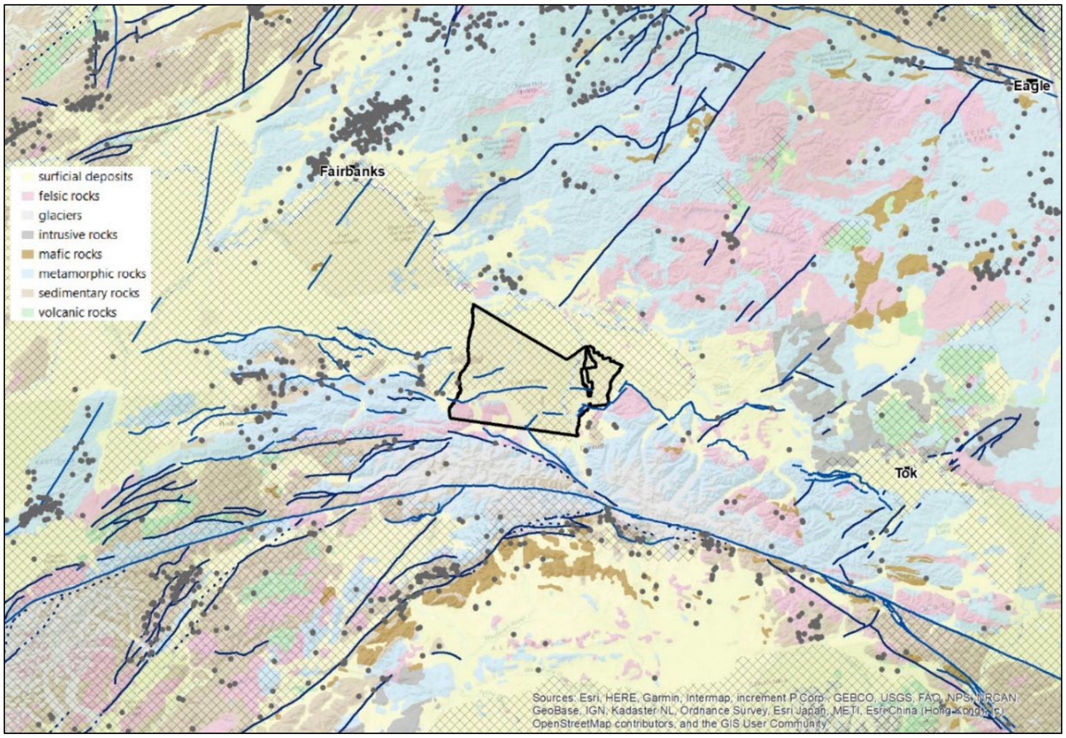
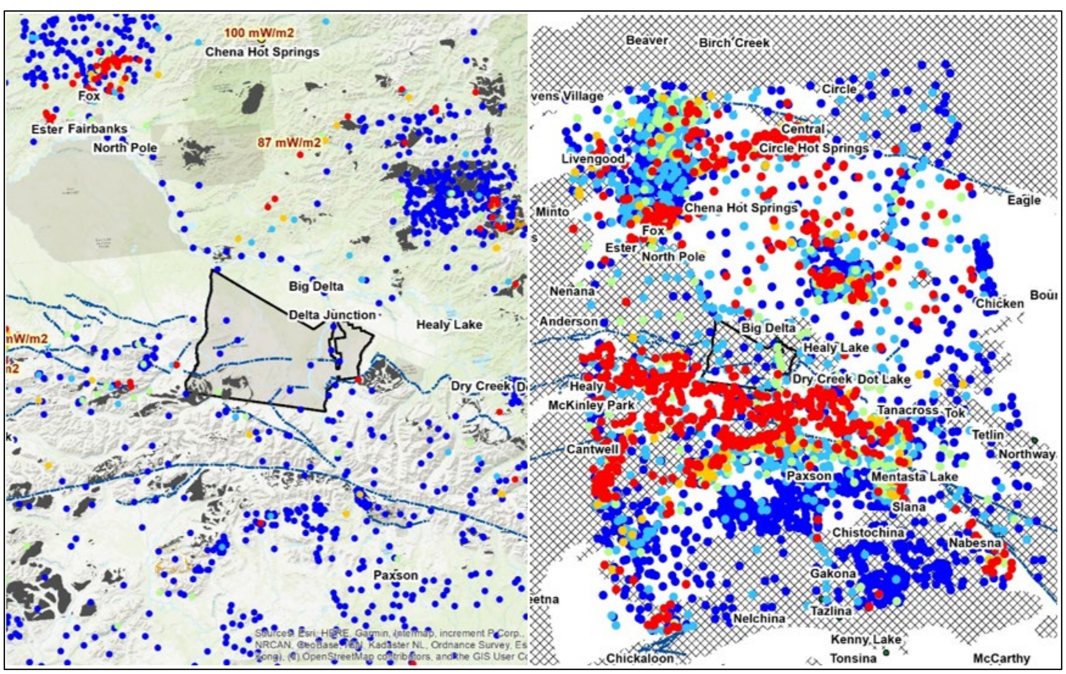


Figure 20. Pathfinder element maps showing faults (*blue lines*) and study area (*black outline*). *Left*, occurrence map of antimony (Sb); *right*, occurrence map of arsenic (As). No anomalous values for Sb were found in the study area. The southern part of the study area has few data points but does have some anomalously high As concentrations. (Data sources: Koehler 2013; USGS 2006, 2013.)



3.1.8 Satellite data and remote sensing

Compiled Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite surface temperature data can be useful to remotely explore for geothermal occurrences. A robust process and tools must be applied to use ASTER (and other) satellite-based platforms for successful regional geothermal exploration. Such an effort is beyond the scope of this study, but later sections will discuss ideas about the utility of such an effort and possible strategies.

3.2 Summary of Phase I data and data gaps

The new heat-flow map of Alaska (Figure 3 from Batir et al. 2016) shows anomalous regional heat flow near Fort Greely, indicating that it could potentially host a "blind" or concealed deep geothermal resource. Regional heat-flow studies are not sufficient alone to determine if a deep geothermal resource is present. Therefore, additional data are required. Through this literature and data review, based on location and the general geologic setting, the most likely geothermal resource types in the study area are (1) a blind sedimentary basin–hosted system, (2) a concealed radiogenic system similar to Chena Hot Springs, or (3) some combination of the two. However, until subsurface data is acquired, many other possibilities exist, including a lack of a resource. Table 2 presents a matrix showing the likelihood of the existence of each play type at Fort Greely based on our literature and data review.

Table 2. Possible geothermal resource types at Fort Greely, their potential uses, likelihood of existing, and development risk.

Geothermal Resource Type	Uses	Likelihood of Existing at Fort Greely	Risk
Aquifer or ground source in permafrost-free zone	Geothermal heat pump	High	Low
Conduction-dominated intracratonic basin (sedimentary)	Direct use	Medium	Medium
Concealed convection-dominated radiogenic hydrothermal	Direct use Electricity generation < 1 MW	Low to medium	High
Concealed convection-dominated deep circulation or magmatic hydrothermal	Direct use Electricity generation > 1 MW	Low	High

The Fort Greely area is a geothermally prospective location that requires further data collection to confirm the local thermal regime. Radiogenic intrusive rocks appear to occur in the subsurface at Fort Greely beneath sedimentary rocks of unconfirmed thickness, so there is potential for anomalous heat flow and a hot sedimentary basin geothermal system. The new heat-flow map of Alaska (Batir et al. 2016) shows high heat flow near Fort Greely, but these are extrapolated values from distant measurements and assumptions about rock characteristics. Crustal heat flow is a function of the heat generation of the earth and the thermal conductivity of rocks. There are no temperature data within 50 km of Fort Greely, and there are no rock conductivity data for the study area. The collection of temperature logs from wells on or near the base, and the collection of rock samples on or near the base for conductivity analyses, would greatly improve heat-flow calculations for the study area. The former task, temperature logging of existing wells, is possible in the study area if one or more of the 17 wells listed in Table 1 are accessible. Radiogenic intrusive rocks, while mostly buried beneath unconsolidated sediments, may outcrop in the southwest corner of the study area, making sampling straightforward.

Many of the data sets acquired as part of the Phase I study (e.g., mineral occurrences as pathfinder elements or remote-sensing data) are either too sparse to be conclusive or need to be collocated with temperature anomalies to be reliably used for assessing geothermal potential. Yukon, Canada, is geologically contiguous to Interior Alaska and is the focus of ongoing geothermal resource assessments. Recent shallow thermal-gradient drilling in two parts of Yukon demonstrates the need to gather additional data and not solely depend on regional-scale data for geothermal well targeting; additionally, the extreme thermal gradient recorded in one thermal-gradient (TG) well of approximately 250°C/km supports the hypothesis that Interior Alaska and Yukon are part of a vast region of anomalously high heat flow.

Mapping of known aquifers and discontinuous permafrost zones in the study area would (1) help determine the feasibility of drilling, whether for shallow or deep geothermal resources; (2) potentially aid in heat-flow mapping efforts; and (3) help determine the feasibility of geothermal heat pumps (GHP) deployment at Fort Greely. Where permafrost is absent, the shallow subsurface at Fort Greely has potential for deployment of GHPs. GHP systems are becoming more popular in cold climates like Interior

Alaska, and the Cold Climate Housing Research Center (CCHRC) in Fairbanks is actively researching the performance and enhancement of GHPs in Alaska (CCHRC 2021a, 2021b).

3.3 Raw and aggregated data archives

Project data archives are ordered on CRREL and NREL machines in a siloed hierarchy with the three main sections containing GIS files, raw data, and literature and documents. The GIS packages are in ArcGIS file format and are set up to use the North American Datum of 1983 (NAD83) Alaska Albers coordinate system. Raw data is kept in the source format, which includes file types such as Excel, Access, LAS, and more. Literature is organized by research domain or document type. Each folder in the database contains read me files with links to data sources and descriptions. Some redundant data between the three exist to preserve the original structure after import into ArcGIS, which is meant to be the main tool for screening and analysis.

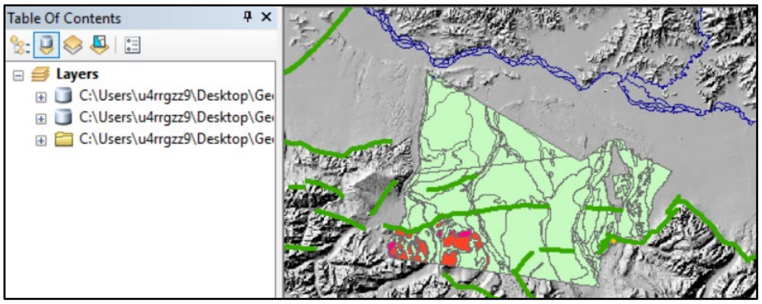
This file system allows for streamlined integration of new information into existing visualization and analysis as well as simple creation of new models. All identified data has been saved into ArcGIS geodatabases, which are reference storage sets. Map documents are used to create models that reference the geodatabases. Both geodatabases and created map documents are organized by data type (e.g., geophysical, geochemical, etc.). This structure allows for the creation of new analyses and visualizations without linking to or changing the original raw data and without altering previously created analyses. As more information is gathered during potential field studies, additional information can be integrated into existing and new geodatabases. Figure 21 is an example of a map document referencing a geodatabase and the existing databases.

This file structure and tool set allows for adaptive development of the play fairway analysis (PFA) model over time. The database is intended to be a living, evolving system that can be used for prospecting of all the different mentioned potential geothermal resource types.

Figure 21. Created geodatabases (*top*), existing map documents (*middle*), and an in-client example of a map document layer structure referencing three different geodatabases to create the image (*bottom*).

FortGreely.gdb	7/26/2019 1:44 PM	File folder
Geochemical.gdb	9/17/2020 10:09 PM	File folder
Geological.gdb	9/17/2020 10:09 PM	File folder
Geophysical.gdb	9/17/2020 10:09 PM	File folder
Geothermal.gdb	9/17/2020 10:09 PM	File folder
Hydrological.gdb	9/17/2020 10:09 PM	File folder
Multispectral Imaging	7/17/2019 3:12 PM	File folder
Surface.gdb	9/17/2020 10:09 PM	File folder
ReadMe.txt	7/25/2019 2:45 PM	Text Document

Delta Junction All.mxd	8/8/2019 2:57 PM	ArcGIS ArcMap Document
Delta Junction Geochemical.mxd	7/26/2019 12:55 PM	ArcGIS ArcMap Document
Delta Junction Geology.mxd	7/26/2019 12:48 PM	ArcGIS ArcMap Document
Delta Junction Geophysical.mxd	7/26/2019 1:02 PM	ArcGIS ArcMap Document
Delta Junction Hydrology.mxd	7/26/2019 1:07 PM	ArcGIS ArcMap Document



4 Resource Location for Interior Alaska—Donnelly Training Area

A number of geological and structural studies could be undertaken to generate key subsurface data that is missing at present for the Donnelly Training Area. A few of these studies (e.g., temperature logging of nearby wells, rock conductivity, gravity surveys, and permafrost mapping) would benefit a range of potential geothermal applications from GHPs to power production.

4.1 Exploring for shallow geothermal resources

Traditional GHPs can be configured in horizontal loops or in vertical loops that can penetrate over 100 m deep. In general, the deeper the configuration, the more stable the subsurface temperature and the larger the volume of thermal mass to exploit. CCHRC in Fairbanks has a track record of conducting research on GHP, including pilot projects at their Fairbanks location. Their demonstration includes a small-scale GHP system to study its performance in cold climates, that is its efficiency and its impact on ground temperature over longer durations. More specifically, CCHRC is studying the subsurface effects on the soil's thermal regime. Additionally, CCHRC is exploring seasonally "recharging" the ground-source systems by solar technology (CCHRC 2021b).

In cold regions, site-specific considerations such as permafrost, thaw level, and seasonal frost are critical. At Fort Greely, there are local permafrost-free zones where groundwater seeps into aquifers through high permeability alluvium deposits. These aquifers are likely bounded horizontally by impermeable clay layers from glacial deposits and laterally by structural features or permafrost barriers. The presence of groundwater means open-loop and standing water column GHP configurations can be considered. Saturated conditions also increase heat exchange for closed-loop systems, making them more efficient (Cunniff and Orio 2013).

Understanding the suitability and appropriateness of GHPs at Fort Greely would involve detailed site investigations, including mapping discontinuous permafrost layers, depth to bedrock, and aquifers. Additional details might include characterization of the shallow subsurface with respect to physical and thermal properties in order to optimize GHP system design. For a large facility, GHP systems typically comprise many wells drilled tens to hundreds of meters, with the number dependent on the heating and cooling needs of the structures. Such a development includes a component of exploration that provides data and guidance in real-time. In general, there is ample opportunity to explore shallow geothermal energy for heating and cooling in Interior Alaska (Zody and Gisladottir 2023).

4.2 Exploring for deep geothermal resources

Geothermal heat is present everywhere in the subsurface. The combination of unique geophysical, geologic, structural, and stratigraphic elements that result in a geothermal resource is known as a geothermal *play*. Hydrothermal resources are sometimes associated with surface manifestations such as hot springs; however, recent research indicates that the majority of hydrothermal resources do not have surface manifestations (Williams et al. 2008).

Batir et al. (2016, 366) observed that "the heat-flow distribution within central Alaska appears to be similar in variation to a backarc geologic provinces such as the Cordilleran Thermal Anomaly Zone," which suggests there is a high probability for geothermal systems to exist within central Alaska; "but they would be heterogeneously located and may be lacking of geothermal surface manifestations" (i.e., they would be blind systems).

Sedimentary basin geothermal systems carry additional risk as they tend to be lower-temperature resources; however, drilling in sedimentary basins is much less expensive than in typical geothermal hard-rock environments. Imaging of the subsurface in detail is also easier in sedimentary environments (i.e., seismic surveys serving as the standard tool of the oil and gas industry).

4.3 Exploring for "blind" or concealed geothermal resources at Fort Greely

Assessing the possibility of a "blind" or concealed deep geothermal resource at Fort Greely requires further data. Effective methodologies for exploring for blind or concealed geothermal resources have been the subject of much recent research. One approach to this problem is the application of the PFA technique to geothermal prospecting. The PFA technique, originally developed by the petroleum industry, defines local areas that have high potential for hosting geothermal plays and eliminates large areas that have a higher potential for failure. This reduces risk during the resource locating process. PFA for geothermal energy exploration involves identifying four or more critical components:

1. Heat
2. Accessible fluids
3. Permeability
4. Caprock or seal

At Fort Greely, although regional-scale data indicate elevated heat flow, much uncertainty still exists for all critical components of a geothermal resource (Table 3). This is due to the sparseness of most available data sets, the uncertainty inherent in extrapolations from the data, and the lack of previous geothermal exploration in the area.

Table 3. Critical components of a conventional geothermal resource, presented alongside key unknowns for Fort Greely, the data available to address those unknowns, and the uncertainty.

Component	Key Unknowns	Key Available Data Sets	Uncertainty
Heat	• Rock types at depth • Volume of plutons at depth • High-heat-producing (HHP) plutons (Cretaceous age) vs. "normal" (Tertiary age) • Role of Wrangell volcanics	• Geologic maps (Alaska Division of Geological and Geophysical Surveys, ADGGS) and 2D cross sections • Whole rock geochemical data (ADGGS, Southern Methodist University) • Airborne radiometric data (ADDGS) • Wrangell magma models (Alaska Volcano Observatory)	High
Accessible Fluids	• Surface hydrology and aquifers • Degree of permafrost	• Sedimentary basin maps (USGS) • Magnetic and gravity maps for structure (USGS)	Medium
Permeability	• Key structures • Stress state / strain rate	• Stress/strain/earthquake map with faults highlighted normal to transtensional orientations • Pathfinder element chemistry • Hydrology studies • Permafrost maps / well logs / soil study	High
Caprock or Seal	• Basement rock: plutonic or metamorphic? • Degree of insulation from unconsolidated sediments	• Sedimentary basin maps (ADDGS) • Magnetic and gravity maps for basin depth (USGS)	Medium

In general, a geothermal play requires the four critical components listed above, although other factors, such as land access or depth, are also sometimes included (Garchar 2016). Moeck (2014) catalogued distinct geothermal "play types" according to specific sets of geologic controls and listed exploration methods and techniques commonly used to locate geothermal resources by play type. While the PFA approach cannot be applied in full at Fort Greely due to limited data and predefined exploration targets, the framework can be applied to better understand what we are looking for in the Fort Greely area (e.g., by defining the characteristics of Chena with multiple data sets and looking for that signature across the region). The first step in constraining the target play type at Fort Greely would be to generate a broad data set applicable to different geothermal resource types and development models, including GHPs. New data collection efforts should focus on developing project-scale heat flow and conceptual thermal regime models of the Fort Greely study area.

4.3.1 Exploration program targeting sedimentary hydrothermal resources

Sedimentary basin hydrothermal systems are more abundant than traditional geothermal resources and represent large untapped potential for geothermal development (Morgan 2013; Allis et al. 2015). Sedimentary basins with elevated temperatures exist throughout the US, but these resources are not yet demonstrated for geothermal viability.

Whether the Tanana Basin has elevated heat flow remains unknown due to a lack of deep measurements. The thickness of the alluvial deposits in the Big Delta region is known to be up to 760 m, but the porosity and permeability of these deposits is likely to be highly variable due to known glacial activity, permafrost, and faults that are likely to act as barriers to fluid flow.

Sedimentary geothermal play types are only just beginning to be viewed as commercially viable, so exploration methods are not as well developed for this play type as for others and are more or less borrowed from hydrocarbon exploration. Typical sedimentary basin studies include reconnaissance of existing well data; seismic reflection studies to determine structure, constrain stratigraphy, and identify porous or permeable formations; and gravity surveys to determine the depth to bedrock. Any drilling in sedimentary basins is likely to be much less expensive than comparable drilling in other geothermal environments.

4.3.2 Exploration program targeting Chena-type hydrothermal resources

Interior Alaska has anomalously high heat flow (Batir et al. 2016), and this may be responsible for the occurrence of Chena-like hydrothermal resources in areas where localized extensional structures allow for fluid circulation. Whether there are concealed, exploitable Chena-type hydrothermal systems present on or near buried granitoid bodies in the Fort Greely study area—or anywhere in Interior Alaska and Yukon—is currently unknown. Fundamental questions about structure, stress state, the heat production of intrusive rocks containing radiogenic elements, the relationship between to the volume of intrusive rocks at depth, and fluid flow are some of the geologic questions that deserve more attention before making major investments in subsurface prospecting for this type of geothermal resource at Fort Greely. To mitigate the risk associated with subsurface exploration, incremental advancement in prospecting in the form of surface exploration is prudent (see Figure 1).

At Chena Hot Springs, localized extension occurs along the axis of least compressive stress between strike-slip faults. The stress state of the active faults at Fort Greely is unknown, but the overall tectonic setting could accommodate localized extensional movement. Detailed geomechanical analysis is needed to better understand the stress field at the study area.

Targeted surface exploration combining temperature logging of existing wells, rock sample collection for thermal conductivity, and whole rock chemistry for radiogenic heat-production measurements would be useful. This would (1) allow for project-scale RHP measurements to supplement the regional-scale estimations presented above, (2) aid in interpolating between known heat-flow values, and (3) validate or refute correlations between radiogenic heat production from rock data versus airborne radiometric data.

Another approach to heat flow could be to generate Curie Point Depth (CPD) maps by following the methodology employed with aeromagnetic data in the Yukon studies. Existing magnetic surveys for Alaska could be used to generate a CPD map similar to what has been done for Yukon, in tandem with analyses of radiogenic heat production of local rocks. While this approach would help refine existing heat-flow studies, it is still regional in scale and may not lead to project-scale prospecting.

4.3.3 Exploration program targeting conventional hydrothermal resources (deep circulation or magmatic)

While the occurrence of high-temperature hydrothermal resources is unlikely beneath the study area, the possibility of their existence cannot be completely ruled out. This is due to the relative proximity of the active Wrangell volcanoes approximately 200 miles south of Fort Greely and due to heat-flow studies that could be interpreted as revealing concealed basin and range–type deep circulation systems.

The Wrangell Mountains, while far from the study area, may have significant geothermal electrical energy potential as they are located above active subduction zones and the presence of active volcanism (Batir et al. 2016). Though data are limited for estimating geothermal potential, high heat flow has been measured in the vicinity of the Wrangell volcanos (97 mW/m^2; Batir et al. 2016).

Conventional exploration techniques, such as geochemical sampling of hot springs and fumaroles for geothermometry, geophysical methods to image subsurface structures and fluid circulation, etc., would be appropriate for these types of plays (Table 4).

4.3.4 Exploration program targeting petrothermal resources

Should existing hydrothermal resources remain elusive but geothermal development remains a priority, enhanced geothermal systems (EGS) technologies could be considered for deployment in either the sedimentary layers or the bedrock beneath the Fort Greely campus. EGS is a reservoir-creation technique used to make an enhanced geothermal system, typically using hydraulic stimulation but sometimes chemical stimulation. NREL and others are researching EGS development in sedimentary basins because costs could be substantially less than in typical geothermal hard-rock environments. Allis et al. (2015) describes the advantages of EGS development in sedimentary basins. A more recent technology is geothermal development in high-heat-flow (greater than 150°C) sedimentary basins by using closed-loop heat-extraction technologies, sometimes known as alternative geothermal systems (AGS). These technologies take advantage of the natural advection of fluid through permeable sedimentary basins to enhance heat transfer from the reservoir fluid to a working fluid circulated within a subsurface closed-loop heat exchanger. A high-thermal-capacity working fluid is injected over a horizontal length (meters to kilometers) of closed loop, analogous to the horizontally drilled portions of oil and gas wells; and the extracted heat is used for heating or electricity generation. A demonstration project of this technology is in progress in Alberta, Canada; and initial results are promising (Eavor 2021).

4.4 Summary of methods for deep geothermal exploration at Fort Greely

Table 4 summarizes the exploration methods for each type of geothermal play considered as part of this study. Column one presents the play type, the second column presents the existing exploration approach (Moeck 2014), the third column present our suggested custom approach for Fort Greely, the fourth column presents our assessment of the uncertainty associated with each play, and the final column present our assessment of the impact if such play would be located. It presents typical exploration methods along with custom methods considered particularly adapted to the study area. Additionally, it includes speculations about uncertainty associated with the custom methods and the potential impact of each custom method.

Table 4. Different geothermal plays that could potentially be at Fort Greely, their corresponding exploration methods (including custom methods), uncertainty, and impact.

Deep Geothermal Play Type	Typical Exploration Methods (after Moeck 2014)	Custom Exploration Methods for Fort Greely (Nondrilling)	Uncertainty	Impact
Conduction-dominated intracratonic basin (sedimentary) play of the type described by Allis (2015)	• Temperature logging of existing wells • Reprocessing of existing seismic reflection data from hydrocarbon exploration • Reconnaissance from existing well data • 2D/3D seismic surveys to constrain stratigraphy and identify porous/permeable formations and structures	• Gravity survey to determine depth of sedimentary basin • Temperature calculations at depth in sedimentary basins near Fort Greely from deep well data	Medium Low	High High

Table 4 (cont.). Different geothermal plays that could potentially be at Fort Greely, their corresponding exploration methods (including custom methods), uncertainty, and impact.

Deep Geothermal Play Type	Typical Exploration Methods (after Moeck 2014)	Custom Exploration Methods for Fort Greely (Nondrilling)	Uncertainty	Impact
Concealed convection-dominated radiogenic play type of the type described by Kolker (2008) and Witter et al. (2018)	• Temperature logging of existing wells • Heat-flow measurements and/or calculations from radiogenic heat production (RHP) • Geophysical imaging • Magnetotelluric and gravity to detect the granitic body • Reflection seismic to identify facture/fault zones	• Geosystem analysis to estimate stress field and hydromechanical conditions • Rock-sample collection for thermal conductivity and for whole-rock chemistry for radiogenic heat-production measurements • Curie point depth map to estimate heat flow from aeromagnetic data	Medium Low High	Medium Low Low
Concealed convection-dominated magma-hydrothermal plays, as described by Lautze et al. (2017) and Shevenell et al. (2015)	• Sampling of surface manifestations • Geophysical imaging: o Magnetotellurics to detect resistivity anomalies o Shallow temperature measurements o Heat-in-place from heat loss studies	• Hydrologic investigations with respect to Wrangell Mountains hydrothermal upflow • Aufeis method	High High	Medium Medium
Petrothermal (EGS or AGS)	• Heat-flow measurements and/or heat-flow calculations from RHP • 2D/3D seismic surveys to constrain stratigraphy and/or bedrock/sedimentary contact	• Innovative exploration methods for glaciated and permafrost zones (e.g., remote-sensing methods like thermal imaging and differentiation)	Medium	High

4.5 Phase II recommendations

From the analyses presented in Table 2 and Table 3 and from an incremental advancement approach to prospecting, we selected two phases of data acquisition and analysis activities from the vast pool of exploration methods presented in Table 4. These two phases (presented below) were selected with the following considerations: (1) data generated would benefit a range of potential geothermal applications from GHPs to power production, (2) the cost of deployment is relatively low (less than $200 thousand), and (3) it is possible to conduct these activities in a single field season.

1. Phase II data acquisition on or near Fort Greely

a. Temperature logging of 14–17 wells
b. Sampling of rocks and/or core collection
c. Gravity surveys
d. Permafrost and aquifer mapping

2. Phase II data analysis

   a. Conductivity measurements of rock samples or core for heat-flow calculations
   b. Whole-rock chemical analysis of rock samples for radioelement concentrations
   c. Updated heat-flow calculations for the Fort Greely area
   d. Inverse modeling of gravity data
   e. Integration with Phase I results and conceptual modeling

Should Phase II results yield positive indications for a geothermal resource, the next step for this project would be drilling shallow TG wells at Fort Greely. TG wells are shallower and less expensive than full-size exploration wells and are typically the first wells drilled on a geothermal project. Information from TG wells is used to delineate the heat anomaly and to establish the geothermal gradient. Sometimes, TG wells are designed so they can be deepened for production if they encounter a resource.

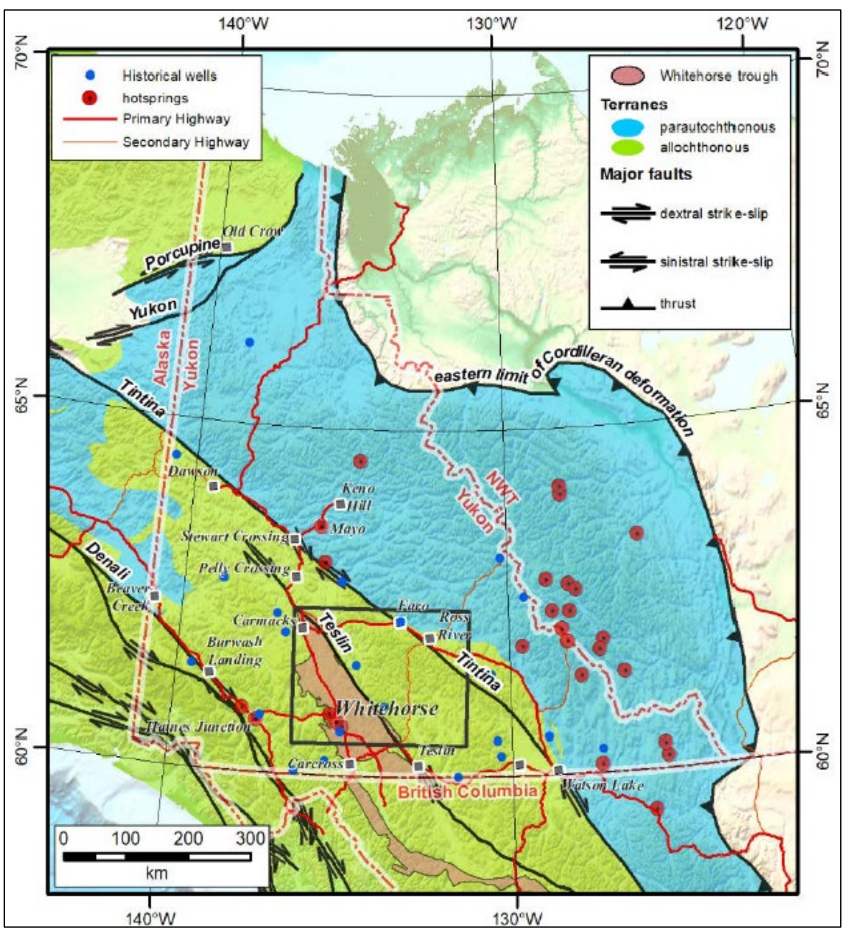
5 Complementary Geothermal Exploration in Yukon, Canada

As previously mentioned, as more exploration occurs in a geographic region, methodology and data sets become more robust, and the risk decreases in that region. The ongoing exploration in Yukon, Canada, can, because of the geographical proximity and similarities, inform exploration in Interior Alaska.

5.1 Hot springs in Yukon

The vast stretch of hot springs that spans Interior Alaska also continues into the southwestern part of Canada's Yukon territory (Figure 22; Fraser et al. 2018). In Central Alaska and Yukon, the Tintina Fault is a major crustal feature and marks the edge of the ancestral North American margin.

Figure 22. Hot springs, major structures, and generalized geology of the southern Yukon. (Image reproduced with permission from Fraser et al. 2018. © Government of Yukon 2022.)



Some hot springs in the southern Yukon, such as Takhini Hot Springs, are associated with plutons of Cretaceous to Tertiary age. They are also associated with the Denali and the Tintina Fault zones. In Yukon as in Interior Alaska, both faults are crustal-scale, strike-slip faults that cut across large swaths of territory.

5.2 Heat flow in Yukon

Like in Interior Alaska, geothermal prospecting in Yukon is hampered by sparse data points and uncertainty in interpolation between known heat-flow values. For the whole of Yukon, there are only eight known heat-flow measurements (Figure 23; Grasby et al. 2012). As also found for Interior Alaska, seven out of the eight measurements are anomalously high at 86, 118, 100, 96, 99, 95, and 105 mW/m^2 (the average heat flow is 64 mW/m^2 for all of Canada; Witter et al. 2018). One exception is at Whitehorse, measured at 60 mW/m^2—close to the Canadian average heat flow. Two measurements in nearby British Columbia are also anomalously high at 98 and 126 mW/m^2.

As part of regional geothermal investigations, radiogenic heat production was calculated for about 560 rock samples in Yukon. Of those samples, 263 out of 560 samples (most from southern Yukon) have anomalously high heat production values of 3–10 $\mu W/m^3$ (the average heat-production value for granite is 2.5 $\mu W/m^3$). An additional 25 samples yielded even higher heat-production values, greater than 10 $\mu W/m^3$. In general, Cretaceous plutons show higher average heat-generation values (average approximately 4.9 $\mu W/m^3$; $n = 484$) compared to Tertiary plutons (average approximately 2.0 $\mu W/m^3$; $n = 47$).

In parallel with the radiogenic heat-production calculations, Witter et al. (2018) calculated Curie point depth (CPD) maps for Western Canada using airborne magnetic surveys. This relatively new method was piloted in Western Canada (British Columbia and Yukon) and has been recently applied to regional-scale investigations in South America, Central Asia, and North Africa. The method uses the relationship between subsurface heat and loss of magnetism in minerals in the Earth's crust. Shallow CPD is usually associated with a high geothermal gradient. When used with other data, such as heat flow, it can function as a regional-scale geothermal prospecting tool. In Yukon, this method yielded "anomalously high values of heat generation in Cretaceous and younger granitoid plutons” (Figure 24; Witter et al. 2018, 1).

Figure 23. Heat-flow map of Yukon. *Warm colors* represent high heat flow, and *cool colors* are low heat flow. Selected heat-flow data points from Lewis et al. (2003) are also shown as *brown dots* labelled with the location and heat-flow value. Portions of central and southern Yukon show elevated heat flow compared to other parts of Yukon. (“N.W.T.” is Northwest Territories.) (Image and caption reproduced with permission from Grasby et al. 2012.)

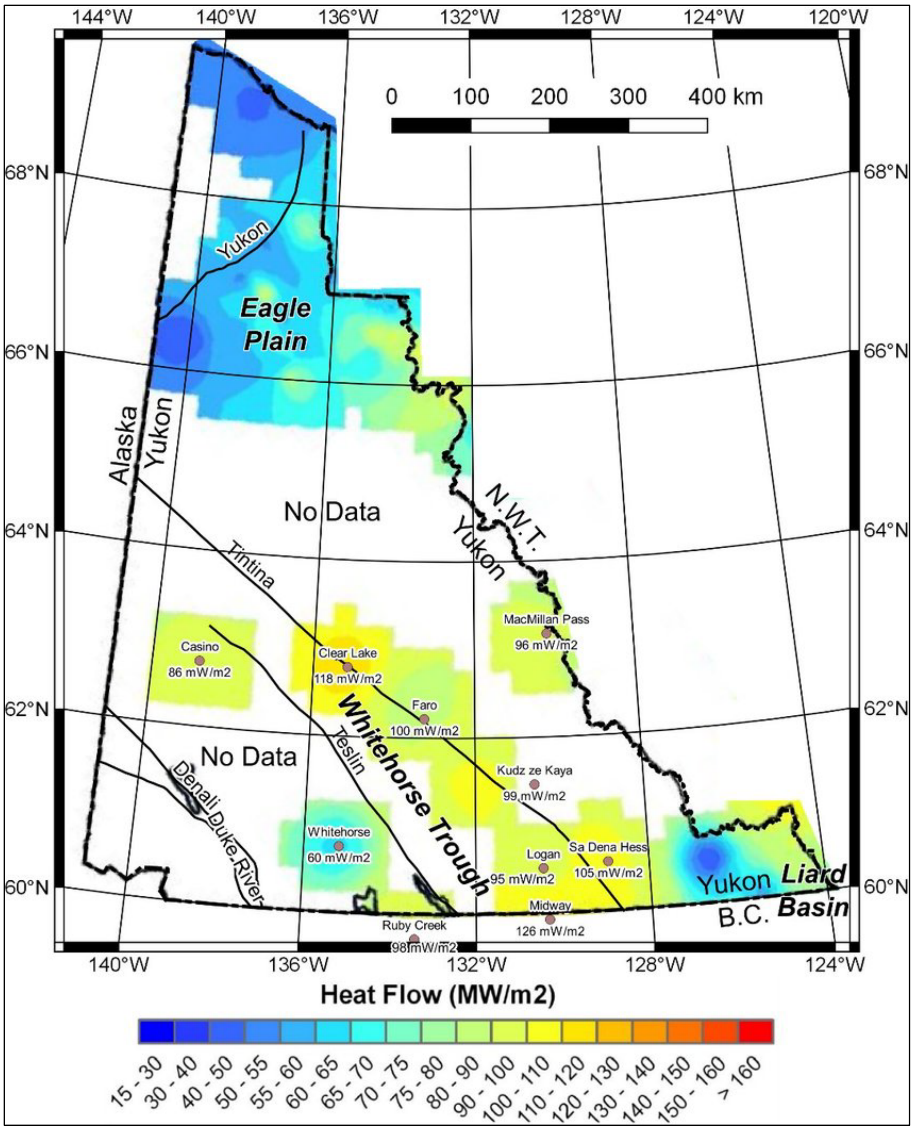
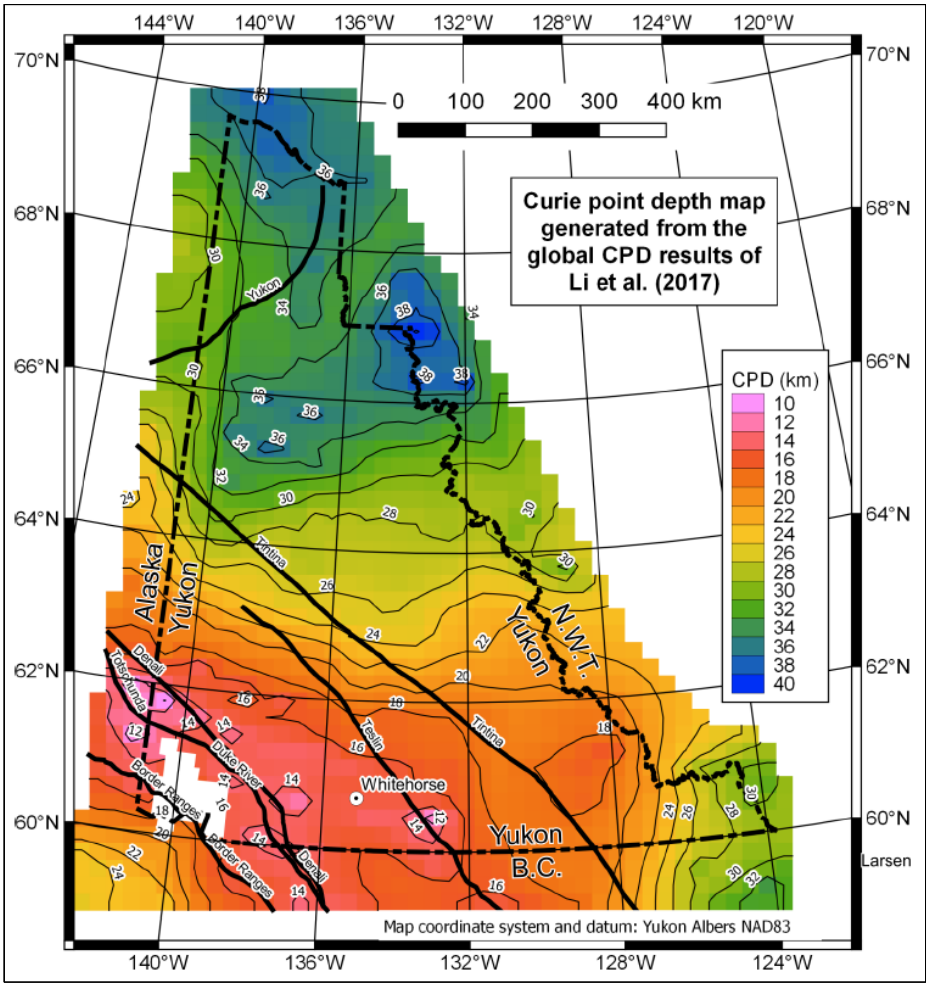


Figure 24. Curie point depth (CPD) map for Yukon, generated from data from Li et al. (2017). *Warm* and *cool colors* represent shallow and deep CPD estimates, respectively. *Contour lines* show CPD in units of kilometers below the surface at 2 km depth intervals. *Black lines* depict major faults from Colpron and Nelson (2011). (Image and caption reproduced with permission from Witter et al. 2018.)

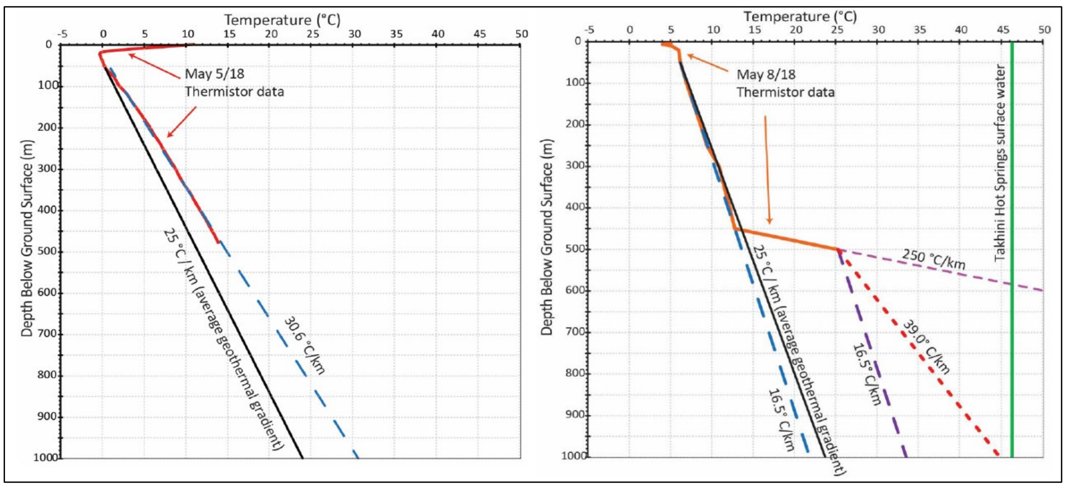


5.3 Thermal-gradient drilling in Yukon

The 2017–2018 heat-flow studies targeted two TG wells in Yukon. One well was drilled near Takhini Hot Springs, and another was drilled in the Tintina Fault trench near Faro. Figure 25, *left*, shows the stabilized temperature profile for the Tintina TG well. The first 100 m shows a temperature reversal that is typical for wells in Yukon (Fraser et al. 2018). Beyond 100 m, a slightly above average geothermal gradient of 30.6°C/km was observed for the entirety of the drilling. No fluids were encountered. While the well was drilled in a fault zone and complex fault structures were encountered downhole, all brecciated rocks were cemented; and there was no evidence of permeable zones.

The stabilized temperature profile for the Takhini Hot Springs TG well (Figure 25, *right*) is intriguing. At depths between 0 and 450 m, the thermal gradient is well below average at 16.5°C/km. However, between 450 and 500 m deep, an extremely high geothermal gradient of approximately 250°C/km was observed; yet the 46°C temperature of nearby hot springs was never attained. The well was drilled to a 500 m total depth, so one can only speculate as to the nature of the thermal gradient beyond 500 m (see colored dotted lines on Figure 25 for alternative scenarios).

Figure 25. Temperature profiles from thermal gradient wells from Yukon, Canada. *Left*, Tintina well; *right*, Takhini Hot Springs well. Both wells were drilled to 500 m. (Image reproduced with permission from Fraser et al. 2018. © Government of Yukon 2022.)



5.4 Implications for Fort Greely

According to Witter et al. (2018), relatively small, low-enthalpy geothermal reservoirs may be numerous across south-central Yukon, depending on subsurface permeability. Two shallow (500 m) TG holes were drilled in in south-central Yukon at sites thought to have high potential for deep crustal permeability. One TG hole—drilled close to 46°C surface hot springs—encountered a permeable zone at about 450 m that flowed fluids at 26°C and demonstrated an extremely elevated thermal gradient for the last 50 m interval). The other hole was impermeable.

This raises a question: Are relatively small, low-enthalpy geothermal (and sometimes concealed) reservoirs numerous across Interior Alaska? If the geologic setting of southern Yukon are analogous to that of the study area, the lessons learned are as follows:

Large-scale active strike-slip faults may not be permeable conduits for circulating fluids; the locations of surface hot springs areas may be evidence for deep crustal permeability; and, therefore, heat-flow studies coupled with detailed prospect-scale structural information could be an effective geothermal prospecting technique for areas with sparse data.

6 Conclusions and Recommendations

To preliminarily assess the opportunities to develop geothermal technologies at Fort Greely, we completed Phase I of a prefeasibility study and designed custom methodology for Phase II. We identified possible geothermal resource types in proximity to Fort Greely, their potential uses, likelihood of existing, and corresponding development risk (Table 2). For each of those plays, we presented their corresponding standard exploration methods, our suggested custom methods, the uncertainty associated with combined methods, and the potential impact of locating each of those plays (Table 4). In addition to supporting prospecting at Fort Greely, this work contributes to the first steps of developing a systematic approach for resource location in Interior Alaska, including resources from radiogenic heating from HHP granites.

Geothermal production technology is well established and has optimal performance in cold regions. It is the resource location that needs further research for Interior Alaska. When prospecting in regions that lack geothermal development, there is increased uncertainty. This inherently results in lack of precedence to calibrate the likelihood of the presence of a resource. The methodology we presented, although it builds on existing work for different regions, is new and therefore introduces additional uncertainty. The geologic setting of the study area, with its rock types, structures, and regional high heat flow, is prospective for geothermal resources despite the lack of surface manifestations. Therefore, this prospect survives the elimination test. Investment in Phase II should account for the higher risk compared to other regions both due to (1) the new methodology and (2) the lack or sparseness of geological data.

Data collection efforts as part of Phase II would benefit from relatively low-cost exploration activities (e.g., temperature logging of nearby wells). This exploration would target data helpful for analyzing the potential of a range of geothermal applications, from GHPs to power production, to better constrain the existence and location of a geothermal resource. The data collected would then be used to determine if a subsequent drilling phase at Fort Greely is justified. If a Phase III is justified, TG drilling would compose the majority of Phase III activities for the Fort Greely project. Recent TG drilling efforts in the geologically analogous Yukon territory of Canada yielded results that could help guide Phase II and III exploration efforts.

Heating functionality is critical in cold regions, and a disruption to fuel supply lines can endanger lives and disrupt the mission. Geothermal resources are in situ resources that can help mitigate these challenges and increase resilience in cold regions. This research is an important first step in the phased risk mitigation process for geothermal development as there is limited deployment of geothermal in Alaska even though geophysical assessments indicate a potentially high amount of resource. This study will help serve future exploration efforts in Interior Alaska, with the ultimate goal to eventually have a systemized methodology for exploration and deployment at Alaskan installations.

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Appendix: Description of Database Structure

Table A-1. Description of database structure.

Data Type	Subfolders	Number of Files
ArcGIS Models and Data	Coordinate Systems	1
	Geodatabases	8 .gdb files + 1 readme
	GIS Data Sets	11 folders containing .dbf files + 1 readme
	Map Documents	6 .mxd files
	Output Files	1 folder "Python Graphs" containing 7 .png files + 13 .png files
	Readme	1
Literature Sources and Reports	Alaska DNR Well Records near Delta Junction	14 .pdf files
	Coal and Mineral Prospecting	3 .pdf files
	Geology	5 .pdf files
	Geothermal	1 folder containing 5 .pdf files, 1 .xls file, 16 .pdf files
	Hydrology	4 .pdf files
	Maps and DGGS Query Results	23 folders
	Project Documents	4 .pdf files
	Satellite Prospecting	5 .pdf files
	Social and Environmental	2 .pdf files
Raw data sets	Aerial Magnetic Surveys	2 .xls files + 1 readme
	Alaska Geochemical Database	1 folder containing 4 metadata files, 2 .accdb files, 4 .xls files + 2 readmes
	Alaska Oil and Gas Conservation Commission	1 .mdb file, 3 .xls files, 1 readme
	Chena Temperature Logs	22 .las files + 1 readme
	CRREL Ecological Study	1 .xls file + 1 readme
	Geochemical OF 82-0325	1 readme
	Geochemical OF 2010-1147	3 .xls files + 1 readme
	Other Geothermal Sites in Alaska	5 .xls files + 1 readme
	SMU Study	1 .xls file + 1 readme
	Readme	1

Abbreviations

ADGGS	Alaska Division of Geological and Geophysical Surveys
ADNR	Alaska Department of Natural Resources
AGS	Alternative geothermal systems
AOGCC	Alaska Oil and Gas Conservation Commission
As	Arsenic
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CAHSB	Central Alaskan Hot Springs Belt
CCHRC	Cold Climate Housing Research Center
Cl	Chlorine
CPD	Curie point depth
CRREL	US Army Cold Regions Research and Engineering Laboratory
EGS	Enhanced geothermal systems
GHP	Geothermal heat pump
GIS	Geographic information system
HHP	High-heat-producing
K	Potassium
Mg	Magnesium
MWwe	Megawatts electric
NAD83	North American Datum of 1983
NGDS	National Geothermal Data System

NREL	National Renewable Energy Laboratory
N.W.T.	Northwest Territories
PFA	Play fairway analysis
ppm	Parts per million
RHP	Radiogenic heat production
Sb	Antimony
SiO_2	Silicon dioxide
TG	Thermal gradient
Th	Thorium
U	Uranium
USACE	US Army Corps of Engineers
USGS	US Geological Survey

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14. ABSTRACT
To enhance energy resilience at military installations in Interior Alaska, we are exploring geothermal energy, which harvests Earth's heat to provide thermal energy, electricity, or both. Parts of Interior Alaska have high subsurface heat flow, likely related to high-heat-producing granites. While electric load is usually the focus of energy resilience; in cold regions, the thermal load dominates energy demand, and operations can be sensitive to it. A local geothermal energy source enhances energy resilience by providing baseload energy and lessening supply chain demand. Geothermal energy technology is mature and often economical, but resource location and assessment remain challenging.

We present exploration methods for a geothermal feasibility study for Interior Alaska and Phase I prefeasibility study results assessing opportunities to develop geothermal at Fort Greely, Alaska. We present possible geothermal resource types, their potential uses, likelihood of existence, and development risk. We also present custom methodology for locating the resources, associated uncertainty, and the impact of finding each resource. Phase I shows geothermal at Fort Greely survives the elimination test. Investment into a Phase II field study to address knowledge gaps should consider the higher risk in comparison to other geothermal plays due to new methodology and sparse existing data.

15. SUBJECT TERMS
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