Exploring for fault-hosted geothermal systems using low temperature thermochronology and thermo-kinematic modeling: a pilot study on the Kigluaik normal fault near Nome, Alaska

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Abstract

Geothermal energy serves a critical role in the transition to a carbon-free energy future. As an effectively emissionless source of baseload power it can serve as the dispatchable complement to intermittent sources like wind and solar. As a power source whose efficiencies are increased in colder climates, it offers an important means to decarbonizing Arctic societies where high latitude and extreme climates make solar, wind, hydro, and battery sources of energy significantly less cost-effective. A major uncertainty when exploring for naturally occurring geothermal systems is whether an active fault mapped at the surface is permeable at depth and is acting as an upwards pathway for hydrothermal fluids. Tools that can assess the fluid flow history and the present behavior of long-lived active faults before drilling are therefore critical to reducing risk and accelerating geothermal development.

High-resolution thermochronology from rocks within and increasingly distant from the surface trace of major faults is a promising means for constraining recent hydrothermal activity. Low temperature thermochronometers such as the Helium system in the mineral apatite are sensitive to even short-lived thermal disturbances and thus offer the potential to quantify even transient hydrothermal events within the fault. Rapid and affordable low temperature thermochronology is now possible thanks to dramatically declining costs in mass spectrometry and improved computational modeling, making it a novel and cost-effective tool for geothermal exploration programs. The proposed study seeks to demonstrate these methods in assessing the geothermal potential of an active regional fault system in western Alaska. Combined with 3D geologic modeling, the results are anticipated to add to our understanding of fault-controlled geothermal systems and help test whether this previously unexplored type exists within Alaska.

Introduction

Although the Earth can provide us with an effectively limitless supply of heat, commercial-grade geothermal systems are limited by the amount of heat and permeability that is found at relatively shallow depths in the Earth's crust. Average heat flux is somewhat easy to quantify, but predicting where permeable pathways are present in the subsurface is much less straightforward (**Siler et al., 2019**). It was with the hope of side-stepping the geological challenge of locating naturally-occuring permeability that a great deal of government subsidy (e.g. >$100M in US DOE grants since 2000) has been devoted towards engineering it in place using technologies that can artificially fracture rocks (i.e. "enhanced geothermal systems"). But due to outstanding challenges in engineering permeability (e.g. scaling, induced seismicity, cost), 99.99% of all geothermal power produced today is from naturally occurring systems. Thus, at least in the near term, successful geothermal development depends on identifying naturally occurring systems and to do so, we need a suite of more affordable and effective exploration techniques.

In the last decade, great progress has been made in understanding fault-controlled geothermal systems, in large part thanks to the progressive development of these systems and their retrospective study across the state of Nevada (e.g. **Faulds et al., 2011**). A key insight from Nevada is that the majority of producing geothermal systems related to extensional fault systems have no clear surface manifestation of their existence, such as hot springs, fumaroles, or sinter mounds (i.e. most are “blind” geothermal systems), implying a much larger resource potential than previously estimated. Only in the last few years have the primary controls on fault-controlled geothermal systems been shown to be related to 1) recency of faulting and 2) the orientations of faults relative to their stress states (**Hinz et al., 2017**), which aids exploration for blind systems. Faults represent brittle failure of the earth’s crust, and pull-apart “normal” faults like those separating the mountains and valleys across Nevada represent the cumulative effect of thousands to millions of years of episodic shear failure and slip under regional extensional stresses. When faults slip, rock failure and frictional deformation create a damage zone proportional to the amount of slip accumulated on the fault. In most rock types, this damage zone is expected to be permeable (**Barton et al., 1995**). Isotopic studies of ancient normal faults have shown that meteoric waters circulate down to the brittle-ductile transition zone (5-10 km depth) along these damage zones (**Haines et al., 2016**). Over time, however, damage zones along faults can become sealed as minerals precipitate out of hydrothermal fluids (**Lowell et al., 1993**). Recognizing whether the fault is still conducive to hydrothermal circulation and upwelling is critical knowledge prior to targeted exploration by drilling. Deducing the temperature history of rocks in and near the fault zone offers a promising means to identify recent and past timescales of hydrothermal activity within the fault zone (**Louis et al., 2019**).

The study of thermal histories in rocks (i.e. thermochronology) makes use of the interplay between the production of radiogenic isotopes from nuclear decay versus the diffusive loss of those isotopes out of the crystal lattice due to Fickian diffusion (**McDougall & Harrison, 1999**). An ideal thermochronometer for geothermal studies is the helium in apatite system, in which He accumulates by alpha decay of U and Th in the mineral but is increasingly lost by diffusion when held at temperatures >40 °C. The interplay of radiogenic ingrowth and diffusive loss over time results in distinct isotopic ratios and spatial distributions that can be measured to high precision with modern mass spectrometers and can be assessed and interpreted through forward and inverse modeling (e.g. **Louis et al., 2019)**. A few studies have shown this to be useful for resolving fluid flow histories within normal fault systems (**Gorynski et al., 2014; Benowitz et al., 2014**). **Louis et al. (2019)** combined low-temperature thermochronology with detailed modeling of conductive and advective heat flow in the normal fault-controlled Beowawe geothermal system in Nevada. Their data and modeling resolved episodic fluid flow over roughly 250,000 years.

This project aims to test and further refine these methods in a remote part of Alaska where active extensional fault systems exist but for which very little data has been collected. A study in this locality has the immediate benefit of aiding ongoing exploration work in the area aimed at meeting the energy demands of nearby Arctic communities, such as Nome, which spends ~$8M per year on diesel generated electricity. It has the broader benefit of helping refine a new exploration tool for discovering new fault-controlled geothermal resources, which have the potential to displace GW of carbon-based forms of electricity in similar tectonic settings in Alaska and around the world (e.g. Nevada, east Africa, central Asia). This project utilizes capabilities and laboratories at Stanford that are exceptionally well-suited to collecting and modeling this kind of data, but which have not been applied to geothermal questions.

Alaska pilot project

Alaska is on the frontline of climate change and its people pay more for electricity than any other state in the continental US, such that locally generated and renewable forms of energy are of great strategic and economic importance. Transitioning away from diesel-, gas-, and coal- generated electricity in Alaska, however, is challenged by the low efficiencies of solar, wind, battery, and hydro at high latitudes and under Arctic conditions. Most geothermal exploration to date in Alaska has focused on geothermal systems with obvious surface manifestations of heat, including active volcanoes and/or moderate to high temperature hot springs, but many of these are far from potential users and complicated by less uniform exploration models. Consequently, only one very small (<0.5 MW) geothermal power plant is operating in the state. A completely unexplored type of geothermal system in Alaska is an extensional fault-hosted geothermal system that has proven highly productive in the state of Nevada. These types of systems are controlled by range-bounding extensional fault systems in regions of the crust that are being actively pulled apart by plate motions. Just like Nevada, western Alaska is undergoing a similar sort of stretching, and is characterized by similar types of fault systems as Nevada (**Dumitru et al., 1995**). Regional strain fields now corroborate increasing amounts of N-S extensional strain westward across Alaska with the concominant formation of extensional fault systems and their associated hydrothermal systems (e.g., **Finzel et al., 2011**), suggesting a broader geothermal potential than previously recognized.

The proposed project here would be to pilot low temperature thermochronologic methods on an active range-bounding extensional fault in western Alaska (Fig. 1) to evaluate its geothermal potential.

Figure 1. Map of the study area showing the Kigluaik range-bounding normal fault system.

Previous studies in this region of Alaska focused almost entirely on enigmatic hot springs north of the active fault system: the “Pilgrim Hot Springs”. The latest studies from 2010-2014 (**ACEP, 2015**) included drilling 8 new wells to max. depth of 1294 ft and achieving max. temp. of 91°C. But ubiquitous temperature reversals suggested drilling was not directly over the main area of upwelling. No further development occurred, likely due to the small size of the resource identified at the hot springs location.

Re-evaluation of the regional data sets by Zanskar Geothermal & Minerals, Inc. (ZGM) suggests the hot springs are surface manifestations of outflow sheets that are many kilometers away from their upwelling source, similar to such occurrences at extensional fault hosted geothermal systems in Nevada (e.g. **Coolbaugh et al., 2006**). In this model, the active range-bounding extensional fault system controls the primary hydrothermal upwelling, explaining the temperature reversals encountered during drilling and the Na-K-Ca geothermometry of fluid samples at the hot spring locality that suggest source temperatures (~145 °C) are much higher than max. temperatures encountered during drilling (91°C) (**ACEP, 2015**).

Methods

3D geologic modeling **–** The first phase would involve generation of a 3D geologic model (e.g., **Siler et al., 2019**) that incorporates all available datasets and those to be provided by ZGM, including new fault mapping informed by LiDAR, new surficial drone-based thermal imaging and 2-meter thermal probing, fault slip history constrained by new alluvial fan and colluvial sediment ages, and stress state inversions from fault slip markers, microseismicity (recorded by temporary portable seismic array) and borehole breakouts (recorded by distortion of wellbore by local stress state).

Low temperature thermochronology **–** A total of 30 samples will be collected from bedrock along fault-perpendicular transects that include both hanging wall and footwall portions of the fault system from 3 different segments of the fault that were identified from 3D modeling to be optimally oriented for permeability. Apatite mineral separates will be extracted using standard mineral separation processes and analyzed at the Stanford Noble Gas Thermochronology Facility, which is optimized for this kind of study. Quantitative modeling will be performed using the open-source code Beo v.1.0 (**Luijendijk, 2019**), which allows for simulating the effect of hydrothermal activity on helium concentrations in apatite from surface outcrops. Benefits of this new code package is that it provides a more realistic representation of spring and land surface temperatures compared to models that apply a fixed heat flux, temperature, or transfer coefficient to the surface. Model parameter space will be informed by the 3D geologic model above and iteratively explored to find best fit solutions to the measured sample results, thereby providing constraints on the hydrothermal evolution of the Kigluaik normal fault system (see examples in **Fig. 2**).

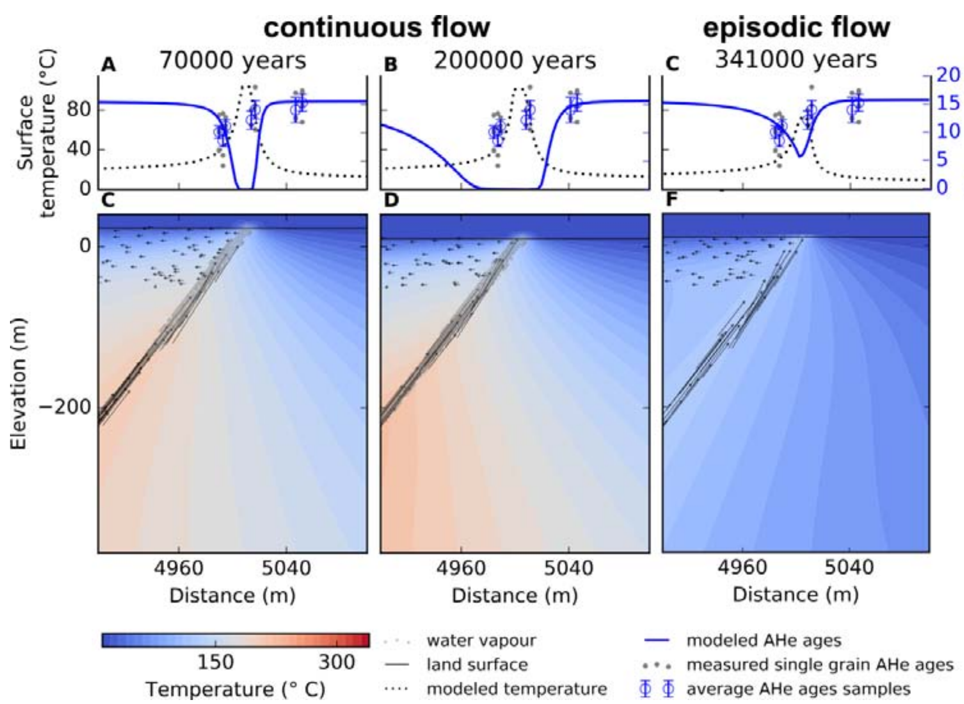

Figure 2. Example plots from Louis et al. (2019, their figure 3) comparing measured thermochronology results (AHe ages) to modeled profiles for different hydrothermal scenarios (upper panel) and representative sections of the model domain (lower panel).

Collaborators and follow-on funding opportunities

This work will be completed in tandem with an exploration and drilling campaign planned by Zanskar Geothermal & Minerals, Inc. (ZGM), on the same active fault system. Potential drilling by ZGM Inc. will allow for an important test of the modeling generated by this research. Methodological collaboration is anticipated with Professor Martin Grove who directs the Stanford Noble Gas Thermochronology Facility. Successful completion of this study would pave the way for future research grants which we envision could apply this exploration methodology at scale across the state of Alaska. Follow on studies could receive support from the National Science Foundation, the Department of Energy, Alaska Renewable Energy Fund, and / or industry consortia.

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BIO of Principal Investigator

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Elizabeth Miller is a professor in the department of Geological Sciences at Stanford University. She received her Ph.D. from Rice University, then completed Post-Doctoral work at Lamont-Doherty Geological Observatory at Columbia University, before coming to Stanford University. She is an expert in extensional tectonics and has spent decades mapping and studying extensional fault systems both ancient and modern, across the Basin and Range province and Alaska, resulting in some 113 peer-reviewed publications and a Career Contribution Award from the Geological Society of America.

She and her students have extensive experience applying cutting-edge thermochronological methods to better understand extensional fault behavior in both Nevada and Alaska. Several of her students now lead some of the most successful thermochronology labs in the US. She and her students have previously mapped and studied the Kigluaik fault system described here but the work proposed herein would be the first effort by her research group to assess the geothermal energy potential of normal fault systems and the first to use thermochronology data and modelling of this data as potential geothermal exploration tools.

Research website: https://tectonics.stanford.edu/
List of publications: https://profiles.stanford.edu/elizabeth-miller?tab=publications
Extensional faulting and thermochronology: https://tectonics.stanford.edu/research-current-cordillera