Remote sensing and modeling of anomalous snowpack associated with areas of geothermally-heated ground as a tool for geothermal exploration and resource assessment in cold environments

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Overview

Hot springs, fumaroles, and geysers are the most recognizable surface manifestations of geothermal systems. These discrete thermal features have potential to be mapped and quantified in support of geothermal exploration [1], resource assessment, and long term monitoring using thermal infrared (TIR) remote sensing. Surface temperature data derived from TIR imagery can also be used to estimate the near-surface heat loss supporting discrete geothermal features that provides a lower bound on the total heat loss from geothermal systems [2]. This measure of heat loss can be used to predict the power potential of undeveloped geothermal systems using existing empirical relationships between surface heat loss and electrical production capacity established from developed resources [3].

For many geothermal systems, thermally anomalous ground represents a less obvious but more spatially extensive surface thermal feature. In many cases, conductive or convective heat loss associated with thermally anomalous ground represents a more significant component of the total near surface heat loss from a geothermal system than is associated with discrete surface thermal features. Areas of thermally anomalous ground may also provide the only surface indication of geothermal activity in the case of blind geothermal systems. These factors point to the importance of investigating thermally anomalous ground within geothermal exploration and resource assessment.

The use of remote sensing to investigate thermally anomalous ground has received comparatively little attention when compared to investigations of discrete surface thermal features. Heated ground presents a more subtle surface manifestation that may be harder to detect using TIR remote sensing owing to the lower temperature of these areas and compounding effects of other environmental factors on recorded ground surface temperatures (e.g. diurnal solar heating effects, topography, and vegetation cover). One approach to mapping and quantifying the heat flux associated with thermally anomalous ground that is appropriate for cold environments with pervasive winter snow cover is to exploit the impact of heated ground on overlying snowpack. For geothermal areas, heated ground may remain snow-free throughout the winter or result in a thinner overlying snowpack that will melt out sooner when compared to surrounding non-geothermal areas (Figure 1). These phenomena can be exploited as tool for geothermal exploration and quantitative resource assessment in cold environments. Snow-free areas or thinned snowpack provide a surface indicator of geothermal activity that can be mapped with areal coverage using various remote sensing techniques. For example, work we have undertaken At Pilgrim Hot Springs, Alaska has exploited both satellite and airborne optical and TIR wintertime remote sensing data to map the extents of snow-free areas providing direct indications of heated ground [1]. This approach offers potential for mapping subtle surface thermal anomalies as snow-free areas or perturbed snowpack represent the time-integrated effect of elevated geothermal heat flux on overlying snow-pack rather than an absolute surface temperature anomaly, which may be small or undetectable. Snowpack simulation models can also be used to directly quantify the elevated geothermal heat flux (conductive or convective) leading to anomalous snowpack conditions. Coupling spatial observations of the snowpack on a specific data derived from remote sensing data with models of

Figure 1. Aerial photograph of Pilgrim Hot Springs, Alaska: geothermally-heated ground is observed as areas of anomalous snow-free conditions in this wintertime image.

snowpack development provides the basis for estimating the geothermal heat flux (GHF) necessary to produce anomalous snow conditions on that day. This approach has been used successfully to predict the GHF associated with heated ground for parts of the Yellowstone geothermal system [4].

Aims

The aim of the work proposed in this white paper is to further investigate the potential of using snow melt anomalies associated with heated ground as a practical tool for exploration and quantitative assessment of geothermal systems in cold environments and in particular low-temperature resources located in the state of Alaska. The project will investigate the synergy of radar remote sensing for mapping of snowpack conditions with snowpack models that will be used to estimate GHF (encompassing conductive and convective heat fluxes) associated with areas of anomalous snowpack condition. This work will be undertaken at Pilgrim Hot Springs, located in Western Alaska that is currently being investigated as a potential power source for Seward Peninsula communities. The proposed research will build upon our existing investigations at this site using airborne thermal infrared remote sensing that has mapped and quantified the convective heat flux associated with fluid outflow [2]. The work proposed will address the specific need to estimate the conductive/convective heat losses associated with areas of heated ground (Figure 1). Together, estimates of heat flux associated with heated ground and fluid outflow will provide a more complete estimate of total near-surface heat loss from the geothermal system that will contribute to improved resource assessment. In the longer term, the development of rapid, remote sensing methods for estimating near-surface heat losses from undeveloped geothermal systems will enable improved geothermal exploration and resource assessment over the large and inaccessible state of Alaska.

Proposed Work

Specific details of the work proposed are described in the sections below:

Radar remote sensing of snowpack conditions: The work proposed will utilize multi-temporal, very high resolution (~1m pixel size) satellite radar imagery acquired by the TerraSAR-X satellite with the aim of mapping snow conditions at Pilgrim Hot Springs over a winter to spring transition period. Observations concerning the evolution of the snowpack interpreted from this data will be used to constrain snowpack simulation models. Satellite radar data provides improved potential for mapping snow conditions over satellite or airborne optical imagery: satellite radar sensors, such as TerraSAR-X, are 'active' remote sensing instruments that provide all-weather imaging capabilities enabling rapid repeat imaging of targets (~every 11 days in the case of TerraSAR-X). Radar data is also sensitive to snow dampness [5] and has potential to directly estimate snow water equivalent (SWE) [6, 7] that is not possible using passive optical sensors. The project will investigate the potential of using estimates of snow physical properties to map thinned snowpack associated with areas of geothermal ground heating (with significance for geothermal exploration) and as a means to directly validate estimates of SWE output from snowpack models.

Field calibration and validation: Field calibration and validation will be undertaken at Pilgrim Hot Springs in support of snowpack modeling and radar data analysis. Field instrumentation will be installed at the site to provide local micrometeorological (air temperature, precipitation, net solar radiation), soil (temperature, heat flux), and snow (snow depth, snow water equivalent) information. Local data acquired by this instrumentation as well as regional meteorological / snow depth information acquired by existing networks will be used as input to snow pack models for the site. We will also install a network of distributed snow depth/temperature sensors across areas previously mapped as being thermally anomalous to track the snow conditions over the winter-spring transition and validate snowpack models. Estimates of geothermal heat flux output from the snowpack models will be validated using existing data such as the results of shallow temperature surveys and temperature gradients from shallow geo-probe holes and deeper exploration wells.

Snowpack simulation modeling: We will apply the snowpack simulation model developed by Watson et al. [4] that simulates the total heat and water balance of a snowpack with areal coverage on a daily basis.

Previously Watson et al. [4] used this model to predict the GHF for snow-free areas in Yellowstone National Park. For this project we will employ the same approach to predict the anomalous GHF associated with areas of geothermally heated ground at Pilgrim Hot Springs using the radar data to constrain the extents of snow-free areas and physical properties of perturbed snowpack. Model results will be validated through comparison of measured and predicted snow parameters (SWE, depth, temperature) for the region outside of the geothermal area and by comparing GHF estimates with comparable direct measurements of GHF from areas of heated ground. Comparison of the results of snowpack modeling using local and regional data will enable assessment of the reliability of the latter for running snowpack models at un-instrumented sites (and applying the same approach to other geothermal systems).

References

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Keywords: remote sensing data (RSD), digital elevation model (DEM), geographic information system (GIS), vegetation cover mapping, soil carbon stock, Central Siberia. Citation: Danilova I.V., Ryzhkova V.A., Korets M.A. Mapping of vegetation cover and soil carbon stock using geographic information system tools, remote sensing data and digiatal elevation model, J. Sib. Fed. Univ.Â Additionally, we used the produced map of vegetation regeneration as a base for mapping of ecosystem carbon stock volume. Methods and materials. The test site (68Â°20' - 68Â°30' N, 88Â°30' - 89Â°00' E) was located in the northern part of Yenisei Siberia in forest-tundra and northern taiga subzones. Thermal infrared (TIR) remote sensing provides a unique tool for mapping the surface expressions of geothermal activity.Â Abstract In areas of anomalously high crustal heat flow, geothermal systems transfer heat to the Earths surface often forming surface expressions such as hot springs, fumaroles, heated ground and associated mineral deposits. Geothermal systems are increasingly important as sources of renewable energy, natural wonders often afforded protected status, and their study is relevant to monitoring deeper magmatic processes.Â Studying surface geothermal activity and heat loss associated with magmaticrelated systems is important for monitoring of subsurface igneous activity. Also cutting the upfront cost of geothermal exploration will further encourage investors to consider investment in this emerging clean energy field. Hence, it is of paramount importance to improve prospecting techniques in order to explore where economic concentrations of geothermal energy are to be expected.Â 1 shows conceptual geologic model of geothermal system where recharge results from meteoric groundwater driven by heat supplied from a buried magmatic system leading to a convective column.Â used to directly quantify the heat flux from areas of geothermally heated ground (Bromley et al., 2011; Carr et al., 2009; Haselwimmer and Parakash, 2012; van deer Meera, et al., 2014). One of the satellites that have been used to map thermal activities is the Landsat satellites.