Methodology used in Identifying the Target Areas

Approach

Subsurface geothermal activity has a thermal expression that can be observed at the surface. Such spatial temperature gradients are within the radiometric resolution that is characteristic of a wide range of satellites that carry thermal sensors. The instruments we will employ resolve temperatures to approximately 0.5°C of their true value, thus feasibly distinguishing “hot spots” or warm exposures. We will take advantage of this thermal sensitivity from a number of satellites to model “hot spots” or anomalously warm thermal regions, which likely reflect of potential geothermal heat sources.

For this effort, we used a hierarchical approach in which we examined data from Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM^+) onboard Landsat platforms and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard the Terra satellite to digitally model warm surface exposures. Geological characteristics such as faulting and other available datasets for known thermally active areas in Colorado were used with candidate areas that have been identified with TM, ETM^+, and ASTER data to rank the potential areas of geothermal activity. The selected areas will be subject to further field testing using field methods such as 2-meter temperature surveys and further analyses using remote sensing data.

Analysis of Landsat Data

Day- and night-time imagery (when available) from Thematic Mapper (TM) scenes with no or minimum cloud cover, were obtained for two dates within the same timeframe of different years from EROS Data Center of the USGS. The scenes were georectified to a common map base.

The temperature of each pixel within each scene was calculated using the thermal band. In order to calculate the temperature an average emissivity value was used for each land cover type within each scene. The NLCD 2001 land cover classification raster data of the zones that cover Colorado were downloaded from USGS site and used to identify the land cover types within each scene. The digital numbers were converted to radiance, and temperature was calculated in degrees Kelvin and then degrees Celsius for each of the land cover types (open water, barren, deciduous forest and evergreen forest, mixed forest, shrub/scrub, grassland/herbaceous, pasture hay, and cultivated crops) using the average emissivity values.

Under the assumptions that the temperature within each scene is normally distributed and the mean temperature may be used to account for the thermal inertia, the mean temperature and standard deviation (σ) of each land cover type were calculated and used to identify areas that have temperatures, equal to, mean plus one σ, mean plus two σ, and greater than mean plus two σ. Areas that had temperature greater that mean plus 2 σ in the two dates were considered Landsat modeled warm surface exposures.

Analysis of ASTER Data

Level L1B ASTER data acquired in the period between 2000 and 2007 were downloaded from EROS Data Center. The thermal images were georectified and corrected for atmospheric effects.

The Emissivity Normalization Algorithm was employed to calculate the temperature of each pixel. The following steps were used for calculating the temperature: (1) an emissivity of 0.96 was used to calculate the temperature of each pixel from the 5 ASTER channels (i.e. each pixel has 5 temperatures); (2) the hottest temperature of step 1 is used to calculate the emissivity of the surface of each channel; (3) calculated emissivity is used to calculate the temperature in degrees Kelvin; and (4) temperature is converted from degrees Kelvin to degrees Celsius. The mean temperature and the standard deviation (σ) of each scene were calculated and used to identify areas that have temperatures, equal to, mean plus one σ, mean plus two σ, and greater than mean plus two σ. Areas that had temperature greater that mean plus 2 σ in the two dates were considered ASTER modeled warm surface exposures.

Selection of Targets

A ranking system was proposed based on the warm surface exposures identified from remote sensing data and geological characteristics. The geological characteristics are important in selection of the potential targets, because they minimize the risk of selecting false thermal anomalies identified by remote sensing data. The criteria used for the ranking system include: hot/warm surface exposures modeled from ASTER/Landsat satellite imagery, alteration mineral commonly associated with hot springs (clays, Si, and FeOx) modeled from ASTER and Landsat data, Colorado Geological Survey (CGS) known thermal hot springs/wells and heat-flow data points, Colorado deep-seated fault zones, weakened basement identified from isostatic gravity data, and Colorado sedimentary and topographic characteristics. Each of these criteria were assigned points with total points adding to eleven (i.e. a perfect target will score eleven points).

Further Analysis and Investigation

Thermal infrared (TIR) remote sensing data can be used to identify geothermal anomalies; however, sometimes it is difficult to distinguish between the geothermal anomalies and the ones caused by other sources such as the solar radiation. Accurate estimates of surface energy exchange components are critical for understanding many physical processes of thermal anomalies. These measurements assist in separating the geothermal activities from others. Moreover, assessing energy budget enables the quantification of soil heat fluxes. Numerous techniques exist for studying surface energy balance, and they include remote sensing, solar radiation models, and eddy covariance.

Remote Sensing and radiation models

Since the study area is regional in scope covering all of western Colorado, it was not feasible to estimate the surface energy balance for such a large area to correct for topographic effects and albedo. However, 5 or 6 targets identified during Phase I and part of Phase II (fieldwork) will be further investigated to consider the effect of topography and albedo using ASTER day- and night-time data using the technique developed by Coolbaugh and others (e.g. Coolbaugh *et al.*, 2007 and Eneva *et al*, 2006) and/or using a model that estimates incoming solar radiation based on digital elevation models (e.g. Fu and Rich, 1999).

Eddy Covariance

The eddy covariance method, a micrometeorological technique, measures mass and energy fluxes over short and long timescales (hour, days, seasons, and years) with minimal disturbance to the underlying vegetation. Another attribute of the eddy covariance method is its ability to sample a relatively large area. Typical footprints have longitudinal length scales of 100–2000 m (Schmid, 1994). We propose to collect direct measurement surface energy balance components using the eddy covariance method. This method, based on solid and tested theory, is essentially based on the degree of covariance between high-frequency measurements of vertical wind and water vapor density.

The main objective is to use field data to calculate radiation and energy budgets of the selected sites. The specific objectives are:

1) To install tripod and instruments to gather data for complete energy budgets of 5/6 sites selected to have potential geothermal activity. Also to obtain remote sensing data for the study areas from remote sensing satellites, Landsat and Terra (ASTER).
2) To use the eddy covariance data for assessing radiation and energy budgets and to use remote sensing imagery with energy budgets to separate geothermal temperature anomalies from other anomalies.
3) To quantify soil heat fluxes.