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PHASE 1 FINAL REPORT

PROJECT TITLE: Validation of Innovative Exploration Techniques, Pilgrim Hot Springs, Alaska

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RECIPIENT: Alaska Center for Energy and Power
University of Alaska Fairbanks
PO Box 755910
Fairbanks AK 99775-5910

AWARD NUMBER: DE-EE0002846

PROJECT LEAD: Gwen Holdmann, Director, Alaska Center for Energy and Power (ACEP), UAF

Co-INVESTIGATORS: Dr. Anumna Prakash, Professor, Geophysical Institute (GI), UAF
Dr. Ronald Daane, Ass. Prof., Water and Environmental Research Center, Institute of Northern Engineering (INE), UAF

Other PHASE 1 KEY PARTICIPANTS:
Christian Haselwimmer, Post-Doc, GI, UAF
Markus Mager, Project Management, ACEP, UAF
Dick Benoit
Bill Cummings
Art Clark, USGS
Jonathan Glen, USGS Menlow Park
Darcy McPhee, USGS Menlo Park

PHASE 1 STUDENTS:
Arvind Chittambakkam, M.Sc. Geology, UAF
Charles Parr, B.Sc. Geography, UAF
Jack Gadamus, M.Sc. Resource Economics, UAF
Jonathan O'Toole, M.E., Mechanical, Sydney
Joshua Miller, M.Sc. Geology, UAF
Kate Schaefer, M.Sc. Interdisciplinary, UAF
Lisa Stowell, M.E., Mechanical, UAF
Peter Illig, B.Sc. Geology, UAF
Zachary Woodbury, M.Sc. Resource Economics, UAF

EXTERNAL PARTNERS / SUB-CONTRACTORS / LAND OWNERS
US Geological Surveys (USGS)
Fugro
Matt Nolan and Jessie Cherry, UAF
Unaatq, LLC
Bering Straits Native Corporation (BSNC)
Mary’s Igloo Native Corporation (MINC)

DOE PROJECT MANAGER:
Ava Coy
Geothermal Technologies Program Project Officer
720-356-1487, ava.coy@go.doe.gov
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LIST OF TERMS AND ACRONYMS

ACEP – Alaska Center for Energy and Power
AEA – Alaska Energy Authority
AEM – Airborne Electromagnetic
ASTER – Advanced Spaceborne Thermal Emmission and Reflection radiometer
BSNC – Bering Straits Native Corporation
DOE – Department of Energy
DGGS – Alaska Division of Geological and Geophysical Surveys
EM – Electromagnetic
ETM+ - Enhanced Thermatic Mapper
FLIR – Forward Looking Infrared Radiometry
GI – Geophysical Institute
MHG – Maximum horizontal gradient
MINC – Mary’s Igloo Native Corporation
MT – Magnetotelleurics
NDVI – Normalized Difference Vegetation Index
PHS – Pilgrim Hot Springs
PSG – Pseudogravity
R2D – Reduced to Pole
UAF – University of Alaska Fairbanks
USGS – United States Geological Survey
WV-2 – Worldview 2
1.0 PROJECT OVERVIEW
The objective of this project is to use a combination of existing and innovative remote sensing and ground-based exploration techniques to develop a preliminary conceptual model of the Pilgrim Hot Springs geothermal resource, and to test and hopefully confirm this model through the drilling of two confirmation slim holes.

This project will take place at Pilgrim Hot Springs, located on the Seward Peninsula in Alaska. The first Phase of this assessment, which is the subject of this report, includes the use of a combination of innovative geophysical remote sensing techniques (including forward looking infrared radiometry, or FLIR) intended to map the spatial extent and total heat flow to the surface and make a preliminary estimation of the developable extent of the reservoir. This work is coupled with more traditional ground-based exploration techniques to pinpoint the location of the upflow zone, map the spatial extent and total heat flow to the surface, and estimate the temperature and depth of the reservoir.

The second Phase of this project (occurring in 2012) will involve drilling and testing a series of holes of varying depth as well as accessing existing wells that were part of a late 1970s and early 1980s resource evaluation effort to confirm the results from Phase I. The third Phase (occurring in early 2013) will involve developing a more complete understanding of the reservoir through flow tests and water sampling of the holes, and development of a numerical reservoir model. The full project Statement of Project Objectives (SOPO) is included as Appendix A.

Figure A. Topographic index map showing the location of Pilgrim Springs (red star) on the Seward Peninsula.
Task 1: Innovative remote sensing techniques.
Task 1 includes airborne and satellite mapping of the geothermal anomaly. The FLIR (forward looking infrared) airborne survey technique has been successfully used at Chena Hot Springs in Alaska, to measure heat loss which correlated closely with values calculated from conductive thermal gradient hole data and convective output. If a FLIR survey coupled with a new iterative digital processing method can be repeatedly shown effective at estimating the heat flow to the surface for systems with a discrete surface expression, this will provide a very low cost and fast method of measuring the natural heat loss of a geothermal system which can be an indication of its maximum possible electrical megawatt output. This Task has been divided into two sub-tasks.

Task 1.1 Satellite-Based Geothermal Anomaly Mapping.
This task outlines the shallow thermal anomaly and calculates the heat flux by utilizing existing Landsat and Aster images with a new iterative digital processing method that is anticipated to drastically reduce the number of false alarms and uncertainties associated with traditional thermal infrared data processing. This processing scheme involves first categorizing thermal data based on ancillary information, such as elevation, slope, aspect, land cover, geologic and geophysical signature, then processing each category separately using a first derivative filtering process. This allows us to identify consistently anomalous pixels before using image stacking to differentiate the most promising geothermal anomalies from false alarms. For each thermally anomalous area we will calculate the kinetic temperature using the inverse Planck's function and will estimate the thermal flux in watts/unit area/unit time. Processed subsets will then be mosaiced back to generate a thermal anomaly map of the area.

Task 1.2 Airborne FLIR Surveys.
Two FLIR surveys were flown over 16 square miles surrounding the hot springs in the fall (2010) and spring (2011) to perform a more detailed assessment of the thermal anomaly and its heat loss. We incorporated a small thaw in the permafrost about 3.2 km NE of Pilgrim Hot Springs. The iterative digital processing method described in Task 1.1 was also used to process the resulting data.

Task 2: Additional Ground-based and Airborne Surveys.
Task 2 includes ground based surveys including a shallow temperature survey, an MT survey, and some new chemical analysis in addition to an airborne geophysical survey. Final interpretations of these will be included in our conceptual model; this report covers our methodology and preliminary findings and results.

Task 2.1 Conduct a Shallow Temperature Survey.
Preliminary review of existing data and airborne imagery of potential thermal anomalies observed from early fall snow melt patterns and ground based magnetic data collected by the USGS in April 2010 suggests the geothermal aquifer may lie along a trend extending from the springs to the northeast. To verify this trend and select targets for Task 3 drilling, holes 5-10 m deep were installed over the entire possible shallow thermal anomaly. These holes were installed by hand with a portable drill by a field crew travelling on foot and did not utilize any drilling mud or sumps.
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These will also be useful in independently estimating the conductive heat loss from the geothermal field. Note: due to challenges with the originally proposed technique, we switched to a Geoprobe system provided by the USGS to install dozens of holes up to 154 ft in depth. This was a highly successful add-on to the original program and is described in the Task 2.1 section.

Task 2.2 Geophysical Surveys.
A combination of ground based and airborne geophysical surveys will be conducted to map subsurface hydrothermal fluid flow and identify key structures controlling the flow.

Sub-Task 2.2a Airborne Geophysical Survey
A high-resolution airborne geophysical survey was conducted, including the immediate survey area and extending to the northeast to provide a regional geophysical context for the site and to map key structures controlling hydrothermal fluid flow. This sub-task was completed in conjunction with and partially funded through the United States Geological Survey (USGS).

Sub-Task 2.2b Ground-based Resistivity Survey
A CSAMT/AMT survey was run over the entire shallow thermal anomaly to assist in defining its margins and help locate the upflow of thermal water feeding the shallow aquifer. This will extend previous results from over the entire thermal anomaly and the locations of these lines will be recorded by GPS. This sub-task will be funded entirely through match funding through the State of Alaska. Note: this task was completed in late August 2012 and interpretation has not been completed and is this not part of this report.

Task 2.3 Repair Existing Wellhead and Collect New Data: Six wells currently have penetrated the shallow thermal aquifer, but the wellheads were in poor condition. These wellheads were replaced so that the wells can be controlled and tested. New temperature and pressure logs were run in as many wells as possible, and new samples were taken for chemical analysis.
2.0 TASK 1.1: Satellite Based Geothermal Anomaly Mapping

Summary; Work Done and Results; Successes/Limitations/Recommendations

2.1 Summary
Satellite images from Landsat, Aster, and WorldView-2 (WV-2) satellites were processed. Use of WV-2 images was an opportunistic expansion of this task beyond what was originally proposed. The images helped to identify persistent high temperature areas, areas of snow-melt in winter images, and areas of greener vegetation in spring-time images, near Pilgrim Hot Springs (PHS). These interpretations were very useful to plan flight lines for detail surveys. Satellite images were not particularly useful for thermal heat flux estimations as the thermal images had a coarse resolution compared to the size of the geothermal anomaly at PHS.

2.2 Work Completed and Results

2.2.1 Analysis of Landsat 7 data
Processing and analysis of Landsat 7 Enhanced Thematic Mapper (ETM+) thermal imagery acquired over the region of PHS was used to delineate geothermal anomalies with a view to planning the airborne thermal infrared (FLIR) and optical survey. A search of the entire Landsat 7 archive for ETM+ images from the PHS region yielded 18 scenes, which had been acquired between August 1999 and July 2010. We selected a subset of eleven datasets for further analysis corresponding to cloud and snow free images.

Processing of the ETM+ data was applied to the low-gain thermal band (band 6L) that records thermal infrared radiation in the 10.40-12.50 μm wavelength region at a ground spatial resolution of 60 m. The discrimination of thermal anomalies was undertaken using the image ‘stacking’ approach described by Prakash et al. (2011). This included pre-processing the band 6L thermal data for each dataset using the three-step procedure described by Chander et al. (2009) that involved: 1) applying sensor gain and offset values to convert the sensor digital numbers (DNs) to measured at-sensor radiance values, 2) converting the at-sensor radiance values to brightness temperature using a modified Planck equation, and 3) calculating kinetic temperature from brightness temperature using a fixed emissivity value of 0.96. For each pre-processed band 6L dataset we produced a thermal hotspot image representing the highest temperature values using a threshold determined from the top 10% of the thermal image histogram. We integrated the thermal hot spot images for each year to identify temporally persistent thermal anomalies that may represent geothermal sources (Figure 1): if a thermally anomalous pixel was identified in data from three different years then it was labeled as a persistent anomaly.

The results of analysis of the ETM+ data highlight five main persistent thermal anomalies located within the broad region of the Pilgrim Hot Springs. Four thermal anomalies appear to be form a broad 5 km swath aligned in an N-S direction located around 1 km west of the main PHS site (Figure 1). A fifth spatially extensive thermal anomaly was mapped towards the western end of Hen and Chickens mountain. We consider that the three thermal anomalies detected south of the Pilgrim River (Figure 1) represent the best candidates for geothermal anomalies. The two hot spots detected north of the Pilgrim River are somewhat large and associated with bare soil and rock exposure that may indicate solar heating effects rather than a geothermal source.
2.2.2 Analysis of ASTER data
We also acquired and processed multi-temporal Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) multispectral thermal infrared data acquired over the PHS site with the aim of identifying geothermal anomalies (Figure 2). Although the 90m spatial resolution of the ASTER thermal bands is lower than that of Landsat 7, ASTER is a multispectral instrument and is routinely used to acquire data during its nighttime ascending orbit. Nighttime thermal data is particularly useful as it minimizes the effects of solar heating, which provide impediments to the detection of subtle geothermal anomalies. The five ASTER thermal bands also enable the effects of emissivity to be accounted for within geothermal anomaly detection.

ASTER data helped to delineate potential surface indicators of geothermal activity in the PHS region such as snow-melt anomalies, anomalous river ice melt, and vegetation growth. Our ASTER data analysis further included the establishment of methods for determining the sub-pixel temperatures of geothermal waters and heated ground as input into geothermal heat budget models. We presented our methods and results (Figure 2; Figure 3) at the NASA HySpIRI workshop and a copy of the presentation is also available directly from the workshop website at http://hyspiri.jpl.nasa.gov/documents/2011-workshop.
Figure 2: Time series of ASTER visible to near-infrared (top) and thermal (bottom) data from Pilgrim Hot springs showing snow-free areas and vegetation growth anomalies associated with geothermally-heated ground.

Figure 3: A larger subset of ASTER winter-time false color composite image with 15m spatial resolution / pixel size. Two prominent snow-free areas are shown with red arrows. Left arrow points to the area near the PHS. Right arrow shows a persistent snow free area (dark) seen in the Pilgrim River, northeast of the PHS.

2.2.3 Analysis of WV-2 data
We expanded the scope of Task 1.1 to include analysis of high resolution visible to near-infrared data acquired by the commercial World View 2 (WV-2) satellite over PHS. WV-
2 images are acquired in the visible and near-infrared region of the electromagnetic spectrum at a very high spatial resolution of 1.2m. The presence of near-infrared band and the high spatial resolution makes the data set very suitable for detail vegetation mapping. Our WV-2 data was acquired during May 2010 and provided indications of vegetation growth anomalies associated with geothermally-heated ground (Figure 4). Figure 4 is a color-coded Normalized Difference Vegetation Index (NDVI) image where NDVI = (Near infrared - Red) / (Near infrared + Red). We validated this work with shallow temperature survey measurements during the 2011 field season.

![Color/near-infrared composite](image)

**Figure 4:** Left: WorldView2 color infrared image acquired in May 2010. Healthy green vegetation (bright pink/ reddish tones) and senescent vegetation (dark brownish red tones) are clearly visible. Right: Processed WorldView2 image showing vegetation vigor. Dashed white line marks the approximate limit of healthy vegetation. Heated ground and heated waters from the shallow geothermal aquifer are undoubtedly responsible for this positive vegetation anomaly that helps to delineate the limits of the geothermal aquifer.
2.3 Task 1.1 Successes/Limitations/Recommendations

The following preliminary observations were made related to the use of this technique in assessing geothermal systems. A full discussion of lessons learned and recommendations for all Phases of the project will be included in the final report.

Task 1.1:

- The processed satellite data was successful in delineating persistent hot spots, winter-time snow-melt areas, and spring time vegetation anomaly areas associated with the geothermal resource.
- Stacking thermal anomalies derived from thermal images of different dates and flagging those anomalies that appeared on at least 3 different images, worked well to delineate persistent temperature anomalies potentially associated with geothermal heating.
- A standard NDVI image generated from a high resolution multispectral image is a quick and easy product to study vegetation vigor and delineate any anomalous vegetation patterns that may be present due to geothermal heating.
- Satellite data helped to narrow down area for airborne survey (discussed in Task 1.2)
- Satellite data had limitations in quantitative estimation of geothermal potential due to the coarse resolution of the thermal bands.
- We recommend wide use of freely available satellite data (such as Landsat data) for preliminary exploration work, followed by the use of other satellite data (such as ASTER, WV-2, IKONOS, etc.), followed by airborne surveys and traditional ground-based exploration, as a routine part of a systematic geothermal exploration program.
- Publications/presentations resulting from this work are reported at the end of this report.
3.0 Task 1.2: Airborne FLIR Surveys and Data Analysis:

Summary; Work Done and Results; Successes/Limitations/Recommendations

3.1 Summary
Airborne acquisition of optical and Forward Looking Infrared Radiometer (FLIR) data, and processing this data for geothermal resource detection and characterization was the heart of Phase 1 of this project. Two airborne surveys, one is Fall 2010 and one in Spring 2011 were undertaken and data were successfully mosaiced and further processed. Optical image served as a high resolution base image for data integration. Thermal data processing algorithms used by the volcanology community were adapted to compute heat flux for geothermal waters and a wind correction procedure was developed to refine heat flux estimates. Using this new approach, thermal flux for PHS at a modest wind speed of 1.5 m/s was estimated at 6.96 MW thermal with a corresponding flow rate of 0.90 feet$^3$/s, which is about twice as high as estimates made in the 1980s for this site.

3.2 Work Completed and Results

3.2.1 Planning airborne surveys
We planned the airborne data acquisition around high and low priority survey areas (Figure 5) to provide flexibility in case of poor weather conditions. The primary survey area covered a ~27 km$^2$ square region centered on the main PHS site encompassing the most likely geothermal anomalies detected from the Landsat 7 ETM+ data (red polygons in Figure 5). The secondary lower priority area covered a larger ~175 km$^2$ area including the sites of the other thermal anomalies detected from Landsat.

The first airborne survey was undertaken from 9-15$^{th}$ September 2010 using the airport at Nome (~70 km south of PHS) as the base for flight operations. There were favorable weather conditions over the study area during the period of the airborne survey that enabled acquisition of data over the entire primary survey area and the northern portion of the secondary survey area. Imaging of the southern portion of the secondary area was not possible owing to persistent cloud cover and turbulence over the northern part of the Kigluaik Mountains. FLIR images were successfully acquired along all the flight lines indicated in Figure 5. Optical imagery was acquired for most of the flight lines however, there were technical issues that mean there are some gaps in the image coverage from the north of the secondary survey area. As our main aim was to acquire FLIR images for the primary survey area we consider that the airborne survey was successful.
Thermal images were acquired using a FLIR systems A320 camera that records emitted thermal infrared radiation in the 7.5 -13 μm wavelength region. The FLIR has a 320 x 240 pixel sensor with 25 micron sensor pitch and 18 mm lens. Visible images (RGB) were acquired using a Nikon D700 digital camera. The D700 used an 85 mm lens (f/1.8), with lens and body calibrated together by Rollei Metric and the lens modified to be fixed at infinity. The FLIR and D700 cameras were positioned side-by-side in a fixed nadir-looking mount within the aircraft. The FLIR camera was setup to continuously record thermal images at a frame rate of 5hz and we used Topoflight Navigator software to trigger the shutter of the D700 camera at pre-programmed intervals along the flight lines. A Crossbow NAV440 GPS/IMU unit was used to record the position and exterior orientation (roll, pitch, and yaw) of the plane during the survey. We selected a flying height of ~1000m to yield approximate spatial resolutions of the thermal and optical images of 1.4 m and 20 cm respectively. At the end of the airborne survey we had acquired over 25GB of FLIR imagery and 70GB of optical data.

For the Spring 2011 survey we carried out extensive planning and testing of airborne systems. The second airborne survey was restricted only to the small area centered at the PHS and took place in April 2011. During this survey optical images were acquired at 20cm resolution and FLIR data were acquired at 1.2 m spatial resolution and we recorded in-flight GPS data that was time synced with the optical and FLIR image frames.

3.2.2 Data pre-processing and field calibration/validation in support of airborne surveys

First airborne survey (Fall 2010): Concurrent to this airborne survey a field party of three undertook ground calibration and validation work to support the processing of the airborne FLIR and optical data. The following tasks were undertaken by the field survey team:

1) Accurate geographic positions of well spaced and notable ground features as well as thermal blankets (Figure 6) were recorded using portable GPS receivers (Garmin and Trimble). These ground control points are important for accurate geo-
registration of the FLIR and optical data. Geo-registration of thermal data is difficult owing to the reduced spatial resolution and lack of distinctive ground targets. We used thermal blankets to provide notable “cool” targets, which are readily delineated from the acquired FLIR data (Figure 7).

2) Wind speed, temperature and humidity measurements were recorded prior to and during the flight. These measurements were radioed back to the airborne survey team to provide information on the atmospheric conditions over the study area. The data are also important for robust calibration of the acquired thermal data.

3) Temperatures of the ground and thermal waters at the main PHS site were recorded using thermocouple sensors (TEGAM). Several ground temperature profiles (Figure 6) were recorded in the vicinity of the main PHS site for the purposes of cross-comparison with retrieved surface temperatures from the FLIR (Figure 9).

4) Two temperature logging systems (HOBO) were setup to provide continuous measurements of ground temperatures after the survey had been completed.

Figure 6: Field calibration and validation data sites for the primary target area of the Pilgrim Hot Springs survey; the data is overlain onto a high resolution color-near infrared aerial photograph (AHAP) of the study area.
Figure 7: Use of low emissivity thermal blankets (cold targets) as ground control points for registration of airborne FLIR and optical image data.

We identified two areas as priority areas: (1) the region around the main hot springs site and (2) an area ~3.5 km north-east along the Pilgrim River where field observations provide some evidence for a geothermal anomaly (Figure 8).

Figure 8: Mosaicked FLIR surface temperature data for the main Pilgrim Hot Springs site (bottom left) and possible geothermal area to the north-east (top right).

Pre-processing of the FLIR data involved calculation of surface temperature values (within ThermoCam Researcher software) using the in-situ measurements of temperature and humidity, and average flying height to correct for atmospheric effects (absorption and
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emission). Comparison of retrieved surface temperature values with the ground based
temperature profiles show reasonable agreement (Figure 9).

For the first airborne survey, the surface temperature images were manually geo-registered
to a high resolution aerial photograph of the region (from the Alaska High Altitude Aerial
Photography program – AHAP) and mosaicked using ArcGIS software. We found that
there was significant overlap of the individual FLIR frames, associated with the relatively
high data acquisition rate (5hz), that meant it was only necessary to use every 5th image
within the mosaicking procedure. For the visible data we manually applied color
adjustments to improve the contrast and registered each image to the AHAP aerial
photograph. The optical images were acquired with minimal overlap so each image was
required to produce a seamless mosaic.

![Figure 9](image.png)

**Figure 9:** Comparison of FLIR derived surface temperatures (black line) with a
field temperature profile (red line) for a selected profile line.

Second airborne survey (April 2011): For the second the image mosaicing was made semi-
automated. We determined the geographic location of each image using the in-flight GPS
information that was time synced with the images obtained from the optical and FLIR
sensor systems. For automated mosaicing we used the 2D3 software package.

For this survey the field validation work that took place a bit later in August 2011 for
logistical reasons. Fieldwork included: 1) gathering in-situ measurements of hot spring
temperatures, validating the locations of springs mapped from FLIR data, and acquiring
in-situ thermal images of hot spring and pools; 2) measurement of the out-flow rate of hot
springs; 3) validation of the extents of snow-melt anomalies and inferred geothermally-
heated ground using shallow temperature probes (1.20 cm long, Figure 10); and recording
the temperature and conductivity of local streams, ponds and along the Pilgrim River to
locate outflow of saline geothermal waters.
Figure 10: Spring FLIR data overlain with shallow temperature measurements (left) for Pilgrim Hot Springs and shallow temperature probe inserted in the ground (right); the 1.20 cm long temperature probe is shown fully inserted in the ground and only the recording unit is shown in this photo.

3.2.3 Mapping using airborne images

FLIR surface temperature data from the Fall 2010 images from the main PHS site enabled the clear delineation of the surface features (natural and man made) associated with the geothermal system such as hot springs, wells, pools, and areas of hot ground (Figure 10). The surface temperatures of these features, integrated over the 1.3 m pixel size of the FLIR sensor, ranges up to 40.5°C. The FLIR results delineate geothermal features that may be difficult to map on the ground such as: 1) upwelling hot springs within pools of water; 2) temperature gradients within pools and streams indicating the dispersion and equilibration in temperature of hot and cool waters; 3) subtle geothermal features, that may represent previously unmapped small springs or areas of hot ground away from the main spring complex. The optical images of the same time provide complimentary information on general landcover in the area (Figure 11).
Figure 11: FLIR (left) and optical (right) data from the Fall 2010 survey over the main Pilgrim Hot Springs site. The FLIR data effectively delineates surface features associated with the geothermal system such as hot springs, pools and warm ground.

Our analysis of the FLIR data from the area NE of the main PHS site (Figure 8) provided little evidence for current geothermal activity. The range of surface temperatures is consistent with the different surface types (vegetation, soil, water ponds) and there are no obvious thermal anomalies that could be related to geothermal activity.

The April 2011 survey data provided further insight for the PHS area. These data were most useful for mapping the extent of the snow-melt areas (Figure 12) that is an indirect indicator of surface heating from the shallow geothermal aquifer. The snow-melt areas also corresponded to areas of no permafrost and areas of anomalous vegetation growth in the summer time near PHS. Overall, we found the Spring time FLIR data to be more useful than the Fall time FLIR data in identifying the limits of the shallow thermal aquifer (Figure 12).
Figure 12: Processed airborne images for parts of the study area. Top left: Temperature map from September 2010 FLIR survey. Top right: Temperature map from April 2011 FLIR survey. The April 2011 more clearly reveals the limits of the shallow hot aquifer. Bottom left: Subset of the April 2011 image indicted with a white box in top right panel. Bottom right: Optical image of the area corresponding to the image in the bottom left panel. The optical image reveals underlying rocks and soils (brown) as the snow has melted over these areas due to geothermal heating.
3.2.4 Developing a heat budget model to quantify the radiant and convective heat flux and flow rate of surface geothermal waters

It is important to first simplify and visualize a conceptual model of the PHS geothermal system (Figure 13) as applied to heat flux estimation from remote sensing data.

![Conceptual model of Pilgrim Hot Springs geothermal system](image)

**Figure 13:** A simplified conceptual model of the PHS geothermal system used for numerical calculations of thermal flux from remote sensing images (processed FLIR data).

We initially started estimating the thermal flux associated with all the surface manifestations of the PHS (hot grounds, pools, springs) by treating all hot pixels in the same way, regardless of whether they were associated with the hot ground hot water (pools, springs) and presented the work at the Fall 2010 American Geophysical Union (AGU) meeting (Prakash et al. 2010). With further investigation it was clear that the hot ground and hot waters heat up differently and lose heat differently and therefore, the thermal flux estimations for these features should follow different approaches. We modified and improved our approach and presented updated results at the 2011 GRC (Haselwimmer et al., 2011) and AGU meetings (Haselwimmer and Prakash, 2011). Both our early work, and our modified and improved approaches are discussed below.

**Early approach:** As a first approach we estimated heat loss from the geothermal system corrected for background temperature and the natural radiative heat loss of the Earth and Sun. The radiant flux was calculated for each pixel representing a geothermal feature using a modified Stefan-Boltzmann equation (see below) with fixed values for surface emissivity and background temperature.
$M = \varepsilon\sigma(Th^4 - Tb^4)$

Where $M$ = radiant flux density (Wm$^{-2}$), $\varepsilon$ = emissivity, $\sigma$ = Stefan-Boltzmann constant, $Th^4$ = temperature of pixel in Kelvin, $Tb^4$ = temperature of background in Kelvin.

To delineate those pixels associated with geothermal areas we created a mask using a temperature threshold applied to the FLIR image. Manual editing of this mask was required as some thermal anomalies were not related to the geothermal system. For example, buildings and some areas of bare ground/rock exposure displayed elevated temperatures due to solar heating effects. Manual editing of the mask was assisted through analysis of the co-registered, high-resolution optical data. The background temperature value used in the thermal flux calculation was the average temperature value from the non-geothermal areas (not including anthropogenic and other non-geothermal temperature anomalies). We used the radiant flux values for each geothermal pixel to calculate total the radiant flux which amounted to $6.2 \times 10^7$ W using this method. However, we were not completely satisfied with the approach or the results as we felt that we under-estimated the thermal flux associated with the hot waters and we had not performed a sensitivity analysis.

Later approach: We then focused on establishing methods for estimating the convective heat flux from geothermal waters (hot springs and pools) at PHS as the convective component of heat was felt to be dominant and a more significant component of the heat transfer mechanism. Fortunately, it is simple to differentiate between pixels associated with hot waters and hot grounds on the FLIR image mosaics and we could easily isolate the hot water pixels for further numerical calculations.

Adapting an approach applied on volcanic crater lakes (e.g. Patrick, 2004), we were able to develop a simple total surface energy budget model to quantify the convective heat flux and flow rate of surface geothermal waters at Pilgrim Hot Springs (Figure 14). Details of the thermal model and the algorithm used for this quantitative analysis are presented in Haselwimmer and Prakash, 2011 and are briefly described below.

**Figure 14:** A total surface energy budget model for the PHS geothermal waters (pools, springs) system used for numerical calculations of thermal flux. Refer to the main text for explanation of each term.
The total heat budget for a water body (in Watts) expressed as:

\[ \text{total} = \Phi_{\text{geo}} + \Phi_{\text{ppt}} + \Phi_{\text{seep}} + \Phi_{\text{evap}} + \Phi_{\text{sens}} + \Phi_{\text{rad}} + \Phi_{\text{sun}} + \Phi_{\text{sky}} \]

Where

- \( \Phi_{\text{geo}} \) = heat input from geothermal fluids
- \( \Phi_{\text{ppt}} \) = heat input from precipitation
- \( \Phi_{\text{seep}} \) = heat flux from seepage
- \( \Phi_{\text{evap}} \) = heat loss from evaporation
- \( \Phi_{\text{sens}} \) = heat loss via sensible heat transfer
- \( \Phi_{\text{rad}} \) = heat loss by radiation
- \( \Phi_{\text{sun}} \) = heat input from solar radiation
- \( \Phi_{\text{sky}} \) = heat input from atmospheric radiation

Simplifying this model further we removed \( \Phi_{\text{ppt}} \) and \( \Phi_{\text{seep}} \) as these heat fluxes are small. The temperature of surface non-geothermal waters was used to account for \( \Phi_{\text{sun}} \) and \( \Phi_{\text{sky}} \) terms. From the FLIR image pixels associated with geothermal pools and springs were isolated and the geothermal heat flux density (\( q \) in W/m²) was calculated on a pixel by pixel basis using:

\[ q_{\text{geo}} = (q_{\text{rad}} + q_{\text{evap}} + q_{\text{sens}}) - (q_{\text{radAmb}} + q_{\text{evapAmb}} + q_{\text{sensAmb}}) \]

Where \( q_{\text{rad}}, q_{\text{evap}}, q_{\text{sens}} \) and \( q_{\text{radAmb}}, q_{\text{evapAmb}}, q_{\text{sensAmb}} \) are radiative, evaporative and sensible heat fluxes for each pixel and at the ambient temperature of non-geothermal waters.

Further, \( q_{\text{rad}} \), the radiative heat flux, was calculated using Stefan-Boltzmann equation:

\[ q_{\text{rad}} = \varepsilon \sigma T^4 \]

Where \( \sigma = 5.67 \times 10^{-8} \) (Stefan-Boltzmann constant in W/m² K⁴), \( \varepsilon = \) water emissivity (0.98), \( T = \) water temperature (°C).

Also, \( q_{\text{evap+sens}} \), the evaporative and sensible heat fluxes were calculated using the formula presented by Ryan et al. (1974):

\[ q_{\text{evap+sens}} = [\lambda(T_{sv} - T_{sv})^{1.3} + b_0 W_2] [e_s - e_2 + C(T_s - T_a)] \]

Where \( \lambda = 2.7 \) (constant); \( b_0 = 3.2 \) (constant); \( W_2 = \) wind speed at 2m height (m/s); \( e_s = \) vapor pressure of water at \( T_s \) (mbar); \( e_2 = \) vapor pressure of water at 2m height (mbar); \( C = 0.61 \) (constant); \( T_s = \) water surface temperature (°C); \( T_a = \) air temperature (°C);

\( T_{sv} = \) virtual water surface temperature (°C); \( T_{sv} = \) virtual air temperature (°C)

This model was applied to FLIR data acquired during Fall 2010 and Spring 2011 surveys. The total heat flux computed was the sum of heat fluxes for each pixel. Flux estimates derived are presented in the section on FLIR model results, validation and wind speed correction.

Estimating flow rates: Assuming a fixed hot spring (81°C) and ambient water temperature the flow rate (\( V \) in m³/s) was calculated from the total geothermal heat flux (\( q_{\text{geo}} \) using:
\[ V = \left[ \frac{\text{geo}}{\left( h_s - h_{\text{amb}} \right)} \right] / w \]

Where \( h_s \) = enthalpy of hot spring water; \( h_{\text{amb}} \) = enthalpy of water at ambient temperature; \( \rho_w \) = density of water (kg/m\(^3\)). Again, flow rates derived from the FLIR Fall 2010 and Spring 2011 are presented in the section on FLIR model results, validation and wind speed correction.

**FLIR model results, validation and wind speed correction:** Summary of hot spring heat flux / flow rate estimates from airborne FLIR data and in-situ measurements is presented in the table below.

<table>
<thead>
<tr>
<th>Source of estimate</th>
<th>Total heat flux</th>
<th>Flow rate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne FLIR - Fall 2010</td>
<td>3.62 MW</td>
<td>0.43 feet(^3)/s</td>
<td>Conservative estimate assuming wind = 0</td>
</tr>
<tr>
<td>Airborne FLIR - Spring 2011</td>
<td>3.67 MW</td>
<td>0.44 feet(^3)/s</td>
<td>Conservative estimate assuming wind = 0</td>
</tr>
<tr>
<td>1979 flow rate measurement [9]</td>
<td>2.00 MW</td>
<td>0.15 feet(^3)/s</td>
<td>Hot stream gauged at Site 1 (See panel 3)</td>
</tr>
<tr>
<td>1983 flow rate measurement [10]</td>
<td>-</td>
<td>0.20 - 0.50 feet(^3)/s</td>
<td>Hot stream gauged at Site 1</td>
</tr>
<tr>
<td>08/2011 flow rate measurement</td>
<td>-</td>
<td>0.39 feet(^3)/s</td>
<td>Hot stream gauged at Site 2</td>
</tr>
</tbody>
</table>

These computed heat flux / flow rate estimates are generally higher than the than in-situ observations (in-situ measurements of flow rate of hot springs probably underestimate total outflow). However, we believe that they are quite conservative as they assume a wind speed of 0 m/s which is unrealistic for the PHS area. The nearest meteorological station (K2 ~50km NE of PHS) reports and average annual wind speed of 3.18 m/s. Therefore, the true heat flux is likely to be higher than this estimates shown in the table above.

Heat flux estimates are very sensitive to wind speeds as shown in Figure 15. With a more plausible, though still conservative, wind speed of 1.5 m/s, heat flux estimated from FLIR is 6.96 MW that corresponds to a flow rate of 0.90 feet\(^3\)/s.

![Effect of wind speed on heat flux](image)

**Figure 15:** Graph showing the effect of wind speed on heat flux estimated for the fall 2010 and Spring 2011 FLIR data for the PHS area
3.3 Task 1.2 Successes/Limitations/Recommendations
The following preliminary observations were made related to the use of this technique in assessing geothermal systems. A full discussion of lessons learned and recommendations for all Phases of the project will be included in the final report.

Task 1.2:

- Our study revealed that airborne FLIR data acquired at a spatial resolution ranging from 1 to 2 m is sufficient for geothermal exploration of small and low temperature resources such as the PHS in Alaska.
- A spring time FLIR survey is better than a Fall time FLIR survey, especially for identifying blind geothermal resources in high latitude snow-covered regions. On spring time FLIR images it is easier to delineate hot waters and hot grounds (associated with snow melts).
- Airborne combined optical / FLIR surveys offer an inexpensive solution for geothermal resource exploration and targeting further field based data collection strategy. For logistically challenging areas, such as in Alaska, these surveys may be the only practical method for the first phase of geothermal exploration.
- Image data processing, especially for quantitative thermal flux estimation requires specialized knowledge and skills, and it would be useful to transfer these skills-set to the next generation of geothermal researchers during college education.
- Our airborne surveys were limited to use of optical cameras. In future, use of multispectral or hyperspectral imaging sensors that have several spectral bands in the near- and shortwave- infrared regions is recommended to better characterize vegetation signatures and alteration minerals associated with the geothermal resource.
- Heat budget model proposed in this study to estimate heat flux and flow rates of geothermal waters can work to characterize both low temperature and high temperature geothermal resources, so the techniques proposed in this project are transferable to any geothermal area in the world.
- For further developing a conceptual model of a geothermal system, identifying upflow zones, and targeting drill-sites, it is important to combine the remote sensing derived information with other traditional ground based observations and measurements.
4.0 Task 2.1: Shallow Temperature Survey.

4.1 Overview
At shallow depths, the Pilgrim geothermal system is dominated by a strong lateral flow of geothermal water that was identified three decades ago with the first six wells drilled into the system. The maximum temperature of this shallow aquifer is slightly below boiling and the depth to the most hydraulically conductive part of the aquifer, at least in places, was less than 100°. This combination of factors produces very high shallow temperature gradients above the thermal aquifer and a sharp temperature decline below the aquifer. The smooth nature of the six early shallow temperature profiles strongly suggested that the aquifer began transmitting hot water within the past few hundred years and that the lower temperatures beneath the aquifer are a result of downward conduction of heat from the aquifer and not a flow of cold water beneath the thermal aquifer. If there were a counterflow of cold water more complexity such as isothermal segments in the temperature profile separated by short intervals of extremely high temperature gradients would be expected. This combination of characteristics at Pilgrim allows the possibility of defining the shallow thermal aquifer with abnormally shallow holes compared to most other geothermal systems. Characterizing the shallow thermal aquifer allows definition of the directions of thermal fluid flow within the aquifer and recognition of the hottest part which most likely would overlie the zone of upwelling hot fluid beneath the aquifer.

The absence of bedrock in the vicinity of Pilgrim hot springs is also an important factor that allowed consideration of low cost and unconventional drilling techniques to insert the tubings in the ground for temperature measurements. The flat swampy topography at Pilgrim is an advantage to the extent that it minimized topographic effects at shallow depths but it also greatly inhibits access to much of the area with machinery.

The first efforts at shallow temperature holes in Pilgrim were in 1979 when about 70 “pipes” were hand driven to a maximum depth of 5 to 9.5 m (Harrison and Hawkins, 1979; Osterkamp et al., 1979). An isothermal map at a depth of 4.5 m was prepared outlining the central part of the shallow thermal anomaly with temperatures between 30 and 80 °C. This effort was simply focused on the heart of the shallow thermal anomaly and none of the holes were deep enough to penetrate into or through the shallow thermal aquifer.

4.2 Backpack drilling program
Preliminary shallow data was collected and geo-referenced during the 2010 field season, and two additional surveys were conducted in April 2011. An attempt was made to utilize a backpack drill obtained from Shaw Tool Ltd and primarily used for mineral exploration and sampling (Figure 16). The goal was to reach greater depths and cover a larger area to better delineate the shallow thermal anomaly and define its margins. A total of 31 holes were drilled to depths of up to 10ft while the area was still snow covered and could be readily accessed by snowmobile. However, a number of challenges arose including holes collapsing before tubing could be installed, and snow up to 6ft deep. These challenges limited our ability to install as many holes as planned or achieve a uniform depth in drilling these holes, which presents some difficulty with interpretation. A map showing the distribution of existing backpack drill holes is shown in Figure 17.
Figure 16: Shaw Backpack drill. Image from Shaw Tool Ltd website.

Figure 17. Distribution of shallow temperature holes at Pilgrim Hot Springs installed with the Shaw backpack drill.
These holes were all located north of the heart of the shallow thermal anomaly and showed a generalized cooling trend toward the north but also showed the overall thermal anomaly to be significantly larger than anticipated by the 1970s exploration effort. However, this back pack drilling effort did not produce results much better than the 1970s effort. Discussion with our USGS partners related to these challenges revealed that they had a track mounted direct drive Geoprobe unit that was touted as being capable of driving pipes to depths > 30 m. The unit is highly mobile yet small enough to travel on the “trails” in the Pilgrim area and has a minimal impact on vegetation off the trails. In addition, it requires no supporting equipment or a mud system. Given these benefits, it was decided to shift the focus of this task to using the Geoprobe to gather additional data related to the shallow aquifer.

4.3 Geoprobe drilling program.
In 2011 sixteen GeoProbe holes with an outer pipe diameter of 2.25" and hole diameter of 1.5" were installed to a maximum depth of 109ft. We acquired additional (shallow) temperature data through use of a track mounted Geoprobe system during the 2011 field season. Locations and temperature gradients are shown in Figure 19. The Geoprobe is a small unit (~5,000 lbs) that drives casing into the ground without the need for circulatory fluids (see Figure 18). Therefore, no fluid or solid wastes were generated during the hole installation process. We used the GeoProbe only on established trails in order to minimize surface disturbance. The GeoProbe has a small footprint, with almost no noticeable surface damage where we drilled other than some flattened grass. We properly decommissioned all of these holes prior the end of the 2012 season, by pulling the pipe and sealing the hole with grout as the pipe is removed.

Figure 18. Installing GeoProbe Holes at PGS.
Figure 19. Location of GeoProbe holes and their temperatures at 60ft.
Figure 20. 2011 GeoProbe, TG hole and existing well temperature gradients.

These depths were somewhat disappointingly shallow as nearly all of them failed to get much below 80 ft and do not penetrate the deep thermal aquifer. In 2012 additional smaller pipes (1.25in outer diameter; 0.5" inner diameter) were utilized in 54 holes which have increased penetration to as deep as 154 ft. Some of the 2012 holes were attempts to deepen 2011 holes. The majority of these still have positive temperature gradients but some of them have encountered isothermal conditions indicative of having reached the shallow thermal aquifer and documenting its temperature. Phase 2 drilling through the shallow aquifer will produce known depths or elevation points of the aquifer so it will be possible to more credibly extrapolate some of the Geoprobe hole temperature profiles short distances to better define the flow pattern within the shallow thermal aquifer. This will be done after the 2012 field season is finished.
5.0 Task 2.2: Airborne Geophysical and Ground-Based Resistivity Survey.
In collaboration with USGS, ACEP conducted a high-resolution airborne magnetic and EM survey in 2011 to provide the regional geophysical framework of the area and help delineate key structures controlling hydrothermal fluid flow and to characterize the basin geometry and depth to bedrock. The preliminary interpretation from USGS of the airborne magnetic and EM survey of the Pilgrim Springs geothermal area (Figures 21-23) are included in this section. Data analysis and modeling, that will comprise future activities as part of this research and through USGS under separate funding will include 2D potential field studies (joint gravity and magnetic modeling) along selected transects, regional geophysical mapping of structures, and 3D potential field and EM modeling.

Figure 21. Index map showing the distribution of sediments (tan colored areas) on shaded topographic relief. Red box shows the area outlined in Figure 24.
Figure 22. Geologic map of the area surrounding Pilgrim Springs (red star). Map after Till et al. (2010). Red box shows the area outlined in Figure 24.

Figure 24. Topographic map of the area surrounding Pilgrim Valley. Pilgrim Springs is indicated by a red star.
5.2 Geology
Most of the Seward Peninsula is composed of Precambrian metamorphic basement and overlying Paleozoic carbonates (Figure 22). Cretaceous alkaline intrusive rocks occur along the eastern part of the peninsula. The Pilgrim River Valley is covered by alluvial fill. The nearest outcrops to Pilgrim Springs consist of plutonic and high-grade metamorphic rocks that occur 2.5 mi to the south in the Kigluaik Mountains, and low-grade metamorphic rocks that outcrop 2.5 mi to the north at Hen-and-Chicken Mountain.

The Imuruk Basin and Pilgrim River Valley are interpreted (Turner and Forbes, 1980) as a graben or half-graben structure that is bound on the south by the Kigluaik Fault – a major rangefront normal fault (~65 km long) that separates the basin from the Kigluaik Mountains to the south. Other local-scale features, inferred from the geophysics (see discussion below), lie adjacent to Pilgrim Springs and may represent important structures controlling local hydrothermal fluid flow.

Although there is no direct evidence of volcanic activity in the Imuruk Basin-Pilgrim River Valley region, the geothermal anomaly at Pilgrim Springs and nearby thawed regions, and high lake temperatures to the north and northeast are indicative of high heat flow in the region that is thought to be, in a general sense, related to recent volcanism in surrounding areas. Alternatively, the source of heat may be radiogenic, derived from the Precambrian basement and Cretaceous intrusive rocks that outcrop in the surrounding uplands and are inferred to floor the Pilgrim Valley.

5.3 Previous Studies
A number of geologic and geophysical reconnaissance studies were performed in the mid-70's through early 80's to assess the origin, character and potential of geothermal resources of the Seward Peninsula and the Pilgrim Springs area, in particular. Geophysical investigations included gravity, magnetic, seismic and resistivity studies.

5.3.1 Gravity data from previous studies
Gravity studies were performed in 1979 and 1980 to assess the depth to bedrock in the Pilgrim River Valley in the vicinity of Pilgrim Springs (Lockhart, 1981; Kienle and Lockhart, 1980). Data were collected (122 stations in 1979, and 184 stations in 1980) regionally and along several traverses by helicopter, boat, car, and on foot. Station spacing along traverses acquired during the 1980 survey was 1-5 km, though much more closely spaced stations were taken in the vicinity of Pilgrim Springs during the 1979 campaign (<1 km in places).

The gravity data from the 1979 campaign reveal a ∼10 mgal triangular-shaped gravity low located immediately southwest of Pilgrim Springs that is characterized by ENE-trending and NE-trending gradients along its northern and southern margins, respectively. Kienle and Lockhart (1980) suggest that these gradients reflect basement normal faults, bounding the low, that have accommodated several hundred meters of vertical offset resulting in downdropping of the basin. It is implied that the location of the springs is controlled by the intersection of these two basement structures.

A gravity profile along a 45 km traverse across Pilgrim Valley (from the 1980 study) reveals a gravity high near the center of the valley suggesting a horst in the middle of the graben. Regional gravity traverses at Imurk, Noxapaga and Pilgrim areas, which all cross
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the proposed rifts of Turner and Swanson (1981), reveal significant gravity lows. Lockhart (1981) suggests these lows are due to low density fill in structurally-controlled basins, consistent with geologic and seismic evidence for such in the Kuzitrin flats and Pilgrim River Valley, and consistent with the regional rift-graben model of Turner and Swanson (1981).

5.3.2 Magnetic data from previous studies
An aeromagnetic grid compilation was made in 1995 (grid spacing of 250m) and provided by John Cady under contract to the State of Alaska, Division of Geological and Geophysical Surveys. The original data are not available (the compilation consists of surveys flown in the late 1960s and early 1970s). The survey that was likely used in this compilation (covering the Pilgrim Springs area) is that described by Cady and Hummel (1976) which was flown at 300m above ground with a flightline spacing of 1.2km along E-W trending flightlines. A base station was not available for this survey. While useful for interpreting regional structures, this grid is of insufficient resolution to resolve features like those at Pilgrim Springs inferred from the gravity.

Ground magnetic measurements (<30 discrete measurements taken at 100ft intervals) were collected along a single N-S profile extending across and south of Pilgrim Springs (Kirkwood, 1979) that indicates a ~50 gamma magnetic low near the hot springs interpreted to be due to leaching of magnetic minerals in the sands and silts by hydrothermal fluids.

5.4 New ground-based geophysical studies
More recently, the USGS has been engaged in geophysical studies of the Pilgrim Springs geothermal area to delineate structures that may provide pathways or barriers to fluid flow and control the location of the springs. This effort entailed the compilation, re-reduction, and editing of existing gravity data, in addition to the collection, in 2010, of new potential field data (including several hundred new gravity data and over 150 km of ground magnetic data), regionally and along several detailed profiles around Pilgrim Springs.

5.4.1 Ground-based gravity survey
The USGS collected 295 gravity stations in the early spring of 2010 using two Scintrex CG-5 gravimeters. Data were collected at 100 to 300m spacing along several profiles in the vicinity of the springs, in addition to regionally throughout the entire project area. Profiles are oriented north south with the exception of one northeast trending profile that extends north east trending profile NEB (Figure 24). Gravity highs occur over the crystalline rock of the Kigluaiks Mts., Mary’s Mountain and the Hens and Chickens Mountain. A local elongate gravity low extends from Pilgrim Springs, where it is ~4.5 mGal southwestward where the lowest values (~10 mGal) occur ~4km southwest of the springs.

These values would suggest basin thicknesses of ~ 350 m to ~800m beneath the springs and deepest parts of the gravity low, respectively (assuming a density contrast of 0.4 g/cc between basement and fill). The margins of the low are characterized by northeast-trending gradients that probably reflect the edges of fault –bounded structural blocks. The southeastern edge of the low near the springs, in particular, lies very close to the springs and may provide an important pathway conveying deep fluids to the surface.
5.4.2 Ground-based magnetic survey

Ground magnetic data were collected using a Geometrics® G858 cesium vapor magnetometer sampling at 0.1 second intervals. In wooded or otherwise difficult-to-traverse areas data were collected on foot. The majority of the data, however, were obtained using a custom-designed snowmachine-towed magnetometer system developed specifically for this purpose.

The height of the magnetometer above the ground surface was about 2 m. A portable Geometrics® G856 proton-precession base-station magnetometer was used to record diurnal variations of the Earth’s magnetic field during the ground-magnetic surveys. Diurnal variations recorded by the base-station magnetometer were removed and the data were filtered to remove cultural “noise”, such as culverts and fences. Ground magnetic data were collected along several traverses in the vicinity of the springs. Ground magnetic traverses are shown in Figure 25.

5.5. Airborne magnetic survey

In 2011-2012 the USGS, in collaboration with ACEP, was responsible designing, supervising, and analyzing a high-resolution airborne magnetic and EM survey.

5.5.1 Data Acquisition

An airborne geophysical survey, was flown by Fugro Airborne Surveys from October 16th to November 1st, 2011 over the Pilgrim Springs area. Data were acquired using Fugro’s RESOLVE system (Figure 26) that is equipped with a multi-coil, multi-frequency electromagnetic system, and high sensitivity cesium magnetometer.

The onboard Cesium vapor magnetometer sampled at a rate of 10 Hz, with a sensitivity of 0.01 nT, while a base Cesium magnetometer recorded the earth’s magnetic field at 1 Hz for diurnal corrections. A GPS electronic navigation system recorded GPS time and satellite data for differential correction of survey positions, yielding a post-survey flight path determined to within ±2 m.

Flightlines were oriented North-South with East-West tielines. The mean survey drape was 38.2 m (Range: 0.4 – 123 m, stdev 8.5 m), though there was an increase in drape at south due to steep terrain. The total coverage of these areas amounted to approximately 556 km.

This new magnetic survey provides significant improvement over existing surveys (Figure 28) in this area by including diurnal corrections, differential GPS positions, tighter flight line spacing (1/4 & 1/8 mile flightline spacing; 2.5 mi tieline spacing), and lower flight elevations (60 meters - helicopter; 40 meters above ground - bird).

5.5.2 Data processing

Fugro performed basic processing of the magnetic data that included removal of an IGRF field and light-line leveling. The USGS performed additional processing applying a variety of derivative and filtering methods, described below, that aid in interpretation by helping to delineate structures and to constrain their geometry. These various transformations were applied to the total magnetic field anomaly grid (Figure 27) that was derived from the leveled and IGRF- and diurnally-corrected data.

5.5.2a Pseudogravity (PSG)
The Pseudogravity (PSG) or magnetic potential transformation (Figure 29) is applied to magnetic data in order to isolate broad magnetic features that are often masked by high-amplitude shallow magnetic sources. The PSG transform converts a magnetic anomaly into one that would be observed if the magnetic distribution of the body were replaced by an identical density distribution. This significantly simplifies the interpretation of magnetic sources, however, there are significant assumptions that can limit the use of this method.

5.5.2b Difference maps
Difference or residual maps (Figure 31) are useful for emphasizing surface and near-surface sources. They are produced by upward-continuing the observed anomalies and subtracting the result from the original grid. This effectively removes the contribution of deeper sources.

5.5.2c Maximum Horizontal Gradients-maxspots
Maximum horizontal gradients (MHG) are used to map the edges of sources (Figure 32). MHG reflect abrupt lateral changes in the density or magnetization of the underlying rocks, and tend to lie over the edges of bodies with near vertical boundaries (Blakely and Simpson, 1986). They are calculated for both gravity and magnetic data to estimate the extent of buried sources, and to define the boundaries of geophysical domains, and internal domain structures.

5.5.2d Reduced to Pole (R2P)
The Reduced to Pole transformation (Figures 33-34) centers magnetic anomalies over their sources.

5.5.2e Domains
We have characterized geophysical domains throughout the study area (Figure 35), in part with the MHG method, but also with other filtering and derivative methods that aid in highlighting the regional structural grain. Regions with a consistent anomaly trend, amplitude, or frequency content are defined as distinct geophysical terranes, and assumed to represent discrete crustal blocks with similar physical properties or sources. Geophysically-defined boundaries may take several forms, such as:
   1) A stepped anomaly that forms along an edge of a large crustal block with relatively uniform density or magnetic properties (e.g., dip-slip fault, or edge of a batholith or caldera).
   2) A long, narrow, linear anomaly generated over a source whose vertical extent is much greater that its width (e.g., a dike or alteration zone along a fault).
   3) A linear feature observed as the abrupt termination, and/or alignment of numerous high and low anomalies of different sizes and intensity (e.g., lateral fault).

5.5.2f Match filter
Match filtering (Figure 36) us used to separate potential field anomalies by depth to their sources, isolating anomalies arising from different crustal levels. A matched-filtering technique (Syberg, 1972; Phillips, 2001) applied to the frequency spectrum of potential field data can be used to isolate anomalies arising from different crustal levels, provided that the depths of anomaly sources are sufficiently distinct.

5.5.2g Depth to source estimates
As part of our ongoing work we are applying a number of different methods for estimating the depth to magnetic sources (including Euler deconvolution, and tilt derivative methods).

5.5.3 Preliminary results
The various filtering methods applied reveal a number of interesting features spanning the shallow to mid-crustal levels. The longest wavelength features are revealed by the pseudogravity (PSG) transformation (Figure 29), that shows a broad high extending southeastwards from Mary’s Mountain to Pilgrim Springs. Similar highs within the survey area are seen further to the southeast over the flanks of parts of the Kigluaik Mountains. A prominent low is observed over the Kigluaik Mountains due south of the springs and northeast-trending elongate low bounds the springs to the southeast. This low is flanked by sharp gradients at its margins and is sub-parallel to the trend of gravity low described above.

Maximum horizontal gradients (MHG) of the PSG reveal much more detail (Figures 29-31) and can be used to locate sharp contrasts in magnetic properties that occur, for example, at faults or contacts. Regionally, the MHG can be used to define structural domains (Figure 36). A series of northeast-trending structures is clearly observed in this region southeast of the springs. In contrast, a dominant northwest trending fabric characterizes the northeastern portion of the survey area between the springs and Hen and Chickens Mountain. This trend is similar to that seen far north and south of the study area and may reflect deep basement structures (Figure 38).

The area south of the springs, however, is dominantly characterized by east-west-trending range-front-parallel structures (Figure 37) that are likely late Cenozoic features associated with north-south extension that formed the basin. A similar E-W trend extends into the area immediately over the springs. Regionally, the springs are characterized by a magnetic high (Figure 33), but this is punctuated by several EW trending magnetic lows, the most prominent occurring directly over the springs (Figure 34). The lows may result from the demagnetization of magnetic material along range-front parallel faults that dissect the basin.

A set of northeast narrow magnetic highs (Figure 38), located between the springs and Marys Mountain, have a signature consistent with mafic dikes. Furthermore, their trends are similar to the trends of Tertiary dikes that outcrop in the Kigluaik Mountains (Figure 38). Indeed, based on the trend of the Precambrian metamorphic belt that forms the Kigluaik and Bendeleben Mountains (including the Hen and Chickens and Mary Mountains, Figure 21) it is expected that the Pilgrim Valley is floored by these same rocks.

5.5.4 Relevance to conceptual model development
It is not clear what is the origin of the heat responsible for Pilgrim Springs. Despite the lack of direct evidence of volcanic activity in the Imuruk Basin-Pilgrim River Valley region, it has been suggested that the springs are related to recent volcanism in surrounding areas. The regional magnetic map provides some support that volcanic activity may have occurred more local to the springs than is suggested by surface geologic mapping (Figure 38). 10-15 km north of Pilgrim Springs is an area, concealed by Quaternary sediments that has a very similar magnetic character to other areas of Tertiary volcanic outcrop. Nonetheless, Precambrian basement and Cretaceous intrusive rocks
that outcrop in the surrounding uplands and are inferred to floor the Pilgrim Valley form a likely source of radiogenic heat that could feed the springs locally. A promising source may lie beneath the deepest parts of the basin inferred from the gravity data (Figure 39), located just a few kilometers southwest of the springs. Joint potential field mapping (Figure 40) and future modeling should help delineate subsurface structures and basin geometry that can be used to test fluid flow models and constrain possible sources and pathways of geothermal fluids.

5.6 Airborne electromagnetic (EM) survey
In 2011-2012 the USGS, in collaboration with ACEP, was responsible designing, supervising, and analyzing a high-resolution airborne magnetic and EM survey.

5.6.1 Data acquisition
Airborne electromagnetic (AEM) systems transmit a magnetic field into the earth. This primary magnetic field induces currents in the ground that produce secondary magnetic fields measured by receiver coils on the airborne system. The receivers record both the in-phase and quadrature (out-of-phase) response as referenced to the transmitted signal. The result of an AEM survey is an electrical resistivity image of the subsurface. Electrical resistivity is not only sensitive to conductive mineral content, but also to ice, clay content, porosity, permeability, saline fluids, and temperature.

We collected frequency-domain airborne electromagnetic (EM) data using Fugro’s Resolve system. This system is sensitive to the frequency range of 400 Hz to 140 kHz. Data were collected using six coil pairs that measure signals at a sample rate of 10 seconds at six frequencies (400 Hz, 1800 Hz, 3300 Hz, 8200 Hz, 40,000 Hz, and 140,000 Hz) and at a nominal altitude of 37 meters. All frequencies were recorded in a coplanar configuration except 3300 Hz, which was recorded in a coaxial configuration. The coplanar configuration utilizes the vertical magnetic dipole field and is sensitive to massive conductive bodies and horizontal layering whereas the coaxial configuration utilizes a horizontal magnetic dipole field which is sensitive to vertical conductive objects in the ground such as thin, steeply dipping conductors perpendicular to the flight direction. The in-phase and quadrature response for each transmitter-receiver coil-pair at each frequency was recorded. The data were processed by Fugro to account for system drift and calibrations.

5.6.2 Data processing
The following products were received from Fugro: Quadrature and in-phase raw data, noise information, apparent resistivity, apparent depth, differential resistivity, and preliminary depth sections. We have begun to analyze and interpret the above products and have performed preliminary inversion on several profiles across the survey region. Apparent resistivity maps (Figure 41) were calculated using a pseudo-layer, half-space model defined by Fraser (1978). This model consists of a highly resistive layer (air) overlying a conductive half-space (Earth). Inputs are in-phase and quadrature components of the coplanar coil-pair at a given frequency. The air layer is fixed at a very high resistivity and data are inverted for two parameters: depth to the surface and half-space (apparent) resistivity. Higher frequencies are sensitive to shallow depths whereas lower frequencies are sensitive to greater depths of investigation.

5.6.3 Preliminary results
Preliminary interpretation of apparent resistivity and differential resistivity maps shows low resistivities around Pilgrim Springs. This conductive region extends to tens of meters below the surface and the most conductive regions extend to the north and northeast. Higher temperatures in this region likely give rise to more conductive sediments and the EM data are sensitive to saline geothermal fluids as well. More moderate resistivities characterize the regions surrounding rivers and streams. These moderate to low resistive areas are likely due to variations in clay content of the sediments.

The high resistivities (> 1000 ohm-m) associated with the mountain ranges (Figure 41, 42) reflect the bedrock that comprises these ranges. An equally resistive region exists between the range front of the Kigluaik Mountains and the dense stream channels surrounding Pilgrim Springs. Although subtle topography exists in this region, it is north of the Kigluaik range front. This region of high resistivity is likely indicative of regions of resistive permafrost at depth. This interpretation agrees with permafrost mapping in the area and further work will be done regarding using the airborne EM data to map permafrost regions at depth.

An east-west trending, low resistivity (100-200 ohm-m) trend exists on both the apparent resistivity and the differential resistivity maps at all frequencies and depths, respectively. This linear trend follows the base of the Kigluaik Mountains and is preliminarily interpreted to indicate a range-front fault. Fault zones can be conductive when they are comprised of rocks that are fractured and may have hosted fluid flow and subsequent mineralization.

Several conductive anomalies appear in the data at greater depths that are more subdued or missing at shallow depths. These include the conductive regions to the southeast of Pilgrim Springs, the area east of Pilgrim Springs at the eastern edge of the map, the region immediately north of Mary’s Mountain, and a narrow conductive conduit that appears at depth between Pilgrim Springs and the conductive region north of Mary’s Mountain. Although these anomalies require further investigation and modeling before interpretations can be made, they may indicate regions of higher permeability or alteration at depth.

Full inversion of the airborne EM data will yield densely sampled models of electrical resistivity along the survey flight lines. We performed one-dimensional (1D) inversions along ten profile lines for all of the frequencies at given locations (Figure 43). In-phase and quadrature data along each profile were inverted using the laterally-constrained inversion of Aucken et al. (2005). Data were inverted for 20-layer models starting from a 50 ohm.m halfspace and with no prior model. In-phase and quadrature data errors were defined as the maximum of a percent error and an absolute error floor. The resulting 1D models were stitched together to form a quasi two-dimensional (2D) resistivity depth section (Figure 44).

5.7 Additional studies: mapping and modeling
We are in the process of developing two-dimensional geophysical models of the subsurface to define the shape and structure of buried units, to locate faults, and to delineate changes in the basement geology. Planned 2D and 3D modeling (using forward and inverse methods) of the data derived from the airborne survey, combined with high-resolution ground magnetic and gravity data will yield a structural model of the subsurface that can be used for testing fluid flow scenarios. In addition, the combined potential field
and EM interpretations will help to identify deeper crustal structures most likely responsible for transporting hydrothermal fluids from their source to the springs, and will enable us to constrain viable heat source and transport models.

By providing a region-wide geologic and geophysical framework, this work will allow for more informed decisions regarding drill-site planning. By identifying structures that may be important targets for drilling, this work may significantly influence drilling strategies and priorities. In addition to directly aiding geothermal studies, this work will be useful to a wide range of ongoing and future regional geologic investigations related to geothermal systems in active extensional basins.

5.8 Conclusions
The aim of this study is to provide 1) a regional geophysical characterization of the area around Pilgrim Springs, and 2) a detailed assessment of the crustal cross-section along selected profiles, with the goal of characterizing the geometry of the basin, and identifying intra-basin and basin-bounding structures that may provide pathways for hydrothermal fluid flow associated with the hot springs.

In 2011-2012 the USGS, in collaboration with ACEP, was responsible designing, supervising, and analyzing a high-resolution airborne magnetic and EM survey. The airborne survey provides high resolution data related to the magnetic and resistivity structures spanning the shallow (upper 100m) to mid-crustal levels.

Data analysis and modeling will comprise future activities of this research that will include 2D potential field modeling along selected transects, regional geophysical mapping of structures, and 3D potential field and EM modeling.
Figure 24: Isostatic gravity map of the pilgrim Springs area (upper panel). New gravity stations collected in the spring of 2010 are show in red. Grey symbols indicate existing gravity data. Gravity profiles are labeled in the lower panel. Gravity highs appear as reds and pinks, gravity lows as blues and purples.
Figure 25: Map showing ground magnetic traverses in the pilgrim Springs area (upper panel). Magnetic field anomalies plotted along magnetic traverses (lower panel). Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
Figure 26a: Fugro Airborne Surveys RESOLVE system on the ground in the Pilgrim Valley

Figure 26b: Fugro Airborne Surveys RESOLVE system just after takeoff
Figure 27: Magnetic field anomaly map derived from data obtained during the airborne survey flown for this study. Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
Figure 28: Regional magnetic anomaly map derived from surveys flown in the late 1960's and early 1970's (Cady, 1977). Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
Figure 29: Pseudogravity map. Pseudogravity highs appear as reds and pinks, gravity lows as blues and purples.
Figure 30: Differential Pseudogravity with spots of maximum horizontal gradient. Pseudogravity highs appear as reds and pinks, gravity lows as blues and purples.
Figure 31: Differential Pseudogravity maps with magnetic lineations interpreted from maximum horizontal gradients. Pseudogravity highs appear as reds and pinks, gravity lows as blues and purples.
Figure 32: Reduced to pole magnetic anomaly map. Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
Figure 33: Differential Reduced to Pole. Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
**Figure 34:** Magnetic lineations interpreted from maximum horizontal gradients, colored by trend (EW – red; NW – blue; NE – green).
Figure 35: Match filtered band pass of magnetic reduced to pole grid, yielding deep (upper panel), intermediate (middle panel), and shallow (lower panel) sourced anomalies. Magnetic highs appear as reds and pinks, gravity lows as blues and purples.
Figure 36: Geologic map (upper panel) and shaded relief (lower panel) of the Pilgrim Springs area superimposed with spots of maximum horizontal gradients of the magnetic field. A prominent regional northwest trending fabric can be seen extending across Pilgrim Springs.
Figure 37: Map showing mafic dikes in the Kigluaik Mountains (red lines). Inset in the upper left shows a rose diagram of dike trends. Inset in the lower right shows the differential magnetic anomaly map with arrows highlighting possible dikes.
Figure 38: Upper panel: Regional magnetic map of the southern Seward Peninsula (After Cady, 1977). Magnetic highs appear as reds and pinks, gravity lows as blues and purples. Also shown are Quaternary and Tertiary volcanics (tan polygons) and Mesozoic intrusive rocks (pink and red polygons); Lower panel: area north of Pilgrim Springs that has a similar magnetic character as other areas covered by Tertiary volcanics.
Figure 39: Isostatic residual gravity map used to map the structural basin.
Figure 40: Map showing Differential resistivity depth slice at 5m superimposed with magnetic lineations to aid the correlation of potential-field & EM features.
Figure 41: Apparent resistivity at 140 KHz (a) and 400 Hz (b) overlayed on topography. Waterways and stream channels are shown in blue and faults are shown in red. Wells are shown with black dots. Apparent resistivity maps show regions of low resistivity (high conductivity) around Pilgrim Springs. At 140 KHz, the areas near rivers and streams are characterized by moderate resistivities (50-300 ohm-m) whereas the Hen and Chickens Mountain, Marys Mountain, and the Kigluaik Mountains are characterized by high resistivities (>1000 ohm-m). At 400 Hz, the mountainous areas are less resistive. This is likely due to the lack of sensitivity of the data at low frequency as opposed to the mountains getting more conductive at depth. However, more conductive regions southeast of Pilgrim Springs appear in the map that are not seen at higher frequencies.

In addition to apparent resistivity, differential resistivity maps (Figure B) were made from the data delivered from Fugro. Differential resistivity (Huang and Fraser, 1996) is a transformation of apparent resistivity to an approximation of layer resistivity at an apparent depth. The method approximates the effect of shallow layer conductance determined from higher frequencies to estimate the deeper resistivity (Huang and Fraser, 1996).
Figure 42a and 42b: Differential resistivity maps at 5 m (a) and 40 m (b) overlayed on topography.
Figure 43: Map showing location of preliminary 1D models (black lines) overlayed on the 20 m differential resistivity depth section.
Figure 44: 1D inversion along line 150. The top panel shows the model with a 2:1 vertical exaggeration with a log color scale from 5-50,000 ohm-m. The black line shows a relative measure of depth of investigation. Any model structure below this line is considered unreliable. The black and red lines above the model section are the measured and inverted bird altitude. Note that the resistivity color scale is reversed from that in Figures A-C. The second panel shows the measured data (in-phase and quadrature) from high to low frequency on the y-axis. The third panel shows the data misfit (black) relative to the target misfit (red). The lower panel shows the data misfit by frequency along the line. The color scale at the bottom goes from -50% to +50%.

Preliminary interpretation of the 1D models along line 150 shows various features in the data (Figure E). The XX bedrock of Hen and Chichens and the Kigluaik Mountains are highly resistive (>1000 ohm-m; note, the resistivity color scale is reversed from that on Figures A-C). Pilgrim Springs is highly conductive, so much so that data are not resolved beneath a few meters. The highly resistive region south of Pilgrim Springs is interpreted to be permafrost and a less resistive feature shows up between this region of permafrost and the Kigluaik Mountains, likely an indication of a range-front fault. The low resistivity (high conductivity) zone north of Pilgrim Springs may be a region of high clay content and alteration.

1D inversion of the entire dataset (work in progress) will allow for a more thorough interpretation of the region as well as joint interpretation with the aeromagnetic data.
Figure 45: Interpretation of 1D model along line 150. Vertical exaggeration = 2.
6.0 TASK 2.3: Repair Existing Wellhead and Collect New Data

Summary; Work Done and Results; Successes/Limitations/Recommendations

6.1 Summary
During the late 1970s and early 1980s, six closely spaced wells penetrating the shallow thermal aquifer were drilled to depths of up to 1000 ft. These wells were never plugged and abandoned, and due to a lack of maintenance they were found to be in extremely poor condition by 2010, with several leaking thermal fluids and valves on most inoperable. In the interest of re-entering these holes to acquire new temperature logs and water samples, we included repair of these wellheads as a necessary prerequisite to collecting new data.

6.2 Wellhead repairs
Four of the six existing wellheads could be replaced. The team completing the repairs was able to replace the gate valves on PS-1, PS-3, PS-4 and MI-1. Wells PS-2 and PS-5 were not found to be leaking and the project was not able to replace the gate valves on these wells due to difficult access conditions (swampy ground made it difficult to get heavy equipment to these sites). New static and flowing temperature and pressure logs have been obtained for the 4 repaired wells. New water samples were taken from 5 of the 6 wells and from the natural hot spring for chemical analysis.

This task was completed in two phases, including:

1) an initial site visit in July 2010 to assess the condition of the six existing wells and develop a work plan for replacing the wellhead assemblies as needed, and
2) a second trip to the site to complete the work outlined in the work plan. This trip took place September 13th-18th, 2010.

For each of the four wellheads that were replaced, the team removed the existing gate valves while pumping down the water level (all 4 are mildly artesian) in order to install new, stainless steel valves. A detailed work description for each well can be found in Appendix B. The team did not alter the configuration of the wellheads except for installing an additional fitting on top of the blind flanges capping the gate valves that can accept a 3in stainless standpipe with a tee and a valve to allow future installation of monitoring and logging equipment. A 1in access port with a plug was also built into the top of the blind flange. Images from the repair of PS-4 are included in Figure 46-48 as examples. A full depiction for each well is included in the report in Appendix B.
Figure 46. Arrows show areas of leaking on PS-4, as well as mineral buildup and scale corrosion

Figure 47. Removing buildup and scale and attempting unsuccessfully to cut the flange bolts with a Sawsall on PS-4.
6.2 Water sampling and chemical analysis
As part of this task, updated water samples were obtained from PS-1, PS-3, PS-4, PS-5, MI-1 and the PHS Lake (which is located adjacent to the church) and evaluated by DRI for common ions and SiO2. The results and a comparison to previous analyses are shown in Table 1. Aqueous chemical data is presented by Liss and Motyka (1994) and we incorporates new samples taken during 2010 of wells PS-1, PS-3, PS-4, PS-5, MI-1 and the main lake spring (Pilgrim 1). PS-2 was not sampled due to subsidence of the well head previously mentioned. The samples collected in 2010 were analyzed by Desert Research Institute in Reno, NV.

6.2.1 Well logs and chemical trends
All of the existing geothermal wells at Pilgrim hot springs are located within a short distance from one another. Each well intersects a shallow 90°C aquifer after which temperature gradients inverted within the well bore. Wells logs indicate drilling intersected mixed layers of sandstone, silts and clays (Woodward-Clyde, 1983) while a layer of pyritization was capping the aquifer (Kline, 1981). PS-1 had the highest flowing temperature at the wellhead during the 2010 sampling survey and also had the highest Cl- and Na+ of the wells (the lake spring had the highest levels of dissolved solids. The total dissolved solids (TDS) in the wells decrease SW from PS-1 (Table 1 below).
Table 1: Hydrochemical Data for PHS Geothermal Wells from 1972-2010.

6.2.2 Chloride (Cl-) Concentrations
Chlorine ion concentrations (Cl-) are important because they enable the identification of mixing trends between the geothermal waters and the cold, ground waters below the shallow aquifer. Geothermal waters are able to interact with host rocks quickly enough (due to high temperature) to attain high levels of Cl- before migration. Thus, springs and wells that have a relatively high flow and temperature and high Cl- levels can be assumed to be connected more directly than other springs/wells that do not have these properties. Looking at the data it is immediately obvious which wells/springs are closely connected to the conduit propagating the geothermal waters. PS-1, PS-2 and the Lake all have Cl- concentrations above 3400 mg/l with the Lake being highest in 1982 at 3730 mg/l. Other wells do not show high Cl- ratios such as with PS-5 being the lowest at 1.7 mg/l in 2010. With Cl- concentrations decreasing as one goes south from the church, it can be assumed that one is moving further away from the source of the geothermal waters. This is the primary evidence for a fault lying close to, or north of the church.

Chlorine concentrations have changed over time in the wells at Pilgrim Hot Springs. PS-1 has showed little change, however it has gone down over 100 mg/l since 1979. This can be explained by a small amount of mixing from the cold water below the geothermal aquifer. Similar trends can be seen in the PHS Lake and somewhat in PS-4.
Increases in Cl- concentrations can be seen in MI-1 (4.7 mg/l in 1982 to 353 mg/l in 2010) and PS-3 (1430mg/l to 2650 mg/l). This is somehow occurring by the influx of geothermal fluid into the wells, or a decrease of flow rate from the sub-aquifer ground water.

The two apparent trends are interesting because it shows that thermal equilibrium in the area has not been maintained. The waters are changing mixing patterns considerably (especially when looking at PS-3 and MI-1. The changes may also be a consequence of changes within the wells.

6.2.3 SiO2 Concentrations
SiO2 concentrations do not vary significantly between samples. The PHS Lake is an exception, however this is most likely due to the fact that the 1982 sample was collected in a cold part of the lake (which means SiO2 would have precipitated as amorphous silica) and the 2010 sample was collected where the hot water was entering the lake (therefore SiO2 levels were more or less retained). Overall the SiO2 levels have gone down a few mg/l for each well (with PS-3 being a slight exception). Silica concentrations at low temperatures (below 100C especially) are directly related to temperature. Thus as the temperatures in the wells have decreased slightly, so has the silica concentrations.

One detail that must be remembered is that due to the fact that the well waters are mixing with the cold ground waters in the wells, the silica levels are not necessarily representative of the concentrations that would be found in the original geothermal fluid. There is a chance that the silica geothermometry is forecasting temperatures that are low.

6.3 New temperature logging
New temperature logs were run in all four holes where wellheads were replaced, using a Kuster K-10 tool. In general, temperature profiles matched reported profiles reported in Woodward-Clyde based on the initial drilling efforts. Figure 49 shows the original temperature profiles for all 6 original holes, as well as the new logs completed in PS-1, PS-3, PS-4, and Minc-1.

PS-4, which was originally drilled to approximately 800 ft, was not accessible below 480 ft during the 2011 effort, presumably due to some blockage in the open hole section of the hole. It is interesting to note that this blockage occurs at the same point where the original log shows the beginning of an isothermal trend which extends to the bottom of the hole, presumably due to circulation within the wellbore.

A full discussion and interpretation of these logs will be included with the development of a conceptual model in Phase 2 (Task 2.4).
Figure 49. Temperature logs from original wells and holes drilled at Pilgrim Hot Springs during 1979-81.

6.4 Successes/Limitations/Recommendations

- The accessibility of these previous exploration holes was an obvious opportunity to collect additional data to compare to prior temperature and water chemistry data available from prior exploration efforts. However, the poor and unmaintained condition of the wellheads indicates the need for DOE to be more stringent on requirements to plug and abandon wells once work on a funded project is completed.
- While the repair effort was successful, it is viewed as at best a temporary fix and we recommend the owners plug and abandon these holes as soon as possible.
- If the wells are not plugged, proper winterization of all the wells is necessary in order to prevent freezing and cracking of the gate valves. In addition, we also recommend installing chains and locks on all the new valves and that all valves should be tested for functionality (opened/closed) at least once a year.
7.0 REFERENCES


Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system, Geophysics: v.43, no.1, p. 144-172.


APPENDIX A:
STATEMENT OF PROJECT OBJECTIVES
(SOPO)
STATEMENT OF PROJECT OBJECTIVES
Alaska Center for Energy and Power, University of Alaska
Validation of Innovative Exploration Techniques at Pilgrim Hot Springs, Alaska

A. PROJECT OBJECTIVES

The objective of this project is to use a combination of existing and innovative remote sensing and ground-based exploration techniques to develop a preliminary conceptual model of the Pilgrim Hot Springs geothermal resource, and to test and hopefully confirm this model through the drilling of two confirmation slim holes.

B. PROJECT SCOPE

The purpose of this project is to test an innovative geothermal exploration technique that, if proven, would reduce the cost of preliminary geothermal exploration for low and moderate temperature geothermal resources. This project will take place at Pilgrim Hot Springs, located on the Seward Peninsula in Alaska. The first Phase of this assessment will include the use of a combination of innovative geophysical remote sensing techniques (including forward looking infrared radiometry, or FLIR) intended to map the spatial extent and total heat flow to the surface and make a preliminary estimation of the developable extent of the reservoir, coupled with more traditional ground-based exploration techniques to pinpoint the location of the upflow zone, map the spatial extent and total heat flow to the surface, and estimate the temperature and depth of the reservoir. The second Phase of this project will involve drilling and testing a series of holes of varying depth as well as accessing existing wells that were part of a late 1970s and early 1980s resource evaluation effort to confirm the results from Phase I. The third Phase will involve developing a more complete understanding of the reservoir through flow tests and water sampling of the holes, and development of a numerical reservoir model.

C. TASKS TO BE PERFORMED

PHASE 1: Innovative remote sensing techniques.

The first Phase consists of airborne and satellite mapping of the geothermal anomaly. The FLIR (forward looking infrared) airborne survey technique has been successfully used at Chena Hot Springs in Alaska, to measure heat loss which correlated closely with values calculated from conductive thermal gradient hole data and convective output. If a FLIR survey coupled with a new iterative digital processing method can be repeatedly shown effective at estimating the heat flow to the surface for systems with a discrete surface expression, this will provide a very low cost and fast method of measuring the natural heat loss of a geothermal system which can be an indication of its maximum possible electrical megawatt output. This Phase has been divided into two sub-tasks.

Task 1.1 Satellite-Based Geothermal Anomaly Mapping.

This task is intended to outline the shallow thermal anomaly and calculate the heat flux by utilizing existing Landsat and Aster images with a new iterative digital processing method that is anticipated to drastically reduce the number of false alarms and uncertainties associated with traditional thermal infrared data processing. This processing scheme involves first categorizing thermal data based on ancillary information, such as elevation, slope, aspect, land cover, geologic and geophysical signature, then processing each category separately using a first derivative filtering
Phase 1 Report (DE-EE0002846)  

process. This will allow us to identify consistently anomalous pixels before using image stacking to differentiate the most promising geothermal anomalies from false alarms. For each thermally anomalous area we will calculate the kinetic temperature using the inverse Planck’s function and will estimate the thermal flux in watts/unit area/unit time. Processed subsets will then be mosaiced back to generate a thermal anomaly map of the area.

Task 1.2 Airborne FLIR Surveys.  
Two FLIR surveys will be flown over 16 square miles surrounding the hot springs in the spring and fall to perform a more detailed assessment of the thermal anomaly and its heat loss. This will incorporate a small thaw in the permafrost about 3.2 km NE of Pilgrim Hot Springs. The iterative digital processing method described in Task 1.1 will also be used to process the resulting data.

Task 2.1 Conduct a Shallow Temperature Survey.  
A preliminary review of existing data and airborne imagery of potential thermal anomalies observed from early fall snow melt patterns and ground based magnetic data collected by the USGS in April 2010 suggests the geothermal aquifer may lie along a trend extending from the springs to the northeast. To verify this trend and select targets for Task 3 drilling, holes 5-10 m deep will be installed over the entire possible shallow thermal anomaly. These holes will be installed by hand with a portable drill by a field crew travelling on foot and will not utilize any drilling mud or sumps. These will also be useful in independently estimating the conductive heat loss from the geothermal field.

Task 2.2 Geophysical Surveys.  
A combination of ground based and airborne geophysical surveys will be conducted to map subsurface hydrothermal fluid flow and identify key structures controlling the flow.

Sub-Task 2.2a Airborne Geophysical Survey  
A high-resolution airborne geophysical survey will be conducted, including the immediate survey area and extending to the northeast to provide a regional geophysical context for the site and to map key structures controlling hydrothermal fluid flow. This sub-task is being completed in conjunction with and partially funded through the United States Geological Survey (USGS).

Sub-Task 2.2b Ground-based Resistivity Survey  
A CSAMT/AMT survey will be run over the entire shallow thermal anomaly to assist in defining its margins and help locate the upflow of thermal water feeding the shallow aquifer. This will extend previous results from over the entire thermal anomaly and the locations of these lines will be recorded by GPS. This sub-task will be funded entirely through match funding through the State of Alaska.

PHASE 2: Drilling  
This Phase involves collecting new data and synthesis of this data from six existing holes, drilling new shallow and moderate depth TG holes to penetrate the shallow aquifer, and siting and drilling two deeper confirmation slim holes.

Task 2. Collection of New Data from Existing Holes and Data Synthesis.  
The purpose of this Task is to collect data from existing holes, and synthesize data to select drilling targets for Task 3.
Task 2.3 Repair Existing Wellheads and Collect New Data.
Six existing and closely spaced wells have penetrated the shallow thermal aquifer due to prior exploration efforts occurring in the late 1970s and early 1980s, but the wellheads are in poor condition. These wellheads need to be replaced so that the wells can be controlled and interference tests performed. New static and flowing temperature and pressure logs will be run in as many wells as possible. New water samples will be taken for chemical and stable isotope analysis. Short term flow and interference tests will be performed to characterize the current condition of these wells.

Task 2.4 Synthesis of New and Old Datasets and Development of a Conceptual Model to Site Task 3 Gradient and Confirmation Holes.
All existing data from the site will be integrated into a conceptual model to assist in determining the location of deeper and hotter fluids. Based on this model the slim hole sites will be sited and permitted for drilling the following year. Completion of task 2.3 is the first milestone for the project, as it will provide the first indication of the overall size of the resource and provide locations for Task 3 drilling.

Stagegate Decision Point after completion of Task 2.
A stagegate decision will be made prior to Task 3 based upon the sufficiency of remote sensing and ground-based data in the identification of potential geothermal resources and the selection of well targets.

Task 3. New Drilling Program.
The purpose of this Task is to access the hotter resource through a drilling program, based on the conceptual model developed as part of Task 2.3. The drilling portion of this phase will be largely subcontracted out, including site access development, rig mobilization and demobilization (possibly helicopter supported), drilling, production logging, performing limited flow testing, casing and cementing, coring, and site remediation. It is divided into two subtasks as follows:

Task 3.1 Gradient Hole Drilling Program.
A minimum of two TG holes will be permitted and drilled to an estimated depth of 500 ft to test the conceptual model and further refine the location for the two deeper confirmation holes. These holes will be completed with 1 1/2” iron pipe so that low temperature Kuster gauges can be run inside the iron pipes. Holes which encounter liquid water will be sampled for chemical analysis.

Task 3.2 Confirmation Hole Drilling Program.
Once these holes confirm the optimal locations for the two confirmation holes, a minimum of two deeper confirmation slim holes will be drilled to verify the model. Considerable flexibility in the drilling plan is necessary until specific sites are chosen and access issues are defined and addressed through the Alaska permitting process. These slim holes are anticipated to be up to 2500 feet deep.

Go/No-Go Decision Point after completion of Task 3.1.
A go/no-go decision will be made prior to Subtask 3.2 based upon the results of Task 1 and 2 activities and precision of TG wells (Task 3.1) in targeting the reservoir.
This Phase will include flow testing, interference testing, and development of a numerical simulation model. This model is required to understand the reservoir dynamics and adopt an appropriate long-term development and production plan. Data from all prior geoscience and drilling programs and testing will be needed to characterize the conceptual model upon which this model will be based to effectively predict future performance, temperature, pressure and flow behavior. In addition, this phase will include Task 5, which involves overall project management and reporting.

Task 3.3 Well Testing.
Very shortly after the two confirmation wells are drilled they will be briefly flow tested to characterize their temperature, pressure, productivity, and producing zone depth. One or more interference tests will be run to obtain pressure data for history matching during the numerical modeling process. It is expected that some or all of the existing wells completed in the shallow thermal aquifer will be either flowed or monitored during the interference testing. At the completion of this task the conceptual model will be updated and form the basis for the numerical modeling performed in task 4.0.

Task 4.0 Numerical Modeling.
A numerical model will be prepared using Tough 2 and incorporating all available and necessary data from the current project and previous work. This model will be utilized to predict possible megawatt outputs from the resource under a variety of possible production/injection scenarios. With completion of the numerical model, all information will be submitted to the DOE independent expert to also determine the capacity of the wells/reservoir.

Task 5.0 Project Management and Reporting.
Reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein. In addition to formal reports, technology transfer of information from this project will take place through a combination of public meetings in communities affected by the project, as well as release of data and results through web-based reporting tools that have previously been developed by the Alaska Center for Energy and Power.
APPENDIX B:
FINAL REPORT: PHS WELLHEAD REAIR
September, 2010
Pilgrim Hot Springs Geothermal Exploration Project

Pilgrim Hot Springs Wellhead Repair
Prepared by: Dan Brotherton, Arctic Drilling, Inc. & Markus Mager, ACEP
Fairbanks Alaska, September 2010

Alaska Center for Energy and Power
University of Alaska
PO Box 755910
Fairbanks, AK 99775-5910
Overview
This task was completed in two phases, including: 1) an initial site visit in July 2010 to assess the condition of the six existing wells and develop a work plan for replacing the wellhead assemblies as needed, and 2) a second trip to the site to complete the work outlined in the work plan. This trip took place September 13th-18th. The goal was to stop the wells from leaking, and make them accessible for instrumentation as part of the DOE funded project ‘Innovative Geothermal Exploration of Pilgrim Hot Springs, Alaska’. This report details the work performed on the individual wellheads during the September trip, which included replacing the gate valves on 4 of the 6 wells, including PS-1, PS-3, PS-4 and MI-1. At this time, none of the wells are leaking to the surface although there are still weak points which need to be addressed in the future.
Recommendations for future work are outlined in this report.
The team performing the work included Dan Brotherton from Arctic Drilling, Richard Eggert, and Max Iyapan from Bering Straits Development Corporation, and Markus Mager from ACEP.

For each of the four wellheads that were repaired, the team removed the existing gate valves and pumped down the water level in order to access the well and install new, stainless steel valves. A detailed work description for each well can be found below. The team did not alter the configuration of the wellheads except for installing an additional fitting on top of the blind flanges capping the gate valves that can accept a 3” stainless standpipe with a tee and a valve to allow future installation of monitoring and logging equipment. A 1” access port with a plug was also built into the top of the blind flange.

We recommend installing chains and locks on all the new valves and that all valves should be tested for functionality (opened/closed) at least once a year. Winterization of all the wells is necessary in order to prevent freezing and cracking of the gate valves. A plan for winterization has been forwarded in a separate communication that is attached to this report.

Mobilization
All new valves (6), parts, tools and supplies, totaling 3842lbs, were purchased or rented by ACEP and shipped to Nome via Northern Air Cargo (NAC). Additional heavy equipment such as 4 wheelers, trailers, a bobcat and an air compressor were rented in Nome from Bering Straits Development Company (BSDC). All parts, tools and equipment were transported to the side on September 13th and 14th and staged at the central staging area (Figure 1). Repair work began on the 15th, and was completed on the 18th.
PS-4 (Completed September 14-15th)

PS-4 supplies the water for the hot tub from a 2in lower valve. The well was leaking from a ½ inch hole in the blind flange on top of the 10in well gate valve and from the corroded 2in valves on each side of the 10in casing underneath the 10in valve (Figure 2).
The lower bolt flange of the 10in valve was covered with mineral buildup and corrosion scale. There was a small pond around the well at the level of the 2in side valves from the constant leaking and overflow from the tub. The team laid down timbers and planks to create a stable work platform and removed mineral build up and rust scale from the lower bolt flange (Figure 3). After various failed attempts to release the old 10in valve from the well flange, the bolts had to be cut off with a torch (Figure 4 & 5)
PS-4
Removing mineral buildup and corrosion scale from lower flange

Figure 3. Removing buildup and scale and attempting unsuccessfully to cut the flange bolts with a Sawzall.

PS-4
Dan cutting bolts off old valve

Figure 4. Cutting bolts to remove old gate valve.
PS-4 has an inner 8in and an outer 10in casing. The outer casing is corroded and thin. The 8in/10in annulus (space between the two casings) continued to produce water after the water level inside the 8in casing was drawn down. This indicates a likelihood that they are set to different depths and water is produced from a different production zone in the annular space than through the main hole. In order to weld on new 2in nipples, this water would need to be drawn down. We were able to partly draw this water down with a 1in suction tube, but it was ultimately decided to not risk changing the 2in nipples after it was determined they are corroded but still sound (probably just as sound as the casing). Dan was not confident that the casing could be welded given its state of deterioriation, so rather than risk creating a difficult to stop leak, the original nipples were left in place and only the 2in valves were replaced with new stainless 2” valves (Figure 6).
The flange on this well is partly eaten away but still appears to be sound. The well is artesian and produces clear water. We installed a new 10in stainless valve with reducer flange on top connected to a 3in threaded nipple with a stainless cap. The well has no visible leaks and has been re-connected to the hot tub via one of the new 2in valves.

Further repairs on this wellhead will be needed in the near future. The 10in casing and the 2in nipples are thin and will eventually start leaking with no way to control or stop the flow. Dan recommends that the 8-10in annulus be cemented from the bottom up to the top via tremie pipe which would seal off the corroded outer casing from the well water and would extend the life of the well.

We are also recommending locks on the 2in valves to guarantee flow to the hot tub, prevent accidently closure (or opening) and to prevent well freeze up since this well will presumably not be shut in through the winter. If this is the case, it is imperative it remains open to prevent the new gate valve from freezing.
PS-3  (Completed September 15-16th)

Prior to repairs, this well was leaking through the standpipe at the top of the well and later, after we started to remove buildup and scale (Figure 8), from a hole in the side of the 10" in valve (Figure 7). We were unable to plug this leak so we dug a sump hole to drain the fluid and temporarily pump it away from the well and surrounding work space.

Figure 7. Image showing leaks and corroded standpipe.
There was significant corrosion to several of the bolts connecting the existing gate valve to the wellhead flange, which necessitated cutting them off with a torch. We were able to drive out some of the bolts once they were cut, but several posed additional challenges and had to be removed in chunks. The torch was damaged during this process.

Eventually we were able to remove the old 10in valve and replace it with the new stainless valve and bolts. The lower flange of the wellhead is severely corroded and the new flange bolts are exposed. The flange thickness is about half of original thickness and there is barely enough material left to secure new flange bolts (Figure 9). The well was completed with a new capped gate valve and blind flange, with a 3in nipple and cap. There is a 2in valve below the flange which was left in place as it is not currently leaking. Dan was not confident the well casing is sound enough to permit replacement of this valve.
PS-3 is hotter than PS-4 and produces clear water. There is also a 6in inner casing in this well that comes to the top of the 10in casing. Once the old valve was replaced, there were no visible leaks. Figure 10 shows a comparison of the old PS-4 valve flange and the old PS-3 valve flange.

Figure 10. Old 10" valves from PS-3 and PS-4. Note severe corrosion on lower PS-3 flange.

Further repairs will be needed to this wellhead soon. Dan recommends cementing the 6-10" annulus from the bottom up with tremie pipe so that side valve can be removed and the main well flange can be replaced. This will protect the well from a permanent leak if one develops from the side of the corroded casing.
MI-1 (Completed September 16-18th)

This well is located on adjacent Mary’s Igloo Native Corporation Lands. The top of the 10in gate valve was split in half, probably due to a freeze break. The valve innards were missing and there was no visible inner well casing. The well is colder than PS-4, and the water temperature of this artesian well appears to fluctuate. When flowed for a short period of time it produced gray, silty fluids.

Due to leaks in the wellhead, a small pond had formed around the well several inches deep. We cleaned out an existing trench leading away from the well and the pond drained away to ground level. We built a work platform around the well and removed mineral build up, rust and scale from the bolts. Dan cut the bolts and drove them out with the torch, and removed and replaced the 10in valve with new stainless steel valve and bolts (Figure 11). The new gate valve is capped with a blind flange with 3in welded nipple and cap.

Prior to repairs, the well was leaking from several holes corroded through casing below the gate valve flange. These leaks continued after installing, capping and shutting the new gate valve. The casing is paper thin midway between the flange and the cement. Dan welded a sleeve around the casing from about 2’’ above the cement level up to the flange, totaling about 14in. In order to weld on the sleeve, he completely removed the side valve, nipple and wellolet from the 10in casing. The sleeve stopped the leaks temporarily but the casing below the sleeve is thin and remains a significant weakness (Figure 12).

Dan recommends installing a 6in inner casing and cementing the annulus from the bottom to the top via tremie in order to prevent further leaking once the casing corrodes further.
PS-1 (Completed September 18th)

PS-1 is the hottest of the repaired wells. This well was buried past the valve handle and covered with several inches of mineral buildup. Before repairs, it leaked out of a corroded two inch elbow from the top of the wellhead, as well as the remains of a 2in valve and a 1in hole in the top of the well cap. These holes were plugged with sticks driven into the openings after some of the mineral build up was removed. We then excavated around the well to just below the lower valve flange covering an 8ft by 10ft area, dug a sump hole for the water pump and laid down blocking and timbers for a work platform. We removed the mineral build up and de-scaled what remained of the bolts (Figure 13 and 14).
When the gate valve was removed, it was evident that the lower flange was almost completely corroded away with no bolt heads remaining and the bolt threads visible from the side of the flange. We used the torch to remove the bolts, removed the old gate valve, cleaned up the flange as much as possible, and installed the new 6in stainless valve topped with a stainless blind flange, 3in nipple and cap (Figure 15).

This well has a 4in inner casing inside the 6in outer casing, and does not have any lower casing 2in valves. There is not much left of the well flange, just barely enough to bolt on the new valve. The well is sealed and does not leak at this time. We backfilled around the well but not to the
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previous level so it is possible to access valve handle. We left the remaining dirt piled to the side of the excavated area.

Dan recommends installing a short (18in) spool section underneath the new gate valve to raise the valve above ground level and permit the well to be backfilled to ground level. This would also eliminate the standing water around the well, which is now below grade. He also recommends cementing the 4in-6in annulus and welding on a new casing flange in order to prevent future leaks.

PS-2

This well buried but inaccessible with rubber tired backhoe. We did not attempt to dig up this well. The wellhead valve is not corroded or leaking.

![Figure 16. PS-2 buried but not leaking. We will need to excavate and replace valve before this well can be accessed with instruments.](image)

PS-5

This well is also not corroded or leaking so we did not replace the valve at this time.
Winterization Plan for Wellheads (Dick Benoit and Gwen Holdmann)

The trick to keeping a wellhead from freezing and then breaking during sub freezing weather is to inject a liquid that is both less dense than water and has a very low freezing point into the wellhead. This fluid needs to be environmentally benign so that when (not if) it is spilled or leaks out of the wellhead it does no environmental damage. Typically a food grade vegetable oil has been used in the lower 48. A small pump is used to pump the oil into the highest opening in the wellhead but if the pressures are very low even a hand operated pump may be enough to do the job. We expect this to be the case for the Pilgrim wells. This pump obviously needs to be able to overcome the internal wellhead pressure and can pump at low rates. You will need to know how much oil has been pumped into the wellhead. Enough oil needs to be pumped into the wellhead to push or displace the water down the well to a point below the freezing level, which is probably not more than a few feet. Therefore, it is necessary to calculate the volume of the wellhead above ground and a few feet of wellbore below ground. We expect this might amount of a few tens of gallons per well. It is important to check the wellhead for leaks, no matter how slow, before injecting the vegetable oil. If the oil leaks out of the wellhead then the water will flow back up in the wellhead and freeze. We recommend doing this on the 4 wells with new gate valves prior to hard freeze-up.
APPENDIX C: RELEVANT PUBLICATIONS


THE UNIVERSITY OF ALASKA IS AN AFFIRMATIVE ACTION/EQUAL OPPORTUNITY EMPLOYER AND EDUCATIONAL INSTITUTION.