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Numerical Reservoir Modeling for Pilgrim Hot Springs, Alaska

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1. Introduction

The state of Alaska has abundant geothermal resources that are of increasing interest as potential power sources for remote Alaskan communities, which are currently heavily reliant on energy from fossil-fuels. In the Alaskan interior a broad zone of geothermal activity (often referred to as the Central Alaskan Hot Springs Belt: CAHSB) is characterized by relatively low-temperature spring dominated systems with surface geothermal fluids at $< 100^\circ C$ and reservoir temperatures determined from geothermometry at $< 150 ^\circ C$ (Kolker et al., 2007). Geothermal activity of the CAHSB is thought to be related to the radiogenic decay of granite plutons (Kolker et al., 2007). A radiogenic heat source model developed for the entire CAHSB suggested that anomalously radioactive plutons are providing the source of heat driving the observed heat transfer to the surface. This implies that the CAHSB fluids fit the category of low-temperature ($<150^\circ C$) geothermal fluids like many Basin and Range systems explored in the western USA. Most hot springs are low-TDS ($<1500$ppm), pH-neutral alkali-chloride type waters (Miller et al., 1973). Na-K-Ca and quartz geothermometers suggest subsurface temperatures in the range of 80$^\circ C$ to 150$^\circ C$ (Miller et al., 1973). Although these hot springs have relatively low geothermometry they are still potentially viable for direct use applications or electricity generation. A commercial geothermal electric plant at Chena hot springs in Alaska about 100 km from Fairbanks uses a binary cycle power plant to generate $0.5 \text{MW}_{\text{Electric}}$ from fluids at $80^\circ C$ temperature (Bertani, 2011).

Pilgrim Hot Springs, located on the Seward Peninsula in Western Alaska, is a geothermal system of the CAHSB that has an intermittent history of direct-use using the $\sim 80^\circ C$ spring water and has been the subject of several studies since 1973 for potential development into an electrical power source based on the 150 $^\circ C$ cation geothermometry (Kolker et al., 2007). As described by Miller (1994) the system potentially has sufficient porosity and volume to be a viable geothermal resource for development. Currently, as part of a joint Department of Energy (DOE) and Alaska Energy Authority (AEA) funded project, Pilgrim Hot Springs is being re-investigated using a variety of state-of-the-art geophysical techniques and exploration drilling for the purposes of better characterizing the resource with a view to developing this system for electricity generation supplying the nearby city of Nome. A key aspect of the current DOE/AEA-funded project has been the development of numerical models of the geothermal reservoir to determine system heat
losses, the subsurface hydrological conditions, and the sustainability of potential resource extraction scenarios. Although less commonly used at the exploration stage of a project, because of the number of constraints available for the shallow geothermal system at Pilgrim Hot Springs, numerical modeling can be more effectively used than is usually the case to forecast the future evolution of the field and its production sustainability (Romagnoli et al., 2010). The 3D numerical code “TOUGH2” has been used to conduct a regional modeling study to investigate likely reservoir responses to production, particularly the interactions between the geothermal reservoir and surrounding cold aquifers and the implications of this for field sustainability. These models can support further analyses of the hydrology of the area, the natural state model for the geothermal system and the sustainability of commercial geothermal production at Pilgrim Hot Springs, Alaska.

In this paper we present the development and results of numerical simulation and stimulation modeling of the Pilgrim Hot Springs geothermal reservoir using the TOUGH2 (Transport Of Unsaturated Groundwater and Heat) suite of software codes. TOUGH2 has been developed by Lawrence Berkeley National Laboratory (LBNL) to perform multi-dimensional simulation of the coupled transport of water, vapor, non-condensible gases, and heat in porous and fractured media. Development of the reservoir simulation models using TOUGH2 was supported by a wide variety of geoscience data including 11 borehole temperature logs up to 388 m deep, cuttings analyses from 5 boreholes (Miller, 2013), MT resistivity soundings, gravity surveys, airborne electromagnetic (EM) mapping, near-surface permafrost extent as interpreted from optical remote sensing images, geothermal heat loss derived from thermal infrared image analyses (Haselwimmer at al., 2013), and numerous derived reservoir property maps and cross-sections. These data were used to characterize the subsurface porosity, permeability and natural state temperature and pressure conditions in the three dimensional model used in TOUGH2, focusing on the drilled system to 388 m depth where temperatures as high as 91°C have been measured. The deeper 150°C detected by the geothermometry is assumed as a probable heat source but the heat flux is constrained by surface heat loss. History matching was used to tune model parameters through the comparison of simulated and observed natural state well temperatures over a series of model runs. Using the best-fit simulation model we developed a
series of reservoir stimulation models by incorporating various injection and production well scenarios.

2. **Study Area**

Pilgrim Hot Springs is located on the Seward Peninsula, Alaska, approximately 97 km north of Nome and 130 km south of the Arctic Circle. The study area is centered at latitude 65.1° N, longitude 164.91° W (Figure 1). The geothermal area is marked by a ~5 km² area of thawed ground populated by broadleaf trees such as poplar, that is in marked contrast to the surrounding sub-Arctic vegetation cover lying on discontinuous permafrost. This permafrost impedes both the downward and lateral movement of water, so that in the broader study area there is little infiltration of precipitation and meteoric waters either pool or run-off at the surface. Pilgrim Hot Springs is located immediately south of the meandering Pilgrim River that lies in a relatively flat valley, which is bounded by the Kigluaik Mountain in the south and Mary’s Mountain and Hen and Chicken Mountain to the north (Figure 1).

*Figure 1*

2.1 **Geology**

The Pilgrim River Valley, represents the downthrown block of a valley graben system, that is bounded to the south by the Kigluaik Mountains and to the north by Mary's Mountain and Hen and Chickens Mountain. South of Pilgrim Hot Springs the valley is separated from the Kigluaik mountains by a north-facing escarpment developed along an active range-front fault that has experienced recent displacement during the Holocene (Turner and Forbes, 1980). Rocks exposed in the Kigluaik Mountains to the south mainly consist of Precambrian units, such as gneissose granite, chlorite-biotite schist, phyllite, metaquartzite and graphitic quartzite (Till et al., 2010). Mary’s Mountain and Hen and Chickens Mountain (Figure 1) form hills that are located about 5 km north of Pilgrim Hot Springs and are comprised of granitic gneisses, intrusive granites and rare amphibolites (Turner and Forbes, 1980). The valley fill includes both alluvial and glaciofluvial deposits, and possible lacustrine sands and silts of Quaternary age (Turner and Forbes, 1980). Alluvial deposits associated with active streams-floodplain, overbank backwater, and slough environments surround the main hot springs and the tertiary sedimentary basin infill
overlies crystalline basement rocks (Till et al., 2010). Unconsolidated to poorly consolidated Quaternary alluvial, fluvial, glaciolacustrine, and brackish lagoon sediments from clay to gravel were intercepted in the wells up to depth of ~315 m where the mica schist basement was encountered below (Miller et al., 2013). The basement was encountered at depths of 314 m and 316 m by the wells PS 12-2 and PS 12-3 respectively that comprised of mica schist with abundant pyrite mineral replacement (Miller et al., 2013).

Although the chemistry of the Pilgrim Hot Springs are incompatible with a direct magmatic source and no volcanic rocks are exposed in this study area, basaltic volcanics found on the Seward Peninsula have inspired alternative proposed mechanisms for the generation of heat in the region. Basalt flows are exposed in the Seward Peninsula to the east of Pilgrim Hot Springs. This volcanism began about 30 million years ago and has continued up to the present (Turner and Swanson, 1981). The presence of these basalt flows along with extensional geological structures on the Seward Peninsula led Turner and Swanson (1981) to propose that the area represents an active rift.

2.2 Previous Work

As one of the highest temperature geothermal systems of the CAHSB, Pilgrim Hot Springs has had a long history of investigation. The University of Alaska Geophysical Institute at the University of Alaska Fairbanks, in co-operation with the Alaska Division of Geological and Geophysical Surveys, undertook exploration and assessment of Pilgrim Hot Springs from 1978-1981 as a part of a DOE funded grant. This work included shallow temperature surveys, a soil-helium survey, exploration drilling, well testing and a variety of geophysical surveys. The drilling of the wells led to the discovery of a shallow 91°C geothermal aquifer with waters. Six wells, namely PS 1, PS 2, PS 3, PS 4, PS 5 and MI 1 (see Figure 2), were drilled during the exploratory phase in the 1970’s. As a part of the current DOE/AEA funded project wells S1 and S9 were drilled during the summer of 2011, and wells PS 12-1, PS 12-2 and PS 12-3 were drilled during the summer of 2012. Geoprobe data were collected during the summer of 2012 from over 60 holes across Pilgrim Hot Springs. Only the well data have been utilized directly for developing this reservoir model domain and the geoprobe data have not been used. Wells PS 1
and PS 2 are each approximately 30 m deep. Wells PS 3 and MI 1 are 75 m and 85 m deep, respectively. Wells PS 4 and PS 5 are 240 m and 270 m deep, respectively.

[Figure 2]

The most detailed capacity assessment available for Pilgrim Hot Springs prior to 2011 was reported by Woodward-Clyde (1983). This report emphasized that the geothermometry suggested a deep reservoir temperature of 150°C. Isotopic chemistry suggested that the deep aquifers are likely charged by surface meteoric waters migrating along the faults in the adjacent ranges to the north and south. The gravity survey suggested that the Pilgrim valley is a sedimentary trough and elongated in the southwest-northeast direction. A conceptual model of the Pilgrim Hot Springs was developed and the discharge of energy was estimated from the modeled geothermal system. The modeled geothermal system considered: discharge of energy to the atmosphere, discharge of energy from numerous springs, discharge of energy in groundwater away from the area and discharge of energy via conductive heat transfer to deeper zones. The accessible geothermal resource base for the modeled part of the geothermal system was estimated to be about 24 MW_{thermal} (Woodward-Clyde, 1983).

2.3 Recent Exploration Work and Datasets

Recent exploration work at the Pilgrim Hot Springs has involved a wide variety of geoscience data collection including: satellite remote sensing, airborne infrared, airborne electromagnetic, magnetotelluric, and gravity surveys, temperature gradients from shallow geoprobe holes and deeper exploratory wells, subsequent lithology analysis and stratigraphy interpretation, and the development of a resource conceptual model. This conceptual model is the basis for the development of the reservoir simulation model for Pilgrim Hot Springs.

Remote sensing images used in the investigation came from operational Earth observing satellites, as well as from special airborne data acquisition campaigns. Time series ASTER data indicated snow free areas and vegetation growth anomalies (Haselwimmer and Prakash, 2012). Thermal infrared data were collected over the study area during September 2010 and April 2011 using a Forward Looking Infrared (FLIR) camera mounted on an aircraft. The objectives of these
FLIR surveys were to identify the thermal anomalies (land surface at an elevated temperature compared to the ambient background temperature) outside the main spring’s site. The second airborne thermal survey successfully provided new observations of anomalous snow melt which were consistent with conductive/convective surface heating around the main Pilgrim Hot Springs area (Haselwimmer and Prakash, 2012). The total heat flux near the surface of the geothermal features estimated from remote sensing is $4.7-6.7 \text{ MW}_{\text{Thermal}}$ (Haselwimmer et al., 2013).

The commercial airborne electromagnetic (EM) survey data was collected by FUGRO using the RESOLVE helicopter electromagnetic system. This airborne EM system provides measurements of the ground conductivity (or resistivity) to depths greater than 100 m over permafrost and crystalline rocks, although its depth of investigation was about 15 m over the very low resistivity thawed alluvium near the hot springs. The airborne EM system had a frequency range between 400 Hz to 140 KHz. The length of the survey covered a distance of 546 km with the height above the ground being 60 m. These data have been utilized to distinguish frozen and unfrozen ground. The size, shape and extent of the reservoir model have been constrained by the detailed outline of shallow thawed ground indicated by the airborne EM survey.

A magnetotelluric (MT) resistivity survey was conducted at Pilgrim Hot Springs on areas accessible during the 2012 summer field season. In total, 59 stations were recorded at 0.001-10000 Hz range with an average station spacing of distance of 100 m apart, with a remote station 5 km SE of the site (Fugro, 2012). Initial 1D MT inversions used for initial correlation with well lithology and temperature (Miller, 2012) were followed by 3D MT inversions by Fugro (2012) used to extrapolate well results. Although resistivity is affected by temperature, porosity and salinity, in the context of most geothermal settings, low resistivity is strongly correlated with smectite clay and this is particularly well illustrated by the Pilgrim Hot Spring system (Miller at al., 2013). The MT survey in our case helped to identify the possible flow path of the geothermal fluids and the plumbing of the system and determine the location of the impermeable clay zones.

Drilling logs and temperature profiles for the eleven wells (PS 1, PS 2, PS 3, PS 4, PS 5, MI 1, S1, S9, PS12-1, PS12-2 and PS12-3) drilled at Pilgrim Hot Springs are available for analysis and data interpretation (Figure 3) The temperature profiles help to determine possible regions of
upflow and outflow of hotter geothermal fluids when correlated with MT survey data. The deepest well in the reservoir is PS 12-2, with the bottom of the wellbore at a depth of 388 m. The bedrock contact occurs at approximately 300 m. The wells PS 12-1 and PS 12-3 are 300 m and 280 m deep, respectively. The wells PS 12-1, PS 12-2 and PS 12-3 penetrate the shallow ~91°C reservoir and the deeper sediments until they reach the basement contact but have temperature reversals that indicate that they do not directly detect the upflow zone.

[Figure 3]

Temperature logs from the eleven wells drilled at Pilgrim Hot Springs (Figure 3) were used to determine intervals of cold water influx and outflow from the reservoir and the location of the potential upflow zone within the model. Lithological logs from the wells were used to parameterize the 3D architecture and physical properties of the stratigraphy within the modeling domain. A simplified version of the 3D stratigraphic model developed using RockWorks 15 by Miller et al. (2013) was used to parameterize the lithological distribution and properties within the modeling domain.

3. Development of Reservoir Simulation Model

The reservoir simulation model encompasses a clastic sedimentary sequence parameterized in three dimensions overlying a homogeneous basement where geothermal heat/water input occurs from a basement source and there are cross-flows of cooler meteoric waters related to gravity-driven flow off the mountains north and south of the domain (Figure 4). Temperatures and heat flow within the domain are considered to be proportional to the basal heat flow. The model was developed utilizing PetraSim software that provides a convenient graphical user interface to the TOUGH2 code.

[Figure 4]

The EOS3 equation-of-state (EOS) module within TOUGH2 has been used that encompasses flows of water, heat, and air. Given the low-temperature of the geothermal system we have assumed water remains under aqueous conditions and a gas-phase was not considered. The
physical properties of water are determined for 0-150 °C and 0-100 MPa, by means of lookup/interpolation tables (Pruess, 1988). Further details of the governing equations used in the TOUGH2 model are described in the Appendix A.

3.1 Reservoir Domain
The extent of the reservoir domain was determined through analysis of the airborne EM data by locating unfrozen ground that presented very high resistivity values; in contrast, frozen ground presented very low resistivity values. The unfrozen areas are assumed to be the areal extent for the containment of geothermal fluids which allows the area to remain unfrozen. The reservoir domain utilized for the modeling work comprises a triangular domain of 68,481 cells with approximate cell-dimensions of 25 m x 25 m in the area of highest density of wells. The gridding density is varied according to the density of the wells at Pilgrim Hot Springs, with higher gridding density where the wells are closely spaced. As a result, the model grid is non-uniform for all the layers throughout the domain. The reservoir domain has been classified into a shallow zone (0-30 m), deeper sediment zone (30-300 m) and bedrock (300-1000 m) (Figures 3 & 4).

3.2 Initial Conditions and Boundary Conditions
The top layer of the reservoir model is assumed to be the ground or the surface whose boundary conditions are the mean annual atmospheric pressure and air temperature. The base layer at a depth of 1000 m corresponds to an arbitrary level within the basement selected based on the interpretations of the MT survey and developed isotherms. The basement rock or bedrock is the deepest layer in the reservoir model. The temperature and pressure for all the grid cells in this layer are applied as fixed boundary conditions. Based on the interpretation of the airborne EM survey at Pilgrim Hot Springs, and shallow temperature measurements (DOE, 2012) we consider that any area surrounding the reservoir model domain is frozen ground and that permafrost exists from 0-100 m along the boundaries of the reservoir. We assume that artesian groundwater exists below the permafrost along the boundaries of the reservoir model domain from 100-300 m depth.

The intervals of cold water influx into the reservoir modeling domain and outflow of cold water was determined through interpretation of the static well temperature logs. The differential
pressure heads between the north and the south account for the forced flow of cold water from the south towards the north. Based on the data from piezometric heads for the old wells drilled during the 1970’s (Woodward-Clyde Report, 1983), we determine the pressure head along the south and north of the domain by extrapolation of the pressure gradient across the reservoir domain in a horizontal direction. The source cells in the south are provided with an additional pressure head of 18 m. The sink cells in the north are provided with a lowered pressure head of 3 m, relative to the surface elevation. We assume that the temperature of the cold water is 4 °C. The enthalpy of the cold water at 4 °C is 16900 Jkg\(^{-1}\). The temperature and enthalpy of the cold water are set as fixed condition in the source cells. Based on the interpretation and analysis of the MT survey from the blind 3D MT inversion at Pilgrim Hot Springs, the cold water influx into the reservoir modeling domain is inferred to occur from the south-west, south and south-east directions (Figure 5).

*Figure 5*

The upflow of geothermal fluids within the basement is parameterized using a single heat source cell and a series of permeable planes (representing basement fractures) that feed heated fluids to the contact between the basement and sedimentary pile (Figure 4). The location and orientation of the heat source and these fractures was determined from interpretation of the MT 3D model inversions (Figure 5). The heat source cell lies at the base layer of 1000 m and is located towards the south-west of well PS 5 (Figure 6). The conduit forms a series of planes of different orientations and depths (Figure 6).

*Figure 6*

Based on the interpretations of the geophysical data, we have developed the reservoir simulation model with respective plumbing and heat source location. Heat source cell is located at 1000 m in the vicinity of well PS 5 and is set as a fixed boundary condition with a temperature of 120 °C based on the isotherms derived from the MT survey and static temperature logs for all wells across Pilgrim Hot Springs and an additional pressure head of 12 m. The conduit originates from the base layer near the vicinity of well PS 5 and orients laterally toward the vicinity of well
PS 12-2 at the basement contact at a depth of 300 m. The reservoir simulation model has been developed based on increasing the temperature gradient for the well PS 5 at a depth of 240 m. The temperature profiles for the wells PS 5 and PS 12-2 support the feasibility of the idea that the heat source and plumbing could be in the vicinity of well PS 5, with up-welling of hotter fluids to the north-west of well PS 12-2. Further investigations have been made to analyze and interpret the MT survey and static temperature logs for all the wells. In this reservoir model, both the heat source and cold water influx into the domain occurs from the southern end of the domain. However, the plumbing has been reoriented in order for the up-welling of hotter fluids to occur in the vicinity of wells PS 12-2 and PS 1.

Porosity and permeability values were determined from the sediment characterization, which act as input parameters for the numerical reservoir model (Miller et al., 2013). The lithology types and their respective properties, with color codes which have been incorporated in the reservoir simulation model, are shown in Table 1 and Figure 4.

**[Table 1]**

### 3.3 Model Runs/ History Matching

The next step (history matching) involved running the reservoir simulation model until the closest matching of the simulated temperatures to the actual static temperatures is achieved. History matching helps to verify the reliability of the natural state simulation where the areal distributions of the simulated values are compared with the measurements at different depths. A good analog to this current modeling work was the development of the numerical model at the Larderello-Travale system using the TOUGH2 which was used to verify the reliability of the simulated values of temperature, pressure, and steam quality with the measurements at different depths (Romagnoli et al., 2010). The computed natural state simulation was used as the initial condition for production history simulation. Once a satisfactory match for the natural state was achieved, the same 3-D distributions of permeability and porosity obtained during the simulation, were utilized to simulate field production history (Romagnoli et al., 2010). In the current work, successful history matching was achieved based on the comparison of the simulated well temperatures with the actual static well temperatures considering the spatial variability of these
wells. The reservoir simulation model with the same initial and fixed boundary conditions was converted into a stimulation model by incorporating injection and a production wells.

The characteristics of the heat source cell represent one of the boundary conditions for the reservoir model. In this work, the heat source cell has been set to 120 °C and $2.7 \times 10^{19} \text{Jsec}^{-1}$ such that source of hotter fluids is unlimited and remains constant over the period of simulation. Each trial simulation run involved providing varying additional pressure head to the heat source cell that was the only variable and unknown parameter. This additional pressure provides for additional momentum for fluids to rise toward the surface, and the temperature of fluids provides the buoyancy. As higher temperature fluids rise toward the surface, they lose more heat via convection causing a greater heat flux near the surface for the reservoir model. In this study history matching has helped to predict the conditions required at the heat source cell and the conduit terminating at bedrock.

4. Development of Reservoir Stimulation Model

The reservoir stimulation model was developed by incorporating the cyclic process of injection and production into the domain. In this scenario 80 °C water was reinjected back into the domain after production that is based upon the assumption of development of 95 °C resource. This stimulation scenario has been developed considering that Chena Hot Springs, Alaska, uses the binary cycle power plants to generate power and allows re-injection of fluids back into the reservoir at the same rate of production providing higher efficiency (Erkan et al., 2008). This may also be applicable at Pilgrim Hot Springs such that the produced fluids are better utilized to sustain the reservoir pressure and reduce the cost of disposing of the produced fluids.

Reservoir simulation model with a 120 °C heat source located at a depth of 1000 m, including all the boundary and initial conditions, has been utilized to develop the reservoir stimulation model by incorporating an injector well and a production well with respective properties as shown in Table 2. The injection well inputs 80 °C water into the domain which has an enthalpy of 335,000 Jkg$^{-1}$ with a 2000 gpm injection rate.

[Table 2]
Although the reservoir simulation model was utilized to generate the injection and production scenario, the end results of the simulation models have not been considered as initial conditions for the stimulation models. The initial plume in the stimulation scenario would have provided a better estimate of temperature changes in the production well. The simulation model was run for a period of 150 years and indicated that the stable conditions were attained after ~95 years. The production well in the stimulation scenario has been located in the region of upwelling of hotter fluids near well PS 12-2. In the stimulation model, production well has been completed between 270 -295 m. This means that the wells do not communicate with or contact the bedrock and the fracture network within the bedrock.

5. Heat Flux Calculation
The reservoir simulation model was developed in order to estimate the heat flux near the surface. It predicts the heat flux for every layer and every cell within the layer entailed by the modeling domain. The reservoir model covers a larger domain and emulates a deeper system. It considers the discharge of groundwater near and away from the area, the discharge of energy near the surface towards the atmosphere, the discharge of energy from springs, and the discharge of energy via the Pilgrim River. In an earlier study, a conceptual model of Pilgrim Hot Springs was developed and the discharge of energy was estimated at 24 MW from the modeled geothermal system (Woodward-Clyde Report, 1983). The modeled geothermal system considered: discharge of energy to the atmosphere, discharge of energy from numerous springs, discharge of energy in groundwater away from the area and discharge of energy via conductive heat transfer to deeper zones. Of the total 24 MW of energy produced, energy lost from the springs and thawed ground was estimated at 2 MW and 6 MW respectively. The amount of energy lost due to the groundwater outflow was 15 MW (Woodward-Clyde Report, 1983). This suggested that the amount of thermal energy associated with the groundwater outflow is way higher than the energy released from the springs and thawed ground.

Similarly, in the current modeling work, the purpose of the reservoir simulation model is to estimate the heat flux near the surface which may be due to the springs, rivers, thawed ground
and ground water outflow. The heat flux near the surface also accounts for the heat lost via springs and river which are represented by their respective grid cells.

The thermal energy for every cell in the layer nearest to the surface was estimated using Equation 8:

\[
\text{Thermal Energy per cell} = \text{Area of cell} \times \text{Heat Flux for cell} \tag{8}
\]

The total thermal energy near the surface is estimated using Equation 9:

\[
\text{Total Thermal Energy near the surface} = \sum \text{Area of cell} \times \text{Heat Flux for cell} \tag{9}
\]

Utilizing the above equations for the layer near the surface, the total heat flux was estimated for all the grid cells in the layer except for the cells representing the permafrost.

6. Results

6.1 Results of Reservoir Simulation Model

The simulated temperatures as seen in the west-east cross section of the reservoir simulation model show the up-welling and outflow of geothermal fluids into the shallow zone (see warmer color peaks in Figure 7). The up-welling zone is rather small and the cross section does not cut directly through the narrow zone. A fault or fractures in the bedrock feeds the geothermal fluids from the base layer until the basement contact is reached. The additional pressure head of 12 m allows the fluids to be forced into the upper sedimentary layers. The silty-sands between 270-300 m may have sufficient permeability to conduct the warmer up-welling fluids that then pass around the thick clay package at 200-270 m by flowing via the indurated sands.

[Figure 7]

These indurated sands might offer high porosity and higher vertical permeability due to possible fractures or pipes in the consolidated sands. The indurated sands support the up-welling of the hotter fluids and feed them into the shallow aquifer. The outflow of geothermal fluids occurs in
the shallow aquifer and is controlled by the highly permeable layers of sands and gravels. The dark blue color at the boundaries of the reservoir domain represents the permafrost from 0-100 m and cold water influx occurs below that depth. We can observe the cold water represented by various shades of blue below the plume (Figure 7). The colors within the plume for both the simulated temperature sections, that represent the temperatures in the plume, show only minor variations possibly due to the current resolution of the grids. The thermal energy estimated from the reservoir simulation model is 28 MW with a 120 °C heat source and an additional 12 m pressure head in the heat source cell.

A comparison of simulated temperatures to the measured static temperatures for PS 12-2, PS 12-3 and PS 5 show the vicinity of the wells to the up-welling of hotter fluids and their outflow regions and plumbing (Figure 8).

[Figure 8]

The wells PS12-2 and PS 12-3 indicate highest temperatures around 30 m and near the basement contact at the depth of 300 m. The highest temperatures near the basement contact suggest that the up-welling of the geothermal fluids from the bedrock occurs in the vicinity of these wells. The highest temperatures near the base of shallow aquifer at 30 m indicate the outflow of geothermal fluids into the shallow aquifer.

PS 12-3 shows a very good match in the lower portion of the profile below 150 m, above this point the simulated temperature do not capture the coldest part of the observed temperature profile nor do they capture the hot water in the shallow aquifer well. This indicates that the resolution of the lithology in the model is not sufficient to distinguish important aquifers that exists in the geothermal system. The opposite is true for well PS 12-2 where aquifers seem to be present in the model but are not present in the observed data. Both the horizontal and the vertical resolution of the hydraulic conductivity in the model play a role in distorting the simulated temperatures. For well PS5 the simulated and observed temperature are in very good agreement overall. In general considering the limited number of controls in this model (mainly liquid water pressure and energy content at the boundaries) and purely applying physical relations between.
water movement and temperature, it is remarkable that most of the simulated temperatures are within 10°C of the observed values. This supports our model of rising geothermal liquid in a flow cold groundwater system.

For well PS 5 (Figure 8), the maximum temperature of 75°C occurs at the base of the shallow aquifer at 30 m. The sharp temperature gradient between 220-260 m in the static measured temperature log is similar to the observed temperature gradient between 250-280 m for the simulated temperature profile. This gives confidence that there is a hot source underneath well PS5 that is likely connected to the up-welling zone. In our stimulation models we use the simulation model that includes a hot source of 120°C underneath well PS5. These simulation results were used to calibrate the boundary conditions of pressure and temperature at the hot source. The observations for wells PS 12-2, PS 12-3 and PS 5 suggest that it is feasible for a heat source at 120 °C to exist in the vicinity of PS 5, and an up-welling of hotter fluids to the north-west of PS 12-2.

6.2 Results of Reservoir Stimulation Model
This reservoir stimulation model estimates between 46 and 50 MW\textsubscript{Thermal} energy available for power generation. The temperature of the production fluid was calculated to be between 82 and 88 °C. We used the values for the following parameters: $m = 135 \text{ kg sec}^{-1}$, $C_p = 4200 \text{ J Kg}^{-1}\text{°C}^{-1}$. The reference temperature for this calculation was assumed to be 0 °C. It is observed that the re-injection model is not in a steady state condition over the short 10 year length of the model run, the system temperature is still rising. The simulated results indicate that both the shallow zone and the deeper sediment zone have warmed significantly when compared to the other two reservoir stimulation models. This production scenario suggests that with one production well and one injection well, production well #1 produces about 50 MW of thermal energy.

7. Discussion
7.1 Reservoir Simulation Model
The history matching process involved iterative simulation modeling applying differing pressure heads to the heat source cell. The simulation runs with the closest possible matching of the simulated temperatures to the actual static temperatures revealed that 12 m pressure head was
optimal for the simulation model. Lower additional pressure heads resulted in cooler and smaller plumes while higher additional pressure heads resulted in warmer and bigger plumes. This may be viewed as a candle-in-the-wind scenario where there should be a correct balance between the cross-flowing wind and the plume formed by the candle for it to remain lit successfully while the winds blow across it. This analogy may also be applied to obtaining the right balance between the cross-flowing cold water and the up-welling hotter fluids which will result in a stable plume with cold water flowing across without cooling the plume. In some trial runs, the pressure head was too small to sustain a stable plume. When the pressure of the cross-flowing cold water was greater than the pressure of the up-welling fluids, we observed disappearance of the plume over the duration of the simulation. However, when the pressure of the up-welling fluid was greater than the pressure of the cold water influx, the plume was sufficiently large and hot to overcome the dampening effects of the cold water influx from the south. Published literature lacks a body of work that discusses the development of reservoir models encompassing scenarios where cross-flowing cold waters and up-welling hot geothermal fluids reach a stable steady state condition.

The heat source cell for the reservoir models has been defined as a fixed boundary condition where the source of hotter fluids is unlimited and remains constant over the period of simulation. This condition ensures that the influx of hotter fluids into the domain from the heat source cell remains constant with respect to thermodynamic properties. This does not represent the real world scenario as the influx of the hotter fluids will vary with time, affecting reservoir conditions. A realistic heat source will have declining influx of hotter fluids along with declining pressures and temperatures as a result of source cooling, but a sufficiently large groundwater system would be able to sustain pressure over the duration of the simulation.

The estimated thermal energy of 28 MW from the simulation model is greater than the value estimated from remote sensing (Haselwimmer et al., 2013). The remote sensing method gave a value of 4.7-6.7 MW for the heated waters and 2 MW for the snow-melt areas. The reason for this substantial difference is that, in calculating the heat flux, the reservoir simulation model considers the discharge of groundwater near and away from the area, the discharge of energy near the surface towards the atmosphere, the discharge of energy from springs, and the discharge of energy via the Pilgrim River, which was covered by the surface layer analyzed. The reservoir
model covers a larger domain and emulates a deeper system while the remote sensing technique estimates heat flux from a very shallow region and a limited area. In an earlier study, a conceptual model of Pilgrim Hot Springs was developed and the discharge of energy was estimated at 24 MW from the modeled geothermal system wherein energy lost from the springs, thawed ground, and groundwater outflow was estimated at 2 MW, 6 MW, and 15 MW respectively (Woodward-Clyde Report, 1983). The groundwater flux to the river is difficult to measure due to the large quantity of water flowing in the river, relative the amount discharging, resulting in a very small amount warming. Another preliminary conceptual model for the Pilgrim Hot Springs estimated the system energy as 26 MW \text{thermal} (Daanen et al., 2012). Our current estimates of 28 MW \text{thermal} match closely the thermal flux estimated from both the earlier studies, possibly due to the fact that our studies similarly accounted for heat loss from thawed ground, springs, groundwater movement and from river outflow.

The availability of further information pertaining to the subsurface geological and hydrological conditions will undoubtedly improve the ability to robustly model the hydrothermal system through better parameterization of model parameters and boundary conditions. Given the lack of data concerning Pilgrim Hot Springs, a number of assumptions had to be made in building the simulation models during this work. For example, the pressure from the wells at Pilgrim Hot Springs had to be extrapolated to estimate the pressure gradient, and subsequently, the pressures for cold water influx from the south toward the north of the domain. The exact location of the heat source and respective plumbing within the system or in the bedrock had to be determined from the available data that has limited coverage. The fracture properties and other thermal properties for modeling were considered by taking values from published literature and the geologic model developed by Miller et al (2013). Also, incorporation of the lithology and stratigraphy into the model required extrapolation into areas where data was unavailable.

7.2 Reservoir Stimulation Model

In the stimulation model for Pilgrim Hot Springs, to counteract the cooling effect of the cold water influx from the Kigluaik Mountains in the South, and to warm the deeper sediment zone, the injection well was chosen to be near well PS5 and screened between 100 and 200 meters. The model uses re-injection properties with high temperature fluids at 80 °C and 2000 gpm.
Pumping-in water at the same flow-rate as the production well is possible in a binary cycle power plant (Fridleifsson and Freeston, 1994), and results in 50 MW of thermal energy and the production of 88 °C water.

A more realistic scenario will consist of re-injection of fluid with a temperature lowered by ~15 °C, which should be around 70 °C. At this temperature the liquids are still considerably warmer than the liquids in the cold water aquifer at depths of 100 m in the domain, but will reduce the production temperature. The effect of production on the reservoir pressure has been analyzed by comparing the pressure at the springs for the stimulation model. This stimulation model showed that artesian pressure at the springs can be sustained.

When fluids with temperatures lower than 80 °C are re-injected in the stimulation model, the thermal energy estimates are expected to be higher than 46 MW and below 50 MW and the temperature of produced fluid is greater than 82 °C and lower than 88 °C. The main advantages of this scenario are that the produced fluids are better utilized to sustain the reservoir pressure and reduce the cost of disposing of the produced fluids.

Another assumption of the reservoir stimulation model is that the production well is located in the region of up-welling of geothermal fluids from the bedrock such that the well communicates with the up-welling fluid at the completion depth of 270-295 m. This region of up-welling has been selected based on the interpretations of the MT survey and isotherms. These results are going to be different from scenarios where producing wells communicate directly with the bedrock fracture that will produce higher flow rates and temperatures.

A final limitation is that these stimulation models are run with the end results of the simulation model as initial conditions. This estimates higher values of thermal energy due to an already existing stable plume within the domain. This plume will, however, dissipate over time resulting in a temperature distribution as observed in the stimulation models, where the plume is not allowed to form due to continuous production from the reservoir.

8. Conclusions and Recommendations
The thermal energy estimated by the reservoir simulation model is around 28 MW$_{\text{Thermal}}$. The history matching of the static temperature logs with the simulated temperature logs for the model provides confidence on the value of heat flux estimated near the surface. Assuming the efficiency of converting thermal energy into electrical energy to be about 10 %, the electrical energy production potential projected from the current heat flux estimates from simulation model is about 2.8 MW$_{\text{Electric}}$.

Based on current 50 MW$_{\text{Thermal}}$ estimates of the thermal energy from the stimulation scenario and an optimal conversion system, such as at the Chena Hot Springs in Alaska, the estimated electrical energy production capacity at PHS is about 5.0 MW$_{\text{Electric}}$. This suggests that geothermal system at Pilgrim Hot Springs has significant potential for direct use applications or power production. Based upon current knowledge of the system it will be optimal to drill a production well in the vicinity of wells PS 12-2, PS 1 and PS 12-3 that was determined as the region of up-welling hot fluids. In fact, the region north-west of PS 12-2 seems promising such that a well drilled there would likely communicate with fractures or conduits in the bedrock. The production capacities of this well should be tested with varying flow rates.

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References


Appendix A

The details of the governing equations used in the TOUGH2 model are described here.

**Single Phase Flow:** The TOUGH family of codes (PetraSim) simulates flow in porous media with a basic assumption that the flow is described by Darcy’s Law.

**Darcy’s Law:** Darcy’s Law is expressed to represent the fluid flow where the discharge $Q$ is proportional to the difference in the height of water, $h$ (hydraulic head), and inversely proportional to the flow length $L$ as given by Equation 1:

$$Q = -KA\left(\frac{h_A-h_B}{L}\right) \tag{1}$$

Where, $Q$ = discharge ($m^3$ sec$^{-1}$); $K$ = hydraulic conductivity ($m$ sec$^{-1}$); $A$ = cross sectional area of flow ($m^2$); $h_A$ = hydraulic head at point A (m); $h_B$ = hydraulic head at point B (m) and $L$ = flow length (m).

**Specific Discharge:** The specific discharge which is also known as Darcian velocity or Darcy flux is given by Equation 2:

$$q = -K\frac{dh}{dl} \tag{2}$$

Where, $q$ = specific discharge ($m$ sec$^{-1}$); $K$ = hydraulic conductivity ($m$ sec$^{-1}$) and $dh/dl$ = hydraulic gradient (dimensionless).
**Mass Balance Equation:** The change in the fluid mass within a fixed volume is given by the sum of the net fluid inflow across the surfaces of the volume and the net gain of fluid from the sinks and sources of the volume. The mass balance is given by Equation 3:

\[
\frac{d}{dt} \int_{0}^{V_n} M^\kappa dV_n = \int_{0}^{T_n} F^\kappa \cdot ndn + \int_{0}^{V_n} q^\kappa dV_n
\]  

(3)

Where, \(V_n\) = volume of arbitrary subdomain \([\text{m}^3]\); \(T_n\) = closed surface \([\text{m}^2]\); \(n\) = normal vector on surface element \(d\tau_n\), pointing inward into \(V_n\); \(M^\kappa\) = specific mass of component \(\kappa\) \([\text{kg m}^{-3}]\); \(F^\kappa\) = specific mass flux of component \(\kappa\) \([\text{kg m}^{-2}\text{s}^{-1}]\) and \(q^\kappa\) = specific mass sink/source \([\text{kg m}^{-3}]\).

**Heat Balance Equation:** The change in heat within a fixed volume is given by the sum of net heat flow across the surfaces of the volume and the net gain or loss of heat from the sinks and sources of the volume. The heat balance is given by the Equation 4:

\[
\frac{d}{dt} \int_{0}^{V_n} M^h dV_n = \int_{0}^{T_n} F^h \cdot ndn + \int_{0}^{V_n} q^h dV_n
\]  

(4)

Where \(M^h\) is the specific bulk heat capacity which is given by Equation 5:

\[
M^h = (1 - \varphi)\rho_R c_R T + \varphi \sum_\beta S_\beta \rho_\beta \mu_\beta
\]  

(5)

Where,

\(M^h\) = energy in Joules per unit volume or bulk heat capacity \([\text{J m}^{-3}]\); \(\varphi\) = porosity;
\(\rho_R\) = density of fluid \([\text{kg m}^{-3}]\); \(c_R\) = specific heat capacity \([\text{J kg}^{-1}\text{K}^{-1}]\); \(T\) = temperature \([\text{K}]\); \(\mu_\beta\) = specific internal energy \([\text{J kg}^{-1}]\); \(\varphi S_\beta \rho_\beta\) = specific mass of phase \(\beta\); \(F^h\) = specific heat flux \([\text{W m}^{-2}]\) and \(q^h\) = specific volumetric heat source \([\text{W m}^{-3}]\).
**Heat Source Cell:** The heat associated with the heat source cell (Equation 6) is a function of cell volume, density of rock, specific heat and temperature gradient:

\[ Q = V \rho C_p \frac{\Delta T}{\Delta t} \]  

(6)

Where, \( Q \) = heat (W); \( V \) = cell volume (m\(^3\)); \( \rho \) = density of rock (kg m\(^{-3}\)); \( C_p \) = specific heat capacity of rock (J kg\(^{-1}\) \(^\circ\)C \(^{-1}\)); \( \Delta T \) = change in temperature (\(^\circ\)C); and \( \Delta t \) = change in time (seconds). The Equation 6 is utilized in Petrasim software to estimate the heat associated with, and released from, the heat source cell or grid which exists within the reservoir modeling domain.

**Mass Flow Rate in Source Cells:** The mass flow rate (Equation 7) is a function of density of fluid, porosity, volume of cell, compressibility of rock and pressure gradient:

\[ m = \rho_{water} \phi V C \frac{\Delta P}{\Delta t} \]  

(7)

Where, \( m \) = mass flow rate (kg sec\(^{-1}\)); \( \rho_{water} \) = density of water (kg m\(^{-3}\)); \( \phi \) = porosity of cell; \( V \) = volume of cell (m\(^3\)); \( C \) = pore compressibility (pascal\(^{-1}\)); \( \Delta P \) = change in pressure (pascal); and \( \Delta t \) = change in time (seconds). The Equation 7 is utilized in Petrasim accounts for the mass flow rate associated with source cells or grids. This equation helps to apply the required pressure conditions to the source cells which involve creation of mass within a fixed volume domain.
**Table 1:** Lithology types and their respective properties which have been incorporated in the reservoir simulation model.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Density (Kgm$^{-3}$)</th>
<th>Porosity (%)</th>
<th>Permeability (m$^2$)</th>
<th>Thermal Conductivity (Wm$^{-1}$K$^{-1}$)</th>
<th>Specific Heat (JKg$^{-1}$K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>2680</td>
<td>35</td>
<td>3.33E-08</td>
<td>2.68</td>
<td>860</td>
</tr>
<tr>
<td>Indurated Sands</td>
<td>2640</td>
<td>1</td>
<td>5.8E-08</td>
<td>2.5</td>
<td>840</td>
</tr>
<tr>
<td>Sandy-Silty Clays</td>
<td>2680</td>
<td>34</td>
<td>1.39E-07</td>
<td>1.73</td>
<td>860</td>
</tr>
<tr>
<td>Interbedded Gravel and Clay</td>
<td>2700</td>
<td>35</td>
<td>2.48E-07</td>
<td>1.8</td>
<td>920</td>
</tr>
<tr>
<td>Sand</td>
<td>2640</td>
<td>32</td>
<td>2.58E-07</td>
<td>1.7</td>
<td>775</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>2640</td>
<td>34</td>
<td>2.64E-07</td>
<td>1.93-2.06</td>
<td>775</td>
</tr>
<tr>
<td>Sandy Gravel</td>
<td>2640</td>
<td>31</td>
<td>4.19E-07</td>
<td>2.82-3.07</td>
<td>920</td>
</tr>
<tr>
<td>Gravel</td>
<td>2700</td>
<td>32</td>
<td>5.58E-07</td>
<td>1.8</td>
<td>920</td>
</tr>
<tr>
<td>Bedrock/Schist</td>
<td>2740</td>
<td>2</td>
<td>1E-13</td>
<td>4</td>
<td>790</td>
</tr>
</tbody>
</table>

**Table 2:** Well properties related to the operation of the production wells and injection wells incorporated in the stimulation model.

<table>
<thead>
<tr>
<th></th>
<th>Production well</th>
<th>Injection well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion depth (m)</td>
<td>270-295</td>
<td>200-300</td>
</tr>
<tr>
<td>Flow rate (gpm)</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Productivity Index (m$^3$)</td>
<td>5x10$^{-5}$</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Permeability (m$^2$)</td>
<td>2.58x10$^{-7}$</td>
<td>2.58x10$^{-7}$</td>
</tr>
<tr>
<td>Radius of grid cell (re) (m)</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Radius of wellbore (rw) (m)</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Completion top pressure (Pa)</td>
<td>2.76x10$^{6}$</td>
<td>2.76x10$^{6}$</td>
</tr>
</tbody>
</table>
Figure 1: Map showing the location of Pilgrim Hot Springs. The red outline marks the limits of the permafrost-free area that was used for the geothermal model.
Figure 2: Map showing the locations of the exploration wells (red dots) drilled around the Pilgrim Hot Springs. The red outline marks the boundary of the model domain that corresponds with the limits of the permafrost-free area. Geothermal waters are highlighted in sea green color on a backdrop of a high resolution aerial photo of the study area. A portion of the Pilgrim River is also visible in the top right side of the model domain.
Figure 3: Static temperature logs from all wells located across Pilgrim Hot Springs.
Figure 4: Lithology types as seen in an east-west oriented cross section across the center of the reservoir model.
Figure 5: Resistivity across profile C from a blind 3D MT inversion at Pilgrim Hot Springs (Fugro, 2012).
Figure 6: Orientation of the plumbing system at the depth of 500-750 m for reservoir model.
**Figure 7:** Simulated temperature section in the west-east direction for reservoir simulation model. The successive red, orange, green, yellow and cyan peaks in the central part of the figure indicate the passage of up-welling geothermal fluids.
Figure 8: Comparison of simulated temperatures to the measured static temperatures for the wells PS 5, PS 12-2 and PS 12-3.