Use of COMSOL Multiphysics to Develop a Shallow Preliminary Conceptual Model for Geothermal Exploration at Pilgrim Hot Springs, Alaska

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ABSTRACT

The Pilgrim Hot Springs near Nome, Alaska, presents a potential high latitude geothermal resource. A small part of the geothermal resource was last explored in the 70's and 80's that resulted in a few geothermal wells with temperatures around 90°C in a shallow aquifer, but deeper temperatures show a strong reversal with depth to as low as 40°C. Our recent study focused on developing new techniques to further explore this geothermal resource. Remote sensing of surface temperature and calculated surface heat flux was used to assess a larger region around the known geothermal anomaly. This information was used to set boundary conditions for a preliminary thermo-hydro model generated using COMSOL and presented here.

The COMSOL Multiphysics finite element package is designed to combine physical equations. The package has a very strong grid building tool that is flexible. We coupled mass and heat transfer in porous media by solving the Richard's equation simultaneously with Fourier's Law. Building complex geometries to guide geothermal liquids through the domain is very intuitive and COMSOL automatically selects optimized solvers based on the physics selected for the model. The results show that a steady state model can be used to simulate the observed strong temperature reversals at Pilgrim Hot Springs. The model calculates heat fluxes for all components and it gives a thermal input of 38 MW.

Future exploration of geothermal systems could combine high resolution remote sensing combined with geological data in a coupled thermo-hydro model to explore remote geothermal resources.

1. Introduction

A number of conceptual and numerical models have been developed for geothermal systems that concentrate on steady-state simulations with up-flow along permeable faults. The Pilgrim Hot Springs geothermal system is believed to have a similar geometric setting. Previous modeling studies of the flow regime using general purpose reservoir simulator (Pruess et al., 1988; Wisian, 2000), have concentrated on exploring the steady-state conditions with

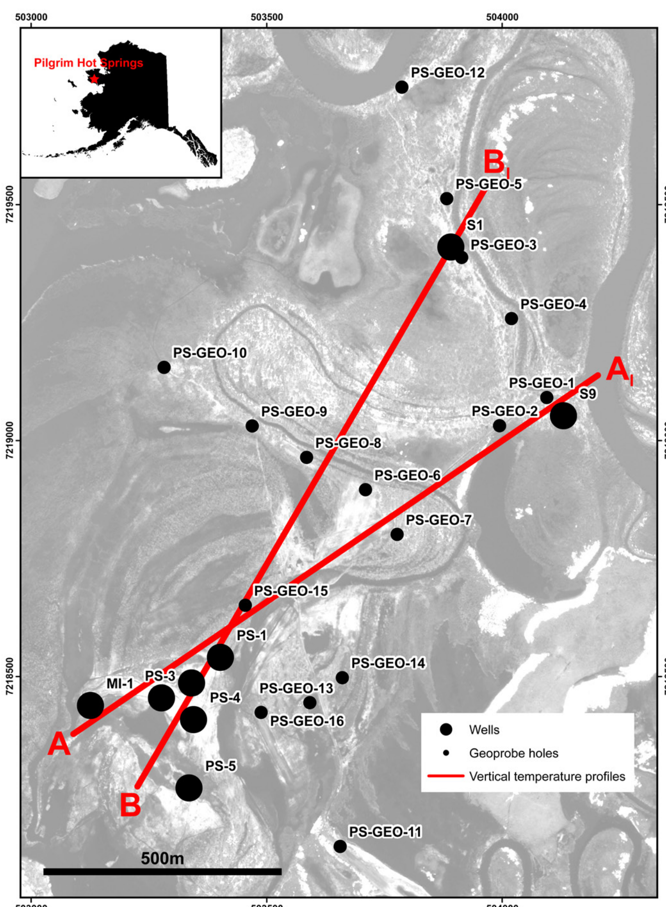

Figure 1. Map of the Pilgrim Hot Springs area with showing locations of wells, geoprobe holes and selected tie-lines. Vertical temperature profiles were generated for the tie-lines for further analysis.

upflow along a permeable fault. The characterization of reservoirs has been based on key parameters such as temperature profiles and the predicted surface heat flow (Blackwell et al., 1983). There are also geothermal systems where up-flow paths have extremely low permeability and lead to cross-range flow (Blackwell et al., 1985). The bulk permeability has been a key factor to predict whether heat is diverted along with fluid from the fault leading to a cross-range flow. Such temperature inversions have been explained as the result of fluid flow within a thin horizontal or shallowly dipping fracture or aquifer (Bodvarsson, 1969). Thus, steady-state models and transient models have been most heavily exploited in the characterization of worldwide geothermal systems. This paper focuses on the use of COMSOL to develop a shallow preliminary conceptual model applied to geothermal exploration of the Pilgrim Hot Springs geothermal system located in western Alaska (Figure 1)

As part of a Department of Energy (DOE) / Alaska Energy Authority (AEA) funded project, Pilgrim Hot Springs is currently being investigated as a potential power source for Seward Peninsula communities including the city of Nome. Previous work on this project has encompassed the use of thermal infrared remote sensing for mapping surface geothermal anomalies and quantifying surface heat loss (Phase 1; Haselwimmer et al., 2011; Haselwimmer and Prakash, 2011), geophysics including airborne magnetics/EM and ground-based CSAMT surveys (Phase 2), drilling of exploration wells (Phase 2), and the development of conceptual / reservoir models (Phase 2) that is work partly described in this paper.

Pilgrim Hot Springs is located on the flood plain of the generally east-to-west meandering Pilgrim River. The site of the springs is marked by an approximately two square mile zone of thawed permafrost characterized by dense brush and cottonwoods that contrasts markedly with the surrounding stunted sub-arctic vegetation growing on unthawed, ~100m thick permafrost (Wescott and Turner, 1981). The geothermal system encompasses a shallow 90°C aquifer located between 15m and 35m below the surface, which is fed from deeper reservoirs of at least 150°C (Liss and Motyka, 1994). At the surface, geothermal waters outflow from a number of naturally occurring springs and seeps. In the regional context, Pilgrim Hot Springs is located on the downthrown block of a E-W trending graben system (Imuruk Basin) that is bound to south by the Kigluaik Fault and the up to 1200 meter elevation Kigluaik Mountains. The normal faulting and nearby basaltic volcanism led Turner and Swanson (1981) to propose a rift model for this part of the Seward Peninsula, which may provide the geothermal heat source via basic intrusions (Liss and Motyka, 1994). Although this provides a regional mechanism for the development of hot waters, no specific heat source or conduit has yet been identified for the Pilgrim Hot Springs geothermal system.

Modeling Data- Static Temperature Logs: The static temperature logs are the most important data incorporated for modeling purposes in COMSOL. The static temperature logs consist for shallow temperature profiles from 0 m-24.4 m. The static temperature logs also exist for the wells (PS1, PS2, PS3, PS4, PS5, MI1) and new wells (S1, S9) (Figure 1.). The wells S1 and S9 are 150 m deep. The deepest wells in the reservoir are PS4 and PS5 approximately around 300 m deep.

The static temperature logs have been used to generate horizontal temperature contours and vertical temperature profiles across the reservoir. A series of tie-lines has been generated across the reservoir based on the location of the wells in the reservoir. The tie-lines have been used to generate vertical temperature profiles using SURFER software.

The horizontal contours have been generated for the entire reservoir considering all the wells at various depth intervals using the SURFER software. The horizontal contours and vertical temperature profiles for the respective tie-lines help to provide a basis for developing the shallow preliminary conceptual model. Two sample tie-lines, A-A' and B-B' across the reservoir are shown in Figure 1. The horizontal temperature contour at 24 meters depth for the reservoir is shown in Figure 2. The vertical temperature profile across B-B' is shown in Figure 3.

Airborne Optical and Thermal Data: Daytime optical images (20cm spatial resolution) and thermal infrared images (1.2

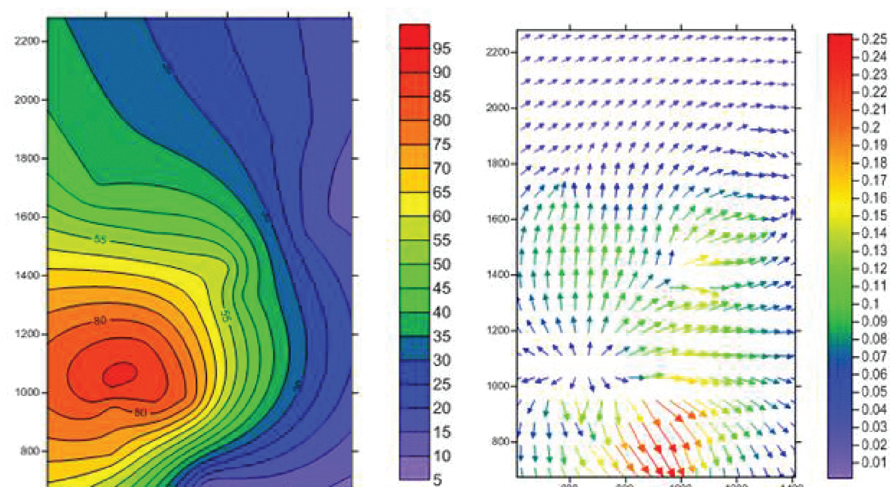

Figure 2. Left panel: Horizontal temperature contour at 24 meter depth using temperatures measured at this depth in summer 2011. Right panel: Temperature vectors indicting the direction of temperature decline.

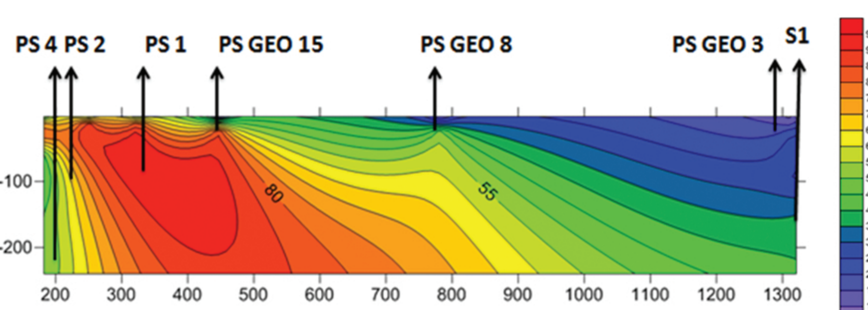

Figure 3. Observed vertical temperature distributions in degrees Celsius on cross section B-B' indicated in Figure 1.

m spatial resolution) were acquired over Pilgrim Hot Springs using a fixed-wing aircraft during Fall 2010 and early Spring 2011 (Haselwimmer et al., 2011). The images were mosaiced and georeferenced. Optical image mosaic was used to analyze the landcover in the study area while the thermal infrared images were used for detail larnd surface temperature mapping and estimating thermal flux from the geothermal waters (Haselwimmer and Prakash 2011).

3. Methods

COMSOL Multiphysics is a modeling package suitable for solving physical equations in a finite element simulation domain. COMSOL has a strong and flexible approach to the development of a numerical grid. Physical equations can be added as needed and interactions between those physical relations can be specified. This means that the level of coupling between equations can vary as needed for the model. For the Pilgrim Hot Springs (PHS) shallow conceptual model we used Richard's equation coupled with Fourier's law (Siegel and Howell, 1981). The Richard's equation in the three dimensional domain handles mass movement through the porous matrix and allows for an unsaturated soil layer near the surface. Fourier's law solves the soil moisture dependent heat flow in the model. We used heat advection in the coupled mode where the liquid water movement is simulated and heat is transported with the water.

Water density is the driving force for water movement in many hot springs and can be used in COMSOL. However the geometry of the hot springs is complex and solving for the density driven water movement was not possible within the complex geometry. We could use the density driven flow for a simplified geometry to find the pressure difference near the source of the hot water relative to the cold surface. We used this pressure in the steady state model as a boundary condition on the Richard's equation to drive the model.

PHS has a very sharp temperature reversal near the soil surface which makes a steady state solution in the model hard to solve. Pressurized cold ground water is assumed to push the hot liquids to particular regions in the unconsolidated solution domain. The geometry in a simplistic way consists of an upwelling pipe from deeper layers to a hot aquifer near the surface. It was assumed that the hot liquids spread in a gravel layer at this depth. At the same time cold water is able to flow into the domain through a gravel layer just below the hot aquifer and therefore cooling this zone and making the strong reversal possible. Hydraulic conductivity of the layers is set at assumed values for three highly conductive zones: the vertical conducting pipe, the horizontal hot aquifer and the cold aquifer with permeability values of $1*10^{-3}$, $5.5*10^{-5}$ and $5.8*10^{-5}$ m/s^2. Between those layers silt is assumed with permeability values of $4*10^{-9}$ m/s^2. The difference in permeability drives the direction of the hot water flow as it finds the path of lowest resistivity. The up flow region is assumed to have a diameter of 20 meters, which in reality is likely larger. The thermal conductivity of the silt and gravel is set to 1.2 and 0.9 W/m^2 respectively.

Temperature and heat flow boundary conditions fill up the remainder of the boundary conditions. At the upper boundary we used a mean annual air temperature -6.5°C for the region of. For the lower boundary we used the temperature of 95°C. The vertical walls are set to a distant temperature of -6.5°C. The cold water enters the simulation domain at a temperature of 4°C. Heat transport with water movement or convection is the dominant heat transport mechanism in the model. Water flow is driven by specifying pressures at the boundary. The hot liquid source was assumed to have a pressure head of 20 m greater than the surrounding. The cold artesian sub permafrost water was set at the boundary to have a pressure head of 5 m above the surrounding pressure head. Initially we set the temperature to 20 °C and the pressure head in equilibrium with gravity forces.

4. Results

Model results are presented in terms of temperature distribution. Temperature distribution in the model is calibrated to temperature measurements in the field in order to understand heat fluxes in the system. During this process the geometry of the model domain was developed and its complexity was minimized, also the hydraulic conductivity of the materials adjusted to match the temperature observations and flow rates in the springs. Figure 4 illustrates the temperature distribution on the outer shell of the model domain.

Another piece of observed data we have is the spring temperatures. We illustrate the comparison between observed and simulated spring temperatures in Figure 6. The comparison shows

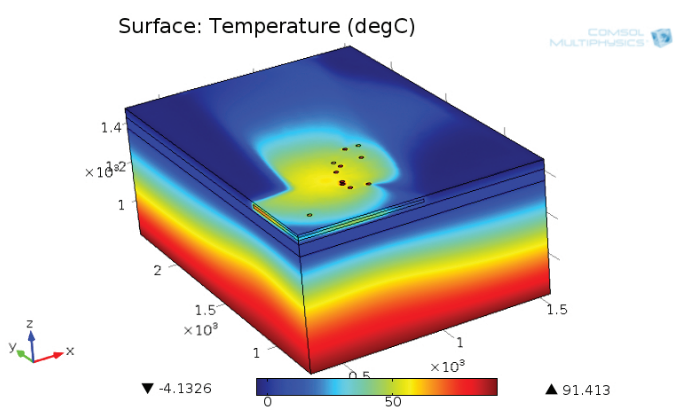

Figure 4. The observed transect A-A' shown in Figure 1 is here presented from the model.

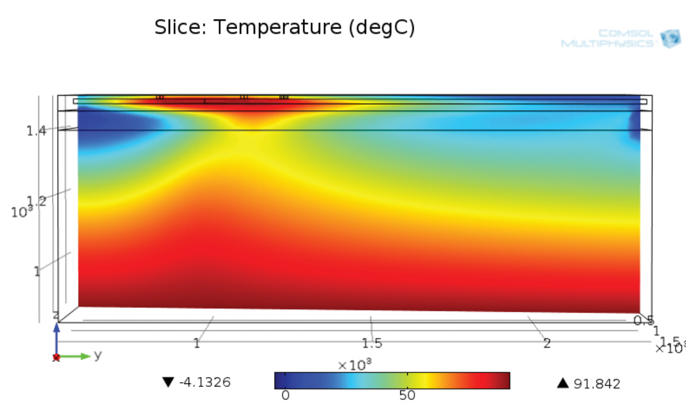

Figure 5. Temperature distribution in the model domain along transect A-A' shown in Figure 1.

that the model generally agrees, but that most spring temperatures are over estimated and one is under estimated. These data reflect that the geometry in the model is not detailed enough to capture all spring temperatures well.

Energy fluxes can be extracted from the model in order to understand the general potential of the geothermal system for power generation. The model provides fluxes of heat and liquid water from the springs and soil surface. The springs in the model produce 0.004 m^3/s (0.14 cf/s) and a total of 10 MW of thermal energy. The soil surface of the model domain releases 7 MW of thermal energy and the hot aquifer releases 20 MW of thermal energy to the surrounding regions. This model shows that a potential of 38 MW of thermal energy moves through the shallow groundwater system near Pilgrim Hot Springs.

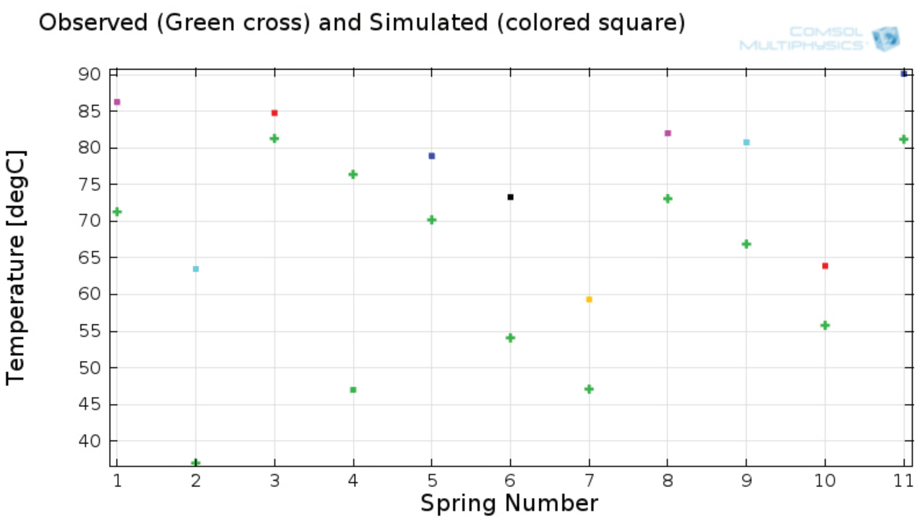

Figure 6. Spring temperatures, comparison between observed (green crosses) and observed (colored squares).

5. Discussions and Conclusions

The results of the modeling exercise shows that the model was not very sensitive to the thermal conductivity of the porous medium. The model was most sensitive to water movement, which makes the geometry of gravel layers in the simulation domain very important, as well as the boundary conditions of the hot and cold water entering and leaving the simulation domain. Most water entered through the south and west boundaries and left the domain on the north where it can drain away with the river. In the high resolution imagery ground water flow is observed to discharge in ponds and creeks in the area just inside the geothermal anomaly where permafrost is absent. It is expected that the permafrost acts as a confining layer on the groundwater and that the mountains flanking the pilgrim river valley contribute to the sub-permafrost groundwater flow. The Woodward Clyde report (1983) mentioned that mountain permafrost would prevent ground water recharge, but the presence of faults and fast drainage of water can allow ground water recharge is cracks before it has a chance to freeze.

The upwelling zone was placed near well PS2 in the center of the geothermal anomaly. This best matches the observed temperatures in the wells. The strong reversal in temperatures with depth was captured well with the model as can be seen from Figure 4. The hot aquifer distributes the hot water horizontally mainly driven by pressure from below and easy relieve of that pressure in the springs. Those springs are connecting the hot aquifer with the surface through a medium of gravel. Spring temperatures are similar in the observed and simulated cases. The hot water continues in the shallow aquifer in the direction of the river and increases the temperature of wells in the north as well as upstream to the South and West.

This limited and shallow model representation of Pilgrim Hot Springs suggests a geothermal flux of 38 MW of thermal energy. From geophysical surveys we know that the entire resource surface area is up to 4 times greater than the shallow system analyzed in this paper. It is also expected from geochemical analysis that hotter water, up to 149°C, could be present deeper below the surface.

COMSOL has shown to be a very useful tool in the development of the conceptual model for the shallow geothermal system at PHS. In a month of simulations many different model could be tested. It was found, for instance, that permafrost cannot exist if the 149°C water is not closer than approximately 1500 meter. This analysis was based strictly on thermal conduction and the boundary conditions for heat flow alone. The high level of integration of the physics and flexible geometry manipulation allows the user to easily run various scenarios in a short amount of time. Individual runs to steady state took only a few minutes with over 400,000 elements. Limitations of the model where observed due to a lack of memory in the computer with the number of elements greater than 800,000. COMSOL Multiphysics team continuously develops new numerical solutions and gridding methods to make the solutions easier and computers are developing fast so that it can be expected that memory limitations will be resolved soon.

6. Future work

The key aspect of remote sensing of geothermal systems is to obtain the thermal flux from thermal infrared observations of the surface (Haselwimmer and Prakash, in review). This flux may be incorporated directly as boundary conditions in the 3D reservoir simulation model. The goal of the modeling is to combine remote sensing information with geological, meteorological and permafrost conditions data to narrow down the geothermal resource for potential exploration in the future, significantly reducing expenses especially for remote field-based exploration.

Acknowledgement

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