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Thermohydrogeologic modeling for the Geothermica Project G2C (Galleries to Calories)

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ABSTRACT

The Geothermica consortium G2C (Galleries2Calories) is investigating the use of mine water in local abandoned underground coal mine workings to cool a large computing facility south of Edinburgh, Scotland. Water heated in the cooling will then be stored in and transported several kilometers through interconnected mine workings where its heat can be extracted via heat pump technology for residential heating. This concept is known as a Geobattery. Most abandoned mines are flooded with water that has almost no seasonal variation in temperature, making them ideal heat sources for heat pumps. The interconnected mine workings minimize the need for drilling, typically the most expensive part of any geothermal energy project involving heat pumps. However, the storage of waste industrial heat in mine workings is challenging both technically and commercially, due to the complexity and uncertainty of the interconnected and often collapsed mine workings. Additionally, dynamic geomechanical, geochemical, and biological processes arise from operation of the Geobattery, as it imposes thermal and hydrological changes to the system. A sophisticated coupled-process modeling approach is necessary to design and optimize Geobattery operation. Modeling efforts began by developing models of the current state of the system. Groups at LBNL and INL are using deterministic and stochastic methods, respectively, with the goal to assess the pros and cons of each modeling approach before embarking on modeling the response of the system to Geobattery operation. Quantitative field data are currently lacking to constrain or validate the models, so we are starting with simple models and doing sensitivity studies to determine the range of expected behavior, and to identify field data that would be helpful to constrain the models. An overarching goal of this research is to increase knowledge and decrease the risk for future mine-water geothermal energy storage and extraction projects.

1. INTRODUCTION

Several challenges of the green energy transition include solving the need for long-term energy storage and addressing the needs of communities that were dependent on the utilization of fossil fuels. The use of abandoned coal mines for thermal energy storage and district heating helps achieve both of these goals. Most abandoned mines are flooded with water that has almost no seasonal variation in temperature, making them ideal heat sources for heat pumps. The interconnected mine workings minimize the need for drilling, typically the most expensive part of any geothermal energy project involving heat pumps. Over the past few decades, a number of projects have successfully transformed abandoned mines into district heating/cooling and thermal energy storage systems. One of the more extensive systems is in Heerlen, the Netherlands, which uses warm water in the workings of abandoned coal mine to provide space heating and cooling to a nearby university and some homes and office buildings (Roijen et al., 2007; Bazargan Sabet et al., 2008; Verhoeven et al., 2014; Adams et al., 2019). In Springhill, Nova Scotia, Canada, water from an abandoned coal mine has been used since 1980 for heating and cooling of several industrial buildings (Jessop et al., 1995). A newer project in Asturias, Spain, uses a closed loop system to extract heat from an abandoned coal mine for a local district heating system (Jardón et al., 2013; HUNOSA, 2019). A HEATSTORE demonstration project in Bochum, Germany, is using an abandoned coal mine to store heat and to provide heating and cooling to nearby buildings (e.g., Hahn et al., 2022). In the UK, the Glasgow Geothermal Energy Research center is examining the potential of using mines in Scotland for thermal energy storage and district heating (e.g., Adams et al., 2019; Monaghan et al., 2022). There are many thousands of legacy mines in the US, the UK, and across the world that could be repurposed in a similar manner (e.g., Watzlaf and Ackman, 2006; Preene and Younger, 2014; Richardson et al., 2016; Adams et al., 2019; Dobson et al., 2023).

For the Galleries2Calories (G2C) project, our international Geothermica consortium team is investigating the use of mine water in abandoned underground coal mine workings near Edinburgh, Scotland to cool a large high-performance computing facility at the University of Edinburgh. The heated water would then be stored in these subsurface reservoirs, transported several kilometers through interconnected mine workings by regional groundwater flow, and used during the winter months for district heating of nearby communities (Figure 1A). The storage of waste industrial heat in mine workings is challenging both technically and commercially, due to the complexity and uncertainty of the interconnected and often collapsed mine workings. Additionally, dynamic geomechanical, geochemical, and biological processes arise from operation of the Geobattery, as it imposes thermal and hydrological changes to the system. A sophisticated coupled-process modeling approach will be used to predict short- and long-term performance of the Geobattery, help in design selection, and for risk assessment. At present, quantitative hydrogeologic field data for our pilot study area are lacking, so our models are simple with adjustable parameters to describe a range of potential responses and behaviors. In this paper, we describe the field site of the Geobattery, review previous studies that are relevant for our work, outline our initial simple modeling approaches, and discuss future work involving calibration of the models to hydrogeologic field data that will be collected as part of the G2C project.

2. FIELD SITE DESCRIPTION

The G2C field site is in the Midlothian Coal Field just south of Edinburgh, Scotland (Figure 1B-1D). The primary heat source is the University of Edinburgh Advanced Computing Facility (labeled ACF in Figure 1C), which will provide 3 MW under its current configuration, but with planned expansion up to 9 MW. The vertical extent of the legacy mine workings varies spatially, but is generally between 50 and 800 m below the surface. The present study will focus on approximately the upper 150 m of the subsurface, to keep drilling and pumping costs reasonable. The lateral distance between the heat source and the residential heat users is about 5 km, aligned with the regional groundwater flow direction. Ambient mine-water temperature and heat source temperature are taken from Todd (2023) and are 12 ^{o}C and up to 50 ^{o}C, respectively.

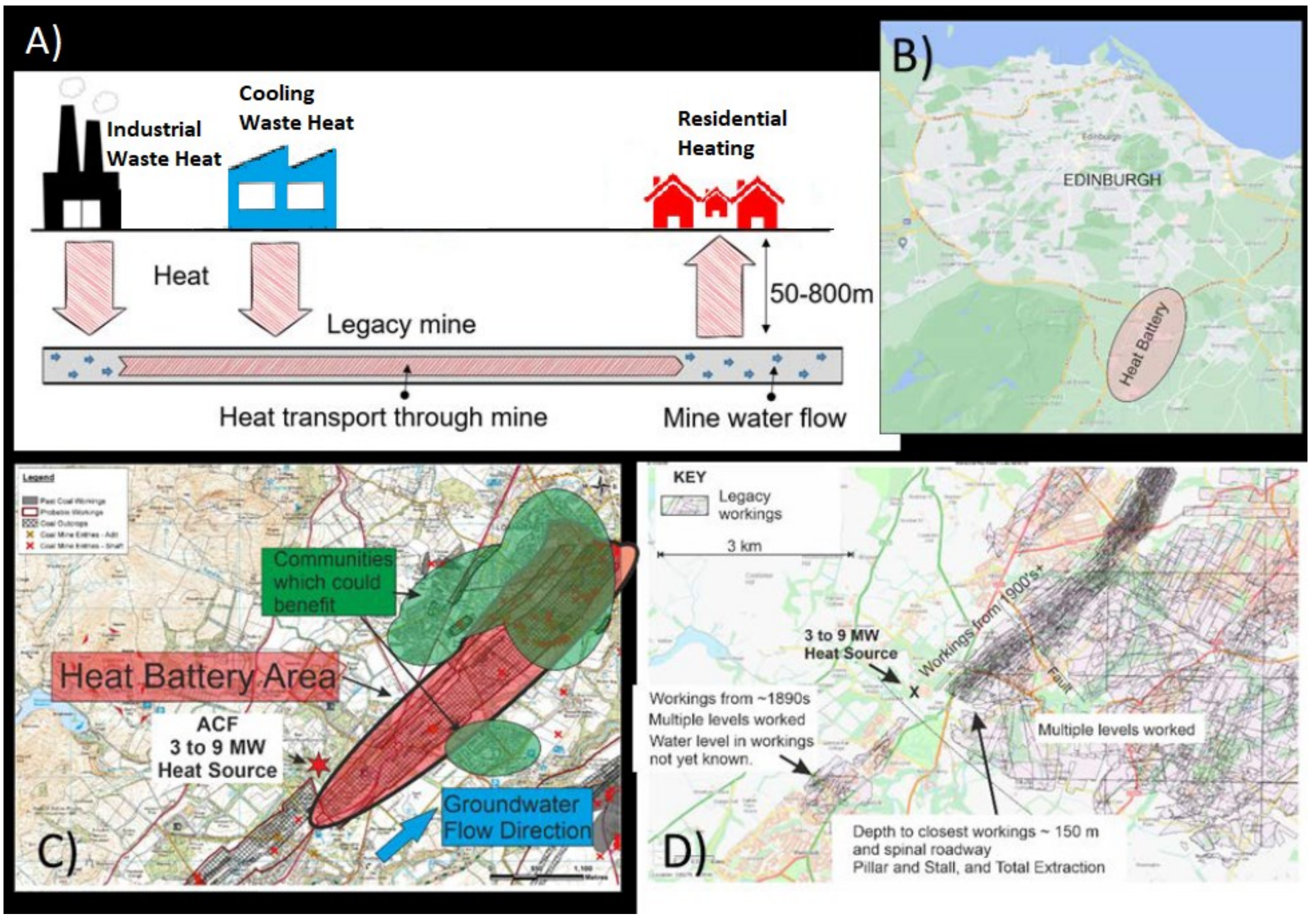

Figure 1. The G2C Geobattery. A) Schematic diagram showing various heat sources, mine-water flow, and heat flow, B) regional map, C) local-scale map showing ACF as cooling-waste-heat source, (D) plan view of legacy mine workings.

The legacy mine workings consist of tilted planar coal seams, separated by low-permeability rock (Figure 2). The coal seams were mined using the room and pillar method, which leaves connected water-filled rooms supported by unmined coal pillars, resulting in a medium that can be represented for the purpose of heat and groundwater flow modeling as a formation with very high permeability. Subsequent to mine closure, localized collapses may have occurred, leaving rubble zones, which are also expected to have high permeability. At the bottom of the mine workings, roadways connect the coal seams hydraulically, but at much greater depth (~300 m) than the focus of the present studies (<150 m), where individual coal seams are assumed to be hydraulically isolated from one another.

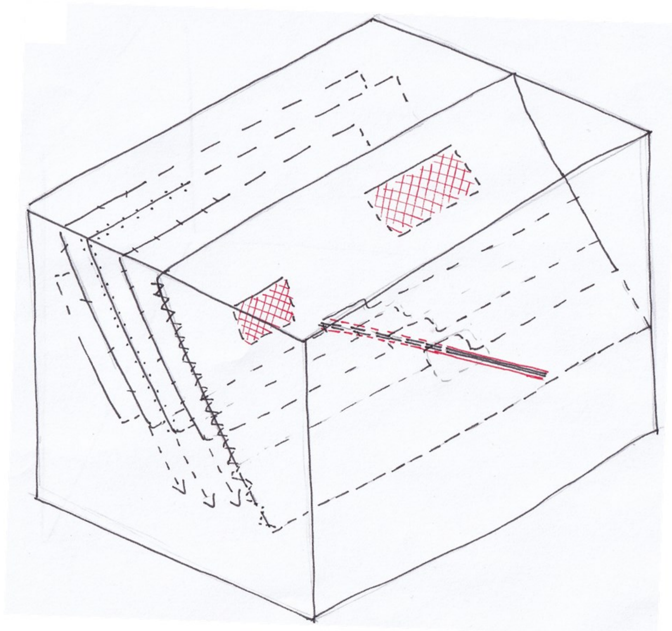

Figure 2. Schematic diagram of the tilted planar coal seams separated by low-permeability rock. The roadway connecting the coal seams at the bottom of the mine workings (~300 m deep) is also shown. Courtesy of Dr. Samuel Graham, University of Edinburgh.

Three separate collieries exist within the Geobattery footprint, Roslin, Burghlee, and Ramsay, with groundwater flow direction from Roslin to Ramsay, a distance of about 5 km (Figure 3). The coal seams intercepted by vertical shafts at each colliery are shown in Figure 4. At the Roslin shaft, coal seam separation ranges from 17 m to 55 m, with most seams separated by about 35 m, and the pit bottom is at a depth of 280 m. Most of the coal seams appear in all three collieries, and some show hydraulic connectivity between them, indicated by red dashed lines in Figure 4. These are the primary pathways for groundwater flow in the Geobattery.

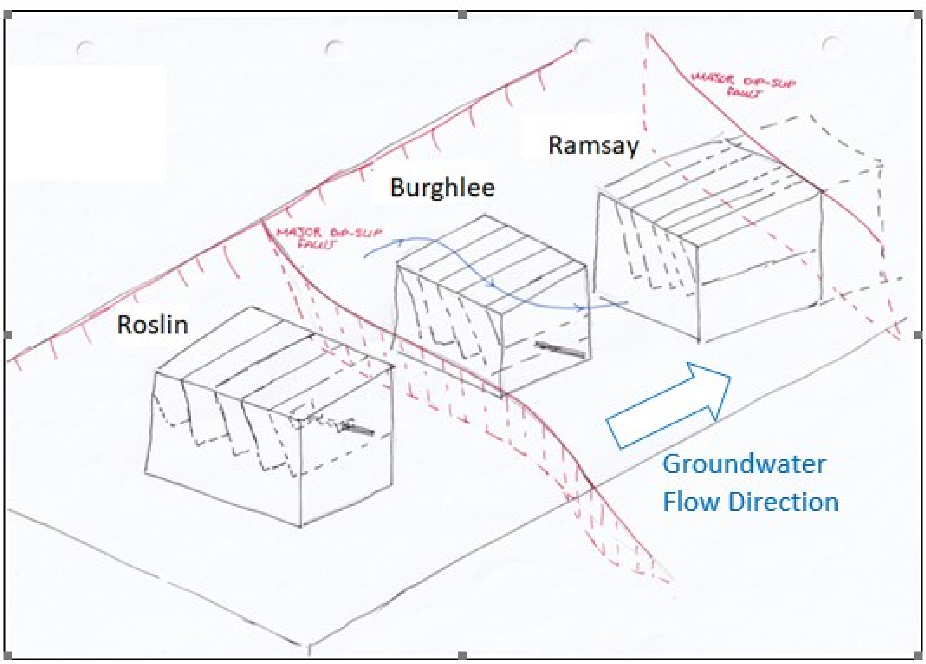

Figure 3. Tilted planar coal seams, separated by low-permeability rock, in the three collieries making up the Geobattery. Courtesy of Dr. Samuel Graham, University of Edinburgh.

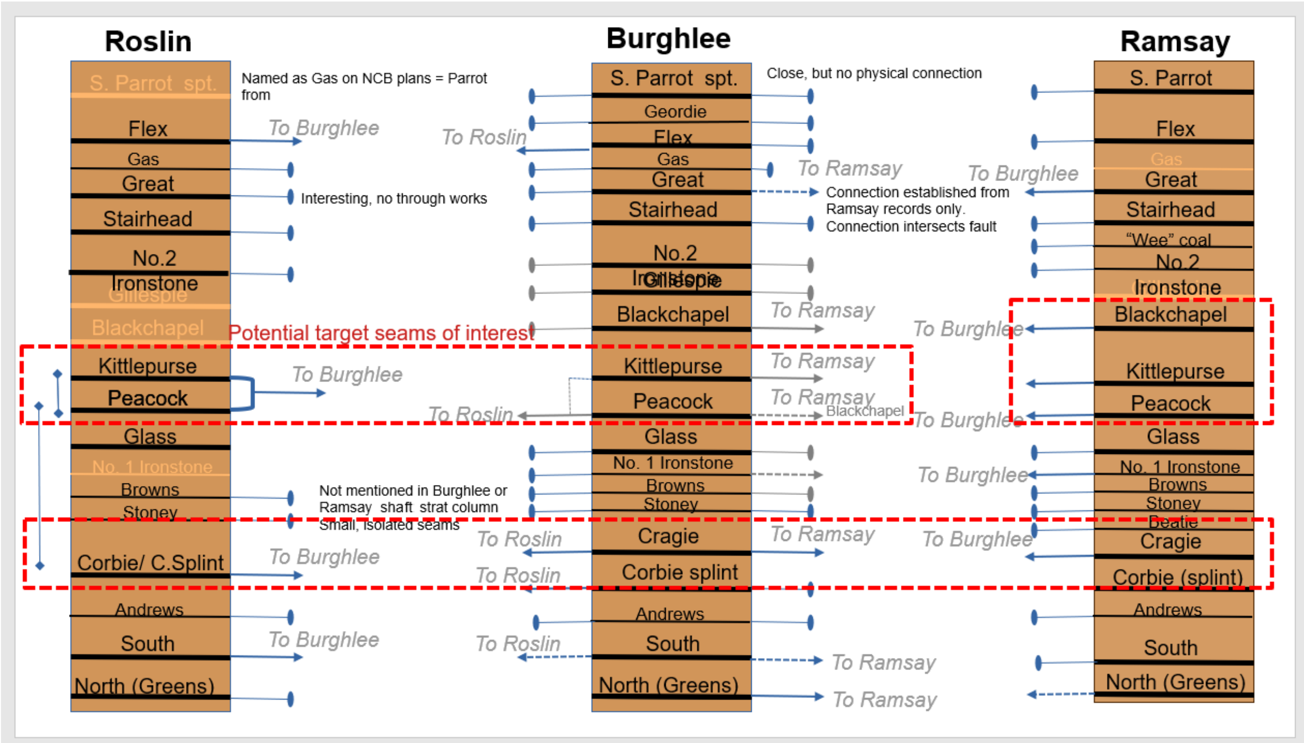

Figure 4. Named coal seams in each of the three collieries. The red dashed lines indicate seams that are hydraulically connected between collieries. Courtesy of Dr. Samuel Graham, University of Edinburgh.

3. PREVIOUS MODELING STUDIES

Previous modeling studies related to the Geobattery concept have examined various aspects of its operation, but did not provide an integrated model of the entire system.

Todd (2023) did coupled thermal-hydrologic-mechanical modeling of the injection of hot water into the Midlothian mine working, to examine the potential for Geobattery operation, which produces changes in pressure and temperature, to destabilize the mine workings. The study focused on an individual coal seam with several pillars and rooms, and did not consider groundwater flow, so it is not directly applicable to our present development of a natural-state groundwater flow model. But the material properties, operating conditions, and room and pillar geometry are very useful, and are adapted for our studies.

Receveur et al. (2022) examined and categorized thermal profiles in mine water observed throughout the UK, and modeled injection of hot water into mine workings to explain the variations noted. In particular, temperature distributions in both flat-lying and dipping coal seams were examined. The studies provide good insights into the movement of hot water under injection and pumping conditions.

Mouli-Castillo et al. (2023) described a strategy for analyzing mine water systems at the early stages of a project, when not much subsurface data are available, with many useful insights for the present work. In particular, a technique for determining an effective flow rate so that a coarse grid produces the same results as a fine grid is valuable. Another means of greatly minimizing the computational effort of numerical models is to only discretize the conduits for mine-water flow, with heat transport into the low-permeability components of the system being handled with analytical or semi-analytical solutions.

Perez Silva and McDermott (2022) did numerical simulations of a simplified room and pillar coal seam embedded in a low-permeability rock, and compared the energy recovery for variations in the geometry of the remaining coal. Large differences in recovered thermal energy demonstrated the strong sensitivity of system behavior to the details of the geology.

4. MODELING APPROACH

In order to manage the use of the Geobattery, static models (reflecting potential initial conditions prior to operation) and dynamic models (incorporating changes arising from heat injection) will be developed. These models will permit flow assessments and investigation of the potential hydrogeological, geochemical, geomechanical, and biological alterations due to the impact of thermal stress on the mine workings. As these processes are highly coupled, advanced numerical modelling techniques will be utilized, including a variety of state-of-the-art simulation tools developed over many years at LBNL and INL, as well as tools developed by the international community. The tools comprise various specialized codes within the TOUGH family of codes (LBNL, https://tough.lbl.gov/), within the MOOSE framework (INL, https://mooseframework.inl.gov/), and OpenGeoSys simulator (www.opengeosys.org). The TOUGH family of codes (Pruess, 2004) is a powerful suite of numerical codes based on the integral-finitedifference method that considers thermo-hydrological (TOUGH3 (Jung et al., 2018)), geochemical (TOUGHREACT (Xu et al., 2014), and geomechanical (TOUGH-FLAC (Rutqvist et al., 2002; Rutqvist, 2011), TReactMech (Sonnenthal et al., 2021) processes. A companion code, iTOUGH (Finsterle, 2017) provides advanced methods to do inverse analysis, sensitivity studies, and data worth analysis, based on forward simulations of any of the TOUGH codes. The thermo-hydro-mechanical-chemical (THMC) coupled processes in the dynamic heat geobattery system can also be modelled by the Multiphysics Object-Oriented Simulation Environment (MOOSE), which is a finite element method-based open-source HPC code developed and maintained at INL (Permann et al., 2020). The MOOSE platform includes tensor mechanics, stochastic tools, porous flow (Wilkins et al., 2021a), and geochemistry (Wilkins et al., 2021b) modules with high-fidelity material laws, fluid equation of state, and geochemical kinetics implemented and validated. The OpenGeoSys code is also a state-of-the-art THMC simulator based on the finite element method. All of these codes are widely used internationally, have been benchmarked against analytical solutions and other numerical models, and validated against field data for a variety of subsurface problems including geothermal utilization, aquifer and borehole thermal energy storage, nuclear waste isolation, CO_2 sequestration, and petroleum production.

The TOUGH, MOOSE and OpenGeoSys codes include specific numerical features to model fluid flow and heat transfer through highly heterogeneous porous or fractured media accurately and efficiently. Although fluid flow and heat transport through mine workings can be conceptualized as flow in a fractured medium, in fact the very different spatial scales of fluid flow paths through mine workings and fractured rock greatly impacts heat exchange between fluid and rocks. To address this challenging range of fluid and heat flow rates, existing constraints and rules of thumb will have to be examined critically during numerical model development and application. For example, several continuum methods of modeling fractured rock using the TOUGH family of codes are listed in Table 1, along with their applicability for several flow and transport problems occurring in a fractured vadose zone. The Geobattery involves single-phase liquid flow, which greatly simplifies many aspects of the problem. On the other hand, the wide range of spatial scales, ranging from flow through intact coal or country rock with micron-sized pore spaces, to flow through rubble zones created by mine-working collapse with millimeter to centimeter channels, to flow through open rooms on the meter scale, where turbulence may occur, greatly increases the complexity of the system. It is expected that some experimentation will be required to determine the most appropriate computational method from Table 1 for each scale.

Table 1. Continuum computational methods for modeling flow and transport in fractured geological media. Application to flow and transport through fractured welded and non-welded tuffs at Yucca Mountain, Nevada (Doughty, 1999).

Method	Number of grid blocks required	Heat flow between fractures and matrix	Steady Moisture Flow	Transient Moisture Flow	Transient Gas Flow	Tracer Transport	Thermal Loading
Matrix only	*n*	n/a	No	No	No	No	No
Fractures only	?	n/a	No	No	No	No	No
Equivalent Continuum Model	*n*	Instantaneous (in equilibrium)	Yes	Maybe*	Yes	Maybe*	No
Double porosity	2*n*	Quasi-steady	Yes	No	Yes	Maybe*	Maybe
MINC	3*n*-5*n*	Transient	Yes	Yes	Yes	Yes	Yes

*for large fracture-matrix interface area and low flow rate

Typical model dimensions used by Todd (2023) include a 1-m thick coal seam with 20 m of host rock above and below, square pillars that are 12 m wide, and rooms that are 6 m wide. Material properties used by Todd (2023) are shown in Table 2. The base case values are shown in bold, and the ranges of values used in sensitivity studies are also shown. The thermal properties may be used to estimate thermal penetration distance L for heat conduction into host rock and coal, using the formula $L = [\lambda/(\rho C)t]^{1/2}$, where λ is thermal conductivity, ρ is density, C is specific heat capacity, and t is time. Values of L, which are useful for guiding model development, are shown in Table 3 for times ranging from 1 to 30 years. Comparing host-rock values of L to the typical coal seam separation (35 m) indicates that for the first few years, it is reasonable to model Geobattery operation considering each coal seam individually, but that for long-term simulations, multiple coal seams should be modeled together, because their thermal fields will interfere. Comparing coal values of L to pillar width (12 m) indicates that temperature changes will propagate throughout the coal pillars early on, with important implications for the way heat transfer from room to pillar is modeled (Table 1).

Modeling efforts for the Geobattery began by developing models of the current state of the system. Because little site-specific monitoring data is available yet for calibrating the models, groups at Lawrence Berkeley National Lab (LBNL) and Idaho National Lab (INL) are using deterministic and stochastic methods, respectively, with the goal to assess the pros and cons of each approach before embarking on modeling the response of the system to Geobattery operation.

Table 2. Material properties used for the preliminary studies, taken from Todd (2023). Bold type indicates the base case for host rock and pillar sensitivity studies.

Parameter		Host rock					Pillar					Room
	St Dev	-1	-0.5	0	0.5	1	-1	-0.5	0	0.5	1	
Density	kg m^{-3}	2200	2350	**2500**	2650	2800	1400	1700	**2000**	2300	2600	1000
Permeability	m^2	1.0x10^{-17}	2.5x10^{-13}	**5.0x10^{-13}**	7.5x10^{-13}	1.0x10^{-12}	1.0x10^{-17}	2.5x10^{-13}	**5.0x10^{-13}**	7.5x10^{-13}	1.0x10^{-12}	1.0x10^{-8}
Porosity	-	0.030	0.123	**0.215**	0.308	0.400	0.010	0.325	**0.055**	0.078	0.100	1.000
Specific heat capacity	J kg^{-1} K^{-1}	600	825	**1050**	1275	1500	1000	1100	**1200**	1300	1400	4184
Thermal expansion	K^{-1}	8.0x10^{-6}	3.1x10^{-5}	**5.4x10^{-5}**	7.7x10^{-5}	1.0x10^{-4}	3.5x10^{-5}	4.1x10^{-5}	**4.7x10^{-5}**	5.3x10^{-5}	5.9x10^{-5}	2.1x10^{-4}
Thermal conductivity	W m^{-1} K^{-1}	1.50	2.38	**3.25**	4.13	5.00	0.20	0.78	**1.35**	1.93	2.5	0.60
Biot coefficient	-	0.30	0.48	**0.65**	0.83	1.00	0.60	0.70	**0.80**	0.90	1.00	1.00
Poisson ratio	-	0.070	0.138	**0.205**	0.273	0.340	0.220	0.270	**0.320**	0.370	0.420	0.320
Young's modulus	Pa	4.00x10^{9}	1.55x10^{10}	**2.70x10^{10}**	3.85x10^{10}	5.00x10^{10}	1.00x10^{9}	4.25x10^{9}	**7.50x10^{9}**	1.08x10^{10}	1.40x10^{10}	1.50x10^{8}

Table 3. Thermal conduction penetration distances (m) for a range of times.

Material	1 year	2 years	5 years	10 years	20 years	30 years
Host rock	13	18	28	40	56	68
Coal	8	12	19	27	38	46

4.1 Deterministic modeling

The starting point for the deterministic modeling is to use the red dashed lines in Figure 4 to identify through-going paths for mine-water flow. Two possible conceptualizations of the resulting model are shown in Figure 5, representing the Kittlepurse, Peacock, and Corbie splint seams. Recall that the mined coal seams are not flat-lying but steeply dipping, so a two-dimensional cross-section model as shown in Figure 5, although adequate for modeling the nearly isothermal natural-state groundwater flow, may not be appropriate at all for the flow of hot water, which will experience strong buoyancy flow through the high-permeability mine workings. Use of irregular-width flow paths (Figure 5B) enables the schematic representation of various features specific to each colliery, such as the faults associated with the Roslin and Ramsay collieries and the underground watercourse associated with the Burghlee colliery.

A key feature controlling performance of geologic thermal energy storage systems is the surface-area-to-volume ratio of the water flow paths, because the surface area controls how much heat exchange with the surrounding rock matrix there is, and the volume of mobile water controls how much convective energy is moving from the source to the users. The goal of the deterministic modeling is to use a simple representation of the through-going mine-water flow paths, and to consider alternative surface areas for heat flow, to gain insight into the range of thermal performance of the Geobattery. This means that for the first step of model development, the natural-state model, we want to build in enough flexibility to enable us to ultimately consider a range of thermal behaviors. Thus, preliminary grids, which do not need to use double porosity or MINC methods, should be designed so that they can ultimately be further discretized as needed.

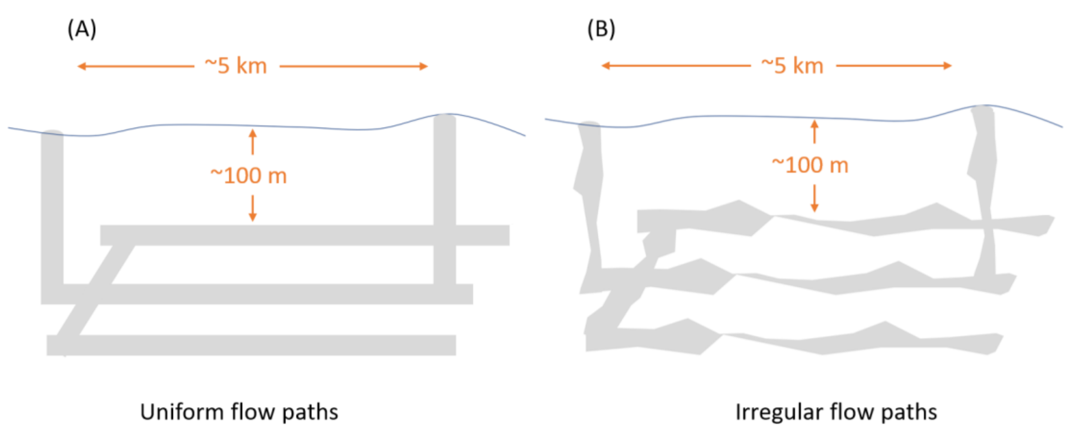

Figure 5. Two alternative schematic representation of flow paths for mine-water flow, based on the inferred connections between collieries identified with red dashed lines in Figure 4.

4.2 Stochastic modeling

The stochastic modeling approach relies on structural and conceptual models depicted in Figures 3, 4, and 5. We use a simplified subset of the original large-scale structural model, preserving essential geometric information concerning the extent of three collieries, individual coal seams' extent, dip, thickness, and the primary fault zone. Boundary conditions, such as the initial regional flow field and the temperature gradient, are derived from natural state models and other field test data. Unlike the deterministic model, the stochastic model substitutes the largely unknown internal structure of the mines, as depicted in Figure 5, with various plausible combinations of realistic input data through a multi-stage modeling approach.

The internal structure is divided into multiple subdomains, each assigned one of three lithological units: rock formation, pillar (or partially mined), and mined seam (Figure 6). Initially, in a thermo-hydrologic (TH) modeling workflow, material properties (porosity, permeability, thermal conductivity, etc.) are randomly assigned to these subdomains. Following Jin et al. (2022), those material parameters within each subdomain are stochastically sampled from specific distributions (e.g., Table 2) informed by literature research and experimental field data. A multitude of simulations and parameter combinations will be conducted performing a stochastic analysis. The objective is to pinpoint the most promising combination of parameters and material properties that replicate the deterministic modeling (including the heat front expansion) and/or field hydraulic test data and to minimize the distribution bounds. Furthermore, the most critical parameters can be identified.

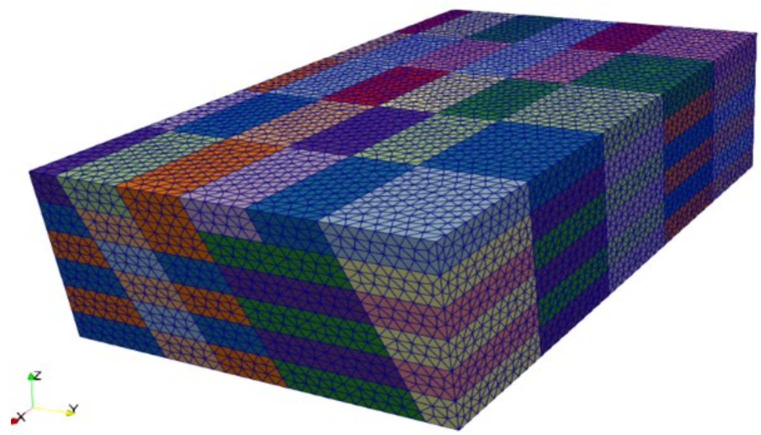

Figure 6: An exemplary mesh of one colliery, highlighting the usage of various subdomains to represent the individual coal seams (see Figure 2 for comparison).

Once the most promising material parameters are known, the initial TH modeling approach will be extended to a thermo-hydro-mechanical model. The goal of this second phase of modeling is to evaluate the effects of various operational conditions on hydraulic and heat front propagation, as well as on the internal stress field and mechanical stability of the collieries.

5. CONCLUSIONS AND FUTURE WORK

In general, the storage of waste industrial heat in mine workings is extremely appealing because it minimizes drilling needs, uses established fluid flow paths, and is generally coincident with both sources and users of waste heat, and these conditions are all met for the Geobattery at the G2C field site. However, there are both technical and commercial challenges in Geobattery operation, due to the complexity and uncertainty of the interconnected and often collapsed mine workings. Additionally, dynamic geomechanical, geochemical, and biological processes arise from operation of the Geobattery, as it imposes thermal and hydrological changes to the system. A sophisticated coupled-process modeling approach is necessary, but there is a lack of quantitative field data on which to base the models. We are therefore developing strategies to construct deterministic and stochastic models of the Geobattery that include adjustable parameters. In the first stage, such models will demonstrate a range of possible behaviors for the Geobattery, and indicate what field data will be most useful to constrain the model predictions. In the second stage, when field work commences in a few months, models will be calibrated to field data, and system behavior predictions repeated. Field data consists of site characterization, field tests, and a suite of novel continuous and periodic monitoring techniques.

An overarching goal of this research is to increase knowledge and decrease the risk for future mine-water geothermal energy storage and extraction projects. As it is very common to begin a project with little quantitative field data, we expect that the lessons learned as we transition the models from generic to site specific by the use of field data will be generally applicable beyond the G2C Geobattery.

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