1. Research field
   1. Research questions
   2. Research aim and objectives
   3. Take home message
2. Research design
   1. Methods
   2. Modeling code
   3. Case studies
      1. Bilston Glen
      2. Dawdon
3. Chapters
   1. Chapter 1:  heat extraction from borehole heat exchanger and shallow recharge potential
      1. GSHP technology
      2. Heat exchanger
   2. Chapter 2: Heat sources and distribution in coal mines
      1. Conceptual models
      2. Hydrology
      3. Heat flow
   3. Chapter 3: Mine modelling – importance of geometric features from mine plans
      1. Mine geometry (type of mining / mining methods)
   4. Conclusion: geothermal potential and sustainability opportunities
4. Time plan (Gantt chart)
5. Resources
   1. Budget (ressources available / needed)
   2. Data management plan
      1. Data repositories and version control
      2. Codes
   3. Training
   4. Conferences
   5. Teaching experiences
6. Supervisory arrangements and collaborations
7. Ethical and Health and safety considerations
8. References

First of all, an inventory of all the existing data ill be made based on available literature and database, and kept updated throughout the PhD lifetime to account for new acquisitions and publications.

Temperature data will be analyzed and classified according to their geographical/geological location, the measurement types, context of the measurements (i.e. flooding conditions, gravity-driven discharge, pumped water) and timing of the acquisition. In areas where flooding is still occurring, changes in fluid temperature or geochemical composition through time might highlight the existence of significant interconnections at specific mine levels. Interconnections between the mine workings/shafts and recharge/discharge zones at the surface or with surrounding aquifers would also be supported by a comparison with structural/geological maps and/or mine abandonment plans. This preliminary analysis will be done to identify the possible impact or contribution of local heat sources / recharge areas on the measured temperature values (i.e. presence of fault, type of rocks and volume of rock type around the monitoring point) or exclude biased data from the analysis. A database will be created to facilitate the access, storage, management and reference to the data throughout the PhD research work and for future access.

1. What is the impact of past mining activities on the thermal state of the mine and on the temperature distribution in mines?
   1. Has the geothermal gradient in mines returned to its initial undisturbed state after a mining period with dewatering and subsequent water recovery?
      1. Does dewatering and ventilation during mining affect the rock temperature?
      2. How long does it take to the local geothermal gradient to re-equilibrate with the regional gradient?
      3. What is the effect of water circulation in large voids on the heat distribution?
   2. Are the mine waters at equilibrium with the host rock temperature?
      1. How long does it take for the volume of water in tunnels to heat up to the surrounding rock temperature?
      2. What defines the temperature profiles within the shaft during periods without production and with production (i.e. number / depth of intersected coal seams, inflow temperature…)?
2. What are the key mine features needed to assess the heat potential of coal mines, at the scale of a mine or a network of interconnected mines?
   1. What is the contribution/impact of the followings on the rock-water heat exchange rate (i.e. rate of heat mining) and evolution of the production temperature defining the sustainability of heat extraction?
      1. Flow path (i.e. tunnel) length
      2. Properties of the host rock (i.e. porosity, permeability) and/or contrasts in material properties with the mining area
      3. The geometry of the mining voids (i.e. galleries / roadway interconnections)
      4. The mining method (i.e. room-and-pillar, goaf)
      5. Total void volume (i.e. galleries, goaf, fractured zone…)
   2. Does the mine geometry affect the heat distribution during heat extraction?
      1. How are the induced flux disturbed by the level of details of the mine geometry (i.e. from mine plans)?
      2. What is the footprint area of heat extracted?
      3. Can 2D vertical and horizontal models can faithfully represent 3D processes?
   3. Does the mine geometry (i.e. mining geometry, roadway network, depth of galleries) contribute to the heat recharge rate and return to equilibrium during flooding/heat recovery?

Most of Scotland is underlain by a crystalline basement, formed by weakly to strongly metamorphosed Lower Paleozoic sedimentary rocks. In the Northern Highlands and Grampian Highlands, the basement is characterized by a thick sequence of metamorphosed sandstone and mudstone units. Weakly metamorphosed sediments (i.e. sandstone and shale) disrupted by folding, faulting and tilting can be found in the Southern Uplands. Those are intersected by intrusions of basic ingenious rock, generally in the form of laccoliths, as well as granite intrusions. Highly metamorphosed granitic and basaltic intrusions seen at outcrop in the Northwest Highlands are likely to be similar to rocks found in the deepest part of Scotland.

The Midland Valley of Scotland (MVS) is a 80 km wide, 150 km long WSW-ENE trending Carboniferous graben that developed on the eroded and deformed remnant of the Caledonian Mountains (Cameron and Stephenson, 1985; Underhill, 1998; Read et al., 2002). It is separated from the Grampian Highlands by the Highland Boundary Fault, and from the Southern Uplands by the Southern Upland Fault. Both of those SW-NE striking fault formed major lineaments during the Caledonian Orogeny (Cameron and Stephenson, 1985). The MVS contains a complex arrangement of several Upper Palaeozoic sedimentary basins and Lower Palaeozoic metamorphic rocks (Cameron and Stephenson, 1985; Trewin et al., 2002; Underhill et al., 2007). It only has a few small granite intrusions at outcrop but contains numerous minor intrusions, mainly of basaltic and andesitic composition. The metamorphic basement only outcrop along the main faults together with the Devonian Old Red Sandstone sedimentary rocks. According to geophysical data, the basement-cover boundary is situated at about 8 km depth in the central part of the MVS.

Magmatic activity in the MVS extended from the Carboniferous to Permian for a period of about 90 Ma (Upton et al. 2004). It is suggested that volcanism led to an increase in the heat flow during the Carboniferous, especially in the active eastern region. Early magmatic activity occurred in the Pentland Hills during the Lower Devonian, in the form of lava flows and ash layers of basaltic, andesitic, trachytic and rhyolitic composition. During the Visean (Lower Carboniferous), basaltic to rhyolitic lavas and intrusions were formed from short-lived volcanoes that erupted in flood plain environment, releasing a vast amount of tuff materials (e.g. Garleton Hills, Arthur’s Seat, Clyde Plateau Volcanic Fm). Volcanic rocks from the Arthur's Seat Volcanic Formation in West Lothian, Edinburgh, and at the southern end of the Midlothian Syncline mostly consist of ankaramite to mugearite lavas, tuffs and volcaniclastic sedimentary rocks (Monaghan et al. XXX). Later Visean and Namurian activity (e.g. Kinghorn and Bathgate Hills volcanic Fms) was dominated by basaltic lavas and tuffs (Smedley 1986, Stephenson et al. 2003, Upton et al., 2004). In the late Carboniferous, short-lived episodes of tholeiitic magmatism extended across the MVS (Timmerman 2004, Monaghan and Parrish 2006). Those moslty occured in the form of dolerite intrusive sills (e.g. Salisbury Crags) and ENE-to ESE-trending tholeiitic dykes emplaced along extensional faults, cross-cutting the shortened and inverted Carboniferous basins (Cameron & Stephenson 1985, Rippon et al. 1996). From the Latest Carboniferous to Permian, alkaline magmatism (i.e. Mauchlin Volcanic Formation) occurred in response to the broader post-orogenic extension associated to the opening of the Altantic (Neumann et al. 2004; Wallis 1989), accompanied by the intrusion of NNE- to NW-trending dykes (Anderson et al. 1995, Upton et al. 2004). The more widespread thermal effect around tholeiitic sills/dykes compared to alkaline ones has been suggested by Murchison & Raymond (1989), as the result of their emplacement in dry and compacted sediments. Those likely exerted a major influence on hydrocarbons maturity within the lower Limestone Coal, Lower Limestone and upper West Lothian Oil-Shale formations, in the Central Coalfield and Midlothian-Leven basins (Monaghan and Brown, 2014).

Table XXX summarizes the proportion of different lithologies (i.e. sandstone, siltstone, limestone, coal, mudstone) for the Carboniferous formations of the Midland Valley of Scotland. Data are based on the analysis of geological cores and samples from the Glasgow Observatory (Geothermal Energy Research Field Site), published by Vincent et al. (XXX) and Entwisle (2019).

\begin{table}[h!]

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\begin{tabular}{||l l l l l l||}

\hline

lithology & UCMS & MCMS & LCMS & LSC - PGP & BELOW \\

\hline\hline

Sandstone & 40 & \textgreater 40 & \textgreater 50 & 40 & 30 \\

\hline

Mudstone & 60 & 30 & 30 & 40 & 50 \\

\hline

Siltstone & & 24 & 14 & & \\

\hline

Coal & & 6 & 4 & & \\

\hline

Ironstone & & & \textless 1 & & \\

\hline

Limestone & & & & 20 & 20 \\

\hline

\end{tabular}

\caption{Percentage of lithologies recorded in existing borehole data. Data for the Lower (LCMS) and Middle (MCMS) Coal Measures are from the BGS Open Report OR19019 (Entwisle, 2019). Data for the Upper Coal Measures (UCMS), Limestone Coal (LSC) to Passage (PGP) Formations and underlying Carboniferous strata (BELOW) were determined from LOGS from 9 boreholes in the MVS (from Vincent et al., 2010) }

\label{table:1}

\end{table}

In mines in the Carboniferous succession of the MVS, the presence of many low conductivity "cap" rocks (i.e. coal, mudstone strata) in the sedimentary cover above the crystalline basement likely creates situations where the vertical upflow of heat is trapped at depth, generating positive heat anomalies. Such blanketting effects has been described by Busby et al. (2011) for the NE England, where low conductivity Carboniferous rocks are present above the Weardale granite, which has a high heat production (Downing and Gray, 1986a,b).

The average thermal conductivity for the formations of the Carboniferous succession in the MVS is shown in Table XXX together with values for common rock types reported by Lee et al. (1984) and Wheildon et al. (1984). 23 borehole measurements of rock thermal conductivity and mean thermal conductivities for specific lithologies for Scotland are also provided by Rollin (1987) and reported in Banks (2008). Browne et al. (1985) noted considerable variations both in the proportion of rock types in each formation in the MVS and in the conductivity for each lithology in the Upper Palaeozoic. Formations thermal conductivity were estimated by Busby (2019) in the UKGEOS Open Report OR19015 by combining the thermal conductivities of individual lithological units as a harmonic mean, based on the data recently acquired from cores at the Glasgow Geothermal Energy Research Field Site. Due to the absence of thermal conductivity values for the Scottish Coal Measures, the Passage Formation and the Kirkwood Formation, the thermal conductivity for representative sections in those formations were estimated from values measured on similar lithologies in 5 boreholes located in the Pennine Coal Measures of northern England.

\begin{table}[h!]

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\begin{tabular}{||l l l||}

\hline\hline

a) Lithology & K (W/m/K) & Reference\\

\hline\hline

Coal & 0.31 & Lee et al., 1984\\

Coal Measures Sandstone & 3.31, 3.58\* & Rollin, 1987; \*Busby (2019) \\

Coal Measures Siltstone & 2.22, 2.23 & Rollin, 1987; \*Busby (2019)\\

Coal Measures Mudstone & 1.49, 1.85\* & Rollin, 1987; \*Busby (2019)\\

Coal Measures Ironstone & 2.35\* & \*Busby (2019)\\

Namurian Millstone Grit Limestone & 3.75 & Rollin, 1987\\

Lower Carboniferous limestone & 3.14 & Rollin, 1987\\

Upper Old Red Sandstone & 3.26 & Rollin, 1987\\

Silurian slates & 3.33 & Rollin, 1987\\

Hercynian granites & 3.3 & Rollin, 1987\\

Basalt & 1.8 & Rollin, 1987\\

Shale & 1.3 & Busby (2019)\*\* \\

Fireclay & 0.59 & Busby (2019)\*\* \\

\hline\hline

b) Formation & K (W/m/K) & Reference) \\

\hline\hline

Scottish Coal Measures Formation & 1.91 ± 0.25 & Browne et al., 1985 \\

Scottish Middle Coal Measures & 2.02 & Busby (2019)\\

Scottish Lower Coal Measures Formation & 1.91 ± 0.25 & Busby (2019)\\

Passage Formation & 2.91 ± 0.15 & Browne et al., 1985\\

Upper Limestone Formation & 2.25 & Busby (2019)\\

Limestone Coal Formation & 2.24 & Busby (2019)\\

Lower Carboniferous & 2.12±0.25 & Browne et al., 1985 \\

Lower limestone Formation & 1.88 & Busby (2019)\\

Lawmuir formation & 4.36 & Busby (2019)\\

Kirkwood Fm & 2.1 & Busby (2019)\\

Clyde Plateau Volcanic Formation & 2.2 & Busby (2019)\\

Clyde Sandstone Formation & 4.19 & Busby (2019)\\

Ballagan Formation & 3.14 & Busby (2019)\\

Kinnesswood formation & 3.66 & Busby (2019)\\

\hline\hline

\end{tabular}

\caption{a) Thermal conductivity for specific lithologies found in the MVS succession, estimated based on laboratory measurements made on water saturated samples extracted from boreholes. \*representative values for the Scottish Middle Coal Measured estimated from 5 boreholes in England. \*\* averages from the Boreland (Anderson, 1940) and Glenrothes (Gebski et al., 1987) boreholes. b) Average thermal conductivity for the formations of the Carboniferous succession of the MVS (from Busby, 2019), estimated from the Maryhill, Hurlet House, Clachie Bridge, Barnhill, Kipperoch (Oxburgh, 1982), Boreland (Anderson, 1940) and Glenrothes (Gebski et al., 1987) borehole logs}

\label{table:2}

\end{table}

\subsection{Hydrology}

Carboniferous sedimentary sequences in the Midlothian Coalfield are composed of low permeability layers (mudstone) interbedded with higher permeability strata (sandstone, limestone) that tend to form complex multi-layered aquifers, both in confined or unconfined conditions. Those aquifers are generally described as minor or moderately productive aquifers due to a relatively low rock permeability, providing borehole yields in the range 5-15 l/s (MacDonald et al., 2004; Robins, 1990; Ball, 1999). The natural layering tends to create complex flow path, dominated by horizontal inter-granular flow and fracture flow. In those formations, groundwater residence time has been estimated to be in excess of 60 years (Ó Dochartaigh et al., 2011). In contrasts, the Passage Formation forms an extensive productive aquifer where groundwater moves dominantly by intergranular flow (Ball, 1999). Lateral compartmentalization also results from the intrusion of igneous rock (dykes, sills, plugs) or faults that can act either as permeable pathways or barriers to groundwater flow.

Despite the presence of coal seams is adding more low-permeability layers between the sandstone aquifer units, the Carboniferous strata extensively mined for coal generally have slightly higher productivity than the aquifers not extensively mined for coal (Dochartaigh et al., 2015). Mining activities indeed resulted in an increase in permeability of the Carboniferous strata both by increasing the void space in zones where seams were mined out and through fracturing of competent horizons above the mined seams. Mining has tend to form “anthropogenically enhanced aquifers” (Banks, 1997) with greater transmissivity than the undisturbed aquifers and locally increased storage capacity. Collapse of roofs above large voids and deformation of the surrounding rock mass might however lead to the opposite effect by reducing both transmissivity and storage (Younger and Robins, 2002). However, only a few aquifer properties data from pumping test are available for boreholes intercepting former mines. Borehole yields used to dewater mines in Scotland during mining activities are shown in table XXX.

A total of 61 topography corrected temperatures acquires from onshore boreholes are reported in Burley et al. (1984), and 17 additional borehole temperature-depth measurements located in the west Midland Valley are reported in the 3rd version of the Catalogue (). Despite most of the measured temperatures are assumed to represent equilibrium temperature, i.e. little affected by cooling due to circulating drilling mud or by mine ventilation systems, Farr et al. (2016) warned that some uncertainties still limit the reliability of geothermal gradient estimates. This includes the lack of knowledge of the depth and timing of temperature measurement after the drilling of the boreholes, the effect of circulation of water within the borehole and the influence of intercepted mine working. Browne et al. (1985) suggested that equilibrium temperatures obtained during heat flow measurements are the most reliable and accurate values, however, they are relatively rare in the MVS.

Knowing the long term temperature variation does matter to know the actual deep heat flux and quasi steady state geothermal gradient. for shallow extraction (< 20 m), daily / annual fluctuations might be of greater interest as it is mostly impacted by daily fluctuations.

Due to the narrow spread of the data, this suggests that the estimated average geothermal gradient might be consistent across Scotland and characterise a regional background heat flow, unperturbed across the basement-cover interface. It is however suggested that the proximity of offshore area or the stretched crust in the MVS, where the crust may be thinner and thus the heat flow higher, may account for a higher geothermal gradient in the deepest part of the curve. This might also be explained by more radioactive granitic rocks within the crust, or continued heat flow from Cenozoic igneous activity (Browne et al., 1987). Other theories have suggested that the heat flow anomaly in the MVS can be explained by a regional upflow of groundwater (Browne et al., 1987; Lee et al., 1987; Robins, 1988), with areas of recharge (i.e. downward flow) mainly located along the northern and southern boundaries of the MVS, where the elevation is higher (Robins, 1988). However, this model has been refuted by Robins et al. (1988) and Browne et al. (1987) based on the lack of evidence from geochemical data and on the fact that deep groundwater circulation is likely to be moderate in volume and confined within isolated discrete pathways.

The thermal character of a reservoir rock is mainly dependent on the effective heat capacity Cp (J/K), thermal conductivity $\lambda$ (W/m.K) and thermal diffusivity $\alpha$ (m2/s) of the materials that forms it, as well as the amount of saturation. Where conductive processes are dominant, the effective fluid-rock heat capacity and heat conductivity both influence heat transfers. Thermal dispersivity mostly account for heat dispersion in areas where convective heat transfers are dominant (Deethlefsen et al., 2016). However, while the specific heat capacity, conductivity and diffusivity of groundwater are well known, the thermal properties of rocks highly depend on their material composition, texture and structure (Allen et al., XXX; Deethlefsen et al., 2016). Studies driven by Allen et al. (XXX) showed that the increase in rock specific heat capacity with increasing temperature was notable for temperature closed to 0°C. Thermal conductivity of most rock types (i.e. quartzitic sandstone, slate, limestone, marble, calcite, gneiss and granite) tends to reduce with increasing temperature, but the formation of cracks rocks does not systematically lead to a decrease of thermal conductivity. Thermal diffusivity appears to be highly dependent on quartz and feldspar content. Quartz-rich rocks (i.e. sandstone or quartzite) tend to have a high diffusivity, while those with a high feldspar content (i.e. limestone, marble) have a lower diffusivity, that was explained by the poor conductive properties of feldspar. For a similar composition, crystalline rocks moreover tend to have higher thermal diffusivities compared to sedimentary rocks Allen et al. (XXX).

**Low-conductivity horizontal rock layers such as mudstone or coal are finally likely to form cap rocks for the inflow of geothermal heat. If heat is generated from an underlying heat source, this might contribute to the formation of thermal anomalies beneath thick layers of coal-bearing formations.**

\section{Mine-water temperature}

Minewater temperatures reported in the BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984) have been analyzed by (Gillespie et al., 2013). Temperatures measured from nine boreholes in the Midland Valley range from 12 to 21°C, with a mean and median of 17 °C. However, despite the temperature of mine waters generally increases with depth according to the geothermal gradient, no correlation has been found between the depth of the measurements and the observed water temperature in the Midland Valley. Robin (1990) reported a range of temperature comprised between 8 and 15 °C for water circulating above 200 m. In autumn 2008, new groundwater samples were collected from boreholes abstracting water from Carboniferous sedimentary aquifers across the Midland Valley, as part of the Scotland Baseline Project. Four of them originate from abandoned flooded mine workings (i.e. either pumped or from gravity-driven discharge zones). Temperatures of two of the measured pumped mine-water were 11.7 and 14.5 °C, in accordance with the typical temperature of natural groundwater from Carboniferous aquifers in the Midland Valley. Temperature of the sampled mine-water pumped from the Polkemmet mine shaft was 19.2 °C, while the measured temperature of the gravity-driven discharged mine-water was 9.8°C. Average mine water temperatures of 11.5-13.3 °C and 14-15°C were moreover reported for the Crynant, Dulais Valley, South Wales Coalfield (Farr et al., 2016) and Caphouse Colliery (Burnside et al., 2019), respectively.

In their study, Farr et al. (2016) assessed the low enthalpy heat recovery potential from coal mine discharges in the South Wales Coalfield based on water chemistry analysis. Despite relatively constant temperature measured at each of the 16 sites during the monitoring period, temperature differences between each of them were attributed to the position of the logger relative to the surface features. By comparing the mine water temperature to the average monthly air temperature, Farr et al. (2016) showed that measured temperature can be influenced by 1) cold recharge entering the drainage system (i.e. shallow logger in gravity driven adit, correlated with air temperature), 2) localized recharge events such as period of intense rainfall (i.e. adits with transfer pumps with more stable yearly temperature) or 3) the absence of connection with surface recharge (i.e. deep warm water with constant temperature throughout the year). Groundwater of different temperature may indeed enter the borehole at different depths, exchanging heat with the surrounding rocks to a degree that will depend on the flow rate, making it difficult to predict the temperature of the pumped water.

Additional temperature data have been collected by the Coal Authority since 1994 (TO DEVELOP). Those includes temperature time series, acquired from data logger placed closed to the surface in shafts. Shafts are generally capped, and can sometimes be filled by collapsed materials from the mines. Temperature profiles in boreholes are moreover punctually acquired during surveys. Table XXX summarizes the data available for the Bilston Glen - Easthouses area, located in the Midlothian Coalfield. \\

\begin{figure}[htp]

\centering

\includegraphics[width=8cm]{Mine\_T.png}

\caption{Temperature of mine water measured in shafts}

\label{fig:Mine\_T}

\end{figure}