Meeting
31/10/2019

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Summary meeting 23/09/2019

Addressed points	**Progress 30/10/2019**
Characterize sources of heat in mines: Local heat production linked to the type/volume of surrounding rock type Fluid flow/upflow along deep faults Zones of conductive/convective heat transfers Chemical reactions in mines (exothermic reactions)	→ Draw cross-sections + cross-analysis with depth of temperature measurements → statistical analysis (need more data from Coal Authority) → See conceptual models → Case-study specific (requires geochemical analysis?) $FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad \Delta H_r = -1538.4\ \mathrm{kJ/mol}$ (1a) Temperature released to water $= \Delta T = \frac{\Delta H}{C_p}$ at constant pressure
Realize a conceptual model of the mines (~800 m deep) : identify the main sources of heat + expected mine geometry depending on the mining method	→ See conceptual models
Focus research on Midlothian, Middle Valley Coalfield (East MVS)	→ Other possible case studies (see report from meeting w/ Ian) - Mine water scheme in Dawdon/Hawthorn/Seaham (pumping since 2004/2008 + new heat scheme in Dec. 2019) - Lanchester (has been using heat from loop system for 6 months (only 1 MW extracted over 4 MW planned)
Model the potential impact of seasonal temperature variations on shallow subsurface temperature (i.e. depth of influence, contribution of solar input in GSHP schemes)	→ + heat replenishment, recharge from shallow zone/outcrops, advection of water, change in geothermal gradient resulting from mine-water extraction/injection, time for new equilibrium to be reached, heat scheme sustainability, (…)
Scientific guidance for the licensing of heat (i.e. terms of the water-heat access agreement)	
Textbook / references Minewater hydrology textbook (ref: Younger et al., 2002) Banks, D. 2008. Thermogeology: Ground Source Heating and Cooling.	✓ Borrowed from library
Next: Skills to acquire: Numerical modelling Meeting at the Coal authority CASE placement Get in touch with David Manning, Newcastle University	✓ Tutorial Hydrology 2 (GMSH and OpenGeoSys) ✓ Meeting with Ian on the 07/10/2019 ✓ January ✓ Meeting 29/10/2019

Summary meeting at Coal Authority, Mansfield Office, 07/10/2019

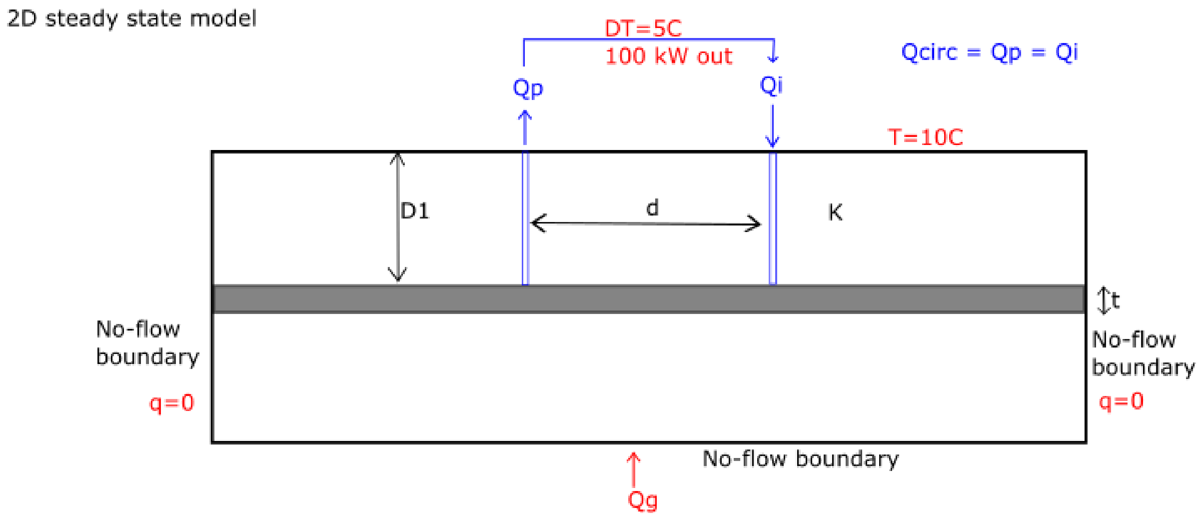
- Meeting Jeremy Crooks, Head of Innovation

- Data overview with Ian
  - Layers of Data accessible at http://mapapps2.bgs.ac.uk/coalauthority/home.html + *Inferis* intranet at the Coal Authority
    - Shafts (geometry and current state) → look at heat transfer above filled shafts
    - Underground workings (seam codes, thickness, type, depth), based on 1 x 2 km digitalized mine plans (more information available on original Mine Plan maps).
      - 3D view at Bilston Glen
    - Spotheight: seam level (floor level, OD)
    - Roadways (may represent major flow path at the bottom of shafts). Unlicensed data > 25 yrs old
    - Monitoring points (outflow, temperature).
    - Coal seams outcrops
    - Geological disturbances
    - Shallow coal (<30 m) + buffer indicating collapse hazards (i.e. Blindwells site: opencast in East Lothian Coalfield)
  - Mine abandonment Plans (*nVision* internal system at the Coal Authority)
  - BGS paper to be published in December (correlation between 100 yrs old rock temperature and current water temperature in the mine)
  - Monitoring data: data available at 260 locations currently being reported in a Summary Excel Sheet (min/max temperature, flow rates at shaft, depth to water…).
    - Temperature
      - Temperature VS time (i.e. Junkies outflow). Continuous logging only at a few sites
      - Temperature/conductivity VS depth (i.e. ETC log, can be repeated over time)
      - Water level logger: inform on the temperature at the depth of the sensor BUT no information on the depth of the sensor. Can inform on seasonal changes in temperature.
      - Manual measurements
    - Pumping tests: step by step increase/decrease in pumping rates over long time periods (6 months – x years) until equilibrium between water recovery/pumping rate is reached

Suggested conceptual models

2D steady state model

- Simulate heat extraction from a single seam with no net inflow / outflow to determine the new steady state heat flow pattern from the surface, together with the lateral extent of the zone influences by mine water extraction.



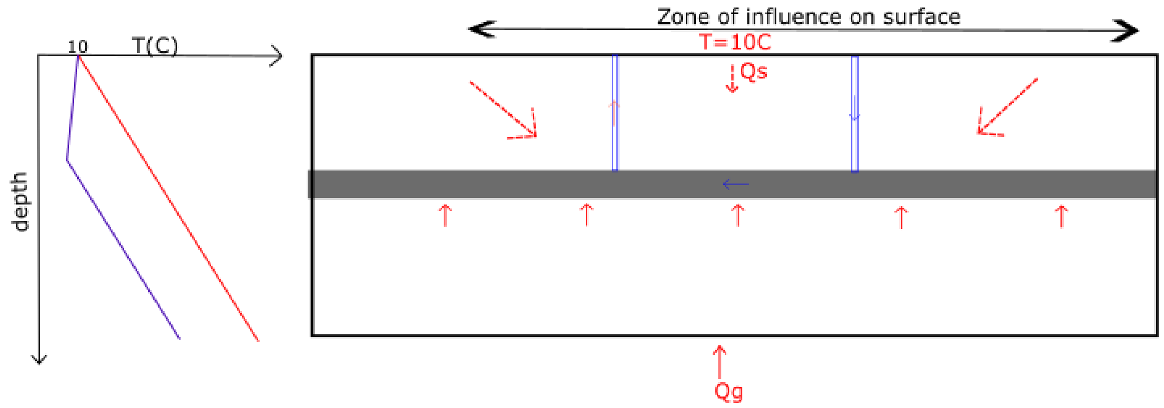
Geometry

- Sensitivity analysis on the model width necessary to determine the minimum lateral extent required to minimize edge effects of the no flow/flux boundaries on the model temperature
- D =100 m [100 – 500 m?]
- d =100 m [100 - 1000 m?]
- t = 2m
- n (seam porosity) = 50%

Boundary conditions:
Borehole abstraction/reinjection modelled as from one cell or as lines
Properties: K (thermal conductivity of sandstone/mudstone)

Questions: To which depth does solar input and/or long-term surface temperature changes affect sub-surface temperature / geothermal gradient?
How does the geothermal gradient re-equilibrate as a result of mine water heat extraction/injection scheme?
What are the effects of seasonal production?

Expected results:



- Decrease in seam temperature due to the reinjection of colder mine water
- Increase in conductive heat exchanges between the host rock (geothermal heat recharge from below) and the coal seam
- Possible negative gradient formed above the coal seam leading to solar heat flux flowing down from the surface
- New steady state reached between solar/geothermal heat recharge and colder water injection (balance + location of solar/geothermal fluxes is of interest)
- The difference between the undisturbed thermal profile (in red) and the new steady state (in blue) represents the heat energy extracted prior to sustainable steady state being reaches (heat mining)

2D steady state model with flow in seam

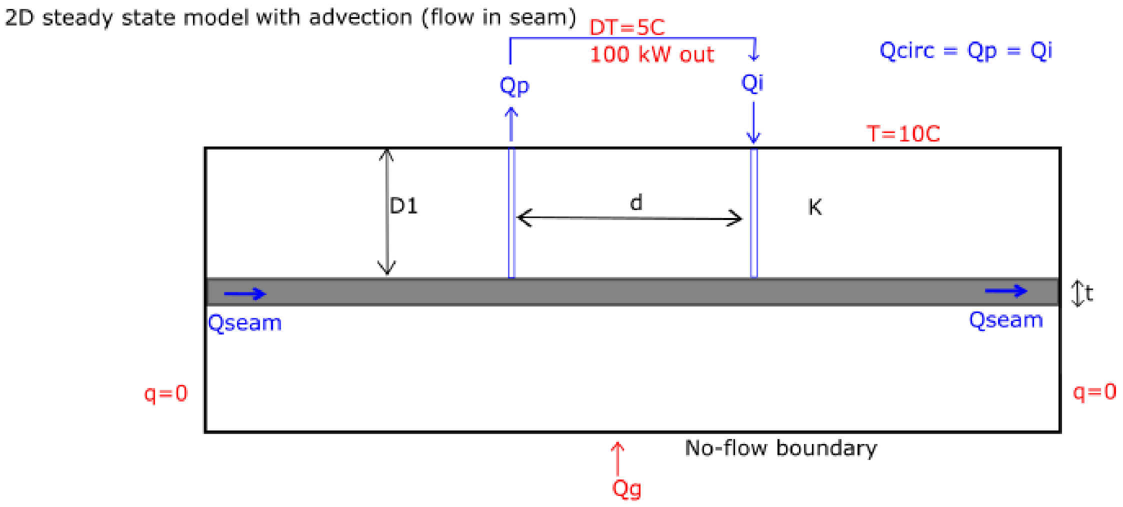
- Regional head gradient is set across width of the model.

Simulate what happens for:

- $Q_{circ} = Q_{seam}$
- $Q_{circ} > Q_{seam}$ (e.g. $Q_{circ} = \frac{1}{2} Q_{seam}$)
- $Q_{circ} < Q_{seam}$ (e.g. $Q_{circ} = 2\ Q_{seam}$)
- If abstraction and injection wells are swapped
- If injection is stopped (i.e. $Q_p > Q_i$)

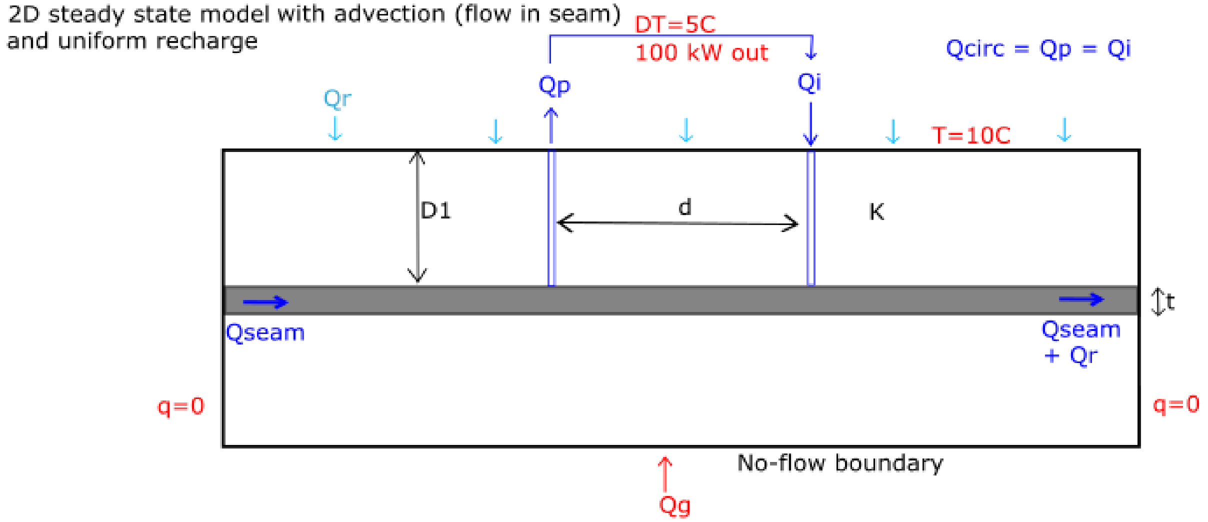
Constraints:

- Modelled regional gradient needs to remain close to what is typically observed ([1:500 – 1:1000]
- Abstraction/injection rates: [10-40 L/s]



2D steady state model with flow in seam and uniform recharge

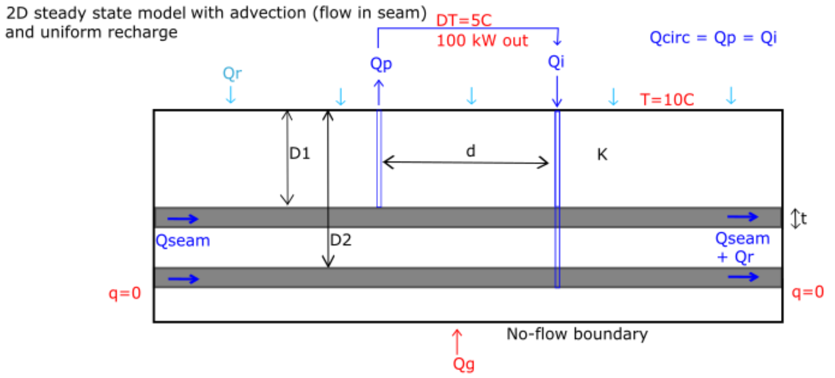
- Flow is induced both along the seam (horizontal flow mainly) and the host rock / strata (vertical flow mainly).



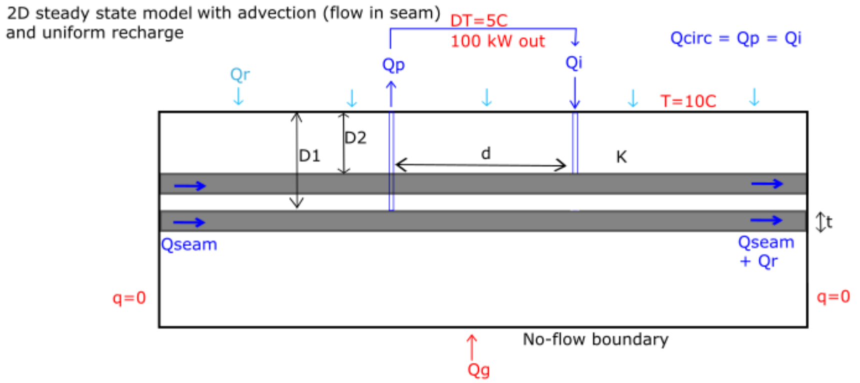
Question: Does the adjective heat flow from surface in the recharge make a significant difference?

2D steady state model with flow in seam and uniform recharge + other features

- Seam below (+ reinjection)



- Seam above (+reinjection)

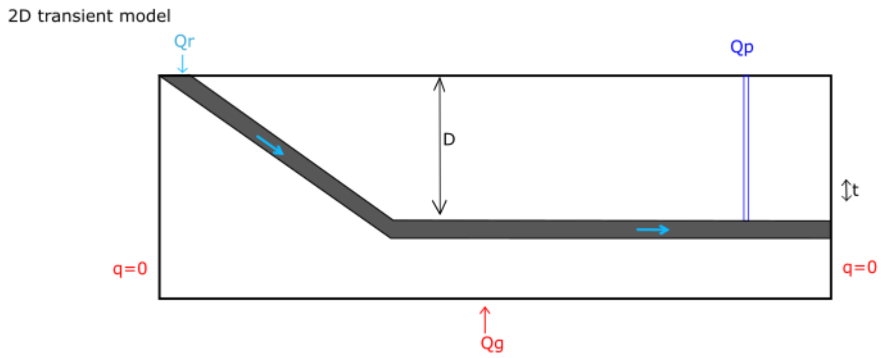


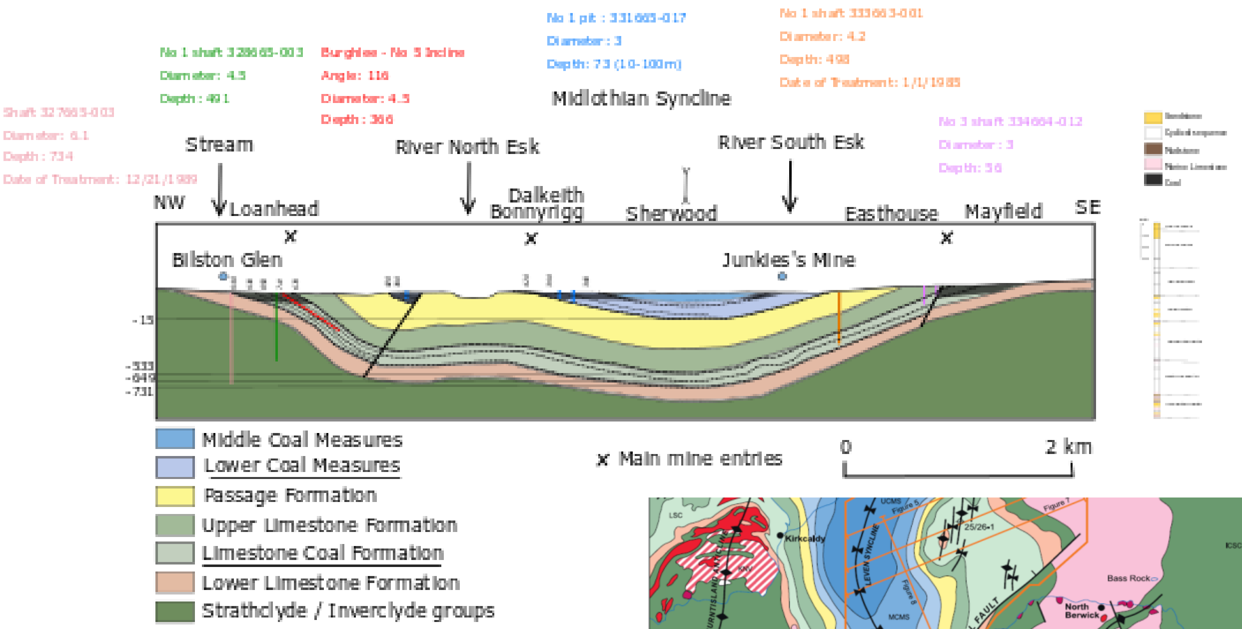
+

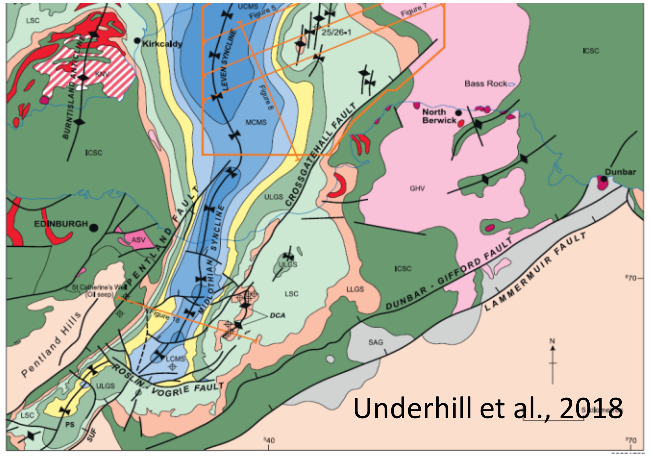
- Interconnections between seams?
- Infilled mine shaft close to the boreholes
- Solar seasonal fluctuations?
- Different mined seam geometries (e.g. goaf / open voids)
- does the number of coal seam affect heat storage/recharge rate ?

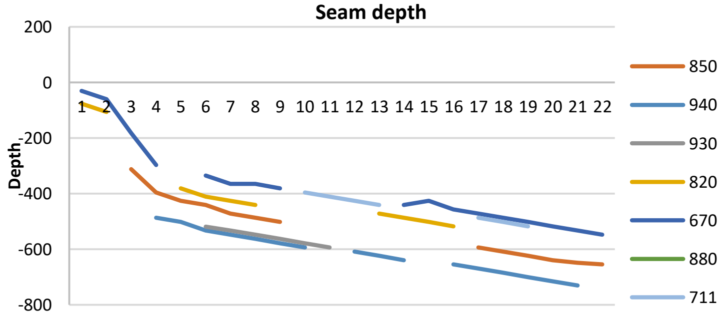
Transient model

- Objective: determine the time to reach the new steady state or breakthrough time.









Geometry: include more realistic geometry such as a dipping layer / seam from outcrop (i.e. Bilston glen, Dawdon and Hawthorne areas) allowing recharge to flow down.

Question: can the temperature of Q be predicted by modelling?

How local geology / mine workings geometry affects mine water temperature (i.e. recharge/infiltration rate, water-rock heat transfers)

Numerical approach

Production =
Injection rate

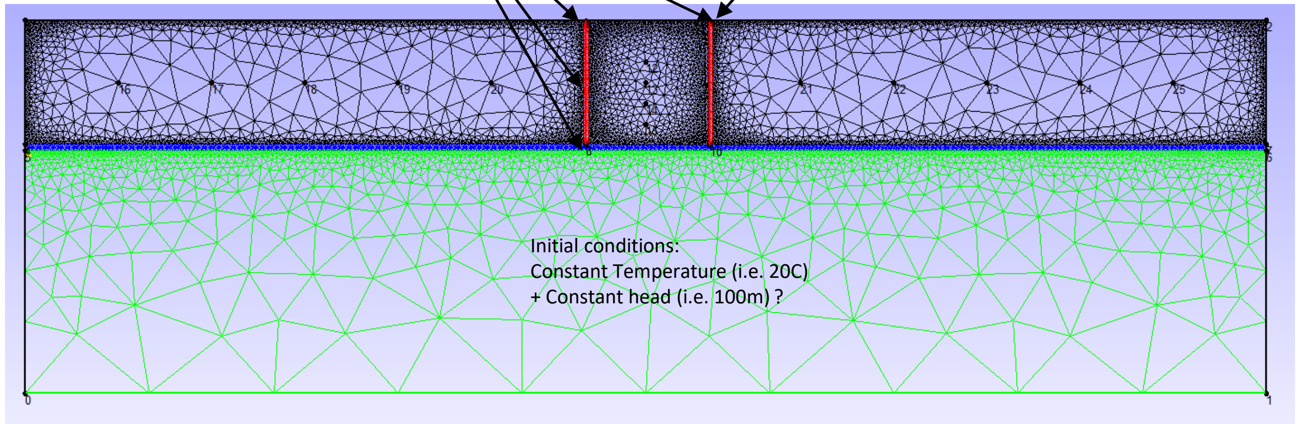
Tinj = 15C

??

Constant temperature (10C) + No flow hydraulic BC

No flow BCs

Or constant head ? i.e. 100m



Initial conditions:
Constant Temperature (i.e. 20C)
+ Constant head (i.e. 100m) ?

No flow BCs

Or constant head ? i.e. 100m

Constant thermal flux + No flow hydraulic BC

Data from Raymond and Therrien (2008)		WORKINGS	HOST ROCK
Hydraulic conductivity (m/s)		2.30E-02	4.50E-05
Porosity		0.25	0.05
Storage (m-1)		2.00E-04	1.00E-05
Transient flow simulation	Q = 0.062 m3/s		
Steady state flow simulation	Infiltration flux at surface node = 140 mm/yr		

Data from Hamm and B.Bazargan (2010)	
Ratio gallery/shaft and rock permeabilitie	1.00E+06
production rate	600 m3/h

Data from Guo et al (2018)	Density	Thermal conductivity (W/m.C)	Heat capacity (J/kg.C)	Porosity (%)	Permeability (m2)
cap rock	2650	2.1	900	1	1.00E-17
fractures zone matrix	2650	2.1	900	5	2.00E-16
fractures zone fractures	1500	2.1	900	70	1.30E-09
caved zone matrix	2650	2.1	900	5	2.00E-16
caved zone fractures	1500	2.1	900	70	2.50E-08
base rock	2650	2.1	900	1	1.00E-17

Group	**0**	**1**	**2**	**3**
Medium	TOP	WORKING	BOTTOM	WELLS
Porosity	0.05	0.25	0.05	1
Tortuosity	1	1	1	1
Storage (specific storage, m-1) if transient	1.00E-05	2.00E-04	1.00E-05	0.00E+00
permeability tensor (hydraulic conductivity, m/s)	4.50E-05	2.30E-02	4.50E-05	1.00E+00
mass dispersion	0	0	0	0

→ Do not work, check input files

Literature review

Conceptual models

Boundary conditions

Thermal

Average air temperature
--> Constant surface temperature, seasonal variations?

No flow lateral boundary

Hydraulic

Constant head (i.e. river)
Constant flux (i.e. if recharge by precipitation + infiltration)

No flow lateral & bottom boundary

Sink / sources

Aquifer + GW recharge
Seawater recharge
Injection + extraction:
--> Flow rate + Temperature (of reinjected water)
Exothermic reaction
Heat flux

Initial conditions

Steady-state temperature
Pre-pumping head
Regional groundwater/ Mine dewatering conditions (Szczepinski, 2019)

Geometry

Rock Mass

Mine workings:
- Shallow Mineworkings
- Intermediate Mineworkings
- Deep mineworkings
(Whitworth, 2002)

Channels:
Shaft, drift, roads, tunnels

Structural/hydraulic barriers (i.e. Faults)
(Banks et al., 2010)

Rock thermal properties:
- thermal conductivity
- specfic heat capacity
- hydraulic conductivity / permeability
- effective porosity
- specific storage coefficient ...
(Raymond and Therrien, 2008)

PROCESSES

Laminar flow
Conduction

Residual void volume:
Depends on volume of mining coal + subsidence (i.e. Guo et al., 2018)
=(mines area x seam thickness) x 0.25 [correction factor accounting for subsidence/pillars/backfilling] (Jessop, 1995)
= 10% thickness extracted (Whitworth, 2002)

Longwall Mining (voids backfilled)

room-and-pillar (voids left empty)

Porosity, length, radius of channel

Turbulent flow

Lateral/vertical interconnectivity (Watzlaf and Ackmann, 2006)

Free/Forced Convection (Burnside et al., 2016; Hamm and Bazargan, 2010)

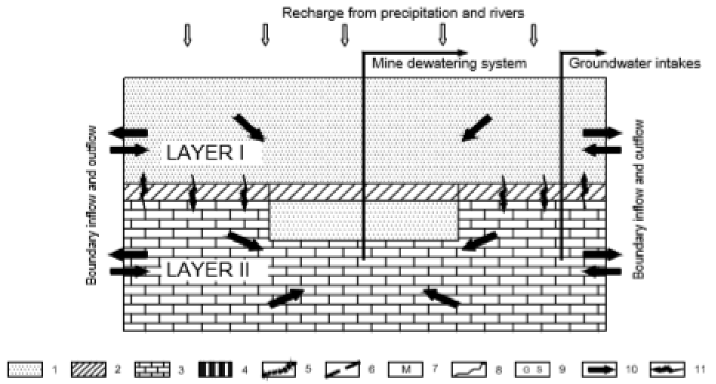


Figure 1. Simplified geological cross-section N-S with the conceptual model suitable for numerical modelling. Explanation: 1—porous, permeable formations; 2—impermeable and slightly permeable formations; 3—fissured-karstic formations; 4—lignite; 5—boundary of the Quaternary aquifer; 6—faults; 7—symbols of aquifers; 8—open-pit limits; 9—dewatering wells barriers; 10—direction of groundwater flow; 11—direction of groundwater percolation [33]. Szczepinski, 2019

K. R. WHITWORTH

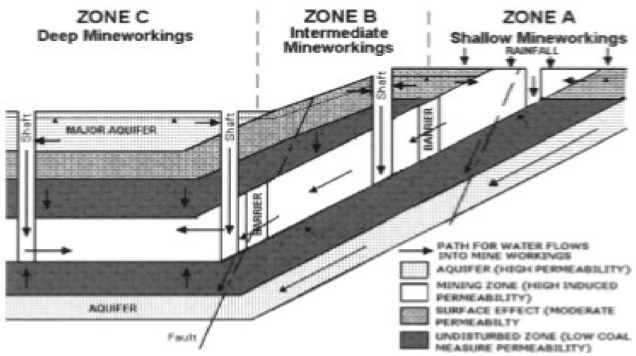


Fig. 10. Schematic diagram of a general conceptual model for water inflow to mine workings.

EFFECTS OF LONGWALL COAL MINING ON AQUIFERS 25

BOOTH, C.J., 2002

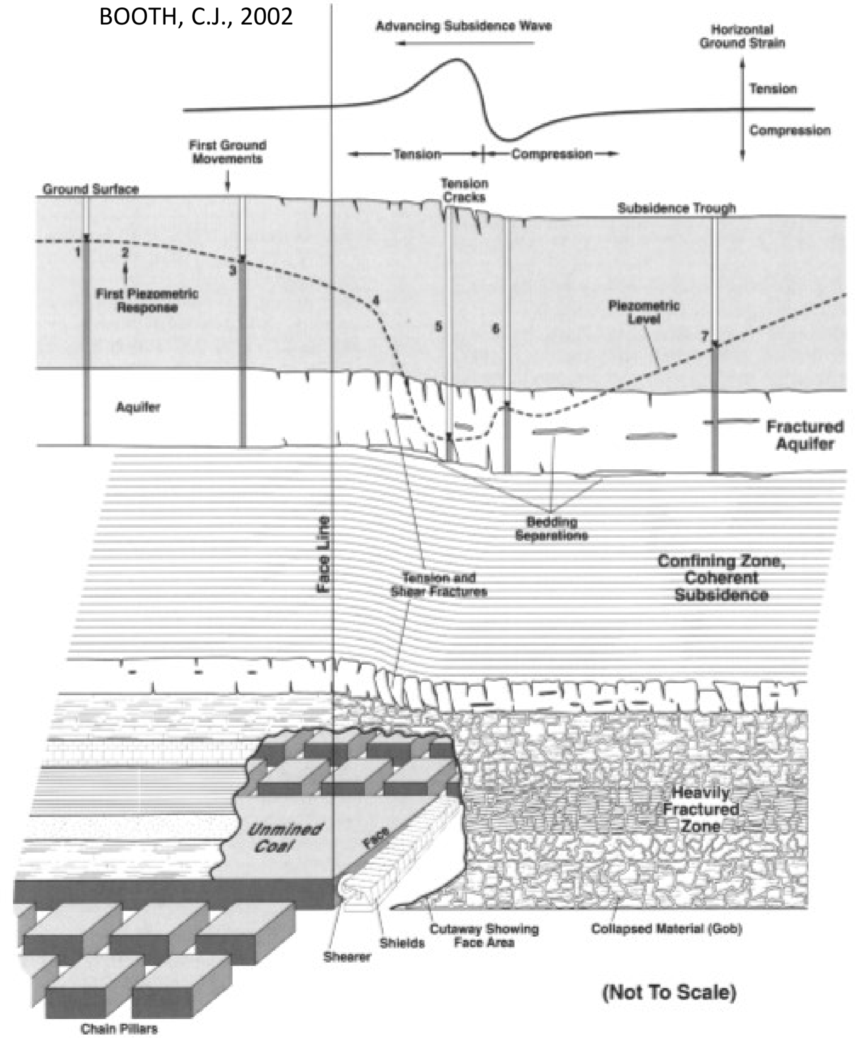
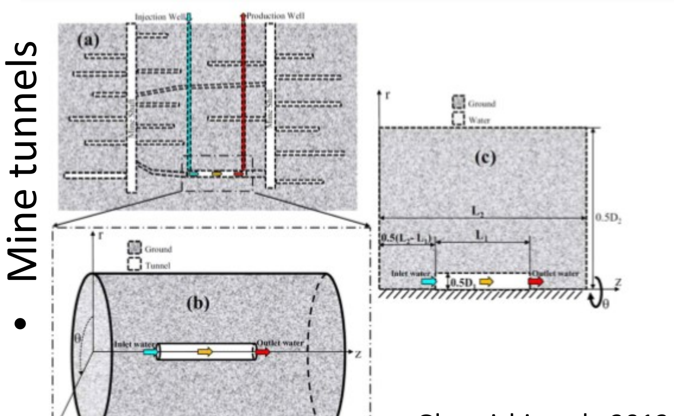


Fig. 3. Conceptual model of potentiometric response to longwall mining. From Booth *et al.* (2000). Reproduced with permission of the Association of Engineering Geologists (*Environmental and Engineering Geoscience*).

Numerical models

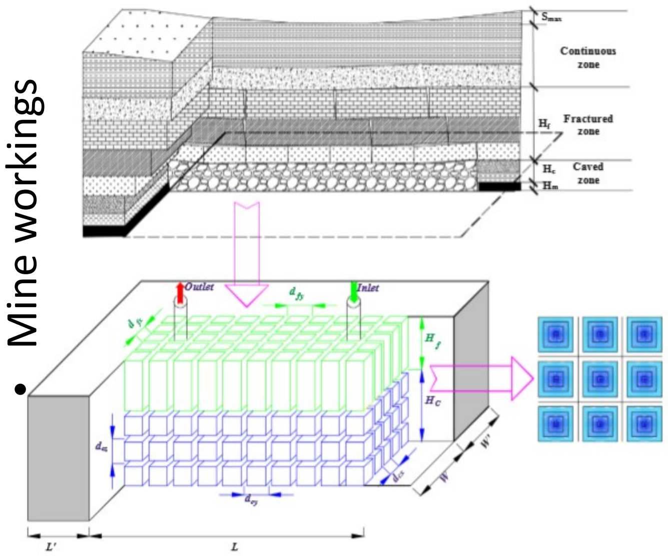
- Mine tunnels



Ghoreishi et al., 2012

FIG. 1. (a) Underground mine schematics, (b) 3D demonstration of the model, and (c) 2D demonstration of the numerical domain.

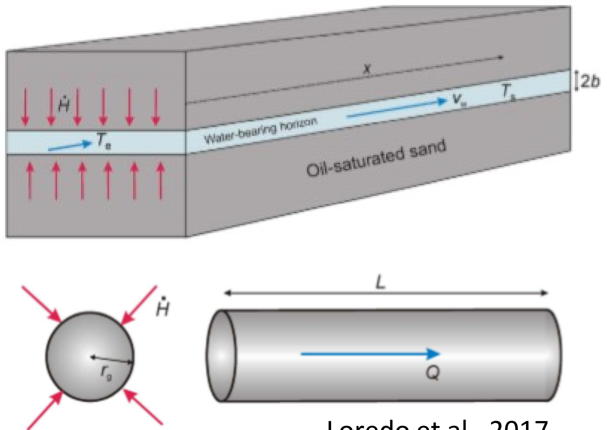
- Mine workings



Guo et al., 2018

Fig.1. Model of abandoned coal mine workings reservoir.

Analytical Models



Loredo et al., 2017

Distribution of void space in mines (Banks et al., 2010):
→ workings void
- depends on worked seam dimensions/dip
- based on geometric/geotechnical calculations

→ void space in tunnel, drifts and galleries (Rogoz et al., 1999)
- depends on dimensions of tunnel / shaft
+ correcting factor for compression/backfilling

→ Voids in fractures induced above workings

→ Voids in pores in dewatered aquifer strata (related to specific yield) — numerically negligible in overall void budget

1 Heat extraction from mine tunnel (Goreishi et al., 2012)

- Analytical model (Loredo et al., 2017)
  - Lauwerier-Pruess-Bovardsson model (1955,1983) Circular tunnel + radially divergent conductive heat transfer (porosity = 1 for tunnels and [0-1] for mined rock) → Formula derived for a planar fracture with aperure b --> conservative values
  - Rodriguez and Diaz (2009) Radial divergent heat conduction from/to tunnel → Approximation over-estimates radius of thermal front + Nu assumes turbulent flow
- Numerical model → Forced convection inside gallery + conduction in the rock mass Ignore infiltration through rock mass) (Ghoreishi et al., 2012)

Results:
- zones of influence around the tunnel depends on:
  - Tunnel diameter
  - Abstraction rate
- need appropriate Nu number (if laminar flow)

2 Goaf = Main Thermal reservoir

Continuous zone (Guo et al., 2018)

Zone of surface cracking
Aquiclude (confining) zone
Fractured zone (anisotropic)
Caved zone (isotropic)
Coal Seam
(Singh and Kendorski, 1981 in Booth, 2002; Guo et al., 2018)

→ Dual-porosity medium
- Primary porosity = small fractures / pores in matrix
- Secondary porosity = mining induced fractures

Results:
Geothermal potential depends on:
- Fracture permeability
- height of fracture zone

3D Numerical models: Case study

Lorraine (France) coal mines
(Hamm and Bazargan, 2010)

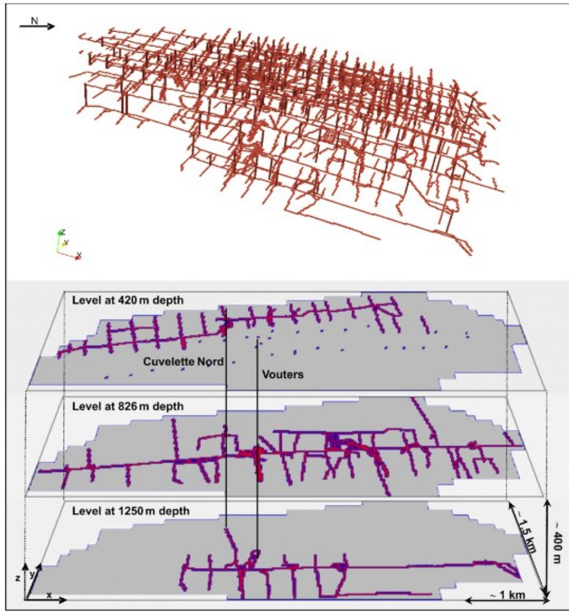


Fig. 7. View of the network of galleries in the Vouters mine (high permeability mesh used in the MARTHE code).

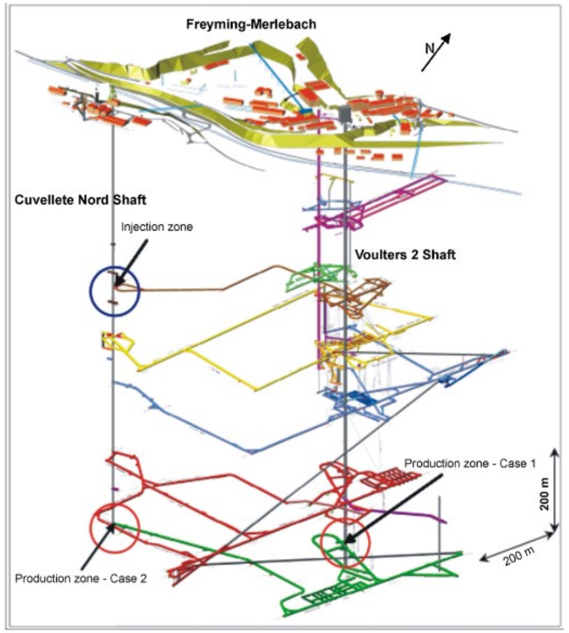


Fig. 8. Production and injection locations assumed in the model.

Set up:

1) Exchanges between shaft and surrounding rock

2) Fluid/heat transport in porous media:
- high velocity/pososity in shaft/galleries
- low velocity in rock mass

No hydraulic connections between production zone / upper galeries

Results:

1) - free density-driven convection before production = main heat transfer in borehole (induce intra-well mixing), depending on DT, size of channels & water properties.
   - forced convection (pumped water from shaft) = induce slight temperature decrease, depending on pumping rate (jessop, 1999)

2) important parameter: ratio gallery/shaft to rock permeabilities

Typical longwall panel
in the Pittsburgh CoalBed (Eastern US)
(Esterhuizen and Karacan, XXX)

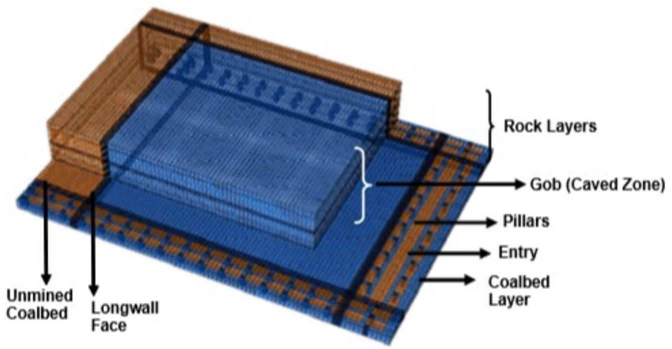
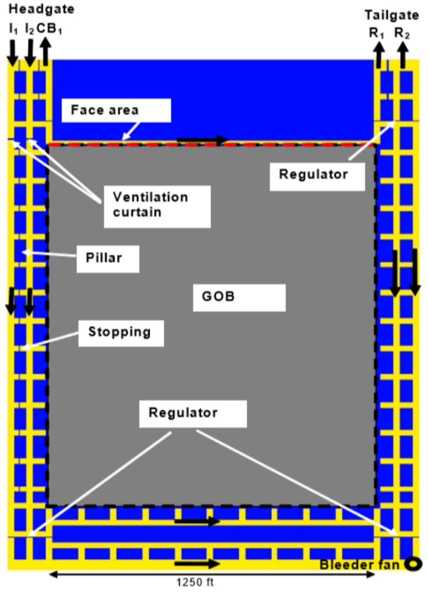


Figure 7. A three dimensional grid model of the gob and the mining layer. The top layers were cropped to visualize the modeled mining layer.



3 reservoirs sections:

- undistrubed rock unit (pre-mining propertie)
- goaf (using heterogeneous k from geomechanical model)
- tailgate/headgate entries + longwall face in mining layer

1) typical dimensions of a panel (1650 x 2300 ft)
2) thickness = typical thickness of caved zone + 12 overlying rock layers
   - high-k "fully caved" zone = ~ 1.5 x mining height
   - total caved rock height =~ 4-6 x mining height (Mucho et al., 2000)

Permeability distribution in goaf ("fully" and "partly caved" zones) calculated from modelled bulking factor (depends on block size and fall height) + goaf compaction, using the Carman-Kozeny equation

3D Numerical models: Case study

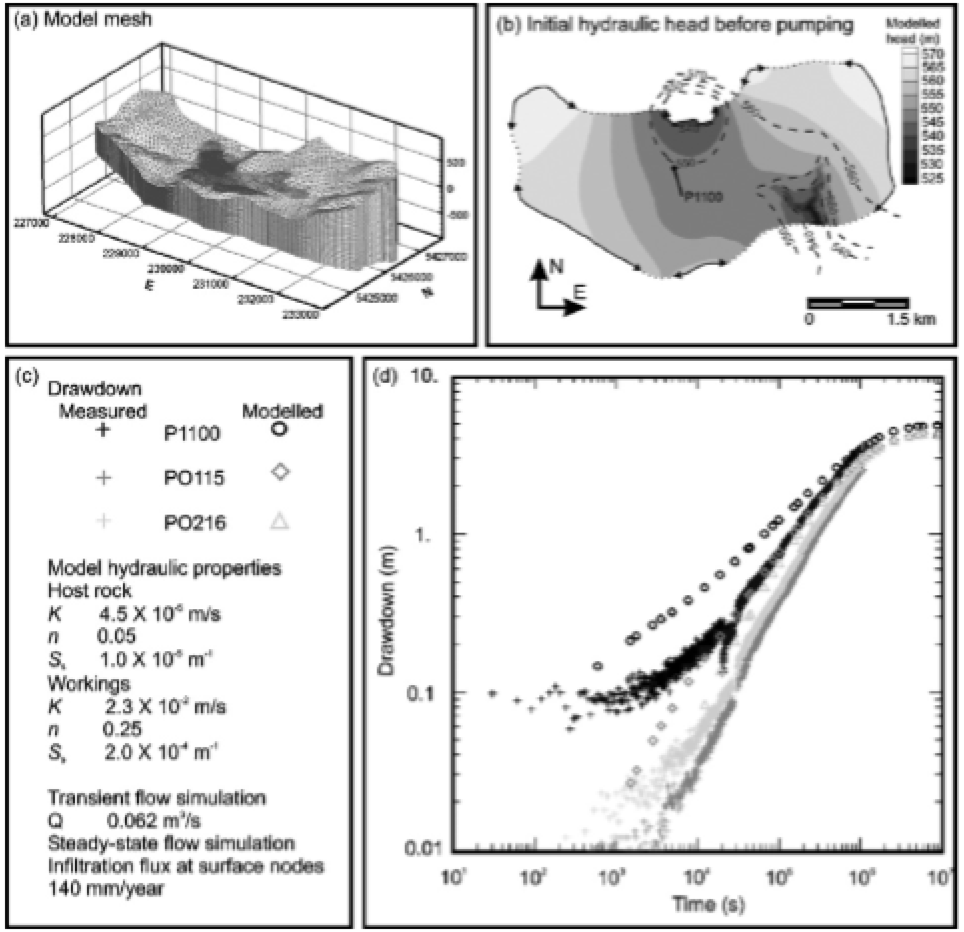


Fig. 7. Model mesh and simulation results obtained during model calibration. (a) Coordinate system (in m) used is the Modified Transverse Mercator NAD83. Legend on the vertical axis shows elevations (m asl). (b) The initial hydraulic heads before pumping shown in plan view were obtained by steady-state fluid flow simulation. The constant head (solid lines with arrows) and impermeable boundaries (dotted lines) and the measured water table elevation (dashed lines) are shown with simulation results. Black dot corresponds to the location of shaft P1100 at ground surface. (c) Model hydraulic properties. (d) Modelled drawdown obtained by transient flow simulation.

Gaspe Mine, Quebec
(Raymond and Therrien, 2008)

Detailed site characterization (geology, hydrology, water levels)
+ mine geometry (depth & workingsm shaft, roads interconnections)
+ rock properties

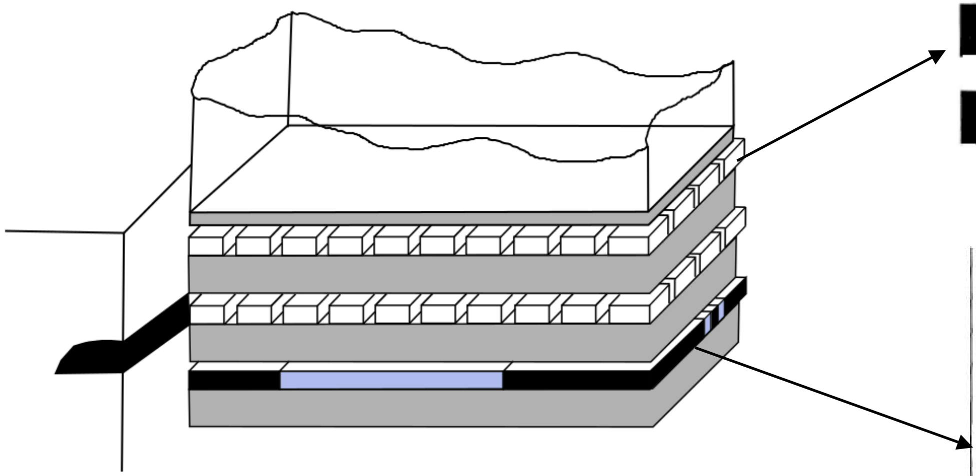
Road/shafts = 1D line elements (pipe flow)
Workings = 3D porous subdomain of high K
Host Rock = 3D porous medium of low K

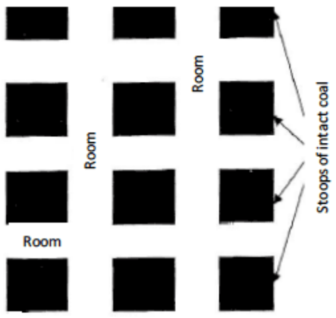
HydroGeoSphere code (Therrien et al., 2004)
solves silmutaneously for
- 1D pipe flow
- 3D laminar flow

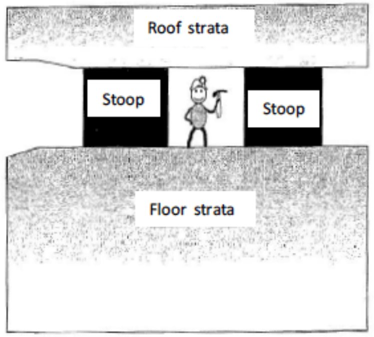
Assumes homogemeous K, n, S for each sub-domain

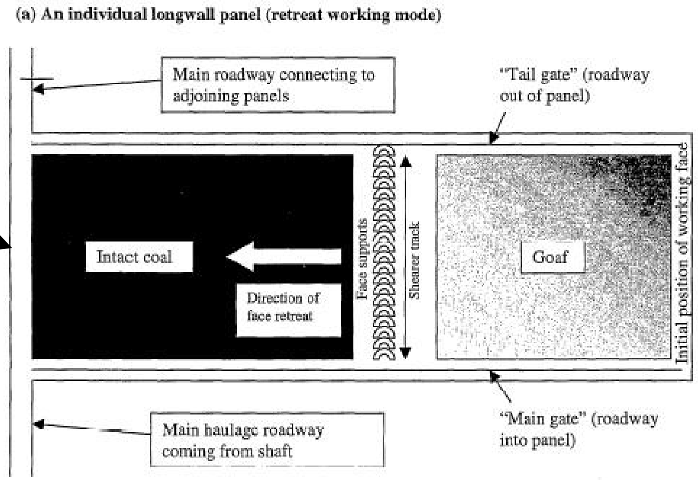
What more can be brought compared to Raymond and Therrien (2008) model ?
(i.e. model does not consider fracture zone, whereas height of fracture zone
has proved to be essential by Guo et al (2018)
+ use corrected geothermal gradient as initial conditions ?

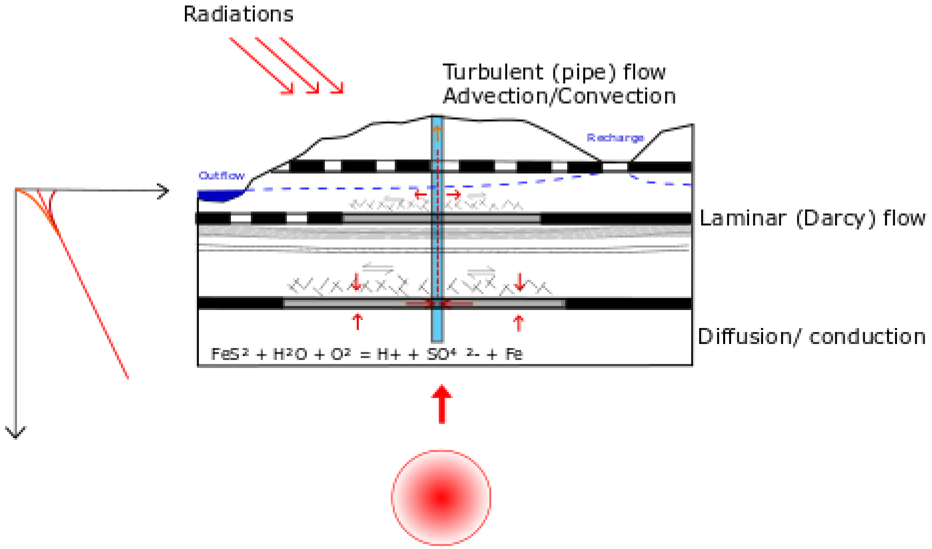
Summary




Room
Room
Room
Stoops of intact coal


Roof strata
Stoop
Stoop
Floor strata


(a) An individual longwall panel (retreat working mode)
Main roadway connecting to adjoining panels
"Tail gate" (roadway out of panel)
Intact coal
Direction of face retreat
Face supports
Shearer track
Goaf
Initial position of working face
Main haulage roadway coming from shaft
"Main gate" (roadway into panel)


Radiations
Turbulent (pipe) flow
Advection/Convection
Recharge
Outflow
Laminar (Darcy) flow
Diffusion/ conduction
FeS² + H²O + O² = H+ + SO⁴ ²- + Fe

Research question: toward confirmation report

- **Topic of research**: “Conceptualize Mine-water temperature” (thanks Fiona)
- **Main research question**: Why different mines have different temperatures?
- **What is to be found ?**
    - What is the main control on mine-water temperature
    - The extent / zone of influence of the heat supply around the well
    - The heat storage/recharge mechanisms in a mine under reinjection scheme
    - The impact of solar energy
- **What is one reason this research matters to the field:**
    - Predictive tool to assess sustainability of heat supply from mine water
    - Guide the licensing of heat
- **Suggested chapters**
    - I. Conceptual model, mathematical approach, sensitivity analysis.

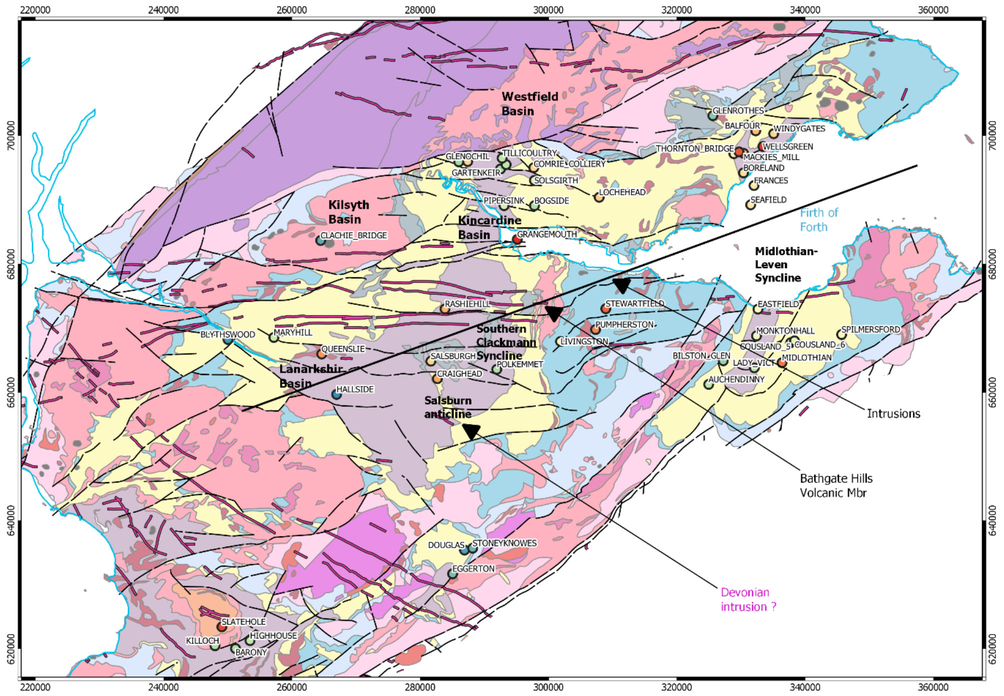
    → Where does the heat comes from ?
    - II. Case study (i.e. Midlothian) : calibration and validation of model.

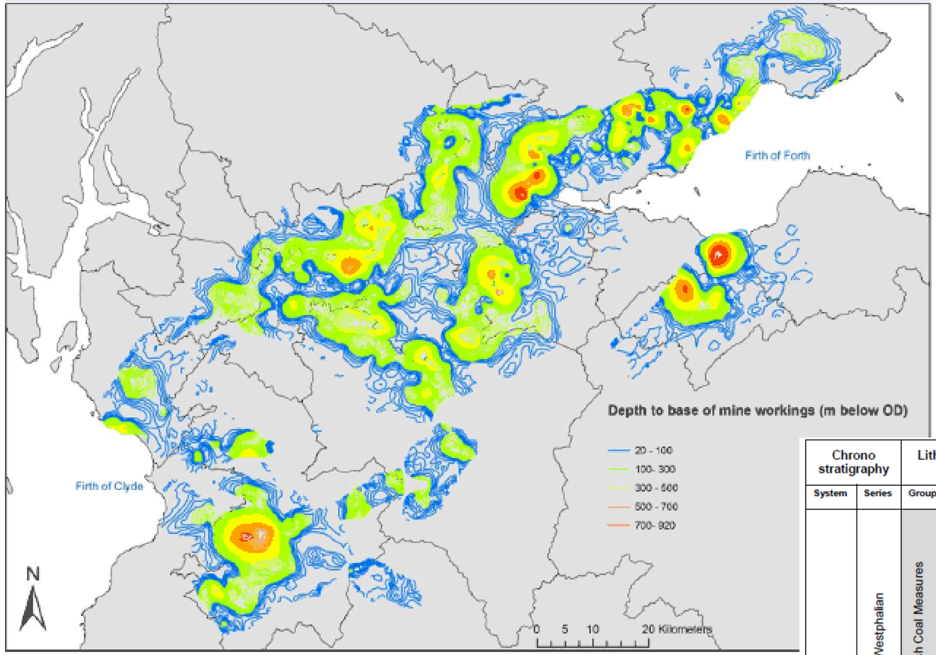
    → What is the extent of the zone of influence of heat mining? What are the recharge mechanisms ?
    - III. Why different mines have different temperatures ?

    → compare modeling results from different mines in the UK with different geometries (validate model)
    - IV. Conclusion: Can the model used as a predictive tool and how can it guide the licensing of heat ?
- **Required data:**
    - Case study to be selected if sufficient amount of data available

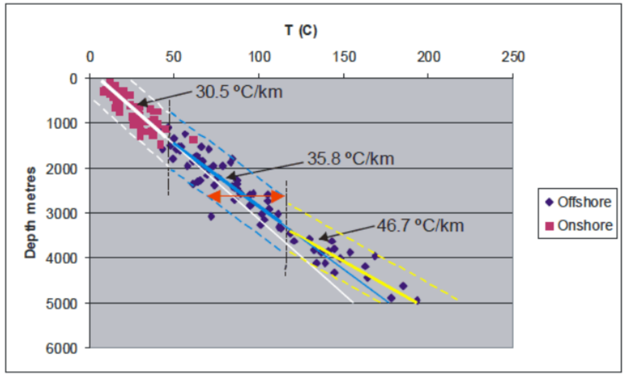
    (i.e. temperature profiles, temporal evolution of surface / bottom-hole temperatures,
    + discharge / flow rate with seasonal variations) + geothermal potential in the area
    - Chemical analysis + maps of recharge / discharge area of coal mine water to determine water origin (BC of the models)
    - High-resolution heat flow maps (identify potential anomalies)
    - Flooding history/pumping tests (pumping rates for mines having a remedial scheme)

Comparison between mines





Chrono stratigraphy		Lithostratigraphy		Lithological summary	Number of coal seams mined				
System	Series	Group	Formation		Ayrshire	Douglas	Central	Fife	Lothians
Carboniferous	Westphalian	Scottish Coal Measures	Scottish Upper Coal Measures Formation	Sandstone, siltstone, mudstone and seatearth in upward-fining successions. At least 750 m thick under the Firth of Forth and 560 m thick in Ayrshire, although not more than 300 m are preserved elsewhere onshore.	0	0	0	0	0
			Scottish Middle Coal Measures Formation	Upward-coarsening sequences of coal, siltstone, and sandstone predominate. Thickness varies: between 300 and 550 m in Fife and Lothian; as little as 150 m in North Ayrshire; over 600 m at New Cumnock	7	5	9	8	5
			Scottish Lower Coal Measures Formation		10	9	9	6	9
	Namurian	Clackmannan	Passage Formation	Fine- to coarse-grained sandstone with some quartz-pebble conglomerate, clayrock, seatearth and coal. Thickness varies from 10 m near Hamilton and parts of Ayrshire to 380 m in the Clackmannan basin.	1	0	0	0	0
			Upper Limestone Formation	Upward-coarsening sequences of mudstone, siltstone and fine- to medium-grained sandstone capped by seatearth and coal. Ranges in thickness from 10 m in parts of Ayrshire to 600 m in the Clackmannan basin, although to the east it is partly replaced by volcanic rocks.	4	3	0	1	1
			Limestone Coal Formation	Repeated successions of mudstone passing upwards into siltstone and fine- to medium-grained sandstone, then seatearth and coal. Virtually no limestone. Thickness ranges from less than 10 m in parts of Ayrshire to more than 550 m in the Clackmannan basin.	13	10	5	12	18
	Visean	Strathclyde	Lower Limestone Formation	Cyclic sequence of sandstone, mudstone, coal, and marine limestone.	0	0	0	0	0



Rock type	Character	K (W/m/K)	Reference
sandstone	sedimentary	3.3-4.9	Lee et al., 1984
mudstone	sedimentary	1.5-2.2	Lee et al., 1984
limestone	sedimentary	2.8-3.0	Lee et al., 1984
coal	sedimentary	0.31	Lee et al., 1984
slate (metamudstone)	metamorphic	2.7	Lee et al., 1984
basement metasediment	metamorphic	3.51	Lee et al., 1984
basement metasediment	metamorphic	3.1-3.5	Wheildon et al., 1984
granite	igneous	3.0-3.5	Wheildon et al., 1984
granodiorite and tonalite	igneous	2.5-2.9	Wheildon et al., 1984
dolerite and basalt	igneous	2.2	Lee et al., 1984
peridotite	igneous	2.2	Wheildon et al., 1984

Meeting 29/10/2019, David manning, Stuart

- New 2km deep borehole near Newcastle
- Potential data sources: Lanchester Wines, UK Geo Glasgow Observatory
- Visit of open pit mine

Giant 2km borehole project fails to bring hot water to Newcastle businesses 73 C water.

Landmark renewable energy project fails to bring hot water to Newcastle, but council have come up with another low-carbon plan

The Newcastle borehole will remain an important research site nationally and has at least shown the possibility to explore geothermal heat in Tyne and Wear.

Next

- London Conference: https://www.geolsoc.org.uk/GSL-7th-London-Geothermal-Symposium

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